APDA - 130

IRRADIATION TESTING of ENRICO FERMI PROTOTYPE FUEL PINS in the CP-5 1957 - 1959

by

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INTRODUCTION

In 1956, an irradiation program was initiated as part of the assistance contract between the Atomic Energy Commission and the Power Reactor Development Company. Under this program, Enrico Fermi prototype fuel pins were irradiated in the Argonne Research Reactor (CP-5) under temperature conditions and to burnups simulating those expected in the Enrico Fermi Atomic Power Plant. The object of the program was to proof-test the zirconium clad uranium-10 w/o molybdenum fuel pins and to verify the predicted allowable burnup of this alloy, based on previous MTR capsule irradiation tests. The first specimen was placed in CP-5 on July 1, 1957.

To date, tests of three full-length pins have been completed with burnups ranging from 0.3 to 1.0 a/o. Results of these tests have verified predicted high-temperature allowable burnups and showed that, under certain conditions, excessive swelling could occur at low temperatures.

The pins were individually irradiated in finned capsules that were cooled by circulating air. The original CP-5 air cooled loops were designed and operated by ANL. The facilities used in this program were essentially the same with some modifications. The inlet and outlet air temperatures, the temperatures at the root of the fins on the capsules, and the air flow rate were continuously monitored to provide an accurate method for determining fuel pin heat generation and the temperature of the fuel pin. The advantages of this type of irradiation facility are (1) the ability to control fuel pin temperature by controlling air flow, and (2) the accuracy with which the pin temperature can be calculated from the temperature measurements that are made.

The metallographic work reported herein was performed at Argonne National Laboratory and at Battelle Memorial Institute. All photographs were taken by Argonne National Laboratory, and consultation and advice on this program was given by several members of the staff at ANL.

IRRADIATION TESTS

GENERAL

To date, three full-length fuel pins have been tested in the CP-5. These pins, identified as CP-5-1, CP-5-2 and CP-5-3, were irradiated to burnups ranging from 0.3 to 1.0 a/o*. Each specimen was fabricated by an identical coextrusion and cold swagging process, then heat treated 1 hour at a temperature of 1475 F. The end-caps of each specimen were somewhat different, as described under TEST RESULTS of this report.

The principal statistics of these tests are given in Table I.

TABLE I

PRINCIPAL STATISTICS OF CP-5-1, -2 and -3 IRRADIATIONS

Test Pin Number	CP-5-1	CP-5-2	CP-5-3
Date placed in Reactor	July 1, 1957	Jan. 26, 1958	July 3, 1958
Date removed from Reactor	April 21, 1958	Mar. 17, 1958	Oct. 13, 1958
Reactor Thimble Number	VT-27	VT-23	VT-23
Reactor Kilowatt Hours	10,937,520	1,965,740	3,902,495
Measured Pin Power at 2 Mw on Reactor	5.8	10.0	11.0
Calculated average a/o burnup	0.85	0.27	0.58
Pin Enrichment	19.35	9.49	10.54

IRRADIATION HISTORY

CP-5-1 Test

As shown in Fig. 1, the CP-5-1 pin was irradiated at a low temperature for the first 1-1/2 months. After that period, the air coolant flow was decreased and a typical temperature profile, as shown in Fig. 2, prevailed for the remainder of the test whenever the reactor was at the rated 2 Mw power. The abrupt reductions in temperature, as shown in Fig. 1, indicate reactor shutdowns. At each of the 674 reactor scrams, the capsule temperature was reduced rapidly to about 150 F, as shown in Fig. 1.

CP-5-2 Test

Irradiation temperatures of CP-5-2 are shown in Fig. 3. Temperatures during the first 10 days of the irradiation were higher than desired, even with the maximum air flow and recirculation of moist air from the blower exhaust. During the reactor shutdown in February 1958, corrective measures were taken to lower the fuel pin temperature by increasing the

* Burnup is given as percent of total atoms fissioned in the fuel alloy.

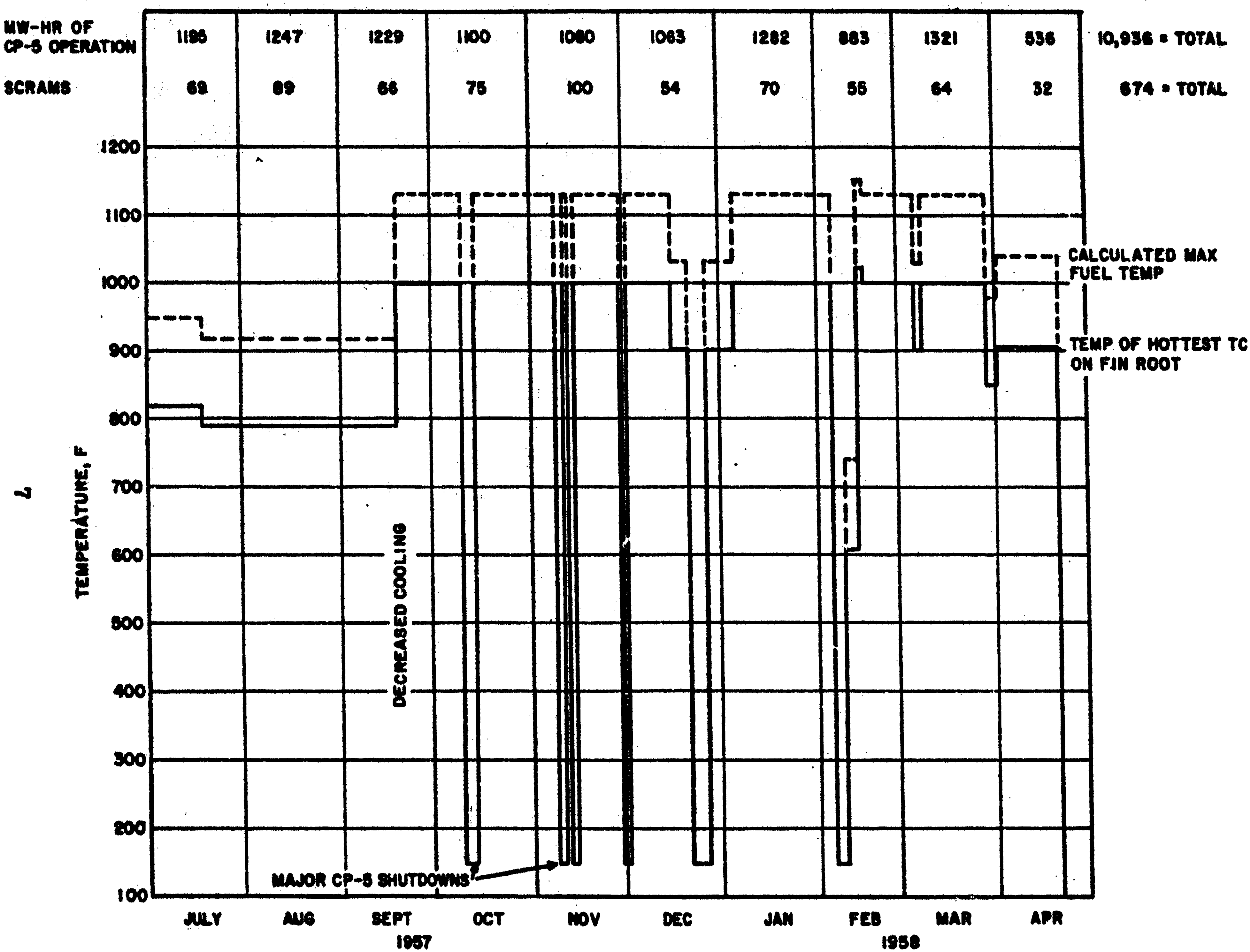


FIG. I IRRADIATION HISTORY OF CP-5-I FUEL PIN

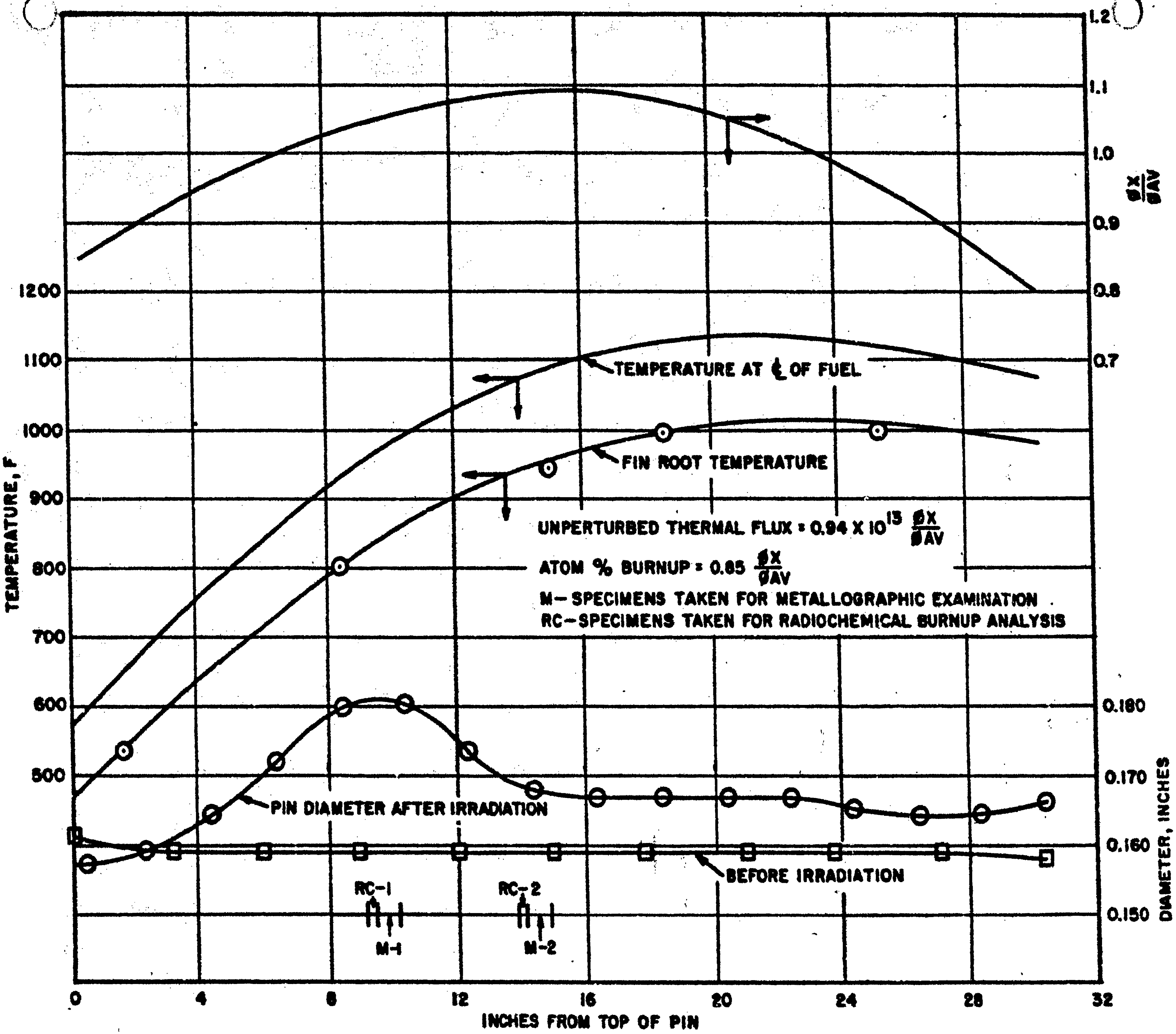


FIG. 2 IRRADIATION RESULTS OF CP-5-1 TEST

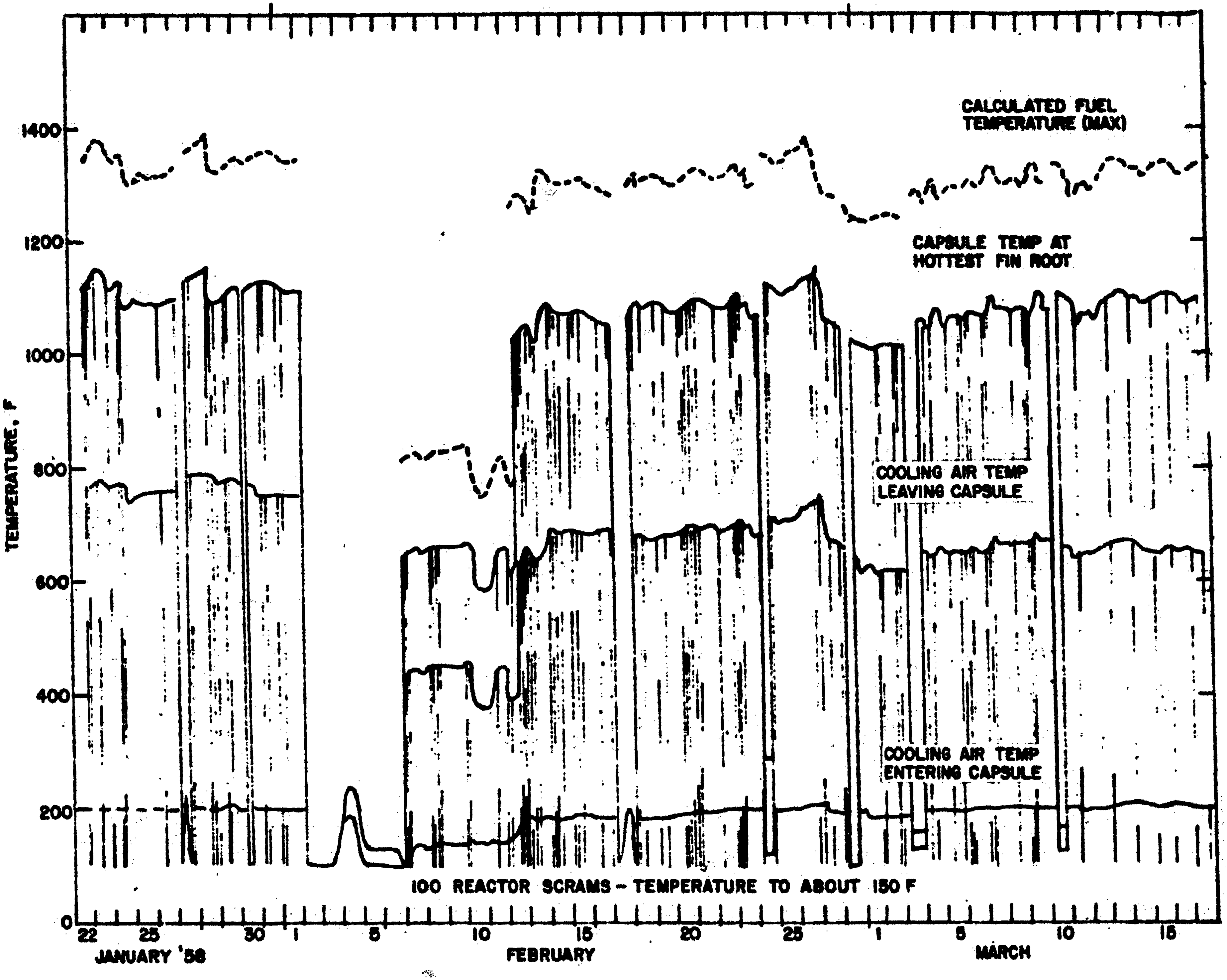


FIG. 3 IRRADIATION HISTORY OF CP-5-2 FUEL PIN

cooling capacity of the system. Immediately following the shutdown period, the reactor was operated at half power, 1 Mw, for a period of about 6 days, resulting in the low temperatures shown. When full power operation (2 Mw) was resumed, using the improved cooling, the typical temperature profile of the pin was as plotted in Fig. 4.

CP-5-3 Test

Irradiation temperatures of CP-5-3 are shown in Fig. 5. When first charged into the reactor on July 3, 1958, the maximum recorded capsule fin-root temperature was 1250 F, which represented a maximum fuel centerline temperature of about 1460 F, 100 degrees higher than desired. After approximately 8 hours of operation, the reactor power was reduced from 2 to 1.8 Mw, resulting in the reduction in temperature to desirable limits. On July 21, the position of the pin was adjusted to be in a slightly lower flux, which then permitted reactor power to be restored to 2 Mw. The temperature profile, shown in Fig. 6, was typical of the period from July 21 to the completion of the test on October 13, 1958.

During each of the 170 reactor scrams, as during the nine major shutdowns, the capsule temperature decreased rapidly to about 150 F.

TEST RESULTS

CP-5-1 Test

The CP-5-1 pin was irradiated to an average burnup of 0.85 a/o. The range over the length of the pin was 0.68 to 0.93 a/o. The fuel centerline temperature ranged from 575 to 1140 F, as shown in Fig. 2.

Pre- and post-irradiation diameter measurements, shown graphically in Fig. 2 and numerically in Table II, showed rather severe swelling of the pin, particularly in the 800 to 1050 F temperature range. The general appearance of the pin was good throughout its length, with no evidence of cracking or rupturing. A photograph of a typical region of the pin is shown in Fig. 7.

