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TL282

AN INVESTIGATION OF SOME OF THE CIRCUMSTANCES PERTINENT TO THE ACCIDENT TO THE NRX REACTOR OF DECEMBER 12, 1952

NEI-26

BY

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[redacted]

CHALK RIVER, ONTARIO

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AN INVESTIGATION OF SOME OF THE CIRCUMSTANCES PERTINENT TO THE ACCIDENT TO THE NRX REACTOR OF DECEMBER 12, 1952

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ABSTRACT

A study has been made of various instrument records in conjunction with verbal reports in an attempt to reach conclusions as to the circumstances leading to the accident and some of the consequences. The report is divided into four parts concerning:

(a) the shut-off rods.
(b) the power transient.
(c) the gasholder
(d) the recordings of other instruments.

The results are summarized at the beginning of each part.

These investigations are not necessarily complete, nor do they cover more than a small part of the consequences of the accident. They are based on information readily available up to the time of writing. Further data must await disassembly of various parts of the reactor structure, and the completion of other investigations underway.

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Introduction

On December 12, 1952 critical height measurements were being made using the NRX reactor to assess changes in reactivity due to the prolonged irradiation of uranium fuel elements. In order to reproduce the vertical flux distribution obtained during normal operation, when the reactor is loaded with "short" lived Xenon poison, the reactor was loaded with the six middle ring shut-off rods. This allowed the polymer to be brought up to a level approaching the normal operating level without the reactor becoming critical. During the morning it was found that the critical level was substantially less than the desired level and did not correspond with either the operating level or the level used in previous measurements. This lower critical height is attributed to an increase in the number of fuel elements with "thin" cooling water annuli loaded into the reacting core. Consequently it was decided to load the reactor further with one outer ring shut-off rod. To do this it was necessary to make changes in settings of the valves supplying cooling and lifting air to the rods.

All the shut-off rods were dropped into the reactor and an agreed procedure begun for raising the desired rod. The first step involved restoring all valve settings to normal. During this step a number of rods were raised by incorrect manipulation of the valves. The mistake was promptly corrected and all rods were believed to have been returned to the "down" position. In attempting to raise the two inner ring rods, all four rods in the first bank were inadvertently raised without accelerating air being available in the head gear. Nonetheless, the reactor should not have gone overcritical. It did in fact do so and the power began to rise rapidly. The electrical circuit holding the rods was promptly opened manually before the power became significant. Although these rods had been raised without accelerating air being available at the head gear they should have fallen under gravity. The indicating lights showed that only two of the rods

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left the head gear. The power rise was not checked and continued until the polymer dump valves were opened. By this time the reactor had been damaged.

This introduction is not intended to be a critical review of the events leading to the accident, but rather to orient the reader for a better understanding of the material in the body of the report.

Figure 9 is appended to show the geometry of the reactor and indicate the locations of the various rods and instruments discussed.

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PART I - THE SHUT-OFF RODS

Summary

A study has been made of the shut-off rod position record from E-7-H-25 and of the records of the currents from special ion chambers in the north and south thermal columns.

These records are not inconsistent with the conclusion that certain shut-off rods were up immediately prior to the accident which were not so indicated at the control desk. The reactor was approximately 12 mk closer to critical than it was thought to be (at the time of the accident). Consequently, when the first bank of shut-off rods was raised, the reactor went overcritical by about 6 mk.

It is concluded that the shut-off rods J-3 and C-9 were up and that M-24 was partially or wholly up. The positions of these rods is attributed to the manipulation of various valves controlling the cooling and lifting air. No explanation is offered as to why the rods remained up after the valve settings were restored to normal.

A further contributory cause of the accident was the failure of all four of the rods in the first bank of rods to fall promptly under gravity. The holding circuit was broken before the reactor reached a significant power. Only rod M-6 fell into the reactor, falling slowly and taking one and a half minutes to reach the bottom.

It is the purpose of this part of the report to attempt to determine the positions of the shut-off rods immediately prior to and during the accident. The records from the shut-off rod position recorder E-7-H-25 and records of the reactor power level, obtained from special ion chambers located in the north and south thermal columns have been examined.

The Shut-Off Rod Position Recorder, E-7-H-25

The positions of the shut-off rods are indicated by limit switches which are actuated by the rod at the ends of the travel. The lower switches actuate the pens of a multipen Esterline Angus recorder E-7-H-25 and a row of green lights on the control desk. Consequently, the recorder and the green lights indicate when rods are in the "down" position. A corresponding row of red lights on the control desk is actuated by the upper limit switches and indicate rods in the "up" position. The indication given by the lower limit switches is known to be unreliable.

The record from E-7-H-25 for the day of the accident and for a period of a week previous to the accident has been studied in conjunction with verbal reports. This study has been made in order to determine the positions of the shut-off rods during December 12th and to assess the reliability of the conclusions. A summary of the record for the period December 5 to December 13, 1952 is given in Table I except for a six-hour interval on December 5. During this interval several attempts were made to start up the reactor and adjustments were made to rods J-3, C-9, Q-9 and J-27.

The table gives the time * of every change of any one of the recorder pens and under "remarks" is listed the event, if known, that probably caused the change.

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* A check was made on the timing of the twelve pens of the shut-off rod recorder (E-7-H-25) by actuating all the pens simultaneously, and it was found that

- pens 8, 9, 10, 11, 14, 17, 18 gave the same time scale reading.
- pens 12, 15, 16 read half a minute late compared to pen 9.
- pen 7 reads one minute late compared to pen 9.
- pen 13 reads one minute early compared to pen 9.

The time reading of pen 9 has been used as the reference time.

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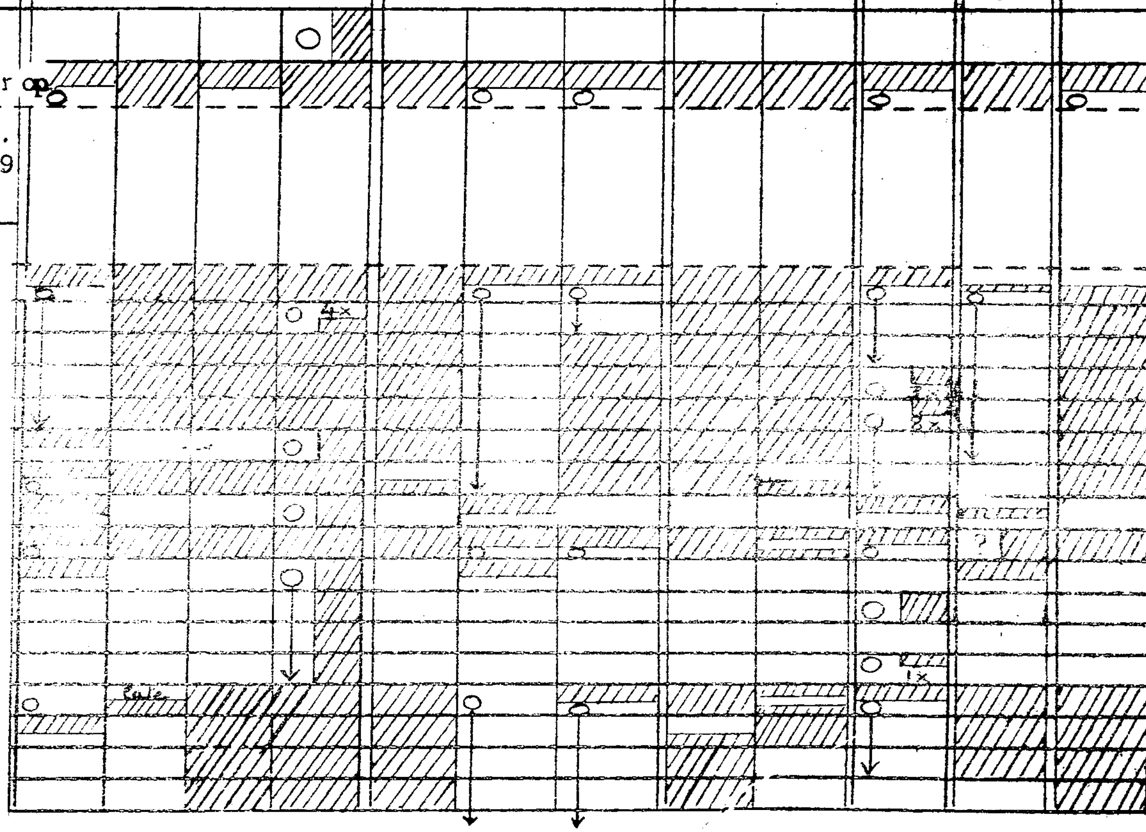
TABLE I

SHUT-OFF ROD POSITIONS AS GIVEN BY E-7-H-25

Recorder Pen Number	7	8	9	10	11	12	13	14	15	16	17	18
Shut-off Rod Ring*	I	I	M	M	M	M	M	M	O	O	O	O
	F-12	M-18	M-6	F-24	Q-15	F-6	C-15	M-24	J-3	C-9	Q-9	J-27
Bank No.	1				2			3		4	5	6

Date	Time	Remarks
Dec.5/52	09.13	Final full power operation
	09.14	Trip following final full power op.
		Several start-up attempts made. J-3 headgear changed, C-9 & Q-9 swabbed and J-27 replaced
Dec.5/52	15.29	Trip from "zero power" after shut-off rod adjustments
Dec.6/52	1 & 2 shifts	
Dec.9/52	05.00	
Dec.10/52	1 shift	
Dec.11/52	2 shift	
	11.49	First bank up
	11.58	First bank down
	13.41	Shut-off rods up
	22.35	Shut-down after C.H.M.No.1
	23.22	Shut-off rods up
Dec.12/52	01.20	
	01.38	
	03.40	
	05.57	Shut-down after C.H.M.No.2A
	10.03	F-12 and M-18 raised
	10.13	J-3 raised
	10.18.5	(C-9 up)** Q-9 raised



* "I" refers to inner, "M" refers to middle and "O" refers to outer

** Events appearing in brackets probably occurred, but pens do not verify.

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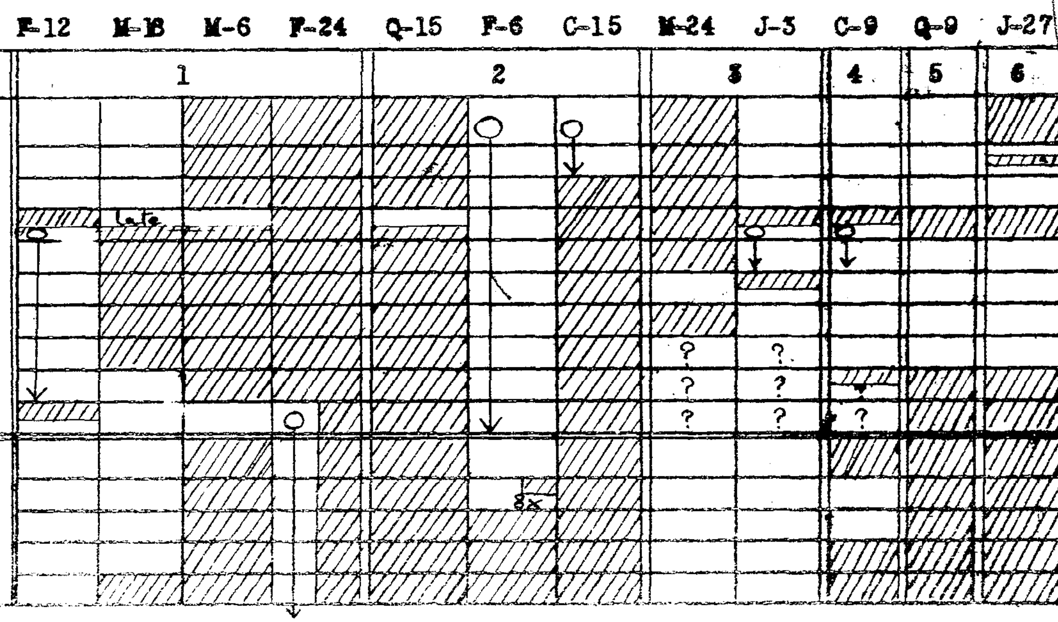
TABLE I (continued)

Date	Time	Remarks
Dec.12/52	10.18.5	(C-9 up) Q-9 raised
	10.20	J-27 raised
	12.53	C-15 probably dropped about 1"
	14.21	Shut-down
	14.36	By-pass valves of banks 6 & 5 opened
	14.37	By-pass valve of bank (4) 3 opened
	14.42	
	14.54	
	14.55	
	15.07	First bank raised
	15.08.5	M-6 arrived at down position
	18.34	
	19.28	
Dec.13/52	05.35	
	22.57	



Code used in Reproduction of E-7-H-25 Recording

Pen registering (shut-off rod down)

Pen not registering and described as being "off" (shut-off rod up)

Pen has been off, has registered, but has immediately gone off again

Pen has been registering, has gone off, but has immediately registered again

Pen has registered approximately three minutes after event is thought to have taken place.

Pen has been off, has registered, but has immediately gone off again four times.

Pen has been registering, has gone off, but has immediately registered again four times

* Pen has been off, has registered has gone off, but has immediately registered again.

* Pen has been registering, has gone off, has registered, but has immediately gone off again.

Recording smudged by ink, but pen probably registering.

Pen registering at a time when it should not be according to "remark" column.

** Pen not registering at a time when it would be according to "remark" column.

Indicates doubt regarding the status of the shut-off rod.

** This symbol has also been used in combination with the remainder of the code.
* This occurrence is probably due to a "bouncing" effect and is not indicated as an inconsistency.

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The following conclusions may be drawn from the Table as to the positions of the rods immediately prior to 15.07 hours:

Almost certainly down:	M-18, M-6, Q-15, C-15, Q-9, J-27
Probably down:	F-12, F-6
No reason to suspect up:	F-24
Either up or down:	C-9
Probably up:	M-24
Almost certainly up:	J-3

The basis for these conclusions is detailed in the Appendix.

Furthermore it should be noted that although the holding circuits were tripped a few seconds after raising the first bank at 15.07 hours, only one rod returned to the bottom, M-6, and as indicated by the recorder, did not arrive there until 15.08.5 hours.

The North and South Thermal Column Ion Chamber Recordings

These instruments were installed for accurate measurement of the reactor power level during the critical height measurements. They are described in more detail in Part II.

The section of these records covering the interval following the shut-down from the preceding critical height measurements up to the accident is reproduced in figure 1. These reproductions represent analyses of the records using a travelling microscope. Since the pen deflections of the recorders only amounted to a few millimetres, they should be regarded with some reserve, particularly since the zero corrections are uncertain. However, essentially all the changes in the power level can be accounted for, from the information given by E-7-H-25, by shut-off rods rising and falling. It is to be pointed out that the magnitude of the changes are not necessarily the same for each record. This can be attributed to distortions in the flux distribution by the rods.

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Also it has been necessary to make some small adjustments in the relative time scales of the records in order to correlate events.

There is no reason to believe that the low point of these records at 14.30 hours did not represent a condition of the reactor similar to that at 05.57 hours and almost certainly (see Appendix) one in which all the shut-off rods and the control rod were down. Consequently, it is evident that all the rods were not down immediately before 15.07 hours.

It is known from the power level preceding the 14.21 hours shut-down that the reactor was approximately 0.3 mk under-critical with the two inner and four outer ring shut-off rods and the control rod up. The reactivity figures for these rods given in Table II (Part II) indicate that the reactor was 36 mk under-critical at 14.30 hours.

Using the expression

$$\text{Power} = \frac{\text{Source strength}}{\text{Reactivity less than critical}}$$

it can be deduced from the north and south thermal power levels at 15.00 hours that the reactor was approximately 5 to 8 and 10 to 12 mk respectively closer to critical than it was at 14.30 hours. The discrepancies can be readily accounted for by uncertainties in the zero errors of the records and by flux distortions in the reactor.

Discussion

The following sequence of events is proposed which summarizes the discussion above and which is consistent with the observations related in Part II of this report.

(1) At 14.21 hours December 12, 1952 the trip shut-down caused two inner and four outer shut-off rods to come down so that all twelve shut-off rods were almost certainly down.

(2) At 14.36 hours the by-pass valves of banks 6 and 5 were opened and shut-off rods J-27 and Q-9 rose.

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(3) Probably the by-pass valve of bank 4 was then opened and C-9 rose.

(4) At 14.37 hours the by-pass valve of bank 3 was possibly opened and J-3 almost certainly rose and stayed up; M-24 seems to have risen, at least partially, even though it was reported that the valve in the air line leading to the base of the rod might have been closed at this time. M-24 then seems to have been fully down at 14.42 hours, but to have left the bottom again at 14.54 hours. The thermal column recordings *, however, tend to suggest that M-24 may not have gone completely up, since both recordings show a much smaller rise at 14.54 hours than fall at 14.42 hours. Although there is no permanent recording for the red shut-off lights, several red lights in banks 6, 5, 4 or 3 were seen to come on at a time appropriate to the above sequence.

(5) At 14.55 hours the by-pass valves of banks 6, 5, 4 and very probably 3, were closed. J-27 and Q-9 fell down completely. The pen recorder would suggest C-9 fell completely and then possibly rose again. Both thermal column records tendto suggest that C-9 never fell at all therefore the pen registration might have been spurious, or that, if it did fall, it immediately rose again. J-3 showed no indication of having fallen, an event consistent with the behaviour of J-3 reported from a test made on December 31, 1952. M-24 likewise, showed no indication of having fallen and very probably stayed up or partially up; an event unlike the behaviour of M-24 reported from the December 31 test. Inferences drawn from this test, however, are questionable.

If then, immediately previous to 15.07 hours outer ring shut-off rods C-9 and J-3 and middle ring shut-off rod M-24 were up, the reactor would be only 24.5 mk below critical (see Table II) rather than the 36 mk that it was considered to be. The fact

* The time setting of the charts was not sufficiently correct to permit comparisons between charts without first meshing the events to obtain a reasonable fit.

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that there was some evidence that M-24 was only partially up would mean that the reactor was somewhat more than 24.5 mk undercritical.

(6) At 15.07 hours the first bank of shut-off rods, F-12, M-18, M-6, F-24, was lifted, (the red lights of these rods were seen to come on) and the reactor went not more than 6 mk overcritical.

(7) A few seconds after the first bank was lifted the manual trip switch was operated. The red lights of M-6 and F-24 were seen to go off.

(8) At 15.08·5 hours, December 12, the pen recorder of M-6 registered. Since the previous history shows no irregularities for this pen it is probable that M-6 had been falling slowly, and finally reached the bottom at 15.08·5 hours. Later investigation showed that F-24 had left the head gear, but had stuck and not entered the reactor.

At 15.08·5 hours the pen recorder of C-9 also registered. Since the previous history of this pen shows considerable irregularities, not too much reliance can be placed on this particular event. However, there is the possibility that C-9 came down at this time.

The slow falling of M-6 is sufficient to account for the decrease in overcriticality approximately twenty seconds after 15.07 hours.

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APPENDIX

From past operations it is known that the pen recordings of E-7-H-25 (and likewise the green lights) do not give reliable information about the location of the shut-off rods. Table I shows that few rods have no inconsistencies between December 5 and December 12, 1952. In the following analysis irregularities are listed and an attempt is made to indicate the probable positions of each shut-off rod immediately before the first bank was raised at 15.07 hours, December 12, 1952. Momentary inconsistencies occurring when a rod either rises or falls, which are attributed to the shut-off rod "bouncing" are not indicated in Table I nor mentioned below.

F-12 On five out of six shut-downs the pen immediately registered, but promptly went off * owing to "bouncing" of the rod. On the remaining occasion there was no registration by the pen at all.

Conclusion: F-12 was probably down.

M-18 No irregularities occurred except on two shut-downs, when the rod was either slow in falling or slow in falling the last few inches required to operate the microswitch.

Conclusion: M-18 was almost certainly down.

M-6 The only irregularity occurred at the 09.14 hours December 5 shut-down when the pen registered and then immediately went off.

Conclusion: M-6 was almost certainly down.

F-24 With the exception of four times on December 6 that it went off and then on, the pen registered continuously.

Conclusion: There exists no suggestion that F-24 was not down.

Q-15 No irregularities existed.

Conclusion: Q-15 was almost certainly down.

F-6 On three shut-downs the pen registered, but then immediately went off. At the 05.57 hours shut-down and thereafter, when

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* The expression "pen went off" means the microswitch at the base of the rod has opened and the pen was no longer actuated.

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it would be expected to do so, the pen showed no registration. If F-6 never came down as indicated by the pen recording, the estimates of reactivity would not be altered since they are based on the critical height determined previous to 14.21 hours and the situation immediately before the accident. Only if F-6 was down until 14.21 hours and then rose before the accident, would there be any change in the reactivity estimates. There is no reason to believe that the changes in valve settings that took place during this interval or were contemplated, would have affected the position of this rod; nor is there an indication in the thermal column records of such an occurrence.

On the other hand, the approximate critical weir box height of 261 cms. obtained previous to 14.21 hours December 12, 1952 is 7 cms. less than the height of 284 cms. for the March 1952 measurements (CRGP-508) if corrected for the increase in number of X-rods with "thin" water cooling annuli, for the air cooling on one X-rod, for the presence of an X-rod in F-18, and for the general "aging" with irradiation (CRGP-508) of all X-rods. This disagreement, along with other factors for which no corrections have been made, such as change in the swelling of irradiated X-rods, is not thought to be sufficient to suggest any change in status of the shut-off rods for the two measurements. If the rod did not come down at 05.57 hours, it was probably not down during the March 1952 critical height measurements, an unlikely coincidence.

Conclusion: F-6 was probably down.

C-15 At the shut-downs the pen consistently registered and then immediately went off. In the case of the 05.57 hours December 12 shut-down, the pen registered again at 12.53 hours, i.e. some seven hours later. Since there was at the same time a very slight fluctuation on the thermal column ion chamber recordings, the possibility that at 12.53 hours C-15 fell, perhaps the "last inch", was suggested.

Conclusion: C-15 was almost certainly down.

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M-24 No irregularities seemed to have existed. On December 12 the pen indicated the rod was lifted at 14.37 hours, was down at 14.42 hours and was up again at 14.54 hours.
Conclusion: Since the pen showed no previous irragularities, there is no reason to think that M-24 probably was not up.

J-3 No irregularities existed until the 14.21 hours shut-down at which time the pen registered and then went off. At 14.37 hours the pen registered and then went off, suggesting the rod had risen. There was no indication later that it ever came down.
Conclusion: J-3 was almost certainly up.

C-9 The history of this rod shows its pen had been very erratic, for during most of the time when the rod was down the pen was off, and on two occasions when the rod was up the pen registered. However, the pen consistently registered and then went off whenever there was a shut-down, and once registered and went off when the rod was lifted. Thus, from the history of the pen the momentary indication at 14.55 hours could indicate that the rod fell down, or rose, or fell down momentarily and then rose again; or did not move at all.
Conclusion: C-9 could have been either down or up.

Q-9 The only irregularity occurred at the 15.29 hours, December 5 shut-down (from "zero" power) when the pen which had been registering owing to the rod having possibly been left down after swabbing, went off, registered and then off again. It did not register again until 11.58 hours, December 11, when the first bank was lowered. At 14.36 hours, December 12 the pen indicated the rod was lifted, and at 14.55 hours lowered.
Conclusion: Q-9 was almost certainly down.

J-27 Previous to the 15.29 hours December 5 shut-down (from "zero" power) J-27 had been replaced and the pen was registering possibly owing to the rod having been left down after replacement. At the shut-down the pen went off and then immediately registered; thereafter there was no indication of any irregularity.
Conclusion: J-27 was almost certainly down.

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PART II - THE POWER TRANSIENT

I SUMMARY

The behaviour of three power indicating and two temperature measuring instruments has been investigated in order that some estimates could be made of the behaviour and reactivity of the NRX reactor during the power transient. The instruments and records investigated were (a) power galvanometer E-7-L-104A. (b) the records of the outputs from special ion chambers installed in the thermal columns for measurement purposes during the current reactivity measurements, (c) the record from the power measurement "Micromax" recorder E-7-L-109A and (d) the records of temperature before and after the "polymer cooler" E-5-T-40 and E-5-T-39.

It is suggested that the following conclusions, which are not inconsistent with the facts observed, can be drawn from these investigations.

(i) Before the first bank of shut-off rods (i.e. F-12, M-18, M-6, F-24) were raised the pile was more reactive by about 10 mk than it would have been with all the shut-off rods down.

(ii) When the first bank of shut-off rods was raised the pile went overcritical by about 6 mk and diverged with a doubling time of about two seconds reaching a power of the order of "100 KW" (108A null) *.

(iii) The pile was tripped and only the shut-off rod M-6 fell into the pile. The pile continued to diverge but at a rate decreasing with time in such a way as to suggest it would have levelled off at about "20 MW" (109A). This effect was probably due to M-6 falling slowly into the pile.

(iv) At "17 MW" (109A) boiling occurred in some of the temporarily cooled rods, expelling light water from the pile and increasing the reactivity by at least 2 mk.

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* See discussion for definition of terminology.

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(v) The pile continued to diverge with a period of the order of 10 to 15 seconds and reached a power between "60 and 90 MW" (109A) when it was checked by opening the polymer dump valves.

(vi) The pile power was greater than "10 KW" (N.T.C.) for a time less than 170 seconds and greater than "1 MW" (109A) for less than 70 seconds.

(vii) No reliable estimate can be made of the integrated power during the transient.

II POWER GALVANOMETER E-7-L-104A

This galvanometer is located at the lower right hand side of the panel at the back of the control desk and measures the current from an ion chamber located in a tangential hole on the north side of the pile at an elevation of 274 cms. from the bottom of the calandria. The galvanometer shunt was set on range 1 giving a nominal full scale deflection 50 cms. at 25 MW (weir box 280 cms.).

The behaviour of this galvanometer as a ballistic instrument was considered. The galvanometer was observed to be critically damped and to take about two seconds to reach equilibrium when a steady current sufficient to produce full scale deflection was applied. It was concluded that the galvanometer did not behave in a ballistic fashion during the power transient, and followed the power indicated by its associated ion chamber reasonably well.

The motion of the light spot on the scale was observed by at least seven persons. They were asked independently to attempt to reproduce the motion of the spot to the best of their recollections by operating a potentiometer supplying a variable current to the galvanometer. (In general the time for the spot to travel from 20 to 40 cms. was timed by another observer using a stop watch). These tests were carried out at nine to fifteen

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days after the incident.

The time for the pile power to double obtained by this method was given remarkably consistently by each observer but ranged from 2 to 17 seconds as given by different persons. The majority opinion favoured the longer times, and, for what this investigation is worth, it is suggested that the time for the pile power to double in this region lay in the range of 10 to 15 seconds.

The polymer dump was initiated just before the galvanometer spot went off scale. It is variously estimated that the spot was off scale for from two to ten seconds.

Some opinion is that this galvanometer did not go very far off scale which would indicate from the nominal sensitivity of the instrument that the pile power did not much exceed "30 MW" (109A). This is not in agreement with the evidence given by E-7-L-109A. It is suggested that the sensitivity was suppressed by the shielding effect of shut-off rods in the pile and by the "low" weir box setting,* and that the upper end of the galvanometer motion can be correlated with the final part of the transient which has been assigned to that period when some of the cooling water had been expelled.

