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SURFACE TEMPERATURES OF IRRADIATED ORR FUEL ELEMENTS COOLED IN STAGNANT AIR

J. F. Wett, Jr.

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OPERATIONS DIVISION

SURFACE TEMPERATURES OF IRRADIATED ORR FUEL ELEMENTS COOLED IN STAGNANT AIR

J. F. Wett, Jr.

DATE ISSUED

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SURFACE TEMPERATURES OF IRRADIATED ORR FUEL ELEMENTS COOLED IN STAGNANT AIR

J. F. Wett, Jr.

ABSTRACT

A problem which arises during shipment of irradiated fuel elements is that of the maximum surface temperature which might be reached when the element is air-cooled by natural convection only. In an attempt to answer this problem, several irradiated Oak Ridge Research Reactor (ORR) fuel elements were raised into a hot cell, and their temperature traverses were measured.

Correlations between maximum surface temperature and the irradiation history of the element were made by using the Way-Wigner formula and the data of Perkins and King. It can be concluded that a decay of 19 hr is sufficient to keep the maximum surface temperature of an ORR fuel element, in air, below a dangerous level.

It is felt that the results of this investigation, while not directly applicable to elements other than those from the ORR, can assist in establishing orders of magnitude and will provide a basis for more generalized extensions.

INTRODUCTION

During the period July–October 1959 an investigation was conducted to determine the relation between the irradiation history and the maximum surface temperature of an irradiated ORR (Oak Ridge Research Reactor) fuel element suspended in stagnant air. The problem of excessive fuel plate temperature is most likely to occur during shipping; hence it is somewhat academic for ORR elements, since they remain in the storage pool for a considerable decay period before shipment to a reprocessing area. However, there are reactors with elements similar to those in the ORR where the problem is far from academic, because decay in a pool may not be feasible for economic or technical reasons. It is felt that the results of this investigation, while not directly applicable to elements other than those from the ORR, can assist in establishing orders of magnitude and will provide a basis for more generalized extensions.

PROCEDURE

A two-fingered probe was used to obtain surface temperatures of the interior plates. The probe consisted of two aluminum tubes into which thermocouples were placed. After the couples were in place, the tubes were flattened in order to provide a good friction fit in a coolant channel. The probes were held together by an aluminum spacer which also provided a fitting for the long rod used in placing the probe in the element.

The south hot cell at the ORR was used for this experiment. The construction of the cell is such that an element being brought from the reactor pool must be passed under the west wall of the cell before being suspended on the cell crane hook. Thus, the thermocouple probe had to be placed in the element while the element was still in the pool. The thermocouple leads had to run from the instruments on the balcony, into the pool, and under the hot-cell wall. This required leads approximately 50 ft long and required that they be waterproofed. The aluminum tubing was continued to the top of the end boxes of the element, at which point the leads continued through Tygon tubing to the instruments. The Tygon was the weak point of the system for high-temperature elements, necessitating new probes and leads for each element. Figure 1 is a photograph of a fuel element suspended in the cell.

Since decay time is such an important parameter, severe restrictions are placed upon the time after a reactor fuel change during which data can be obtained. Further, the ORR runs on a three-week schedule, and that, combined with conflicting usage of the hot cell, places limitations upon the quantity of data which can be obtained in a reasonable time. Consequently, it was decided to limit the objective to obtaining a semiempirical relation between element irradiation history and maximum fuel plate surface temperature.

Since the magnitudes of the temperatures to be expected were unknown, it was necessary to start

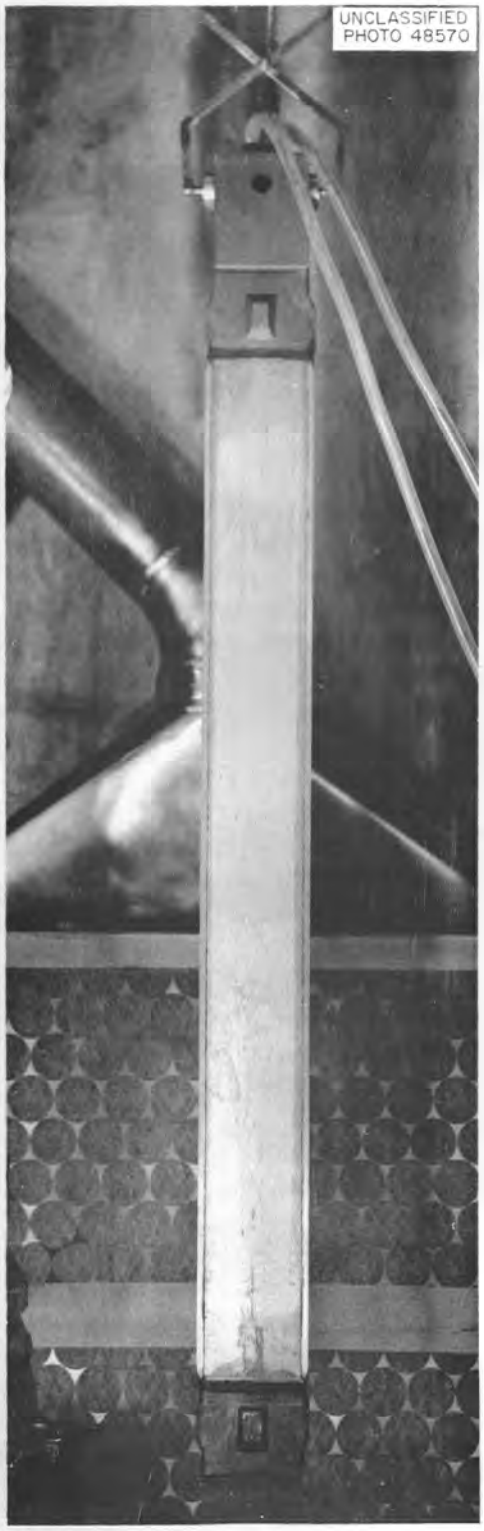

Fig. 1. Fuel Element Suspended in Cell.

with elements whose decay times were long enough to assure reasonable temperatures. After a feel for the magnitudes was obtained, the decay times were shortened for each subsequent run.

For the first series of tests, one thermocouple was placed in each probe. One probe was placed 4 in. and the other 16 in. from the top of the fuel plate. For the second series, six thermocouples were used, three in each probe. They were placed nominally 2, 6, 10, 14, 18, and 22 in. from the top of the fuel plate. The position of these couples was checked by use of a torch before they were put into use. For the first series of tests, mentioned above, both the temperatures were read on separate recorders. However, as knowledge of the transients was gained, all temperatures were read on a multipoint recorder. The ambient temperature of the hot cell was also taken. All elements were hung vertically.

Radiation through the cell at no time exceeded ~30 mr/hr. A more detailed report on the radiation aspect will be issued in the future.

