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Analysis of the EBR-I Core Meltdown

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The EBR-I reactor has been described in detail;[1,2] but for easy reference, a brief summary of the description is presented here. It is U^{235} fueled, unmoderated, NaK cooled and is reflected with natural uranium. The enriched part of the core is about 8½ in. high and is a hexagonal array of over 200 rods a little less than ½ in. in diameter, the array being about 7½ in. across flats. These rods also contain natural uranium, extending 4 in. below the core and 8 in. above. The core section is separated vertically from the internal blanket which is an array of natural uranium rods about 8/10 of an inch in diameter and 20 in. long. The core section and internal blanket are cooled by NaK flowing down through the internal blanket into a lower plenum, then up through the core and out to the heat exchanger.

This cooling system is arranged so that any flow rate from no flow to full flow can be obtained. In the shutdown condition the NaK in the core and outer blanket is isolated from the primary cooling system and a natural convection loop by-pass to a small heat exchanger is formed. This allows the system to cool itself during shutdown.

Surrounding the sodium retention tank on the sides and at the bottom is the air-cooled outer blanket cup made up of natural uranium bricks. It can move vertically on a hydraulic elevator until the entire core is exposed. During normal operation this cup is run slowly up or down and its position is very seldom adjusted. On a reactor scram the cup drops rapidly. Fine shim control rods are located in this, the outer blanket, while six boron carbide safety rods are located in the first ring of the internal blanket at the points of the core hex. These safety rods are forced rapidly out of the reactor on scram. Moving with the safety rods on scram is a fast-acting natural uranium plug constituting the lower central part of the outer blanket cup.

EXPERIMENT

It had been found earlier that the reactor had a prompt-positive power coefficient of reactivity under abnormal operating conditions where the ratio of power-cooling rate was abnormally high and the rate of change in power level was abnormal. To investigate the resulting instabilities the transfer function for the reactor was obtained experimentally through a series of oscillator tests both at high power, intermediate power and very low power with varying ratios of power level to coolant flow rate.[2] To provide additional information for the analysis it was decided to repeat an experiment performed some time earlier in which the reactor was started from critical at very low power (a few watts) on a period of about one minute, and the power allowed to rise. In the previous experiment the ratio of power to the time derivative of the power was found to decrease continuously until it had reached a value of about six seconds, whereupon the experiment was terminated. Because of time lags introduced by the use of the slow power indicator (optical galvanometer) and thermocouple recorder in this first experiment, the proper relation between reactivity, temperature and power was not determined.

For the new experiment the power level indication was to be obtained on a Brush recorder, the signal being taken from a compensated $B^{10}F_3$ ion chamber. A thermocouple attached to one of the central fuel slugs was arranged to record coincidentally on the second Brush channel. A second fuel slug thermocouple was arranged so that a recording was obtained on a Leeds and Northrup Speedomax Recorder, having a two-second full-scale swing time. In addition to this a third thermocouple, which is normally used during operation to record fuel slug temperature, was attached to a Brown 24-hour circular chart recorder. The operating pile period meter was disconnected from the scram circuit. Two power level scram circuits were used with the trip setting well above the normal operating power of 1150 kw. The reactor cooling system was in shutdown condition with the natural circulation loop, containing about 50 gallons of NaK, flowing at 1.5 gpm. The temperature in the core was 65°C. A record is kept of the inlet and outlet NaK temperatures and of flow rate for the loop on 24-hour circular recorders. For operation the current from a $B^{10}F_3$ chamber is shown on a Brown strip chart recorder up to about 30 kw. Above this power the optical galvanometer is used.

The reactor was made critical at an initial power level of about 11 watts following the normal procedure. The power level trace on the Brush recorder was calibrated against the normal reactor instruments. The reactivity was increased by use of the control rods until the reactor was on about a 60 second period.