A doubling time of 10 to 15 seconds requires a positive reactivity of 2.3 to 2.9 mk.

III POWER RECORDS GIVEN BY SPECIAL ION CHAMBERS LOCATED IN THE THERMAL COLUMNS

A boron coated TQT ion chamber was inserted into each thermal column to give accurate indication of pile power during the current reactivity measurements. One of these chambers (the south) was backed off by an uncoated chamber to balance out any

* Records of the readings as a function of the weir box setting at a constant pile power showed that the sensitivity would be reduced by about 10% at 260 cms. height.

gamma ray effects. It was confirmed that, as expected, the gamma ray effects were negligible. Each neutron chamber was connected to an AEP 1478 D.C. amplifier located in the control room. Each amplifier had a range of input resistors available by switching. The output voltage from the final cathode of the amplifiers was fed via potential dividers to recording millivoltmeters. A smoothing time constant of about five seconds was incorporated in the potential dividers. The ion chambers were estimated to yield a current of 10^{-4} amps at 30 MW. The north thermal column instrument was a Minneapolis-Honeywell "Electronik" recorder, operating with a chart speed of four inches per hour, and the south thermal column a Leeds and Northrup "Speedomax" with a chart speed of one inch per hour. At the time of the incident, the amplifiers were operating on a range giving a full scale deflection at the order of 10 KW pile power.

The general nature of the records during the power transient is shown by accompanying photostat reproductions. The pile power, initially of the order of 100 watts, rose rapidly to greater than "10 KW", and about 170 seconds later fell back rapidly below "10 KW". In order to obtain any useful information concerning the rate of rise of pile power, it was necessary to examine these records with a travelling microscope. The position of each edge of the record trace and each edge of the nearest time index line was measured for various deflections on the chart. A value was then obtained for the centre to centre distance between the trace and time index used, at various deflections of the pen. In each case the results indicated that the recorder pens travelled at a constant speed across the chart. The transit times obtained from the known chart speeds were 29.8 and 71 seconds for the north and south thermal column instruments respectively. Although the south thermal column recorder itself was much faster than the other, the longer transit time is attributed to time constant effects in the associated equipment and inaccuracies in the chart. The matter has not been investigated further.

The north thermal column recorder was taken for further investigation. The analysis described above is presented in figure 2. The actual D.C. amplifier and recorder used were removed from the control room and set up alongside the electronic pile analogue. The output power indication from the analogue is in the form of a voltage up to a maximum of 200 volts. This was converted to an effective infinite impedance constant current source simulating an ion chamber by feeding the voltage to the D.C. amplifier input through a $2 \times 10^8 \Omega$ resistor. The impedance conditions were satisfied on the range used during the power transient since the input impedance was $5 \times 10^8 \Omega$/gain of feedback $= 5 \times 10^5 \Omega$. The input was loaded with 3000 pf, the estimated capacity load in the pile installation. In this way it was hoped that all time constant effects were reproduced.

In the first instance a number of power transients were simulated by suddenly unbalancing the D.C. amplifier, thus presenting the recorder with a gross overload signal. The transit time of the pen was found to be 20.4 seconds consistently. The traces obtained were analysed by the method described and plotted in the same manner as figure 1. Each analysis gave essentially a straight line but the transit time deduced varied from 22.8 to 37.2 seconds as compared with the directly measured time of 20.4 seconds. A typical analysis giving a transit time of 26.5 seconds is shown in figure 3. It is believed that this spread of deduced times originated from lack of perpendicularity and variation of the angle between the time and deflection axes of the recorder within the scale of measurements. This is not surprising.

It is concluded that figure 2 indicated that the pen travelled at its maximum rate across the chart, probably with a transit time of 20.4 seconds.

The pile analogue was set up to attempt to place a limiting value on the pile reactivity during the initial rise in

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power. A continuously variable control worth 30 mk positive was added to the normal analogue controls in order to simulate the first bank of shut-off rods. The recorder chart speed was increased to twenty-four inches per hour to obtain accurate and readily interpretable records. The step reactivity controls of the analogue were set so that as the "shut-off rod" control was brought to maximum reactivity, the "pile" would become overcritical of various known amounts. The proper initial power was set in within an accuracy of about twenty per cent. To simulate the lifting of the first bank of shut-off rods, the continuous control was turned from minimum to maximum manually in an estimated time of two seconds and in a roughly linear fashion. The "pile" was then allowed to diverge until the recorder reached full scale, and the "true" behaviour of the power as indicated by the analogue output meter observed meanwhile. A series of runs was taken for various amounts overcritical and the results are shown in figure 4. Figure 5 has been obtained from the behaviour of the analogue output meter and added to show the actual rates at which the "pile" power rose in comparison with the recorder.

It is concluded from comparison between figures 2 and 4 that the pile went at least 6 mk overcritical when the first bank of shut-off rods was raised with the consequent doubling time of power less than two seconds.

IV PILE POWER RECORDER E-7-L-109A

This instrument is a Leeds and Northrup "Micromax" recorder set up to record 1 m.a. current full scale. It is connected to a unique, partially fedback D.C. amplifier located at the pile face. The associated ion chamber is located in a tangential hole at the south side of the pile at an elevation of 111.5 cms. above the bottom of the calandria. The full scale deflection normally corresponds to a pile power of 60 MW (weir box at approximately 280 cms.).

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The record of the power transient consisted of a barely inked broken line and an attempt to analyse it by the method given above proved unsatisfactory indicating an excessive tilt of the instrument axes compared with the width of the transient. However, examination of the trace showed that the stationary positions of the pen during successive attempts made by the instrument servo-mechanism, to achieve balance, could be readily distinguished. Since the time intervals between successive balance attempts is well defined a very good plot could be made of instrument reading against time. This is shown in figure 6.

The initial portion of the rise indicates that the pile power was beginning to level off when the power rose above a level of about "15 MW" (109A). However, a sudden change in the rate of rise occurred at "17 MW" (109A), and the recorder rose linearly at its maximum rate to full scale and then returned most of the way down at maximum rate. (This was confirmed by investigation of the recorder behaviour). The change in the rate of rise indicates a sudden increase in reactivity and was probably due to expulsion of water from some of the X-rod cooling channels.

The recorder and its associated amplifier were removed from the pile building and set up beside the pile analogue. Investigation of the amplifier circuit showed that approximation to an equivalent ion chamber source from the analogue could not be readily reached. The response of the amplifier to transient input signals showed that the overriding time constant lay in the recorder. The output of the analogue was consequently fed directly to the recorder. The chart speed was increased to three inches per minute. In order to estimate the reactivity increase which occurred at "17 MW" (109A), the analogue was brought to critical and levelled off at this indicated level on the recorder. The reactivity was then increased by a known amount and the "pile" allowed to diverge. This was repeated for varying amounts of excess reactivity. The results of these runs are plotted in figure 6. For an excess reactivity of 2.5 mk or greater the recorder ran up at its maximum rate. It is concluded that the increase of reactivity was 2.5 mk or greater.

One point which may be significant showed up on these tests. If sufficient overload signal were applied to the recorder, the needle of the balance indicating galvanometer would jam and the recorder remain at full scale deflection after the signal was removed and until the galvanometer movement was freed. The amount of overload signal required was somewhat dependent upon the existing deflection of the pen during its application but it was shown that a current of 1.5 m.a. or greater would always jam the galvanometer movement. The D.C. amplifier proved capable of delivering this current. If it can be presumed that the adjustment of the recorder had not been disturbed by removal from the pile building it may be concluded that the pile power while exceeding "60 MW" (109A) did not exceed "90 MW" (109A), otherwise the movement would have jammed and the recorder remained at full scale deflection.

It should be noted that the pile power exceeded "1 MW" (109A) for less than sixty-two seconds.

Mr. Clayton has investigated the shape of the lower part of the power rise so that some estimate could be made of the initial reactivity of the pile before the power became significant. If the shape of the rise is attributed to prompt temperature poisoning effect, calculation indicates that at low power the pile was 6.2 mk overcritical. The calculation, however, indicates that the pile would have levelled off at about 100 MW due to prompt temperature poison. Visual inspection of figure 6 suggests that the pile might have levelled off at approximately 25 MW but for the sudden increase in reactivity. It is concluded that the shape of the curve is not attributable to the temperature effect. A much more likely explanation is that the shut-off rod M-6 was falling relatively

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slowly during this period. This is consistent with the observation reported in Part I, that it arrived at the bottom one and a half minutes after the trip. It is intended to make a theoretical investigation of this explananation.

V DISCUSSION

For the purpose of discussion the reactivity values of the control and shut-off rods calculated from data given by Hurst (TecPI-42) using $M^2 = 312\ cm^2$, are given in Table II.

TABLE II

Shut-Off Rod Circle	Reactivity mk
Inner	10.0
Middle	5.3
Outer	3.1
Control rod	3.3 ★

The following time table of events would seem to fit the observations:

(1) With the weir box set at 260 cms., the six middle circle shut-off rods in the pile, and the X-rod G-15 aircooled, it had been shown that the pile was approximately 1 cm. in polymer height, i.e. 0.3 mk, below critical.

(2) The remaining shut-off rods were dropped in at 14.21 hours, and valve changes made to arrange to keep down one more outer shut-off rod. During these valve changes a number of shut-off rods were inadvertently raised and supposedly lowered again. It is evident that at 15.00 hours several still remained up.

(3) During preparations to raise the two inner rods the whole of the first bank was inadvertently raised, i.e. F-12, M-18, M-6 and F-24 at 15.07 hours.

(4) The pile went overcritical by at least 6 mk and began to diverge rapidly.

★ This value is given by the Reactors Branch.

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(5) Before the power reached a significant level the trip circuits were operated but only rod M-6 fell into the pile. (F-24 left the top of the rod assembly but stuck before entering the reacting core).

(6) The pile continued to diverge covering the power range of "1 MW" (109A) to "17 MW" (109A) in less than seventeen seconds. By this time a substantial deflection was observed on the galvanometer E-7-L-104A. The rate of divergence was decreasing at this power level due to M-6 falling relatively slowly during this period.

(7) At "17 MW" (109A) the reactivity suddenly increased by at least 2 mk caused by the expulsion of cooling water from a number of temporarily cooled rods, and the power continued to increase at an enhanced rate for less than a further seventeen seconds.

(8) The galvanometer (E-7-L-104A) deflection increased at a rate indicating the pile to be of the order of 3 mk overcritical.

(9) The polymer dump valves were opened at a power of "25 MW" (104A) and the power continued to rise for a short time and then rapidly fell. The maximum power attained was between "60 MW" (109A) and "90 MW" (109A).

(10) The total time elapsing from the initiation of the transient to the pile power falling to less than "10 KW" (north thermal column) was less than 170 seconds.

The following deductions would appear to fit the facts and the programme above:

(a) In the first instance the pile went overcritical by approximately 6 mk, but not much more than this. At this time the pile was believed to differ from the previous condition when it was known to be 0.3 mk undercritical by:

2 middle shut-off rods out	=	+ 10.6
Control rod in	=	- 3.3
4 outer shut-off rods in	=	- 12.4
Net reactivity change	=	- 4.1 mk

i.e. the pile should still have been well below critical even though all the first bank had been raised. However, the pile did go 6 mk overcritical and was therefore more reactive than expected by $6 + 0.3 + 4.1 = 10.5$ mk.

It is therefore evident that several other shut-off rods were also up which were not so indicated. The amount of reactivity required could have been readily supplied by M-24, J-3 and Q-9 and is not inconsistent with the conclusion given in Part I.

(b) The expulsion of cooling water increased the reactivity by at least 2.5 mk. The value for the reactivity effect of the water is given as 0.28 mk per rod. There are sufficient damaged rods in the pile to readily account for 2.5 mk even if it is supposed that only half the water was expelled from these rods.

It will have been noted that all power levels quoted have been given in inverted commas, together with a note in brackets of the instrument from which they have been taken. There is clearly a discrepancy of a factor of the order two between E-7-L-104A and E-7-L-109A. This is not unexpected in view of the manner in which the pile was loaded. Consequently, any figures stated for overall pile power must be regarded with considerable reserve on three counts.

(a) the pile flux distribution was considerably distorted in azimuth,
(b) there would be a marked radial concentration of power at the inner regions of the pile,
(c) ion chamber 104A was close to the top of the pile.

VI THE INTEGRATED POWER DURING THE TRANSIENT

An attempt was made to obtain a value for the integrated power produced during the transient by investigation of the recorded temperatures of the polymer being circulated through the cooler.

The records are reproduced on the accompanying photostats.

(a) E-5-T-40 - Polymer Temperature Before Cooler

The following is a summary of the behaviour of this temperature:

Chart Time	E-5-T-40
14.30 - 15.00 hours	Temperature constant between 56°-57°. A step rise to 56.8° from 56.3° - similar step rises occur on the other chart and it is believed that this one is not connected with the accident.
15.19 hours + .2 min.	A sharp rise to 61.2° - the rise takes about two minutes.
15.21 hours + .3 min.	Temperature changes from sharp rise to constant. This probably occurred when the circulating pumps were stopped as the polymer was dumped.
15.21 hours + .3 min. to 15.28 hours + .5 min.	Temperature constant at 61.2°, presumably the heated polymer is now static in the cooler - the river cooling water was <u>not</u> flowing in the cooler.
15.28 hours + .5 min.	Sharp spike drop in temperature followed by partial recovery to 60° then rapid exponential like decrease to 47° at 16.00 hours.

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The latter part of the discontinuity due to the accident, i.e. from 15.28 hours on (chart time) is very difficult to explain and is presumably connected with the presence and possible mixing of cold river water. Especially difficult is the drop in temperature of the polymer temperature at the input to the cooler. Note that the temperature after the cooler does not drop in a similar fashion but returns slowly to ambient temperature.

The No. 2 cooler containing the "after" the cooler thermometer, is in the lower header room and would likely be cooled by the presence of the cold river water.

The No. 1 cooler containing the "before" the cooler thermometer is in the No. 2 storage tank room. We have not been able to find any reasonable explanation for the sharp drop in temperature of this cooler at 15.28 hours (chart time).

(b) E-5-T-39 - Polymer Temperature After the Cooler

The following is a summary of the behaviour of the temperature:

Chart Time	E-5-T-39
14.30 - 14.50 hours	Temperature level at 57.3° following a slow increase from 54.7° at 12.00 hours.
14.51 hours	Spike drop to 53.5° and recovery of temperature to 57.2°.
15.01 hours	Sharp drop to 53° and remains there until 15.06 hours.
15.06 hours	Sharp rise to 61.2°. Appears to remain constant for five or six minutes then decreases slowly and smoothly (in contrast to the temperature at input to cooler) and reaches 55° at 18.00 hours.

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The sharp rise in temperature beginning at 15.06 hours (chart time) and 15.19 hours + .2 minutes (chart time T-40) are believed to be a result of the accident, i.e. T-40 chart is considerably off time and T-39 is approximately on time.

The peculiar behaviour of the temperature "after" cooler (T-39) before the accident has the following explanation.

As part of the experiment underway it was required to hold the polymer temperature constant. It had been rising slightly and at the time of the accident an operator on the main floor was adjusting the valve on the river water to the polymer cooler. This valve had been closed previously and the polymer temperature adjusted by cooling on lower tube sheets. He relates that some minutes before he had opened and closed this valve (accounting for the down pip at 14.51 hours on T-39) and again just before the accident he had opened this valve and when the alarms (health on the main floor) went the valve was open. He received instructions from bridge to close the valve and evacuate the room.

The rise of 8° recorded on T-39 is therefore the result of two events:

(1) the river water was shut off, the coolers having been on or partially on for a few minutes.

(2) the heat generated in the polymer by the accident.

With this partial understanding of the polymer temperature records, the only pertinent information is the temperature rise of 4.4°F recorded at the input to the cooler. This, however, must be used with caution in estimating the total energy generated in the pile during the transient. There is no reason to believe that the temperature had reached its maximum value when the circulation pumps were turned off, almost certainly at 15.21 + .3 minutes as indicated by the flat top of the temperature

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pulse. Additional factors are:

(1) The time lag in the instrument recording the temperature. This is a resistance thermometer coil of wire enclosed (and thermally insulated) in a brass tube, which in turn is installed in a stainless steel well in the cooler header. Tests of the brass tube alone show that the instrument takes thirty seconds to record a temperature rise of 15°. The response time with the well included is not known but could be quite long.

(2) The mixing in calandria is unknown, i.e. whether or not an average sample is being fed to the cooler. Since the polymer to cooler is drawn from the lower part of the calandria, it presumably received less than the average heat during the transient.

(3) Effect of cold or hot river water (the river water coming from the bottom of the rods is considerably hotter than the polymer) on the polymer. This might have occurred due to mixing or by river water running over the polymer pipes.

(4) Chemical effects.

The heat liberated by uranium converted into oxide by the action of steam is very large and amounts to 2.6 megajoules/Kgm. of uranium. The temperature rise of the polymer could be accounted for by the consumption of 57 Kgm. of uranium.

How much uranium was, in fact, consumed will not be known until the calandria has been examined so that as yet no allowance can be made for this effect.

The chance of hot river water contributing to the polymer temperature is believed to be small. If this is true, the temperature rise of polymer then represents a minimum for the temperature rise of polymer in the calandria during the transient. It is worthwhile to calculate this minimum energy dissipation in the polymer assuming that it all increased by $4.4^{\circ}F$.

Polymer in calandria filled to 260 cms. level = 123 x 260
= 32000 pds.

$$\Delta t = 61.2 - 55.8 = 4.4^{\circ}F$$

$$\begin{aligned} \text{heat} &= 4.4 \times 32000 = 14 \times 10^{4} \text{ BTU} \\ &= 14 \times 10^{4} \times 1054.8 \text{ joules} \\ &= 14.8 \times 10^{7} \text{ joules} \\ &= 148 \text{ megajoules.} \end{aligned}$$

The percentage of the total pile power that appears in the polymer is normally 4.1% after prolonged running at high power. This is taken from the pile records as an average of ten values with the pile between 27 and 29 MW. The individual values range from 3.83 to 4.24%.

In the case of a fast transient, the value will be less than this because the radioactive periods of minutes and longer which normally contribute to the heating of the polymer will be absent. This correction is small, however, since approximately one half of the heat in the polymer is generated by fast neutrons and one half by the gamma rays and of the gamma rays about 60% are prompt (RDP-44). Therefore, the 0.8% of the polymer heat normally due to radioactivity is missing and the percentage of the pile heat appearing in the polymer is 3.3%. Therefore, the estimated energy produced in pile during transient

$$= \frac{148}{3.3 \times 10^{-2}} = 4500 \text{ megajoules.}$$

If we take a power pulse of the shape plotted in figure 6, and of duration 35 seconds above 17 MW, the time beyond 1 MW being 62 seconds and beyond 6 KW, 166 seconds. The triangular spike above the 17 MW level will then contribute $4500 - (17 \times 35) - 17\left(\frac{62 - 35}{2}\right) = 3670$ megajoules and the peak power is $\frac{3670}{17.5} + 17 = 230$ MW. This is the minimum value under the above assumptions with the proviso that no heat was added to the polymer from the cooling water or by chemical action.

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In view of the difficulty in exact interpretation of the records, and of the possible effect of burning uranium, it is recommended that no reliance be placed on the above figures, for the integrated reactor power during the transient.

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PART III - THE GASHOLDER (RX 127)

I. SUMMARY

Within a few minutes of the accident, the recorder indicating the height of the main gasholder (RX 127) connected to the helium system showed that the gasholder had fallen to the bottom and then risen very rapidly to the top. The record and various circumstances associated with the behaviour of the helium circuit have been investigated.

With the information brought to light at the time of writing, no satisfactory explanation of the behaviour of the gasholder can be offered. The possibility of a relatively violent chemical reaction in the calandria within a few minutes of the accident is not ruled out.

A good deal of detailed information concerning the pile structure would be desirable. In view of the amount of work involving the pile staff and the difficult working conditions in Building 100, it did not seem desirable to press for this information at the present time. Until the condition of the calandria and of various sections of the helium system is known, no further profit seems obtainable by continuing this investigation.

II. THE GASHOLDER POSITION

The height of the gasholder is recorded by a Leeds and Northrup "Micromax" recorder, which prints the position every fifteen seconds. The position indication is obtained from a potentiometer driven by a wire attached to the top of the gasholder. The indicating system appeared to be in good working order when inspected after the accident. A summary of the record during and after the accident is shown in figure 7. The time scale is taken directly from the chart.

Further observations of the gasholder position have been reported by various people. A few minutes after the polymer

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dump began, the gauge in the basement showed the gasholder to be at the bottom. At about 17.45 hours December 12, the gasholder was up and oil was seen on the floor of the gasholder room. On January 21 it was a few inches from the bottom. Further, the pressure of helium in the pipe work near the top of the calandria dropped to zero, at nearly the same time as the polymer dump began. The pressure has been reported by one person to have fluctuated wildly a few minutes later. As far as is known the pressure remained at zero thereafter.

The behaviour of the gasholder may be summarized as follows. At 15.08.5 hours it began to fall in a roughly linear fashion with time and about three minutes later it had nearly reached the bottom. It then rose rapidly to nearly the top of the recorded travel, possibly coincidentally with pressure fluctuations in the calandria, and remained there until 01.40 hours December 13. During the rise, the recorder printed once and hence the rise time was less than 30 seconds. At 01.40 hours, the gasholder fell nearly halfway in less than 15 seconds, paused for about one minute, and fell essentially to the bottom in less than another 15 seconds, where it remained until 09.45 hours December 16. At this time the gasholder began to rise slowly, eventually reaching a level of 6.5 inches at 12.00 hours where it remained.

III. OTHER INFORMATION WHICH MAY BE PERTINENT

A number of observations which may or may not be pertinent to the behaviour of the helium system are recorded below:

(a) The Recombination System

The temperature of the gas before and after the catalyst in the recombination system is recorded by a Leeds and Northrup "Micromax" recorder. The recombination system circulates gas taken from the top of the calandria at about 2 cu.ft/min. and returns it to the top of the calandria. A summary of the recorded temperatures during and following

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the accident is shown in figure 8. The times noted are taken from the chart. The sharp pips occurring about once per hour are associated with the standardizing procedure of the recorder.

If we make allownace for the first standardizing pip, both the temperature before and after the catalyst began to rise at about 15.07 hours, but remained together until about 15.20 hours. The outlet temperature then began to rise more rapidly than the inlet. At 15.55 hours, when the inlet had risen to 24°C and the outlet to 48.5°C, a discontinuity occurred, the temperatures converged and then fell away together. This effect appears to be associated with turning off the circulating blower. The blower was started up again on December 13. A 4°C rise across the catalyst showed that there was still some hydrogen-oxygen mixture available but this rise did not persist for more than an hour.

The average temperature rise across the catalyst during normal operation appears to be about 2°C corresponding to a concentration of the order of 0.2% oxygen in the presence of excess hydrogen (D_2 + H_2).

(b) Composition of Gas in the Calandria and Gasholder

The gas contained in the calandria and gasholder was sampled through valves 641 and 801 respectively on January 21 and analysed by both the Chemical Control Branch and by the Physical Chemistry Group. These analyses are not in good agreement, but the Chemistry Group showed the bulk of the gas to be air containing 2.5% hydrogen (D_2 + H_2) in the calandria and 3.0% hydrogen plus 6.8% helium in the gasholder.

(c) The Polymer Storage Tanks

The level gauges E-5-H-49 and E-5-H-50 showed that, at 16.00 hours following the accident, No. 1 tank had filled to 292 cms. and No. 2 tank to 56 cms. Subsequently, over a period of an hour, the

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level in No. 2 tank fell to 50 cms., and then the level in both tanks rose slowly over a period of a week. Despite the fact that the polymer lines to the tanks were blanked off, the indicated levels continued to rise slowly, and at the present time No. 1 tank gauge is off scale ($>$ 320 cms.) and No. 2 tank at about 60 cms. (January 22).

It should be noted that the polymer line to No. 2 tank was valved off at the time of the accident and that shortly afterwards all valves to the tanks were closed.

(d) The Gasholder

The gasholder was inspected by two of the authors on January 22. The room contained about 2 feet of water covered with a thin layer of oil. The gasholder seal contained liquid to within six inches of the top. There was no obvious signs that the gasholder had suffered any damage.

The liquid in the gasholder and on the floor was sampled and analysed by the Chemical Control Laboratories, who reported that (a) the liquid on the floor was light water, (b) the liquid in the gasholder consisted of a two inch layer of oil covering water containing 24% D_2O. They also reported the following beta-gamma activities:

Gasholder	(1) oil	- 5.5×10^{10}	c.p.m./ml.
	(2) water	- 4.2×10^{9}	c.p.m./ml.
Water on the floor		- 1.9×10^{5}	c.p.m./ml.

It is estimated that the gasholder contained of the order of 6000 lbs. of water-polymer mixture.

IV. DISCUSSION

The gasholder is reported (ME-224) to have a capacity of 535 cu.ft. at the 50 inch level. It normally maintains a pressure of 12 ins. of water in the helium system and is loaded with approximately three tons of lead.

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The initial rate of fall of the gasholder occurring at 15.08 hours is not inconsistent with the appearance of a large hole in the calandria. A leak rate of 140 cu.ft/min. indicated by the rate of fall does not appear to be inconsistent with the flow rate possible at 12 ins. pressure through the helium lines connecting the gasholder to the calandria ★.

The following rapid rise of the gasholder in less than 30 seconds, implies an incoming flow of 920 cu.ft/min., or 5720 I.G.P.M., which flow rates cannot be explained by any effect associated with dumping the polymer (maximum rate 330 g.p.m.) or leakage of light water into the system. (The maximum flow normally delivered to the pile is 3300 g.p.m. There was no indication of a large increase in this). A pressure of the order of 5 lbs/sq.in. ★ appearing in the calandria could explain the rate of rise, provided the pressure was maintained during the delivery of 460 cu.ft. of gas. The rapid burning of about 70 Kgm. of uranium under water could produce the required amount in the form of hydrogen. Although the continued burning of hot uranium under water is possible due to the large evolution of heat (2.6 megajoules/Kgm) the consumption of such a large amount seems unlikely.

The remaining possibility of a hydrogen-oxygen explosion is not very acceptable either. The amount of energy required to raise the gasholder could be readily supplied by the burning of 0.11 cu.ft. of hydrogen. However, this energy must be transmitted through a long run of pipe work. Also the recombination unit showed no evidence for the appearance of explosive mixtures of hydrogen and oxygen in the calandria at this time. Indeed the maximum temperature rise occurring at 15.55 hours suggests a maximum hydrogen concentration (in the

★ Before these conclusions can be accepted as reliable, a more detailed knowledge of the physical layout of the piping connecting the gasholder to the calandria will be required. They are not consistent with some opinions expressed by the Pile Operating Staff.

presence of excess oxygen) of less than 5% [*], possibly an explosive mixture, or less than 25 cu.ft. in the then nearly empty calandria. This corresponds to the consumption of less than 4 Kgm. of uranium. It might be added that the gas analyses offer little assistance in solving this problem since any evidence they might have offered was lost long before the samples were taken.