RESULTS

Ten elements were raised into the hot cell. One of these was raised six times, one three times, and one twice, giving a total of 18 datum points. The irradiation history of the elements is shown in Table 1, and the equilibrium temperatures reached by the various elements are shown in Table 2. The temperature of the hot cell was 90°F.

Element OR-103 was left hanging in the hot cell over a weekend so that temperature decay data could be taken. After it had been suspended for approximately 30 hr at a maximum surface temperature of 220°F, two distinct jumps in activity were detected by a continuous air monitor which was monitoring the hot-cell air. Unfortunately, this occurred during the night, and analyses were not made. The element was then submerged as a safety precaution. Element OR-103 was subsequently reinserted in the reactor with no adverse effects. Figure 2 shows the temperature of OR-103 at both 4 and 16 in. below the top of the fuel plate, plotted vs the decay time, and Fig. 3 shows the temperature transients. Not shown on Fig. 3 is the fact that the boiling point of the surface moisture could be clearly seen. It manifested itself as a slight pause in the transient. This was due to steam cooling of the thermocouple.

Table 1. Irradiation History of Fuel Elements

Element No.	Last Cycle Prior to Measurement			Cycle Before Last Cycle				Cycle Before Next to Last Cycle			
	Irradiation Time (hr)	Weight of U^{235} at Beginning of Cycle (g)	Average Flux	Irradiation Time (hr)	Decay Time* (hr)	Weight of U^{235} at Beginning of Cycle (g)	Average Flux	Irradiation Time (hr)	Decay Time* (hr)	Weight of U^{235} at Beginning of Cycle (g)	Average Flux
			$\times 10^{14}$				$\times 10^{14}$				$\times 10^{14}$
103	321	194.7	0.6	120	744	199.8	0.95				
87	321	193.7	1.2	120	744	200.3	1.23				
97	321	143.2	1.1	120	744	146.1	0.74	312	1464	155.6	0.14
94	144	150.7	1.04	264	540	164.2	1.2	120	1908	166.7	0.92
82	200	173.5	0.91	100	679	176.2	0.92	300	906	182.3	0.53
100	200	146.3	1.18	100	679	148.8	1.03	120	1289	153.5	1.15
151	200	199.6	1.02								
87**	417	176.5	0.87	321	747	193.7	1.2	120	1827	200.3	1.23
158	417	200.0	0.75								
164	536	200.0	1.01								

*In addition to decay times given in Table 2.
**Second test.

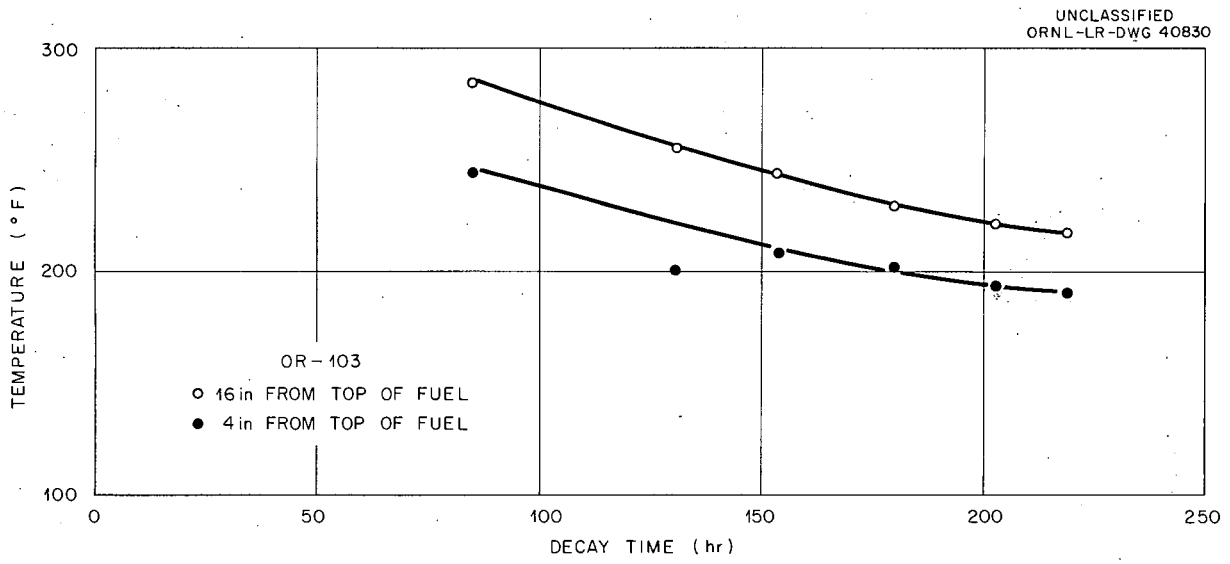

Fig. 2. Temperature of OR-103 at 4 and 16 in. Below Top of Fuel Plate.

Figure 4 is a more detailed trace of a transient and shows this point clearly. The transients of Fig. 3 are quite typical of all those recorded.

The first two elements monitored with the six-thermocouple probe were OR-158 and OR-87. Figure 5 shows the equilibrium temperature traverses of these elements. Notice that the hot spot of OR-87 is *above* the midplane of the length ("center line") rather than below, a result of inverting the element. ORR elements are symmetrical about their midplane, with respect to length, and are inverted during their lifetime to increase fuel burnup. The burnup of OR-158 was measured by A. L. Colomb[1] of the Operations

[1] *Reactor Operations and Radioactive Waste Quarterly Report, July–September 1959*, ORNL CF-59-9-111, p 24.

Table 2. Equilibruim Temperatures of Irradiated Fuel Elements Cooled in Stagnant Air

Element	Decay Time (hr)	Distance from Top of Fuel (in.)	Measured Temperature (°F)	Element	Decay Time (hr)	Distance from Top of Fuel (in.)	Measured Temperature (°F)
103	85	4	245	158	723	5.8	155
	131	16	285			9.3	160
	131	4	201			15.7	159
		16	256			19.4	157
	154	4	209	87*	723	2.5	189
		16	245			4.1	195
	180	4	203			5.8	197
		16	230			9.3	201
	203	4	195			15.7	193
		16	222			19.4	184
	219	4	191	164	19.25	2.5	541
		16	218			4.1	558
87	104	4	312			5.8	593
		16	352			9.3	634
	176	4	249			15.7	641
		16	302			19.4	620
97	108	4	298		40.25	3.5	430
		16	341			6	465
94	780	4	153			14.5	518
		16	175			17.8	505
82	34	4	395			21.5	475
		16	473		61	3.8	368
100	31	4	385			7.3	410
		16	440			11.5	438
151	28	4	366			13.3	450
		16	496			17.3	450
158	723	2.5	151			21.5	430
		4.1	154				

*Second test.

Division. The normalized fuel burnup is shown in Fig. 6. The point of maximum fuel burnup, that is, the point of maximum heat production, occurs approximately 1.5 in. below the midplane. The maximum temperature occurs approximately 0.75 in. below the midplane.

