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AN EXPERIMENTAL DETERMINATION OF FISSION PRODUCT HEATING AFTER SHUTDOWN OF THE LOW INTENSITY TRAINING REACTOR

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AN EXPERIMENTAL DETERMINATION OF FISSION PRODUCT HEATING AFTER SHUTDOWN OF THE LOW INTENSITY TRAINING REACTOR

SUMMARY

Experiments have been performed in the Low Intensity Training Reactor to measure the rate of fission product heat dissipation from the fuel pieces after loss of water. The measurements provide evidence that:

(1) the fission product power in a single fuel piece containing 140 gm U-235 can be expressed as

$$q = 14\,P \left[t^{-0.2} - (t + T)^{-0.2} \right] \text{ Btu/hr}$$

where P = reactor power before shutdown, kilowatts

t = time after shutdown, seconds

T = operating time before shutdown, seconds

(2) as much as 75% of the fission product heat is lost by conduction to other parts of the reactor before the fuel reaches a maximum temperature,

(3) the LITR may be operated at a power level of about 1500 to 2000 kw without danger of melting the fuel even if the cooling water is suddenly removed.

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INTRODUCTION

The Reactor Safeguard Committee has specified that a safe operating level for the Low Intensity Training Reactor would be that level at which the fuel plates would not be melted by fission product heat if the cooling water normally in contact with them were suddenly and completely drained. The problem has been analyzed mathematically by Poppendiek and Claiborne in ORNL 976, but the necessity for several pessimistic assumptions resulted in a low estimate of the safe power level. Realizing that the mathematical approach was limited by the dearth of applicable information available, it was decided to attack the problem by means of a full-scale experiment under conditions which would closely resemble the imagined accident but at power levels known to be safe. Fortunately, construction of the LITR was at an early stage, and it was possible to equip the reactor for this particular experiment and to perform the experiment before the reactor was used for other purposes.

The general arrangement of the reactor is illustrated in Figs. 1 and 2. The fuel lattice at the center of the tank is filled with 15 fuel elements, 3 safety rods, and 20 removable beryllium reflector pieces, all fabricated according to Materials Testing Reactor specifications. The lattice is surrounded by a stack of beryllium brick weighing approximately 3,000 lbs. The brick are supported on a 2,000 lb. aluminum casting.

Heat generated by the decay of fission products in the fuel plates may escape the fuel by radiation to surrounding components, by natural convection of air within the tank, and by conduction. However, losses by radiation and convection are estimated to be small by comparison with the conduction loss.

The path of conducted heat is down the fuel assembly to the supporting grid, through the skirt plates on which the grid rests, to the lower support casting and upward into the beryllium reflector. The heat capacity of this system with such masses of aluminum and beryllium is large - approximately 1700 Btu/^{o}F. In fact, were the heat transfer resistances along the conduction path sufficiently low, all the shutdown heat from operation at several megawatts could be soaked up by the reflector and castings without endangering the fuel. The experimental approach is to determine by actual temperature measurements, under pessimistic operating conditions, the maximum level at which natural cooling will be sufficient to prevent melting of the fuel plates.

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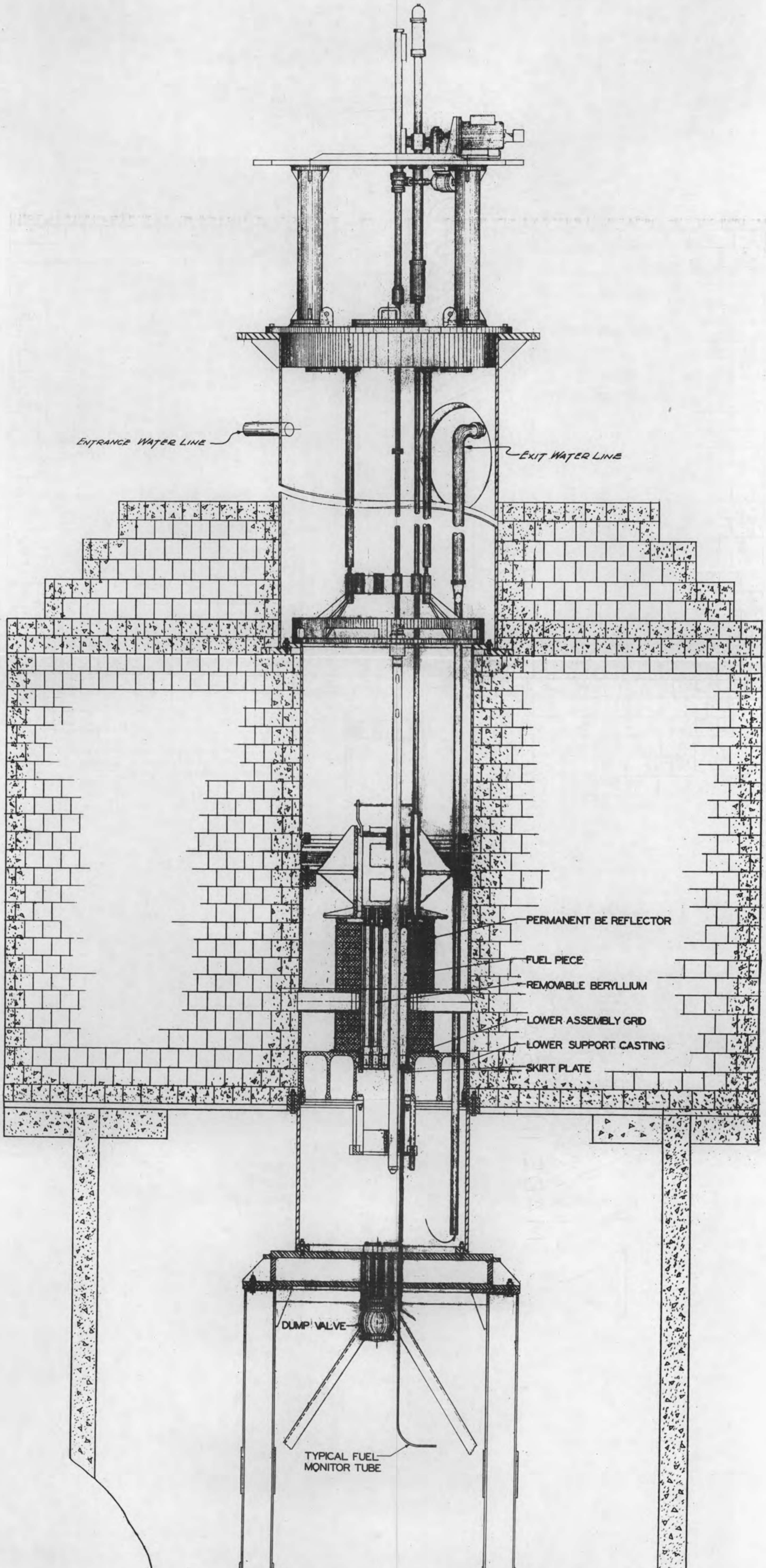