The subsequent fall of the gasholder together with the fact that it now contains water and that No. 2 storage tank is partially filled, represent a number of circumstances which are difficult to tie together. In the first case, it seems likely that the gasholder was mechanically stuck at the top of its travel. That the helium system was open is evident from the fact that it did fall (unless some valve, not reported, was opened in the helium system at this time). The rate of fall is so rapid, apart from the hesitation which is probably mechanical, that it does not appear to be possible for the contents of the gasholder at this time to have leaked out through the calandria with the pressure available. The initial fall of the gasholder demonstrates the rates to be expected. It is therefore suggested that the oil seal of the gasholder was almost completely "blown" at this time, but that the water observed in the seal later had not yet entered. That the seal was blown is supported by the large amounts of oil later reported in the basement, by the fact that this oil had evidently not been expelled by the water entering the gasholder (the seal was not completely full) and that there is now very little oil in the seal. Furthermore, if the oil seal had been filled with water flowing in through the helium lines previous to this time, a "water lock" would have formed in the lines and prevented the gasholder falling at all. The gasholder could not have been under a significant vacuum (not 12 ins. of water even if the oil seal had not

* Phillips gives results in EI-83 which would suggest that this figure should be of the order of 1%.

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been blown) nor could the prompt compression of the gas in the system explain more than a small fraction of the fall.

The partial filling of No. 2 storage tank must be attributed to water entering through the helium balancing line. This could have come from the top of the calandria but this seems unlikely since gas appeared to be still circulating in the recombination system, or by spill over through the balancing line from No. 1 tank. The observed behaviour of the level gauges in these tanks does not suggest that No. 1 tank was sufficiently full to spill, but it would seem necessary to investigate the behaviour of these instruments carefully before this possibility is ruled out. The instruments are at present inaccessible.

The slow rise of the gasholder on December 16 can be readily attributed to water flooding the gasholder room provided the helium circuit connected to the gasholder was sealed. A water lock greater than 12 ins. high in the lines would effectively seal the gasholder from the calandria. December 16 was the first day on which the water level in the basement rose sufficiently to spill over into the gasholder room. The rising level in the room would slowly force air from the inside of the inner dome into the gasholder through the pipe connecting the oil overflow pan to the oil seal. The water levels attained are adequate to explain the effect, and the "backlash" effects of water trapped in the gasholder room and of the water lock in the tube connecting the oil seal to the oil pan which are large enough to explain why the gasholder did not fall when the basement was pumped dry. It is evident that the oil seal must have been at least partially full at this time.

The following is a summary of the possible sequence of events:

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December 12 15.08 hours	Calandria punctured, and gasholder began to fall.
15.11 hours	Gasholder rose rapidly to the top, its oil seal being blown at the same time. This must be attributed to the rapid generation of large volumes of gas in the system. The gasholder stuck at the top.
December 13 01.40 hours	The gasholder fell rapidly. The oil seal was still not made.
After 01.40 hours December 13 and before 09.45 December 16	A mixture of heavy and light water appeared in the oil seal.
December 16 09.45 hours to 12.00 hours	The gasholder rose six inches due to water flooding the gasholder room. A blockage must have existed in helium lines to the gasholder at this time.

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PART IV - THE RECORDINGS OF OTHER INSTRUMENTS

SUMMARY

The recordings of all other instruments in the control room of Building 100 were inspected. Photostatic copies of the sections of these records pertinent to the accident together with those already discussed are attached to this report. Any changes in instrument readings noted are briefly discussed.

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RECORDS INSPECTED

E-7-L-38	- N.E. Corner Building 100
E-7-L-31	- Instrument Room
E-1-T-10	- Temperature Rise Through Unit
E-1-F-16	- H.P. Water to Unit
E-1-L-29	- Inlet to Tank 103
F-1-L-30	- Inlet to Tank 104
F-1-L-29	- Inlet to Tank 103
E-7-L-109AX	- Esterline Angus Power Recorder
F-7-L-1B	- S.W. Corner Building 100
E-7-L-4A	- N.W. Corner Building 100
E-3-F-8	- Air Flow in No. 1 Inlet
E-3-L-20	- Air Exhaust Duct
E-7-L-111	- Power Output Chamber 111
F-1-L-25	- Outlet Tank 104
	Gasholder level in Inches
E-5-H-37	- Weir Box Position
E-6-P-22	- Process Air
E-1-P-8	- Water Pressure In and Out
E-2-T-10	- Temperature of Water from Control Rods
E-3-F-9	- Air Flow in No. 2 Inlet
E-7-H-25	- Shut-Off Rod Position
E-5-H-60	- Weir Box Position
E-1-T-17	- Temperature at 3" Water Outlet
E-3-F-7	- Air Flow from Unit
E-7-H-21	- No. 1 Control Rod Position
E-5-T-40	- Polymer Temperature Before Cooler
E-5-T-39	- Polymer Temperature After Cooler
	North Thermal Column
	South Thermal Column
E-7-L-109A	- Power Recorder Micromax
F-1-L-23	- Neutron Monitor
E-7-L-2A	- S.E. Corner Building 100
E-4-T-60	- Temperature Before and After Catalyst

OFFICIAL USE ONLY

OFFICIAL USE ONLY

E-1-T-10 - Temperature Rise Through Unit

Temperature peak at 442 on chart. The scale is full scale = 500 div. = 30°C.

Therefore the temperature rise across the unit during transient = $\frac{442}{500} \times 30 = 26.5°C$.

E-1-F-16 - H.P. Water Flow to Unit

Flow at time of transient = 75.6 div.
The scale is - full scale = 100 div. = 4000 g.p.m.
Therefore the water flow through unit = $\frac{75.6}{100} \times 4000$

$= 3024.0$ g.p.m.

Note: Slight rise to 75.9 div. in water flow at about 15.10 hours, presumably at the time of the transient.

The power indicated by the temperature rise of the H.P. Water is then

$$26.5 \times \frac{9}{5} \times \frac{3024 \times 10}{60} \times \frac{1054.8}{10^6} \text{ MW} = 25.3 \text{ MW.}$$

This is a minimum value as the temperature indicating element is slow and will not record the maximum temperature. The temperature measuring element is the same as that described under E-5-T-40 and E-5-T-39.

E-2-T-10 - Temperature of Water from Control Rods

Print "1" is control rod water temperature
Print "2" is temperature of water from J-9
Discontinuities appear on the records at 15.17 hours. The rise is not recorded on chart and we see only the tail of return to normal some eight or nine minutes later.

Full scale = 200°F

OFFICIAL USE ONLY

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E-3-F-9 - Air Flow in No. 2 Inlet

Level at 8000 pds/hour until 15.10 hours.

15.10 hours - a bump to 8700 pds. lasting fifteen minutes. Then level again at 8000 pds/hour until 16.25 hours.

16.25 hours - a sharp rise to 48000 - presumably the fans were turned on at this time.

E-1-T-17 - Temperature at 3" Water Outlet

Record is smooth all day. No indication of transient.

E-3-F-7 - Air Flow From Unit

Level at 11.5 before the accident. Just perceptible bump at 12 at 15.15 hours. Bump lasts until 15.30 hours. No explanation has been found for increased flow in both air inlets and also from the unit.

E-5-H-37 - Weir Box Position (Printed)

Three sheets.

06.18 hours - Weir box raised from 188.8 cms. to 260 cms. where it remains until 16.47 hours when it is raised to 304.8 cms.

E-5-H-60 - Weir Box Position (Line)

Time scale is wrong on this chart. The correct time 08.50 hours was marked the morning of December 12.

The raising of weir box from 187 cms. to 256 cms. on this chart at 11.35 a.m. corresponds in time to the 06.18 hours weir box change on chart E-5-H-37 (above). The increase of weir box level from 256 cms. on this chart to 296 cms. corresponds in time to 16.47 hours change on E-5-H-37.

OFFICIAL USE ONLY

Water Pressure In and Out - E-1-P-8

Blue trace - out - Normal has been 28 p.s.i.
On chart blue trace is flat through the transient with a step drop to 29.8 at 16.15 hours.
Level at 29.8 until 22.00 hours.
Drop to 28 at 22.00 hours. Thereafter level.

Red trace - in - Normal is 156 p.s.i. Flat at 156.5 before transient.
15.08 hours a spike up to 160 and down to 154 - perhaps caused by a small explosion connected with the accident or a temporary stoppage and restoration of part of the flow. Then level at 156.5 until 15.40 hours. 15.40 hours a spike drop to 136 and recovery to 155.
15.40 - 16.07 hours - a uniform drop from 155 to 146.
16.07 hours - a sharp drop to 29 where it remains until 16.52 hours.
16.52 hours - Drops to 16. Thereafter level at 15 to 16 at 21.45 hours where it drops to 13.5 and remains level to 23.45 hours.
23.45 hours - drops to 10.0 and thereafter remains level.

F-1-L-29 - Inlet to Tank 103 - Water Activity

103 is No. 1 Tank.

Level constant between 0.04 and 0.045 until 15.15 hours + .5 minutes (chart time).

At 15.15 hours + .5 minutes a sharp burst just off scale for about one minute with a steep return to 0.1 at 15.20 hours and to 0.4 at 15.30 hours.

Jitters to zero from 16.00 to 16.30 hours and then level to 0.04.

At 22.40 hours a rise to 0.3 to 0.4 and at 01.57 hours December 13, goes sharply off scale and remains off.

Note: Chart shown in two sections on separate sheets.
Full scale = 1 division = 1×10^{-9} amps.

F-1-L-30 - Inlet to Tank 104 - Water Activity

104 is No. 2 Tank.

Level at 0.24 until 15.07 hours, at which time a sharp rise to 0.48 and return to normal 0.24 at 15.15 hours.

At 15.45 hours, a series of variations begin and level oscillates between 0.24 and 0.35 until 21.50 hours.

At 21.50 hours a spike to 0.9 and return to region of 0.3 where it remains.

Full scale = 1 division = 1×10^{-10} amps.

F-1-L-25 - Outlet from Tank 104 - Water Activity

Level at 0.15 until 15.07 hours.

15.07 hours rise to 0.27 and short flat top about one minute wide.

Sharp drop to 0.2 at 15.12 and more gradual drop to 0.15 at 15.18 hours.

Full scale = 1 division = 1×10^{-10} amps.

E-3-F-8 - Air Flow in No. 1 Inlet

Level at 6.7 before accident.

15.08 hours - slight bump to 7.0 which lasts until 15.30 hours.
15.30 hours - return to normal level 6.7 until 16.23 hours.
16.23 hours - sharp rise to 45. Presumably due to the fan being turned on after the accident.
Full scale = 6.7 divisions = 6700 pds/hour.

E-3-L-20 - Air Exhaust Duct

Indicates radiation level in air exhaust duct.
Level at .185 until 15.17 hours.
15.17 hours - meter goes rapidly off scale and remains off.

OFFICIAL USE ONLY

E-7-L-111 - Power Output Chamber No. 111

Level at 15 divisions until 14.42 hours.

15.07 hours - rapid rise shown by "1" printed at 550 divisions. Rapid fall to base line. A very short tail can be seen where the decrease merges into the normal, background at 14.43 hours.
Scale, full scale = 1000 divisions = approx. 40 MW.

E-7-H-21 - Control Rod Position

Chart is 12 hours out in time. Normal 8 a.m. stamp is 8 p.m. December 12.

Also this instrument does not record properly near zero, the "1" print should be disregarded and rough indication taken from "2" print.

Chart Time

10.25 hours - 18.2 cms. indicated and drops to 2.2 cms. at 10.25 hours. This means that rod went from 0 to about 2 cms. at 10.25 hours.

10.25-10.50 hours - Level constant at 2 cms.

10.50 hours - jitters and goes to zero at 10.54 hours. Reading is constant until 11.22 hours.

11.22 hours - jitters and by 11.30 hours rod is up and reading is 310 cms. which remains constant until 14.21 hours.

14.21 hours - rod drops to zero and remains there. (Chart indication is 18 cms. but "1" print is disregarded near zero reading.

E-7-L-109AX - Esterline Angus Power Recorder

Instrument not operating.
Trace remains at zero, i.e. -0.3 scale divisions.

OFFICIAL USE ONLY

F-7-L-1B - S.W. Corner Building 100

Level at .03 until 15.14 hours.

Square pulse from about 14.10 to about 14.36 hours in response to ZEEP.

At 15.14 hours (chart time) a vertical rise off scale remaining off until about 19.10 hours. Return is followed by slow decay to 0.5 at 00.00 hours 23 seconds.

Scale - full scale = 1 division = 0.5 tolerance/8 hours

Detects gammas.

E-7-L-4A - N.W. Corner Building 100

Level at 0.03 until 15.25 hours.

ZEEP pulses also show on this instrument.

At 15.25 hours a steep rise to .64 and return to 0.1 at 15.30 hours. Followed by a slow decay back to normal reading of .03 by 18.00 hours.

Scale = 1 division = full scale = 0.5 tolerance/8 hours.

Detects slow neutrons.

E-7-L-3B - N.E. Corner Building 100

Level at .17 divisions until 15.09 hours at which time record goes rapidly off scale and remains off.

Previous square pulses at 14.12 hours to 14.40 hours and from 10.15 to 10.40 hours are caused by operation of ZEEP.

Full scale = 1 division = 0.5 tolerance/8 hours.

Instrument detects gamma rays.

E-7-L-31 - Instrument Room Radiation Level

Level at .06 until 15.07 hours at which time record goes rapidly off scale and remains off.

Full scale = 1 division = 4 tolerances.

Instrument detects gamma rays.

E-7-L-2A - S.E. Corner Building 100

Level at .035 until 15.06 hours at which time a sharp spike to just off scale and immediate return at 0.55. Remains at this level for two or three minutes and drops to 0.27 where it remains for about half an hour. At 15.50 hours a sharp drop to 0.08 followed by gradual decay to 0.04 at 17.00 hours.

Full scale = 1 division = 0.5 tolerance.

Instrument detects slow neutrons.

F-1-L-23 - Neutron Monitor

Square pulses 10.05 - 10.30 hours (amplitude = 0.5) 14.00 to 14.28 hours (amplitude = 0.98) are caused by ZEEP operating.

Transient starts at 15.07 hours and goes off scale for about one minute and returns to normal at 15.15 hours. Remains at zero until 01.50 hours December 13, when it goes off scale and remains off until 19.00 hours. Returns to scale and decays slowly to half full scale at 05.00 hours December 14 and to 1/10 full scale at 11.00 hours December 14 followed by a gradual tail to zero.

Chart is 4 minutes slow at 12.00 hours December 22.

WJH/ACJ/PRT:kc

Chalk River, Ontario.

March 31, 1953.

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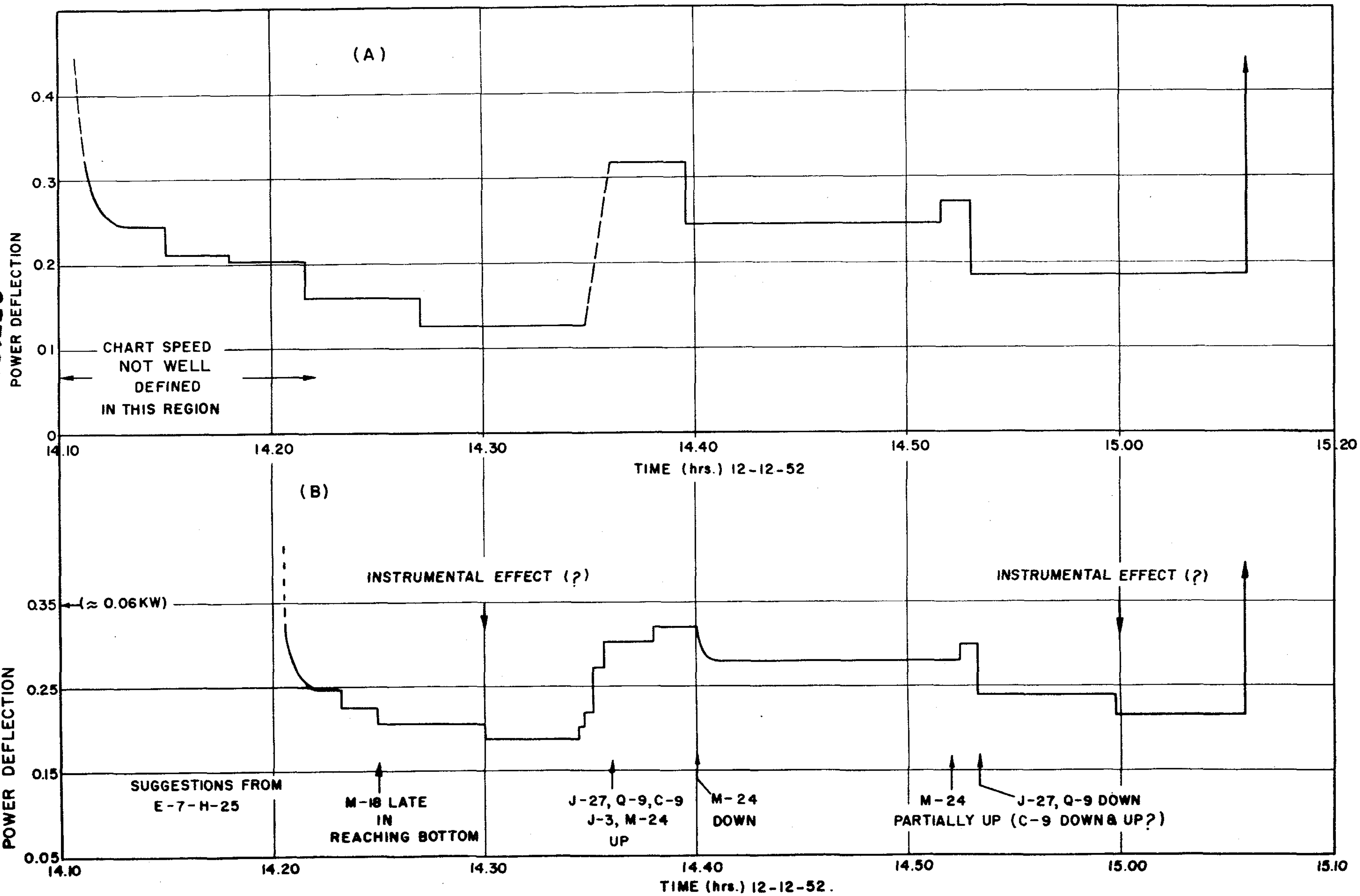

ENLARGEMENT OF (A) SOUTH & (B) NORTH THERMAL COLUMN ION CHAMBER RECORDINGS.

FIG. I.

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[redacted]

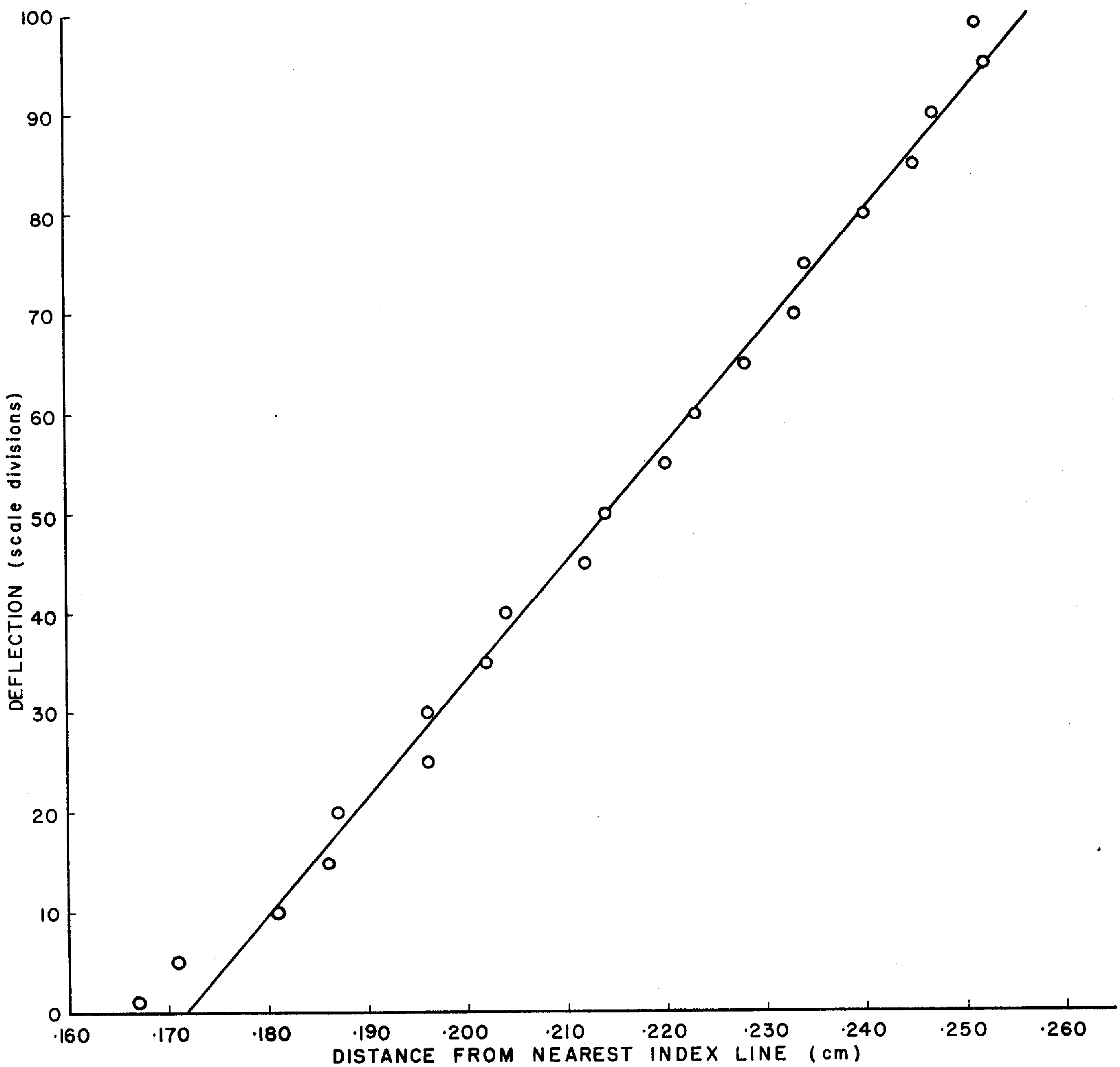

FIG. 2 NORTH THERMAL COLUMN. ANALYSIS OF RECORD

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[redacted]

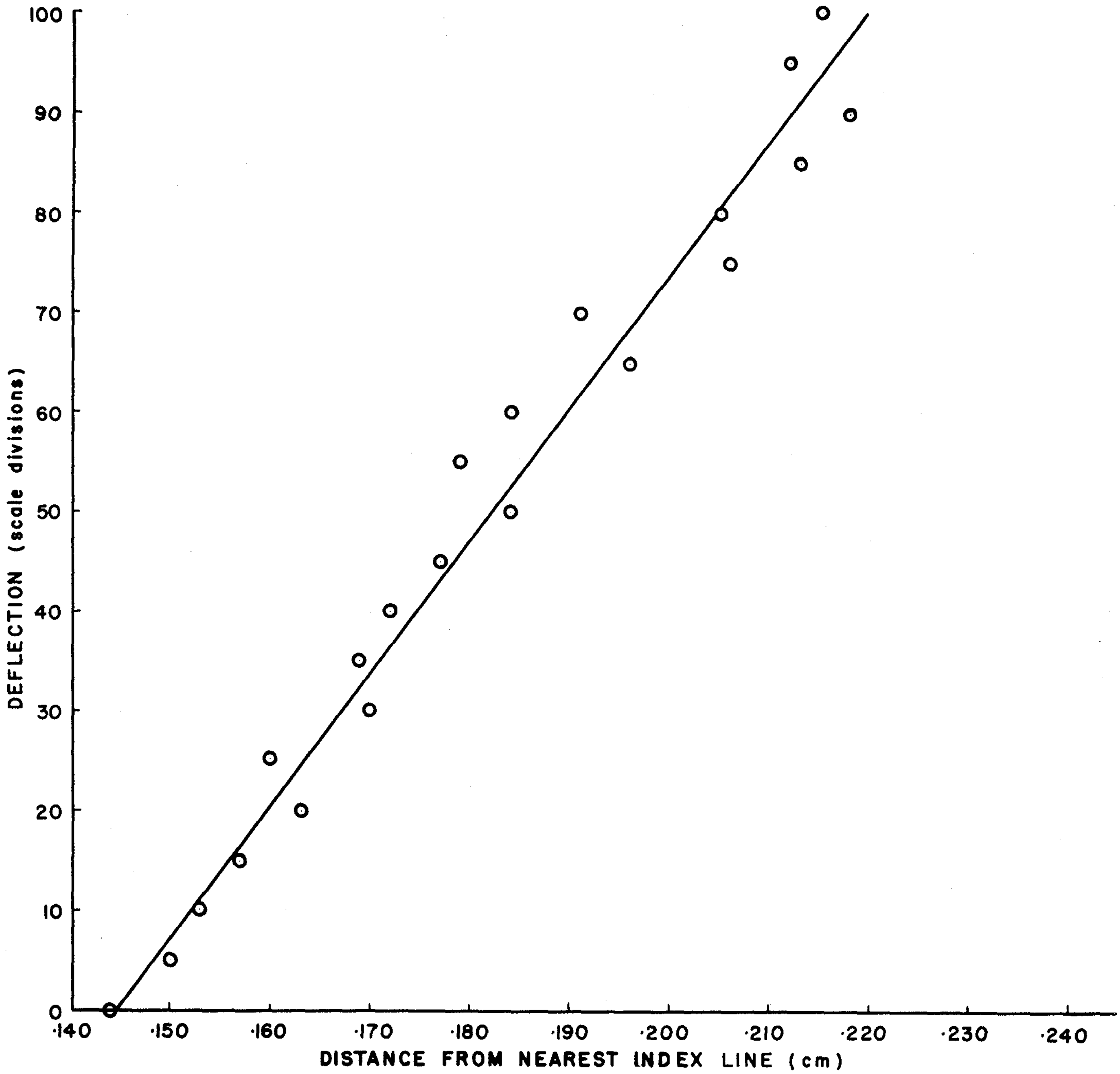

FIG. 3 BROWN RECORDER AND DC AMPLIFIER. EFFECT OF OVERLOAD SIGNAL

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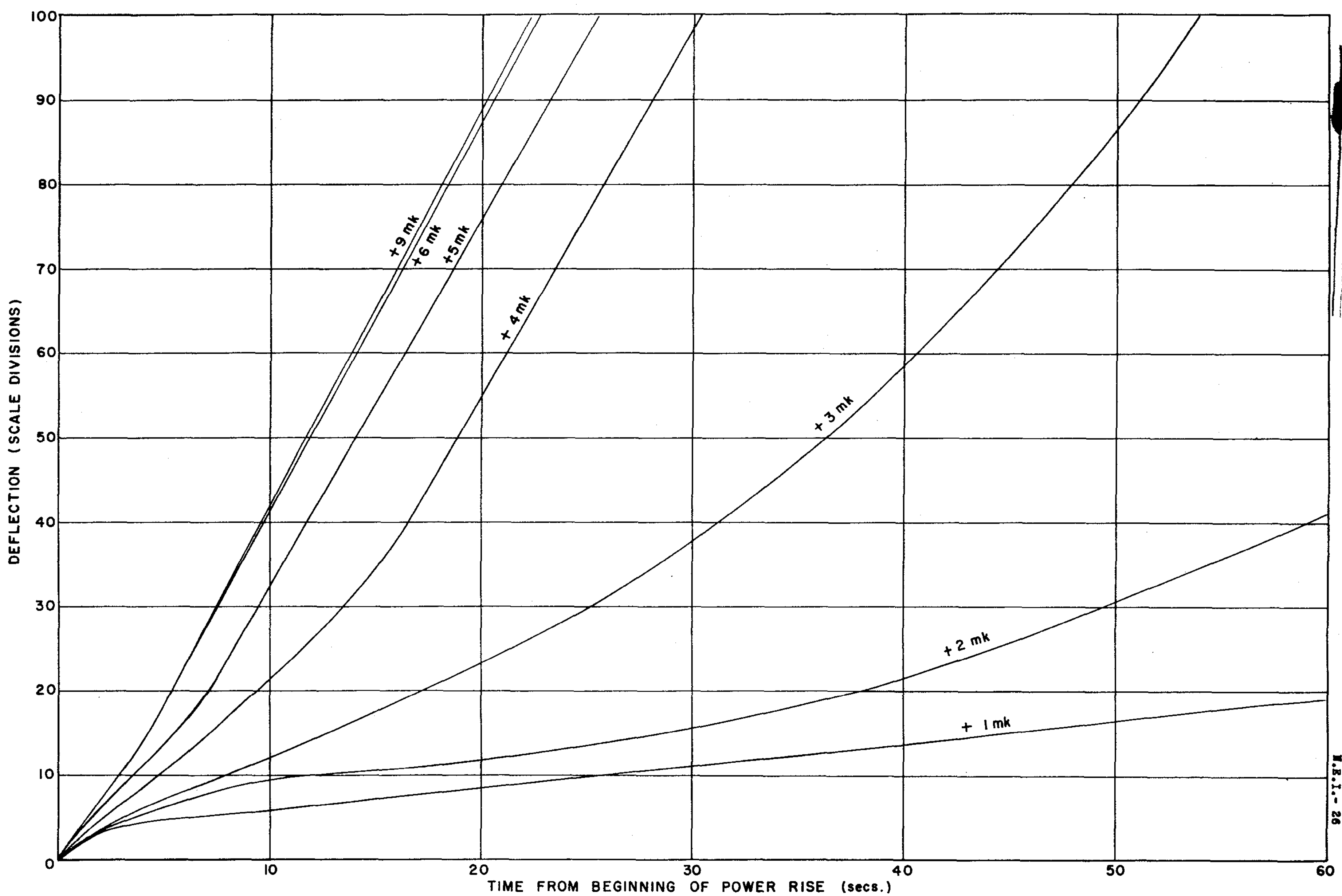

BROWN RECORDER AND D.C. AMPLIFIER FROM N.T.C. CONNECTED TO PILE ANALOGUE
CHART SPEED 24"/hr. EFFECT OF REMOVING 29.5 mk. IN ~ 2 secs.