Figure 7 shows the temperature traverses for OR-164 for various decay times. In this case, the maximum temperature appears to be approximately 1.5 in. below the center line.

ANALYSIS OF RESULTS

As stated previously, the major objective of this work was to determine a semiempirical relation between maximum fuel-plate temperature and

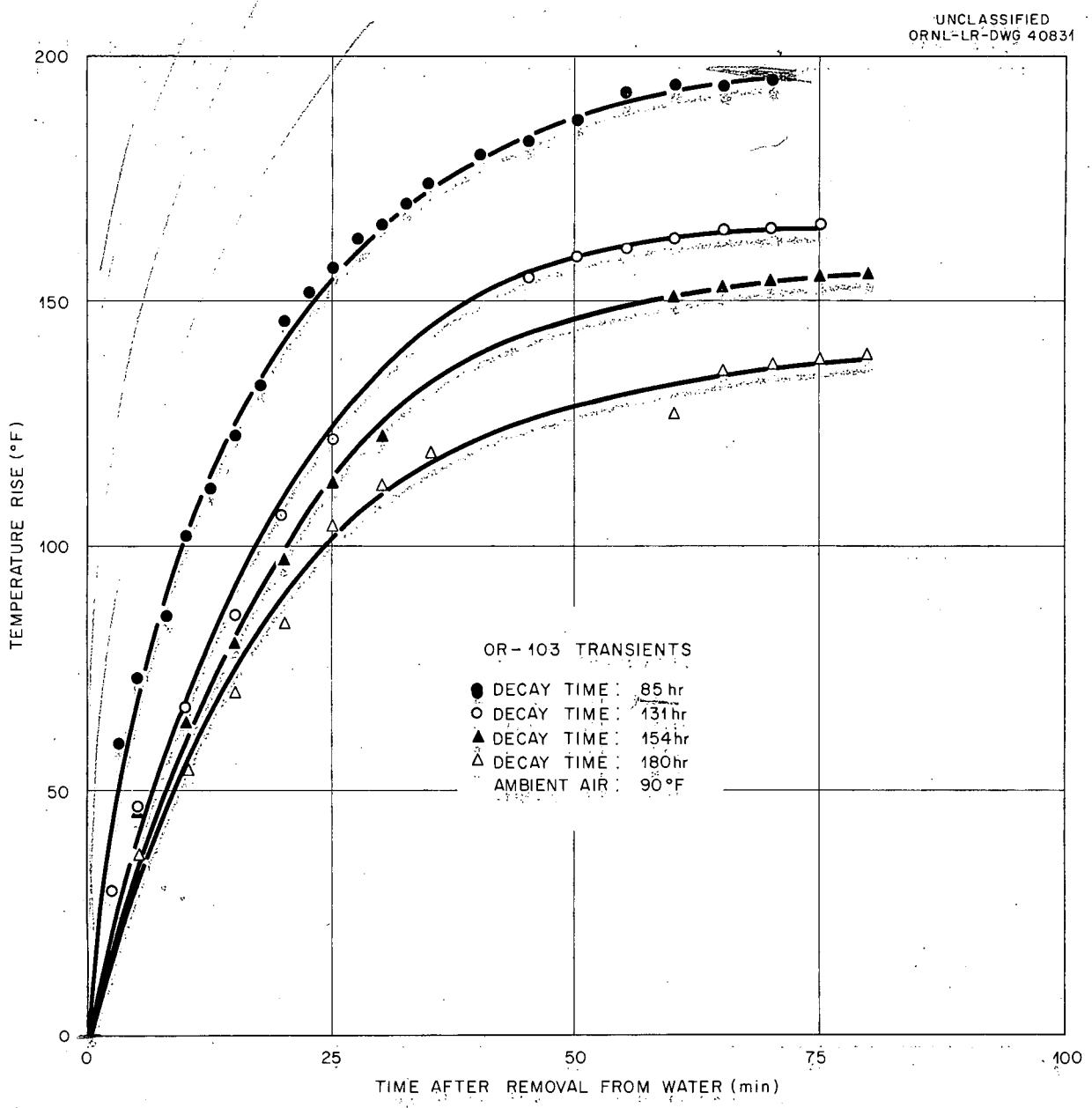

Fig. 3. Temperature Transients of OR-103.

the irradiation history of the element. The analysis was based on the maximum temperature difference between the surface of a fuel plate and the ambient air. The following assumptions are made:

1. All the heat is lost by convection.
2. The change in temperature of the air passing through the elements is small.
3. The heat transfer coefficient is constant.[2]

Then

$$\theta = \frac{1}{hA} q ,$$

[2] M. Jakob, *Heat Transfer*, vol 1, p 467, Wiley, New York, 1949.