FIGURE 1
MTR MOCK-UP ASSEMBLY FOR LOW POWER EXPERIMENTS

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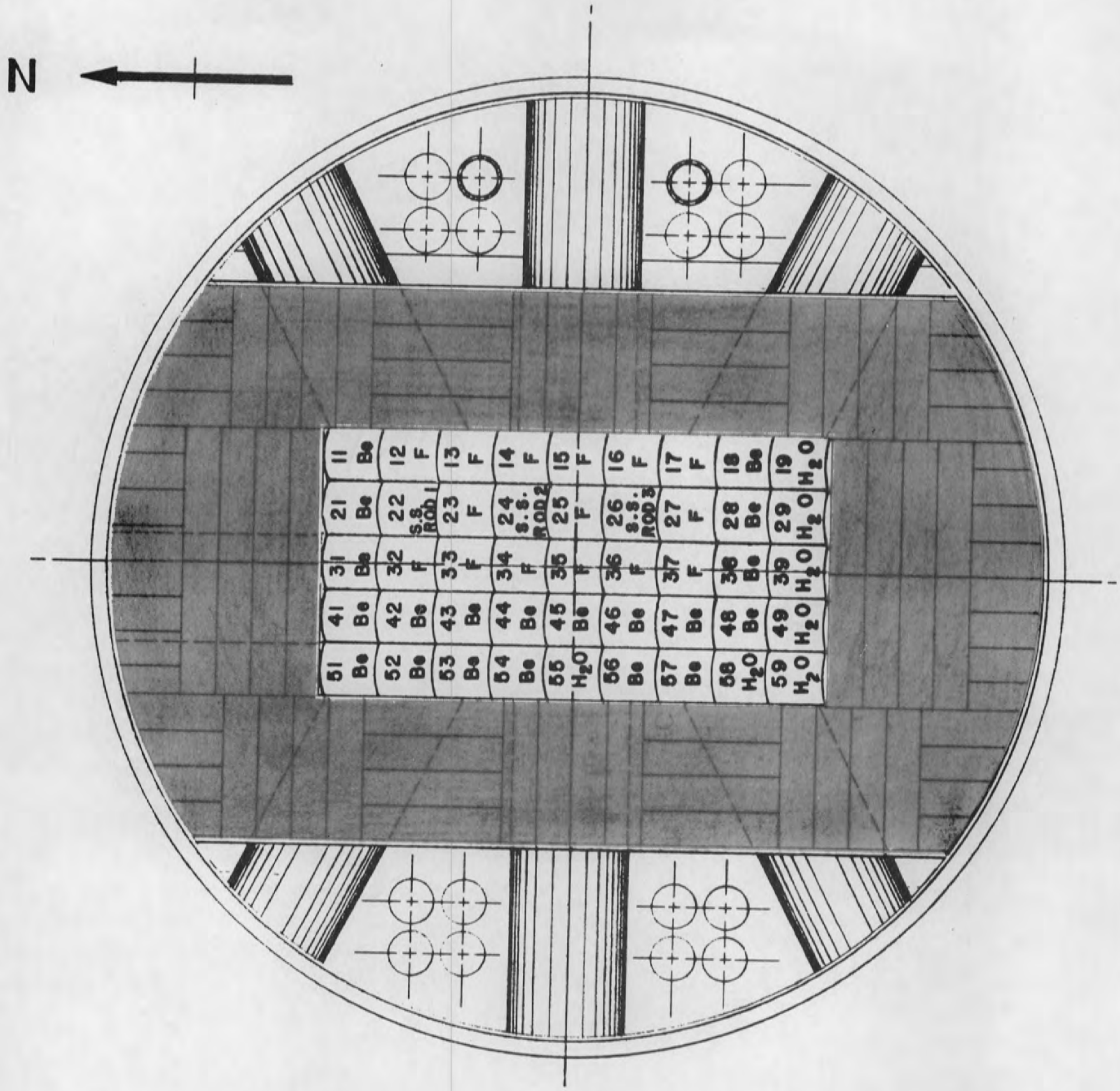

FIGURE 2

LITR LATTICE REFLECTOR ARRANGEMENT

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THEORY

This experiment is fundamentally another attack at the problem of determining the rate of release of fission product energy. However, it differs from similar previous investigations by attempting to measure, full-scale, the fraction of decay energy absorbed by the reactor fuel.

The data of several workers has been correlated by Wigner and Way in CC-3032. The rate of energy dissipation after fission is shown to vary approximately as

$$\alpha t^{-1.2} \quad \text{Mev/sec-fission} \qquad (1)$$

In the present experiment, the constant α will depend on the fraction of energy which results in heating of the fuel plates. From the geometry and structure of the Materials Testing Reactor fuel elements used in the LITR, one would assume that this fraction would include practically all of the β energy in addition to a small contribution from γ decay.