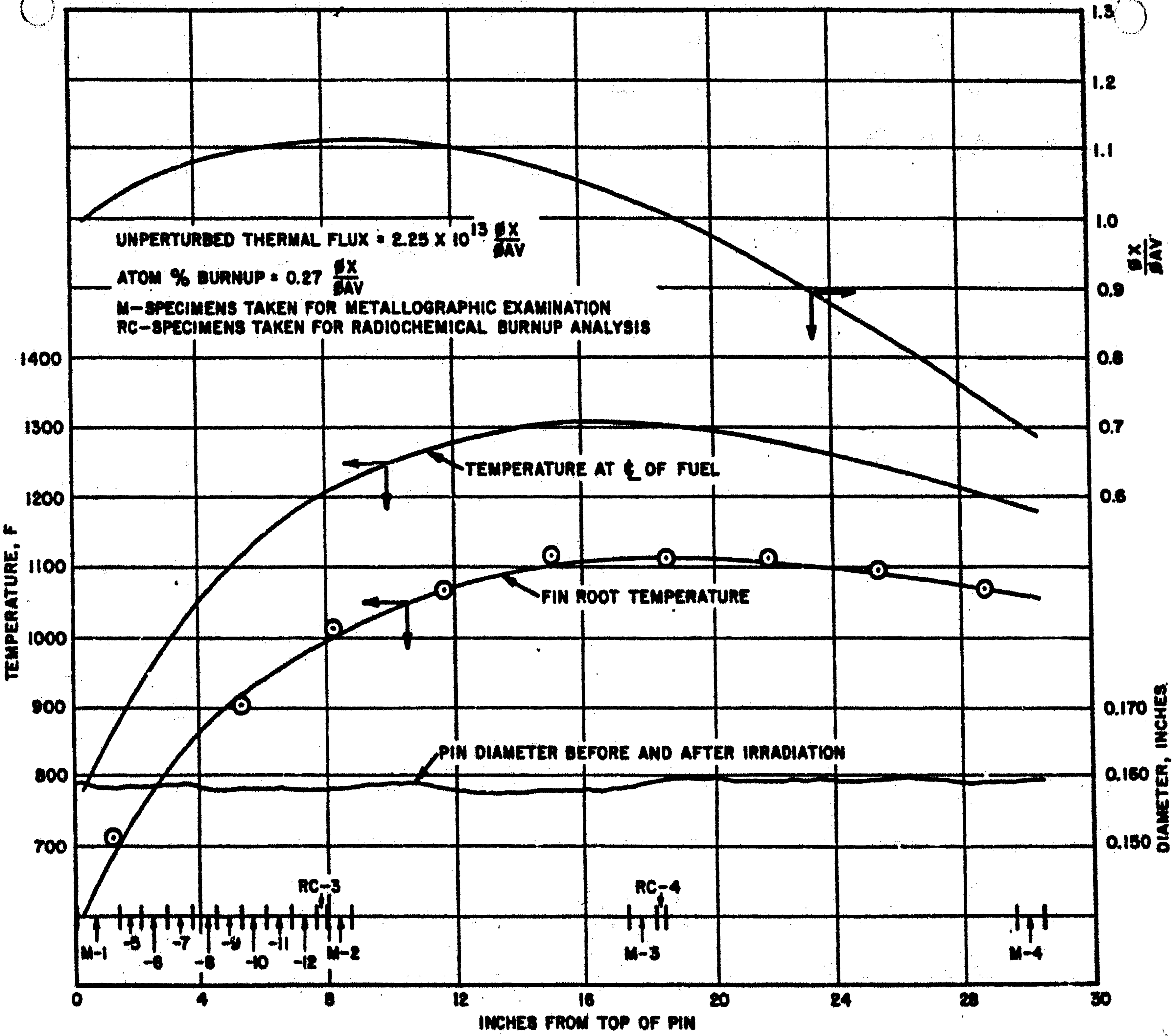


FIG. 4 IRRADIATION RESULTS OF CP-5-2 TEST

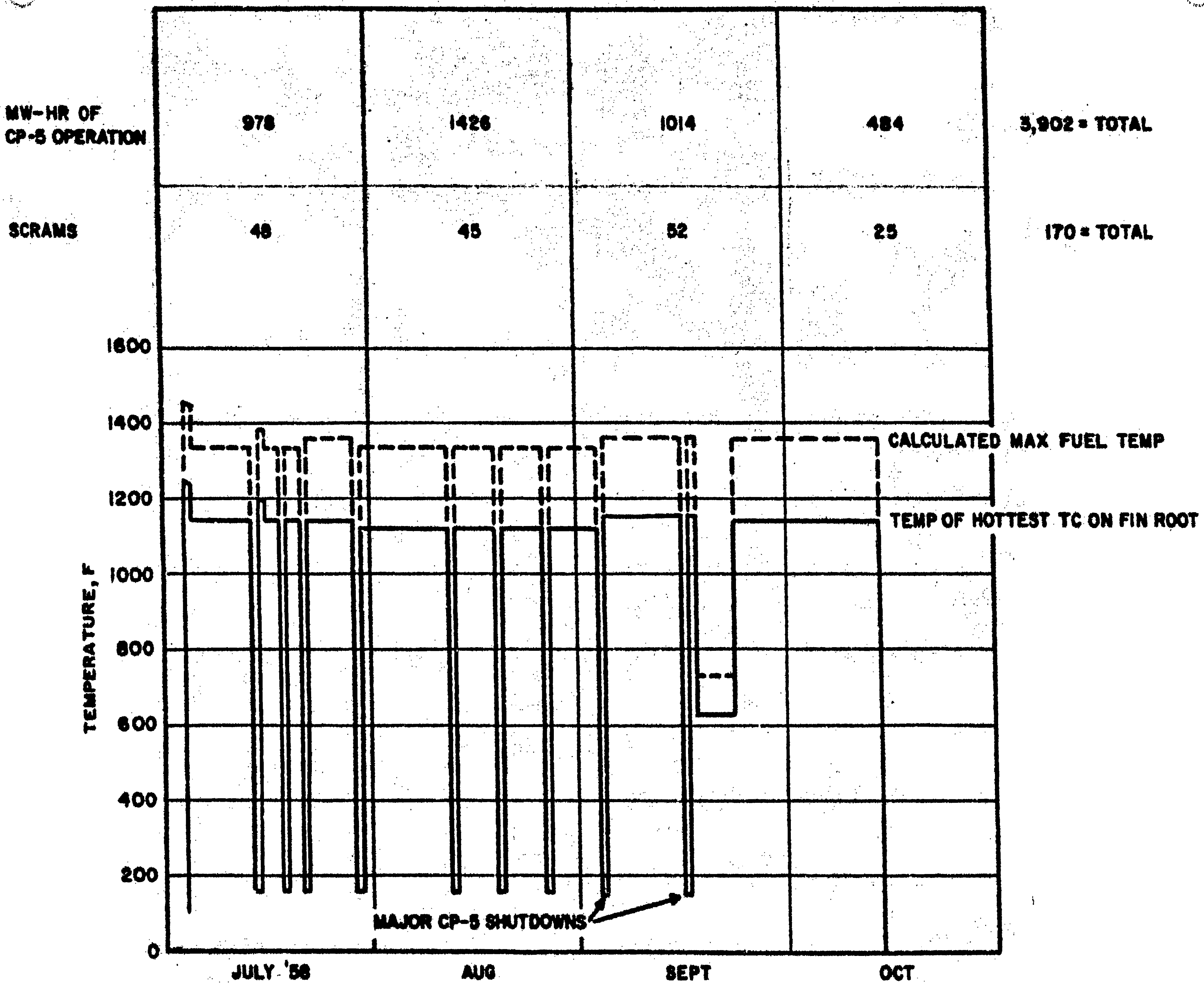


FIG. 5 IRRADIATION HISTORY OF CP-5-3 FUEL PIN

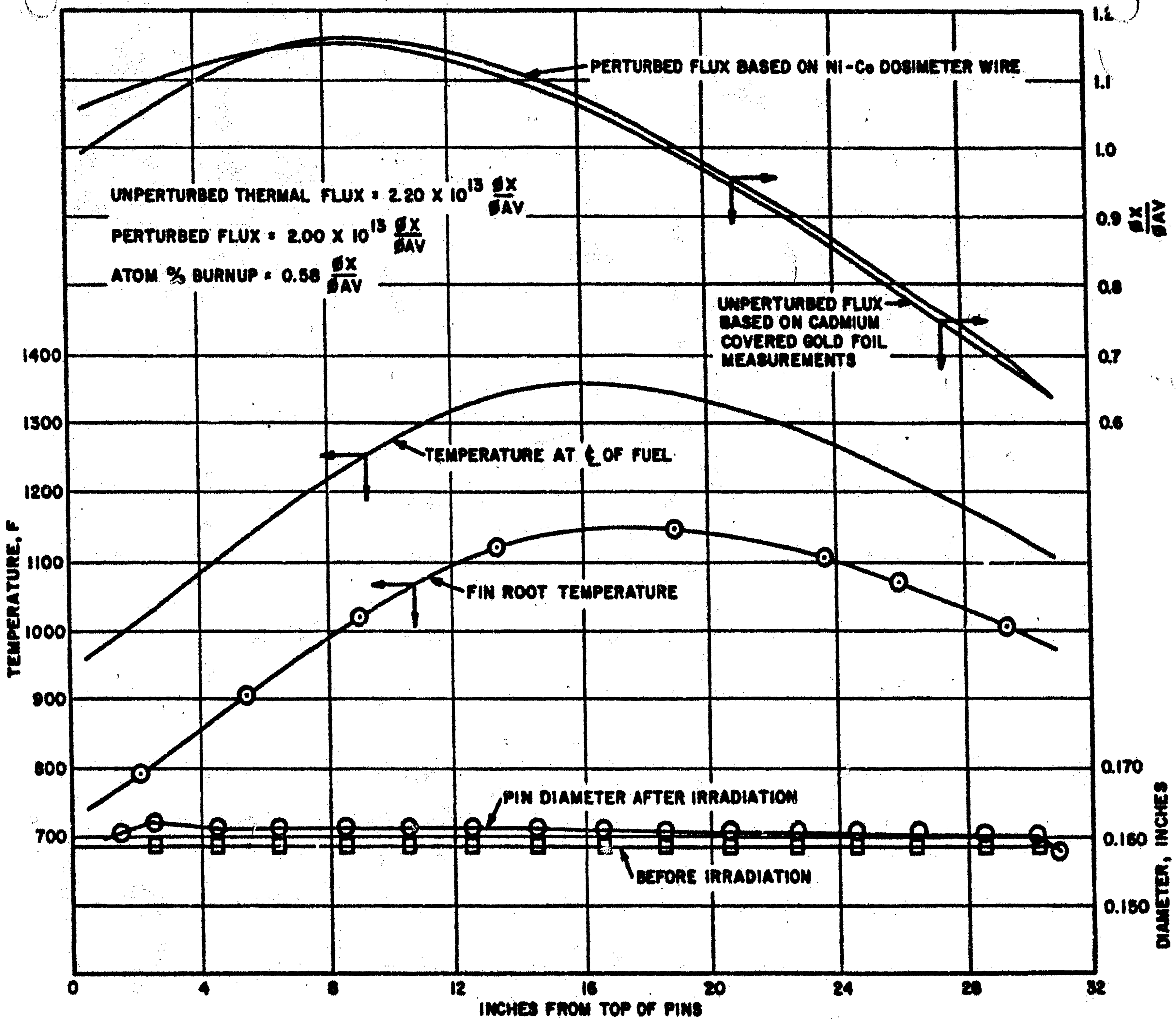


FIG. 6 IRRADIATION RESULTS OF CP-5-3 TEST

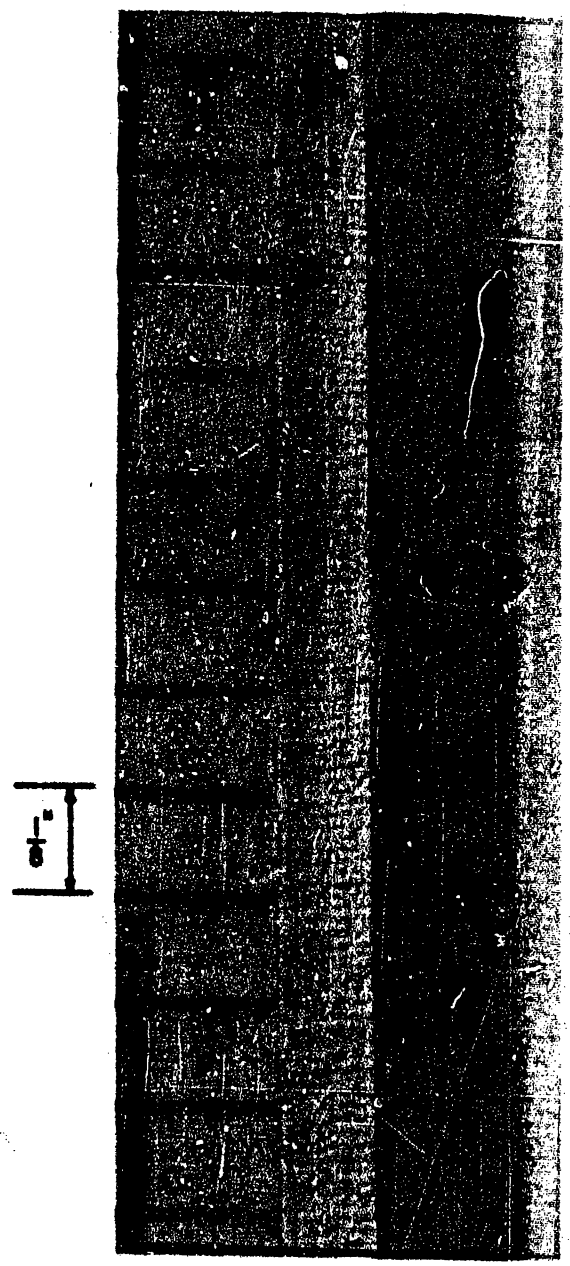


FIG. 7 TYPICAL APPEARANCE OF CP-5-I PIN AFTER IRRADIATION

Table II

Pre- and Post Irradiation Diameters of CP-5-1, -2, and -3 Test Pins

Length, inch, From top of pin	CP-5-1 Pre	CP-5-1 Post	CP-5-2 Pre	CP-5-2 Post	CP-5-3 Pre	CP-5-3 Post
0	.1610	.159 EC	.163	.163 EC		
1					.1588	.1595
					.1600*	.1605*
2		.159			.1590	.1622
			.159	.158	.1588*	.1618*
3						
	.1592					
4		.161			.1591	.1609
					.1591*	.1605*
5						
6		.171			.1590	.1605
	.1590		.159	.158	.1593*	.1608*
7						
8					.1592	.1608
		.180			.1594*	.1612*
9		.181				
	.1591					
10					.1592	.1615
		.180	.159	.159	.1592*	.1615*
11						
12		.174			.1587	.1610
	.1591				.1587*	.1610*
13						
14		.168			.1587	.1610
			.159	.159	.1588*	.1610*
15	.1590					
16					.1588	.1612
		.167			.1588*	.1614*

Table II (Cont'd.)

Length, inch, From top of pin	CP-5-1 Pre	CP-5-1 Post	CP-5-2 Pre	CP-5-2 Post	CP-5-3 Pre	CP-5-3 Post
17						
18	.1590	.167	.159	.159	.1590 .1588*	.1610 .1608*
19						
20		.167			.1587 .1587*	.1605 .1605*
21	.1590					
22		.166	.159	.159	.1587 .1588*	.1601 .1601*
23						
24	.1591	.166			.1588 .1588*	.1601 .1600*
25						
26		.164	.159	.159	.1588 .1588*	.1593 .1600*
27	.1590					
28		.163			.1588 .1588*	.1595 .1595*
29		.166			.1590	.1593
30	.1610 .1500 EO		.161	.162 EO	.1588* .1585	.1595* .1593
31					.1589*EO	- - EO
32						
Length	31	31-5/8	30-13/16	30.9	30-29/32	31
Density (g/cc)	15.66**	13.40	15.6	14.8	15.69	15.33

* Measurements 90° apart at same height.
** CP-5-1 Control Pin.

The end-caps on this pin were of a butt-welded type. As shown in the pre-irradiation photographs, Fig. 8, the welds were somewhat defective. Since both end-caps were separated from the pin upon removal from the capsule, it is not known at what stage of the test the caps broke off. Post irradiation photographs of the bottom end of the pin and the severed end-cap are shown in Fig. 9.

Two specimens were taken from the pin, at the location shown on Fig. 2, for radiochemical burnup analysis. Analysis of RC-1 showed a burnup of 0.87 a/o, which is within experimental precision of the calculated value of 0.89 a/o. Sample RC-2 was reported to be 1.33 a/o, while the calculated value was 0.93 a/o. From the analyses received on CP-5-2, which effectively confirmed the calculated burnup profile, the experimentally-determined value for RC-2 is believed to be in error. The results of the radio-chemical analyses are shown in Table III for both the CP-5-1 and CP-5-2 pins.

Two specimens were taken for metallographic examination. A detailed discussion of the results of the examination is included under EVALUATION OF TESTS RESULTS of this report.

Table III

Radiochemical Burnup Analyses

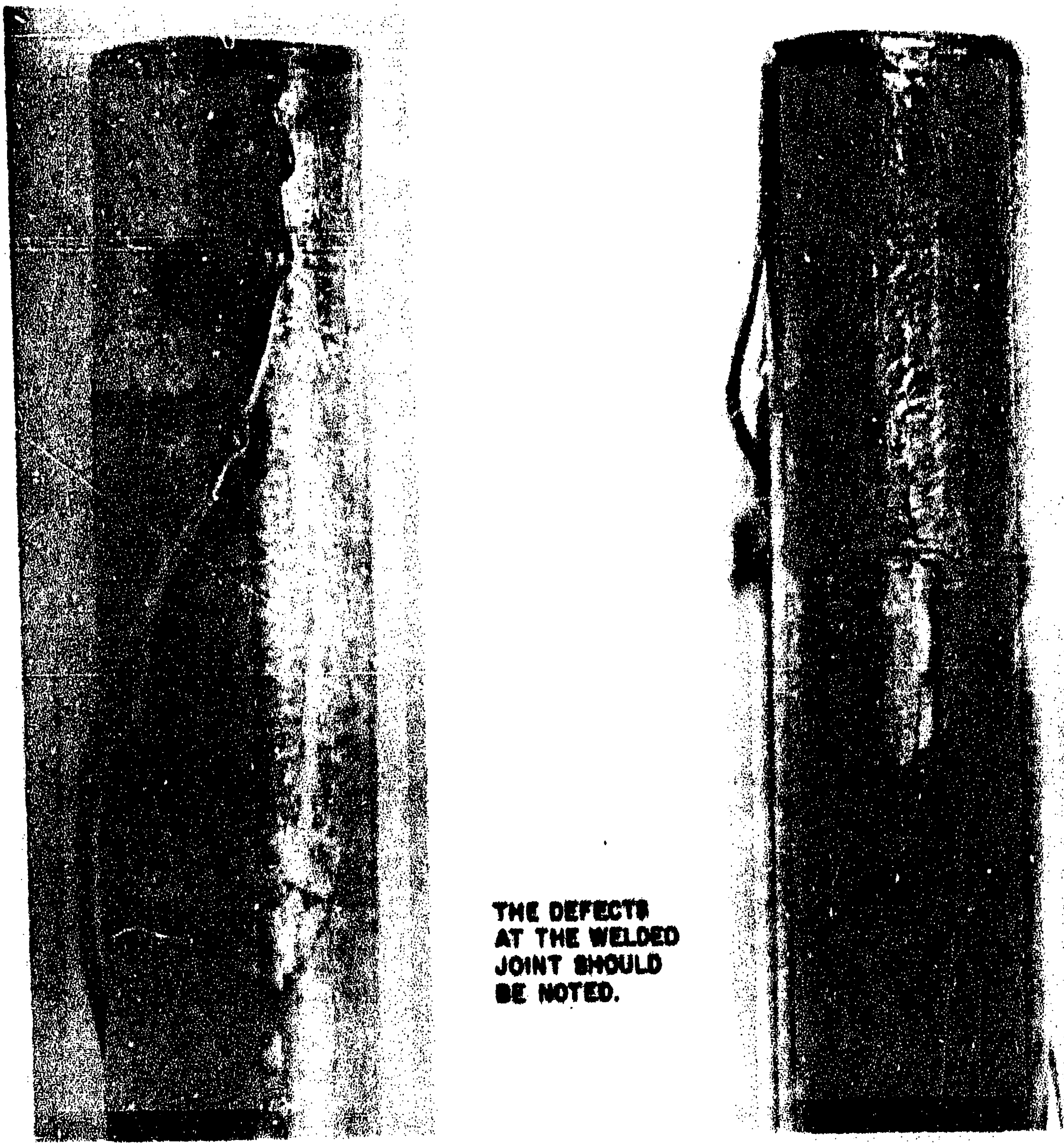
Fuel Pin No.	Specimen No.	Radiochemical Burnup Analyses - a/o	Calculated Burnup %
CP-5-1	RC-1	0.87	0.89
	RC-2	1.33	0.93
CP-5-2	RC-3	0.28	0.29
	RC-4	0.27	0.28

CP-5-2 Test

The CP-5-2 pin was irradiated to an average burnup of 0.27 a/o. The range over the length of the pin was 0.18 to 0.30 a/o. The fuel centerline temperature ranged from 780 to 1320 F, as shown in Fig. 4. Pre- and post-irradiation diameter measurements, shown graphically in Fig. 4 and numerically in Table II, showed essentially no diametric change resulting from irradiation.