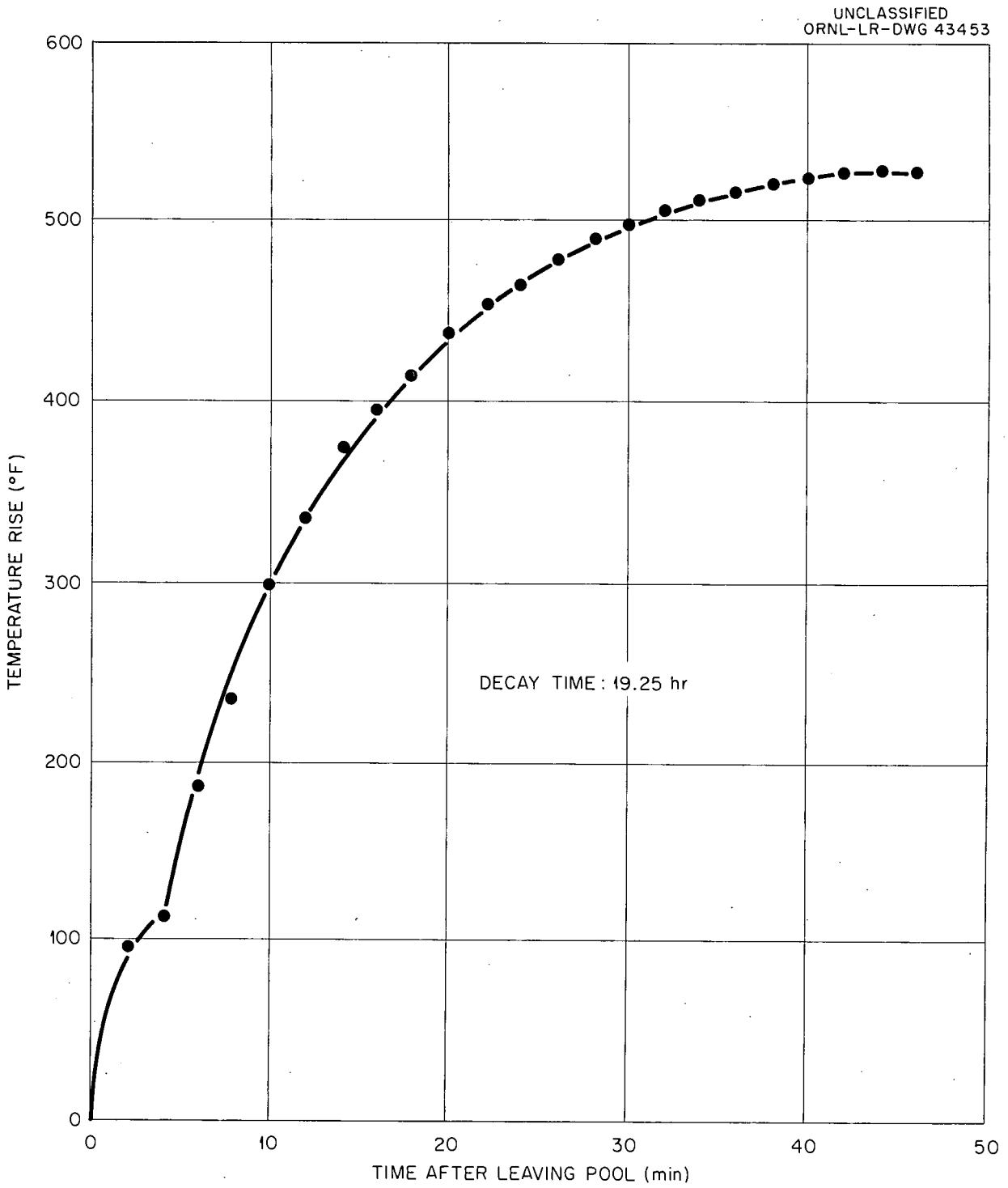

Fig. 4. Temperature Transient of OR-164 at Position 5 in. from Top of Element. Slight pause in transient was due to steam cooling of thermocouple.

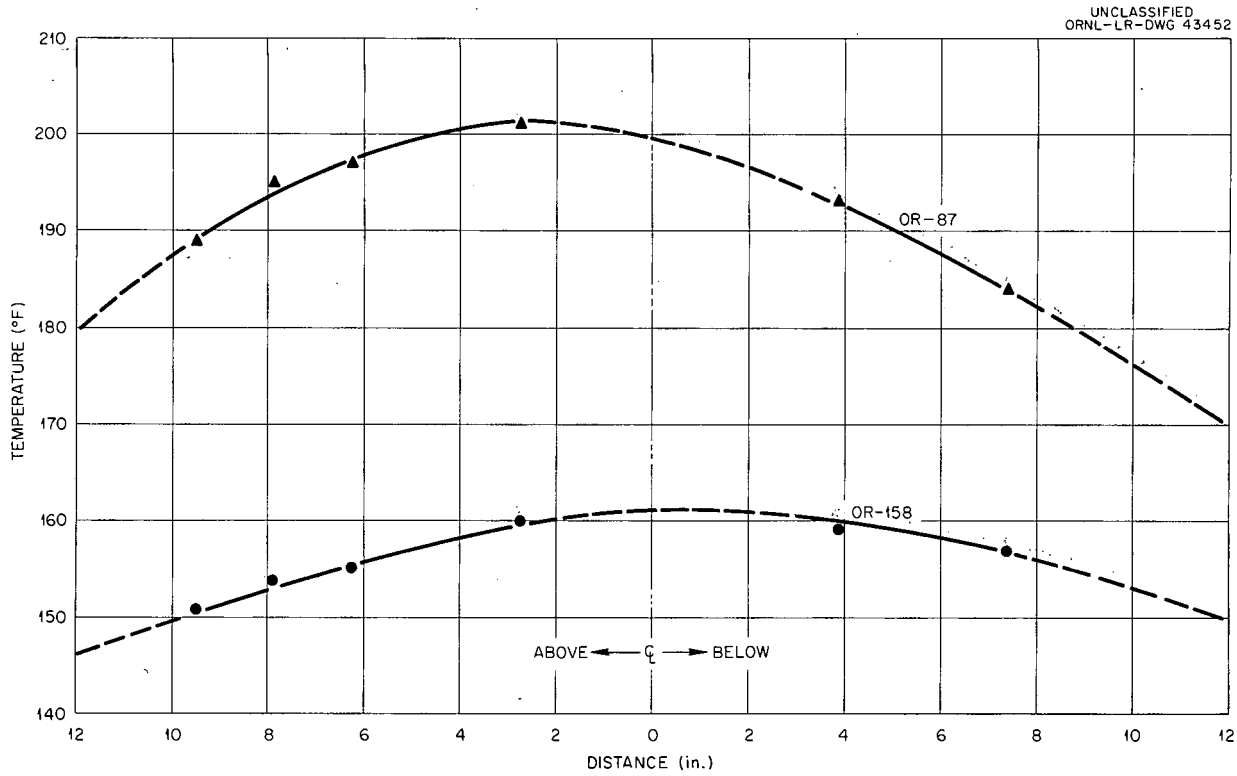

Fig. 5. Temperature Traverses for OR-87 and OR-158.