FIG. 4.

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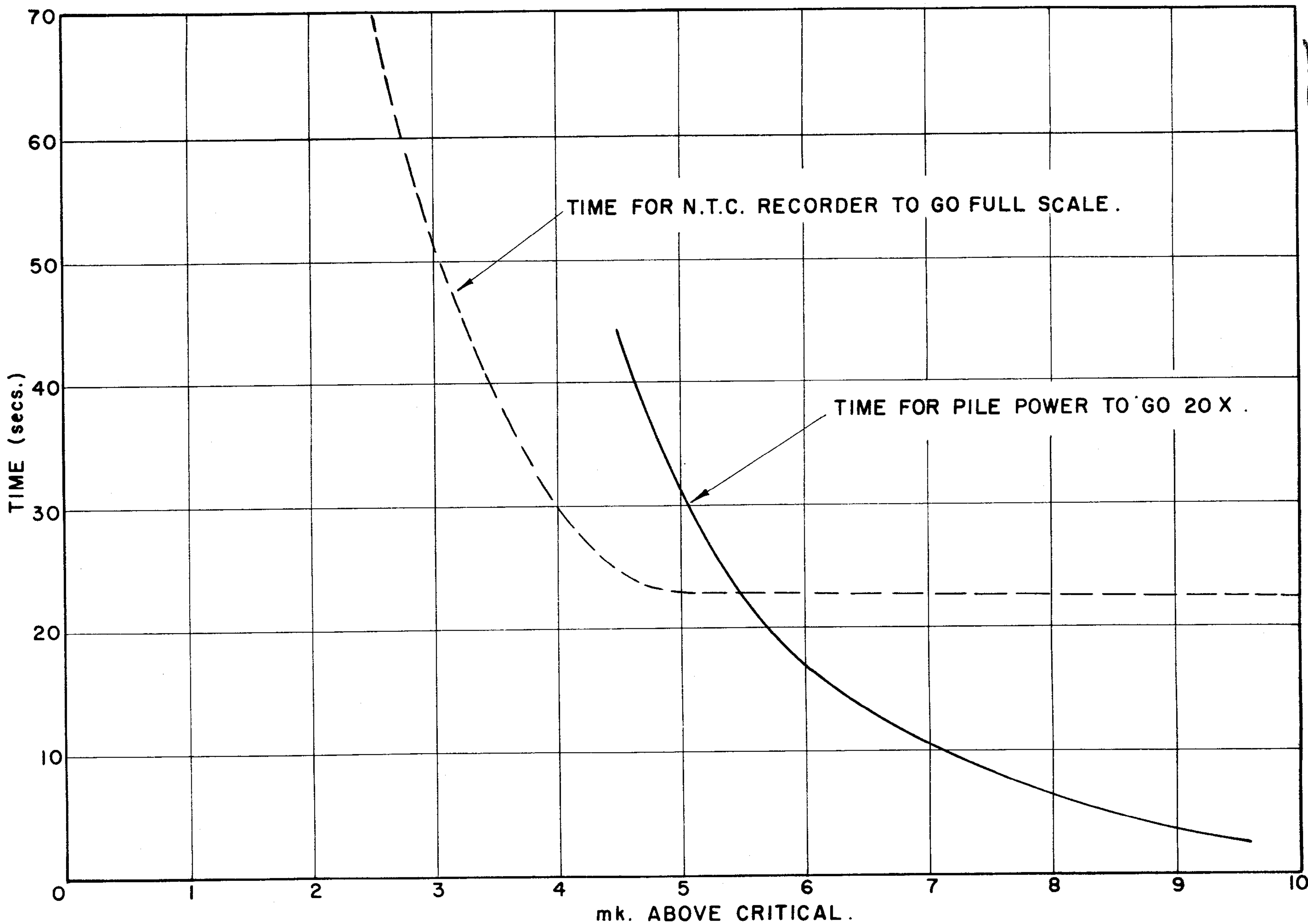
OFFICIAL USE ONLY

OFFICIAL USE ONLY



RATES OF RISE FROM PILE ANALOGUE EXTRACTING 29.5 mk. IN ~ 2 secs.

FIG. 5.

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OFFICIAL USE ONLY

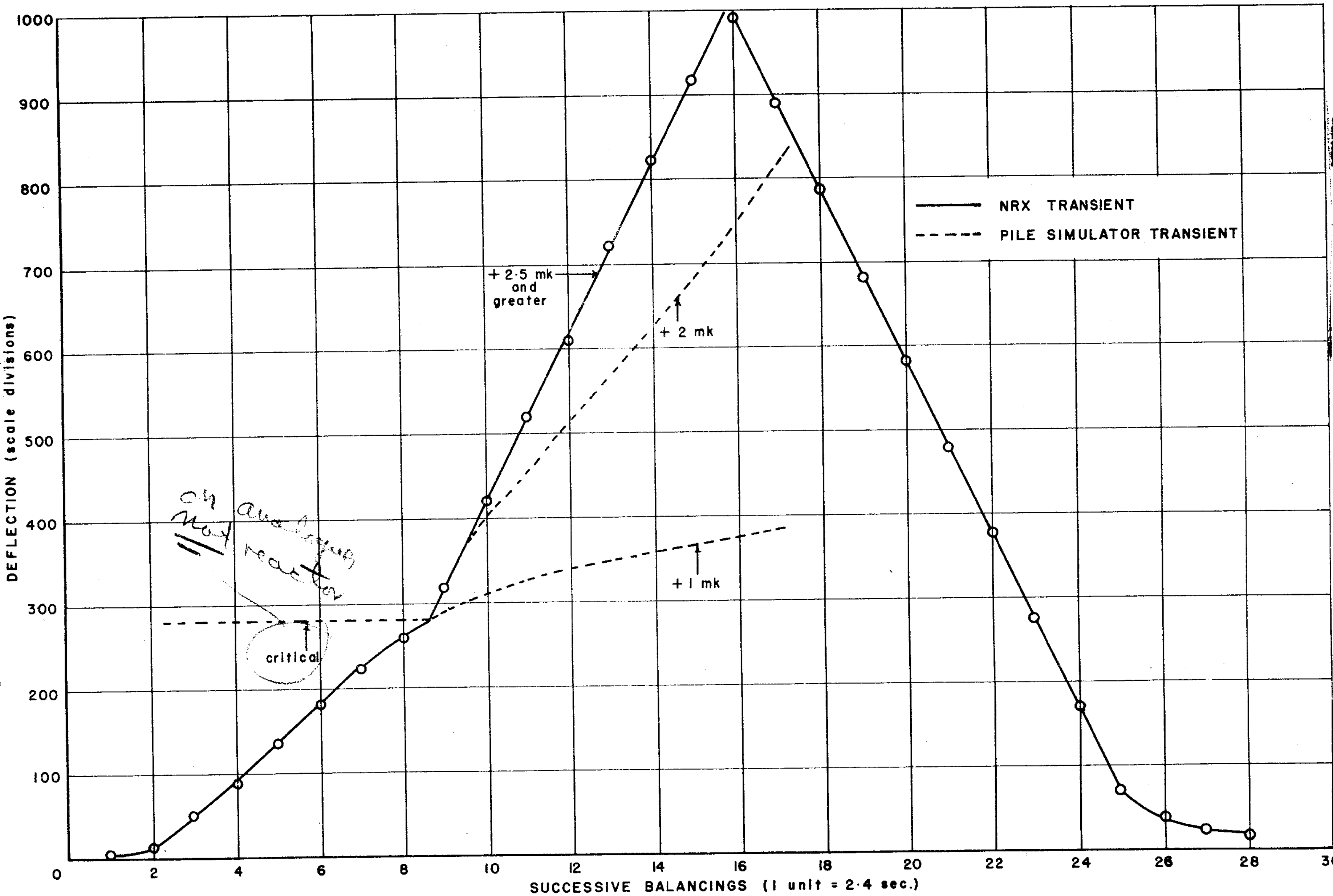

FIG. 6 E-7-L-109A ANALYSIS OF RECORD. POSITIONS OF RECORDER PEN ON SUCCESSIVE BALANCINGS

H.E.I. / 26

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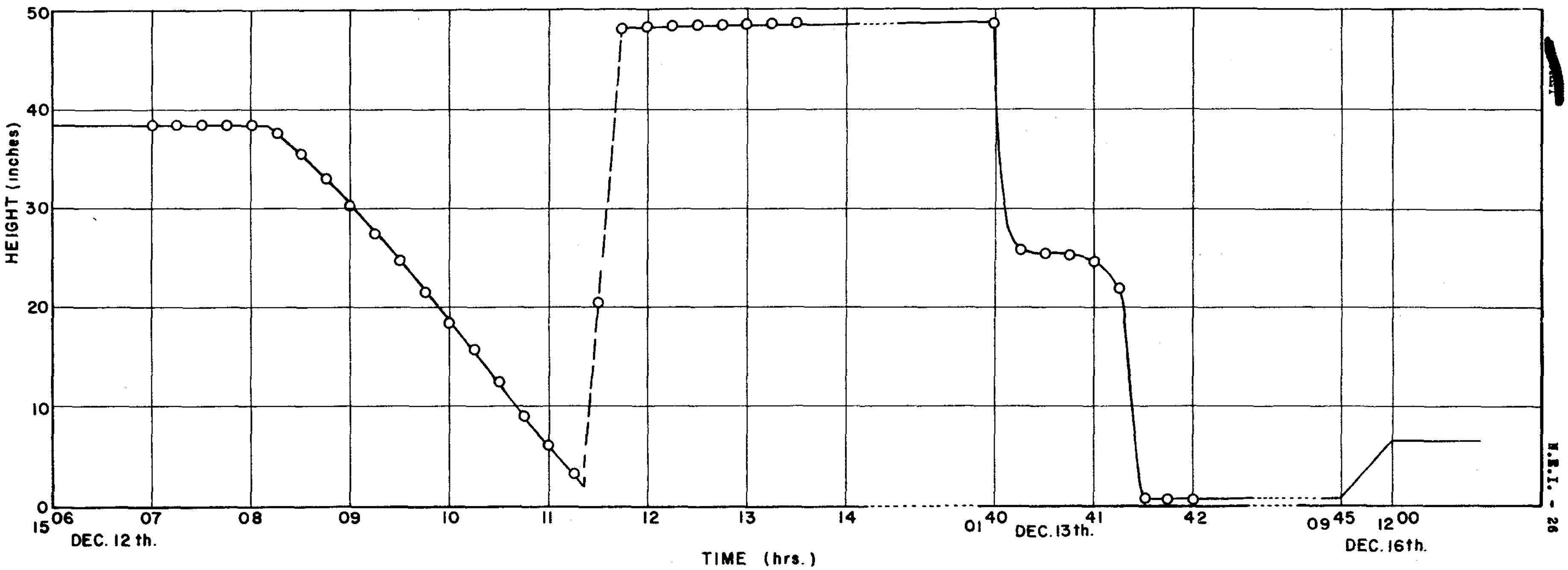

GASHOLDER HEIGHT

FIG. 7.

[redacted]

M.E.I. - 26

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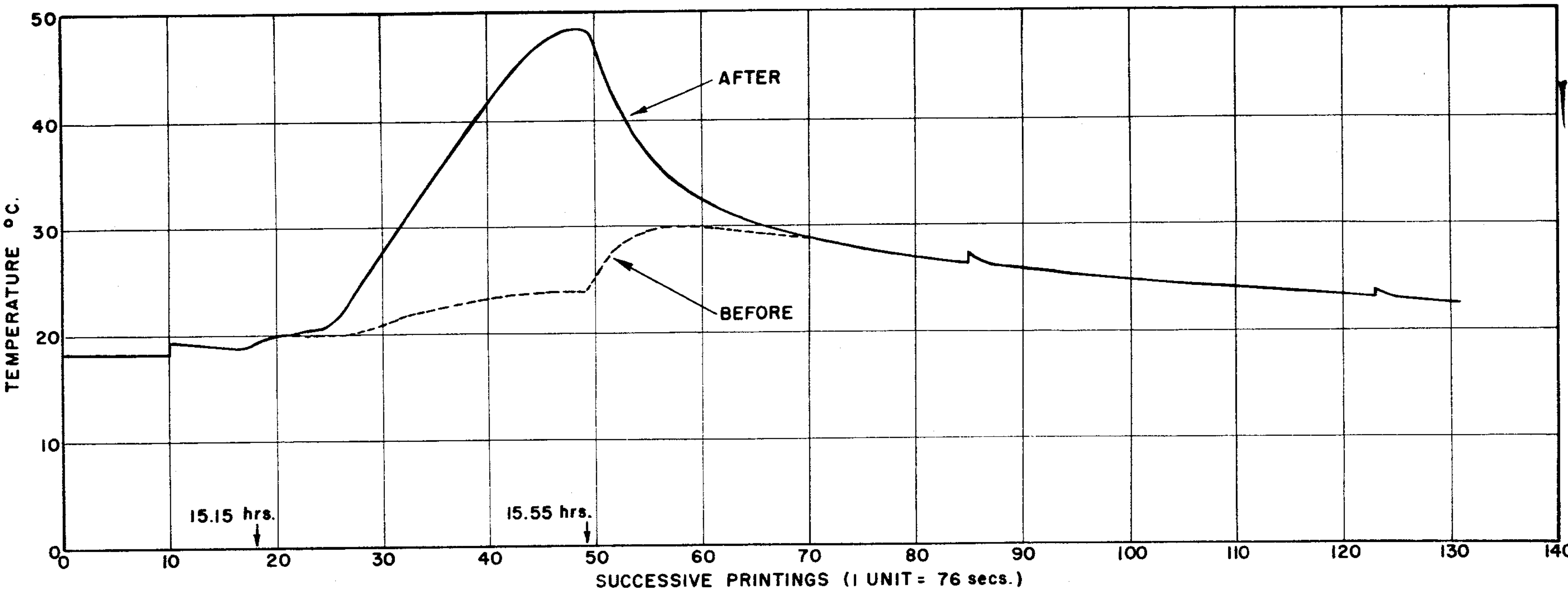

TEMPERATURES BEFORE AND AFTER THE CATALYST.

FIG. 8.

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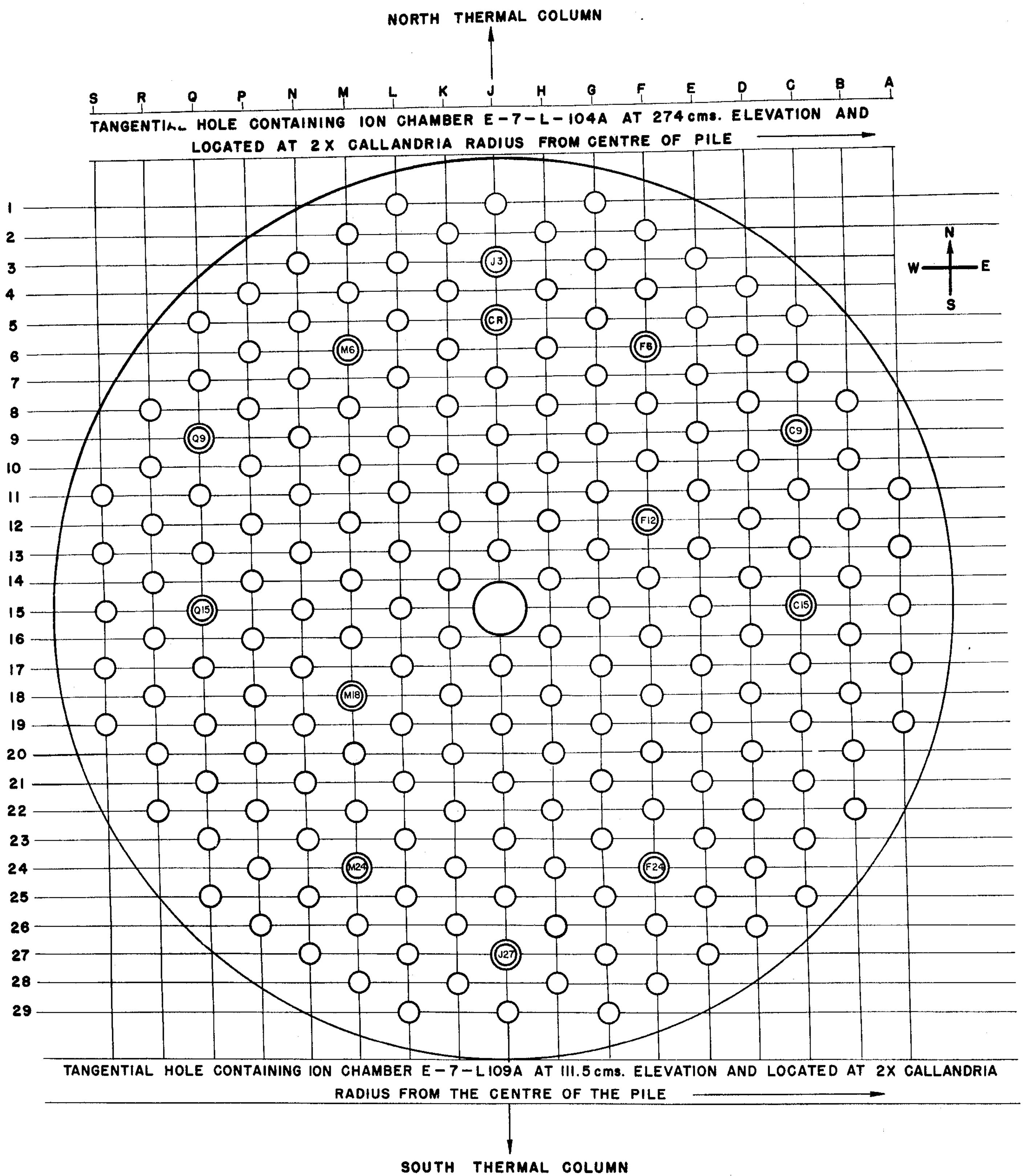
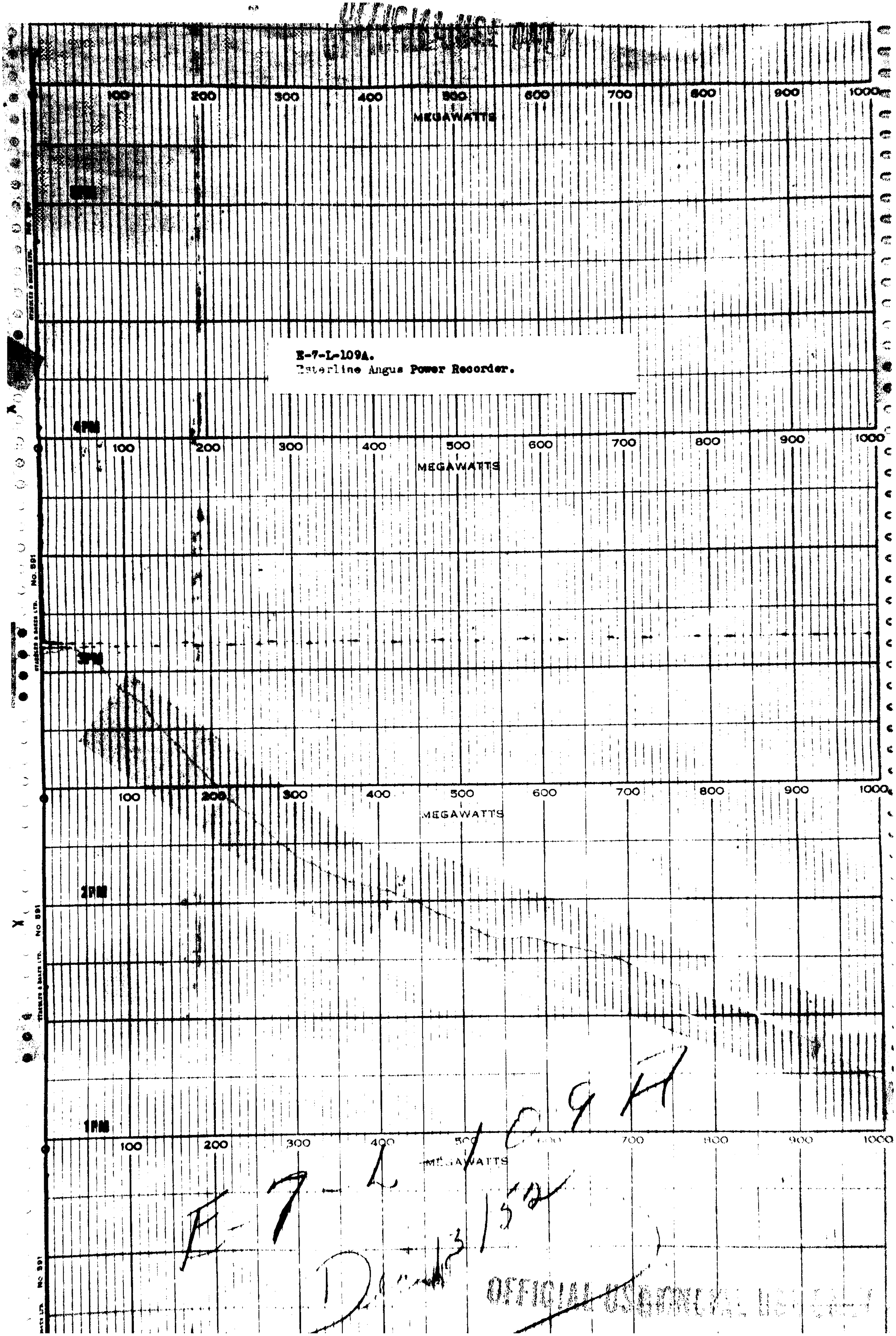
H.E.I. - 28



SCHEMATIC CROSS SECTION OF THE NRX LATTICE SHOWING THE SHUT-OFF ROD AND CONTROL ROD LOCATIONS AND THE RELATIVE LOCATIONS OF THE VARIOUS INSTRUMENTS DISCUSSED. SHUT-OFF RODS (A) INNER CIRCLE F12, M18. (B) MIDDLE CIRCLE Q15, M6, F6, C15, F24, M24. (C) OUTER CIRCLE Q9, J3, C9, J27.

FIG. 9.



E-7-L-109A.
Esterline Angus Power Recorder.