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This took about 200 seconds from time mark 0, and the power level had reached about 50 watts. The power level increased at this constant period until 320 seconds from mark 0 at which time the level was 500 watts. The "period" here is defined as the power divided by the time derivative of the power. From this point on, the "period" began to decrease at an increasing rate. Four hundred and ninety-seven seconds from mark 0, the period had evidently shortened considerably and the power level was approaching half of normal operating power as observed on the optical galvanometer. The fuel element temperature indicated on the Leeds and Northrup recorder was beginning to increase. The shutdown signal was given, and the safety rods and plug were scrammed at about 499 seconds from mark 0. This caused the optical galvanometer to hesitate only momentarily. When it became evident that the reactor was not shutdown, but that the power began increasing above normal operating power, the reactor scram button was pushed and at the same time an instrument scarm was indicated aurally and visually. On the reactor scram signal the natural uranium outer blanket cup dropped from around the core and internal blanket.

Immediate examination of the Brush trace indicated that although it had gone off scale for about 2 seconds the power level was rapidly decreasing and the reactor was sub-critical. Available thermocouple readings were examined. The fast Brush trace indicated that the thermocouple was not recording fuel temperature at all but apparently had become shorted out even before the experiment began and was recording NaK temperatures well away from the region of the fuel. A maximum reading of about 200°C was obtained here. The Leeds and Northrup recorder also indicated that either before the experiment or during the course of the experiment, especially the latter stages, its thermocouple was not reading the fuel slug temperature but was reading a temperature close to the fuel slug, since its peak recording was only about 350°C. The shape of these two temperature records was typical of that which would be obtained as a sharp front heat wave passed through the medium whose temperature was being recorded. The temperature trace coincident with the power trace on the Brush recorder indicated that the heat wave did not hit the thermocouple until about a second after the power peak, just about the time the power trace came back on the scale. The power peak would have been caught on the Brush recorder if the signal had been attenuated by a factor of 10 as had been done when the pen reached the upper limit of the chart several times previously during the power rise. This is indeed unfortunate since this was probably the first real opportunity to accurately record a large accidental power surge.

Examination of the operating thermocouple record on the 24-hour circular chart indicated that this thermocouple had remained in operation and that the peak fuel slug temperature recorded was about 650°C. Because of the long full-scale swing time of this instrument it was obvious that the temperature had not been followed accurately, and that the peak had been missed.

The pumps were started and the primary coolant circuit put in operation, but it was immediately evident that the natural circulation in the loop was adequate to take care of the shutdown heating. Shortly after the pumps started a NaK radioactivity level alarm went off. This indication, along with the indication of a flow block, made it clear that the core had been damaged and that some melting had occurred. From the off-scale time of the power trace and the last apparent period it was estimated that the power increase could have continued for about one second, with a peak value < 15,000 kw. By this time Health Physics instruments indicated that there was air contamination in the building and it was evacuated until an adequate survey could be made. This survey indicated a low-level contamination by fission product gases which had evidently come out of the hole in the shield through which a bundle of thermocouple wires passed. There was no significant exposure of operating personnel, although very small amounts of thyroid activity were recorded.[3]

ANALYSIS

The original purpose of this experiment was to obtain the reactivity coefficient both for reactor power and for fuel temperature. Examination of the experimental data available indicated that the power-time data from the Brush recorder was valid, but that since the thermocouples failed to function on the fast record, no matched fuel temperature data was available. Using the power-time data the reactivity-time data could be obtained from the kinetics equations. Total energy release-time data could also be obtained by integration of the power-time records. Calculation of the heat balance at each point in time, coupled with information on specific heats of the various materials, allowed estimates of the fuel temperature-time relation.