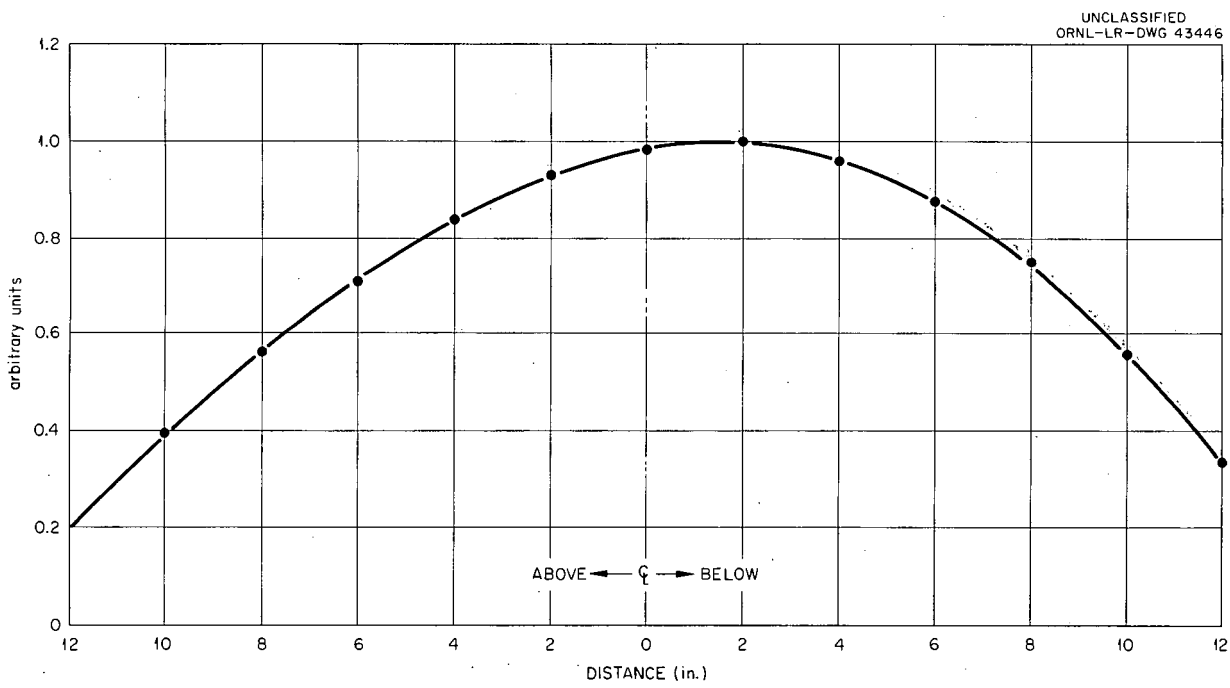

Fig. 6. Normalized Burnup Curve for OR-158.

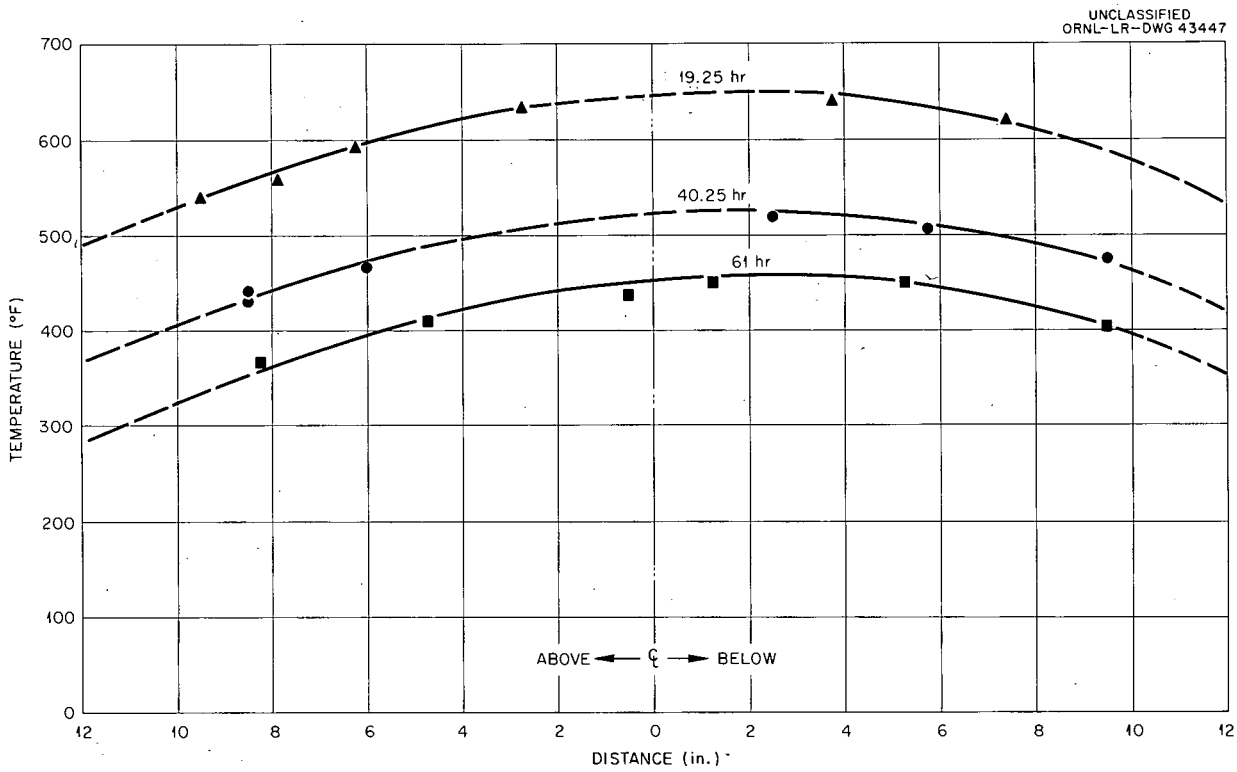

Fig. 7. Temperature Traverses for OR-164 for Various Decay Times.

where

θ = temperature difference between fuel plate surface and ambient air, °F,

h = heat transfer coefficient, $Btu \cdot ft^{-2} \cdot hr^{-1} \cdot (°F)^{-1}$,

A = fuel element heat transfer area, ft^2,

q = heat transfer from element, Btu/hr.

Now, the heat transferred from an element is proportional to the energy released by the decaying fission products; also, the area is a constant. Thus

$$\theta = CQ \ ,$$

where

C = constant,

Q = energy released by fission products.

There are at least two very convenient ways of calculating Q. One is the familiar Way-Wigner formula,[3]

$$\frac{P}{P_0} = 6.22 \times 10^{-2} \left[t^{-0.2} - (T + t)^{-0.2} \right] \ ,$$

where

P_0 = the operating power of the element,

t = decay time, sec,

T = irradiation time, sec.

Also,

$$P_0 = \frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c} \ ,$$

where

$\bar{\phi}_i$ = average flux in the ith element,

$\bar{\phi}_c$ = average flux in the core,

[3] H. Etherington, *Nuclear Engineering Handbook*, p 7–15, McGraw-Hill, New York, 1958.

W_i = weight of U^{235} in the ith element,

W_c = weight of U^{235} in the core,

P' = reactor power.

Then since $P \sim Q$ one obtains

$$\theta = 6.22 \times 10^{-2}[t^{-0.2} - (T+t)^{-0.2}] \frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c} C_1 .$$

A second method is the use of the beta and gamma decay curves presented by Perkins and King.[4] The sum of these curves will be referred to as Y. It has the dimensions Mev/wsec. It must be multiplied by the element operating power,

$$\frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c} .$$

Thus, one finds that

$$\theta = C_2 \frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c} Y .$$

The problem now evolves to that of determining C_1 and C_2. Of all the data points available, five represent elements which had only one cycle in the reactor. The θ's for those five were used to calculate mean values for C_1 and C_2. The values found were

$$C_1 = 2.2 \times 10^5 ,$$

$$C_2 = 4.5 \times 10^{-8} .$$

The assumption is made that the θ's for all cycles are additive, that is, each cycle is computed as though it were the element's only cycle, and the resultant θ's are added to give the actual θ of the element. No proof will be offered except pragmatic. It is obvious that the effect of past cycles becomes more pronounced as the decay time increases. However, even with short decays they often contribute 10% to θ.

If one divides the calculated θ_c by the measured θ_m one obtains a measure of the error between the two. Figure 8 shows θ_c/θ_m vs θ_c. One sees that a systematic error is present and that this error is apparently a function of θ.