The external appearance of the pin was good, as shown in Fig. 10, a typical section of the pin.

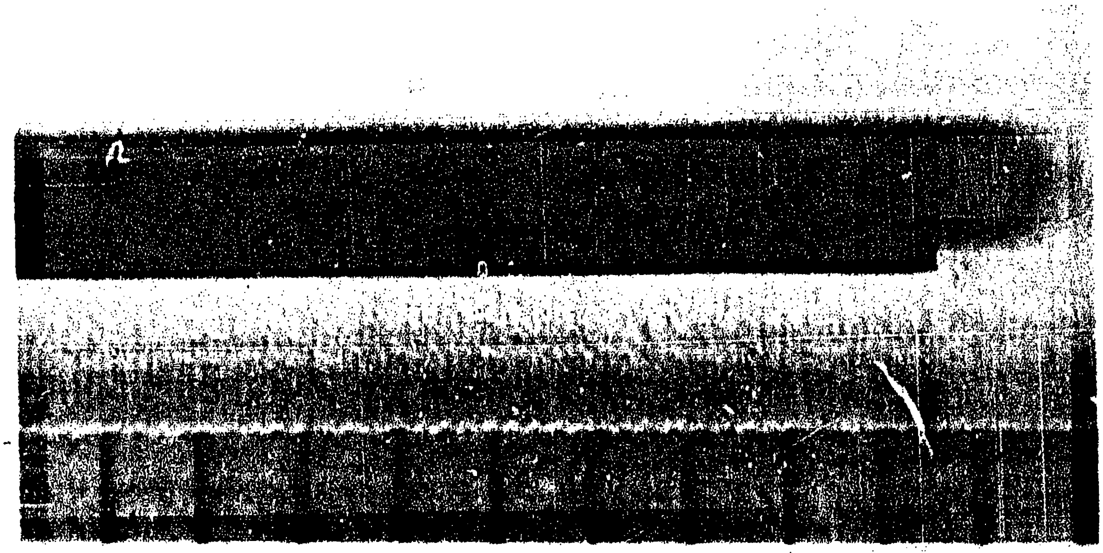
This pin was equipped with modified swaged end-caps; a stainless steel cap, with a zirconium plug, was irradiated on the hot end of the pin and zirconium cap on the cold end. These caps differ from the Enrico Fermi reference swaged caps in that the Fermi fuel pin ends are pointed prior to



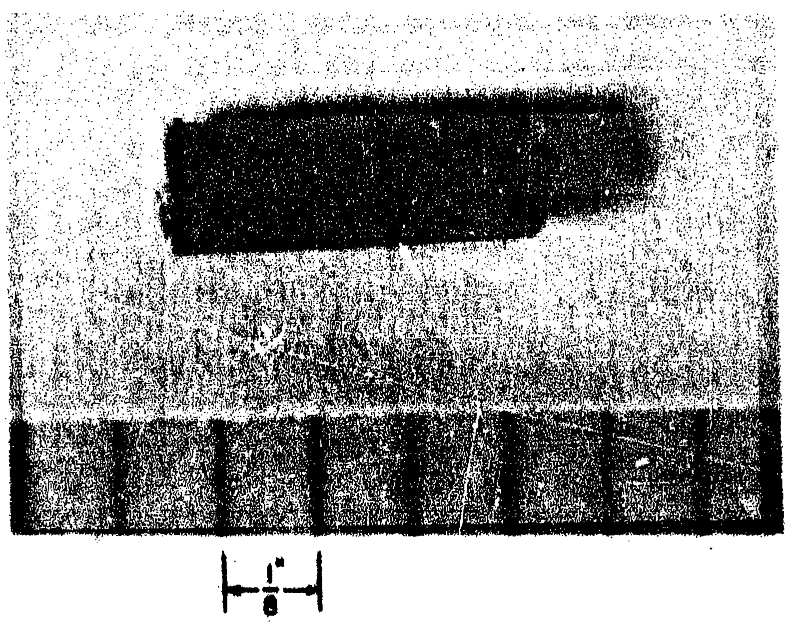
BOTTOM END-CAP

TOP END-CAP

FIG. 8 PRE-IRRADIATION PHOTOGRAPHS OF BUTT-WELDED END-CAPS ON CP-5-I TEST



BOTTOM END OF PIN SHOWING FRACTURE AT WELD



BOTTOM END-CAP

THE WHITE IN PHOTOGRAPH IS PAINT

BOTTOM END-CAP

FIG. 9 BOTTOM END AND END-CAP OF CP-5-I PIN AFTER IRRADIATION

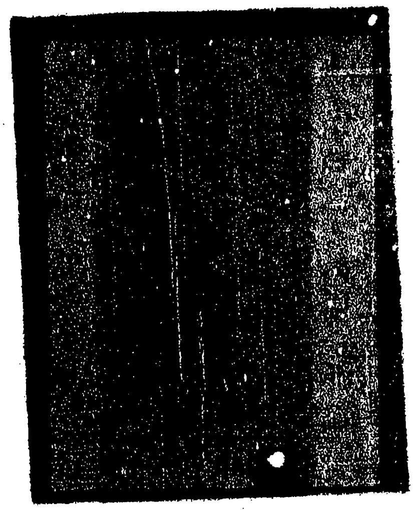


FIG. 10 TYPICAL APPEARANCE OF CP-5-2 PIN AFTER IRRADIATION

applying the reference caps, where the ends on the CP-5-2 pin are square.

Pre- and post-irradiation photographs of the stainless steel end-cap are shown in Fig. 11. Although, externally, the end-capped appeared unaffected by irradiation, the post-irradiation examination did reveal hairline cracks at the internal corners of the stainless steel. It is not known if these cracks developed during irradiation or if they were present prior to irradiation as a result of fabrication. There was no apparent affect of irradiation on the zirconium end-caps, as shown in Fig. 12.

Two specimens were taken from the pin, at the locations shown in Fig. 4, for radiochemical burnup analysis. The results of the analyses, as shown in Table III, confirmed the calculated burnup.

Twelve specimens were taken from the pin, at locations shown in Fig. 4, for metallographic examination. The metallographic examination, which is discussed in detail under EVALUATION OF TEST RESULTS of this report, clearly showed that the gamma phase had transformed to the thermally-stable alpha-plus-delta phases.

<u>CP-5-3 Test</u>

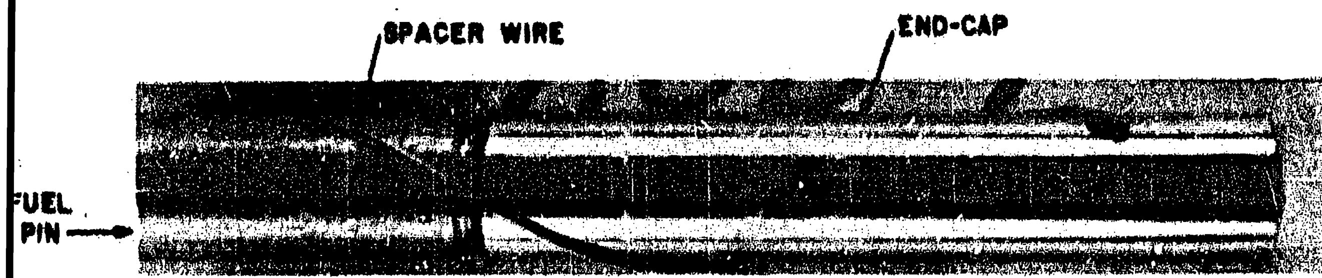
The CP-5-3 pin was irradiated to an average burnup of 0.58 a/o with the range over the length of the pin between 0.37 and 0.67 a/o. The fuel centerline temperature ranged from 950 to 1360 F.

Pre- and post-irradiation measurements, shown graphically in Fig. 6 and numerically in Table II, indicate a maximum swelling of about .0032 inch, which is approximately 2%. The general appearance of the pin was good, although the clad was somewhat discolored. The discoloration was not detected in the areas under the zirconium spacer wire and the nickel-cobalt dosimeter wire, as shown in Fig. 13. It is believed that the discoloration was due to oxygen pickup from the NaK.

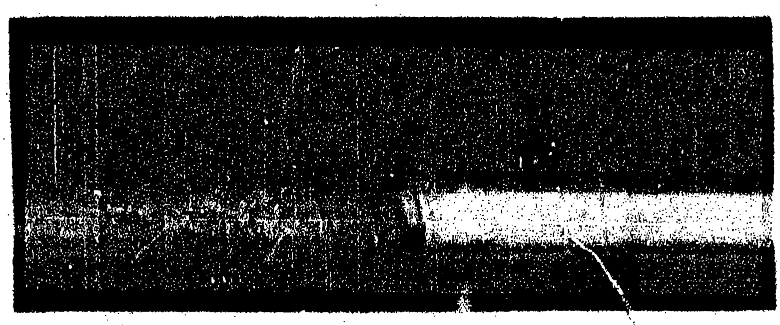
This pin was equipped with an Enrico Fermi reference zirconium cap at the hot end and a swaged stainless steel cap on the cold end. Pre- and post-irradiation photographs of the zirconium and stainless steel caps, Figs. 14 and 15, respectively, show no apparent irradiation affects on the end-caps.

In addition to the conventional post-irradiation examination, simple beam deflection tests were made on the CP-5-3 irradiated specimen and on the control pin. The observed pin deflections and calculated moduli of elasticity are shown in Table IV. While the results indicate a decrease in the modulus resulting from irradiation, the measured decrease, approximately 4%, is within the limits of experimental accuracy of the deflection measurement, that is, if the accuracy of measurements was 1/32 inch, the uncertainty would be 5 to 10%.

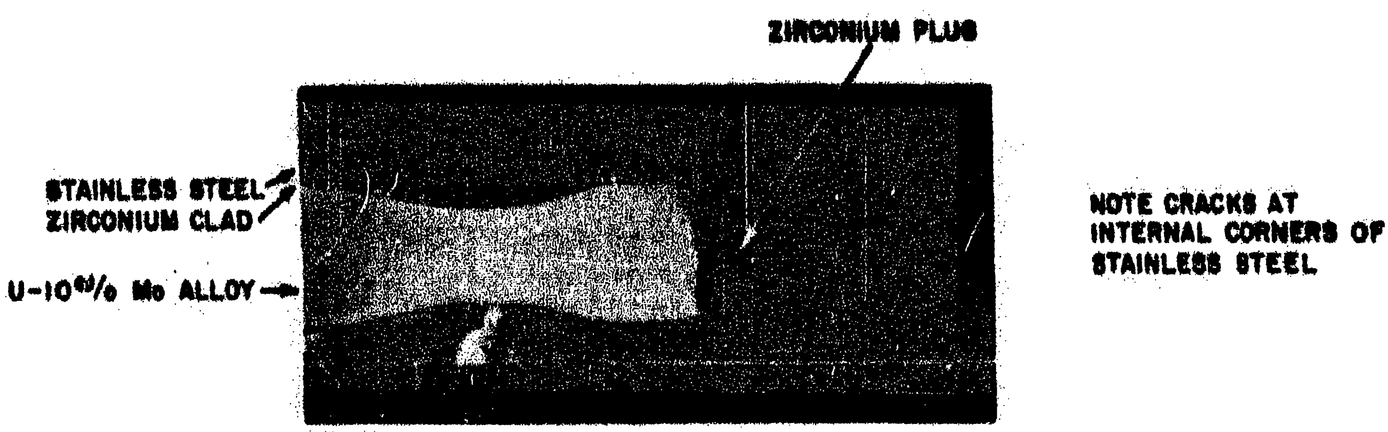
Analysis of the cobalt-nickel dosimeter wire, which had been helically wound on the pin during irradiation, confirmed the shape of the unperturbed flux profile, as shown in Fig. 6.



PRE-IRRADIATION PHOTOGRAPH OF END-CAP

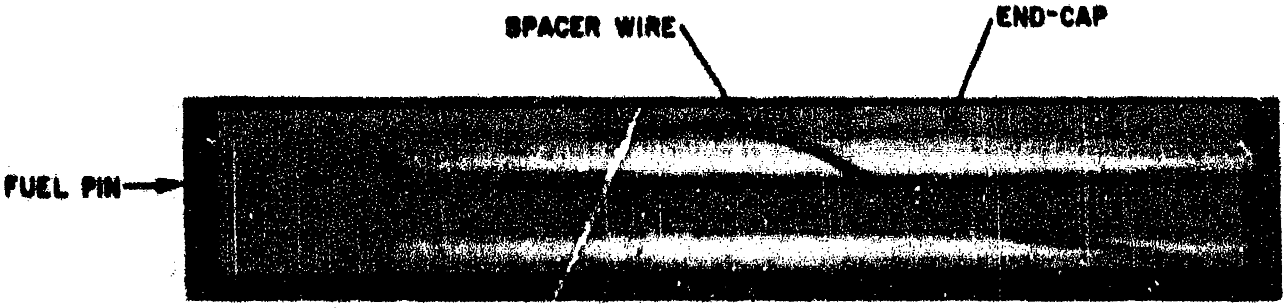


POST-IRRADIATION PHOTOGRAPH OF END-CAP

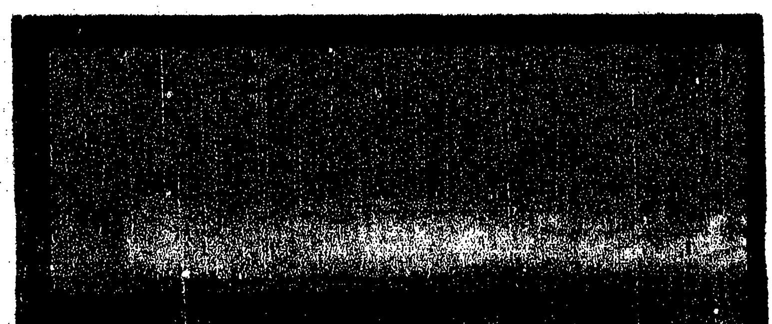


POST-IRRADIATION PHOTOGRAPH OF LONGITUDINAL SECTION OF END-CAP

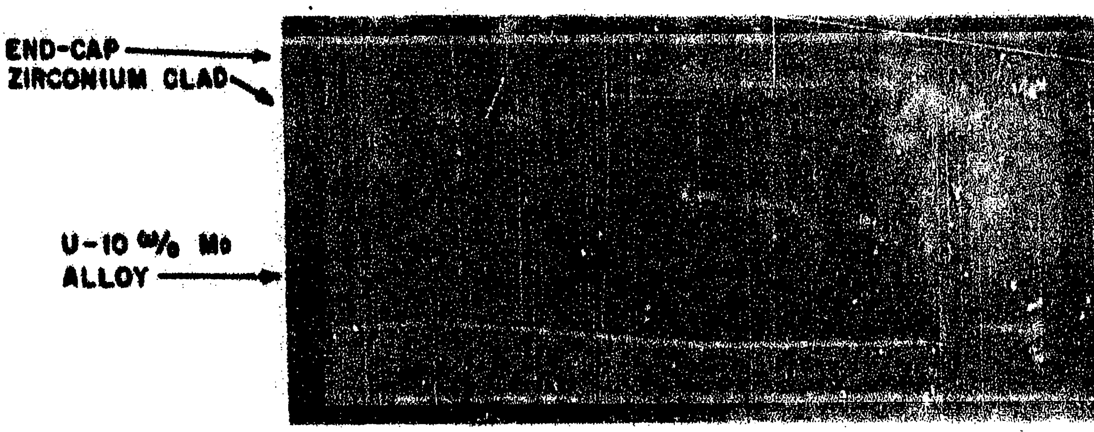
FIG. 11 PRE- AND POST-IRRADIATION PHOTOGRAPHS OF STAINLESS STEEL END-CAP ON CP-5-2 PIN



