General Electric Company
KNOLLS ATOMIC POWER LABORATORY
Schenectady, NewYork

December 23, 1958
S3G 75-182; Task 18.1

The Manager
Schenectady Naval Reactor Operations Office
United States Atomic Energy Commission
Knolls Atomic Power Laboratory
Schenectady, New York

MASTER

Attention: Lt. E. B. Ackerman

Subject: S3G Core Instrumentation; Neutron-Sensitive Thermocouple and Cable

Enclosure: KAPL-M-KEW-1, "Performance of A Miniature High-Temperature, High-Level-Radiation, Neutron-Sensitive Thermopile", dated December 9, 1958.

Dear Sir:

This forwards the above enclosure for information. This document was prepared after carrying out various in-pile tests at MTR as part of the program for development of in-core neutron flux monitoring device.

Very truly yours,

E C Rumbaugh
E. C. Rumbaugh, Manager
SAR Reactor Core

H L Mars
H. L. Mars, Supervising Engineer
SAR Reactor Core Instrumentation

KEWatkins:HLM:dar

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M. J. Sears

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KAPL-M-KEW-1

General Electric Company
KNOLLS ATOMIC POWER LABORATORY
Schenectady, New York

MASTER

PERFORMANCE OF A MINIATURE HIGH-TEMPERATURE, HIGH-LEVEL-RADIATION NEUTRON-SENSITIVE THERMOPILE

by

K. E. Watkins

December 9, 1958

E C Rumbaugh
Authorized Classifier

12-11-58
Date

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SUMMARY

A miniature high-temperature neutron-sensitive thermopile has been designed, developed, and tested by KAPL and Leeds and Northrup for directly and rapidly performing power reactor core flux measurements using a standard fast-response, high-sensitivity recording potentiometer for readout.

The thermopile developed for this application utilizes a boron-10 coated sensitive element with a thermal shunt element to minimize effects of ambient temperature and changes of ambient temperature.

Test facilities at MTR have been used to check performance of this design under in-pile conditions including high temperature and neutron and gamma radiation levels of magnitudes encountered in reactor cores. Of three thermopiles tested, extended operation at 510°F ambient temperature over the range of 5×10^{12} to 2×10^{14} thermal nv (neutrons per cm^2 per sec) has been obtained with little difficulty. Exposures have been made up to 8×10^{19} nvt without failure. Sensitivity has been observed to be adequate for use of the device over the range tested, even after the partial depletion of boron-10 produced by 4×10^{19} nvt exposure (design lifetime). Calibration has been checked against flux wire calibrations and reactor power levels, and linearity of response is excellent above 10^{13} nv.

Extended operation at high (greater than 10^{14} nv) thermal neutron fluxes is accompanied by an appreciable boron-10 burnup rate so that either a correction or flux wire calibration of the instrument must be made for absolute measurements over long time intervals. For operation intervals of several hours at lower fluxes (below 10^{14}nv), no correction is necessary since the error introduced by boron-10 burnup is negligible.

Design response time is 70 milliseconds. Response time was measured to be less than 200 milliseconds. Measurement of response time was not possible below this value due to time required to change (flux) position of the thermopile and due to limit of time resolution of readout equipment. For quick changes of position over large increments at high flux levels, a transient (due to gamma heating effects) exists requiring about 30 seconds to disappear.

A. INTRODUCTION

The tests reported on in this memo were carried out as a part of a KAPL-L&N program to design, develop, and apply a thermal-neutron measurement device for power reactor core measurements such as flux profile mapping and monitoring of flux conditions during core transients. Specifications and design are discussed by references (1) and (2). These are summarized briefly below:

1. Design flux range: 5×10^{12} to 10^{15} nv.
2. Design temperature: 560°F (ambient), 800°F (sensing element temperature due to ambient plus gamma and neutron heating).
3. Materials and construction to withstand added temperature produced by neutron heating (of sensing element) and gamma heating.
4. Overall dimensions: to pass through 1/8 inch (nominal) ID tube with 1-1/2 inch bend radius.
5. Design time constant: 0.070 second.

In addition to the above considerations, it was necessary to design for the following desired performance:

1. Life time of at least 100 hours at 10^{14} nv (3.6×10^{19} nvt).
2. Materials and design chosen to minimize formation of radioactive isotopes which would constitute a health hazard when removed from a reactor core.
3. Sensitivity to be adequate for reliable measurement of signals over the specified flux range by the end of specified life of 3.6×10^{19} nvt.
4. Accuracy to be within ± 10 percent of the true value of thermal neutron flux.

The device designed and constructed by Leeds and Northrup for this purpose was derived from previous work on ambient temperature independent thermopiles for radiation pyrometry and is based on using a platinum foil with a boron-10 coating to produce a temperature due to the combined effects of neutrons and gammas. Temperature due to neutrons predominates, since the total energy liberated by gammas in the boron-10 is much less than that liberated by neutrons. The foil is connected to thermocouple wires of molybdenum and alumel. By use of a thermal shunt element, the effect of ambient temperature is minimized. (Figure 1)

Readout instrument for the thermopile was selected on the basis of expected thermopile output (hundreds of microvolts to a few microvolts) over the range and lifetime specified. Also, a fast response was required.

Three development models of this device have been tested at MTR. The first two were tested in beryllium reflector fixed positions, and the third one was tested in the KAPL-30 loop at MTR. The KAPL-30 loop contains a flux monitor tube which provides neutron flux and temperature levels in the region of interest.

The first two test assemblies (KAPL-MTR Experiment Nos. 28-30-2L and 28-79) were identical and each was placed within a capsule containing heaters. By use of the heaters, the ambient temperature could be increased above the ambient temperature (less than 100°C at the MTR test position). Each capsule also included thermocouples for monitoring temperature and flux wires for checking exposure. Reference (3) provides construction details. The third test assembly (KAPL-MTR Experiment No. 30-15) was not placed within a heater capsule. The construction was based on using the same thermopile construction as for the first two, but with an attached semi-flexible four-lead MgO-insulated cable. Two leads of copper were for the thermopile and the remaining two leads (one chromel, one alumel) were terminated in a thermocouple for monitoring the temperature of the thermopile. Figure 2.

B. TEST PROCEDURE

The 28-30-2L and 28-79 test assemblies were installed in fixed positions in the MTR beryllium reflector region. By adjustment of the capsule heaters, the thermopiles were checked for thermal compensation. Flux variations were introduced through normal reactor operation. Calibration of thermopile output versus thermal neutron flux was made by checking against power level indicated by MTR plant ion chambers. Total neutron exposure was measured by flux activation wires which were later counted.

The 30-15 test assembly was inserted to various preselected positions in the flux monitor tube of the KAPL-30 loop at MTR. These positions were determined from the flux wire calibration of the flux tube for the preceding cycle. Nominal positions used corresponded to thermal neutron fluxes of 5×10^{12} nv, 10^{13} nv, 5×10^{13} nv, 10^{14} nv, and maximum insertion (2×10^{14} nv). These points covered the full distance (18 inches) calibrated by flux wire. In addition to the scanning at these calibration check points, the 30-15 test assembly was checked for thermal compensation by changing loop temperature while the thermopile was held at a fixed position and examining for a change in thermopile output. Thermopile response time was checked insofar as possible by manually rapidly shifting the position of the thermopile over a small increment.

Measurement of thermopile output in each test was by use of a Leeds & Northrup Catalogue 60151-C6-4, Recording Potentiometer. This readout instrument provided the high sensitivity and fast time response needed. An additional feature of great value is a variable range control, permitting full scale values from 1/4 to 1-1/4 millivolt, thereby, giving excellent signal resolution.

C. TEST RESULTS

1. First Thermopile (KAPL-MTR Experiment No. 28-30-2L)

This test assembly was inserted in the A-43SE position (no vertical spacer) at MTR during shutdown on June, 1957, between cycles 87 and 88. This position of the thermopile corresponded to 4.65×10^{13} thermal nv and 2.5×10^{12} fast nv with MTR at full power determined by post-irradiation checking of the flux wire included in the assembly.

Resistance checks of the assembly before and after insertion revealed damage to the test assembly heater during insertion. The heater coil was grounded and, therefore, could not be used to check thermopile in-pile performance with various ambient temperature conditions. Thermopile temperature remained in the range of MTR coolant temperatures (less than 100°C).

Data was obtained during startup on June 8, 1957. Assuming a linear relationship between MTR power level and local thermal flux level at the thermopile, the results were:

MTR Power Level Megawatts	Thermal nv at Thermopile	Thermopile Output Microvolts
5	5.82×10^{12}	7
10	1.16×10^{13}	24
20	2.32×10^{13}	54
30	3.49×10^{13}	87

After a few minutes at 30 megawatts (thermopile temperature about 110°C), the thermopile failed and no further in-pile data was obtained. Post-irradiation examination of the thermopile was inconclusive in determining cause of failure due to damage to the thermopile during hot cell disassembly. Total exposure at time of failure was about 10^{15} thermal nvt.