The total decay energy for a single fission after a decay time of t seconds following T seconds bombardment can be obtained by integrating (1):

$$\int_{t}^{t+T} \alpha t^{-1.2}\, dt = 5\alpha \left[t^{-0.2} - (t + T)^{-0.2} \right] \text{ Mev/fission} \qquad (2)$$

Also, q - the total rate of energy release in a mass of fuel after cessation of bombardment - can be found simply by multiplying (2) by the fission rate.

The fission rate for the actual experimental conditions was calculated from gold foil determinations of the thermal neutron flux. The reactor

[redacted]

power level at the time of the foil measurements was 29 watts*. For the center fuel element, the fission rate per kilowatt of reactor power is:

Average thermal flux in fuel piece #25 containing 135.9 gm 235 $\doteq 3.67 \times 10^8$ neutrons/cm^2-sec

$$\text{Fission rate} = \frac{3.67 \times 10^8 \times 135.9 \times 6.02 \times 10^{23} \times 545 \times 10^{-24}}{235 \times 0.029}$$

$$= 2.4 \times 10^{12} \text{ fissions/sec}$$

After multiplying (2) by the fission rate and converting Mev/sec to Btu/hr

$$q = 6.58\,\alpha P \left[t^{-0.2} - (t + T)^{-0.2} \right] \text{ Btu/hr} \qquad (3)$$

where P is the power level in kilowatts prior to shutdown.

If one assumes that the temperature rise of the fuel will be observed to approach a maximum at time, t, then q, the steady-state generation at t, can also be expressed as

$$q = \frac{k\ A\ \Delta T_{max}}{x} \text{ Btu/hr} \qquad (4)$$

where k = thermal conductivity of aluminum, Btu/hr-ft^2-^{o}F-ft

A = cross-sectional area of fuel assembly, ft^2

ΔT_{max} = maximum temperature rise of fuel plate, ^{o}F

x = length of conduction path to end box, ft

Equating (3) and (4) and solving for ΔT_{max},

$$\Delta T_{max} = \frac{6.58\,\alpha P\ x}{k\ A} \left[t^{-0.2} - (t + T)^{-0.2} \right] \ ^{o}F \qquad (5)$$

---

* The actual power output of the reactor was determined in a separate experiment by J. W. Hill and J. J. Hairston, ORNL CF 51-11-91. The various power levels indicated in Table II were related to the 29 watt level by silver normalizing foils located outside the lattice.

For the present, let $K = \frac{6.58 \alpha x}{k^* A}$ (6)

Then, $\Delta T_{max} = K P \left[t^{-0.2} - (t + T)^{-0.2} \right] \ {}^{o}F$ (7)

This expression relates four measurable quantities, fuel temperature rise, reactor power, decay time, and operating time. It thus permits an experimental evaluation of the constant K by operating at safe power levels before draining the cooling water and measuring the fuel temperature. With K known, and assuming that the decay exponent -0.2 is verified also, one can estimate from equation (6) the value of α and thence from (5) the maximum safe power level at which the LITR may be operated.

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* The thermal conductivity of aluminum is assumed to be constant over the temperature range (100° - 160°F) of the experiment.

[redacted]

EXPERIMENTAL

The general plan for each experiment was to operate the reactor at constant power for the required time, then to shut down by draining the water (not by dropping control rods) and to follow the temperature until a maximum was passed.

The sequence of operations for a typical experiment will be described. Approximately 5 min. before the steady operating period was completed, the cooling water pumps were stopped and the inlet and outlet valves closed to prevent leakage of water back into the reactor. Operators were stationed at the pump switch and at the valves in the event water should be required suddenly. One manhole cover was removed at the top plug to allow air to enter the tank as the water drained out. Next, drainage was begun by means of a 6-in. remotely operated gate valve at the bottom of the reactor tank.

The reactor was held at constant power as the water level above the lattice dropped. Removal of the water also meant removal of the shield above the lattice, and although the beam of radiation was directed skyward, Health Physics personnel stationed at strategic ground positions reported that during the 300 kw run the radiation level gradually increased to a maximum of several hundred mr/hr for a few seconds prior to shutdown. For this reason it was considered inadvisable to attempt measurements at higher power levels.

Approximately 2-1/2 min. were consumed in lowering the water level (with the reactor operating at constant power) from the top of the tank to a point 1 ft. above the fuel plates. Removal of water below this point (i.e., removal of the top reflector) caused the reactor to become subcritical and shut down. During the next 12 sec., as indicated by recorders on ion chambers, the water drained past the fuel plates. After another 30 sec., the tank was completely empty and the drain valve was closed. The manhole cover was replaced at the top plug to seal the tank and prevent the entrance of additional cooling air.

Temperature records were begun at the time the dump valve was opened. Table I indicates the various points measured by means of iron-constantan thermocouples and a potentiometer. Readings were continued

[redacted]

TABLE I

Location of Thermocouples

Thermocouple	Location
1	West side plate of fuel piece #35, 6 in. above center
2	6 in. above center of center fuel plate in fuel piece #25
3	Center of fuel piece #25 (center of lattice)
4	East side plate of fuel piece #15, 6 in. above center of plate
5	East side plate of fuel piece #15 at center of plate
6	East side plate of fuel piece #15, 12 in. below center of plate
7	East side plate of fuel piece #15, 16 in. below center of plate
8	Top of lower assembly grid, east edge, between positions 14 and 15
9	Monitor tube in lower end box of fuel piece #15
10	Bottom of east skirt plate directly below thermocouple #8
11	Lower support casting, 4 in. east of thermocouple #9
12	Beryllium stack, 3 in. east of fuel edge, 4 in. above center of center - east thimble.

for 2 hrs. which was sufficient time in every experiment for fuel temperatures to reach a maximum and begin to decrease. A typical temperature record is plotted in Fig. 3.