PRE-IRRADIATION PHOTOGRAPH OF END-CAP

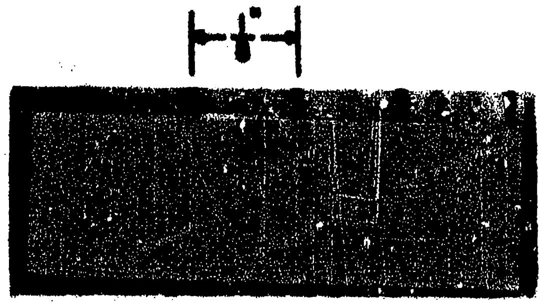


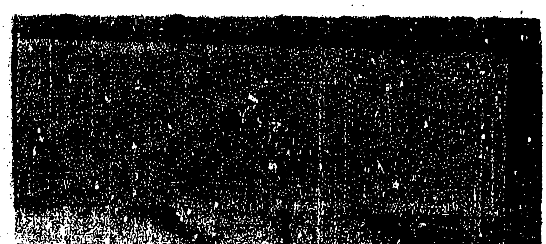
POST-IRRADIATION PHOTOGRAPH OF END-CAP



POST-IRRADIATION PHOTOGRAPH OF LONGITUDINAL SECTION OF END-CAP

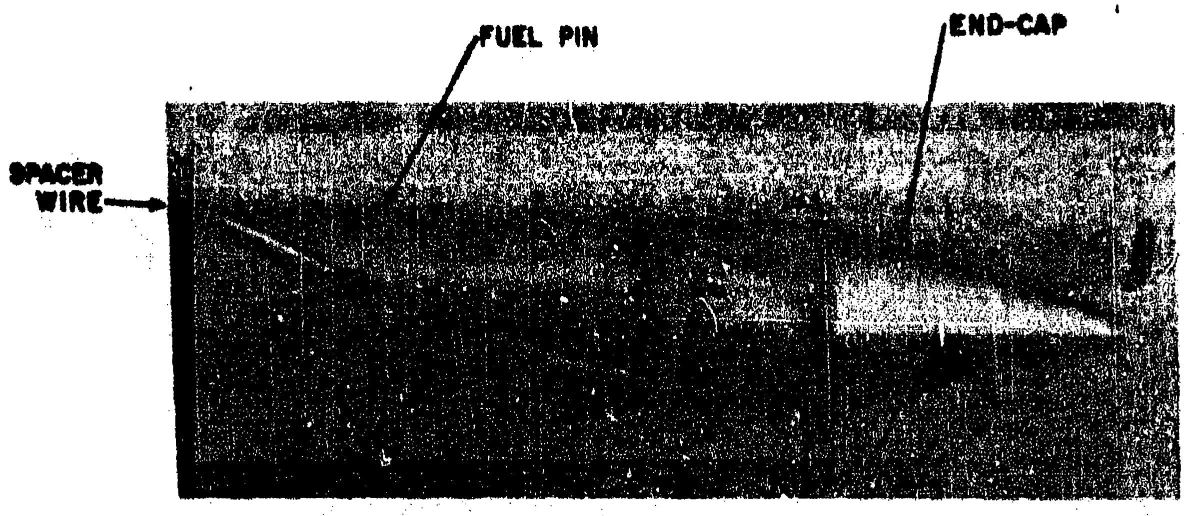
FIG. 12 PRE- AND POST-IRRADIATION PHOTOGRAPHS OF ZIRCONIUM END-CAP ON CP-5-2 PIN



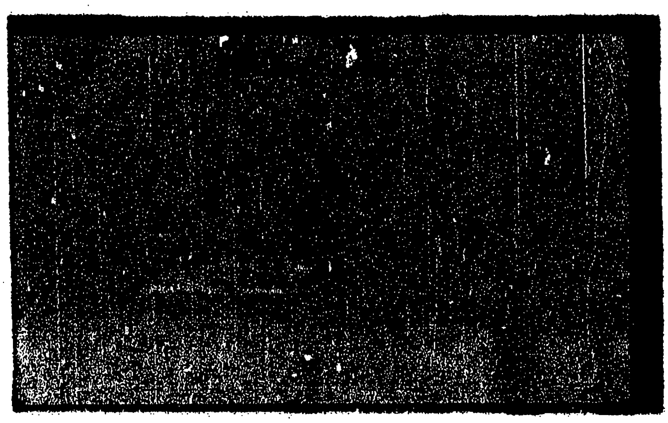


NOTE GENERAL DISCOLORATION OF PIN EXCEPT IN AREAS UNDER ZIRCONIUM AND NICKEL-COBALT WIRES

FIG. 13 SURFACE APPEARANCE OF CP-5-3 PIN AFTER IRRADIATION

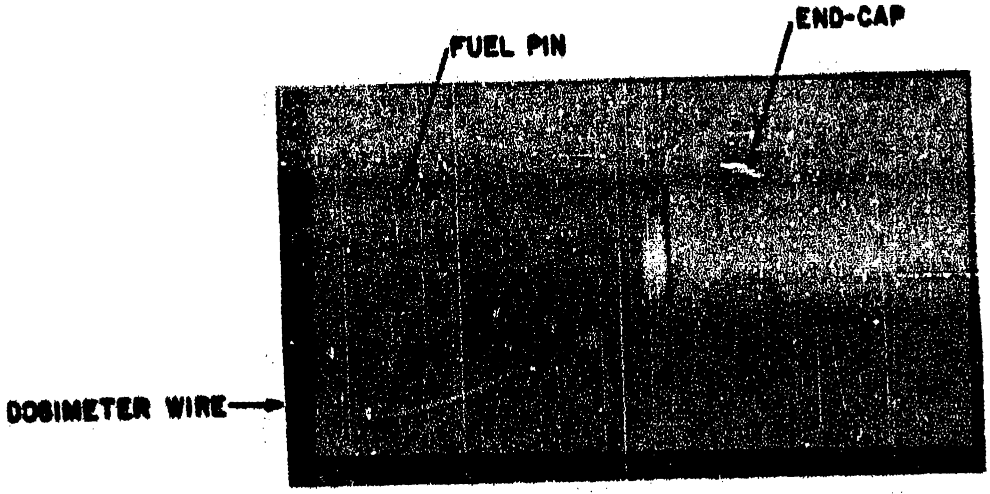


PRE-IRRADIATION PHOTOGRAPH OF END-CAP

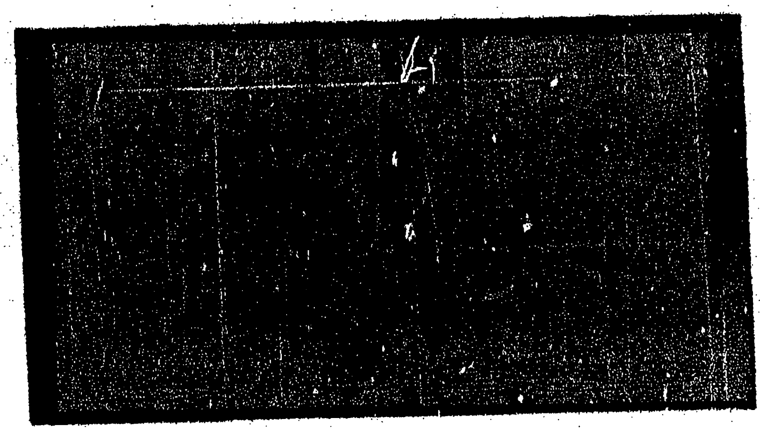


POST-IRRADIATION PHOTOGRAPH OF END-CAP

FIG. 14 PRE- AND POST-IRRADIATION PHOTOGRAPHS OF ZIRCONIUM END-CAP ON CP-5-3 PIN



PRE-IRRADIATION PHOTOGRAPH OF END-CAP



POST-IRRADIATION PHOTOGRAPH OF END-CAP

FIG. 15 PRE- AND POST-IRRADIATION PHOTOGRAPHS OF STAINLESS STEEL END-CAP ON CP-5-3 PIN

TABLE IV

DETERMINATION OF COMPOUND MODULUS OF ELASTICITY AT ROOM TEMPERATURE BY THE BEAM DEFLECTION METHOD, CP-5-3 PIN

	Control Specimen		Irradiated Specimen	
Added Weight at Center of 28 Inch Span, ± 0.005 grams	Deflection in 32nd Inch, ± 1/32	Compound Modulus psi	Deflection in 32nd Inch, ± 1/32	Compound Modulus psi
0	11	8.24×10^6	11	7.92×10^6
56.7 grams	15	9.93×10^6	15	9.70×10^6
94.6	18	10.45×10^6	18	10.05×10^6
148.0	22	11.05×10^6	22	10.64×10^6

NOTE: The irradiated pin was assumed to be a beam of uniform cross section. Diameter = 0.1605 inch. The effect of the short lengths overhanging the supports was neglected.

EVALUATION OF TEST RESULTS

PREVIOUS IRRADIATION TESTS*

Previous to the prototype CP-5 tests, approximately 100 specimens were irradiated in the Materials Testing Reactor. Variables, such as burnup, radiation temperature, alloy composition, and post fabrication heat-treatment, were studied. The radiation stability curves, shown in Figs. 16 and 25, were drawn on the basis of the results of these tests. The following conclusions were made for U-10 w/o Mo alloy irradiated at fission rates in excess of 8×10^{13} fissions per cc/sec.

1. For irradiation temperatures less than 1100 F, swelling increases linearly with burnup up to about 1.8 a/o.

2. There is little or no effect of radiation temperature on swelling up to about 1100 F for burnups less than 1.8 a/o.

3. At radiation temperatures in excess of 1100 F, there is a strong dependence on burnup and radiation temperature.

4. The burnup dependence at radiation temperatures in excess of 1100 F is not linear but appears to be a power function of burnup.

5. Within the limits studied, burnup and irradiation temperature were the only variables that showed significant effects.

LOW TEMPERATURE IRRADIATIONS

For the purpose of evaluating the CP-5 test results and comparing them with the MTR results, it is best to consider the high and low temperature irradiations separately.

As previously stated, there was a linear effect of burnup on swelling to burnups of 1.8 a/o at temperatures less than 1100 F in the MTR tests. This effect is shown in Fig. 16 in which the MTR curve represents the maximum diameter increase observed under the stated irradiation conditions. Values from the three CP-5 pin tests for irradiation temperatures less than 1100 F are also shown. By comparison, it can be seen that, while CP-5-2 and CP-5-3 were essentially within the diameter increase limits predicted by the MTR tests, the CP-5-1 pin swelled considerably in excess of that predicted. And since no fabrication or materials defects have been noted, the only plausible explanation for this discrepancy is based on the transformation kinetics of the U-10 w/o Mo alloy.

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* Leeser, D.O., Rough, F.A. and Bauer, A.A., "Radiation Stability of Fuel Elements for the Enrico Fermi Power Reactor", 2nd Conference on Peaceful Uses of Atomic Energy (Geneva, 1958) Paper No. 15P-622.

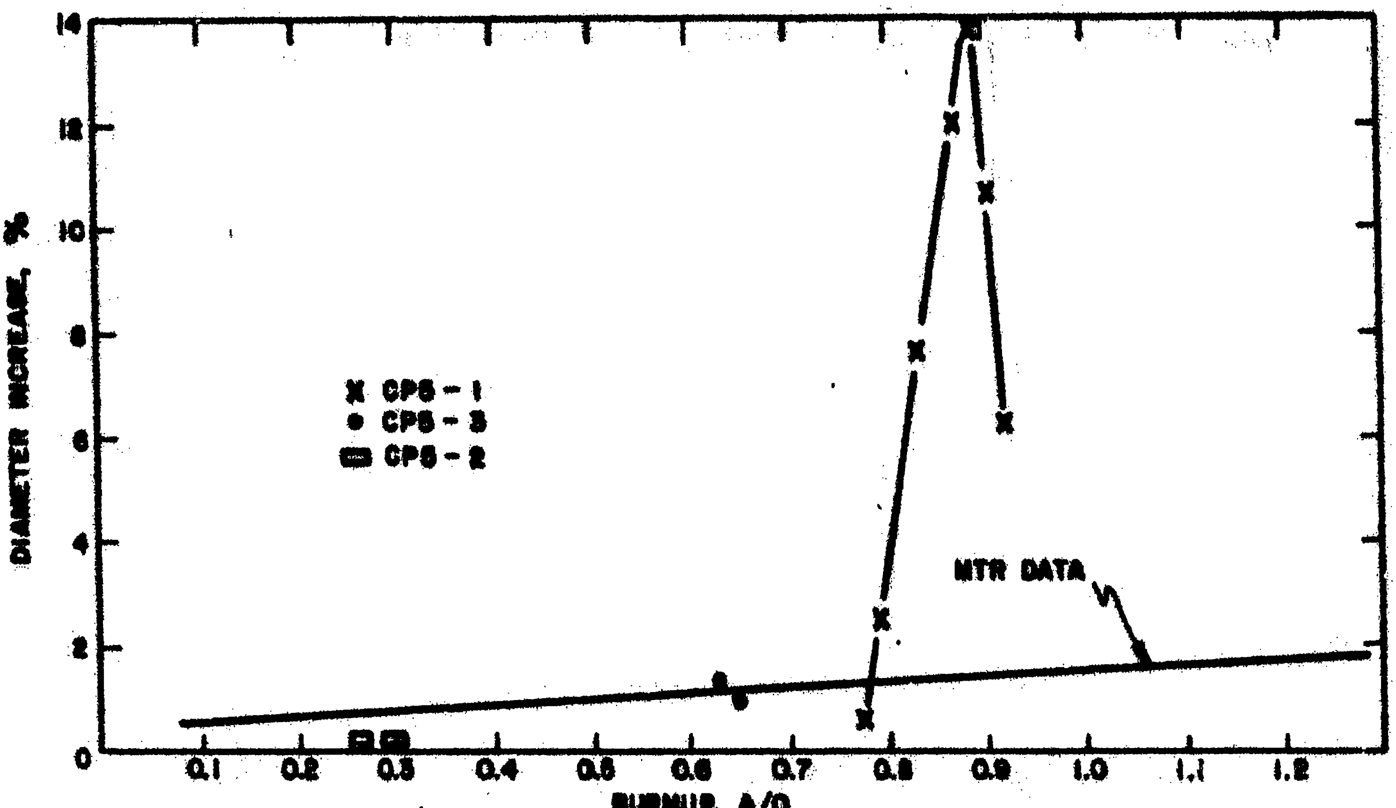

FIG. 16 PERCENT DIAMETER INCREASE AS A FUNCTION OF BURNUP AT IRRADIATION TEMPERATURES LESS THAN 1100 F

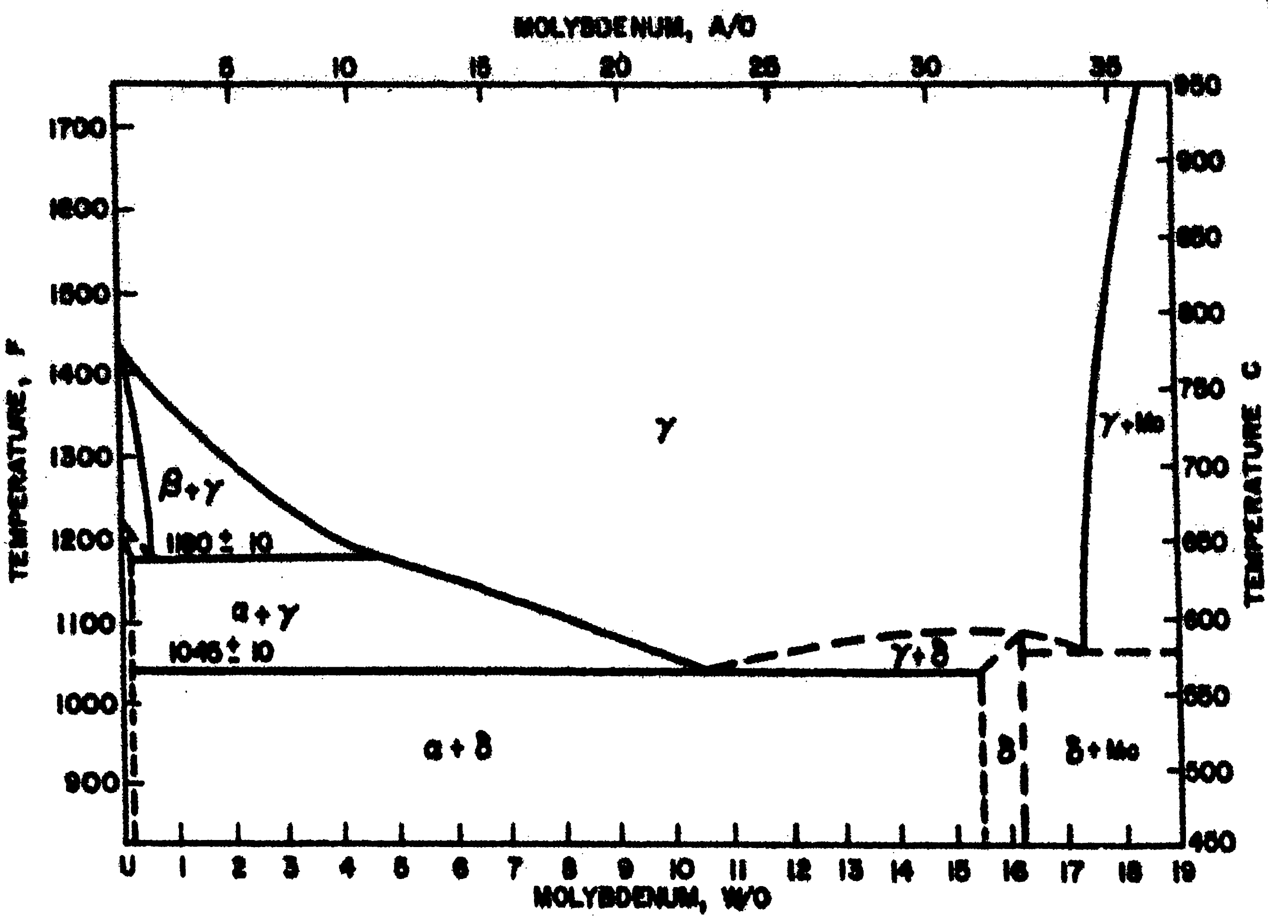

FIG. 17 U-Mo EQUILIBRIUM DIAGRAM TO 19 WT % Mo

The low temperature portion of the phase diagram for the U-Mo system is shown in Fig. 17*. Under equilibrium conditions, and for the U-10 w/o Mo alloy, the alpha-plus-delta phases are stable below 1045 F, alpha-plus-gamma are stable between 1045 and 1060 F, and gamma is stable above 1060 F. Upon isothermal transformation of the gamma phase to alpha-plus-delta, the "nose" of the Time Temperature Transformation curve appears at about 900 F, and transformation is initiated after 10 to 20 hours, depending on the fabrication history and purity of the alloy.

It was shown by several investigators** that, while under irradiation, the high-temperature gamma phase becomes thermally stable at low temperatures, and it was believed that the stabilization of the cubic gamma phase accounted for the good radiation stability of the alloy. Theories based on the displacement spike concept were proposed to explain this effect, but no quantitative evaluation could be made. Thomas*** and others at BAPD proposed that there existed a temperature dependent critical fission rate required to maintain the gamma phase, and that if this critical rate was not achieved, the alloy would revert to the thermally stable phases. Because the fission rates of the CP-5 tests ranged from 2.5 to 4×10^{13} fissions/cc/sec while the MTR tests were at a minimum of 8×10^{13}, it was felt that perhaps transformation had occurred and resulted in the large diameter increase observed on the CP-5-1 test. To ascertain whether the alloy had transformed, post-irradiation examination of sections from the CP-5-1 and CP-5-2 pins was performed.