2. Second Thermopile (KAPL-MTR Experiment No. 28-79)

This test assembly was inserted in the A-39NW position (vertical position spaced just below core center line) at MTR during the shutdown in June, 1957, between cycles 88 and 89. This position corresponded to 5.9×10^{13} thermal nv and 3×10^{12} fast nv with MTR at full power, determined by post-irradiation checking of the flux wire included in the assembly.

Resistance checks of the assembly before and after insertion revealed that the thermopile was isolated from ground, indicating the separation of the thermal compensation shunt from the base (or from the receiver). The effect of this condition is to reduce the ambient temperature compensation of the thermopile and increase the output emf of the thermopile. This condition was verified by use of the capsule heater, which produced a thermopile output of 28 microvolts at 200°C and zero nv. Normal thermopile response under this condition produces an output of only 3 or 4 microvolts. Consequently, when the reactor was started up, the heater was left off to keep the thermopile temperature to a minimum and minimize the effect of loss of ambient temperature compensation.

On June 26-27, 1957, the reactor was brought up to full power in steps, the thermopile following each step satisfactorily except for evidence of sensitiveness to ambient temperature transients. When MTR reached full power, the thermopile output was 340 microvolts. The thermopile was operated continuously for the duration of the cycle, which ended on July 15, 1957. During the cycle, various extraneous causes resulted in changes in MTR power level, with several scrams, shutdown, and start-ups. Each startup was made in steps, affording a check of thermopile output versus power level (viz., thermal neutron level). By the end of the cycle, the thermopile was operating satisfactorily, with an output of 103 microvolts at MTR full power (corresponding to 5.9×10^{13} thermal nv). Accumulated thermal neutron exposure by the end of the cycle was 8×10^{19} nvt.

Boron Burnup

As was expected, the output of the thermopile for a steady reactor power level decreased slowly due to depletion of the boron-10 coating on the thermopile receiver. For intervals of several hours, the burnup effect is negligible.

The decrease in sensitivity of the thermopile should follow the exponential $E = E_0 e^{-kt}$ where E = thermopile output at time "t", E_0 = thermopile output at time t = o, and k is the decay constant. For the first few days, the decrease agrees with this fairly well, E_0 being equal to 340 microvolts and k = 0.000128, with t = exposure time in minutes at full power. However, for later times the signal does not decrease as rapidly as the equation indicates. This may be due to a change in compensation with target temperature.

Temperature (Ambient)

The temperatures indicated by the thermocouples in the test assembly during the cycle varied between 265°C and 295°C with MTR at full power, and dropped to about 100°C during reactor down time. Consequently, it is estimated the thermopile ambient temperature was well above 200°C during most of the cycle.

Sensitivity

The initial sensitivity of the thermopile was about 5.8×10^{-12} μv/nv. Decrease in sensitivity was produced by boron depletion as discussed above.

Linearity

Calibration of the thermopile was made difficult due to an intermittent condition existing during reactor startup (transients) which showed up as a rapid signal decrease once a given reactor power level was reached. This may have been caused by the loss of the thermopile thermal shunt noted above or by external effects. During two reactor startups, fairly good calibration data was obtained.

Assuming a linear relationship between MTR power level and local thermal neutron flux level at the thermopile test position, the data obtained at these times of reactor startups during the cycle are listed below:

Initial Startup (6/26/57)

Unreliable data due to transient condition.

After about 5 x 10^{18} nvt (6/28/57)

MTR Power Level Megawatts	Thermal nv at Thermopile	Thermopile Output Microvolts
20	3 x 10^{13}	163
30	4.4 x 10^{13}	230
35	5.2 x 10^{13}	267
40	5.9 x 10^{13}	297
After about 5.5 x 10^{18} nvt (6/29/57)		
5	7.4 x 10^{12}	40
10	1.5 x 10^{13}	80
15	2.2 x 10^{13}	95
18		115
25		160
30	4.4 x 10^{13}	190

The thermopile output signal showed rapid superimposed variations amounting to one or two microvolts through most of the cycle. This may have been due to vibration of the test assembly caused by reactor coolant flow or to intermittent grounding of shielding of the lead out cable. The disappearance of this interference near the end of the cycle when a new roll of chart paper was put into the recorder suggests that the amplifier gain may have been set excessively high.

The recording accumulated throughout the cycle contained many step changes of signal level and a one-hour period of high-amplitude spikes on the signal. Information explaining these were missing from the record and the eventual return of the signal to the value existing before the interference gave assurance that the thermopile was not the cause.

3. Third Thermopile (KAPL-MTR Experiment No. 30-15)

This experiment differed from the first two thermopiles in that it permitted movement of the test assembly (within the flux monitor tube of the KAPL-30 loop). By this movement, the region of thermal neutron flux of interest could be scanned. An additional advantage was the correlation of thermopile calibration with a flux wire calibration of the flux monitor tube. The ambient temperature in this facility was normally about 500°F.

The test assembly shown by Figure 2 was inserted in the flux monitor tube on January 31, 1958, and an initial calibration with loop temperature at 325°F was made as follows:

Thermal Flux (nv) by Flux Wire Calibration	Temp. Indicated by Thermopile-Thermocouple °F	Thermopile (Equilibrium) Output Microvolts
5×10^{12}	325	17-1/2
10^{13}	337	50
5×10^{13}	382	230
10^{14}	423	488
2×10^{14} (Maximum available)	471	979

The insertions made for the last three values were accompanied by a thermopile transient which produced overshoots of about 10 percent peak value before returning to equilibrium values in about 30 seconds. The effect of gamma heating was shown clearly by the temperature indicated by the thermocouple attached to the base of the thermopile.

Small step decreases of about one or two microvolts amplitude were observed to appear occaionally at the higher fluxes. These were random and occurred at intervals of from a few minutes to a half hour or more. These represent signal excursions of less than 1 percent.

With the test assembly at the 2×10^{14} nv position, the loop temperature was brought up to normal (500°F) within one hour. With this ambient temperature, the thermopile base temperature was 622°F. After 21 hours at 2×10^{14} nv and 500°F ambient, the thermopile calibration was repeated twice by withdrawing to 5×10^{12} nv position and inserting to each test position and then withdrawing to each test position. The data obtained is shown below:

After 1.5×10^{19} nvt (21 hours at 2×10^{14} nv)

	Thermal nv	Thermopile Signal Microvolts
"Insert" calib:	5×10^{12}	7
	10^{13}	26
	5×10^{13}	113
	10^{14}	222
	2×10^{14}	440
"Withdraw" calib:	2×10^{14}	435
	10^{14}	217
	5×10^{13}	107
	10^{13}	21
	5×10^{12}	8

The linearity is observed to be excellent except for the 5 x 10^{12} nv position. Boron burnup effect on decreasing the signal is appreciable at the 2 x 10^{14} nv level. Transient overshoots lasting about 30 seconds were again observed at higher fluxes as originally.

The test assembly was reinserted to the 2 x 10^{14} nv position following the 1.5 x 10^{19} nvt calibration and left in this position for the rest of the MTR cycle. After 8.4 x 10^{19} nvt (February 5, 1958), the thermopile output at 2 x 10^{14} was 5 microvolts. The record was lost shortly after this point, however, about 24 hours later (on February 6, 1958), the thermopile failed by suddenly reversing polarity to a meaningless steady value.

Boron Burnup

The output of the third thermopile at maximum flux (2 x 10^{14} nv) exhibited a much greater boron burnup effect as expected. At such a high flux level, the signal decrease rate was too great to consider the effect negligible for more than a few hours. At the initial exposure at maximum flux, the rate of decrease was significant over a period of a few minutes. The boron burnup is illustrated by the attached log of thermopile performance, January 31, 1958 through February 5, 1958. The thermopile output is plotted at various points with straight lines connecting these points. These straight lines correspond to straight line segments of an exponentially-decreasing signal.

The burnup pattern deviation from a true exponential (discussed for the second thermopile) also was noticed for the third thermopile.

Temperature (Ambient)

The ambient temperature and the temperature of the thermopile are shown on the log of thermopile performance.

There is some evidence during the initial changing of loop temperature from 325°F to 500°F that the thermopile output is affected by rapid changes in ambient temperature or gradients produced during loop temperature change.

Sensitivity

The initial sensitivity of the third thermopile was about 4.7 x 10^{-12} µv/nv, which is somewhat lower than that of the second thermopile. This could be due to the loss of the thermal shunt of the second thermopile, which tends to increase its output.

Linearity

Calibration checks were made at initial insertion and again after 1.5 x 10^{19} nvt. The results are shown in Figure 4. It can be seen that the calibration is of excellent linearity above 10^{13} nv and that the relative calibration remains the same after exposure.

The calibration of the third thermopile is compared with the flux wire calibration in Figure 5.

The third thermopile output signal was free of the superimposed variations noted on the second unit; however, the signal recording accumulated through the exposure period contained occasional step decreases of one or two microvolts amplitude.