From the power-time data of the Brush recorder, and with the use of ANL digital computer codes RE 29 and 31, reactivity-time data corresponding to the power level trace was obtained. The codes operate on the one group, space independent kinetics equations:

$$\dot{n} = \frac{k_{\mathrm{ex}}}{\ell} n - \sum_i \dot{c}_i$$

$$\dot{c}_i = \frac{(1 + k_{\mathrm{ex}})\beta_i}{\ell} n - \lambda_i c_i \qquad i = 1, 2, \ldots 6$$

$$k_{\mathrm{ex}} = f(n, t)$$

where

n = neutron population proportional to the power level
c_i = ith delayed neutron precursor group
k_{ex} = reactivity above delayed critical
ℓ = prompt neutron lifetime
β_i = fraction of ith delayed neutrons per prompt neutron

λ_i = decay constant of ith delayed neutron precursor

The two codes are complementary, RE 31 yielding excess reactivity from power-time input, and RE 29 yielding power for reactivity-time input.[4] The former was used first, then the resulting output data was smoothed and fed back with the RE 29 code for a check. By continually making small corrections a reactivity-time relationship was finally obtained which would yield a power-time relationship matching the experimental power curve everywhere in time to within one per cent between time zero and 500 seconds when the power trace went off the chart. The rapid reduction in reactivity from $k_{ex} = 0.0055$ to $k_{ex} = 0.0025$ brought about by the safety rods and plug scram and the increase, in 0.6 seconds, back to 0.50% k_{ex} agrees with the reactivity worth of rods and plug. The early analysis made in the spring of 1956 yielded power, energy, reactivity and temperature estimates for the time before the power trace went off-scale.[4] These are reproduced here in Table 1 and displayed in Figs. 1 and 2 for reference. The temperatures given in Ref. 4 have been revised slightly to allow for the fact that fuel elements having an exponentially rising heat source begin to store a larger percentage of the total energy release in the fuel slugs as the "period" gets shorter and shorter. "Period" here is defined as the ratio of power to the time derivative of the power. The effect is not significant for periods longer than about five seconds and does not really become important until the period reduces to less than one second. Development of this heat retention fraction relation for a cylindrical fuel element stagnant in NaK, with an exponentially rising heat source, is also available in Ref. 4.

Since the information noted above is available in an unclassified report,[4] this paper deals with the more recent analyses and studies aimed at answering the questions which have arisen. These questions are concerned primarily with what went on during the time that the power level trace was off the paper and correlating the information with evidence disclosed on examination of the core after removal[5] in the summer of 1956. In addition to the questions on power-energy-reactivity-temperature relations, the mode of material motion is sought. The most significant question requiring answers, however, is one posed regarding the shutdown mechanism: was the reactor shut down by dropping the outer blanket or was it shut down because of change in reactivity due to expansion of the core materials as discovered after the core was removed for examination? This is rather an important point since, if the latter were the case, it would appear that the reactor had a sort of a natural fuse which would prevent a really bad accident from happening. An auxiliary question which arose, because it finally develops that dropping the cup had really shut the reactor down, is: supposing the cup had not been dropped, would the core expansion then have shut it off and if so, how much worse would the accident have been?

Table 1. Correlated Data from ANL Digital Computer Codes RE 29 and RE 31

Time, seconds	P *power, kilowatts*	*Total energy release, kilowatt-seconds*	$P/\dot{P}$ *"period," seconds*	k_{ex}, *excess reactivity*
0	0.011	0	∞	0
50	0.013	0.59	189	0.000275
100	0.019	1.37	105.7	0.000550
150	0.034	2.64	69.1	0.000825
200	0.082	5.30	49.7	0.001100
250	0.209	12.10	53.8	0.001100
300	0.529	29.3	53.9	0.001100
320	0.767	42.1	53.7	0.001100
340	1.123	60.8	51.6	0.001120
360	1.67	88.3	49.3	0.001147
380	2.54	129.7	46.1	0.001190
400	3.97	193.6	43.4	0.001240
420	6.42	295	39.9	0.001300
440	10.97	464	34.7	0.001400
460	20.6	767	28.4	0.001554
480	49.5	1,405	18.31	0.001931
485	68.7	1,696	13.25	0.002174
490	106.3	2,120	9.95	0.002509
495	215	2,870	5.12	0.003180
498	483	3,820	2.15	0.004300
499	1002	4,490	0.882	0.004984
499.2	1200	4,720	0.617	0.005296
499.35	1718	4,950	0.970	0.005575
499.37	1750	4,990	± ∞	0.005527
499.4	1728	5,030	− 0.832	0.005495
499.47	1470	5,150	− 0.425	0.004925
499.5	1384	5,190	− 0.727	0.004835
499.68	1250	5,420	± ∞	0.004370
499.7	1252	5,450	8.03	0.004385
499.9	1507	5,710	0.730	0.004731
500	1750	5,890	0.613	0.004991
500.1	2090	6,080	0.514	0.005259
Off Scale				
Extrapolated data for cup starting down at 500.45 seconds				
500.2	2590	6,310	0.426	0.00553
500.3	3360	6,600	0.346	0.00581
500.4	4650	7,000	0.273	0.00610
500.45	5660	7,250	0.273	0.00625
500.5	6600	7,500	0.345	0.00632
500.55	7500	8,000	0.475	0.00634
500.6	8200	8,600	0.740	0.00632
500.65	8800	9,200	1.670	0.00626
500.695	9000	9,700	± ∞	0.00617
500.75	8800	10,200	− 1.300	0.00604
500.8	8300	10,500	− 0.860	0.00586
501	5600	11,700	− 0.560	0.00485
501.5	1700	13,300	− 0.490	− 0.00125
502	500	13,900	− 0.480	− 0.0115
503	80	14,000	− 0.480	− 0.0428