Two specimens of the CP-5-1 pin, taken from the locations shown in Fig. 2, were examined. The etching characteristics of the section taken from the 980 F region of the pin indicated transformation had occurred, but the structure was not resolved metallographically, therefore identification of transformation products was not made. The structure exhibited a mottled or spheroidal appearance, as shown in Fig. 18, rather than the lamellar appearance normally associated with transformation of this alloy. It is believed that the swelling and fission gas bubble formation affected the microstructure. There was no indication of gross defects, such as cracks or clad non-bonds.

The second specimen, taken from a portion of the pin which normally operated at about 1080 F, showed a coarse precipitate, as shown in Fig. 19. Although the precipitate was not identified, it is believed the structure represents the beginning of transformation to the thermally stable phases since this portion of the pin operated at about 950 F during the last month of irradiation.

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* Austin E. Dwight, "The Uranium-Molybdenum Equilibrium Diagram Below 900C", Journal of Nuclear Materials, March, 1960.

** Konobeevsky, S. T., Praudyuk, N. F. and Kutzitseu, Proceeding of the International Conference on the Peaceful Uses of Atomic Energy, 7, 433-440 (1956).

Bleiberg, M. L., "A Kinetic Study of Irradiation Induced Phase Changes in Uranium-9 w/o Molybdenum Alloy", Nuclear Science and Engineering, v.5, Feb. 1959, P 78-87.

*** Thomas, D. C., and Fillnow, R., Private Communication.

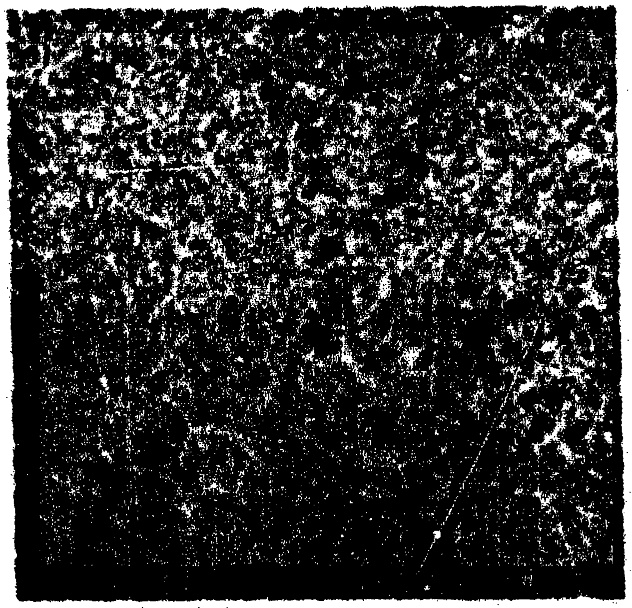

FIG. 18 MICROSTRUCTURE OF CP-5-I SPECIMAN IRRADIATED AT 980 F TO 0.89% BURNUP

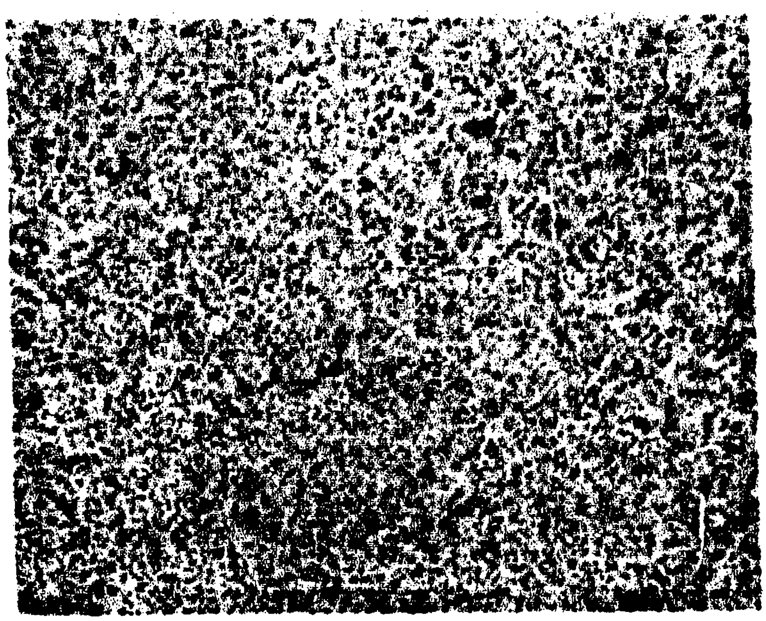

FIG. 19 MICROSTRUCTURE OF CP-5-I SPECIMAN IRRADIATED AT 1080 F TO 0.92% BURNUP

The metallography of the CP-5-1 pin was enlightening but it did not offer conclusive evidence that transformation had occurred. However, the work on CP-5-2 did offer such evidence. As shown in Fig. 4, specimens were taken from that portion of the pin which operated over the temperature range of 880 to 1210 F. The photomicrographs, Figs. 20 through 24, show the amount of transformation that occurred. Fig. 20 shows almost complete transformation at a temperature of 900 F. The extremely fine transformation products are typical of the alloy transformed at this temperature. The patches of white are believed to be untransformed gamma grains. Fig. 21 shows that the lamella transformation products are considerably coarser for material irradiated at 1060 F, and that the amount of transformation has decreased at this temperature. Evidence of alloy inhomogeneity is apparent from the striated transformation structure. Fig. 22 shows that at higher irradiation temperatures, 1125 F, lesser amounts of lamellar-type transformation occurred. Fig. 23 shows that at an irradiation temperature of 1165 F, an unidentified grain-boundary precipitate was present. It is believed that this could be alpha transformation.

A panoramic view of the microstructures observed on the CP-5-2 pin are shown in Fig. 24. Comparing the microstructures, the calculated central-metal temperatures, and available U-Mo phase diagrams, it would seem that the calculated central-metal temperatures are on the order of 25 to 100 F on the high side. Assuming the grain-boundary precipitate shown in Fig. 23 is not representative of transformation, the highest temperature at which the lamellar-type transformation occurred was 1135 F. This corresponds to a $\gamma \rightarrow \alpha + \delta$ phase transformation temperature of 1065 F, as shown in Fig. 17. The diagram reported by Rough & Bauer* indicates this temperature to be 1110 F. In the event that the structure shown in Fig. 23 does represent transformation, the highest temperature at which this was observed was about 1165 F.

On the basis of the metallographic examination and the test results, the following conclusions were drawn:

1. The swelling observed on the CP-5-1 pin was not due to any gross defects, such as cracks or clad nonbonds in the fuel specimen.

2. The swelling apparently was associated with the transformation to the thermally-stable $\alpha + \delta$ phases. The extremely large amount of swelling that accompanied the transformation can not be satisfactorily explained at this time.

3. The CP-5-1 pin underwent a large number of thermal cycles due to reactor scrams. Out-of-pile thermal cycling tests** on unirradiated-transformed material resulted in only very slight dimensional changes, therefore this is discounted as an explanation of the swelling, although the combination of thermal cycling and irradiation may have an effect.

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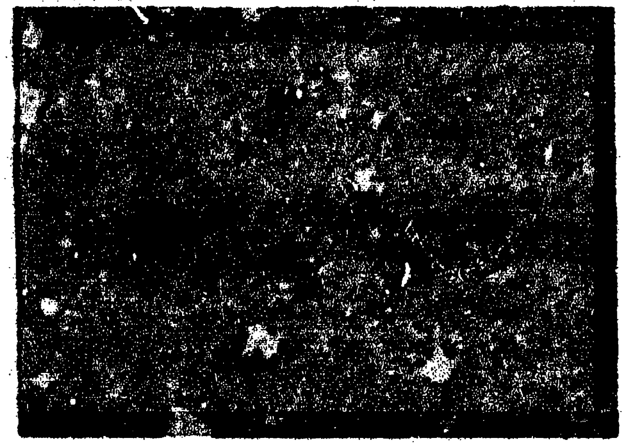
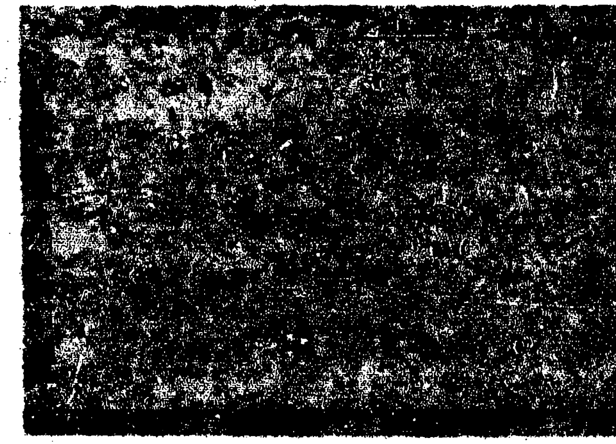
* F.A. Rough and A.A. Bauer, "Constitutional Diagrams of Uranium and Thorium Alloys", Addison-Wesley Publ. Co., Inc. (1958)

** Unpublished Data, APDA.



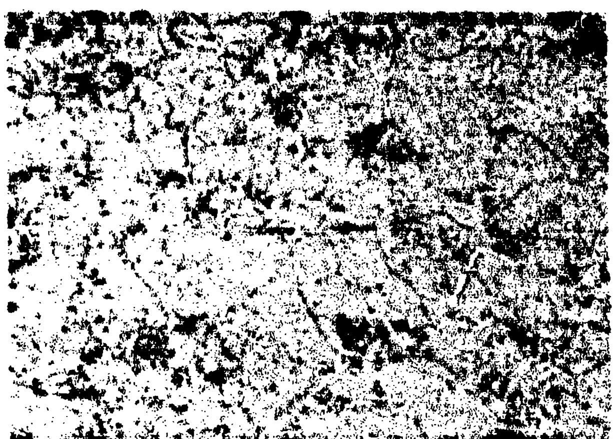
250X HEAT ETCHED

FIG. 20 MICROSTRUCTURE OF CP-5-2 PIN IRRADIATED AT 900 F TO 0.28% BURNUP



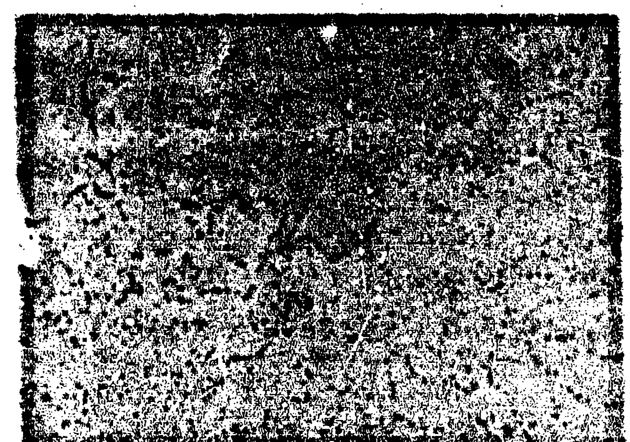
250X HEAT ETCHED

FIG. 21 MICROSTRUCTURE OF CP-5-2 PIN IRRADIATED AT 1060 F TO 0.29% BURNUP



250X HEAT ETCHED

FIG. 22 MICROSTRUCTURE OF CP-5-2 PIN IRRADIATED AT 1125 F TO 0.29% BURNUP



250X HEAT ETCHED

FIG. 23 MICROSTRUCTURE OF CP-5-2 PIN IRRADIATED AT 1165 F TO 0.3% BURNUP

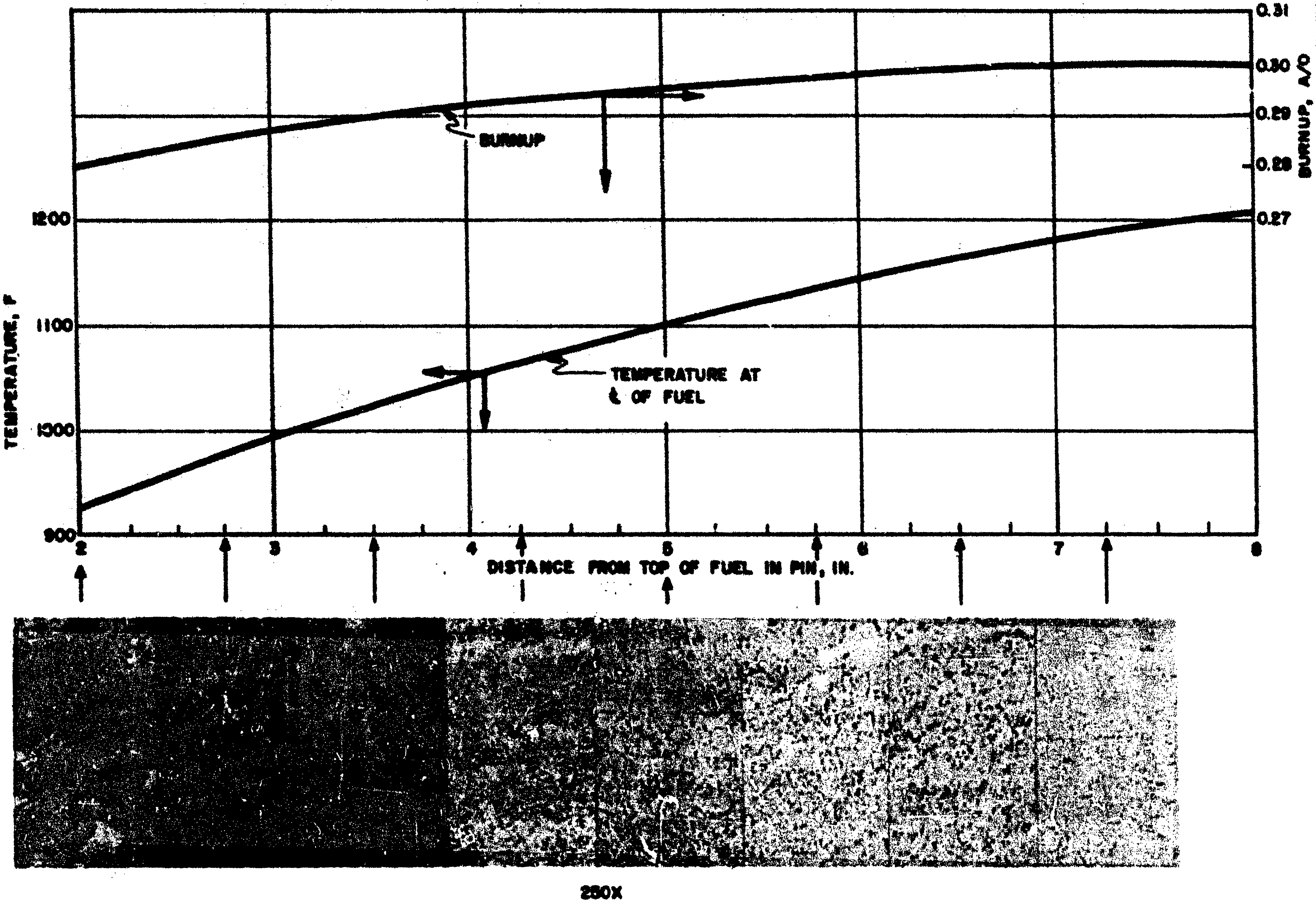


FIG. 24 PANORAMIC VIEW OF CP-5-2 MICROSTRUCTURES AFTER IRRADIATION

4. The critical fission rate for maintaining the metastable phase during radiation over the temperature range of 925 to 1100 F appears to be somewhere between 4×10^{13} fission/cc/sec, the fission rate of the CP-5-2 pin, and 8×10^{13}, the minimum fission rate of the MTR specimens.

HIGH-TEMPERATURE IRRADIATIONS

At temperatures in excess of 1100 F, swelling appeared to show a rather strong temperature burnup dependence. Although the data were rather meager, being based on four temperature-controlled MTR capsules, an attempt was made to develop curves showing diameter increase as a function of burnup for the temperature range of 1130 to 1165 F and for a temperature of 1320 F. These curves are shown in solid lines in Fig. 25. Included in Fig. 25 are the results of the three CP-5 pins covering a burnup range from 0.26 to 0.92 a/o and a temperature range from 1130 to 1360 F.

The CP-5-2 and CP-5-3 pins show swelling well within the limits predicted from the MTR data, while the CP-5-1 pin showed swelling approximately the same as, or slightly greater than, predicted by the MTR data. The reason for the apparent discrepancy is not known at the present time. However, there appears to be several variations in the irradiation history that may explain the variance.

In the CP-5-1 test, the pin temperature was considerably lower than that shown in Fig. 2 for the first 2-1/2 months of operation (See Fig. 1). This could have resulted in transformation to $\alpha + \delta$ of that portion of the pin that nominally operated in excess of 1100 F. The burnup achieved during this time would be about 0.27 a/o. On raising the temperature, the alloy would have retransformed, thus causing an adverse effect on swelling.

The average fission rates across the cross section of the three pins was 2.5×10^{13} fissions/sec/cc for CP-5-1 and 4.2 and 4.8×10^{13} for CP-5-2 and -3, respectively. If one considers high temperature swelling to be similar to or a function of creep, then swelling would be a time dependent function and one would predict greater swelling for lower fission rates.

A third variation in the irradiation histories of the three pins is the number of thermal cycles to which the pins were subjected - 674, 100, and 170 for CP-5-1, -2, and -3, respectively. The role of thermal cycling on high temperature irradiation is not known but it could have an effect.