Time Response

A rough check of time response was made by rapidly changing position of the thermopile. Pre-irradiation tests showed a quick insertion over a physical distance of 1/4 inch required about 200 milliseconds. Response time of the readout recorder was made small relative to this by selecting a relatively small flux change over this 1/4 inch. By this method, response time of the thermopile was measured to be less than the time lag introduced by the experimental method, i.e., 200 milliseconds.

For large changes of ambient thermal neutron flux, several seconds were required for making the position adjustment, therefore, a check of thermopile time response was not possible. For large changes of flux at higher flux values, the thermopile exhibited a gamma heating effect which required as long as 30 seconds to disappear. Figure 6.

D. CONCLUSIONS

From the series of tests discussed above, it is considered that the thermopile design tested meets the design specifications in most respects. However, the tests have not resolved a few items:

1. Reliability

The tests reported on here are not considered adequate for judging reliability. The fixed position tests involved installation problems. The third test indicated reliability is probably good.

2. Reproducibility (Among individual thermopiles)

The tests were not sufficiently duplicative to gauge reproducibility of thermopile characteristics.

In general, these tests have shown the thermopile to be a simple and effective means of performing in-core neutron flux measurements within the range of interest. Readout is very simple, being comparable to ordinary thermocouple readout. Induced activity is kept relatively low, since the sensitive material (boron-10) does not itself evolve radioactive products. This feature is well adapted to the planned use of the thermopile for insertions and withdrawals during reactor operation without interfering with reactor operations. The small physical size of the thermopile provides good flux resolution and also minimizes flux perturbation due to the thermopile. Time response and thermal transients are such that a relatively slow and continuous traverse through a core should produce a comparatively rapid and accurate flux profile measurement.

Errors in the data were introduced from the following sources:

1. For the in-pile thermopile tests, it was assumed that local thermal neutron flux at the test position was linearly proportional to reactor power level (as indicated by out-of-core ion chambers). This can introduce considerable error, depending on adjacent experiments, rod motion in the vicinity, local fuel depletion status, position of MTR ion chambers, and other variables.

2. In changing position of the third thermopile (30-15) for calibration purposes, error in position produces an error in calibration. The position of the sensitive element within the thermopile also introduced an error, since all position information was referenced to the end of the assembly.

3. The third thermopile (30-15) calibration was checked against a flux wire. The flux wire material was cobalt, which has an activation cross section which varies considerably from the capture cross section of the boron-10 in the thermopile; i.e., the assumption of flux wire measurement being a thermal nv measurement involves some error.

4. Readout measurement error is present to the amount of about 0.5 percent (manufacturer's specification).

5. An error is introduced due to flux depression effects of (1) the flux wire, for the flux wire calibration, and (2) the thermopile, for thermopile calibration.

E. RECOMMENDATIONS

1. The value of the thermopile is shown by these tests and justifies the development of a suitable cable which is capable of moving this device in and out of the SAR (S3G) core. This cable is presently in last stages of development.

2. Additional tests inpile under steady reactor conditions such as pertains at MTR are needed to more completely delineate the weak points of the thermopile performance and, thereby, point the way to design improvement. An important phase of this is to evaluate any synergistic effect of exposure to same integrated flux at different flux levels on boron burnup effect.

3. Thermopiles of this type will be valuable in securing in-core measurements in SAR (S3G) and should be supplied for such service. Units for this purpose are presently being manufactured.

4. Use of this thermopile design for measurements in reactors other than SAR (S3G) should be considered, since it has the desirable features of availability, low cost, small size, and simple readout.

5. When suitable operation of this thermopile with SAR (S3G) is demonstrated, consideration should be given to a design change of sensitive material from boron-10 to uranium-235 to improve on the burnup error. The thermopile vendor is presently making calculations on this.

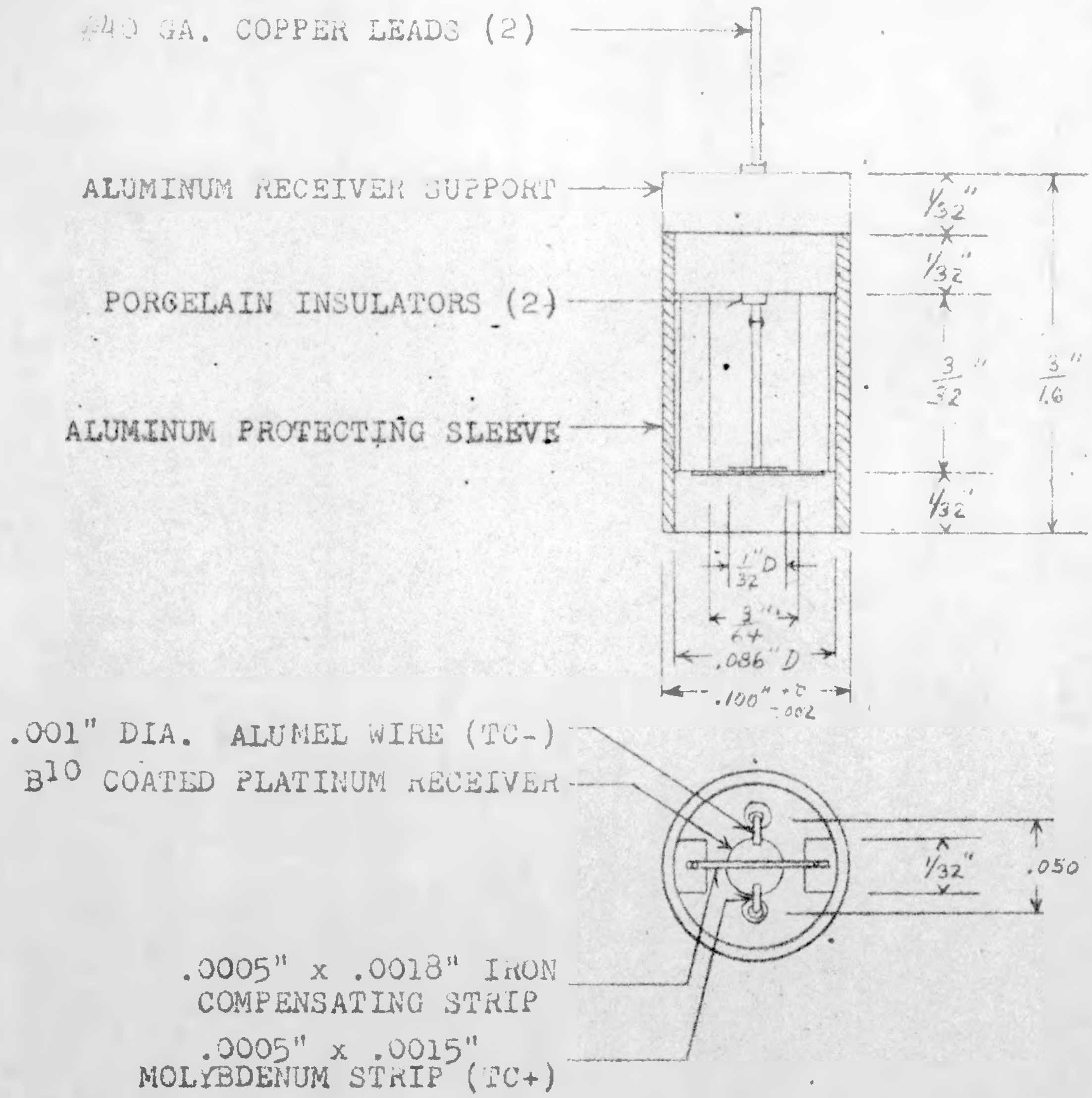
F. REFERENCES

1. Robertson, D., "Progress Report No. 1, Neutron-Sensitive Thermopile for Reactor Applications", AECU-3416.

2. KAPL Specification No. KPE-1019, "Neutron-Sensitive Thermocouple and Cable for Reactor Applications".

3. KAPL Drawing No. 604C234, "Thermopile Assembly".

NEUTRON-SENSITIVE THERMOPILE



REFERENCE: LEEDS & NORTHRUP SKETCH #PD-186.