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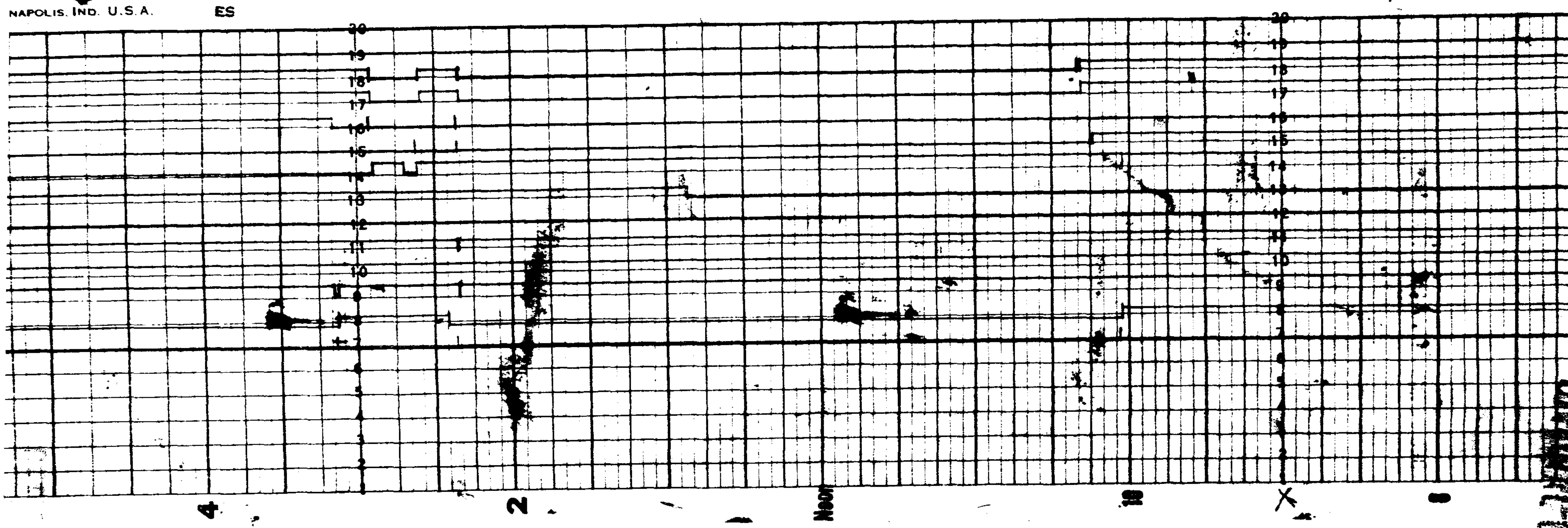
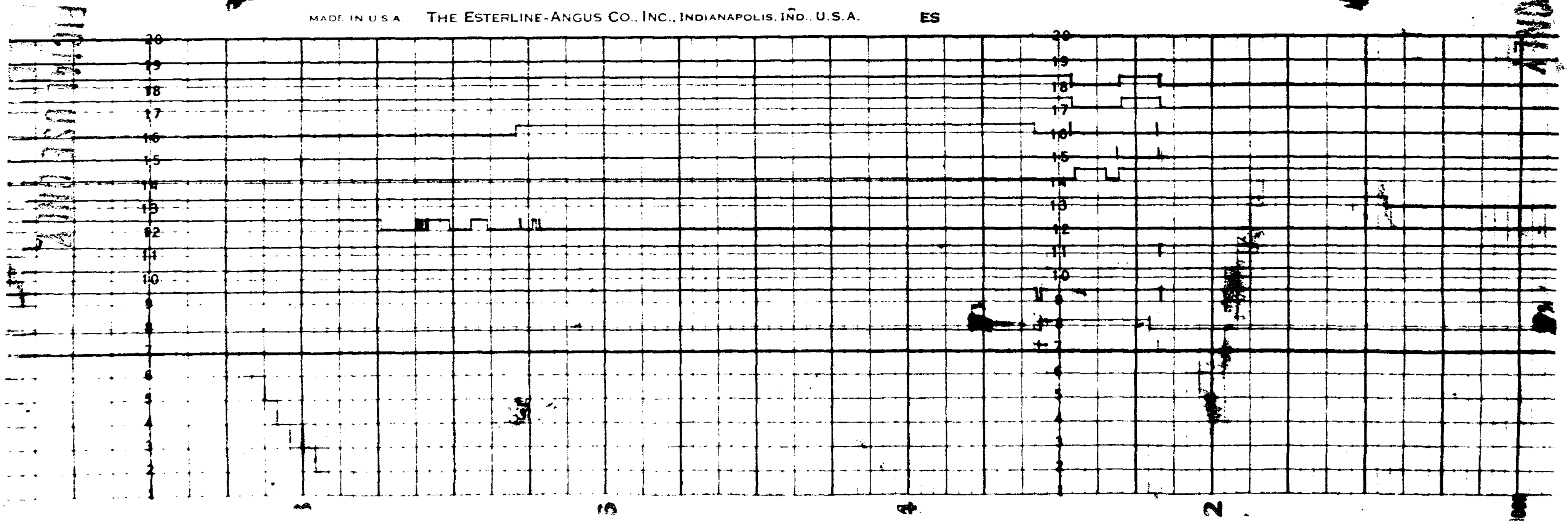
E-7-H-25.
Shut-Off Rod Position.



E-7-H-25.
Shut-Off Rod Position.



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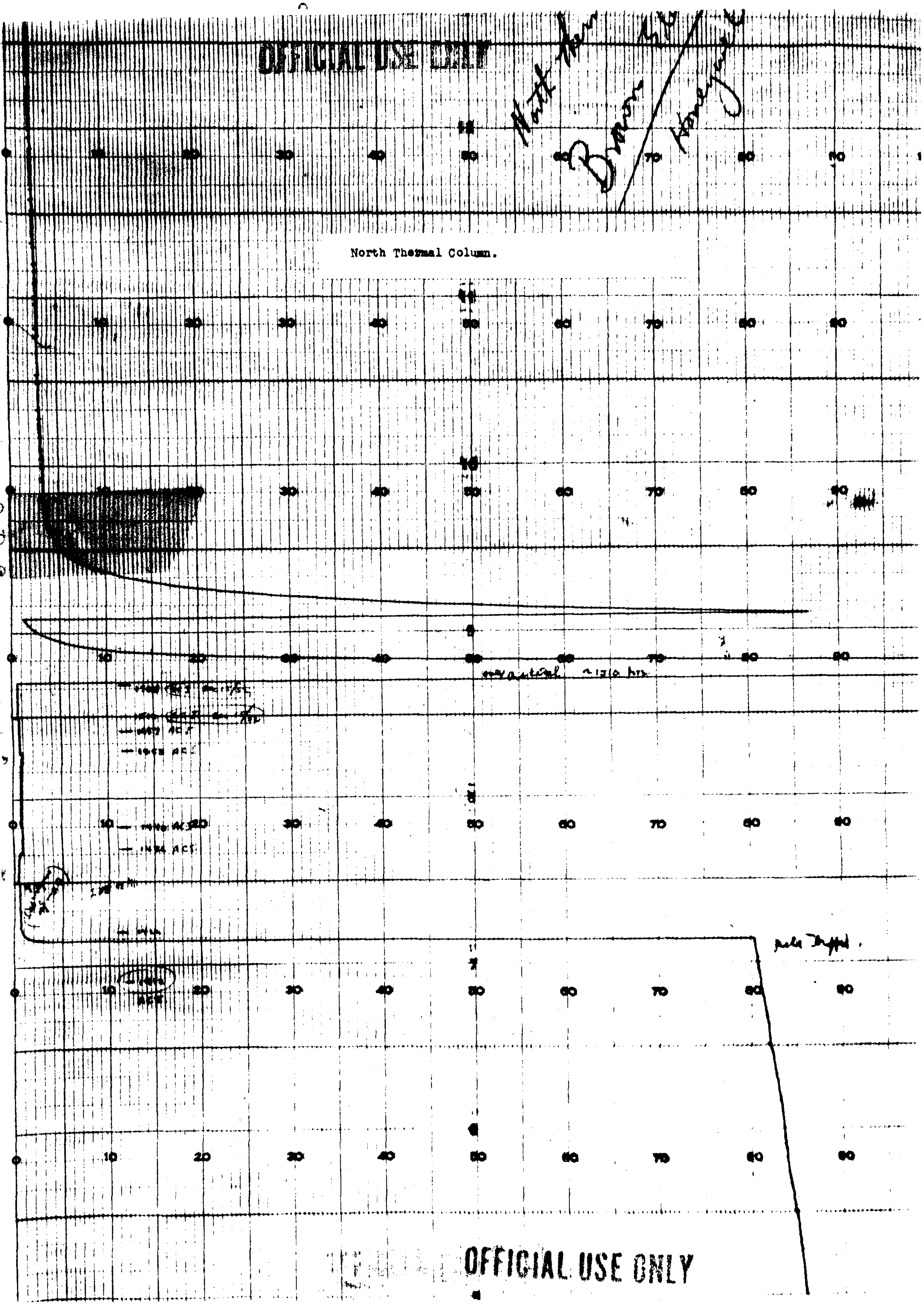

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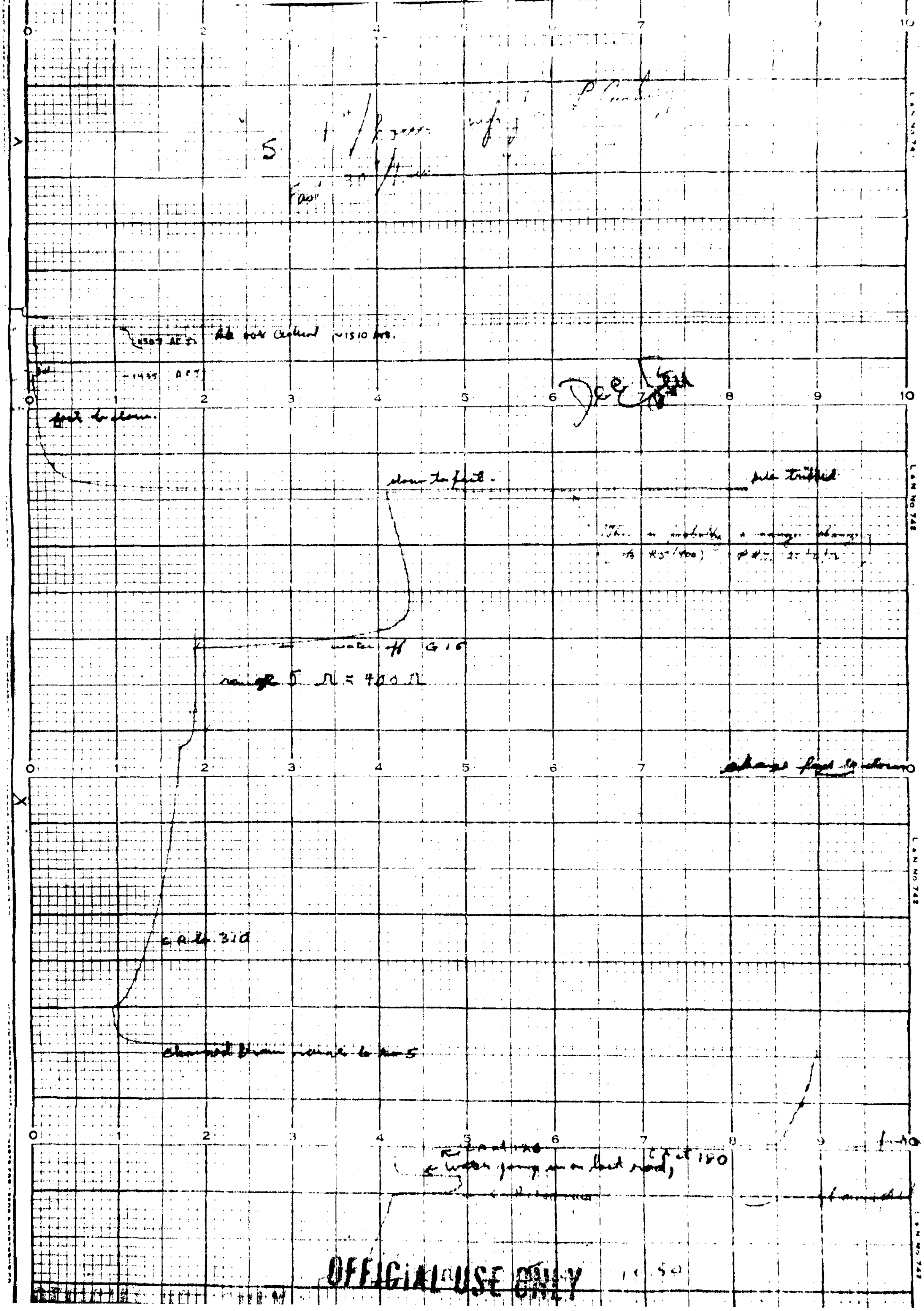
South Thermal Column.



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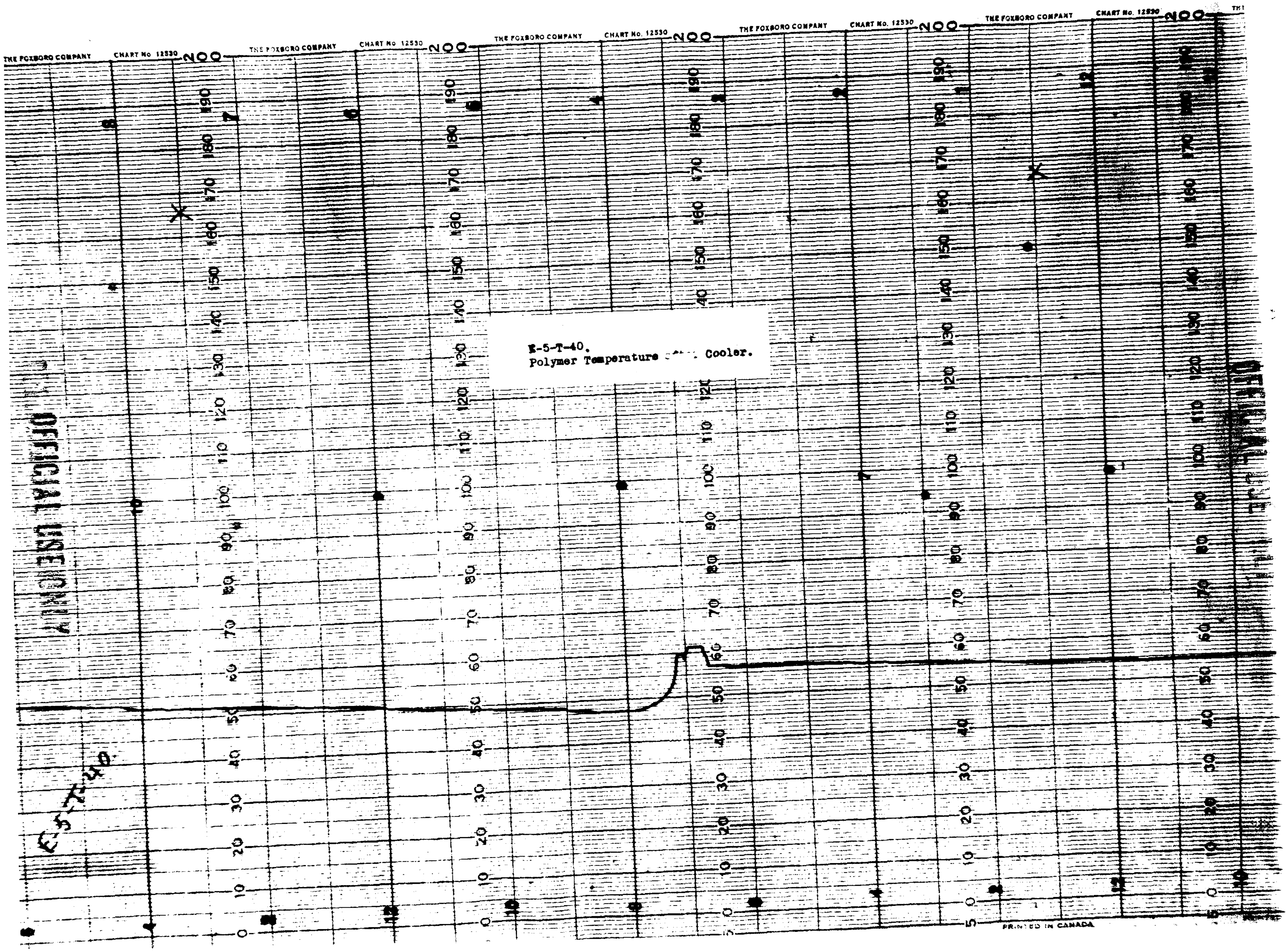
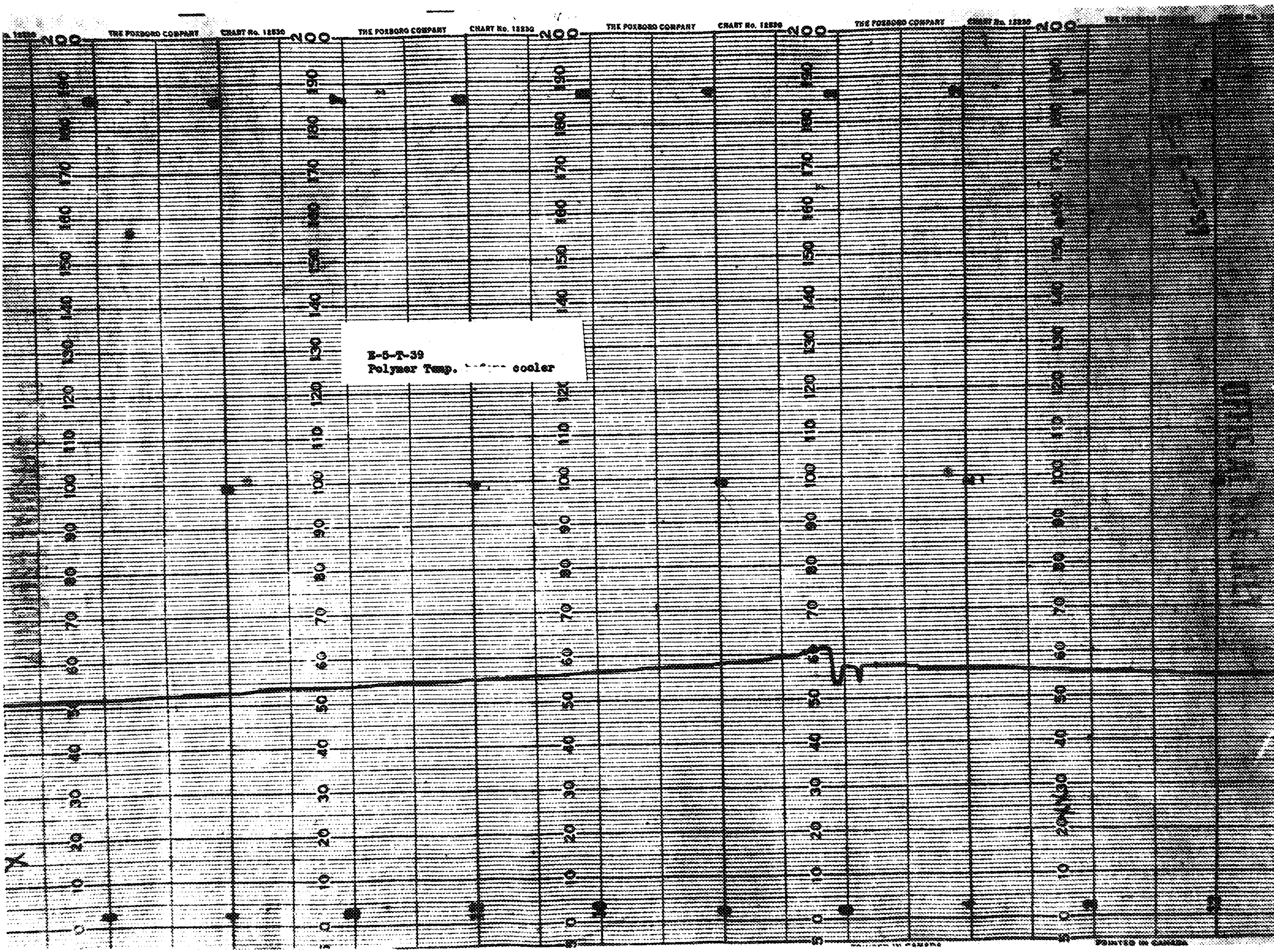
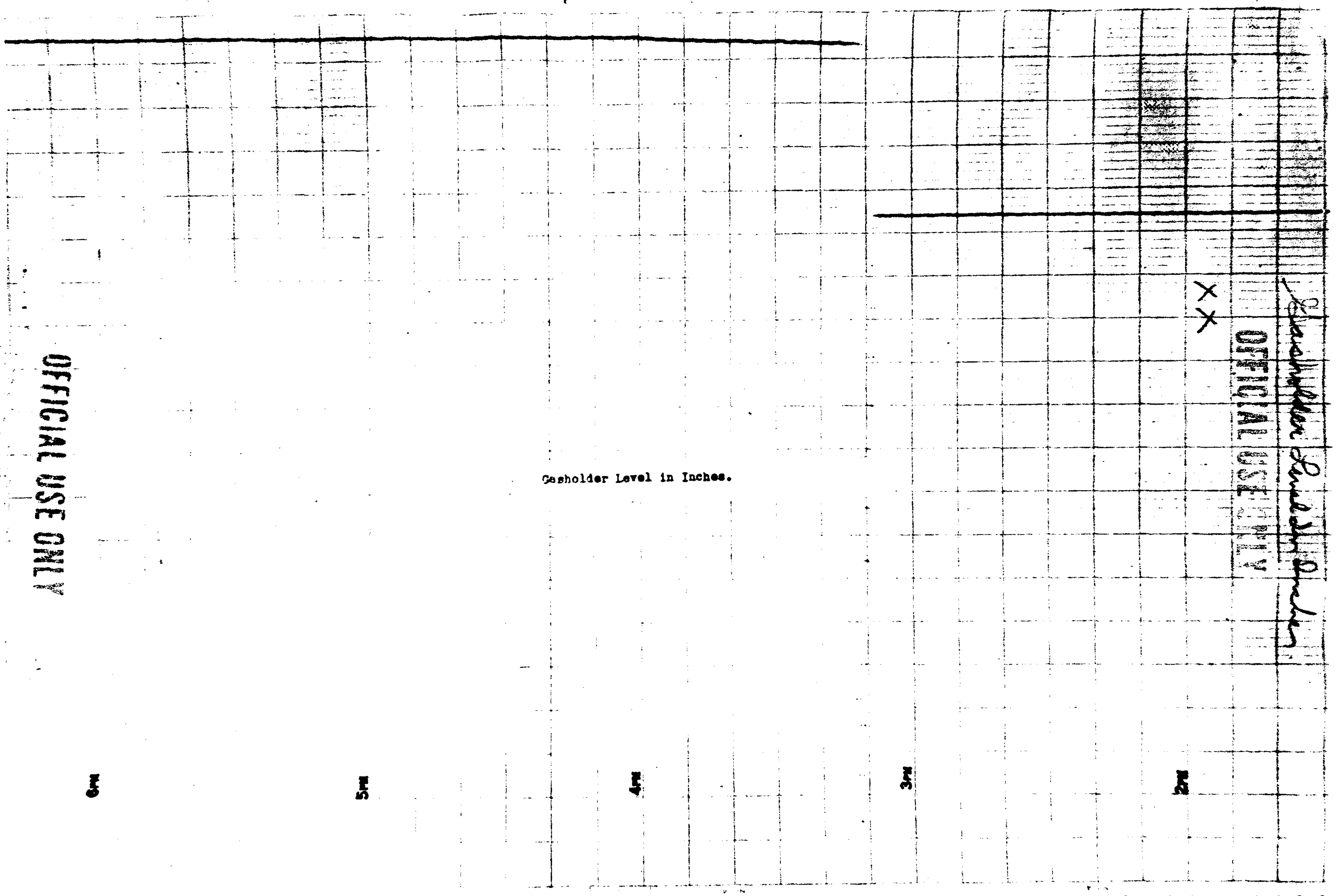


E-5-T-40.
Polymer Temperature [illegible] Cooler.


THE FOXBORO COMPANY
CHART No. 12830
E-5-T-39
Polymer Temp. cooler
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
PRINTED IN CANADA



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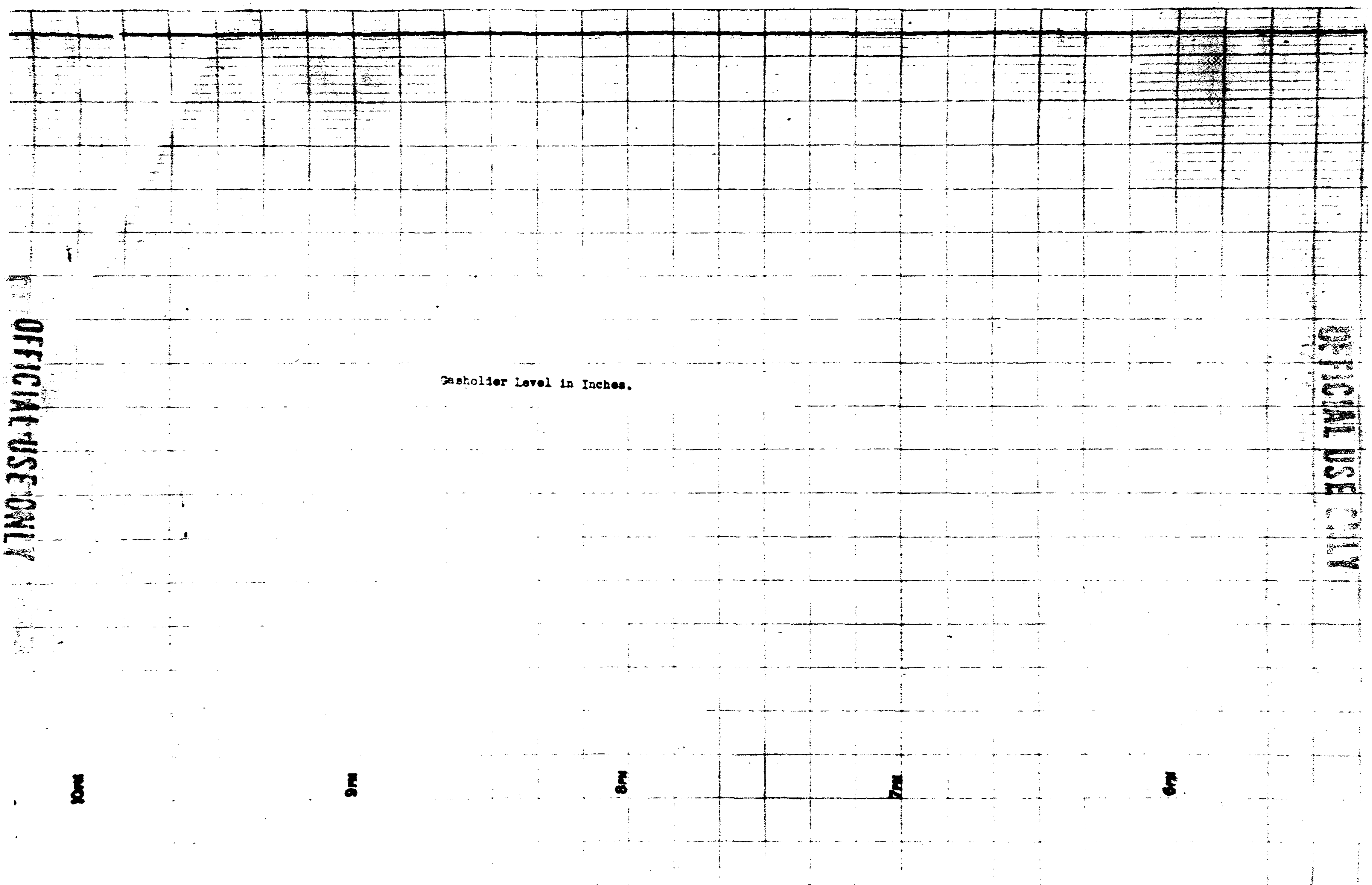