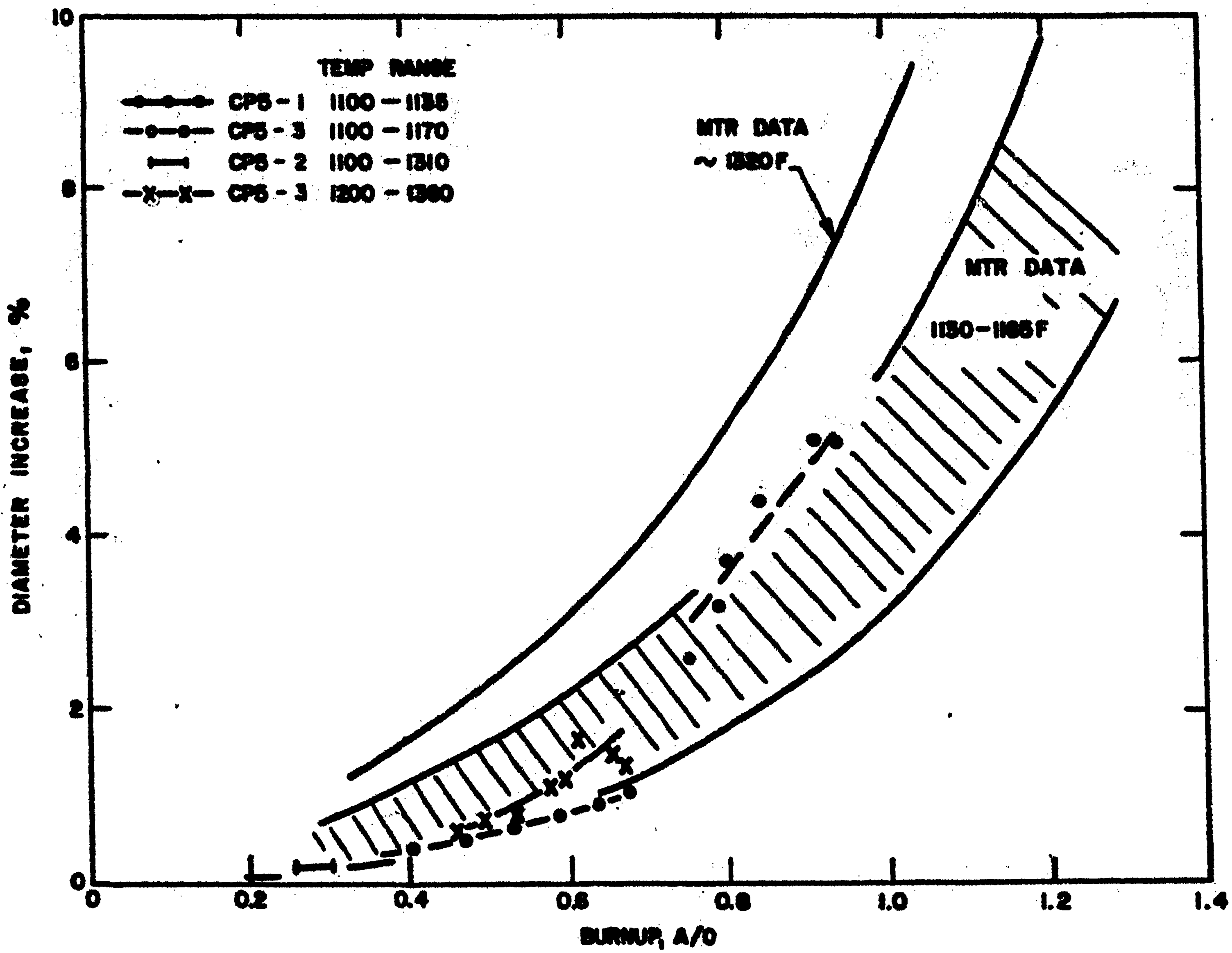


FIG. 25 PERCENT DIAMETER INCREASE AS A FUNCTION OF BURNUP

GENERAL DESCRIPTION

The pins were irradiated in longitudinally finned stainless steel capsules similar to those used earlier by ANL for irradiation of Experimental Breeder Reactor II fuel pins*. The heat generated by fission was removed by a stream of air flowing axially along the capsule at a maximum flow rate of 340 lb/hr, which corresponds to a linear velocity of about 275 ft/sec. The pins were NaK bonded to the capsule wall with a helically-wound 0.010-inch zirconium wire preventing contact of the pin and the wall.

The capsule surface temperature was monitored by 10 thermocouples located at the fin roots and positioned in a spiral pattern at intervals of about 3 inches along the capsule. Two additional thermocouples were used to monitor the inlet and outlet air temperatures.

Air was drawn past the capsule by a 25 hp Roots blower located downstream from the in-pile portion of the loop to assure the presence of a negative pressure in the thimble. In the first irradiation, an open loop was used, while in the CP-5-2 test, the air was recirculated. Control problems encountered in the latter prompted the reuse of once-through air flow in the third experiment.

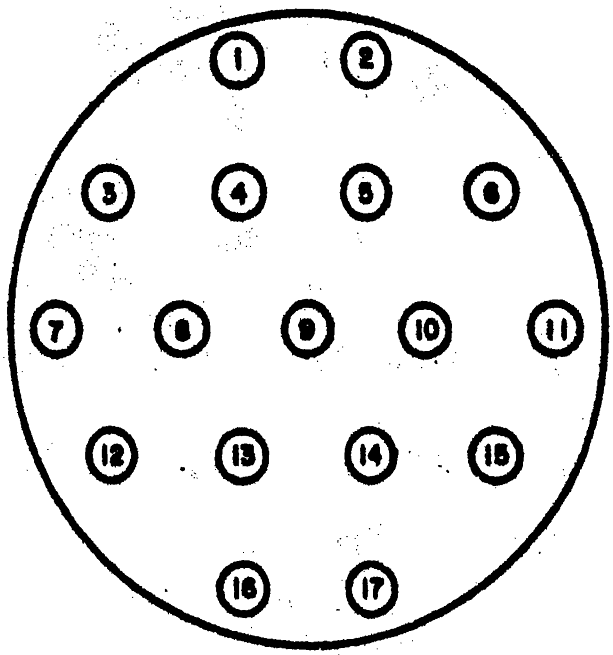
REACTOR PENETRATIONS

Vertical thimble holes, designated VT-23 and VT-27, were assigned for the irradiation of Enrico Fermi prototype fuel pins during the 2 Mw operation of the CP-5. Fig. 26 shows the location of the vertically-oriented thimble penetrations. CP-5 is scheduled to begin operation at 5 Mw power level in 1960. In anticipation of this power increase, the loop installed in VT-23 was moved to VT-26. Because the neutron flux at 2 Mw was about 2.5 times greater in VT-23 than in VT-26 and VT-27, the two air cooled facilities to be used for the remainder of the program will be comparable to the high-flux thimble used in the earlier irradiations. Additional irradiation facilities of a "water-boiler" type will be installed in the CP-5 fuel positions VT-16 and VT-17 for Enrico Fermi fuel pin irradiations following the 5 Mw start-up. These latter facilities will be described in a later report of this series.

IRRADIATION CAPSULES

The finned capsules were machined from solid bar stock of Type 304 stainless steel, having the pin cavity closed at each end with helium arc-welded stainless plugs. Fig. 27 shows an assembly drawing of the shield plug, the thimbles which channel the coolant flow, and the capsule. Figure 28 shows a cutaway view of the capsule. A central hole 0.200 inch in diameter contains the 0.158 inch diameter fuel pin with its helically

*ANL-5371, Quarterly Report of Reactor Engineering Division, Oct-Dec. 1954, P. 184.



FUEL ZONE POSITIONS

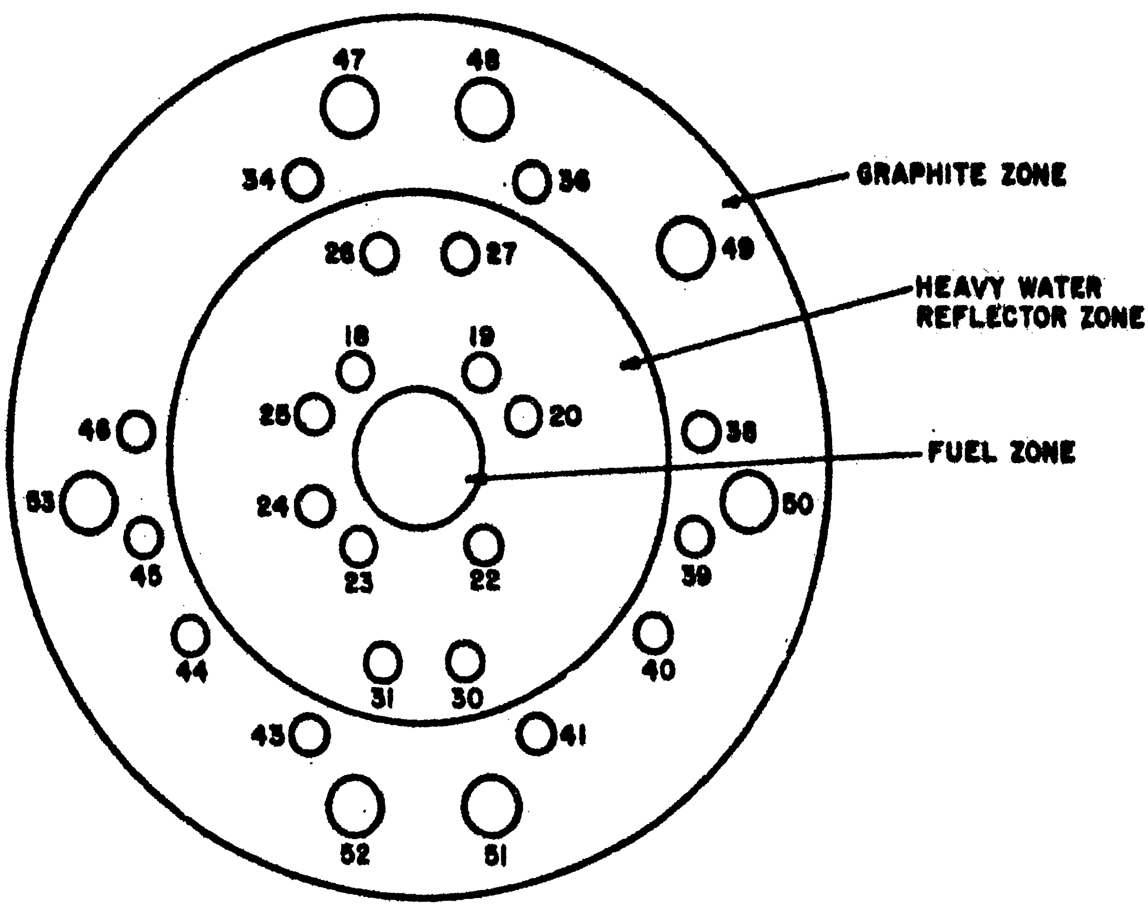


FIG. 26 VERTICAL IRRADIATION HOLES IN CP-5

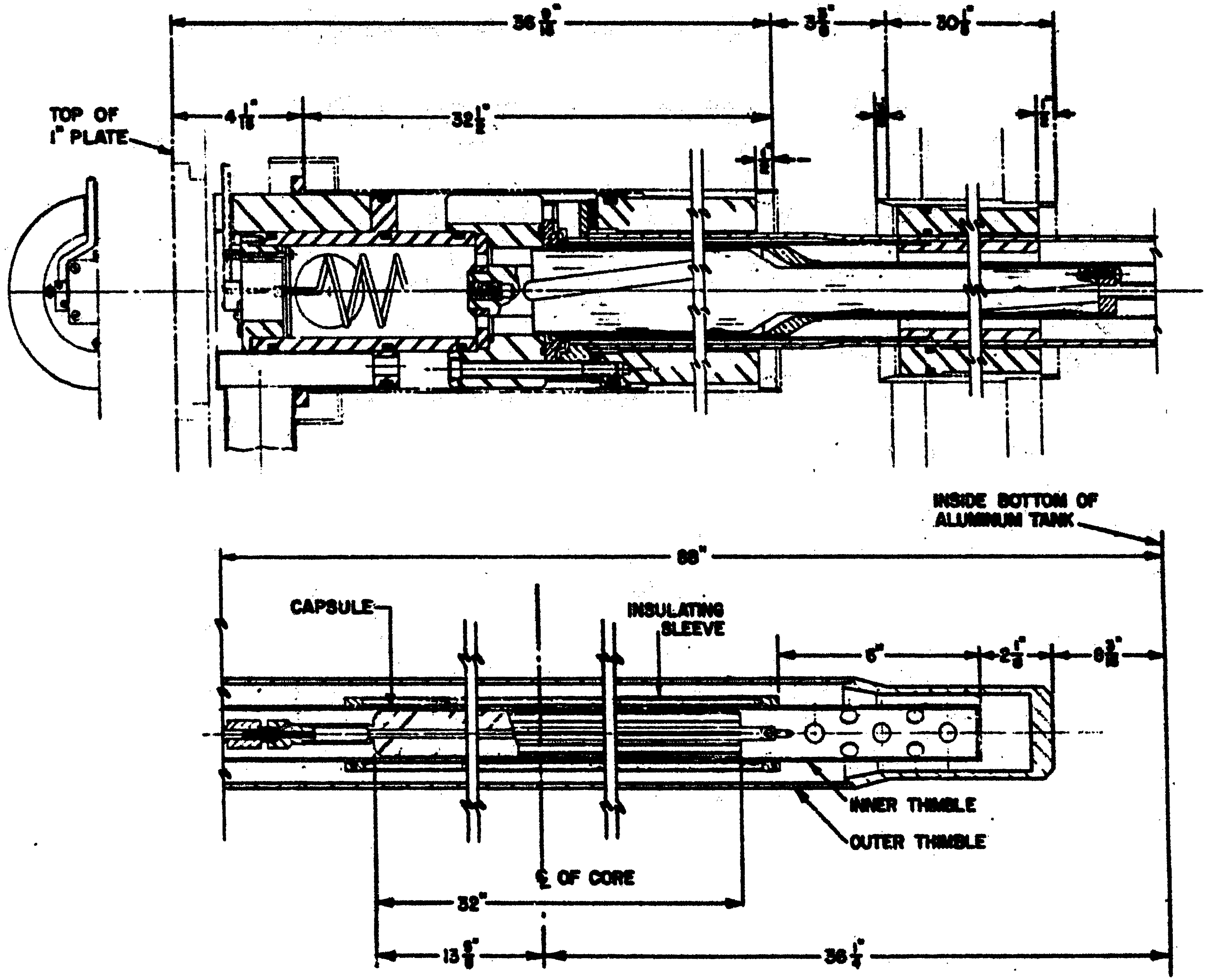


FIG. 27 THIMBLE ASSEMBLY FOR HOLES 26 & 27

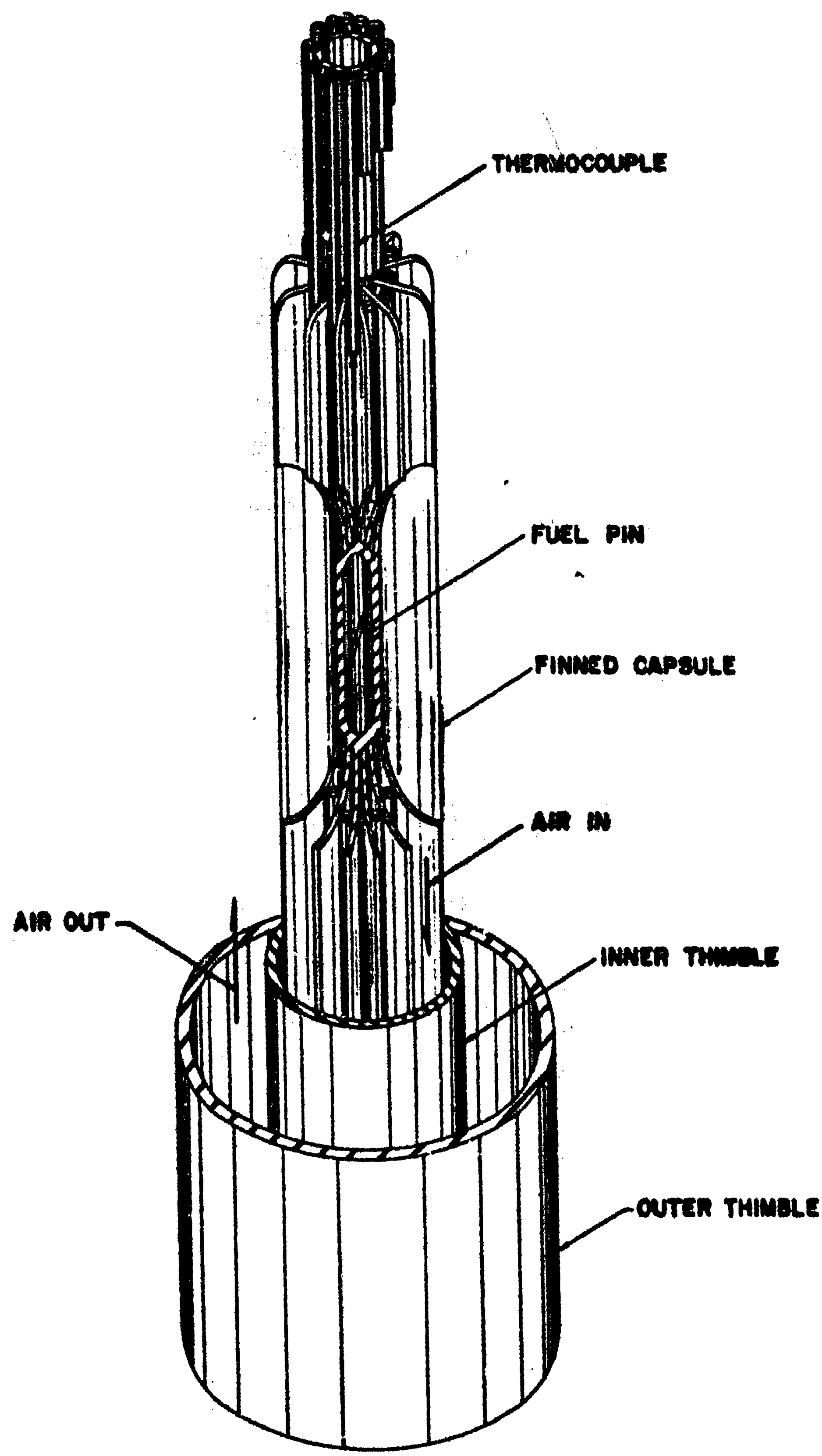


FIG. 28 CUTAWAY VIEW OF CP-5 CAPSULE

wound 0.010-inch diameter spacer wire and NaK bonding fluid. Twelve fins, 32 inches long and 0.030 inch thick, conduct heat to the cooling air. An expansion chamber is located above the finned portion of the capsule to accommodate NaK expansion during high temperature operation.

The two finned capsules used for the CP-5-1 and CP-5-2 irradiations had an overall finned diameter of 1.05 inches, and a circumferentially-finned spacer separated the capsule from the inner thimble wall. The capsule used for the CP-5-3 irradiation and those prepared for the remaining irradiations of this type are 1.31 inches in diameter and have a fin thickness of 0.045 inch. The increased overall diameter leaves no room for a spacer between the fins and the inner thimble wall. No substitute for the spacer was provided with CP-5-3, but in succeeding installations a magnesium-oxide-filled insulating sleeve will be secured around the outside of the inner thimble opposite the finned capsule. The increased heat transfer area provided by the longer fins, and the improved fin efficiency resulting from the increase in thickness, allow higher heat generation rates without raising the fuel temperatures at any given value of coolant flow.

COOLING SYSTEM

Inlet and discharge air lines connect to the manifold fitting at the top of the thimble. Air passes down through helical slots in the thimble shield plug and is channeled along the capsule fins by the inner thimble wall. The heated air exits through holes in the bottom 6 inches of the inner thimble and passes upward between the inner and outer thimble walls. About 85% of the heat generated is transferred to the reactor heavy water coolant through the outer thimble wall and the remainder is carried away by the capsule cooling air.