i	β_i	λ_i
1	0.00025	14.3
2	0.00085	1.612
3	0.00241	0.456
4	0.00213	0.1535
5	0.00166	0.0315
6	0.00025	0.01246
	$\beta = 0.00755$	

Prompt neutron lifetime: $l = 4 \times 10^{-8}$ seconds
Delayed neutron data:

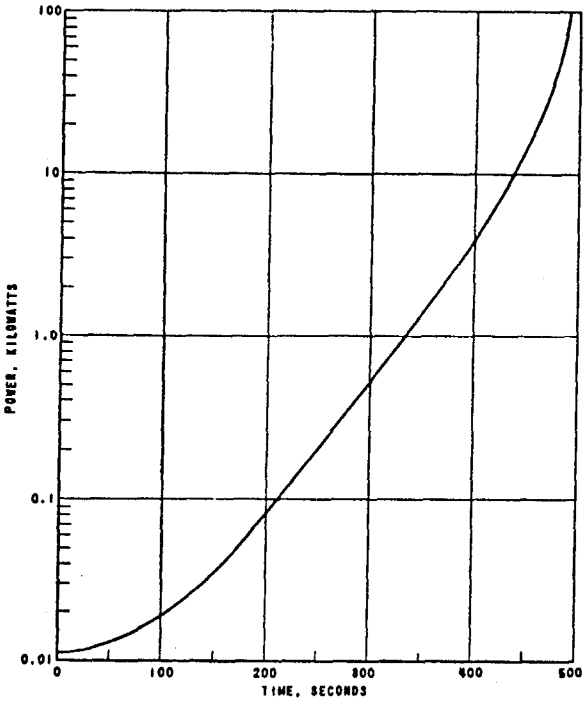

Figure 1. EBR-I meltdown power level

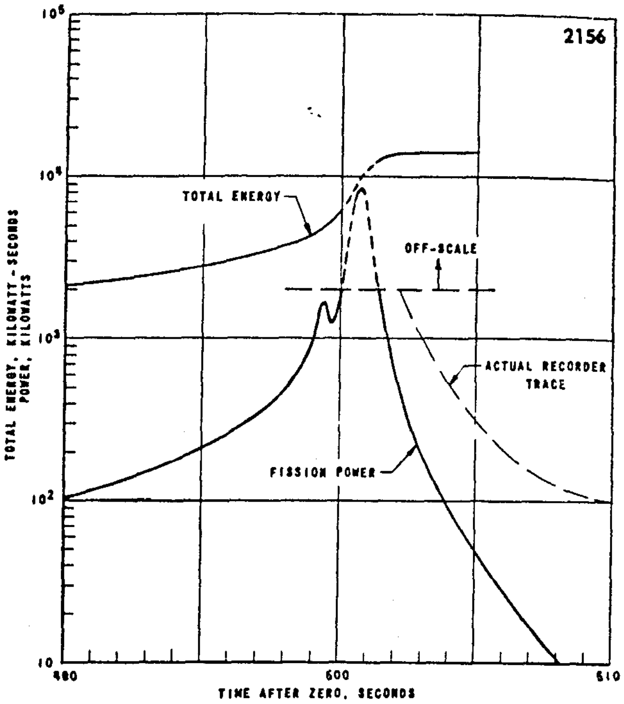

Figure 2. EBR-I meltdown power peak

The first step in these newer studies was to extrapolate the excess reactivity-vs-time curve from 500 seconds, where the trace went off-scale, to 501 seconds. Using this extrapolation and ANL digital computer code RE 29, the power-vs-time data was extended for one more second. From this power-vs-time data, energy release-time data was calculated. Quantity of material and heat content data then gave a temperature-time relation.

There are 58,200 grams of uranium plus zirconium in the core (291 grams per element). It requires 60 calories per gram or 250 watt seconds per gram to raise the slug from 65°C to just above the melting point. Eighty-three per cent of the total recorded heat is released in the core, the rest in the blanket. On the average, during the rise, about 85% of the energy released in the core is stored in the fuel. Hence, on the average, about 1.2×10^{-5} of the total energy release is stored in an average gram of fuel. Spatial distributions of power generation in the form of fission ratio distributions are available.[1] Examination of this information leads to the conclusion that the peak to average power production ratio is 1.4, so that 1.7×10^{-5} of the total energy released is stored in the central gram of the center fuel slug. From this figure and the 250 watt seconds per gram required to melt, it is found that the total energy release for the core at the time the central gram first melted, if it did, is 1.5×10^7 watt-seconds. By this time the reactor would have reached about a 50 millisecond period and if the excess reactivity (now 0.0073) is not reduced, in a very small fraction of a second (90 milliseconds), the reactor will be prompt critical.

Since the cup here is assumed *not* to drop, the only way in which the reactivity could be reduced is to move the material out from the center of the core. To move the material a force is required and the source of this force must be the vapor pressure of the NaK. The required pressure differential is available from the NaK bond between the uranium slug and the stainless steel jacket, but rupture of the jacket is first necessary. There are three processes working together to bring this about, the first is a reduction in strength of the stainless steel jacket with temperature (between 1000°C and 1430°C the ultimate strength reduces from 8000 psi to 0). The NaK vapor pressure at the melting point of the uranium has reached about 150 psi and is climbing rapidly. Furthermore, the low melting eutectics of uranium and the components of stainless steel are forming rapidly.

