AN EXPERIMENTAL INVESTIGATION OF DYNAMIC
THERMAL PERFORMANCE OF A FLAT SOLAR ENERGY COLLECTOR

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ABSTRACT

An experimental investigation of the dynamic thermal performance of a flat solar collector was conducted in the heat transfer laboratory of Concordia University.

A lamp of 1.6 kilowatts, having a peak energy at a wavelength of 1.1 μm, was used to simulate the solar radiation.

A pump was used to circulate water through the collector. This pump was controlled by the difference between the water temperatures at the collector outlet and at the water storage tank outlet which was connected to the collector inlet via the pump.

The thermal efficiency of the solar collector depends on the control of the temperature difference and the water flow rate passing through the solar collector. In order to increase the efficiency of the solar collector, the following are recommended:

(1) a control with a small temperature difference.
(2) a maximum continuous water flow rate for a fixed temperature differential control, which ensures a constant temperature of the water at the outlet of the collector.

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C_p	specific heat of water at constant pressure, in J/g °C
E_p	pumping power averaged over a total period of a cycle, in watts.
E_s	power given to solar collector, in watts.
M	mass circulated through the solar collector during the pumping period, in kg.
Q	output heat carried by the flowing water through the solar collector during a heating and pumping period, in kJ
q	rate of output heat carried by the flowing water through the solar collector, averaged over a total period of a cycle, in watts.

T_i	temperature of the cold water entering the solar collector, in ^oC.
T_m	mean temperature of the water collected from the outlet of the solar collector during the pumping period, in ^oC.
t_h	heating period (pumping is stopped), in seconds
t_p	pumping period, in seconds
t_t	equal $t_h + t_p$, total period of a cycle, in seconds
ΔT	temperature control differential (TCD): difference between the water temperatures at the solar collector outlet and at the water storage tank outlet which is connected to the collector inlet via the pump, in ^oC.
ON:	the temperature difference at which the control switches on the power to the water pump.
OFF:	the temperature difference at which the control switches off the power to the pump.
$\dot{V}$	volume flow rate through the solar collector during the pumping period, in cm^3/s
$\dot{V}_m$	maximum continuous flow rate through the solar collector, in cm^3/s

ρ water density, in g/cm^3.

λ wave length, in μm.

η thermal efficiency of the solar collector, in %.

CHAPTER 1

INTRODUCTION

The supreme religious cult of the ancient Egyptians was worship of the Sun, which they considered to be the source of human life.

The world use of energy has been increasing recently at a rate of roughly 5.7% per year, reaching 7×10^{12} watts in 1971. The rapid consumption of fossil fuels has alarmed the world and urged scientists and researchers to find and develop other sources of energy. Two energy sources that will last as long as mankind lasts are solar energy and nuclear fusion energy.

The total solar radiation in space is as high as 4×10^{27} watts. From which 2×10^{17} watts reaches the earth. Solar energy will only be utilized when it is competitive with alternative energy sources. The most immediate large scale applications would be for the heating and cooling of buildings, heating water, and supplying heat for industrial and agricultural drying operations. Sunlight can also be utilized directly for pollutionless electric power generation.

The flat solar collector is the most popular device to collect solar energy at modest temperatures, and the most frequently considered device for use in the heating of domestic water.

For a solar water-heating system with forced convection, a pump is required. The pump should start to circulate water through the solar collector when the water temperature at the collector outlet is higher than that of the water in the storage tank. The flow should stop when the water temperature at the collector outlet is equal to or lower than that of the water in the storage tank. In the literature very little information on the effect of the pumping characteristics on the thermal efficiency of a solar collector is available. The purpose of the present investigation is to determine this effect experimentally, in order to utilize the solar collector system more efficiently.

CHAPTER 2

THE FORCED-CIRCULATION SYSTEM

2.1 GENERAL

In order to investigate, experimentally, the dynamic thermal performance of a flat solar collector, a forced-circulation system was designed and installed in the heat transfer laboratory of Concordia University as shown in Fig. 2.1.

2.2 DESCRIPTION

The components of the system are shown in Fig. 2.2 and described briefly as follows:

2.2.1 SOLAR COLLECTOR

The flat collector is 91.5 cm wide and 122 cm high. Forty-two 1.27 cm diameter copper tubes flattened to an oval cross-section and parallel to the height of the collector, are connected to two horizontal 2.5 cm diameter headers at the top and bottom of the collector, with adequate T-joints. The tubes are coated with a black enamel paint. The solar collector is covered with two glasses which have an air space of 2.54 cm in between, each glass having a thickness of 3.2 mm and a transmittance of 87%. The wooden frame is well insulated at the bottom. The flat solar collector was inclined 43° to the horizontal.

2.2.2 LAMP

A lamp, having a power of 1600 watts and a peak energy at $\lambda = 1.1\ \mu m$, was chosen to simulate the source of solar energy. The lamp was placed normal to the flat collector at a distance of 34.5 cm from its surface. An efficiency of the lamp of 80% was estimated. During the experiments the lamp was always on.

2.2.3 WATER STORAGE TANK

The water to be supplied to the solar collector was stored in an insulated tank in which a constant head was maintained. Water from the city water supply was flowing continuously through the tank, entering at the bottom and leaving to drain at the top. This continuous flow ensured a constant temperature inside the storage tank, this temperature being equal to the temperature of the tap water which could be adjusted.

2.2.4 CIRCULATING PUMP

Water was pumped through the solar collector entering at the bottom of the collector and leaving at the top. A pump, the suction of which was connected to the water storage tank, provided water circulation at different flow rates through the collector.

The pump was controlled to operate on an ON-OFF basis. The period between ON and OFF positions, in which the pump circulated water through the solar collector, is called the pumping period.

2.2.5 FLOW CONTROL VALVE

A valve at the outlet of the solar collector controlled the water flow rate through the collector. The water flowing through the solar collector during the pumping period was collected in a container and weighed accurately. The system was carefully designed to prevent water from flowing through the collector when the pump was stopped.

2.2.6 TEMPERATURE CONTROL DEVICE

A temperature control device controlled the ON and OFF operation of the pump. The device was controlled by the water temperature difference, ΔT, between the outlet of the solar collector and the outlet of the storage tank which was connected to the collector inlet. The device could be set to achieve desired values of ΔT. Each setting had two operating points: a "ΔT-ON" which controlled the ON of the pump, and a ΔT-OFF which cotrolled the OFF of the pump. ΔT-OFF was smaller than ΔT-ON.

2.2.7 TEMPERATURE RECORDER

During the experiments, it was very important to continuously record the temperatures at four points. These four points are shown in Fig. 2.2 and are described below.

Pt 1 is at the surface of the outlet pipe of the water storage tank, which is connected to the collector inlet.

Pt 2 is in the water inside the solar collector inlet pipe.

Pt 3 is at the surface of the outlet pipe of the solar collector.

Pt 4 is in the water inside the outlet pipe of the solar collector.

Four copper-constantan thermocouples were connected to these points and to a multipoint temperature recorder.

Two control wires connected points 1 and 3 to the temperature control device.

2.3 SYSTEM OPERATION.

Fig. 2.3 shows the temperature records during 9 cycles of the system operation. The temperature readings starting from the bottom of the figure refer to the following stage of the experiment: The temperature control device was set at a fixed ΔT; the power was supplied to the lamp; the pump was not running; the temperature of the water at the collector outlet was higher than that of the water in the storage tank. The radiation increased the surface temperature of the solar collector and heat was transferred to the water inside the collector tubes and raised its temperature until the water temperature at the collector outlet, point 3, was " ΔT - ON " degree higher than the temperature at the tank outlet, point 1. At that instant the temperature control device switched on the power to the pump which circulated cold water from the storage tank through the collector, displacing the warm water inside the collector and cooling the collector. Temperature at point3 dropped until it reached " ΔT - OFF " degree higher than point 1. At that instant the temperature control device switched off the power to the pump. The time elapsed between the switching on and off of the power to the pump is the pumping period t_p . When the flow of water through the collector stopped, the temperature of water inside the collector started to increase again until a temperature difference between points 3 and 1 reached " ΔT - ON" , that elapsed period is the heating period t_h . The pump started and the cycle was repeated. The total period of a cycle $t_t = t_p + t_h$.