Figure 1

ACTUAL SIZE: 

TEST ASSEMBLY - 3RD NEUTRON-SENSITIVE THERMOPILE AND CABLE

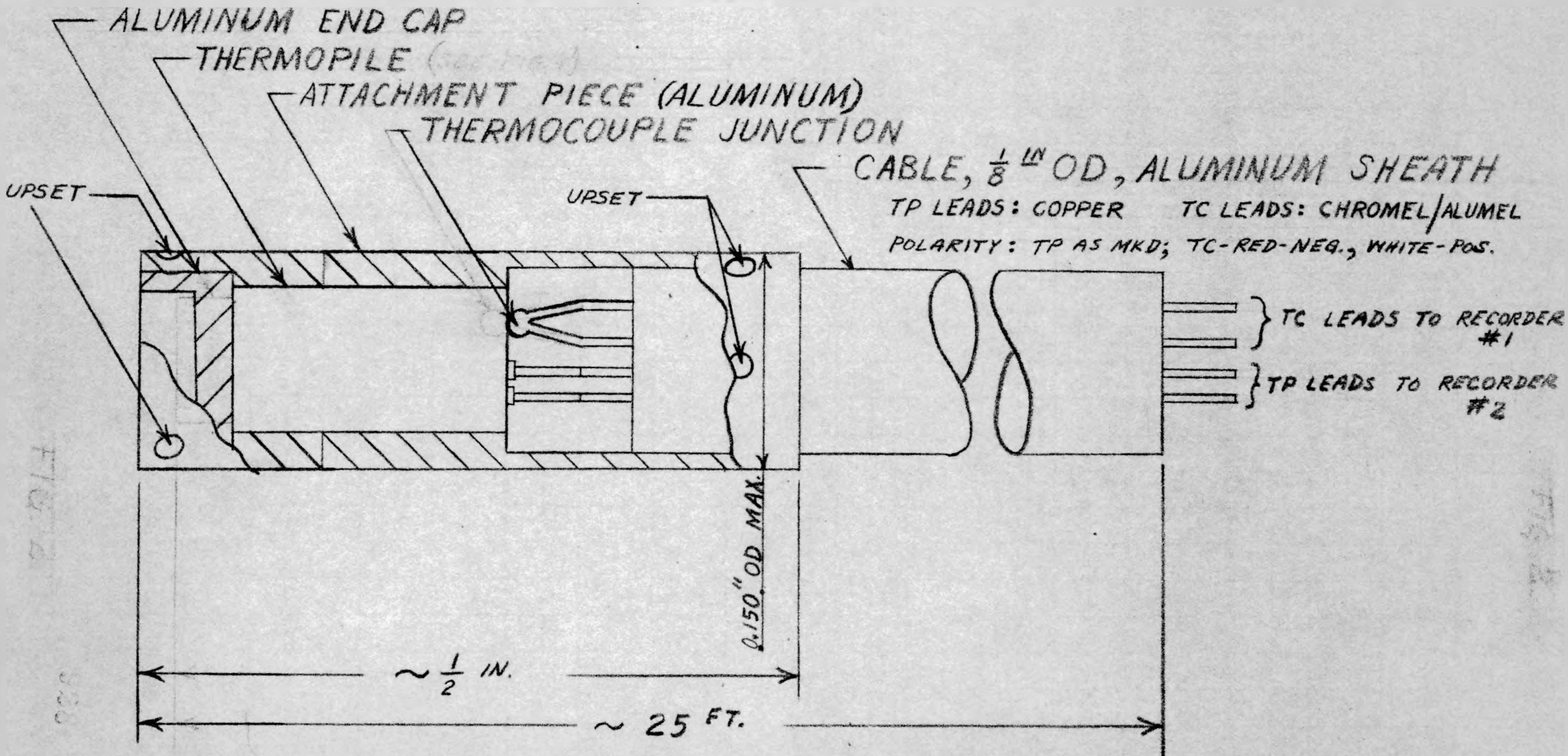


Figure 2
SK-KW-1028
REV. 1

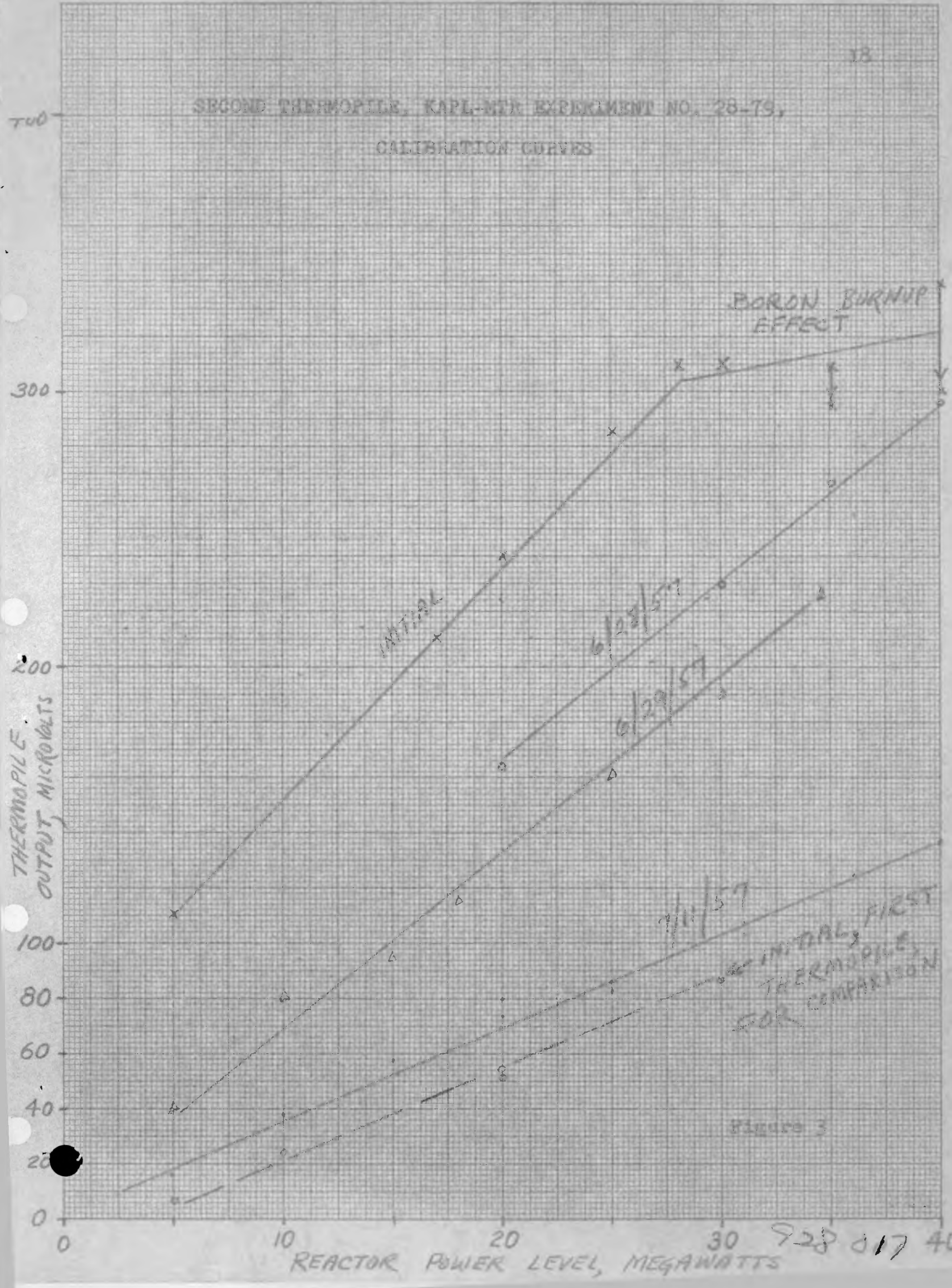

SECOND THERMOPILE, KAPL-MTR EXPERIMENT NO. 28-79,
CALIBRATION CURVES
BORON BURNUP EFFECT
INITIAL
6/28/57
6/29/57
7/1/57
INITIAL, FIRST THERMOPILE, FOR COMPARISON
THERMOPILE OUTPUT, MICROVOLTS
REACTOR POWER LEVEL, MEGAWATTS
0
10
20
30
40
20
40
60
80
100
200
300
400