For eutectic formation to penetrate the 20 mil wall in the order of one minute, the temperature must be between 850°C and 950°C, although the melting point of the eutectic is just over 700°C. Certainly to accomplish this eutectic formation penetration in a small fraction of a second the uranium temperature must be somewhat above the melting point in order that good contact and film breakage can occur. It is not now known how rapidly this eutectic formation will take place at temperatures of 1100°C to 1200°C. However, to estimate the minimum severity of the accident which would have occurred if the expansion of the core alone had shut the reactor down, it would be necessary to assume that the penetration occurs within a few tens of milliseconds.

Examination of the time dependence of the energy release indicates, however, that it is not necessary to use the eutectic formation mechanism to obtain the loss of integrity of the stainless steel jacket. Fifteen milliseconds after the core uranium first begins to melt the total energy release has increased 15%. Because of the flatness of the power distribution at the center and the heat of fusion, nearly 10% of the core is at the same temperature. At this point the ultimate strength of the stainless steel becomes equal to the stress set up by NaK vapor pressure. The jacket ruptures and the uranium may leave for the outer regions. The pressure difference between the NaK in the fuel slug and that in the cooling channels adjacent to the fuel elements is at least 100 psi. Since the pressure difference required to overcome gravity and the head of NaK is only about 5 psi, the dispersal of uranium could be very rapid and extend much farther than the evidence indicates. In fact the central fuel would get to the blanket regions, which is controverted by the evidence from examination.[5]

Estimates were made[6] of the reactivity of the core for the disposition of material observed after the melt-down. A number of treatments were accorded the various regions, and one and two-dimensional diffusion theories were applied. The change in reactivity from the original core was found to lie between 0.050 and 0.058 ($\delta k/k$). It is concluded from this that the reactor was subcritical by $> 4\%$ plus the worth of the blanket right after shutdown.