CHAPTER 3

PARAMETERS AFFECTING THE FLAT SOLAR COLLECTOR PERFORMANCE

3.1 MAIN PARAMETERS

The main parameters that affect the performance of the flat solar collector are:

1. the flow rate
2. the temperature control differential ΔT
3. the collector inlet water temperature
4. the solar radiation
5. the ambient temperature.

3.2 FIXED PARAMETERS

Three parameters were set constant throughout the experiments :

1. the solar power at $1600 \times \frac{80}{100} = 1280$ watts
2. the temperature of the water in the storage tank, which was pumped to the solar collector, at 11.2 $^{\circ}$C.
3. the ambient temperature at 22.7 $^{\circ}$C.

3.3 VARIABLES USED IN THE EXPERIMENTAL INVESTIGATION

Thus the remaining variables which were used in the experimental investigation were the flow rate $\dot{V}$ and the temperature control differential ΔT.

CHAPTER 4

METHOD OF INVESTIGATION

4.1 OPERATING RANGE

In order to study the operating range of the system, the first ten experiments were run by changing alternatively the flow rate and the TCD ΔT. It was observed that when the flow rate is small for a fixed ΔT setting, equilibrium condition of heat transfer could be reached such that the collector outlet water temperature, which controlled the operation of the pump, would not drop to ΔT - OFF. For such a case the pump operated continuously. A manual stop of the pump was required. Therefore there exists a maximum continuous flow rate at which a heat transfer equilibrium condition can be obtained. This condition was considered as the lower limit of the operating range. The upper limit of the operating range was arbitrary chosen in such a way that the pumping period was never less than 120 seconds.

4.2 EXPERIMENT PROCEDURE

Based on the results of the preliminary tests, the experiment procedure was established as follows:

1. Supply power to the lamp.
2. Choose a setting for the temperature control differential ΔT.
3. Set the control valve to obtain a certain flow rate.

   (starting from a mean value about 19 cm^3/s)
4. Start the heating period, use a stop-watch to measure the time, and record t_h .

5. Collect all the water flowing through the solar collector during the pumping period, measure and record t_p .
6. Weigh the collected water and record the mass.
7. Repeat steps 4 to 6 .
8. When the pump stops and the heating period starts change the control valve setting in order to increase or decrease the flow rate.
9. Repeat steps 4 to 8 until the whole operating range is covered.
10. Choose another setting for the temperature control ΔT.
11. Repeat steps 3 to 11.

Four values of ΔT were used in the experiments.

CHAPTER 5

EXPERIMENTAL RESULTS AND ANALYSIS

5.1 TEMPERATURE CHART

The temperatures at points 1, 2, 3 and 4 were recorded on temperature chart. On this chart the following data were also recorded : the experiment number, the heating period t_h, the pumping period t_p, the collected mass M, the flow rate $\dot{V}$ and the temperature control ΔT, and other useful observations.

5.2 CALCULATIONS

The mean temperature, T_m , of the water flowing out of the solar collector during a pumping period t_p, was computed by integrating the water outlet temperature recorded on the chart, point 4 during t_p.
The density of the water ρ was found at T_m.
The water flow rate was calculated as = $\dot{V} = \frac{M}{\rho\, t_p} \times 1000.$
The heat gained by the flowing water during a pumping period, is given by: $Q = M(T_m - T_i)\ c_p.$
The output power per cycle, $\dot{q} = \frac{Q}{t_t} \times 1000$ was calculated.

5.3 TABULATIONS

The results and the calculated parameters were tabulated in TABLES 1 to 4.

5.4 ANALYSIS

5.4.1 ΔT and t_h.

The results show that the heating period t_h is nearly constant for a fixed temperature control ΔT, and thus does not depend on the flow rate. Consequently for the four values of TCD , four respective values of t_h

were obtained. The higher the temperature control differential, the longer is the heating period. Fig. 5.1 shows the characteristics of the temperature control device. ΔT - OFF increases nearly linearly with ΔT-ON. Fig. 5.2 illustrates the relation between the heating period t_h and ΔT.

5.4.2 t_p

Figures 5.3 to 5.6 show the pumping period t_p as a function of $\dot{V}$ at different values of ΔT and t_h. The higher the flow rate, the shorter is the pumping period. A higher flow rate displaces more rapidly the hot water out of the solar collector.

5.4.3 M

The total mass of water collected during a pumping period increases with a smaller rate of flow through the solar collector. While the cold water is flowing through the solar collector, displacing hot water and cooling the collector, the collector is being heated by the lamp's radiation. For low water flow rates, a heat transfer equilibrium condition of the solar collector can be obtained. There exists a maximum flow rate, $\dot{V}_m$, for a fixed ΔT, at which such a condition occurs. The water temperature at the outlet of the collector then stays constant and just above the temperature at which the temperature control device would cut off the power to the pumps. For such a case, the water mass collected will approach infinity. The results show that $\dot{V}_m$ is higher for lower ΔT values.

It was observed that at a very high water flow rate, due to a lag in the control system, the pump would stop at a lower temperature then the set point and thus more water was collected. The temperature control sensors were attached to the outer surfaces of the inlet and outlet pipes of the solar collector (they were too large to be introduced into the pipe). When the flow rate was very high, the water temperature at point 4, dropped at a higher rate than the pipe surface temperature at point 3 did.

5.4.4 . Q and $\dot{q}$

Figures 5.7 to 5.10 show Q as function of $\dot{V}$ at different values of ΔT and t_h . Figures 5.11 to 5.14 show $\dot{q}$ as function of $\dot{V}$ at different values of ΔT and t_h .

For a fixed ΔT, the output heat Q per cycle gained by the flowing water, from the solar collector, decreased as the flow rate increased. Q reached a minimum value , then increased slightly again. Because the output heat is expressed as : $Q = M\,C_p\,(T_m - T_i)$, the large mass of water collected at a low flow rate resulted in a large Q . The mean water outlet temperature T_m was slightly higher at low flow rate but could be considered constant for a fixed ΔT.

For a fixed ΔT, the rate of heat output $\dot{q}$ decreased as the flow rate increased. $\dot{q}$ reached a minimum value , then increased rapidly again. It can be observed that the minimum values of $\dot{q}$ occured in a narrow region of the flow rate. This phenomenna is expected as the flow changes from laminar to turbulent.

In the laminar flow region, the pumping period decreases as the flow rate increases. It results in the increase of the number of cycles per unit time. The increase in the number of heating periods causes an increase in heat losses from the collector to the surroundings. Thus the heat transmitted to the flowing water decreases.

In the turbulent flow region, the turbulence increases the heat transfer rate from the collector to the flowing water and thus the rate of heat gained, $\dot{q}$, increases as the flow rate increases. The temperature control ΔT greatly affected the rate of heat output $\dot{q}$. The higher ΔT, the higher is the surface temperature of the solar collector, and in turn the higher is the rate of heat loss to the surroundings. The expected decrease of $\dot{q}$ as ΔT increases is shown in Fig. 5.15.

5.4.5 PUMPING POWER E_p

A typical installation, as shown in Fig. 5.16, is considered in order to calculate the pumping power required. The solar energy collector is installed on the top of a pitched roof of a one story family house, the water storage tank and the pump are installed in the basement. The solar water heating system is chosen as a closed system. The energy accumulated in the tank can be transferred to the home hot water supply system through a heat exchanger installed in the water storage tank. The essential energy required to pump the water through the circulation system, is the energy loss due to friction in piping and fittings.

It is assumed that the system includes ten 90° elbows, a check valve, a gate valve and 15.2 m of tubing (including the collector).