The absolute power levels of these runs were based on foil measurements by J. W. Hill. Ion chambers of several types were also used to compare the power levels. Data were collected for nine different levels from 0.5 kw to 300 kw, each for a 2-hr. operating time. Also, the effect of longer operating times was measured with runs of 2, 6-1/2, and 24 hr. duration at the level of 150 kw.

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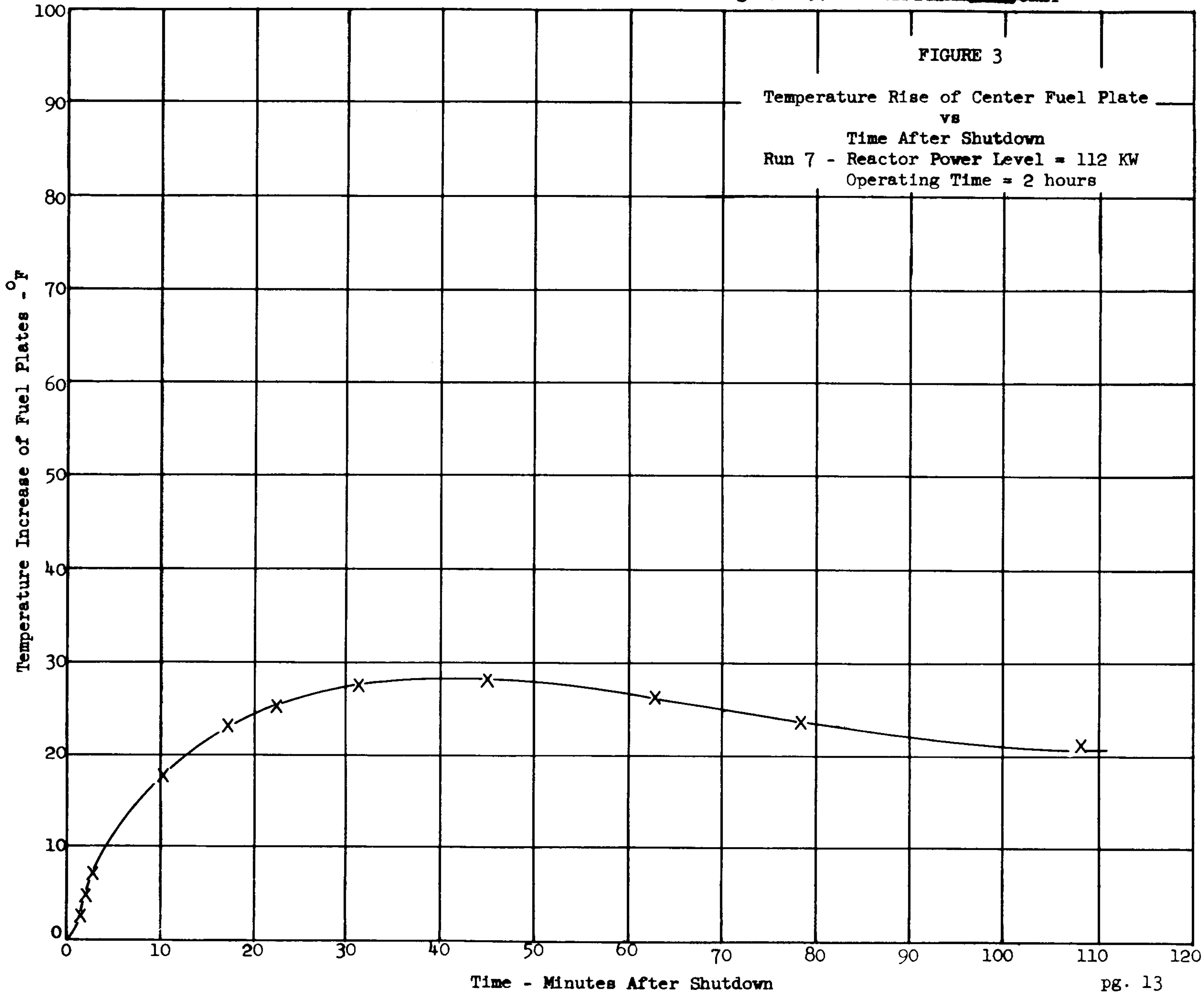

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DISCUSSION OF RESULTS

The series of runs at constant operating time was aimed at evaluating the constant K of equation (7). The purpose of the runs at constant power level was to ascertain the exponent of this equation.

It is apparent from Fig. 4, a plot of the first series, that the temperature rise of the fuel plates varies linearly with reactor power if the operating time is held constant. An increase of $0.20^{o}F/kw$ operating level is indicated for a 2-hr. operating period.

The effect of longer operating periods is shown by Fig. 5, the plot of runs at the 150 kw level for operating times of 2, 6-1/2, and 24-1/2 hr. The calorimeter measurements of total β and γ decay energy reported by Day and Cannon in CC-2176 were normalized to the 24-1/2 hr. run and plotted on this figure also. Both groups of data substantiate the exponent of the general equation. The broken section of the curve is calculated from equation (5).

Values for the constant K were calculated from the data of Table II and appear in column 6. With the exception of the first two runs at very low power levels, the K values are reasonably consistent. With the overall constant K known, it is possible to obtain a value for the energy constant α of equation (1) by proper substitutions in (6): K is 4.4, $A = 0.0275$ ft^2, $k_{Al} = 115$ and x is estimated to be 0.97 ft. from the neutron flux distribution plotted in Fig. 6. Substituting these numbers in (6), α is found to be 2.2 and the basic equation for the rate of decay of energy liberated in the fuel becomes $2.2\ t^{-1.2}$ Mev/sec/fission. The plate temperature profile of Fig. 7 is the basis of an independent calculation of α and indicates a value 10% higher.