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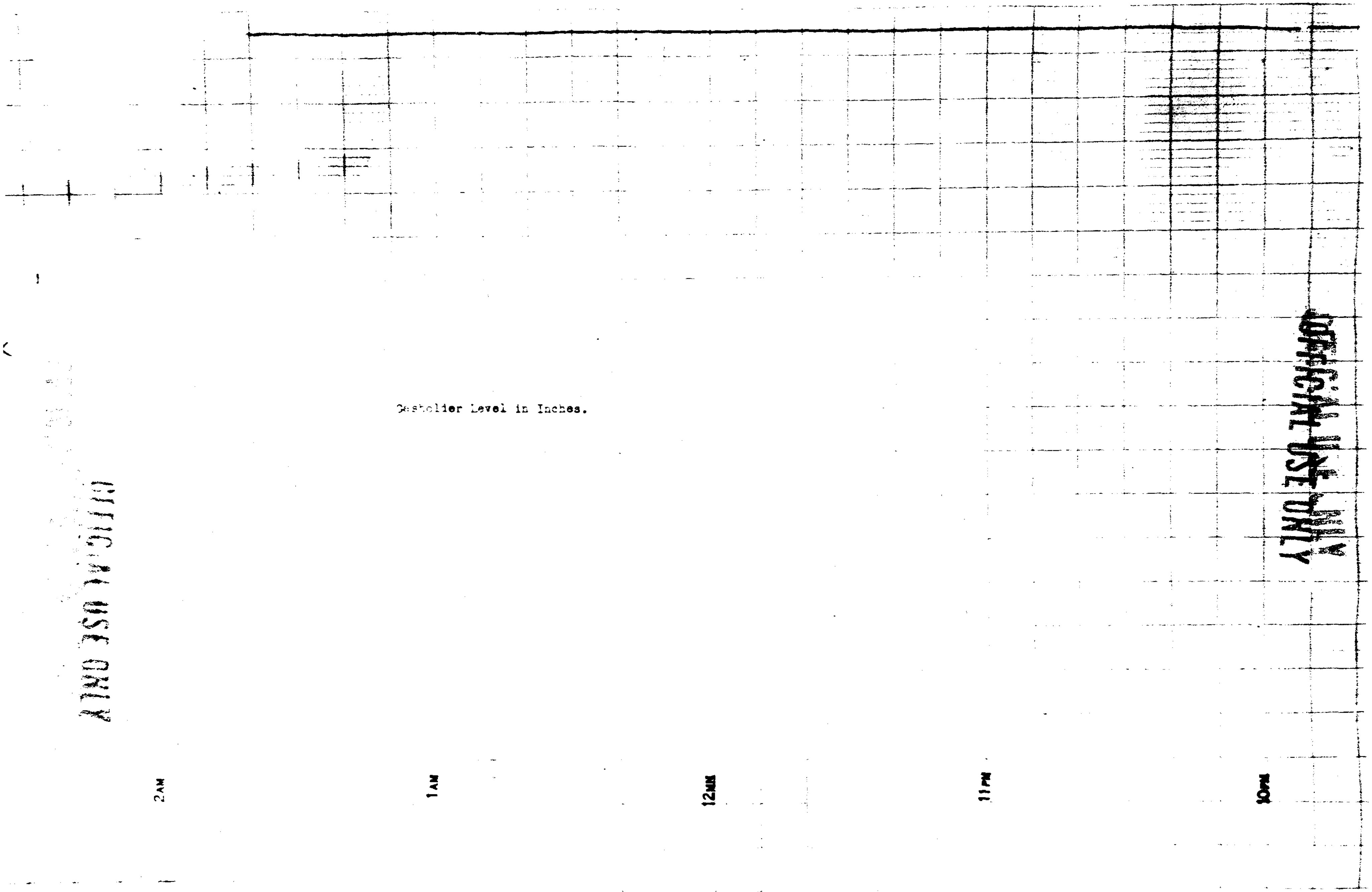

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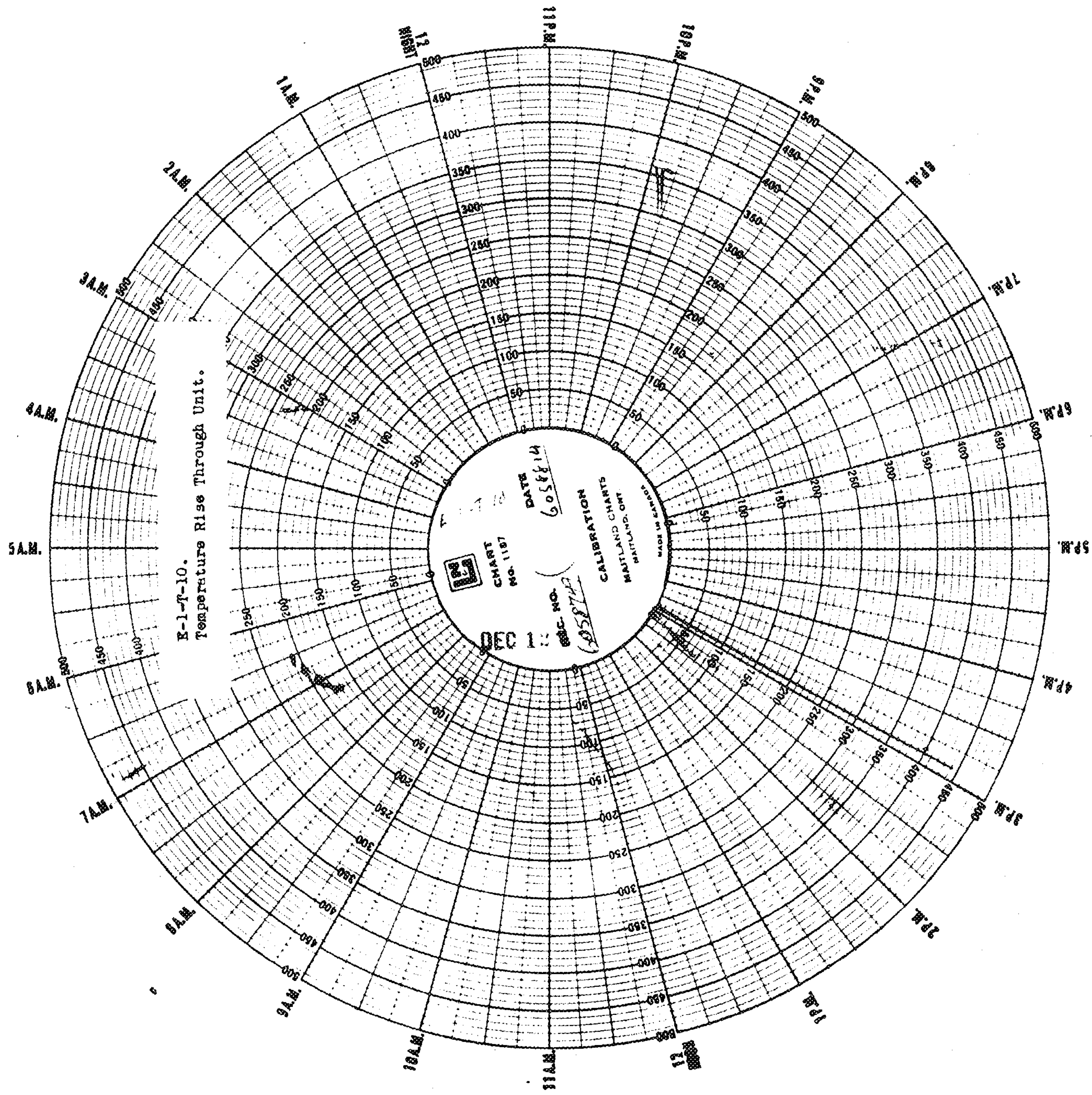

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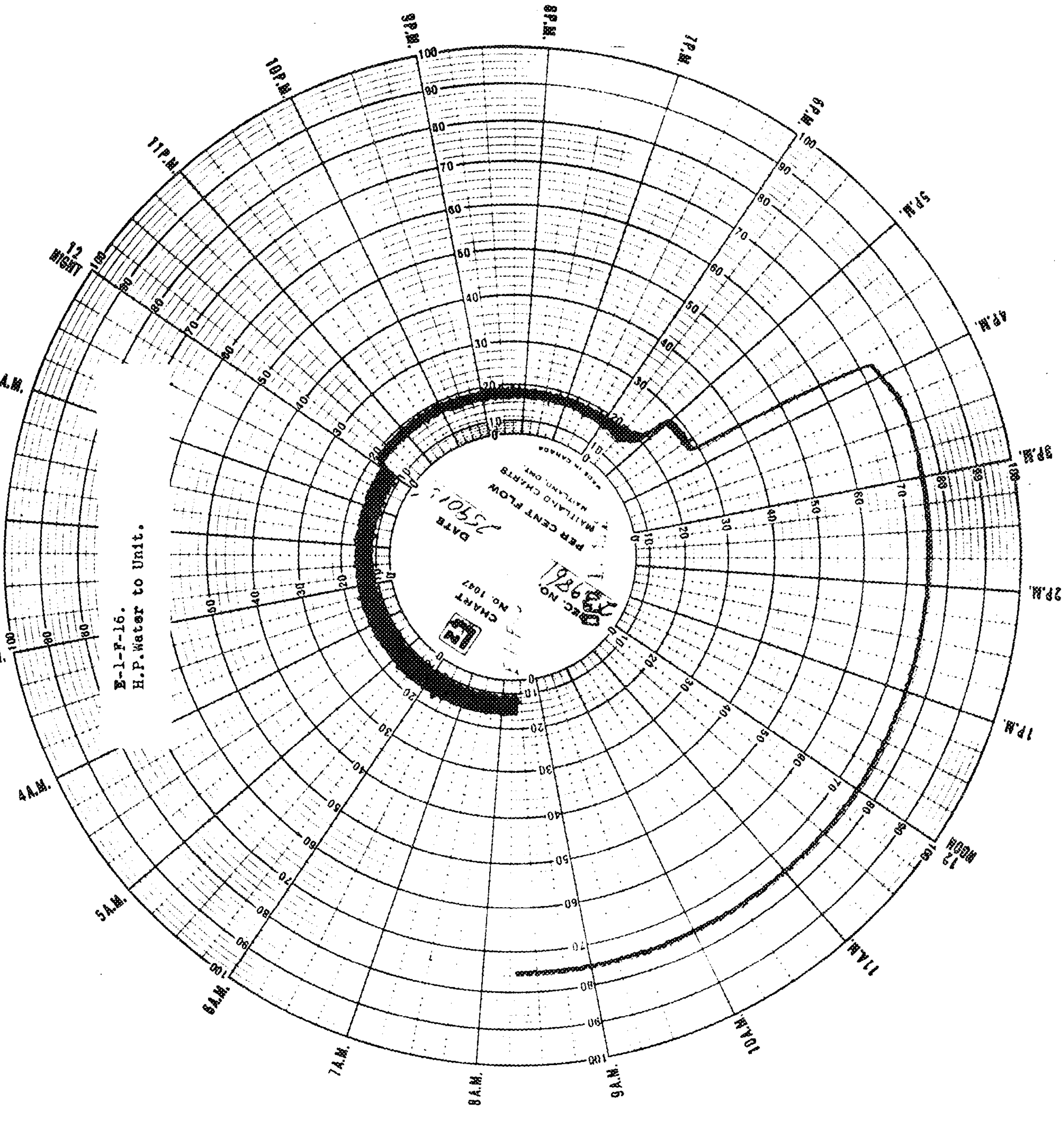

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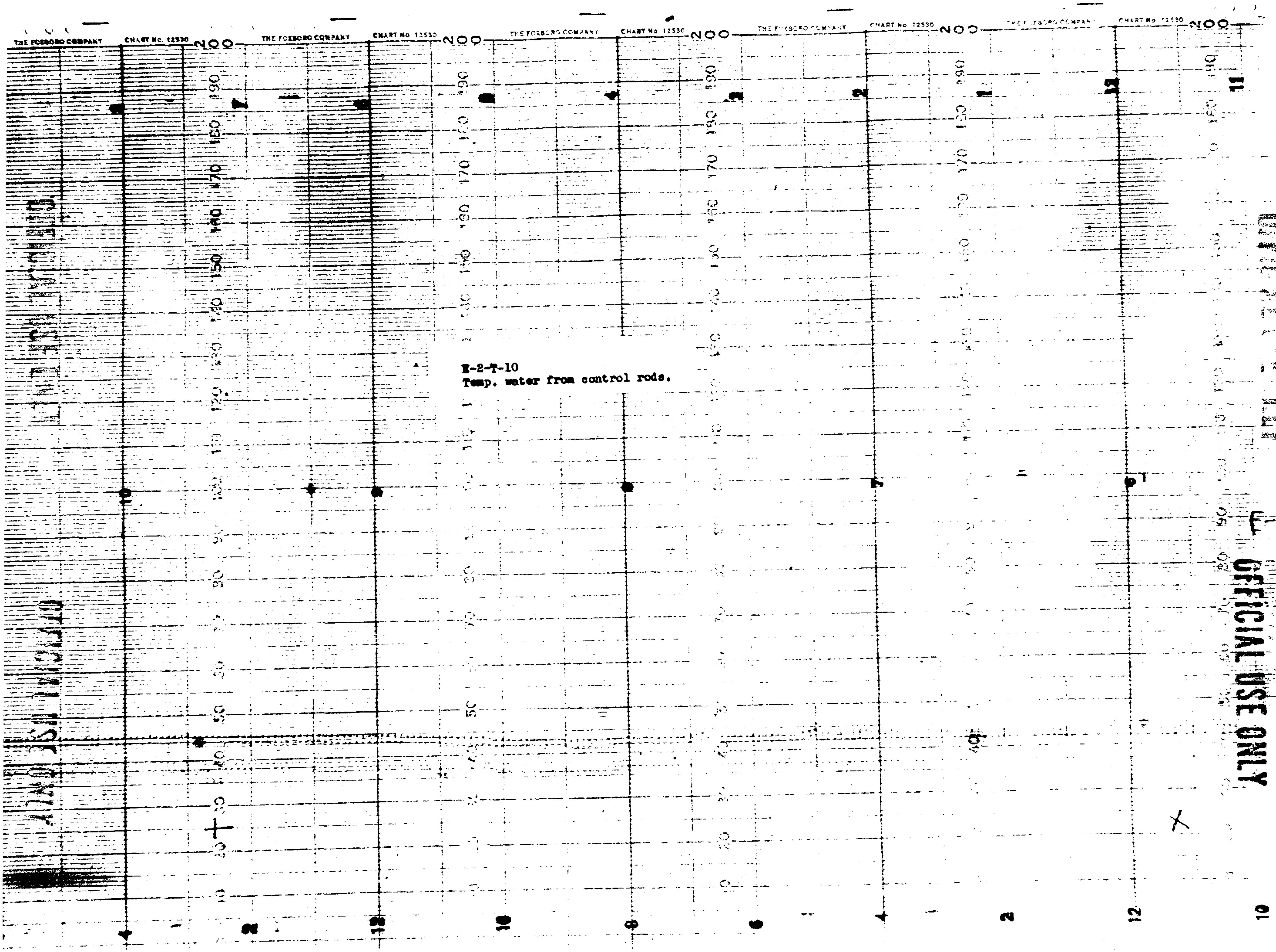

E-2-T-10
Temp. water from control rods.

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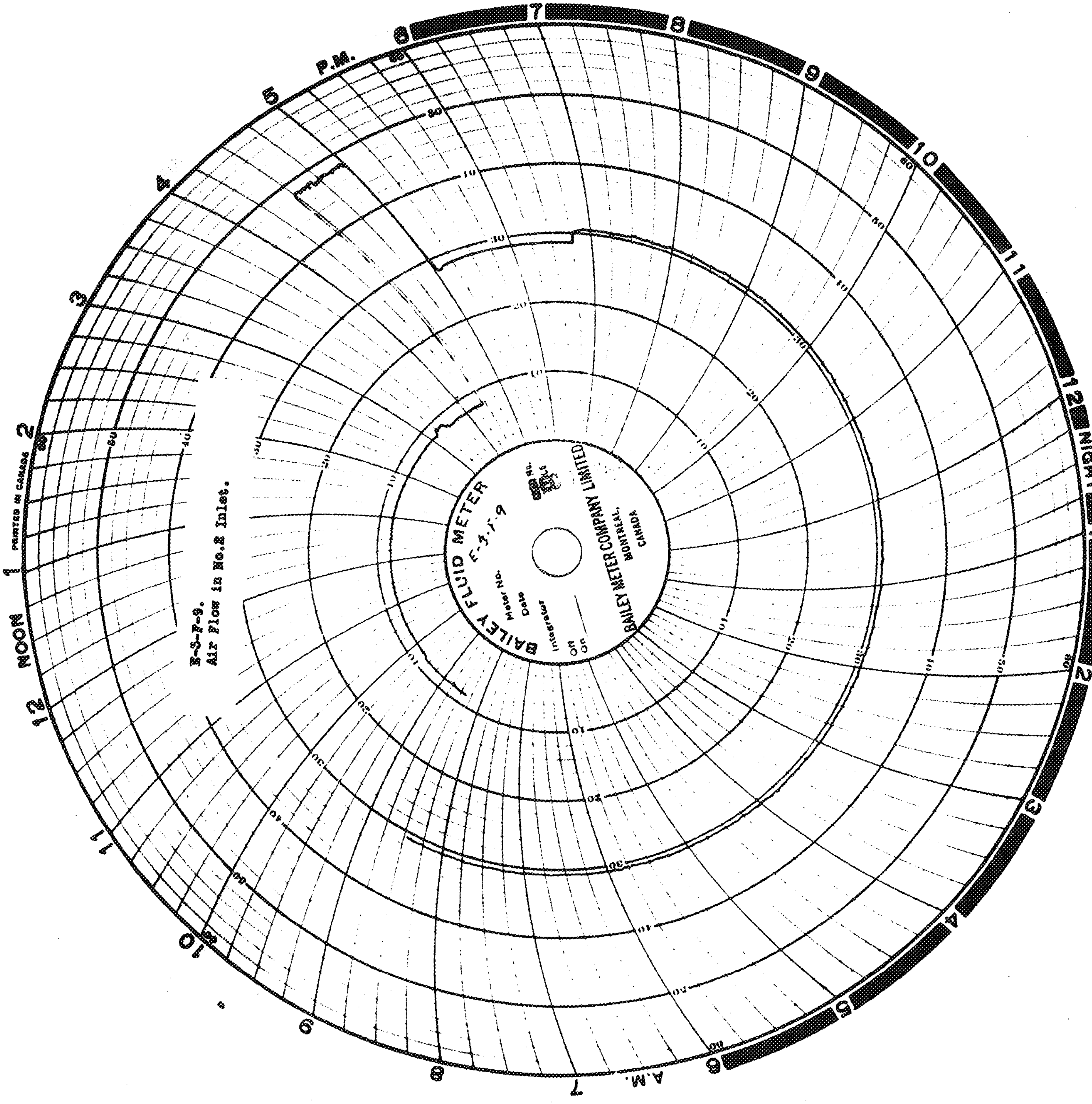

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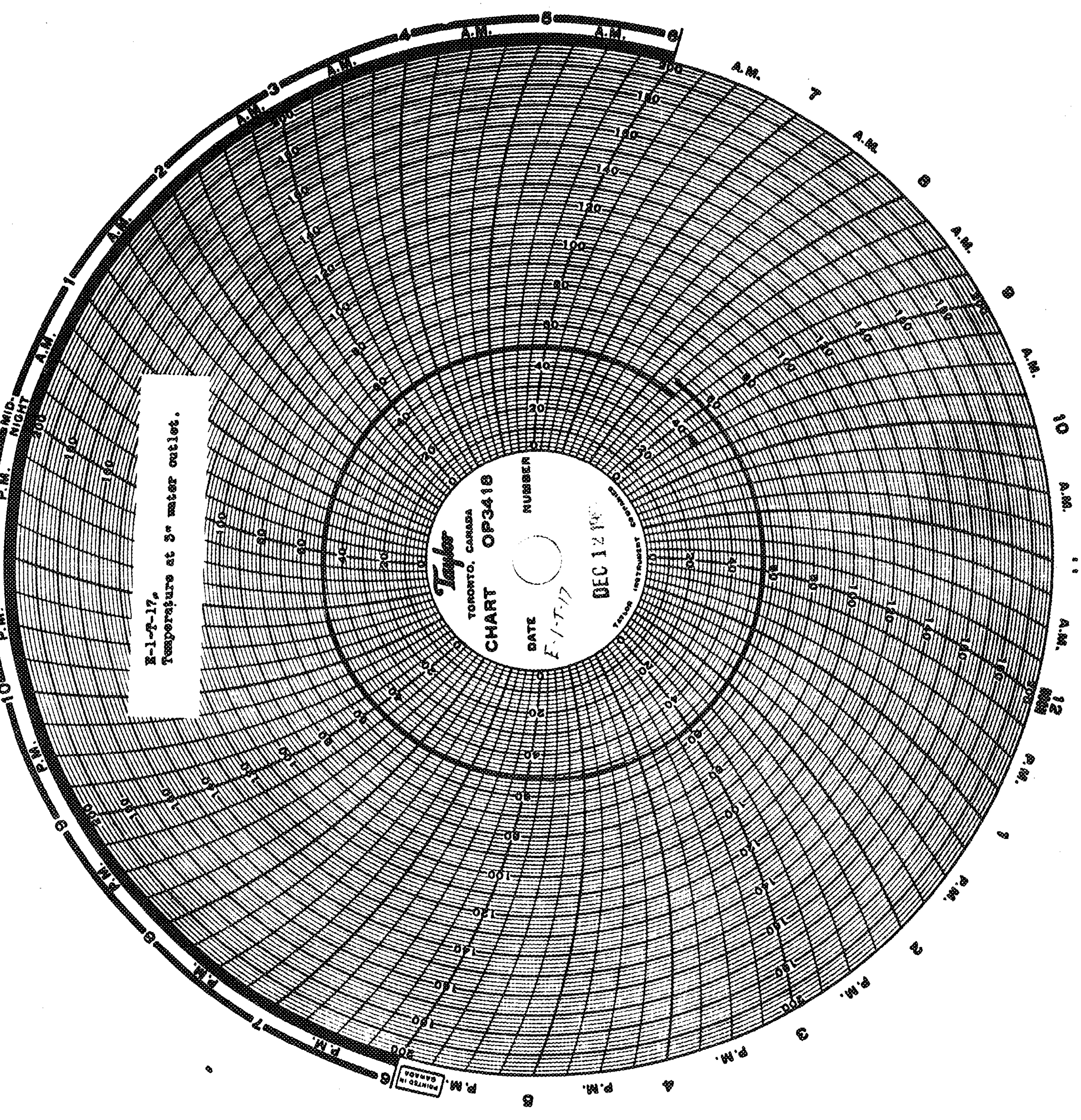

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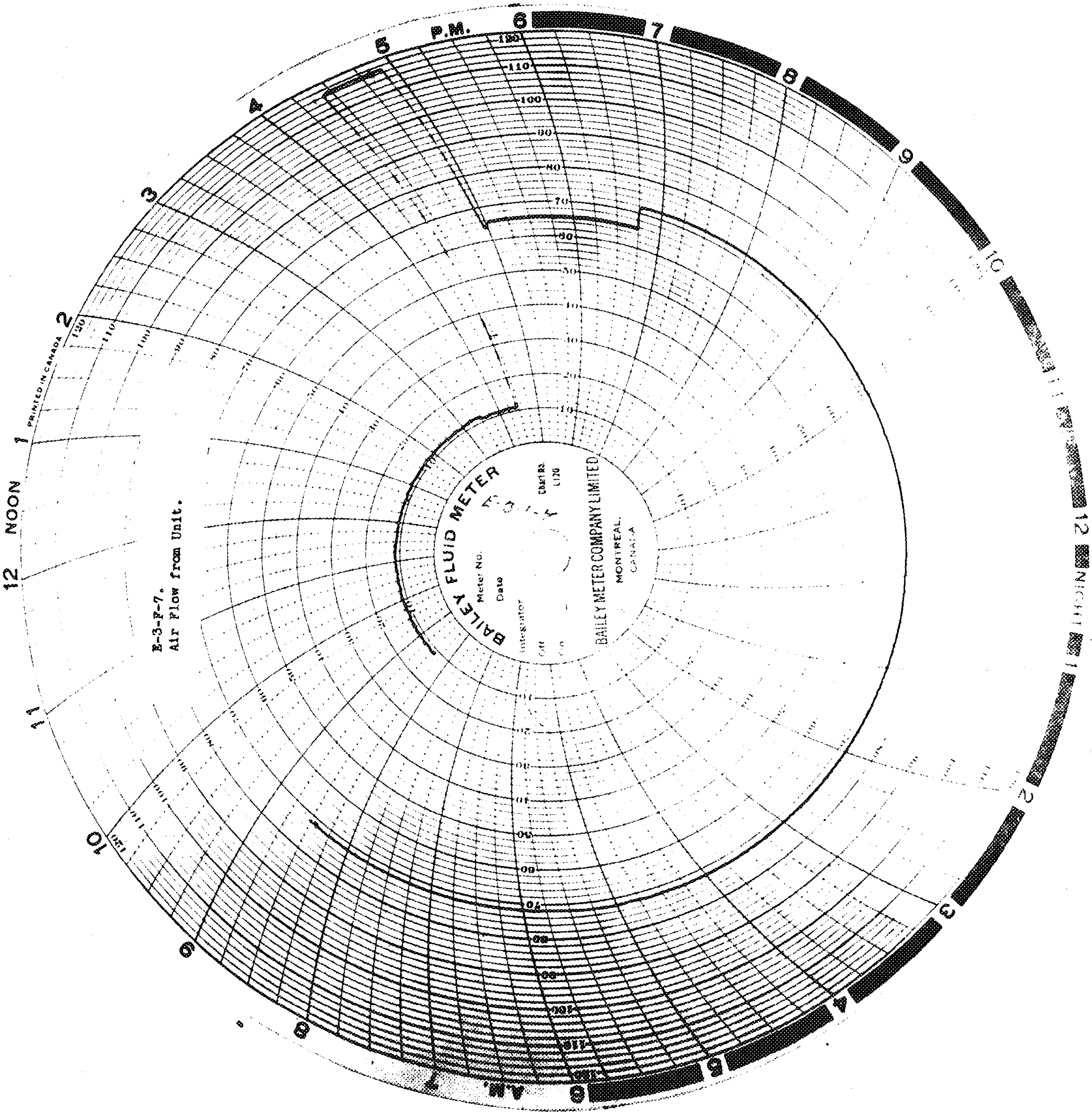
OFFICIAL USE ONLY



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5

E-5-H- 37.
Weir Box Position.