Air is circulated through the cooling loops by Roots vacuum pumps rated at 369 cfm at 20 inches mercury vacuum. A pair of 3 inch pipe lines connect each assembly at the top of the reactor to the basement location of the blowers. Arrangement of the piping is such that fresh air may be drawn from the basement area and exhausted through filters and the blower cooling-water spray to the reactor-building ventilating system. Provisions are also made for recirculation and for throttling of the air in any desired proportion. The air metering orifice is installed in the line between the reactor and the vacuum blower. The loops are shown pictorially in Fig. 29 and schematically in Fig. 30. Figure 30 also shows the booster blower and external equipment for the "water-boiler" series to be used in the 1960 program.

Air flow resistance of the thimble shield plug is such that the air cooling system used for the 1957-1959 program cannot be expected to reduce the peak operating temperature of a 10% enriched fuel pin below 1350 F when the reactor operates at 5 Mw power. The additional booster blowers, rated at 157 cfm at 5 psi, should make possible a reduction in the maximum specimen temperature without reducing the specimen enrichment during 5 Mw operation.

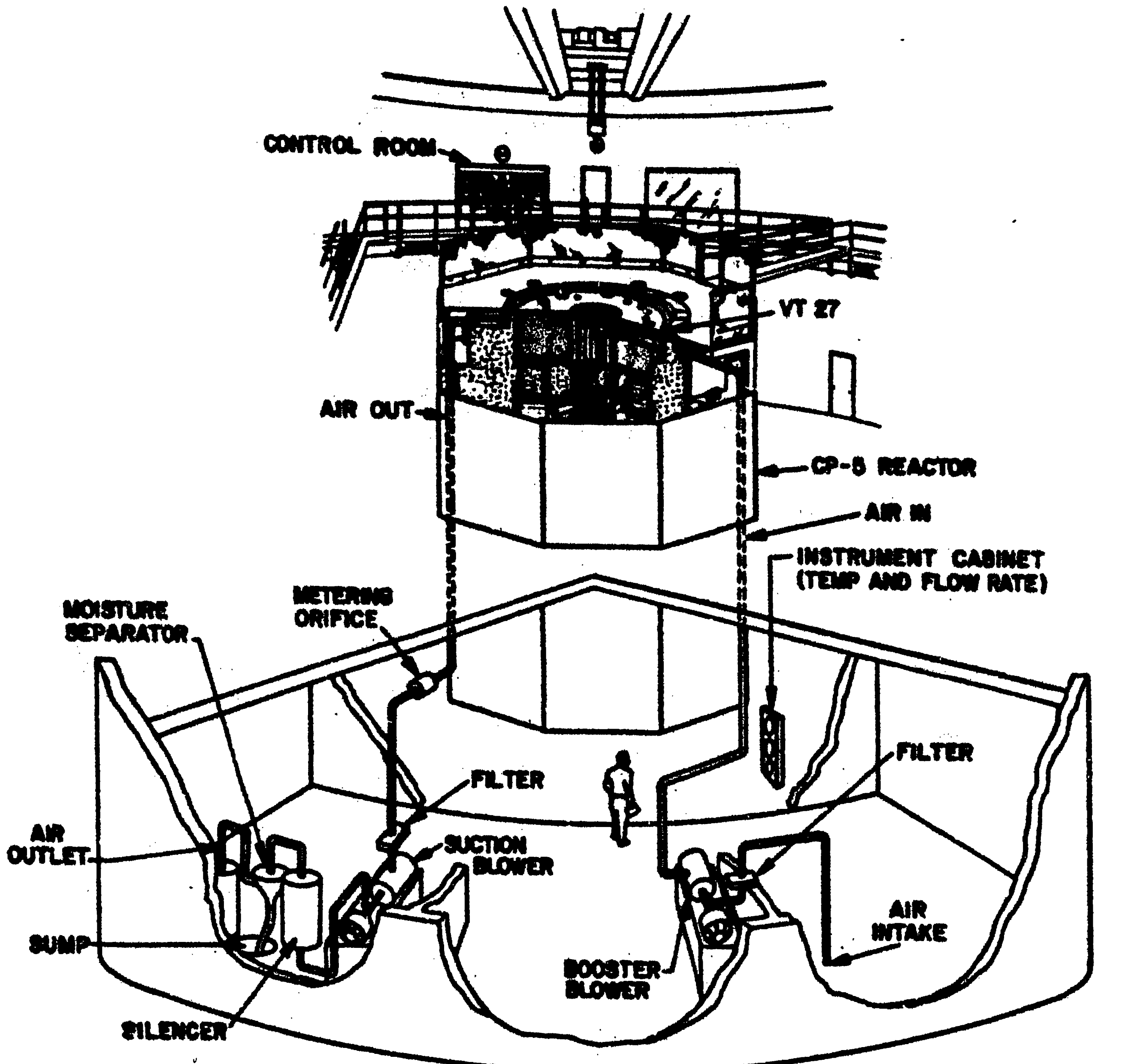


FIG. 29 EQUIPMENT FOR AIR-COOLED IRRADIATION EXPERIMENTS

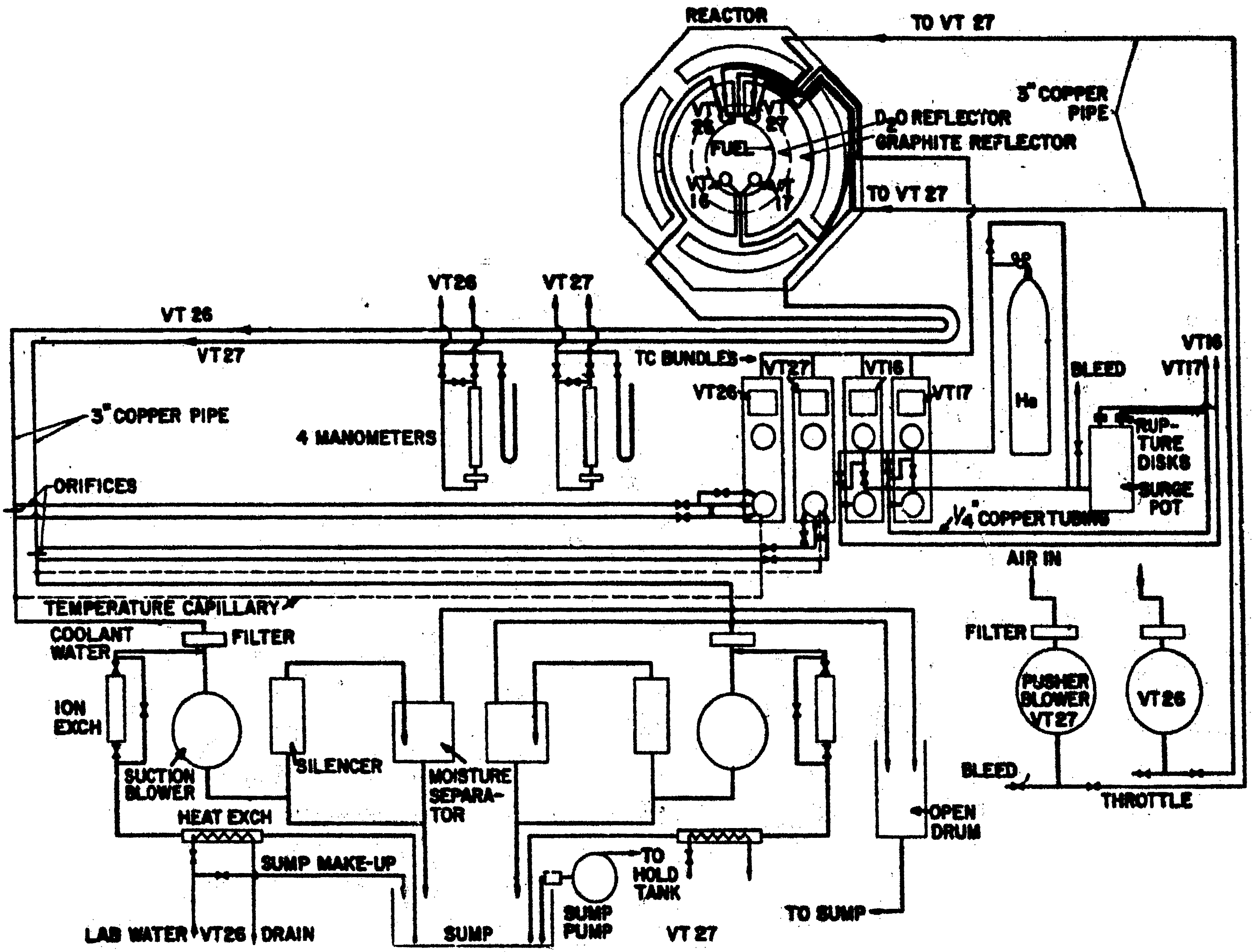


FIG. 30 SCHEMATIC OF EQUIPMENT IN CP-5 IRRADIATION PROGRAM

INSTRUMENTATION

Ten thermocouples are installed on the finned capsule, and two additional thermocouples are positioned to measure the air temperature entering and leaving the finned area. Fig. 31 shows a close-up of a typical thermocouple installation made by spot welding the thermocouple wires to the capsule tube at the base of the fins. The thermocouples consist of 28 gauge asbestos and glass insulated chromel-alumel wire sheathed in 0.095 inch OD stainless steel tubes. The exposed ends of the wire are protected just above the junction by a two hole ceramic insulator. Thermocouple leads from the finned capsule pass up through the aluminum suspension tube, along one of the helical slots in the shield plug, and out through a pressure tight electrical connector in the inlet air line. Thermocouple terminal strips are provided at the top of the reactor and extension leads connect with recorders in the basement. A 12-point strip chart potentiometer and a single pen circular chart potentiometer provide a temperature record for each installation. The hottest thermocouple is connected to the circular chart recorder to provide a continuous fast-response reading.

During 1957 and 1958 operations a differential pressure and a static pressure manometer provided information for air flow through the metering orifice, and a thermometer was used for the orifice air temperature. Recently, a three-pen circular chart meter was installed to record the orifice pressure and temperature data. Furthermore, the manometers formerly used for air flow metering were connected to measure the differential pressure across the finned tube and the static pressure in the reactor thimble. For this purpose, pressure probe tubes will be installed in the thimble, along with the thermocouples.

Interlocks between the pressure and vacuum blowers prevent pressurizing the exhaust air line leaving the reactor thimble. A pressure switch installed on the exhaust air line is set to shut down the reactor on loss of vacuum in this line. A scram relay is also connected to the circular chart recorder to shut down the reactor on abnormal increase in temperature or thermocouple failure. A warning light notifies the reactor operator of high temperatures approaching the scram setting.

SPECIMEN HANDLING PROCEDURES

Capsule Assembly and Specimen Loading

The capsule arrives from the shop with the bottom end-plug welded in place and leak tested. Thermocouples are then installed, as shown in Fig. 21. Thermocouples are spaced at about 3 inch intervals along the axis of the tube, one to a groove to form a helical pattern. On capsules fabricated for future tests, dummy protecting tubes will extend along the grooves from the thermocouple junction downward to make the cross section for air flow identical in each groove.

After installation of the thermocouples, the entire assembly is placed in a dry box containing an oxygen- and-moisture-free atmosphere of either helium or argon. Successive evacuations and fillings are used to purge the dry box. A small quantity of sodium-potassium eutectic

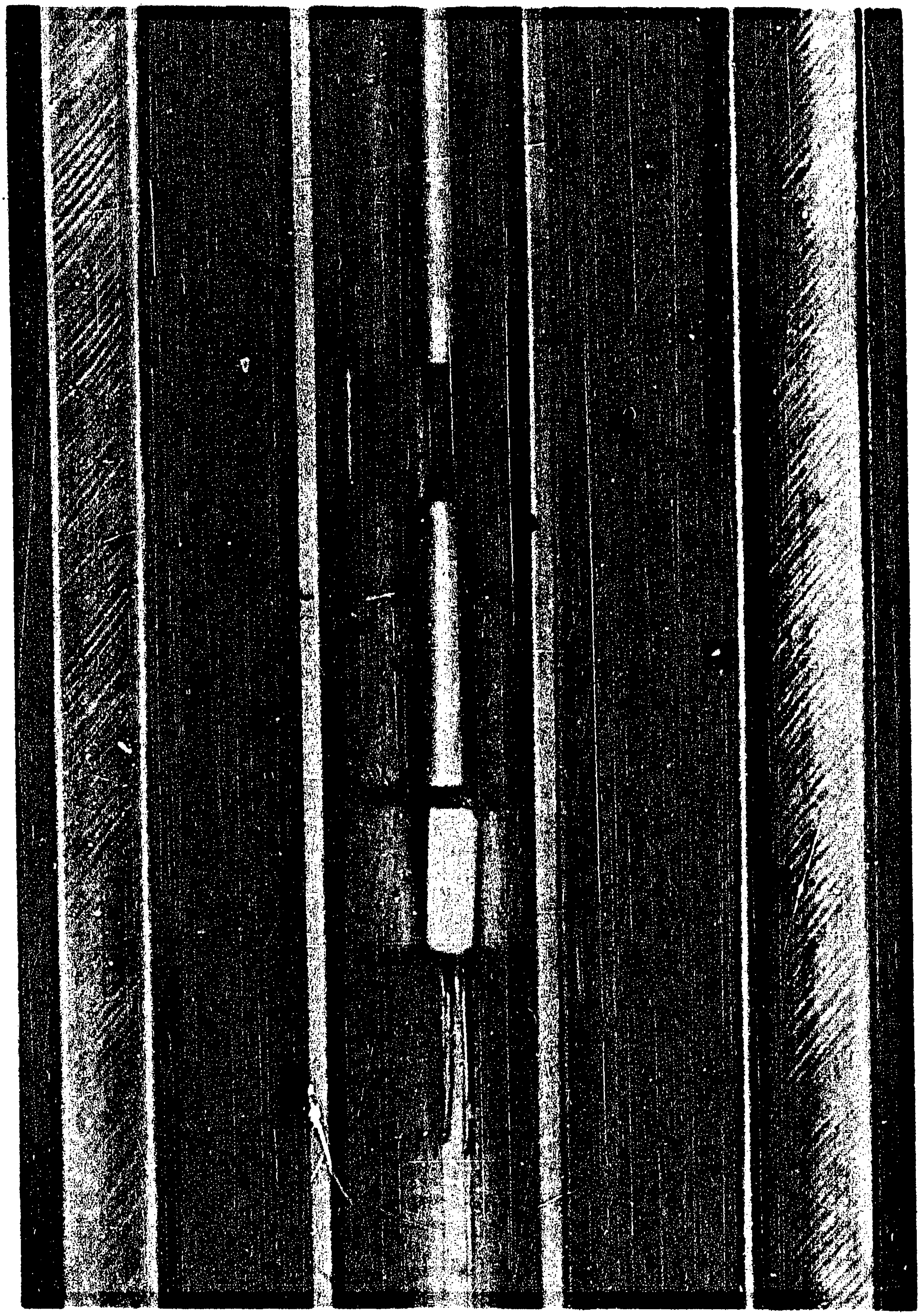


FIG. 31 TYPICAL THERMOCOUPLE INSTALLATION AT FIN ROOT

alloy (NaK) is placed in an open watch glass. When the bright surface does not tarnish, a clean atmosphere is assumed. A long tube on a hypodermic syringe is used to place a predetermined quantity of NaK in the tube; approximately 6-1/2 cc of NaK is used to bond a full-size fuel pin. The fuel pin is then carefully lowered into the capsule and an electric continuity probe is used to check the NaK level. The top end-plug is then installed and welded into place. In the case of CP-5-1, the welding was completed in the dry box, but CP-5-2 and CP-5-3 were welded after removal. Helium is introduced through the gas sample tube in the top end-plug and the weld is leak tested. The gas sample tube is then sealed and the top assembly is tested for helium evolution under high vacuum.

After the final capsule seal is tested, the installation of the aluminum extension tube and thermocouple extension lead is completed. The capsule is next placed in a vertical muffle furnace and heated for 8 to 12 hours at a temperature of 1000 F to promote wetting of capsule and pin surfaces by the NaK, and to check the operation of all thermocouples. The time range of 8 to 12 hours was selected on the basis of published isothermal-transformation curves which indicated that transformation of the gamma phase would not occur under these conditions. However, subsequent study on the as-fabricated fuel pins showed that a slight amount of transformation had occurred (about 5%), therefore bonding temperatures for future tests will not exceed 650 F.

At the reactor, and just before charging, the extension tube is attached to the thimble shield plug, and the assembly is lowered into the designated vertical thimble.

Removal From Reactor and Cave Operations

Upon completion of the irradiation, the capsule is raised from the reactor into a lead-lined transfer cask containing a chamber 44 inches long with gates at both top and bottom. A cable is attached to the shield plug and threaded through the cask centered over the opening. The entire assembly is withdrawn from the reactor until the capsule is in the cask and the lower gate can be closed. A cable is attached to the capsule, and the aluminum tube is sheared off above the position of the attachment so that, when lowered to the bottom gate, the capsule and tubing stub will permit closing the top gate of the cask. A small offset notch is provided for the cable in the top gate jamb. This cable arrangement facilitates subsequent handling of the capsule. The capsule is stored for a period of 1 to 3 weeks prior to examination in one of the ANL high level caves.

In the cave, the capsule is opened by severing the expansion chamber with a tubing cutter. The NaK is carefully destroyed in a beaker of isobutyl alcohol. The fuel pin specimen is then removed, and the remaining NaK is washed from the pin with alcohol. Final cleaning and drying of the fuel pins with acetone will precede the post-irradiation examinations, which include dimensional measurements, radiochemical burnup analyses, and metallographic examination.

TEST OPERATION

Flux Measurements

Flux measurements, taken prior to the irradiations, were made by exposing gold foils secured on a wooden stick inserted in the inner thimble. Thermal flux was determined by subtracting the neutron flux calculated from foils enclosed in cadmium envelopes from that caldulated from foils enclosed in thin aluminum envelopes. Flux measurements taken in VT-23 and VT-27 are shown in Fig. 32 and in Table V.