Now, having determined the rate of energy emission, additional information is available from the general expression. If no heat were lost from the fuel plate during the decay period, its maximum temperature should equal the integrated heat after shutdown divided by the heat capacity of the fuel piece.

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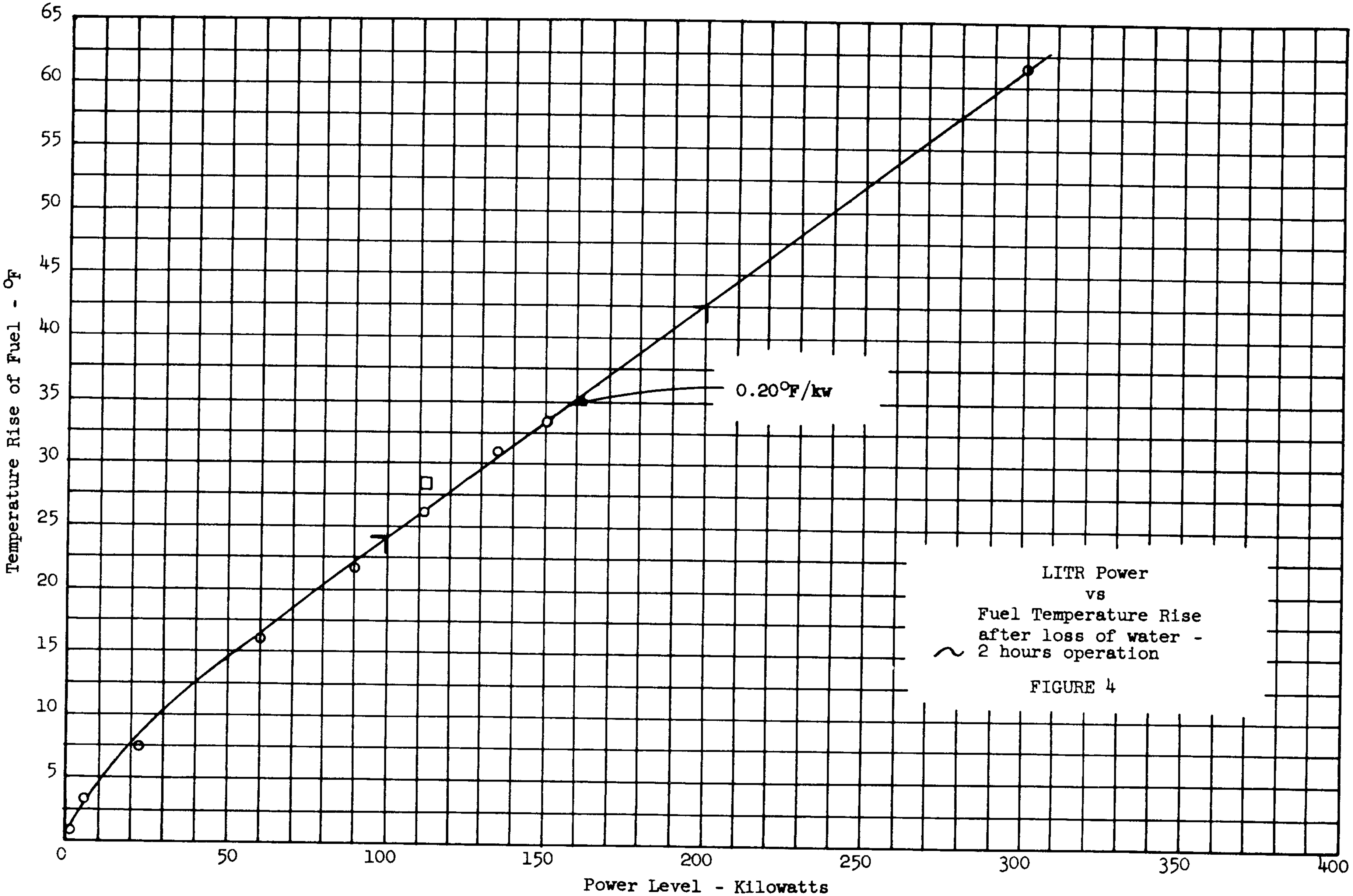

LITR Power
vs
Fuel Temperature Rise
after loss of water -
2 hours operation

FIGURE 4

[redacted]