4

OFFICIAL USE ONLY

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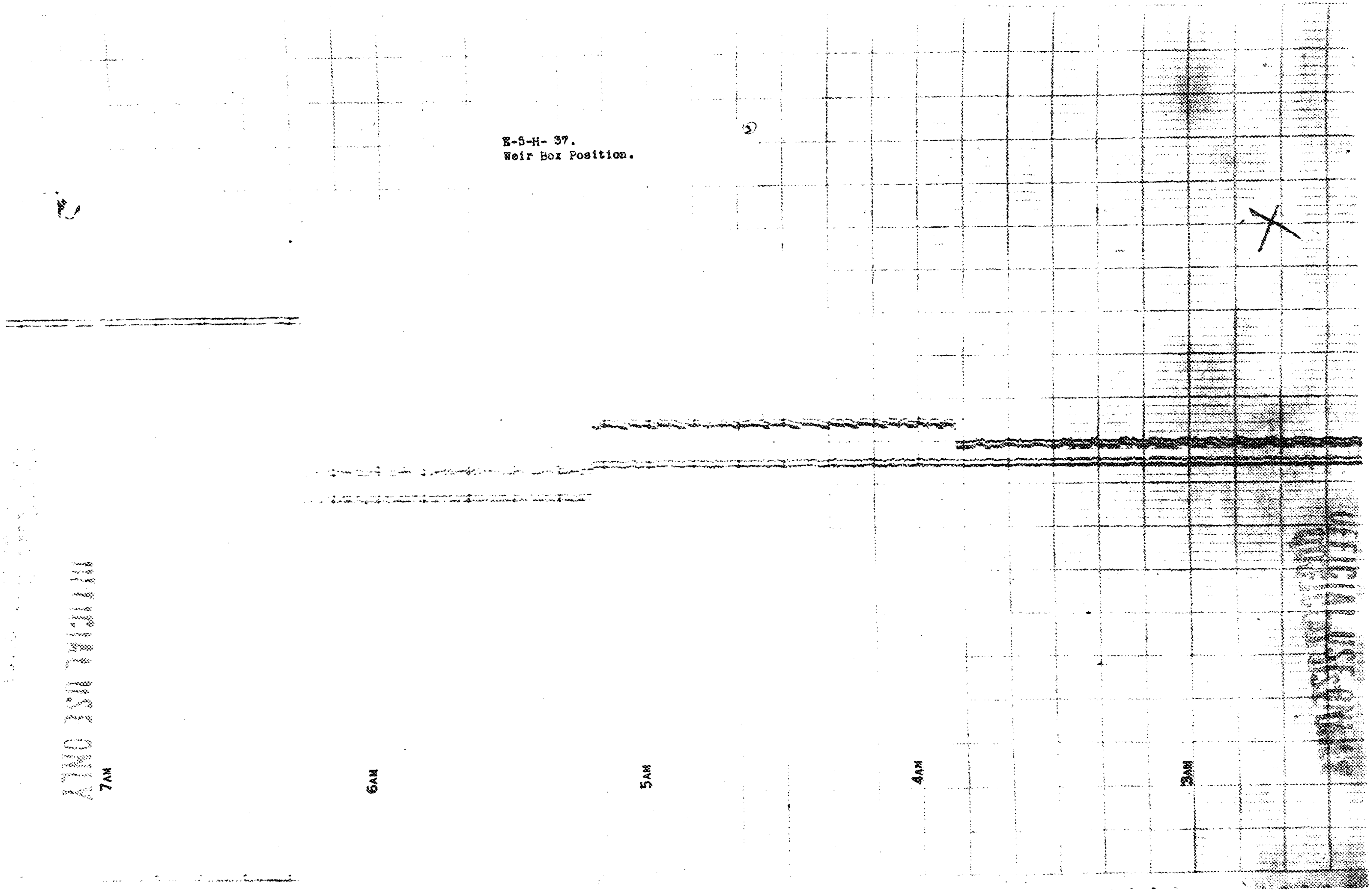
5PM 4PM 3PM 2PM 1PM

E-5-H- 37.
Weir Box Position.



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E-5-H-37

E-5-H- 37.
Weir Box Position.

DEC 1 3 1952

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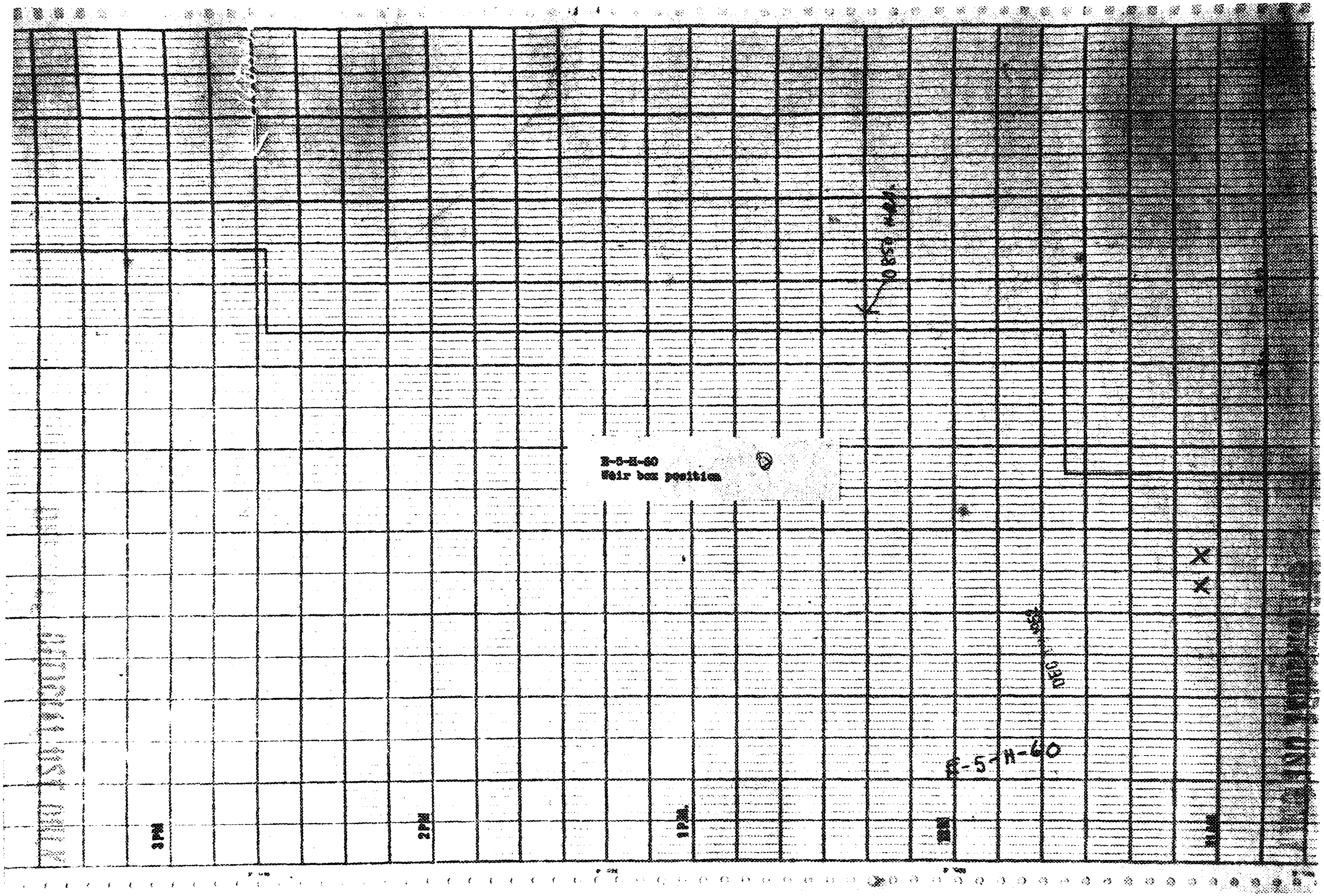
12N

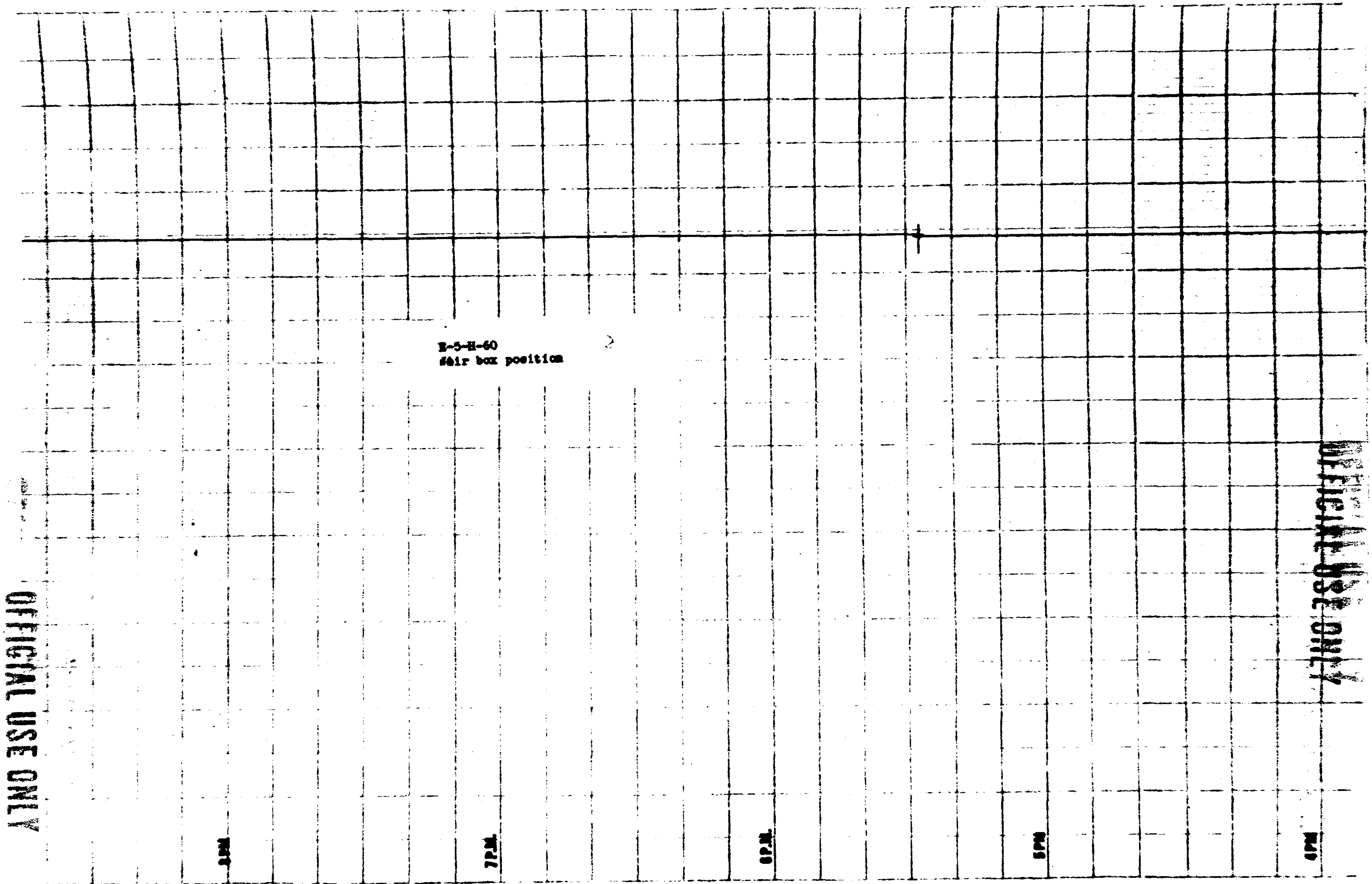
11 AM

10AM

9AM

8AM


E-5-H-60
Weir box position
E-5-H-60
3PM
2PM
1PM



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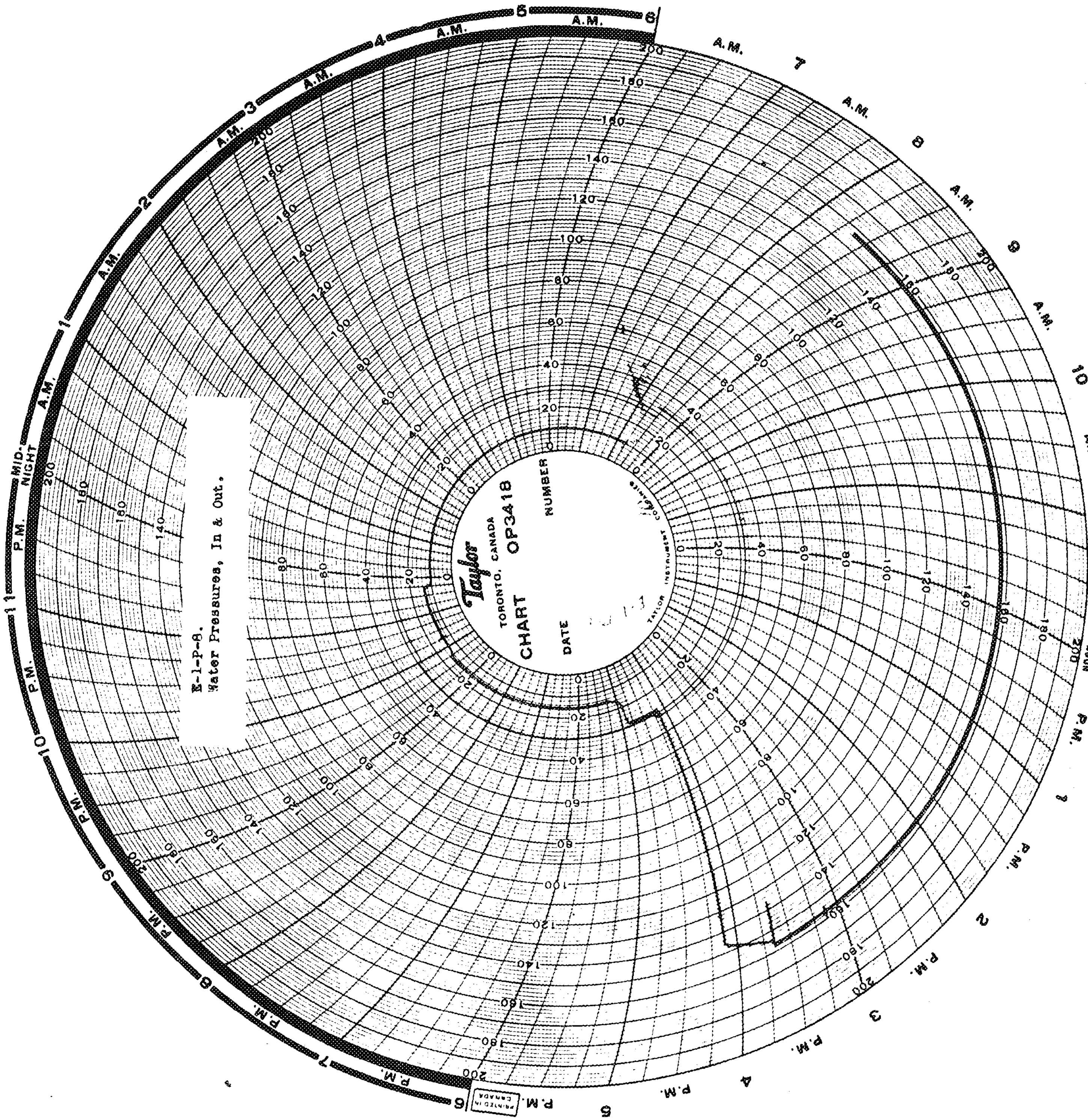

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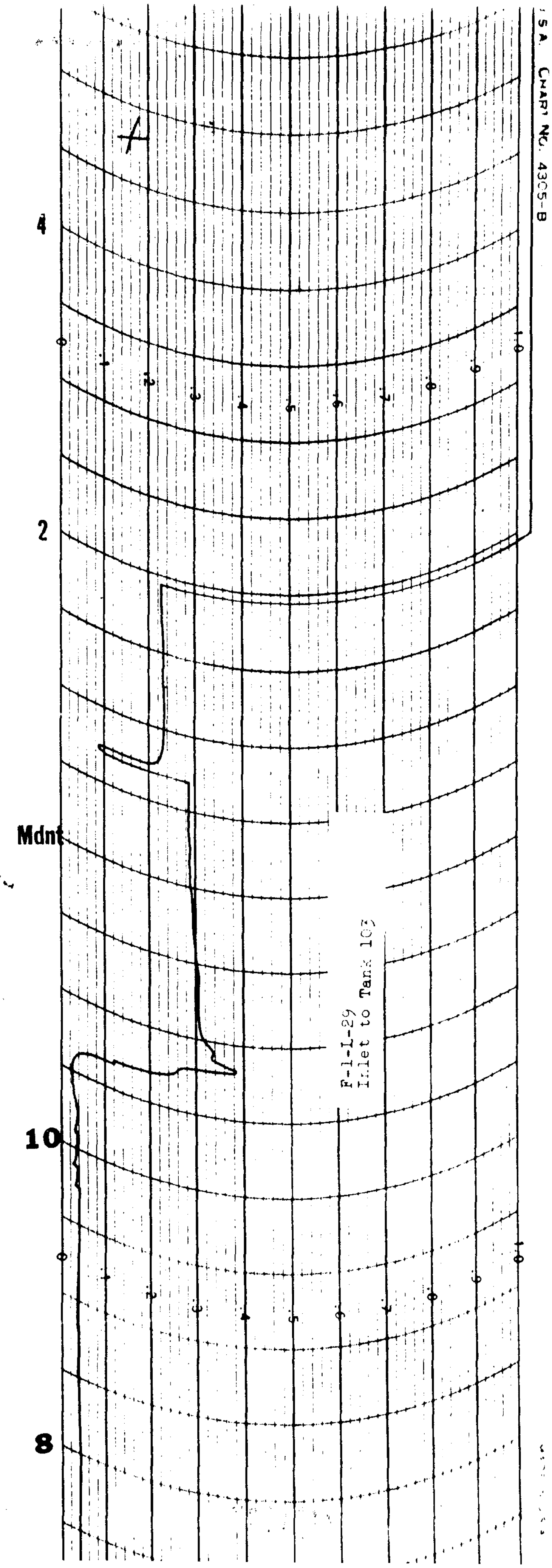

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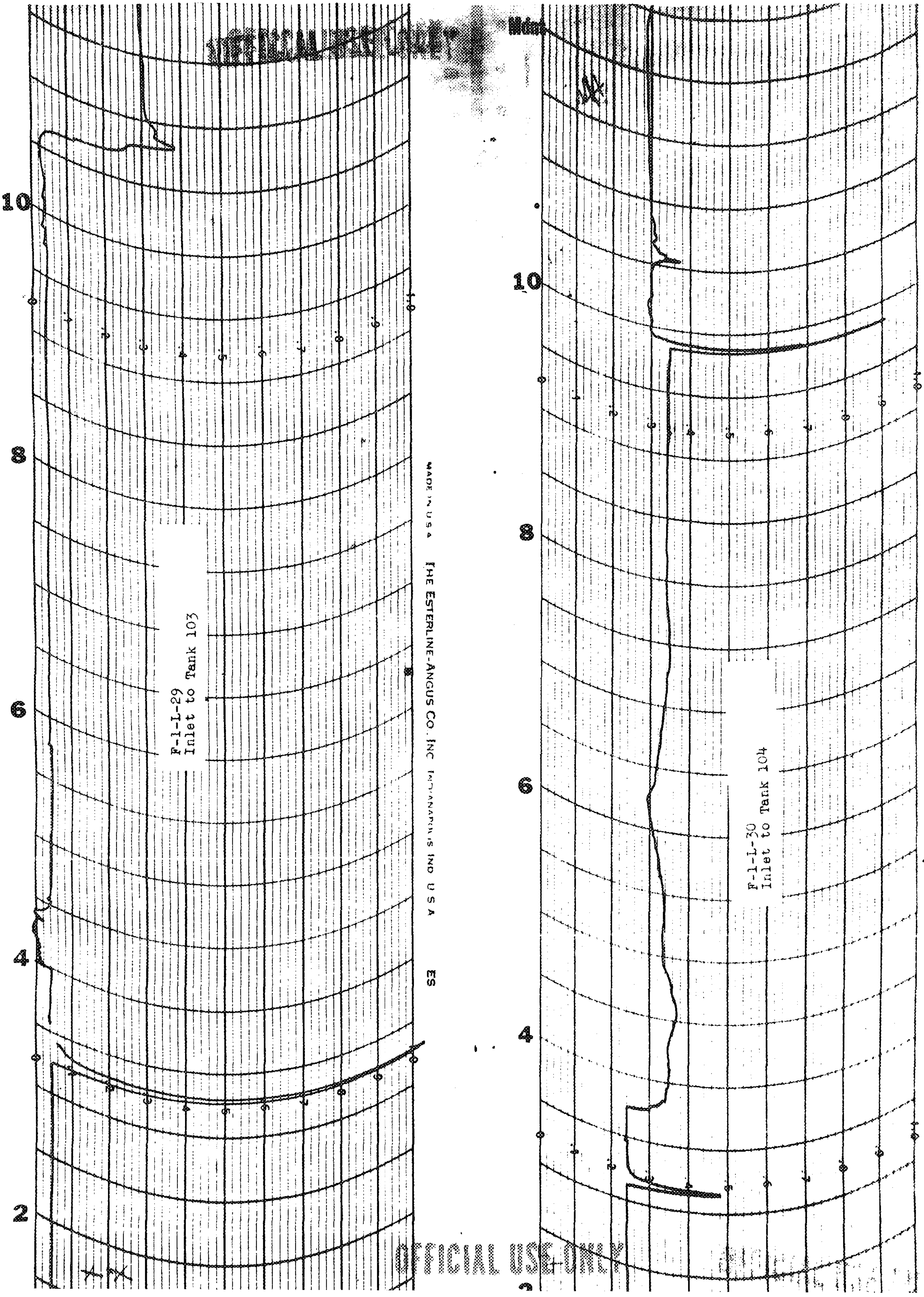
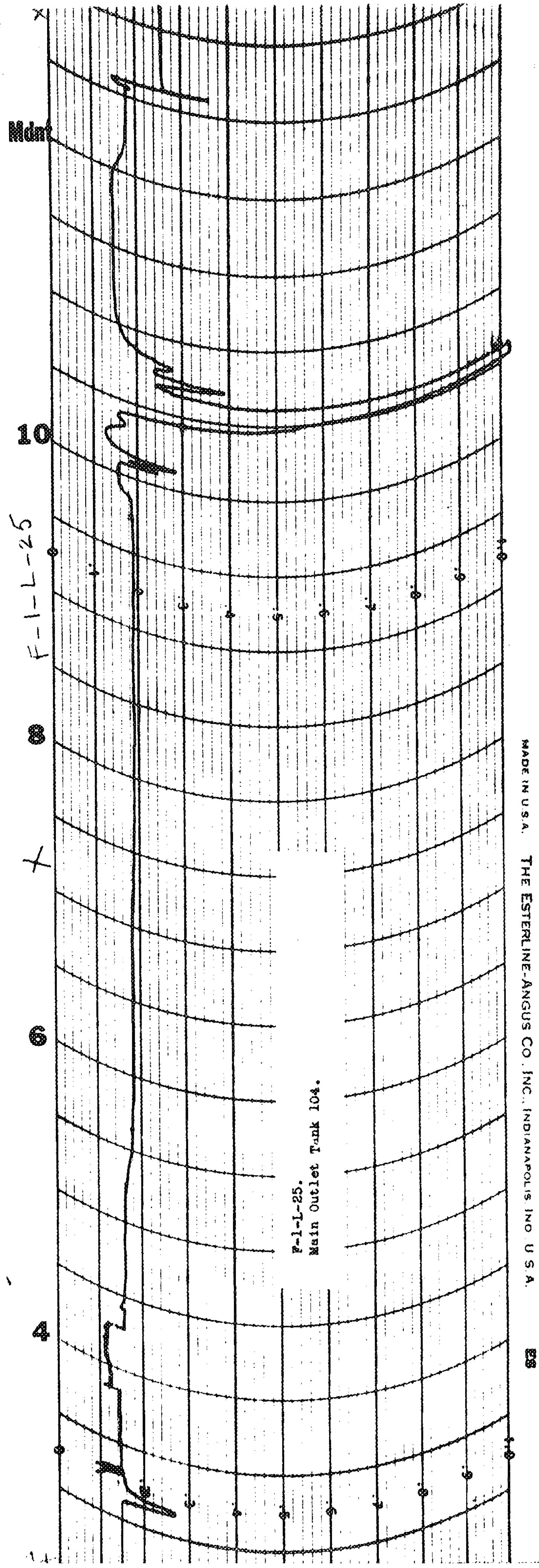


F-1-L-29
Inlet to Tank 103
F-1-L-30
Inlet to Tank 104
MADE IN U S A
THE ESTERLINE-ANGUS CO. INC INDIANAPOLIS IND U S A
ES
10
8
6
4
2
OFFICIAL USE ONLY

OFFICIAL USE ONLY



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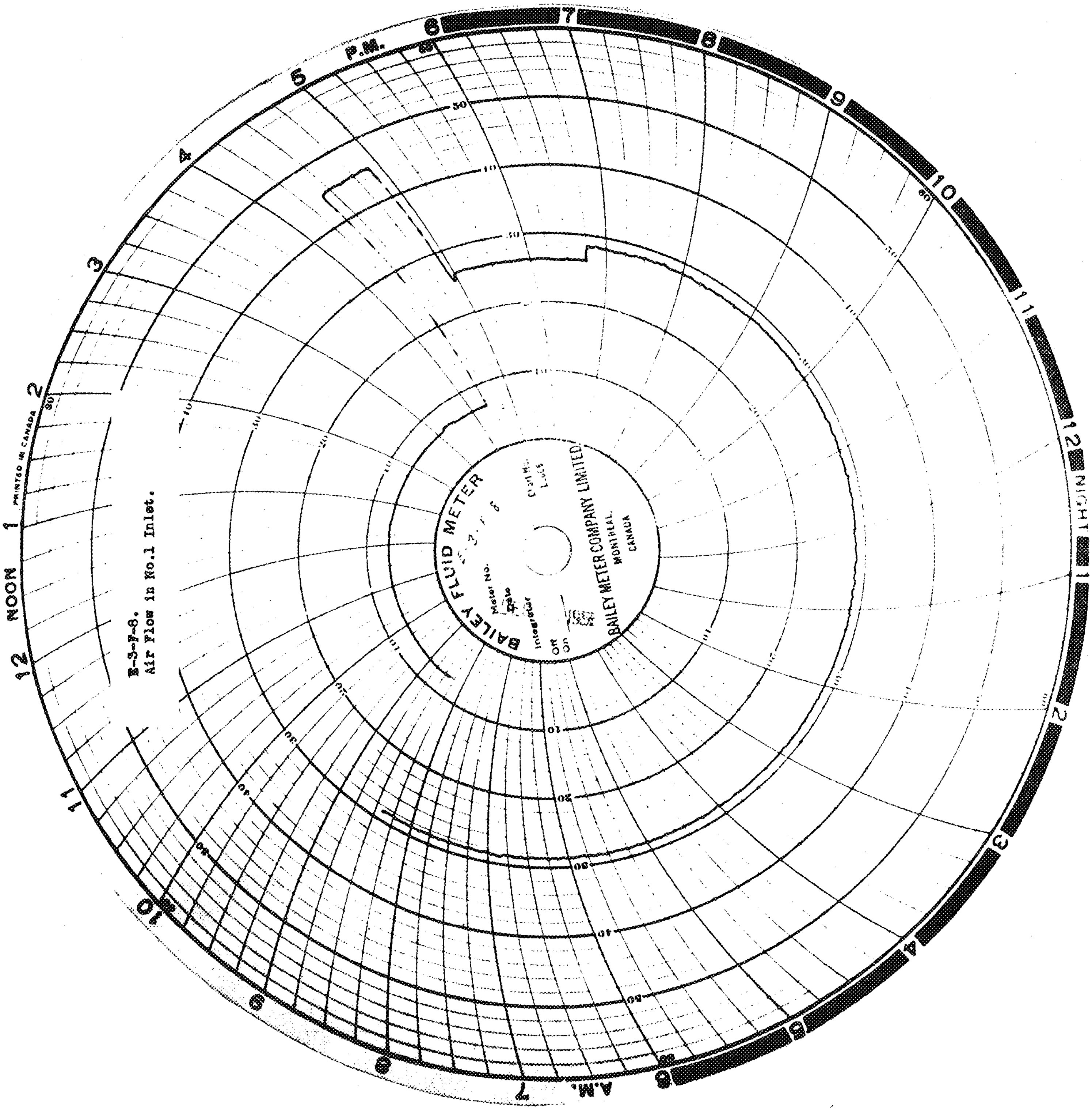