TABLE V

NEUTRON FLUX MEASUREMENTS

VT-27

Inches From Bottom Of Inner Thimble	December 11, 1957			June 5, 1958		
	Gold	Gold In Cadmium	Thermal	Gold	Gold In Cadmium	Thermal
0	$.518 \times 10^{13}$	$.09 \times 10^{11}$	$.52 \times 10^{13}$	$.468 \times 10^{13}$	$.08 \times 10^{11}$	$.47 \times 10^{13}$
6	.734	.29	.73	.690	.23	.69
12	.934	.67	.93	.877	.94	.87
18	1.09	1.30	1.08	1.03	1.87	1.02
24	1.12	1.85	1.10	1.05	2.35	1.03
30	1.07	1.93	1.05	.97	1.90	.95
36	.95	1.89	.93	.85	1.86	.83
42	.75	1.29	.74	.66	1.06	.65
48	.52	.40	.52	.45	.35	.45
52					.07	

VT-23

Inches From Bottom Of Inner Thimble	August 21, 1957			June 6, 1958		
	Gold	Gold In Cadmium	Thermal	Gold	Gold In Cadmium	Thermal
0	$.96 \times 10^{13}$	$.197 \times 10^{12}$	$.94 \times 10^{13}$	$.93 \times 10^{13}$	$.125 \times 10^{12}$	$.92 \times 10^{13}$
6	1.57	.78	1.49	1.52	.604	1.46
12	2.03	2.41	1.79	2.06	2.04	1.86
18	2.70	4.53	2.25	2.63	4.56	2.17
24	3.05	5.58	2.49	3.09	6.11	2.48
30	3.14	4.55	2.69	3.09	5.86	2.50
36	2.64	2.67	2.37	2.74	4.01	2.34
42	1.85	.87	1.76	2.03	1.67	1.86
48	1.10	.19	1.08	1.25	.425	1.21
52				.62	.0876	.61

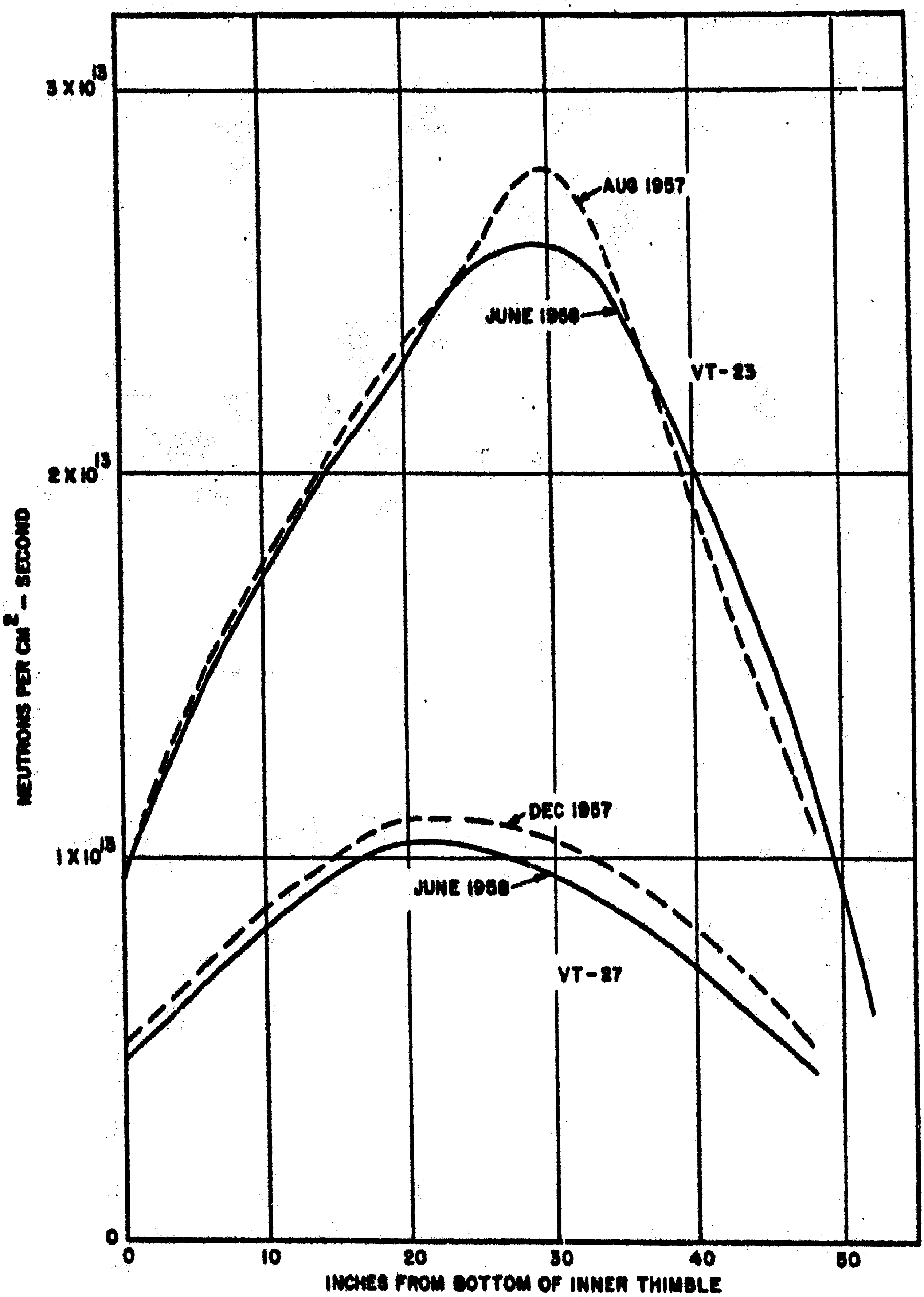


FIG. 32 THERMAL NEUTRON FLUX AT 2 MW

Irradiation History and Temperature Calculations

The history of the irradiation consists of a continuous record of temperatures measured at the fin roots, inlet and outlet air stream temperatures, and the temperature, pressure, and pressure drop at the flow orifice. Specimen power generation is calculated from the familiar heat balance equation:

$$q = WC_p \, (t_o - t_i)$$

Where q = heat generation per unit time, Btu/hr

W = mass velocity of the coolant, lb/hr

C_p = specific heat of the coolant, Btu/lbF

t_o = outlet temperature F

t_i = inlet temperature F

The local power generation at any elevation on the 30.5 inch specimen is given by the equation:

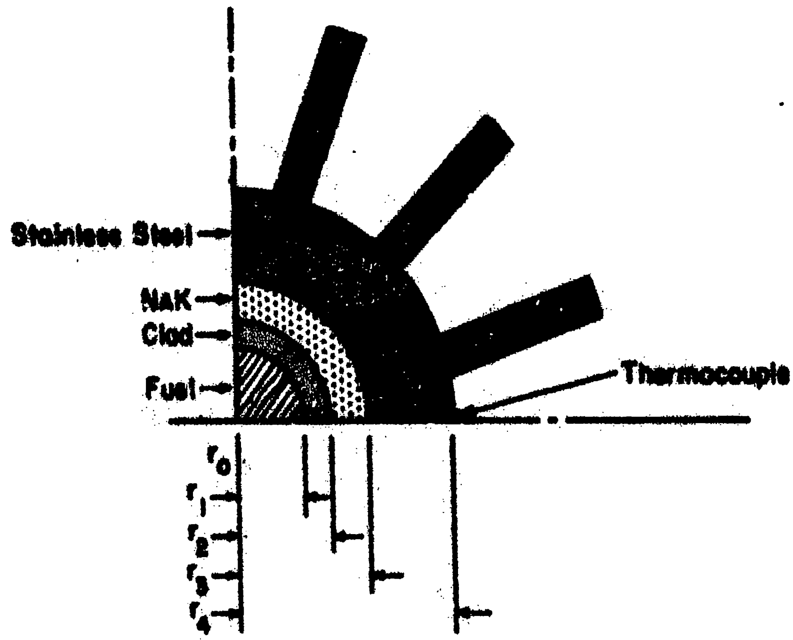
$$q_x' = \frac{q\,(12)}{30.5} \; \frac{\phi x}{\phi A}$$

Where q'_x = local heat generation rate, Btu/hr ft

$\frac{\phi x}{\phi A}$ = ratio of local flux to average flux as plotted in Figs. 2, 4, and 6.

The centerline fuel temperature at any elevation is equal to the temperature measured at the fin root (at the same elevation), plus the sum of the temperature drops across the capsule, NaK, zirconium clad, and fuel.

A one-quarter cross section of the capsule is shown in the sketch below.



Referring to the radii noted in the sketch, the centerline fuel temperature is calculated as follows:

$$t_{\mathbb{C}_{L,x}} = t_{root_x} + \frac{q'x}{2\pi}\left[\ln\frac{r_4}{r_3}\left(\frac{1}{k_{34}}\right) + \ln\frac{r_3}{r_2}\left(\frac{1}{k_{23}}\right) + \ln\frac{r_2}{r_1}\left(\frac{1}{k_{12}}\right) + \frac{1}{2k_{01}}\right]$$

where k_{34} is the thermal conductivity of the material between r_3 and r_4, i.e., stainless steel, etc.

Usually a maximum fuel temperature is specified in these irradiations. Ideally, the procedure for achieving this temperature is as follows:

1. Irradiation begins with a greater than necessary coolant-flow rate.

2. The hottest thermocouple is identified, and the preceding calculation is made for the $\phi x/\phi A$ ratio existing at the elevation of this thermocouple.

3. Coolant flow is gradually reduced to bring the calculated centerline fuel temperature opposite the hottest thermocouple to the specified value.

This thermocouple is connected to the single pen recorder, and it is set to scram the reactor at about 30 F above the normal operating value. All the other thermocouples are connected to the multi-point recorder.

EVALUATION OF TEST FACILITY

Capsule irradiations are classified as outlined below.

Temperature Unmonitored and Uncontrolled

These capsules can be of simple design, and are by far the cheapest type. They are often used in irradiation programs designed to screen several fuel material candidates and in programs involving a large number of tests where the characteristically wide data scatter can be resolved by statistical analysis.

Temperature Monitored but Uncontrolled

These capsules are often selected as the best compromise between the more expensive types involving temperature control and the less technically attractive, but cheaper, unmonitored type. As in the previous type, specimen temperatures are determined only by the size and composition of the specimen, the neutron flux, and the design of the capsule. Without a means of control, specimen temperatures change as the reactor flux changes and as burnup proceeds. With temperature monitoring, however, one has the data with which to analyze the results of the test in view of these changes.

Temperature Monitored and Controlled

Controlled capsules are more expensive than the two previous types, but the advantage of maintaining constant temperature conditions by compensating for changes in reactor characteristics and burnup often warrants the added cost.

Auxiliary Heaters

Auxiliary heaters are probably the most common means of temperature control. External equipment is held to a minimum, and automatic control is conveniently provided. The principal disadvantage is that the heaters often fail during the test, and the failures are irrepairable.

Adjustable Thermal Barrier

Capsules having adjustable thermal barriers are used by some experimenters and are being developed by many others. A gas-filled annulus with control over the gas composition is an example of this type. Generally speaking, this type of facility requires more external equipment than the capsules controlled with auxiliary heaters, but failures can usually be repaired. Since a gas annulus or a similarly effective thermal barrier is usually utilized, this type of capsule is generally applicable only for experiments in which the heat generation per unit length is relatively low (perhaps < 0.3 kw/inch).

Heat Sink Temperature Control

Control over the heat sink temperature offers another means of specimen temperature control. The reactor coolant is usually the ultimate heat sink, but a controllable intermediate heat sink can be provided. The intermediate sink may be static or flowing.

Static Heat Sink

An example of the static type heat sink is a facility developed by ANL for the irradiation of EBR-II fuel elements.* It employs a water-filled annulus between the specimen encapsulated in sodium and the reactor coolant. The pressure in this annulus can be controlled over a wide range. Nucleate boiling occurs in the water annulus, thus the intermediate heat sink temperature is the saturation temperature at the applied pressure.

Flowing Coolant

The facility described in this report is an example of the flowing intermediate heat sink classification. It probably involves more external equipment than any of the above types, therefore, it may be the most expensive facility to set up. However, the advantages are:

1. Failures, other than in thermocouples on the capsule, can be repaired.

2. Specimen heat generation can be accurately calculated thermodynamically and correlated with the reactor kwhr meter which then serves as a burnup integrator.

3. Uncertainties in specimen temperatures are small (see section on ANALYSIS OF UNCERTAINTY FACTORS IN TEMPERATURE CALCULATIONS).

4. A wide range of temperatures can be studied with a single irradiation of a long specimen.

Number 4 is probably the most valuable feature of this facility. In all other types listed above, the temperature range is determined by the flux range, therefore temperature and burnup cannot be studied independently in the same specimen. The temperature profiles in the three pins described in this report are quite similar to the calculated profiles of pins in the Enrico Fermi reactor. A pin 30 inches long is felt to be the technical equivalent of ten 3-inch specimens successfully irradiated in controlled capsules.

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*R. Schiltz, et al, Facility for the Irradiation of EBR-II Fuel Elements, ANL-5940.

ANALYSIS OF UNCERTAINTY FACTORS IN TEMPERATURE CALCULATIONS

In calculating the fuel centerline temperatures from the temperatures measured at the capsule surface (fin roots), conventional equations for conduction in cylindrical geometries were used. Factors to account for deviations from nominal dimensions, instrumentation errors in the determination of pin power, uncertainty associated with the true meaning of the recorded surface temperatures, and uncertainty in the thermal conductivities of the materials should be considered in an effort to evaluate the probable error in this calculation. Since it is extremely unlikely that all deviations would occur simultaneously, an overall uncertainty factor based on the deviation of each individual factor by two standard deviations (2σ) was calculated by statistical methods.

Using the CP-5-3 data as an example, Table VI shows the method of determining the uncertainty in the temperature at the center of the fuel pin. The column $\Sigma 2\sigma$ gives the temperature difference due to two standard deviations of each uncertainty in question. The over-all temperature uncertainty is obtained from the square root of the sum of the square of $\Sigma 2\sigma$. The application of two standard deviations represents a probability of 95% that the centerline temperature will lie within the calculated limits. As shown at the bottom of Table VI, these limits are $\pm$ 56 F from the calculated 1379 F.

TABLE VI

UNCERTAINTY ANALYSIS OF CENTRAL METAL TEMPERATURE CALCULATION FOR CP-5-3 SPECIMEN

Uncertainty	Factor for Capsule Temperature Drop ΔT_{ss}=103°F F	2σ	Factor for Bond Temperature Drop ΔT_b=42°F F	2σ	Factor for Clad Temperature Drop ΔT_c=15°F F	2σ	Factor for Fuel Temperature Drop ΔT_f=69°F F	2σ	Summation Σ(2σ)	[Σ(2σ)]^2
Dimensions										
a. Length	1.02	2.1	1.02	0.8	1.02	0.3	1.02	1.4	4.6	21
b. Diameter	1.05	5.2	1.05	2.1	1.05	0.8	1.00		8.1	66
Power: Flux, Instrumentation, Calculations	1.10	10.3	1.10	4.2	1.10	1.5	1.10	6.9	22.9	524
Temp. Measurement										
a. Thermocouple location	1.45	46.3							46.3	2150
b. Thermocouple errors	1.13	13.4							13.4	180
Thermal Conductivities										
a. Stainless Steel	1.05	5.2							5.2	27
b. NaK			1.10	4.2					4.2	18
c. Zirconium					1.10	1.5			1.5	2
d. U-10 w/o Mo							1.20	13.8	13.8	190
								TOTAL		3178
			Square Root (95% Confidence)							56

Central fuel temperature = 1150 + 103 + 42 + 15 + 69 = 1379 ± 56°F

As a general check on the validity of the measured capsule surface temperatures, a similar analysis can be made in which the capsule temperature can be calculated starting with the air inlet temperature (200 F). The hottest point on the capsule surface (CP-5-3) was measured as 1150 F. This point is located 18 inches from the top of the fins. Assuming first a linear coolant temperature rise along the capsule, and then correcting for the flux profile, the coolant temperature rise from the inlet to this point 18 inches below the top of the fins, is 250 F. The film coefficient was calculated from the empirical correlation*:

$$St = 0.04\, e^{-0.055\, n}\, Re^{-0.2}$$

where n is the number of longitudinal fins (12 in this case).

The value of the film coefficient calculated at a flow rate of 340 lb/hr is 32.4 $\frac{Btu}{hr\ F\ ft^2}$. The fin efficiency calculated by the method presented in McAdams** is 0.612, and the effective heat transfer surface area calculated from this fin efficiency and the dimension of the capsule is 0.685 ft^2/ft. The average power generation per foot of pin is 14,750 Btu/hr, and the $\phi\, x/\phi A$ at the hot spot is 1.05 (see Fig. 6). Therefore, the film temperature drop is:

$$\Delta T = \frac{q'x}{Ah}$$

$$= \frac{14{,}750\ (1.05)}{0.685\ (32.4)}$$

$$= 698\ F$$

From these crude calculations, the measured surface temperature at the point in question should be 200+250+698 = 1148 F, which is remarkably close to the measured temperature of 1150 F. An uncertainty analysis was made on these calculations and is presented in Table VII. The 2σ uncertainty is large (217 F) due chiefly to the large film temperature drop and the relatively great uncertainty (20%) associated with its calculation. Obviously, the excellent agreement between the calculated temperature and that actually measured is good fortune. The real value of this latter analysis is appreciated in the planning of irradiations when the location of the specimen in the flux is specified to obtain the desired temperature profile.

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*P. Fortescue and W. B. Hall, Journal of British Nuclear Engineering Conference, Vol. 2, No. 2, p 83 - 91, April 1957.

**W. H. McAdams, Heat Transmission, Third Edition, p 271, McGraw Hill Book Co., Inc. (1954).

TABLE VII

UNCERTAINTY ANALYSIS OF CAPSULE SURFACE

TEMPERATURE CALCULATION IN CP-5-3 SPECIMEN

Uncertainty	Factor for Coolant Temperature Rise ΔT_c = 250 F		Factor for Film Temperature Drop ΔT_f = 698 F		Summation	
	F	2σ	F	2σ	$\Sigma(2\sigma)$	$(\Sigma(2\sigma))^2$
Coolant Flow						
a. Orifice Error b. Nonuniformity	1.10	25	1.10	69.8	94.8	8,950
Dimensions						
a. Length	1.02	5	1.02	14.	19.	361
b. Perimeter			1.08	55.8	55.8	3,110
Power						
a. Flux Variation b. Instrumentation c. Calculations	1.10	25	1.10	69.8	94.8	8,950
Film Coefficient			1.20	140	140	19,600
Temperature Measurement						
a. Thermocouple Location			1.10	69.8	69.8	4,850
b. Thermocouple Errors	1.04	10	1.03	20.9	30.9	950
					Total	46,771
					Square Root (95% Confidence)	217

Capsule surface temperature 18 inches below top of fins = 200 + 250 + 698
= 1148 ± 217 F