Figure 3

THIRD THERMOPILE, KAPL-MTR EXPERIMENT NO. 30-15,

CALIBRATION CURVES

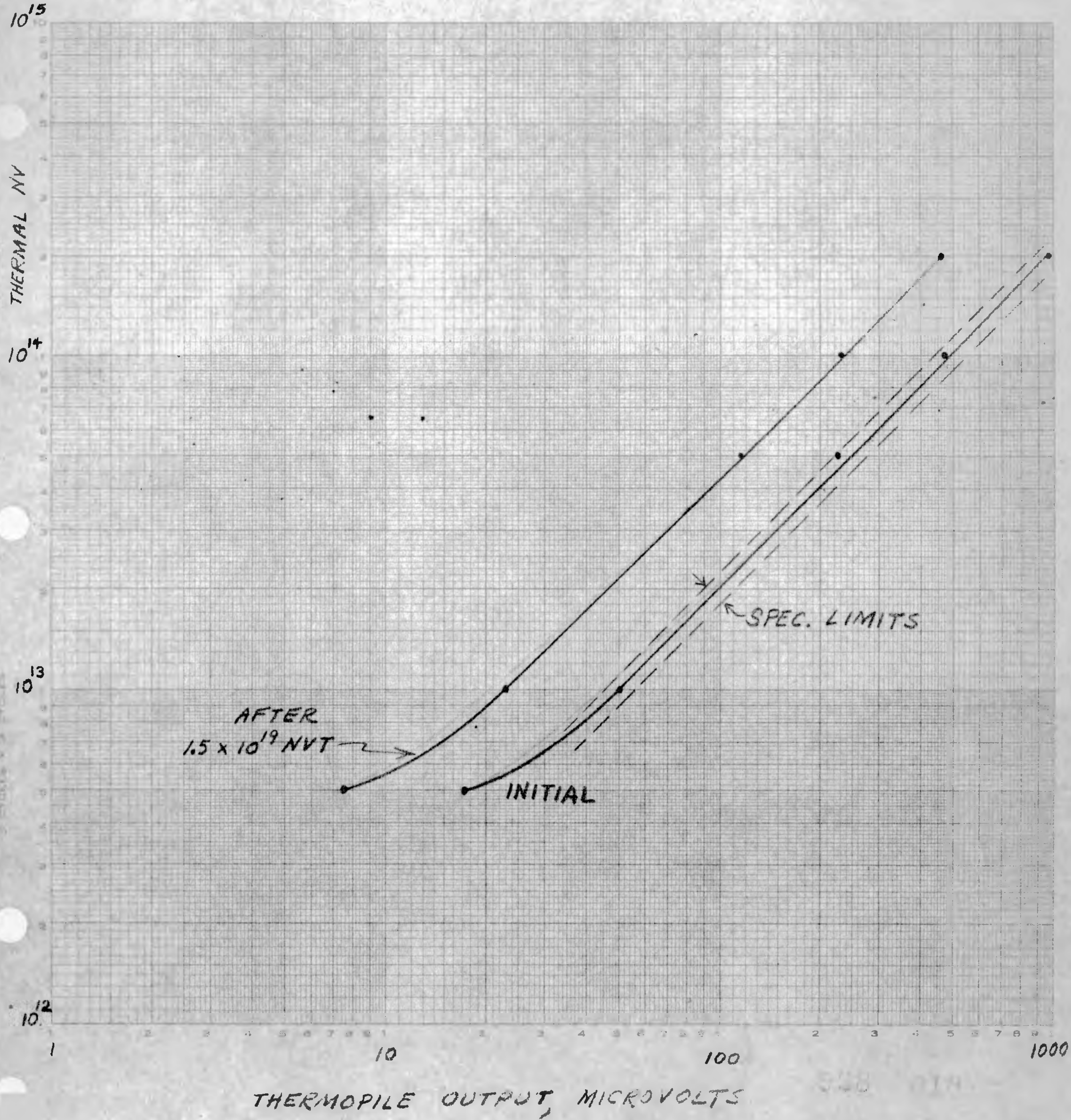


Figure 4

928 18

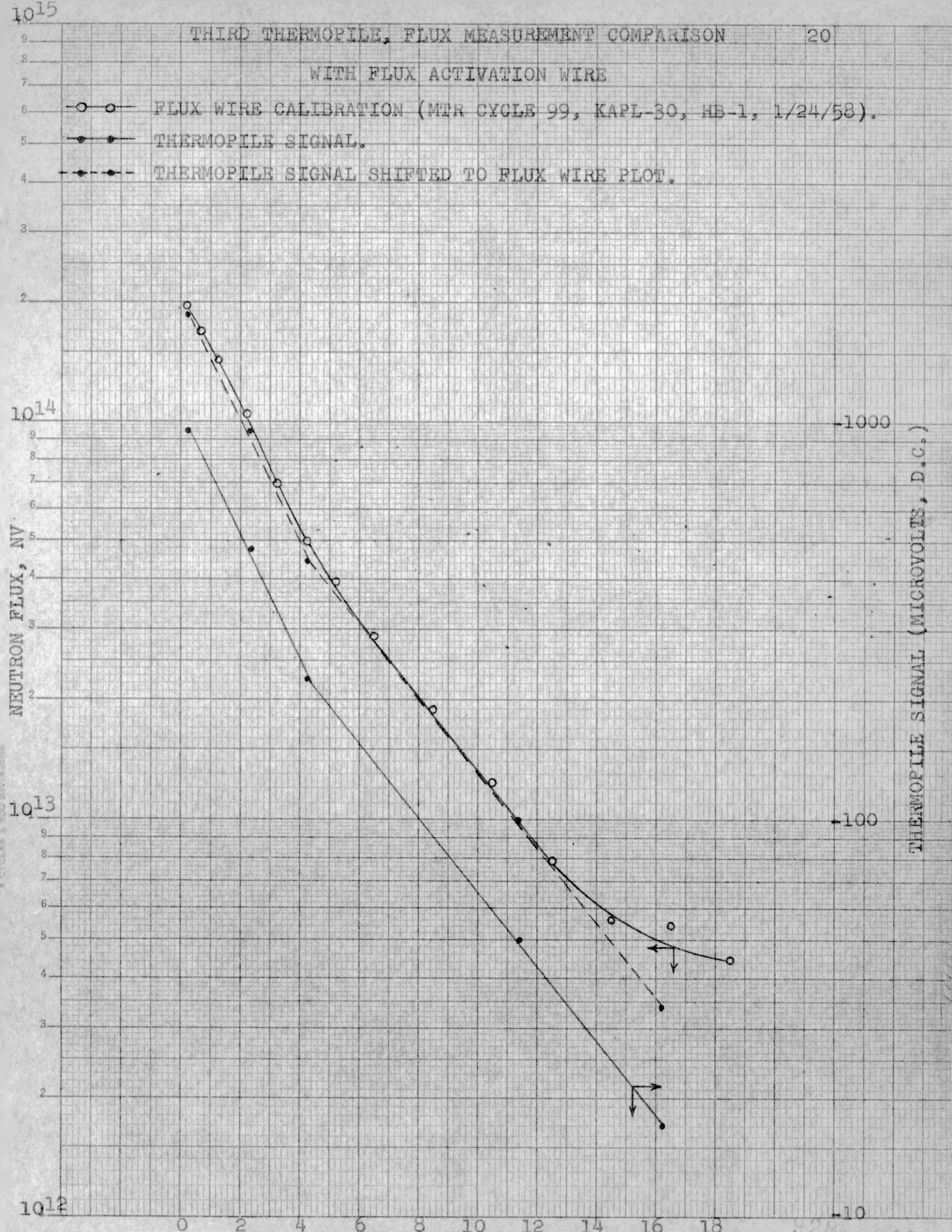

THIRD THERMOPILE, FLUX MEASUREMENT COMPARISON
WITH FLUX ACTIVATION WIRE
FLUX WIRE CALIBRATION (MTR CYCLE 99, KAPL-30, HB-1, 1/24/58).
THERMOPILE SIGNAL.
THERMOPILE SIGNAL SHIFTED TO FLUX WIRE PLOT.
NEUTRON FLUX, NV
THERMOPILE SIGNAL (MICROVOLTS, D.C.)
POSITION IN FLUX TUBE
10^{15}
10^{14}
10^{13}
10^{12}
1000
100
10
0
2
4
6
8
10
12
14
16
18
SEMI-LOGARITHMIC
KEUFFEL & ESSER CO.
359-73LG