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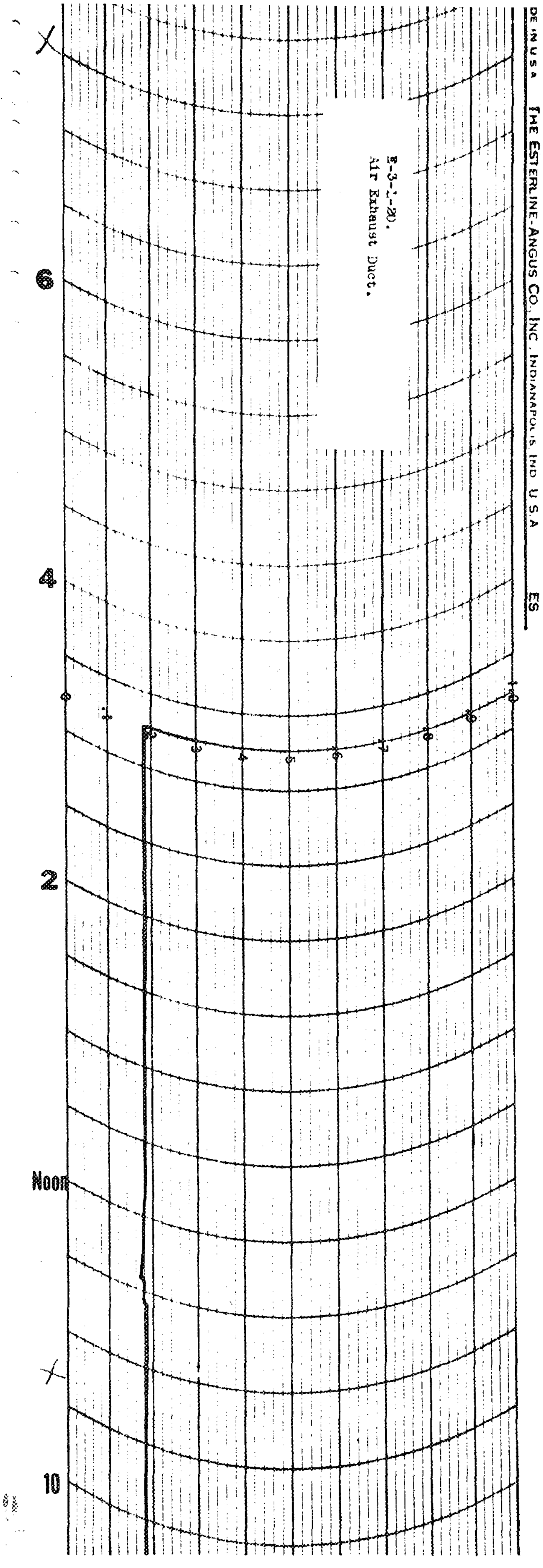
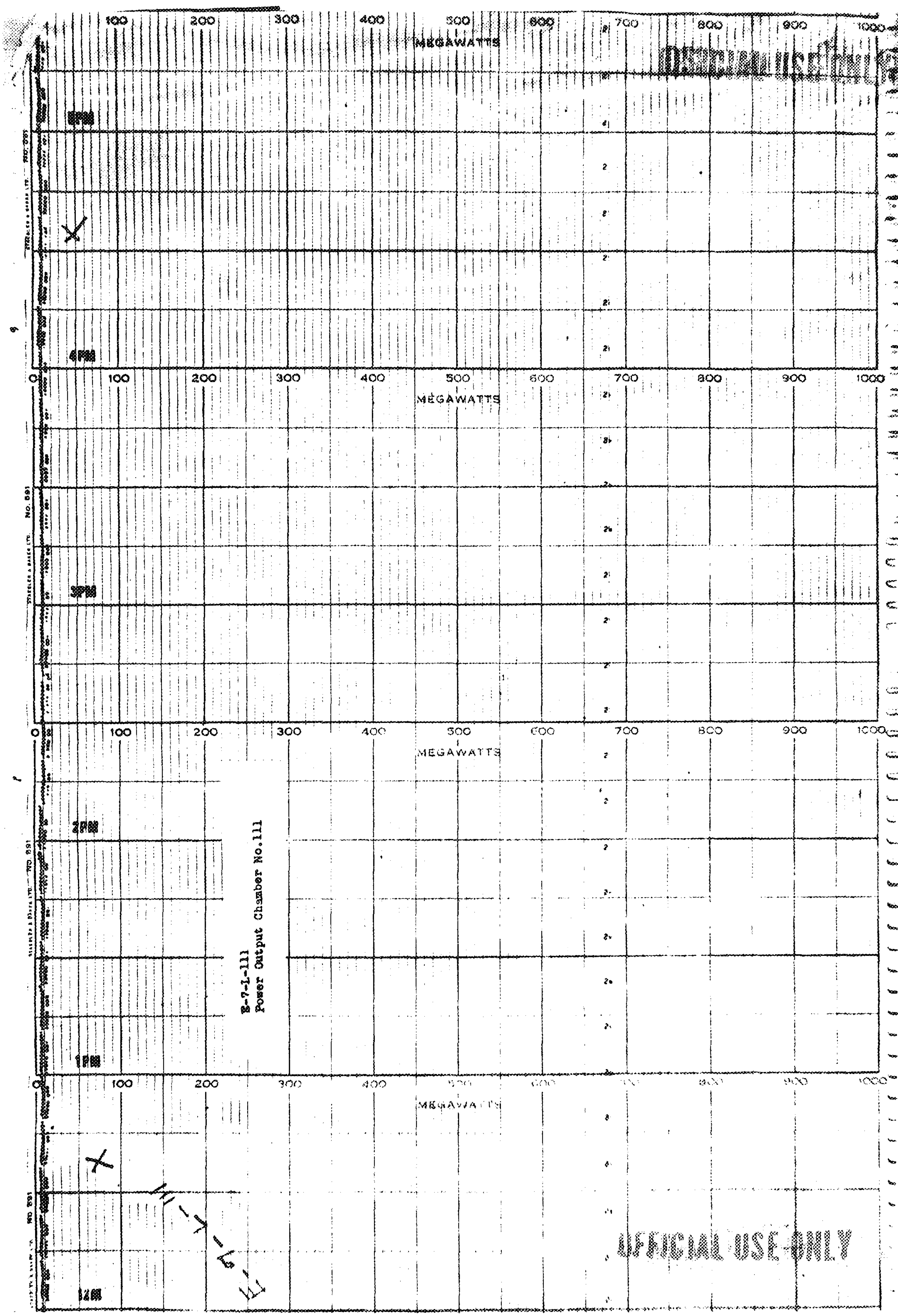
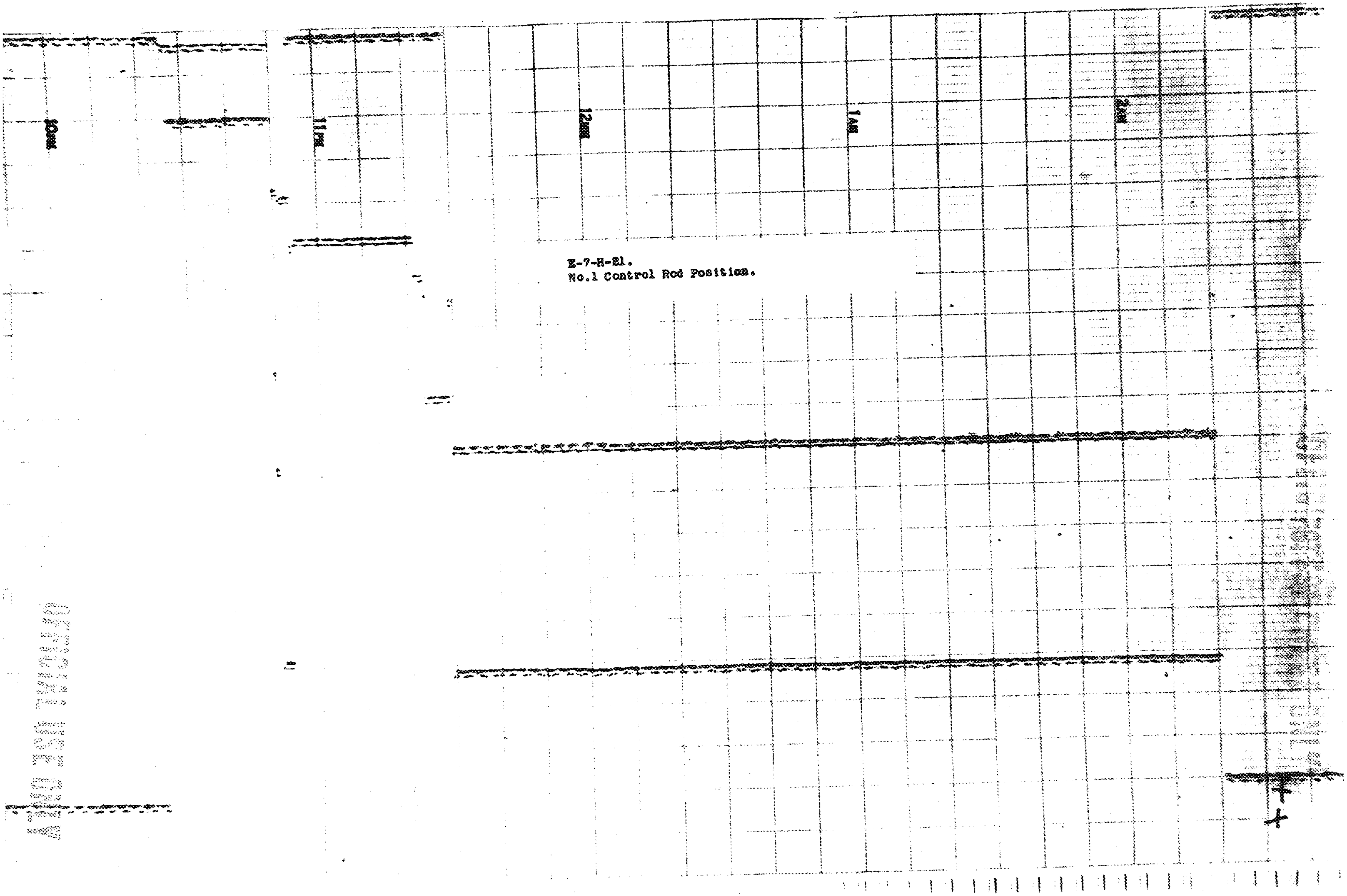


THE ESTERLINE-ANGUS CO. INC. INDIANAPOLIS IND U.S.A
ES
Air Exhaust Duct.
6
4
2
Noon
10



MEGAWATTS
0
100
200
300
400
500
600
700
800
900
1000
5PM
4PM
3PM
2PM
1PM
12M
E-7-1-111
Power Output Chamber No.111
OFFICIAL USE ONLY



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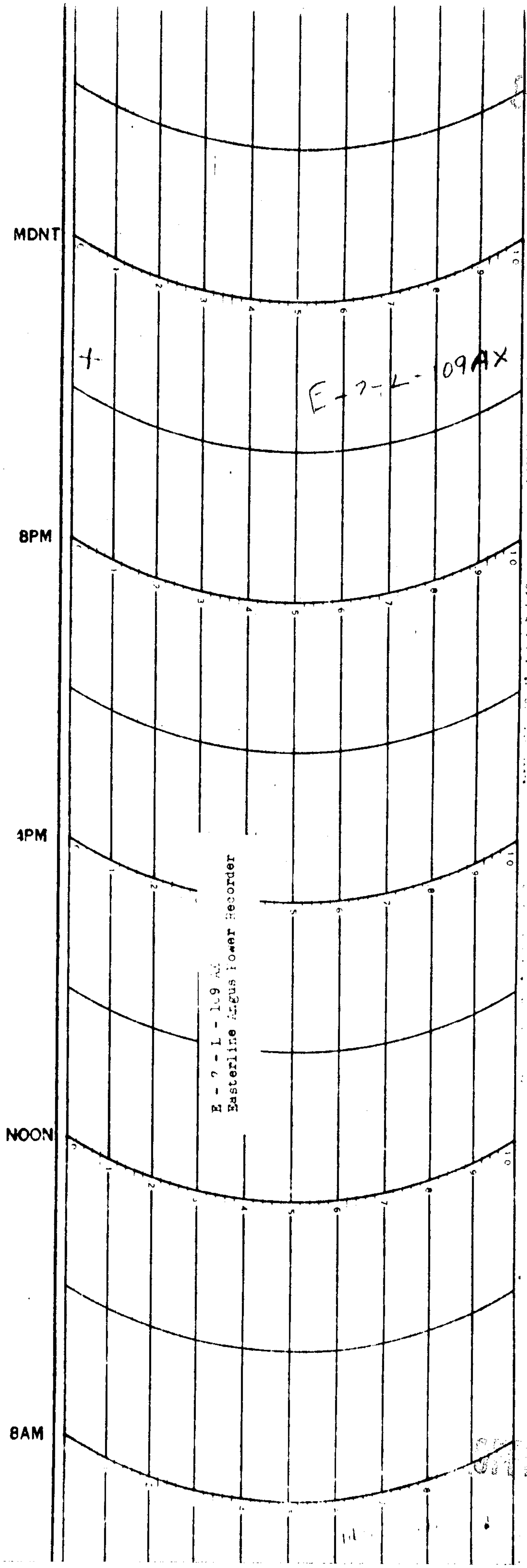

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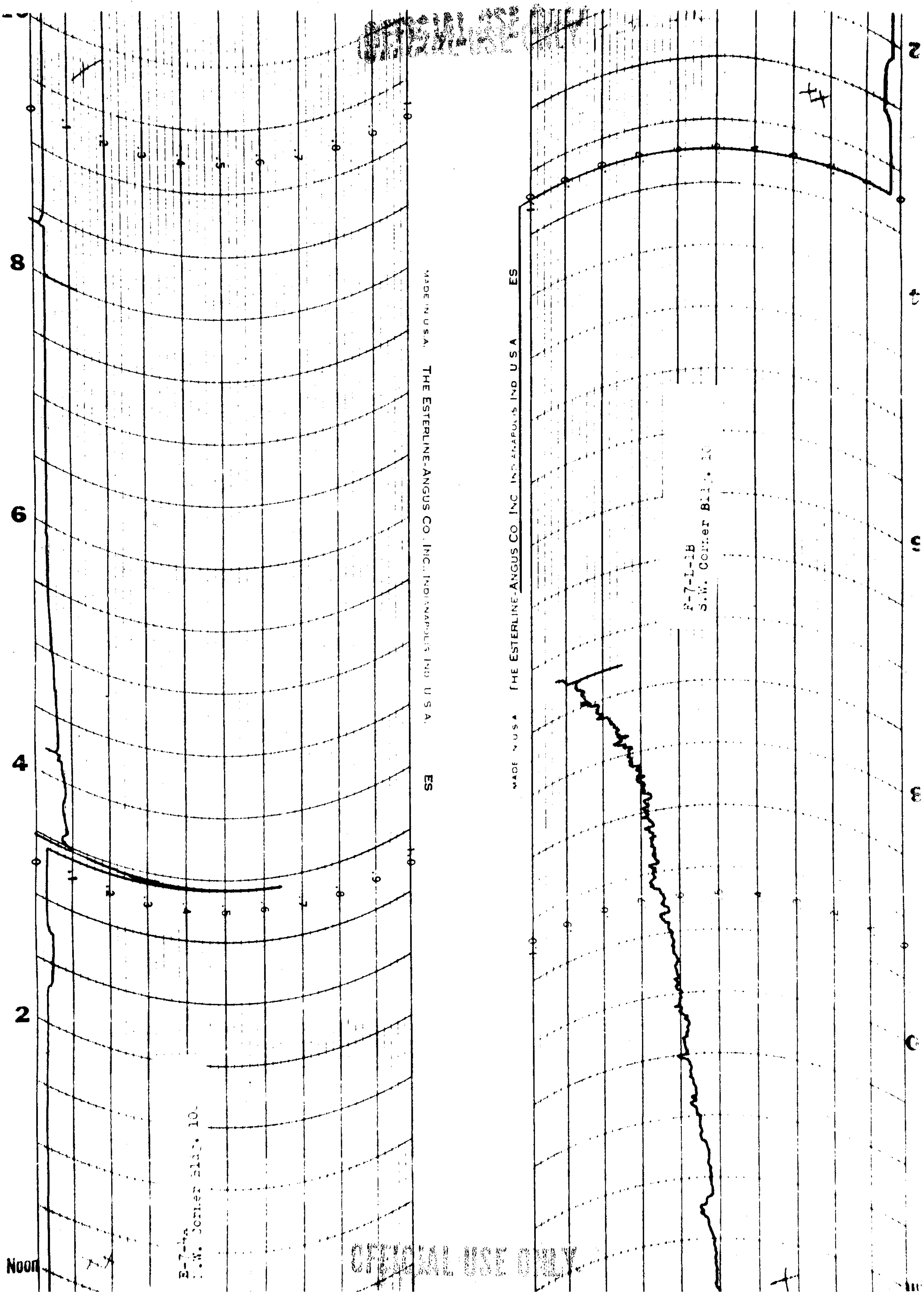

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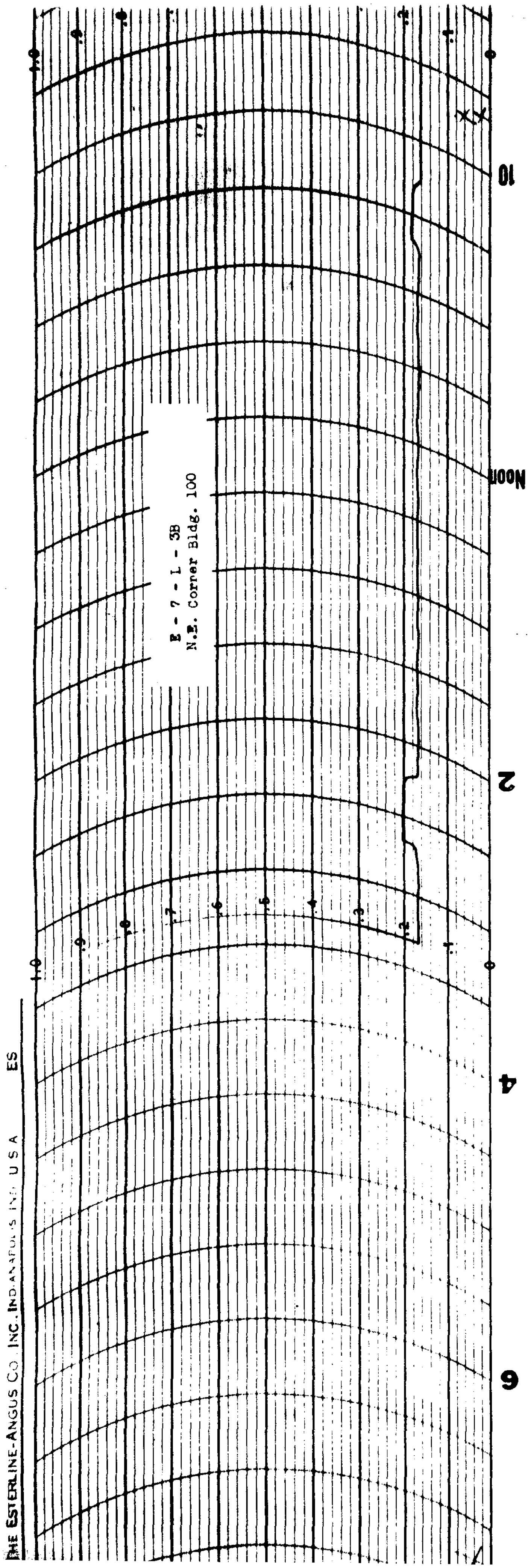
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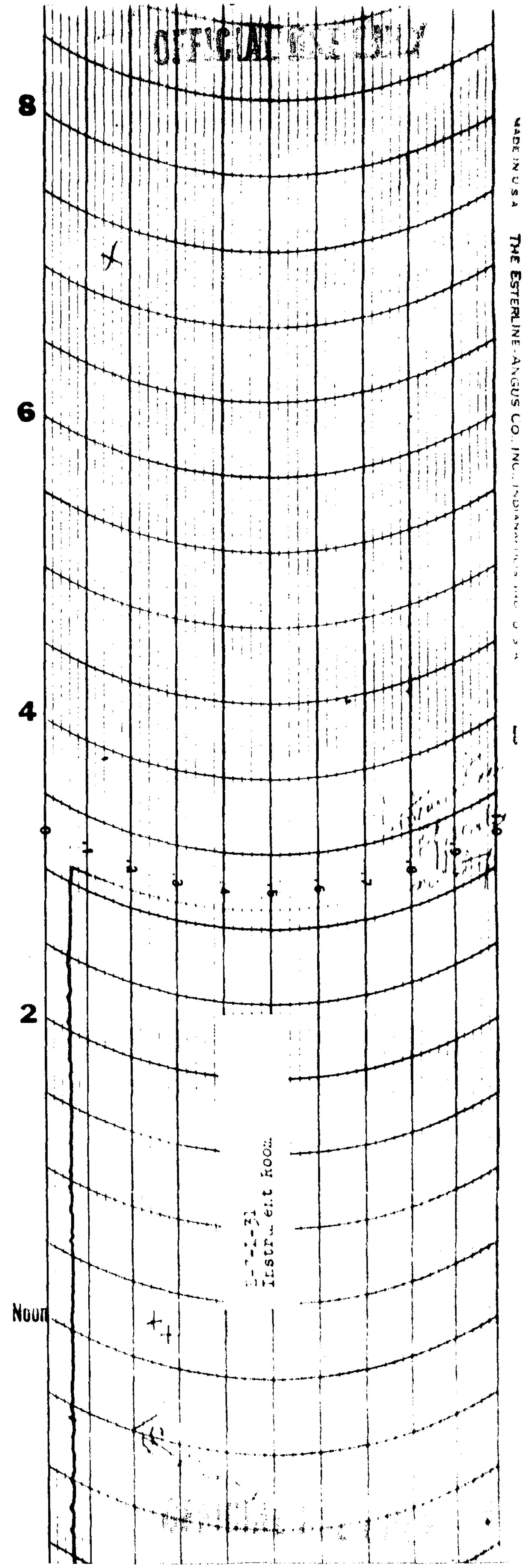
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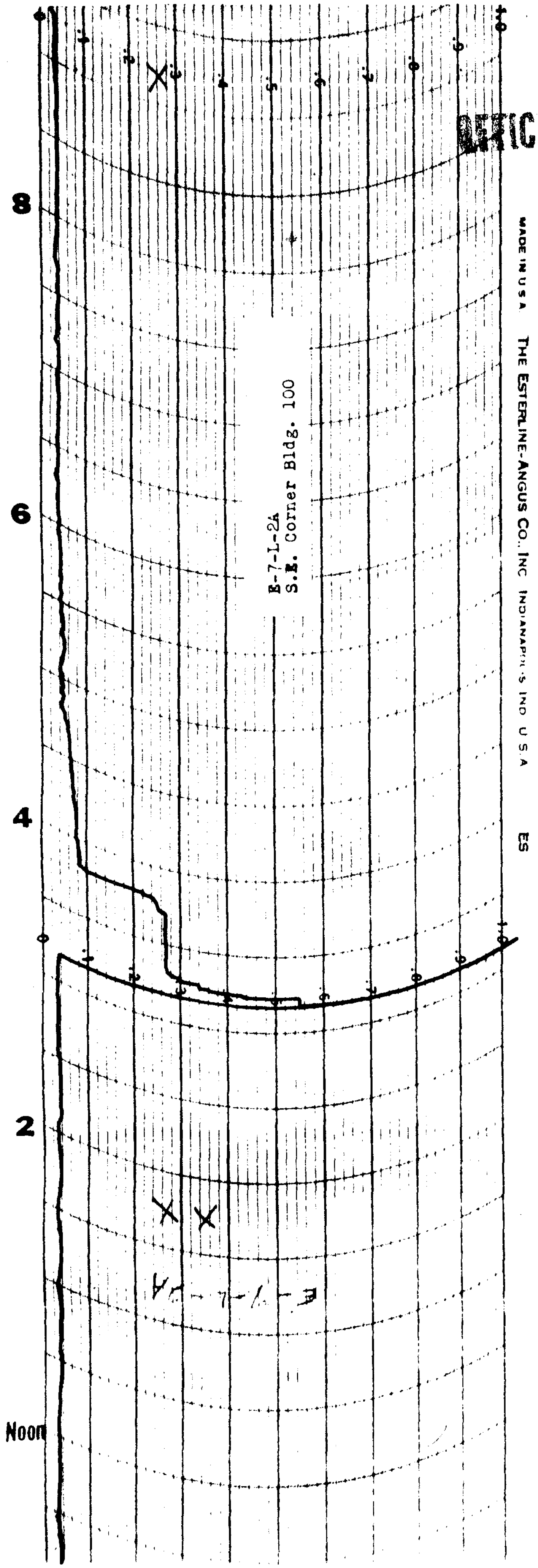

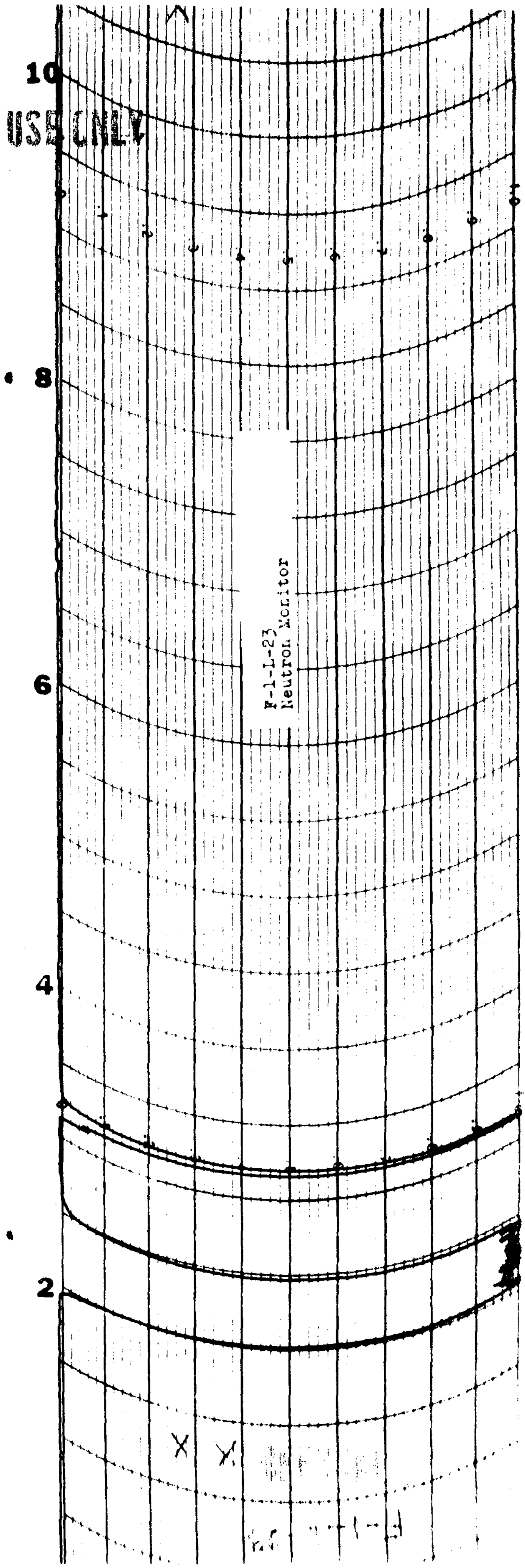

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