$L = 15.2 + 10 \times 0.3 + 1 \times 2.4 + 1 \times 0.15 + 1.2$ (inlet and exit losses) $= 22$ m

The following equations were used to compute the friction losses:

$$R_e = 10 \frac{d v \rho}{\mu}$$

For laminar flow $\quad H = \dfrac{1.27 \ L \mu \dot{V}}{d^4}$

For turbulent flow $\quad H = \dfrac{82.59 \ f \ L \ \rho \dot{V}^2}{d^5}$

where

R_e		Reynolds number
L		total equivalent length, in m
d		inside diameter of tube, in mm
v		water velocity in pipe, in cm/s
ρ		water density, in g/cm^3
μ		water viscocity, in centipoise
$\dot{V}$		flow rate, in cm^3/s
f		friction factor
H		head (friction losses), in m of water

(reference # 11)

The pumping power $E'_p = 9.8 \times 10^{-3} \dfrac{\dot{V} H}{80\,\%}$ watts

assuming a pump efficiency of 80%.

where $\dot{V}$ flow rate, in cm^3/s

H head (friction losses), in m of water

The power E'_p was consumed during the pumping period t_p only, and in order to analyse the efficiency of the system, an adjusted pump power should be computed and used :

$$E_p = \frac{E'_p \; t_p}{t_t} \quad \text{watts}$$

The results are tabulated in TABLES 1 to 4.

5.4.6 SYSTEM EFFICIENCY

The efficiency of the system can be defined as :

$$\eta = \frac{\dot{q}}{E_p + E_s} \times 100$$

Values of η were calculated and recorded in TABLES 1 to 4. Fig. 5.17 shows η as function of $\dot{V}$, for four values of ΔT. The efficiency curves are similar to those of $\dot{q}$ versus $\dot{V}$. The pumping power is very small compared to the solar power E_s and to $\dot{q}$.

CONCLUSIONS

The flat solar collector under investigation operates at high efficiency when the temperature control ΔT is small.

The investigation shows that for a fixed temperature control ΔT, the efficiency of the solar collector increases as the flow rate decreases in the laminar flow region and as the flow rate increases in the turbulent flow region.

Although the pumping power is small compared to the power absorbed by the water flowing through collector, the pumping power increases rapidly with an increasing flow rate. Thus, for a fixed thermal efficiency of the solar collector, it is more economical to operate the forced - circulation system at the small flow rate in the laminar region than at the large flow rate in the turbulent flow region.

On the other hand, there exists a maximum continuous flow rate, $\dot{V}_m$, for a fixed temperature control ΔT, at which a constant temperature of the water at the outlet of the solar collector can be obtained. This flow rate depends on the temperature control ΔT, it increases as the ΔT decreases. It shows that the flow rate $\dot{V}_m$ achieves best thermal efficiency of the collector for the fixed temperature control ΔT.

In the light of the experimental results of this investigation, it can be concluded that in order to operate the flat solar collector at high efficiency, the temperature control ΔT should be set at a minimum acceptable value depending on the applications, and the water be pumped continuously through the collector with the flow rate, $\dot{V}m$, which achieves a heat transfer equilibrium condition.

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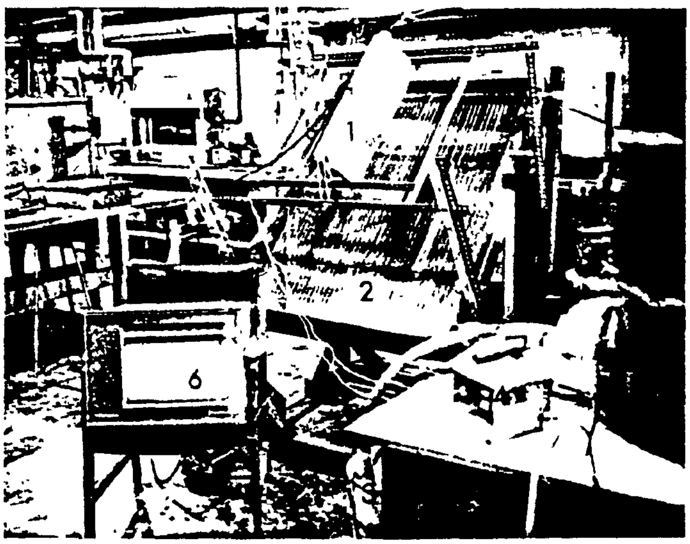


1 Lamp
2 Solar Collector
3 Pump
4 Temperature Control Device
5 Water Tank
6 Temp. Recorder
7 Flow Control Valve

Fig. 2.1 APPARATUS

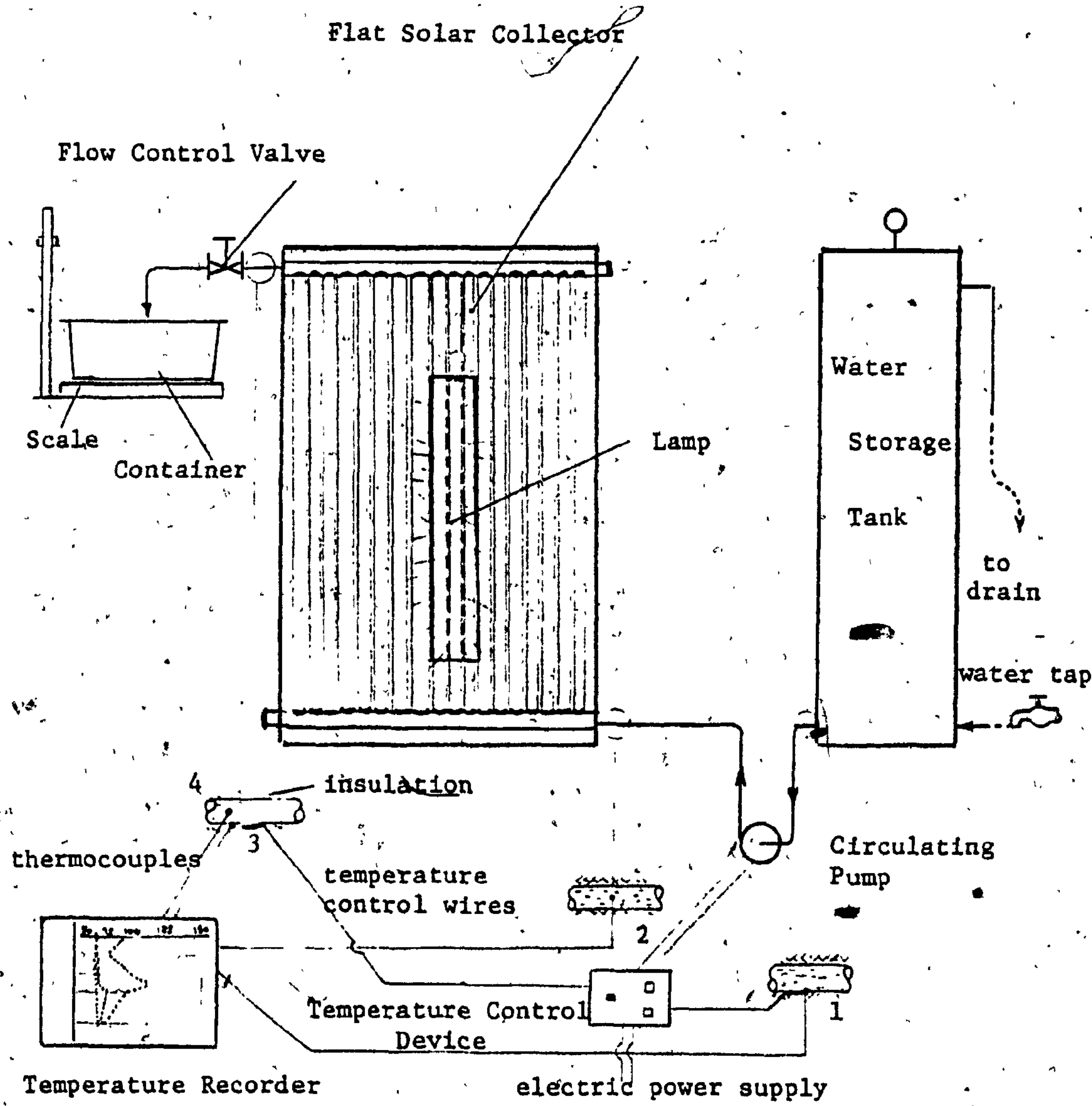
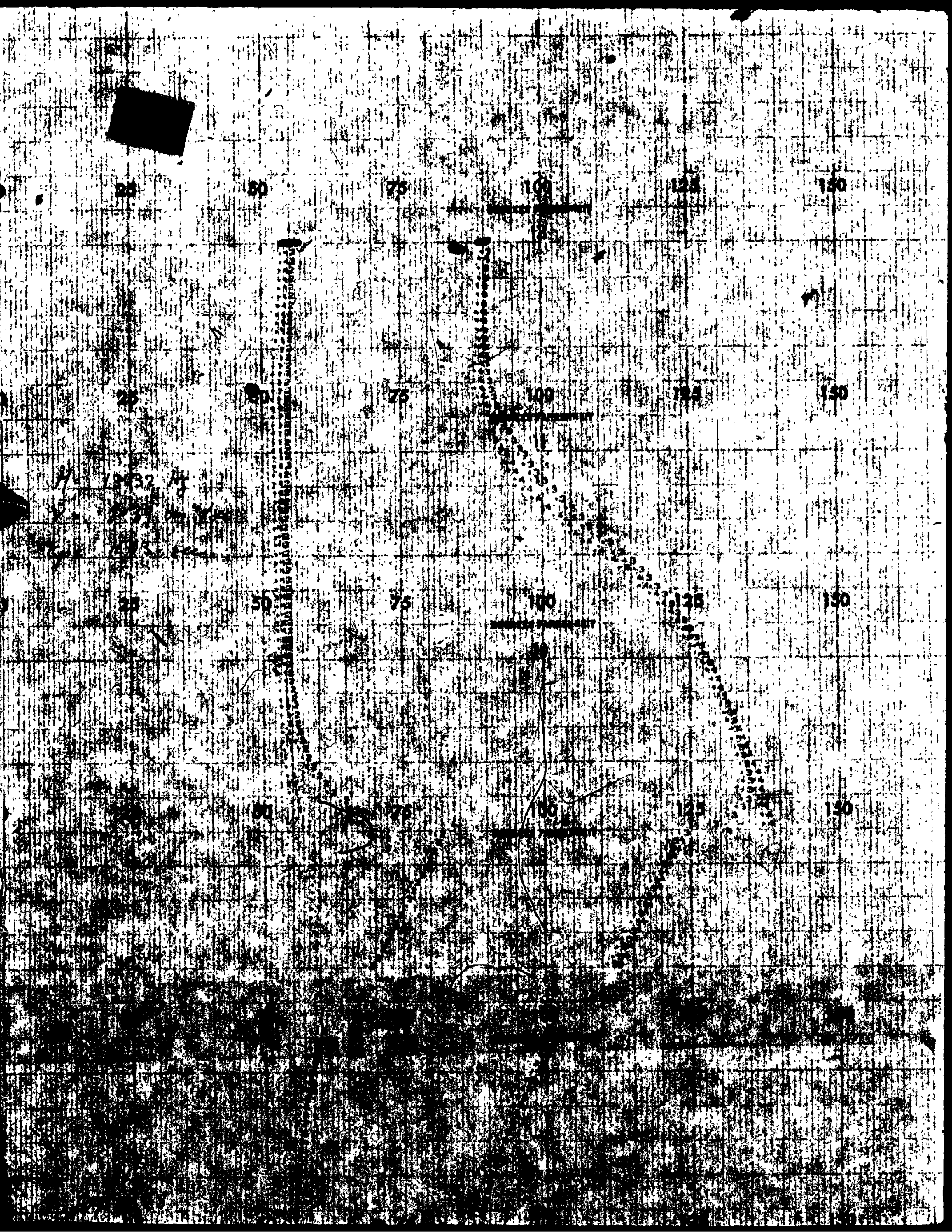