Figure 5

THIRD THERMOPILE, RESPONSE TO LARGE CHANGE OF NEUTRON FLUX

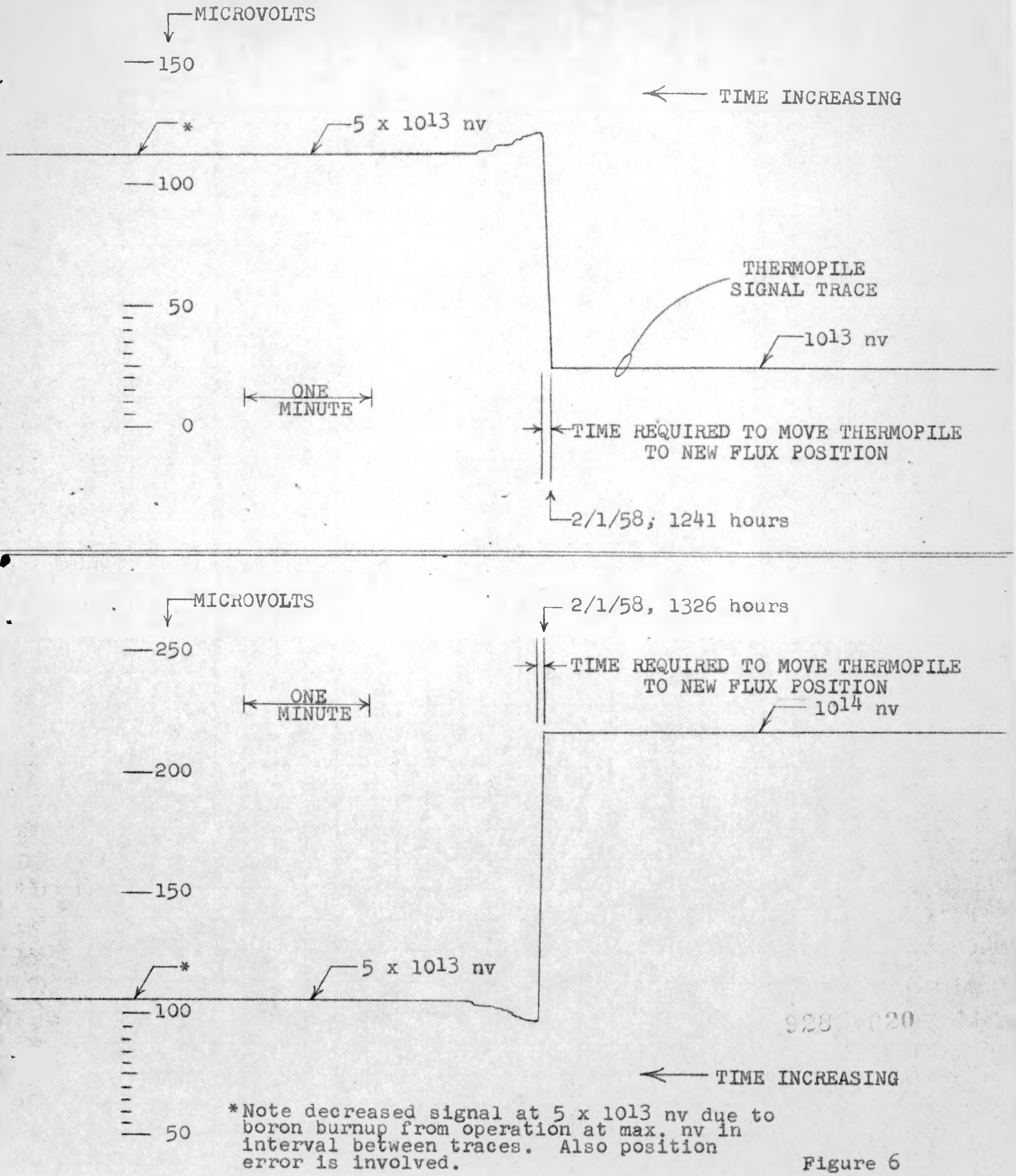


Figure 6

PERFORMANCE OF THIRD THERMOPILE TESTED AT MTR

1-31-58

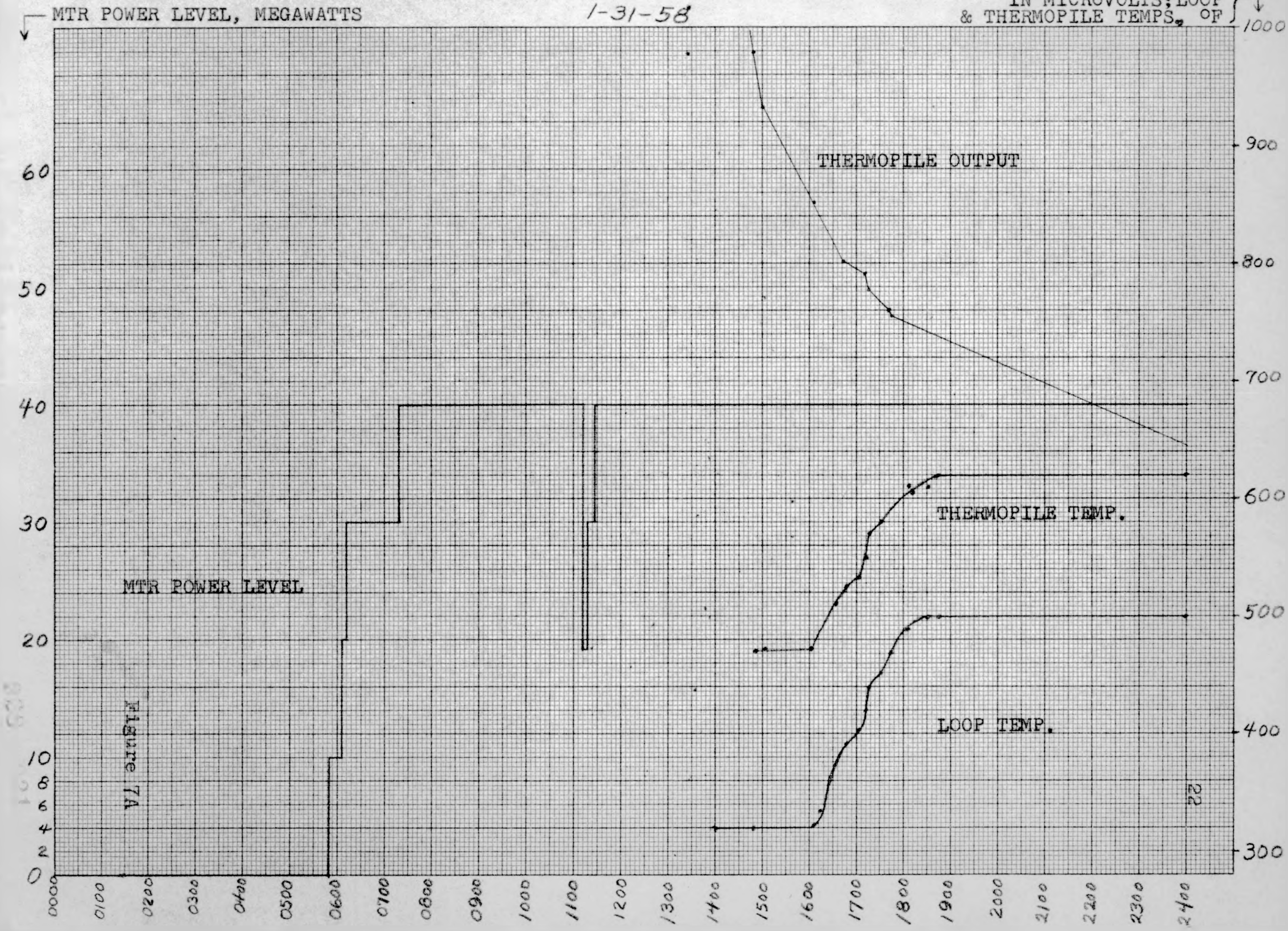


Figure 7A

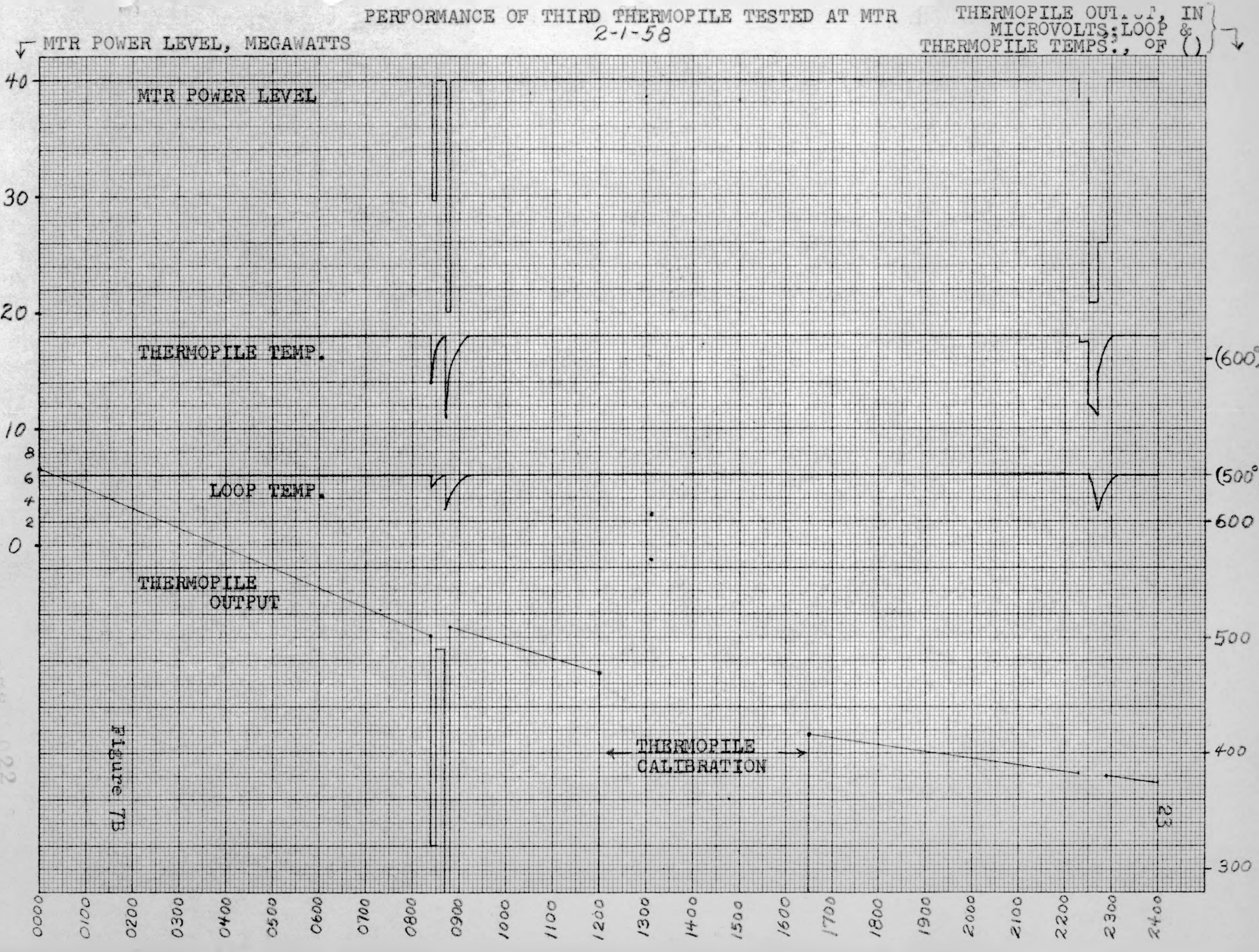

PERFORMANCE OF THIRD THERMOPILE TESTED AT MTR
2-1-58
MTR POWER LEVEL, MEGAWATTS
THERMOPILE OUTPUT, IN MICROVOLTS; LOOP & THERMOPILE TEMPS., °F ()
MTR POWER LEVEL
THERMOPILE TEMP.
LOOP TEMP.
THERMOPILE OUTPUT
THERMOPILE CALIBRATION
40
30
20
10
8
6
4
2
0
(600°)
(500°)
600
500
400
300
0000
0100
0200
0300
0400
0500
0600
0700
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400