Upon re-examining the assumptions previously stated, one finds several sources of error. All the heat is not lost by convection. The hottest elements, that is, those with surface temperatures over 450°F, will begin to lose noticeable amounts by radiation. An undetermined amount of energy will be released in the side plates due to gamma ray absorption. It is known that for vertical plates suspended in air (e.g., the side plates and exterior fuel plates), the heat transfer coefficient is a function of the temperature difference between the ambient air and the plate surface.[5] One might then expect that $h \sim a\theta^n + b$. Applying such a correction to the data of Fig. 8, one obtains $a = 0.0064$, $n = 0.72$, $b = 0.5$. This leads to the formulations:

$$\theta(0.0064\theta^{0.72} + 0.5) = 1.37 \times 10^3 [t^{-0.2} - (T+t)^{-0.2}] \frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c}$$

and

$$\theta(0.0064\theta^{0.72} + 0.5) = 4.5 \times 10^{-8} \frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c} Y ,$$

where Y is as previously defined. If one now plots θ_c/θ_m as in Fig. 9, one sees that the systematic error is gone.

By use of standard procedures[6] one finds that for the Way-Wigner form

$$\theta_c/\theta_m = 1.091 \pm 0.088 ,$$

and for the Perkins and King data

$$\theta_c/\theta_m = 1.055 \pm 0.061 .$$

No attempt was made to remove the positive bias since it was felt that an overestimation of temperature was the preferable error.

[4] J. F. Perkins and R. W. King, *Nuclear Sci. and Eng.* 3, 726–46 (1958).

[5] W. H. McAdams, *Heat Transmission*, 3d ed., p 173, McGraw-Hill, New York, 1954.

[6] W. H. Reddick and F. H. Miller, *Advanced Mathematics for Engineers*, chap. 9, Wiley, New York, 1955.

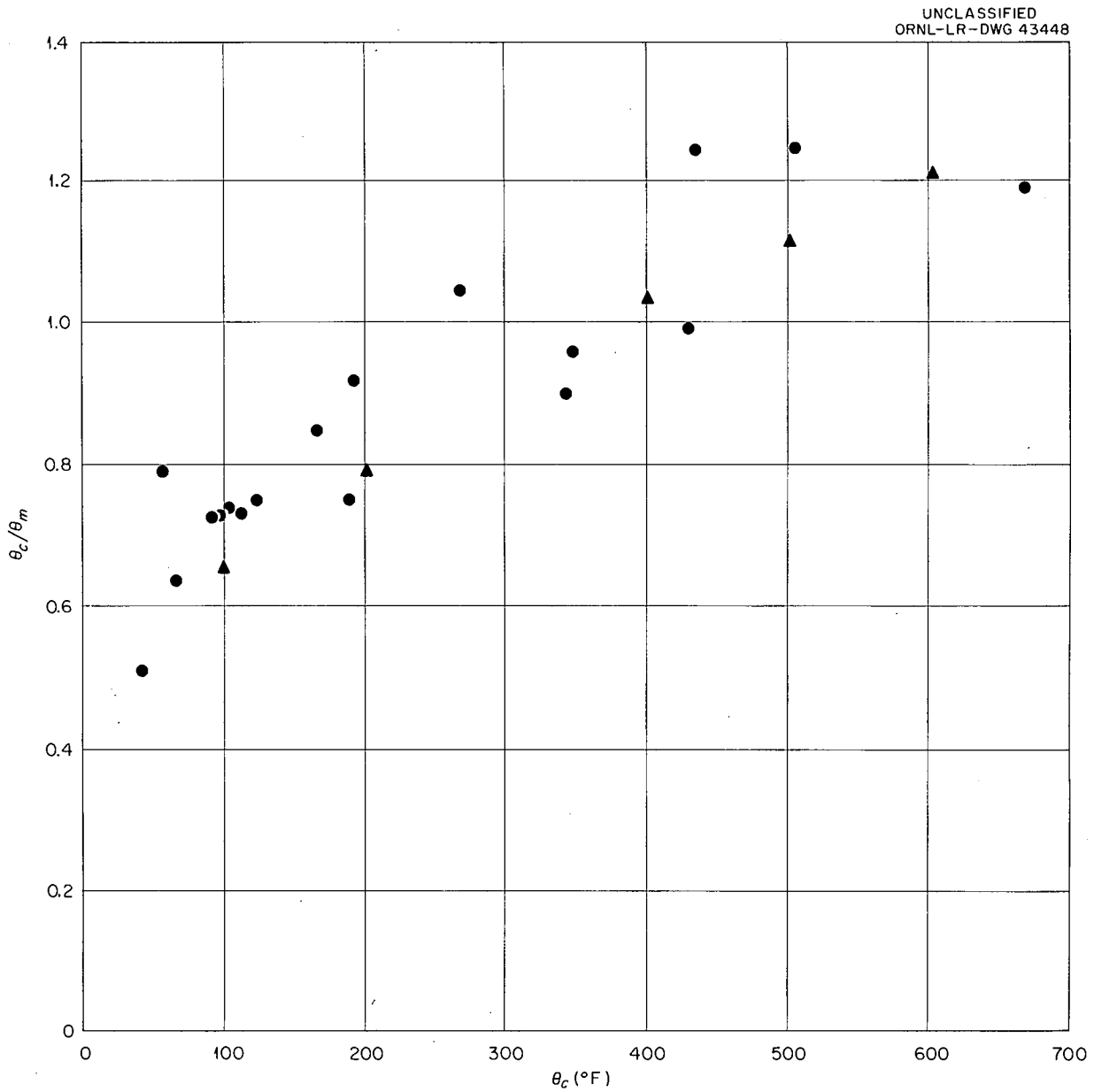

Fig. 8. Variation of θ_c/θ_m, Using h = Constant.

ANALYSIS OF ERRORS

There are two major sources of error inherent in this experiment. The first is the obvious one of experimental error. The second is less obvious. As stated, the objective was to correlate temperatures with reactor history. Thus, the second type of error is that associated with computing and reporting the element's history.

Experimental Error

The location of the thermocouples within the probes presented some problem. The probes containing three thermocouples presented more trouble than those containing only one. It is thought that the couples were located within $\pm\frac{1}{4}$ in.