Fig. 2.2 - Schematic diagram of experiment set-up showing solar collector, circulating pump , controls and storage tank.



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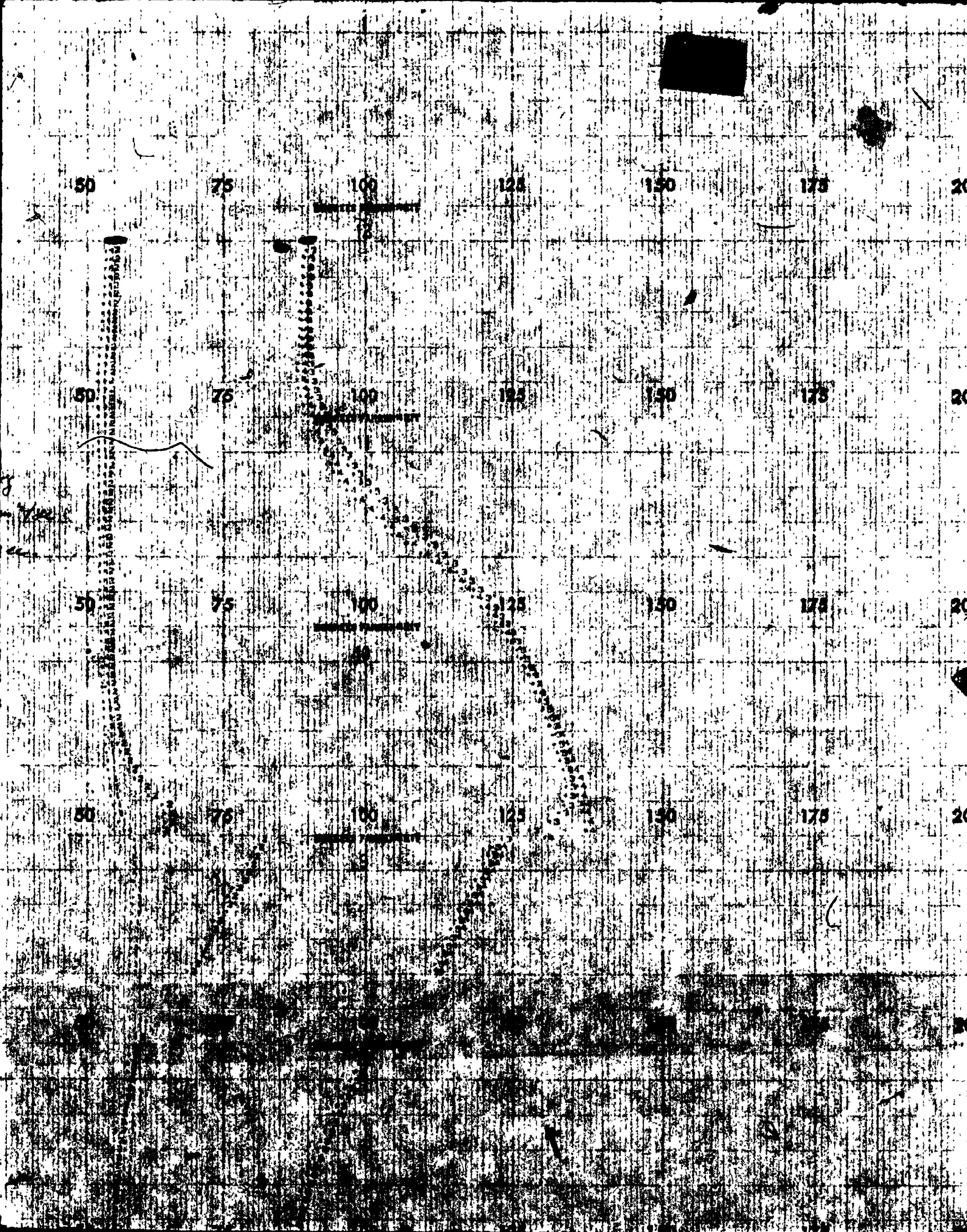