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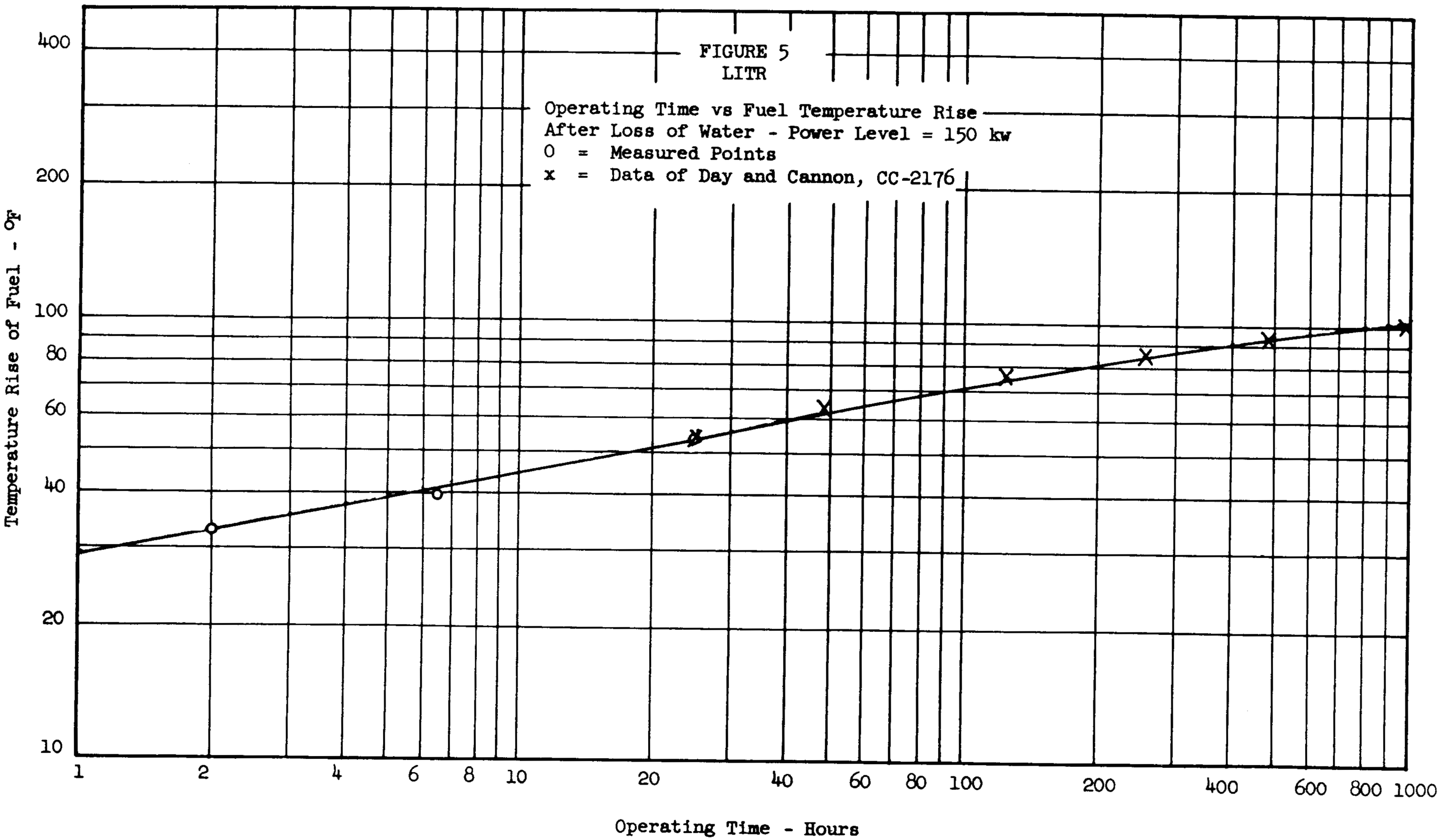

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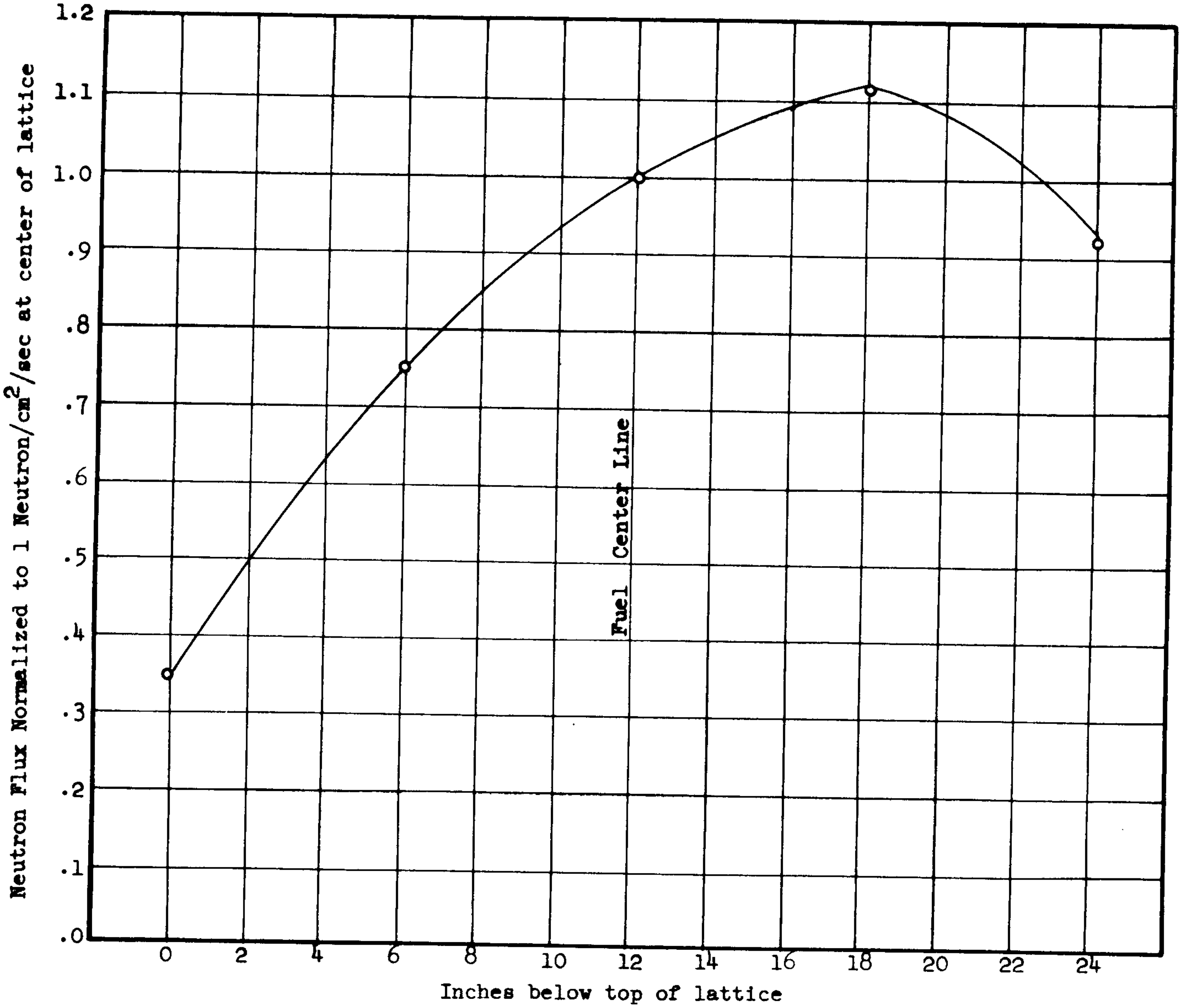

FIGURE 6

Vertical Traverse of Thermal Neutrons in Assembly No. 25.