If it is assumed that the reactivity reduction is completely effected in one *e*-folding time (about 50 milliseconds) after the uranium first melts, the total energy release would finally be at least 2.5×10^7 watt seconds. The relations for energy release, heat stored, temperatures and rupture data for this part of the analysis are displayed in Table 2.

Under these circumstances all of the fuel slugs out to the seventh ring, or more than 50% of the core, would have exceeded temperatures of 1400°C. The fuel in the core extremities would attain temperatures above the melting point of uranium and the temperature near the center would have exceeded 2000°C.

It should be remembered that this is the most optimistic picture one can paint for shutdown due to core expansion. The energy release could easily have been 50% greater. Shutdown due to core expansion alone does not seem to be in agreement with the evidence obtained on the examination of a core after its removal. Not only would the chromel-alumel thermocouple wires have melted but the heat transfer subsequent to the burst would have provided more than enough energy to bring about melting of a good portion of the internal blanket above and below the core and may have led to penetration of the stainless steel flow separator between core and internal blanket.

Table 2

Time, seconds	*Total energy release, kws*	*Heat in central fuel, cal/gram*	*Central uranium temp. °C*	*Stainless steel*		*NaK pressure stress, psi*
				Temp. °C	*Tensile strength, psi*	
500.78	14,900	254	1130	1000	8000	1000
500.79	15,900	272	1240	1100	4000	1600
500.80	17,400	298	1400	1200	1000	3800
500.81	19,200	328	1590	1430	0	6000
500.82	21,500	368	1840			
500.83	24,600	421	2170			

Table 3

Cup starting down-time, seconds	*Peak power reached, kilowatts*	*Total energy released, kilowatt-seconds*
500.35	5,600	10,700
500.40	6,600	12,000
500.45	9,000	14,000
500.50	12,200	16,000

If the above shutdown mechanism did not operate it must be assumed that the shutdown was effected by dropping the cup. To analyze this action there is available experimental information on the reactivity worth of the cup versus position (total worth is 8%), and also time-travel information for the cup including dead time for scram circuit time, solenoid operations and valve opening.[7] Number 3 scram circuit was calibrated as scramming at 250 cm on the optical galvanometer when tap 3 was used. During the transient test, tap 2 was used, requiring 50% higher chamber current to register. Considering similarly the other scram circuit which had been calibrated on tap 2 and was now set on tap 1, requiring 33% higher current, and allowing a maximum deviation of 10% based on past history, the scram signal was generated at some time between 500.05 and 500.20 seconds from mark 0. Tests indicate about 100 milliseconds circuit time and 200 ± 100 millisecond relief time for cup actuation. The most probable starting time for the cup travel is 500.45 seconds.

The reactivity-time data previously derived for the time after the trace went off-scale was modified systematically by subtracting the reactivity-time data for the cup travel from it, starting at various times corresponding to possible scram signal times. Using again computer code RE 29, the resulting power curves were obtained for cup starting times between 500.35 and 500.50. The peak powers and total energy releases obtained are given in Table 3.

The value for the most probable starting time of 500.45 seconds indicates a peak power of 9000 kilowatts and a total integrated power of 14,000 kw-secs.

Considering temperatures in the case of the most probable starting time where the integrated power reached 14,000 kilowatt-seconds, it is found that the central 50% of the core reached the melting point but did not exceed it because of the rather large requirements for heat of fusion. The fuel elements between the sixth and seventh rings, which are about the average position, reach temperatures of about 900°C. At the edge of the core in the central plane the temperatures are about 800°C, while the ends of the outer fuel elements reached temperatures a little over 600°C. These temperatures are given in Table 4.