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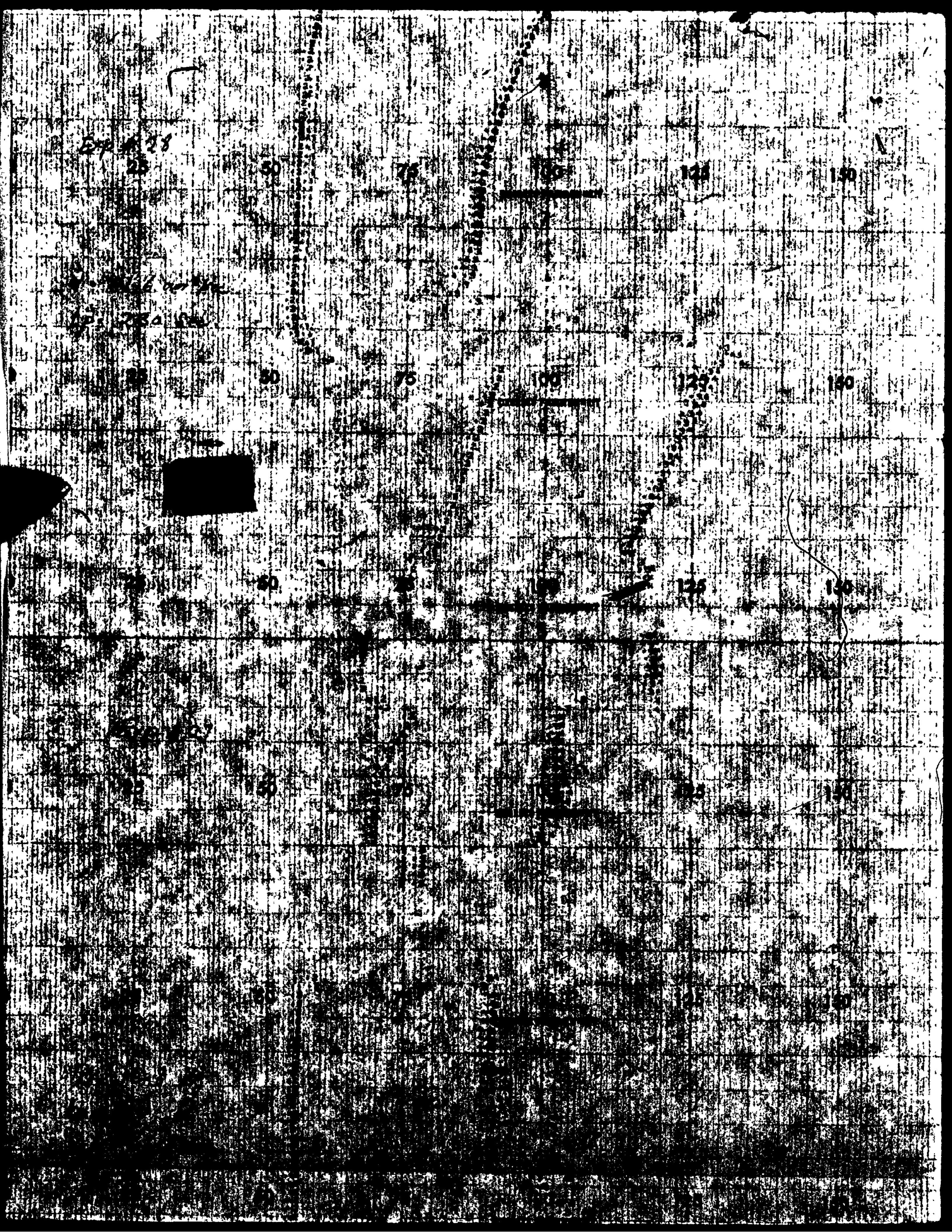
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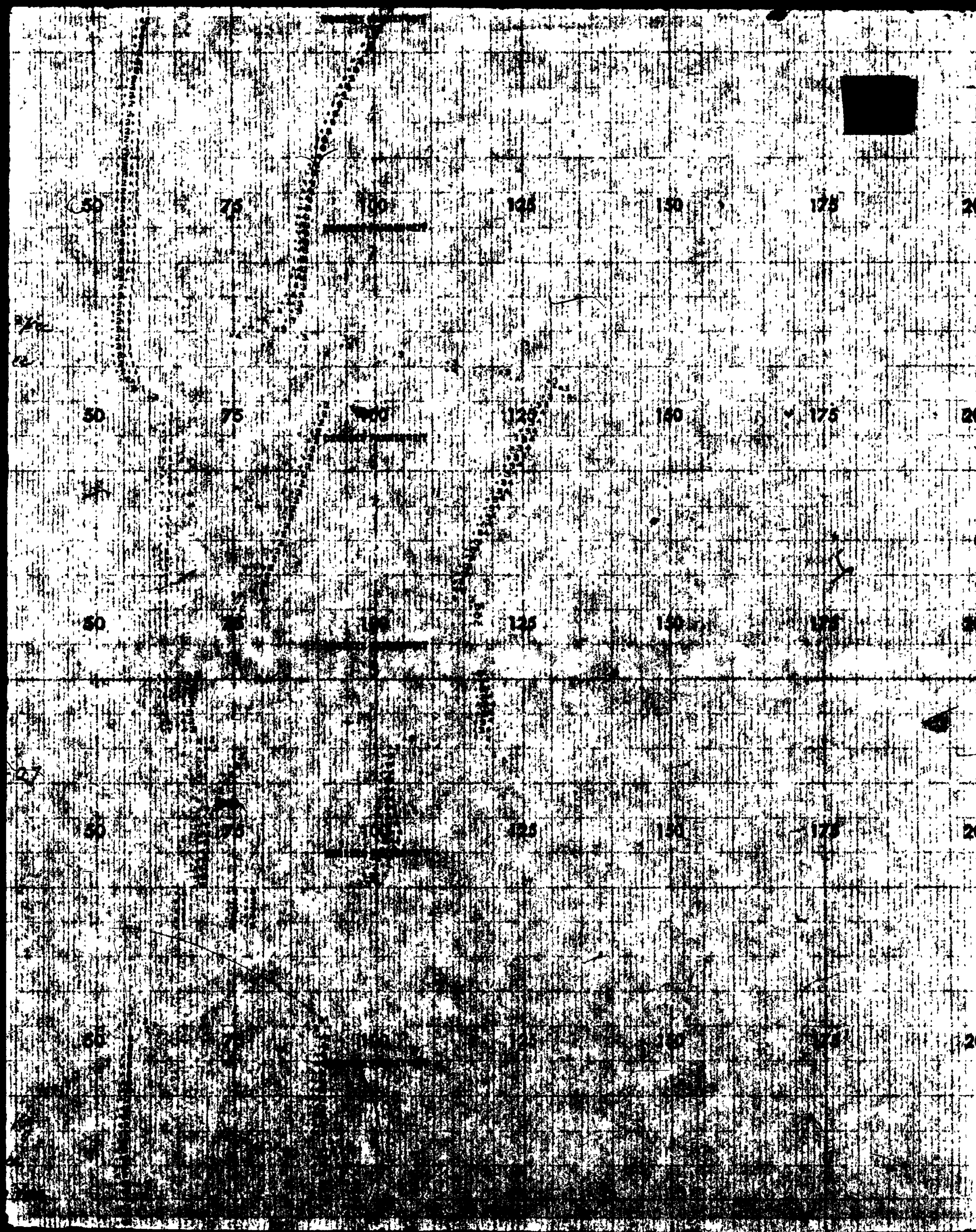
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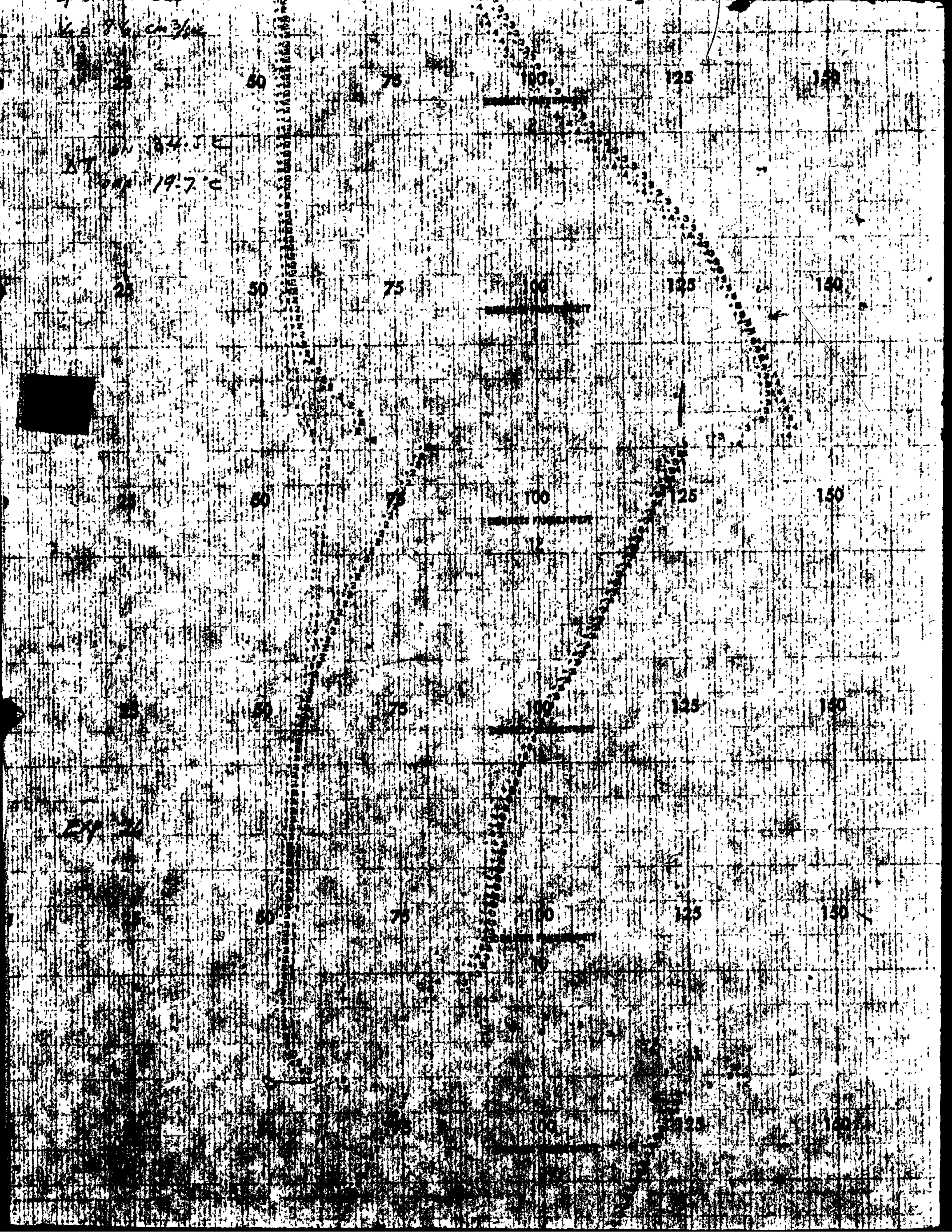