Thermal Flux at Center of lattice 4.59×10^{12} neutrons/cm^2 - sec.

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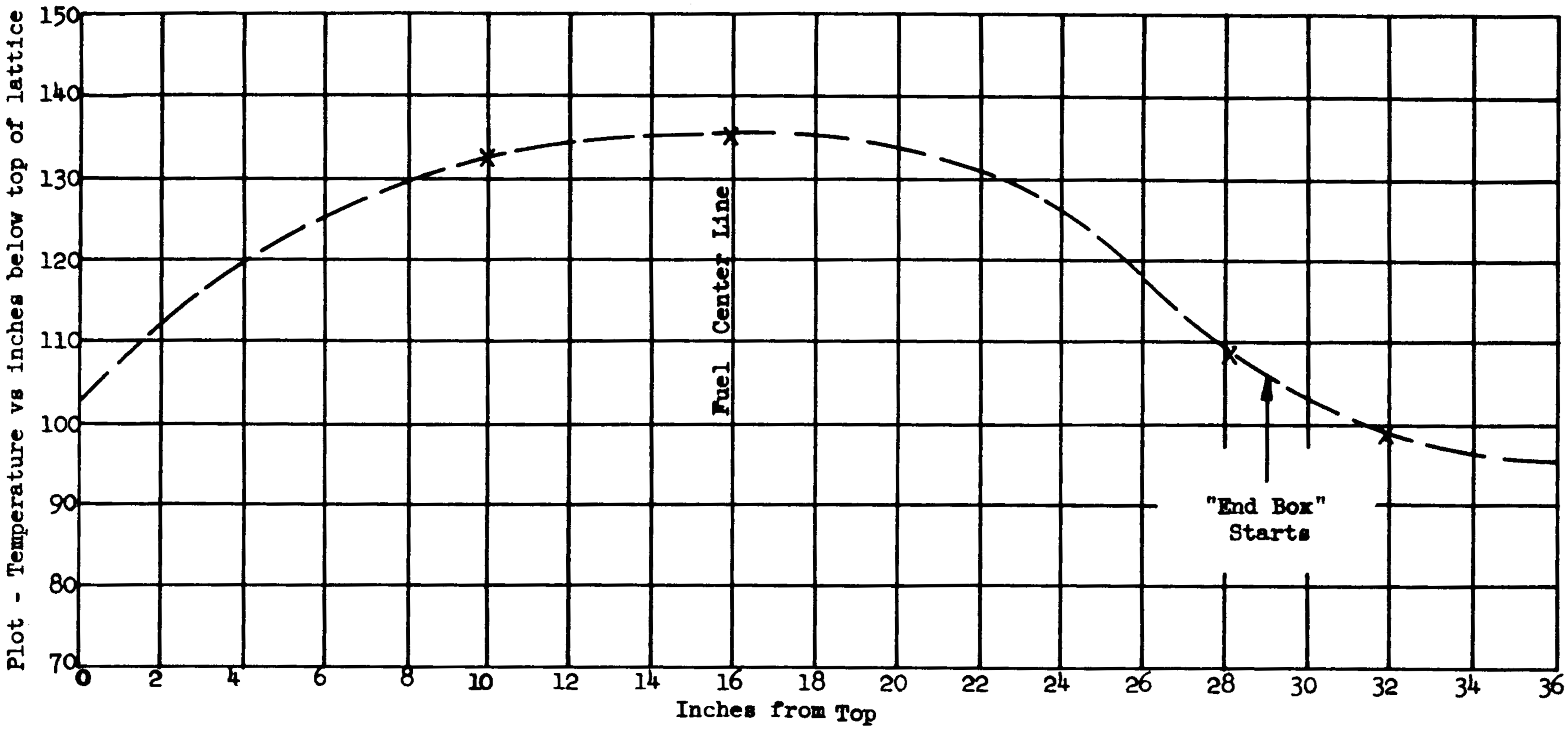

FIGURE 7

Temperature profile of fuel piece #15 following loss of water - after 2 hours at 300 KW.

TABLE II

Experimental Results

Run No.	Power kw	t - sec.	T - sec.	ΔT_{max} °F	K*
1	0.5	1500	7200	1	29
2	5	1500	7200	4	11.6
3	22.5	2100	7680	7.5	5.0
4	60	2100	9000	16.5	4.6
5	90	2400	9000	22	4.3
6	112	2400	8100	26	4.3
7**	112	2260	7800	28.5	4.5
8	135	2400	7500	31	4.4
9	150	2700	7920	33.5	4.5
10	150	2400	23400	40	3.3
11	150	6000	88200	53	4.7
12	300	3100	7560	62.5	4.7
				Mean***	4.4

* $$K = \frac{\Delta T_{max}}{P\left[t^{-0.2} - (t + T)^{-0.2}\right]}$$ (See Equation 7)

** In run number 7 plugs behind the permanent beryllium reflector were removed. This caused the water behind the beryllium to drain faster and resulted in slightly higher fuel temperatures.