Figure 7B

PERFORMANCE OF THIRD THERMOPILE TESTED AT MTR

2-2-58

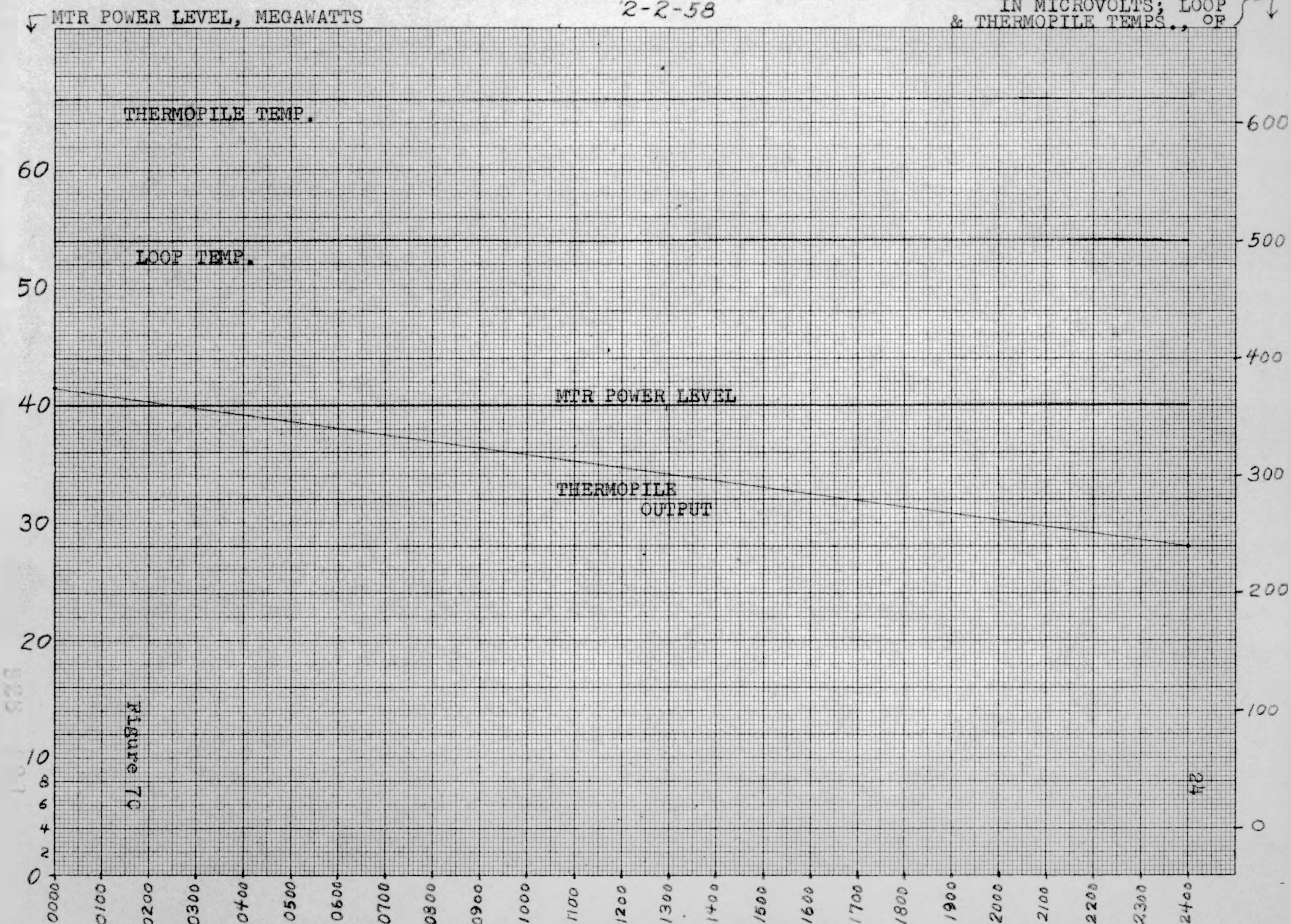


Figure 7C

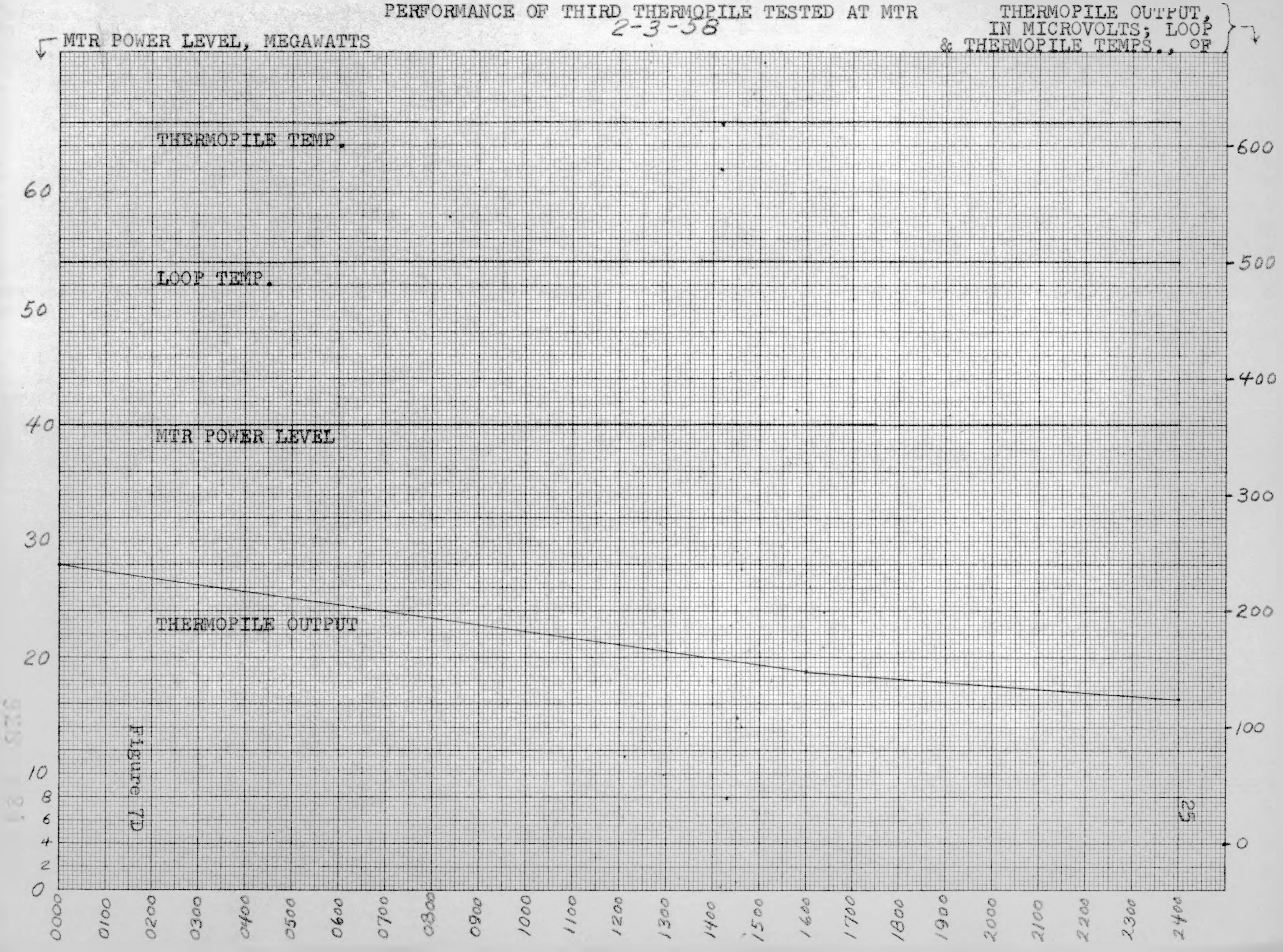
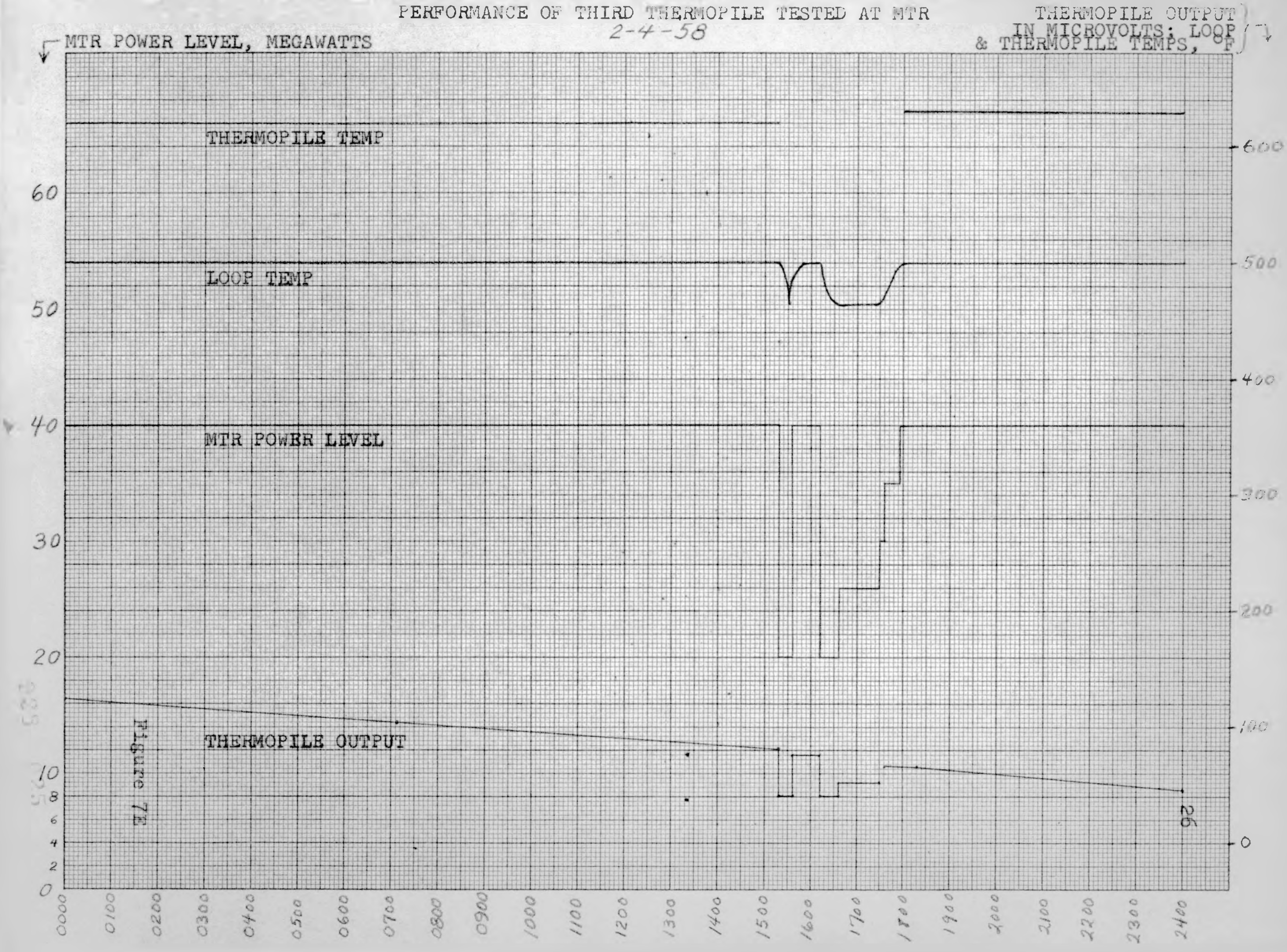

PERFORMANCE OF THIRD THERMOPILE TESTED AT MTR
2-3-58
MTR POWER LEVEL, MEGAWATTS
THERMOPILE OUTPUT, IN MICROVOLTS; LOOP & THERMOPILE TEMPS., OF
THERMOPILE TEMP.
LOOP TEMP.
MTR POWER LEVEL
THERMOPILE OUTPUT
0 2 4 6 8 10 20 30 40 50 60
0 100 200 300 400 500 600
0000 0100 0200 0300 0400 0500 0600 0700 0800 0900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400