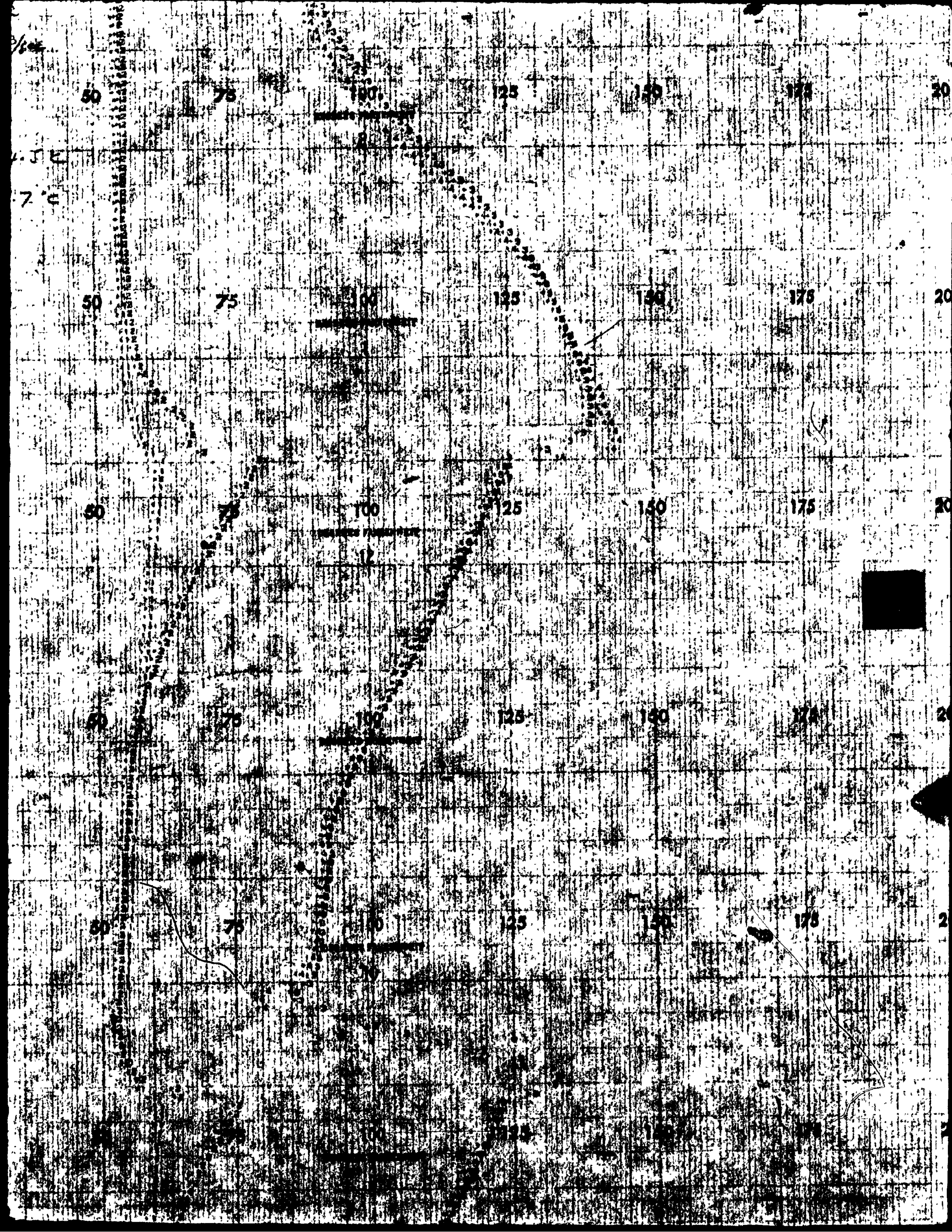
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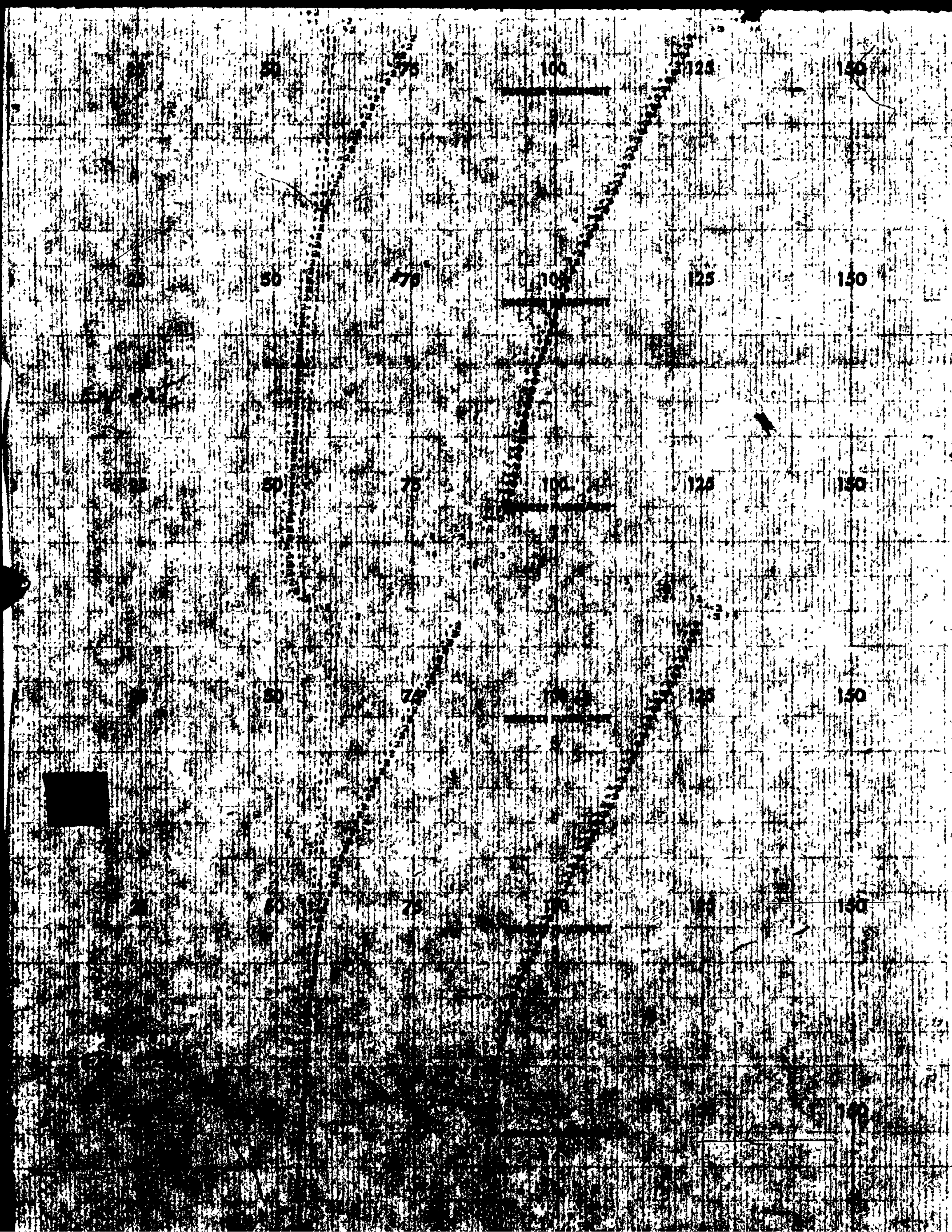
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