*** Runs 1 and 2 not included.

[redacted]

Thus, from (3)

$$q = 6.58 \times 2.2\ P \left[t^{-0.2} - (t + T)^{-0.2} \right] \text{Btu/hr}$$

$$Q = \frac{14\ P}{3600} \int_0^t \left[t^{-0.2} - (t + T)^{-0.2} \right] dt =$$

$$4.86 \times 10^{-3}\ P \left[t^{0.8} - (t + T)^{0.8} + T^{0.8} \right] \text{Btu/assembly} \qquad (8)$$

The heat capacity of the fuel plates per assembly =

7.5 lbs. x $.22$ Btu/lb.-°F = 1.65 Btu/°F

$$\Delta T_{max} = \frac{Q}{cp} = \frac{4.86 \times 10^{-3}\ P}{1.65} \left[t^{0.8} - (t + T)^{0.8} + T^{0.8} \right] {}^{\circ}F \qquad (9)$$

Choosing Run #12 as a typical case, ΔT_{max} calculated from (9) = 258°F, whereas the measured value is only 58°F. This difference indicates that 78% of all the heat generated is conducted away to the surrounding mass of metal before the fuel reaches its maximum temperature.

The time required to reach the temperature maximum after a very long period of operation can be estimated by adjusting (9) to the measured conditions and equating with (7):

$$6.5 \times 10^{-4}\ P\ (t^{0.8}) = 4.4\ P\ (t^{-0.2})$$

[redacted]

Solving for t, the maximum fuel temperature should be reached at approximately

$$t = \frac{4.4}{6.5 \times 10^{-4}} = 6.8 \times 10^3 \text{ sec.}$$

The maximum safe operating level can now be estimated from (5). Assuming the worst case of an infinite operating time previous to the accident

$$P = \frac{1100 \times 160 \times 0.0275}{6.58 \times 2.2 \times .97 \times .172} = \sim 2000 \text{ kw}$$

That this level is considerably higher than has been previously calculated on the basis of several pessimistic assumptions is not surprising. The explanation for the difference can be found in the low values of contact resistances indicated by the miscellaneous temperatures noted on Fig. 8 For instance, the resistance to heat flow from the fuel end box to the lower assembly grid is practically zero; the grid to skirt plate resistance is approximately 1/20th of that estimated for previous calculations. These low values are probably the result of good metal contacts at the points of heat transfer between components. The theoretical treatment of Poppendiek and Claiborne in ORNL-976 might be profitably repeated on the basis of the thermal resistances indicated by these measurements.

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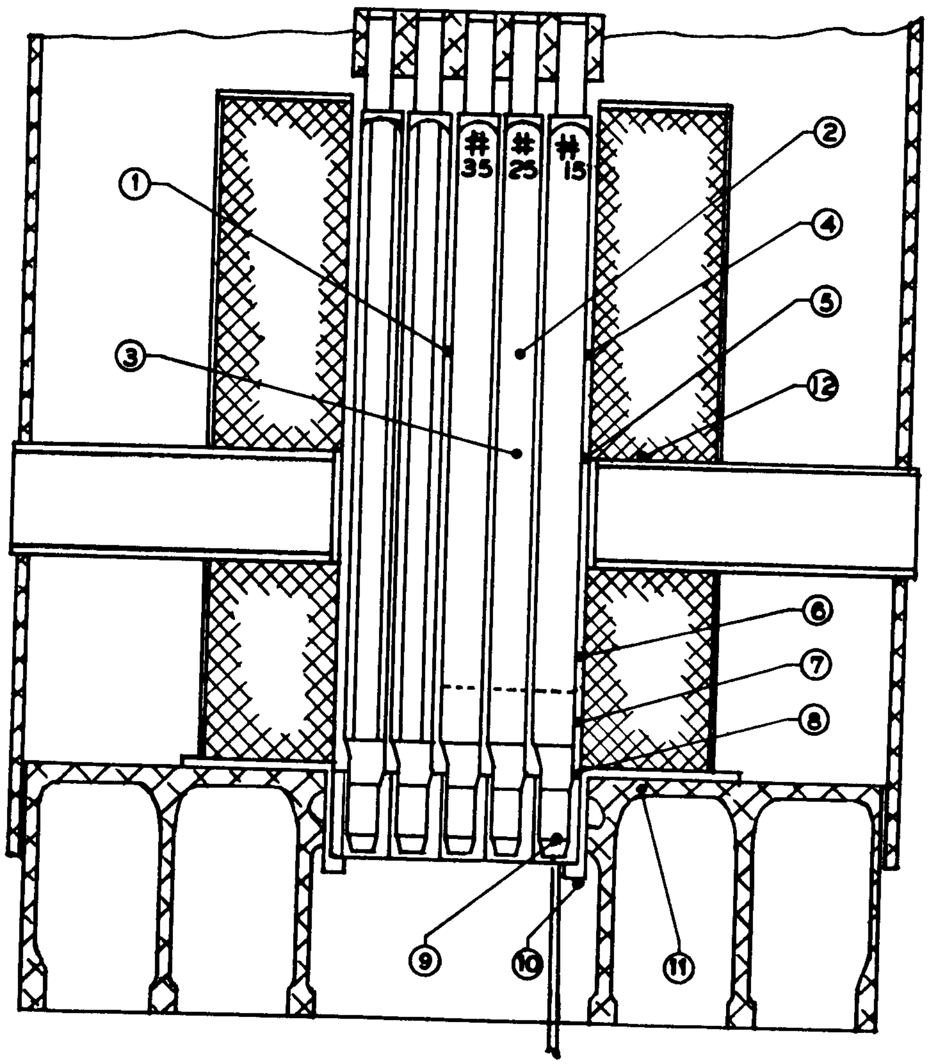
FIGURE 8

Maximum Temperatures at Miscellaneous Points After Loss of Water Following Two Hours Operation at 300 KW.



1 - 99°F
2 - 146°F
3 - 150°F
4 - 133°F
5 - 136°F
6 - 108°F
7 - 98°F
8 - 101-1/2°F
9 - 87°F
10 - 91°F
11 - 85-1/2°F
12 - 86-1/2°F

[redacted]

ACKNOWLEDGMENT

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