Figure 7D



PERFORMANCE OF THIRD THERMOPILE TESTED AT MTR
2-4-58
MTR POWER LEVEL, MEGAWATTS
THERMOPILE OUTPUT IN MICROVOLTS: LOOP & THERMOPILE TEMPS, °F
THERMOPILE TEMP
LOOP TEMP
MTR POWER LEVEL
THERMOPILE OUTPUT
Figure 7E
60
50
40
30
20
10
8
6
4
2
0
600
500
400
300
200
100
0
0000
0100
0200
0300
0400
0500
0600
0700
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400

26

PERFORMANCE OF THIRD THERMOPILE TESTED AT MTR
2-5-58

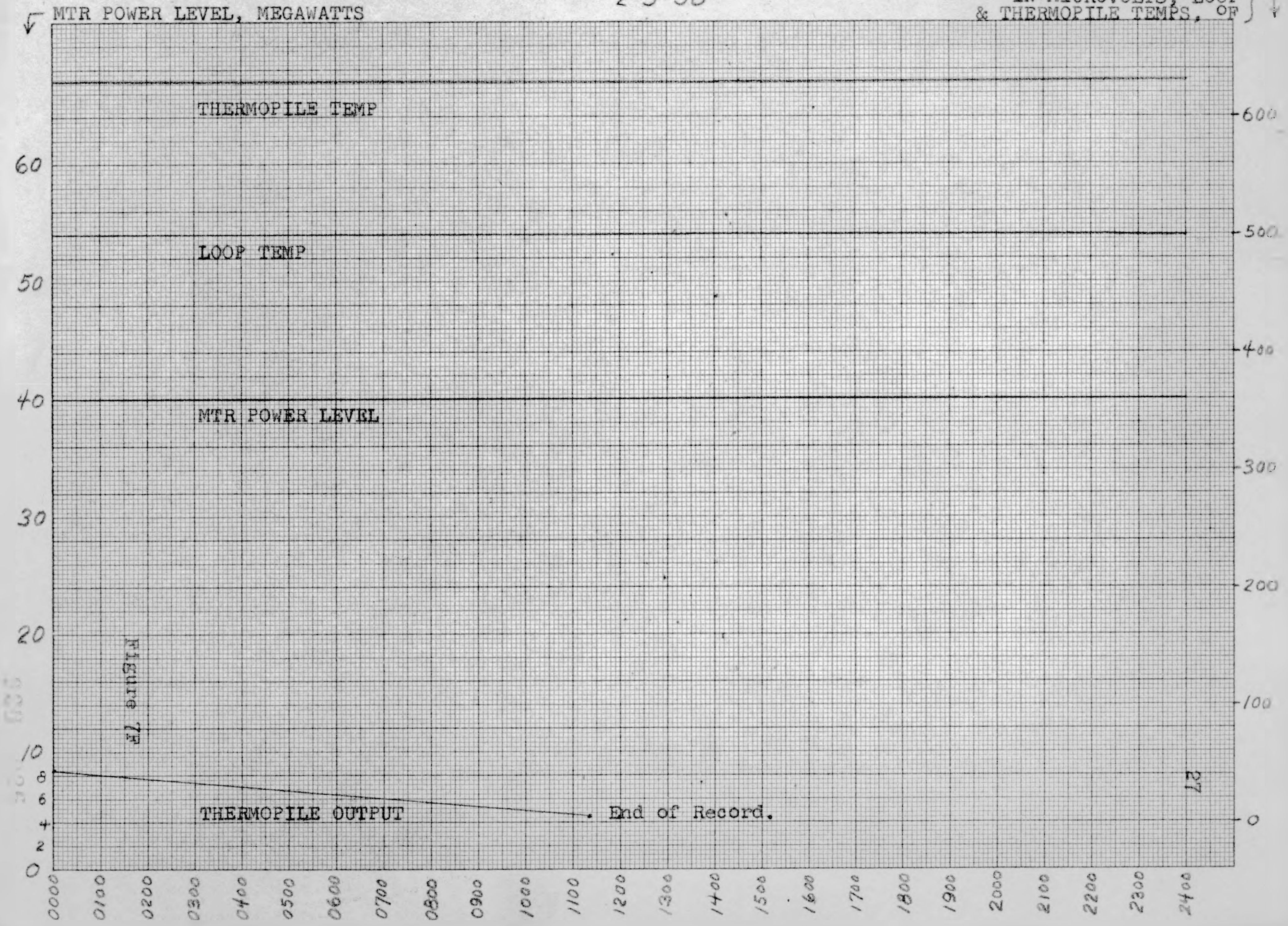


Figure 7F