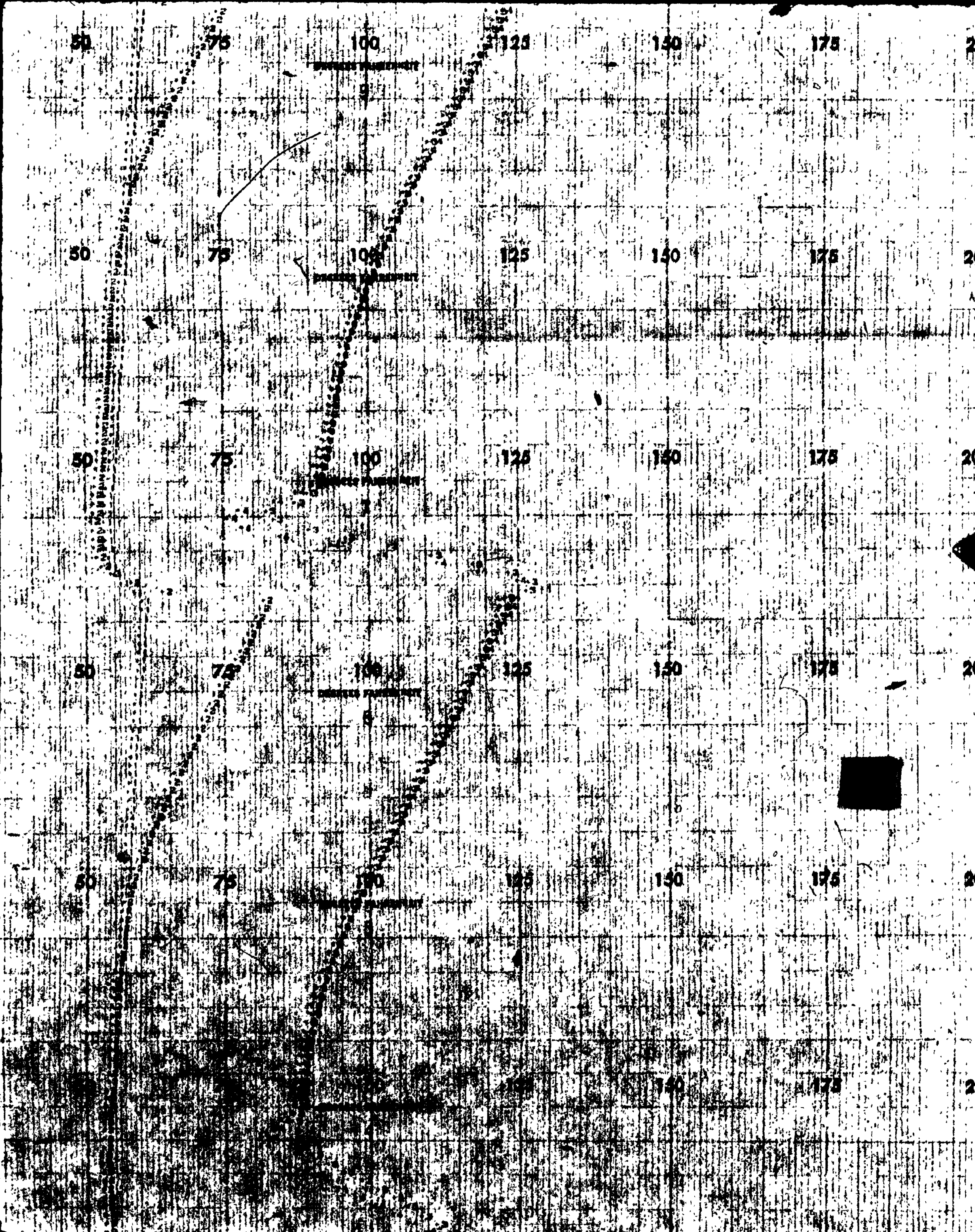
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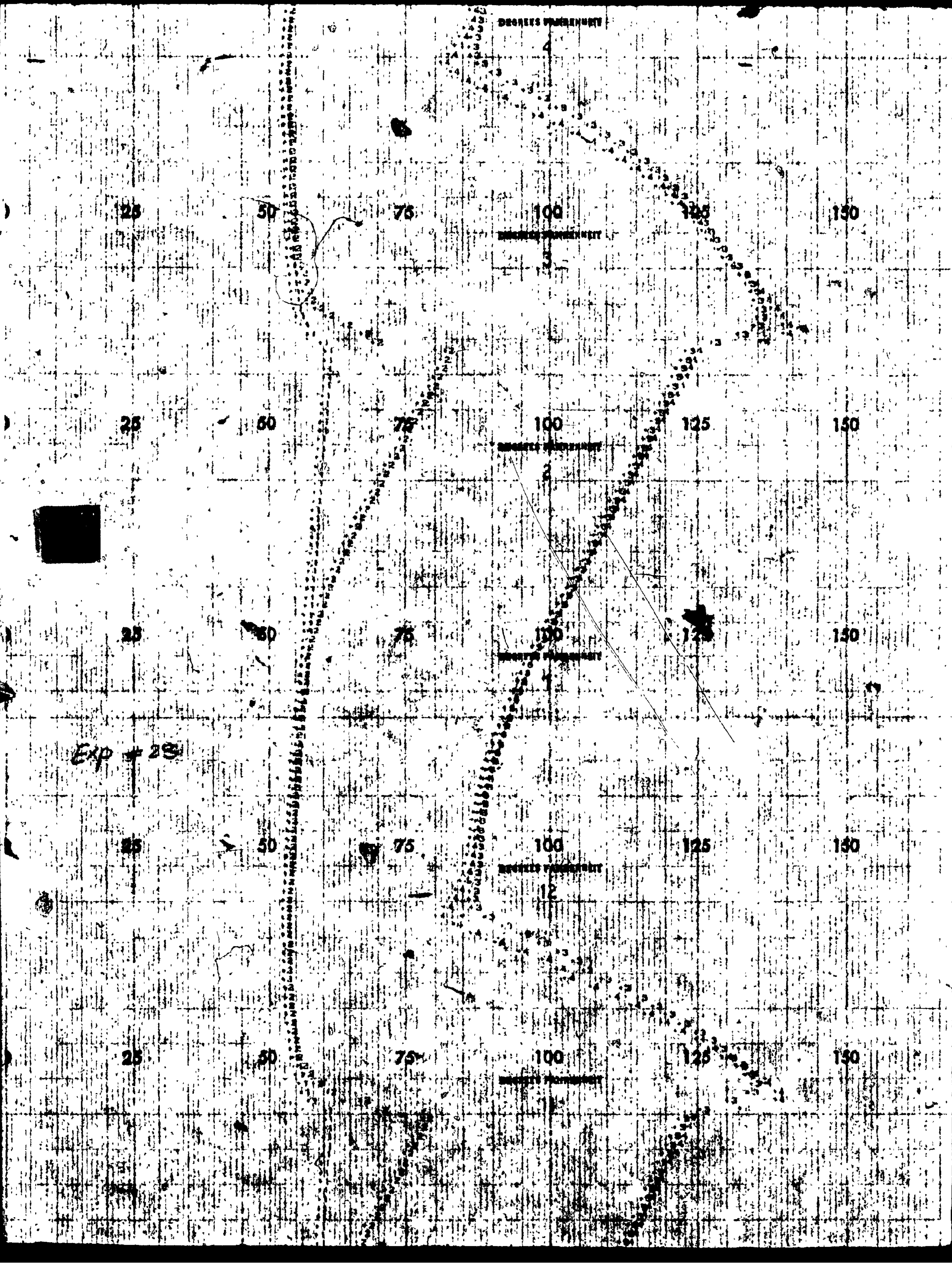
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