The location of the probes in the elements presents a possible source of error. Out of neces-

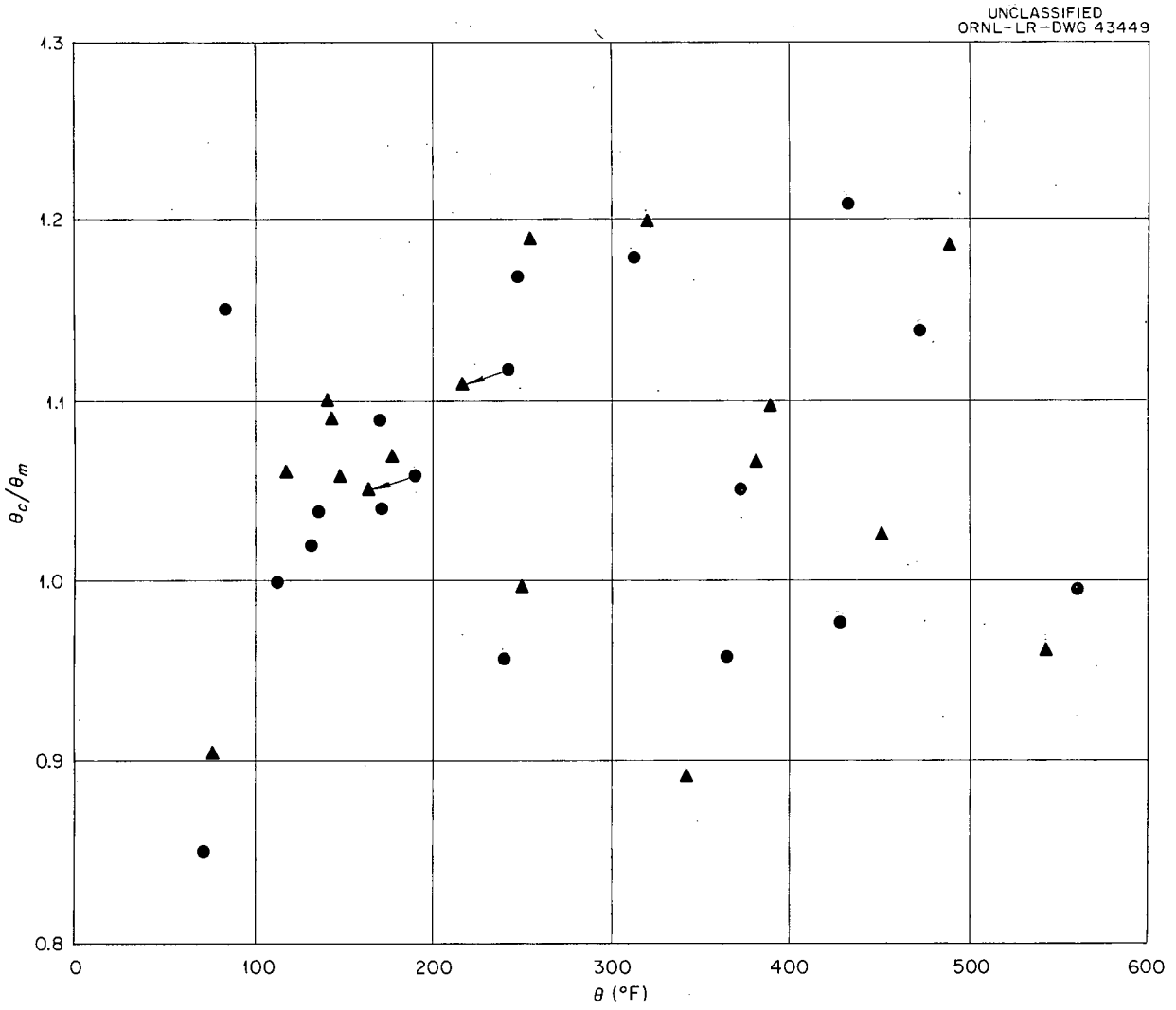

Fig. 9. Variation of θ_c/θ_m, Using $h = C\,(0.0064\,\theta^{0.72} + 0.5)$.

sity these probes had to be positioned through 12 ft of water. It is obvious that one could not always measure the same channel. Examination in the hot cell did show that the probes were inserted to the proper datum level.

The friction fit of the probes could lead to false readings. Probes which did not fit tightly were discarded. It is believed that the measured equilibrium temperatures closely approximated those of the adjacent plates.

The presence of the probes undoubtedly perturbed the air flow and hence the temperatures. The magnitude of this error is unknown.

Normal errors associated with recorders and the taking of data were undoubtedly present.

Historical Errors

Measurement of flux may easily have been in error by 15%.[7]

The power of the reactor fluctuates and may for considerable periods be 1 or 2% different from the nominal.

Weights of fuel elements (except for new ones) and of cores are calculated by use of measured fluxes. Hence, one might easily obtain a compounding of the flux uncertainty.

---

[7] R. J. Nertney, *The First Report of the Heat Transfer Subcommittee of the Phillips Reactor Safeguard Committee*, IDO-16343 (June 1, 1957).

EFFECTS OF PARTIAL SUBMERGENCE IN WATER

The MSA Research Corporation has done research on cooling a stainless steel subassembly similar in construction to an ORR element.[8] The subassembly was heated by induction at rates of 260 and 600 Btu·hr^{-1}·in.$^{-3}$. MSA found that temperatures rose uncontrollably when the subassembly was less than 30% submerged in water. When the subassembly was more than 30% submerged, water "percolated" up the channels, cooling the plates.

Partial-submergence checks were run on OR-158 and OR-164. Element OR-158 was generating heat at ~6 Btu·hr^{-1}·in.$^{-3}$, and no rise in temperature was observed at any point during the submerging process. Data for OR-158 are shown in Fig. 10.

[8] M. J. McGoff, *Subassembly Cooling at Decay Heat Power Levels*, MSAR-59-78 (July 17, 1959).

Element OR-164 was generating heat at a rate of 111 Btu·hr^{-1}·in.$^{-3}$. When the element was lowered so that the fuel plates just touched the water, a sudden rise in temperature was noticed. However, the rise did not get out of control, but the temperature oscillated at a point lower than the original. The couples farthest from the water showed the most oscillation. As the element was lowered farther, the oscillations damped out until the temperatures behaved similarly to those of OR-158. No transport of water up the channels was observed. Data for OR-164 are shown in Fig. 11.

SUMMARY AND DISCUSSION

It can evidently be concluded that an ORR element can be safely cooled in stagnant air after a decay of 19 hr. It seems reasonable to suspect that the decay period could be safely extrapolated to 12 hr.