The heat in the uranium will immediately flow out to the stainless steel and NaK adjacent to it. Hence within two seconds temperature perturbations on the general axial and radial variations will disappear. The total heat transfer from center to edge of core and out will be small during this local redistribution

Table 4. Maximum Temperatures in Fuel Elements, 14,000 kws Release

Rod ring number	Inches above center 0	1	2	3	4
Central	1130	1130	1130	1010	830
1	1130	1130	1130	1000	830
2	1130	1130	1130	980	820
3	1130	1130	1130	970	810
4	1130	1130	1120	950	800
5	1130	1120	1070	910	790
6	1110	1080	990	860	760
7	980	960	900	810	700
8	830	810	730	710	600

Table 5. Temperature in Core (°C) about 2 Seconds after Maxima

Distance from center, in. Radial	Axial 0	1	2	3	4
0	960	940	870	790	670
1	950	930	860	780	670
2	910	890	830	760	660
3	820	810	780	700	620
4	680	670	640	580	450

time. Table 5 shows the temperatures in the core about two seconds after those of Table 4.

The heat of formation of the uranium-iron eutectic provides a heat source in addition to fission. It has been recently measured and found to be ~4 calories/gram of eutectic formed.[8] This additional heat would tend to counterbalance heat transferred from the core so that the heat content temporarily remains about the same. Much of the heat is now going to the vaporization of the NaK so that in a short time the NaK vaporization temperature at atmospheric pressure provides a new upper limit for the temperature in the central region. Out to the sixth ring of rods the temperature remains about 800°C over three quarters of the rod length and then drops to about 630°C at the upper and lower ends. The seventh ring of rods reaches to just below NaK boiling temperatures at the center dropping off continuously somewhat in accordance with the original power distribution to a value of about 560°C at the ends. The outer rods attain a temperature of about 650°C in the central portion, dropping off to about 420°C at the end. It is possible that central portions of the core remain above the uranium-stainless eutectic melting temperature for 5 seconds.

It should be remembered that because of the relatively slow gross heat transfer from the core to the NaK and the surrounding blanket, the temperatures in the central region of the core certainly exceeded NaK boiling temperatures for several seconds after the burst. The temperatures in the central 40–50% portion of 1130°C probably resulted in rapid penetration of the stainless steel jackets. The general eutectic formation for this half of the core occurred at the same time. The NaK pressure gradient forced the central material outward and extruded the outer melted material rapidly into the coolant channels in the upper and lower blanket regions and the outer rods. Sufficient chilling took place at once to "freeze" this extruded material, blocking further outward motion. Because material had generally moved away from the center the outer melted zone was then at higher density than the inner zone. As soon as outward motion stopped the molten eutectic began to fall down and collect in the dish formed by the frozen extruded material. Fallout from the outer zone halted when the temperature dropped below melting point. Fallout from the central region continued longer, resulting in a more extensive eutectic depletion. The upper fuel slugs of partially melted rods could drop to and through the melted eutectic mass collected at the bottom. NaK vapor pressures generated are estimated to be between 10 and 30 psi. Such pressures would yield a gradient which would easily overcome gravity and the NaK head above the core. An explanation for the fact that the material penetrated higher into the upper blanket than it did downwards into the lower blanket is that first, NaK was flowing upward through the core creating an inertial resistance until flow stopped and reversed. The inertia of the NaK to motion opposite normal would be greater than in the other direction even if the NaK were not initially flowing. Secondly, the fission distribution shows a peak slightly above the core center.

It should be noted that the peak temperatures were not reached until about 1.5 seconds after the power peak, or about the time the power trace came back on scale. Also note that the power trace two seconds after the peak is not true power; first because the dropping cup removed attenuating material, and second because the shutdown gamma heating is not registered. Removal of attenuation would cause a reading one to two orders of magnitude too high, whereas shutdown heat from sources other than delayed neutrons would require an increase in power level estimates by an indeterminate amount.

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