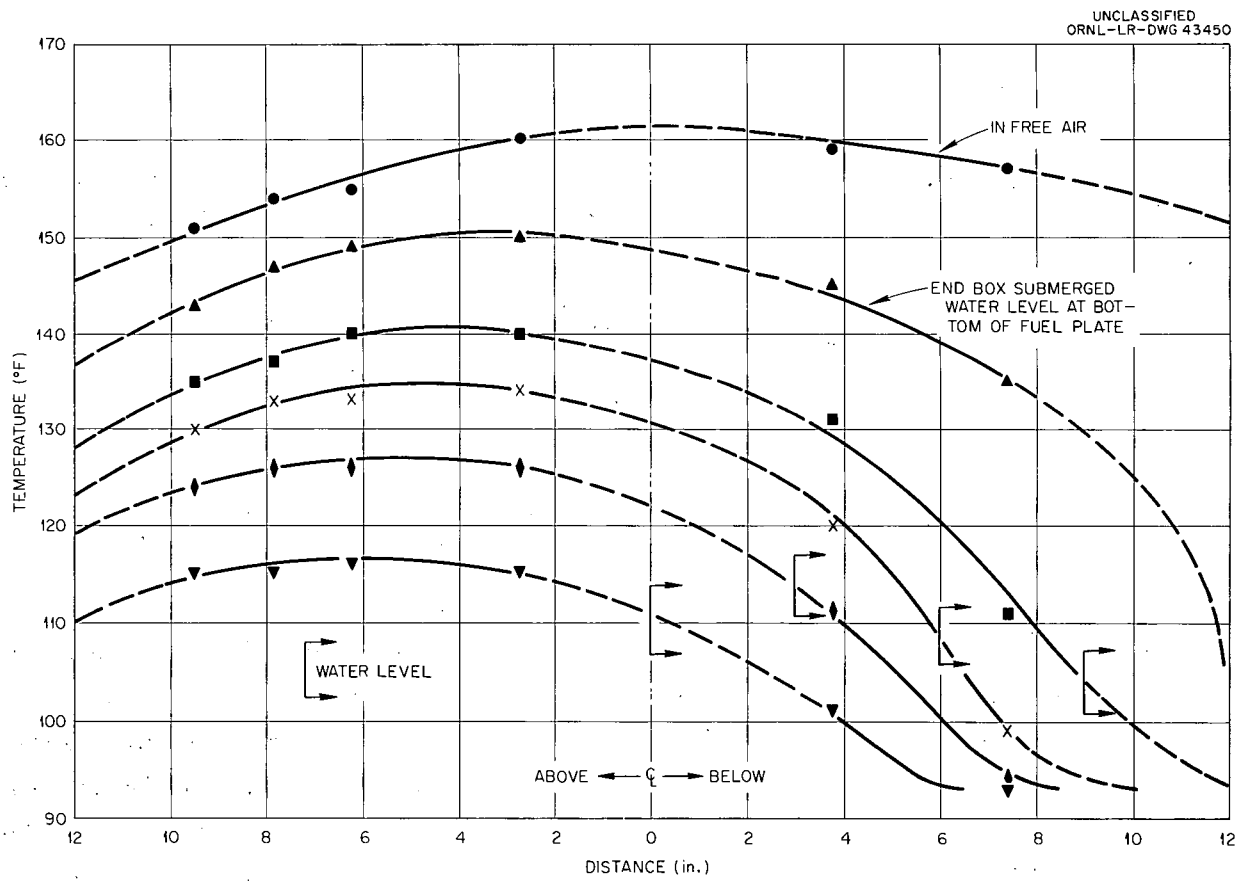

Fig. 10. Effect of Partially Submerging OR-158 in Water.

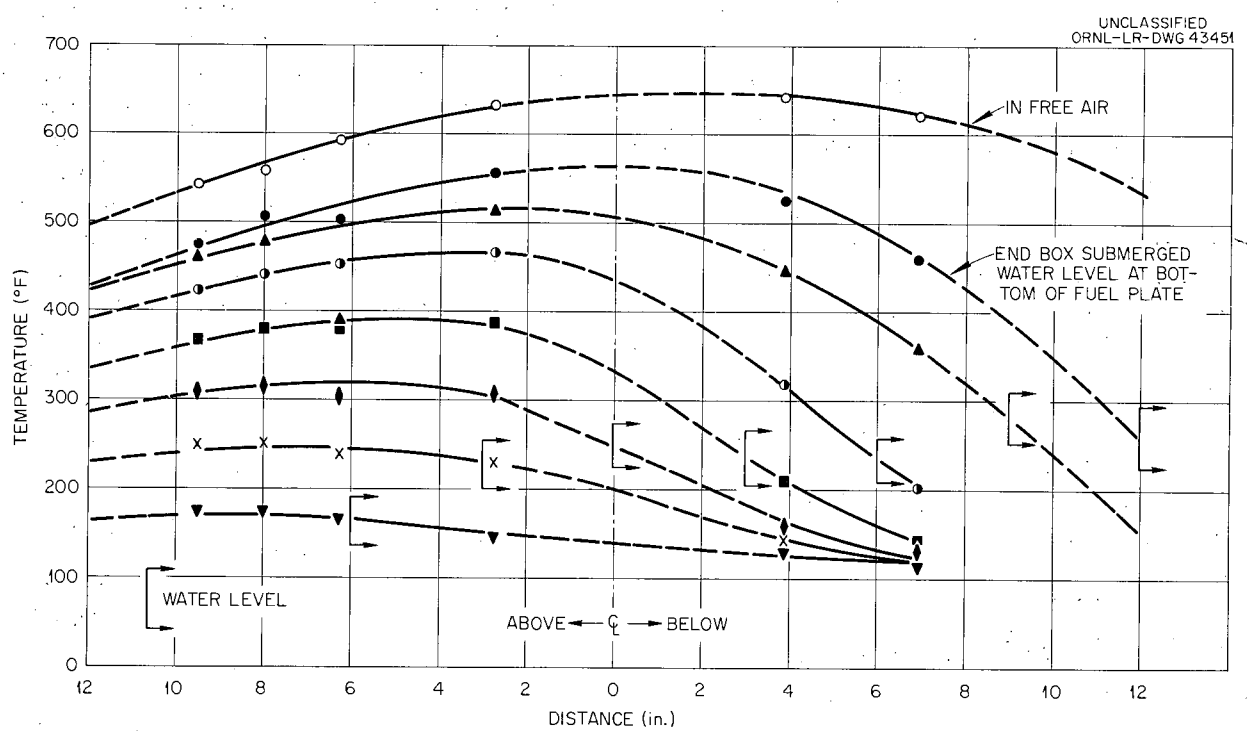

Fig. 11. Effect of Partially Submerging OR-164 in Water.

Two correlations between surface temperature and irradiation history have been developed. One uses the Way-Wigner equation to determine the heat source, the other uses the data of Perkins and King. They are

$$\theta(0.0064\theta^{0.72} + 0.5) = 1.37 \times 10^3 \left[t^{-0.2} - (T + t)^{-0.2}\right] \frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c}$$

and

$$\theta(0.0064\theta^{0.72} + 0.5) = 4.5 \times 10^3 \frac{\bar{\phi}_i W_i P'}{\bar{\phi}_c W_c} Y ,$$

where the terms are defined in the text.

Temperatures measured during the partial submergence of fuel elements strongly indicate that there probably is a power density above which partial submergence causes higher temperature than no submergence at all. It is noted that the surface temperatures in OR-164 were above the boiling point at some distance (~ ½ in.) below the water surface. It is suspected that boiling occurred in the channels. It is believed that the boiling, a rapid vaporization of water, and the heat-sink characteristics of the pool kept the temperatures from rising uncontrollably.

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