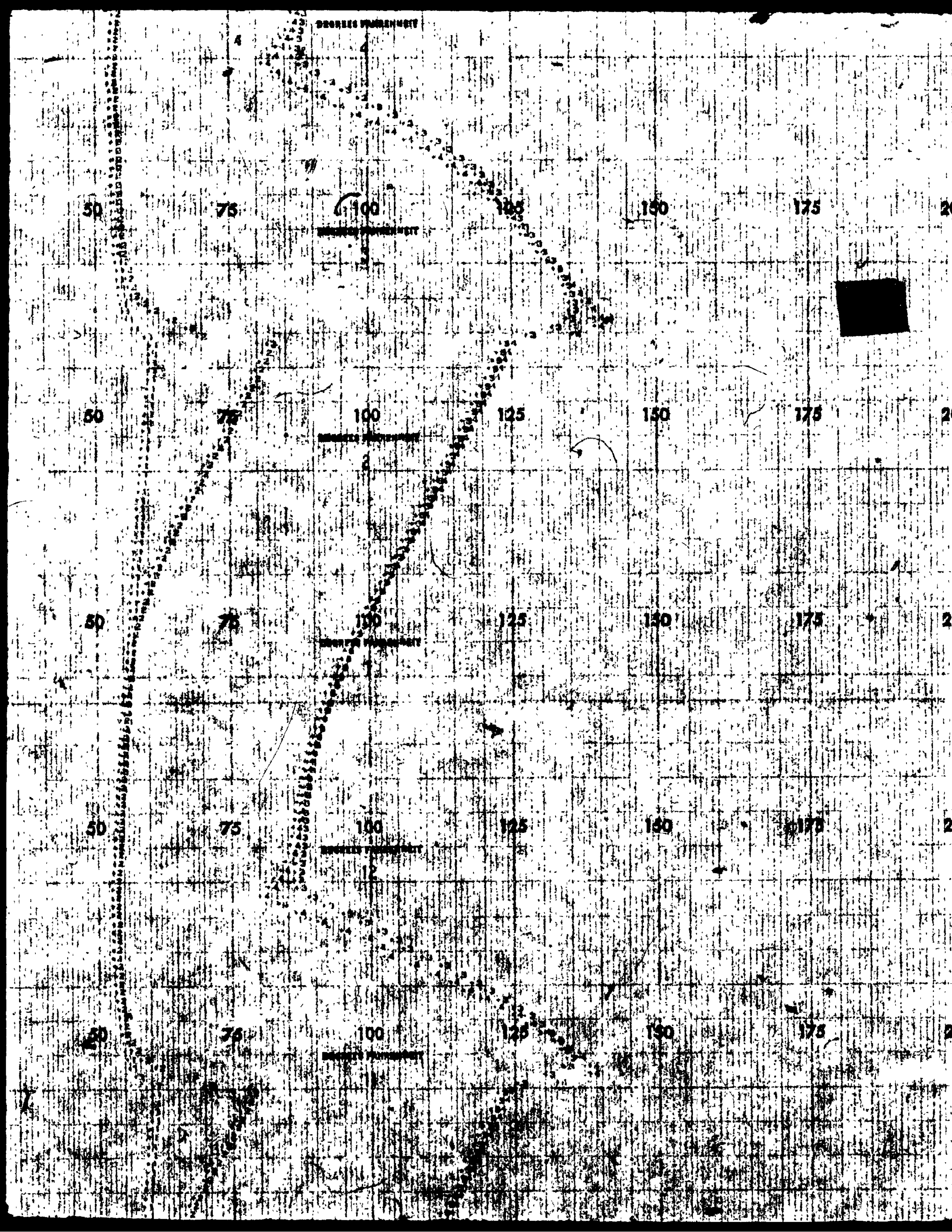
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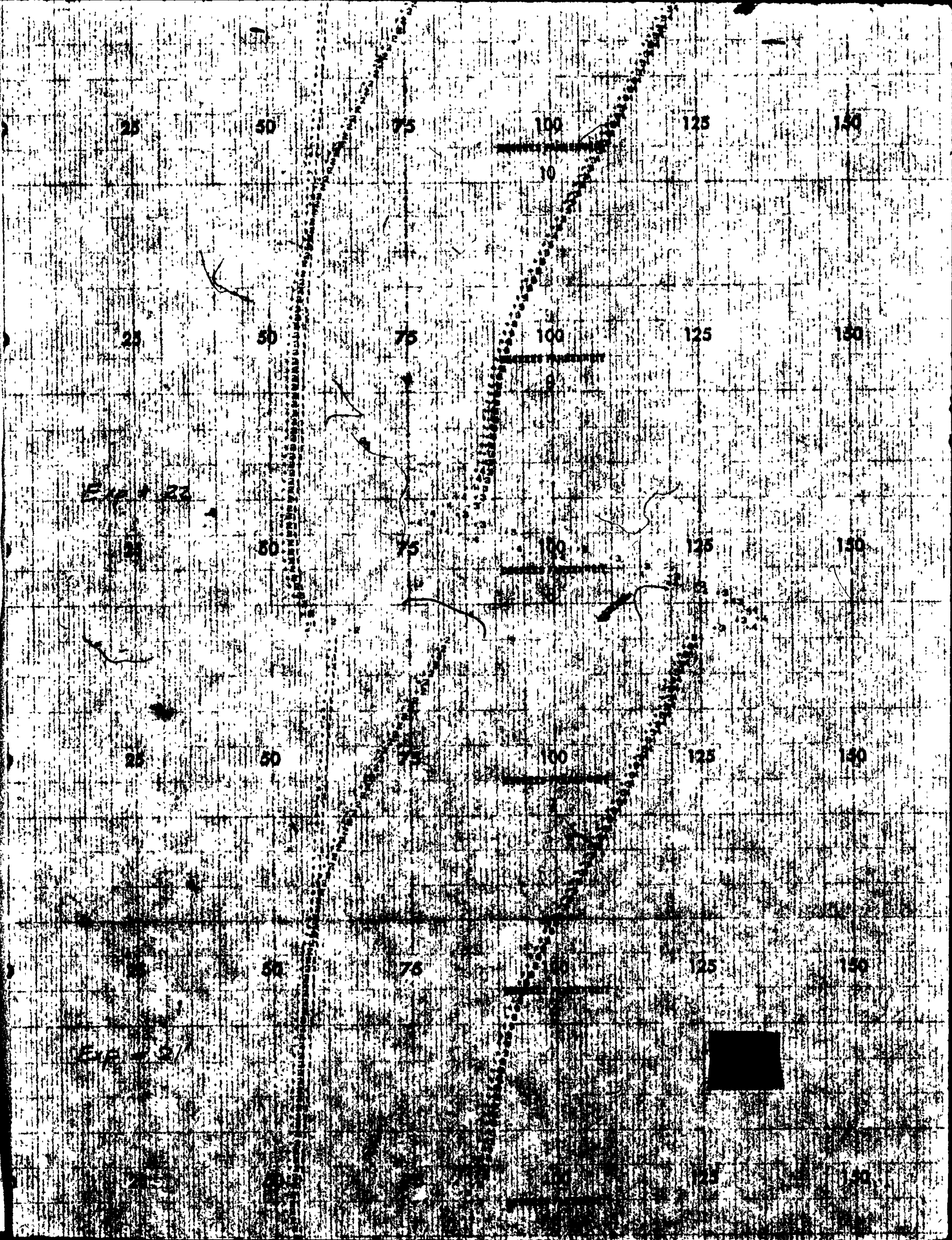
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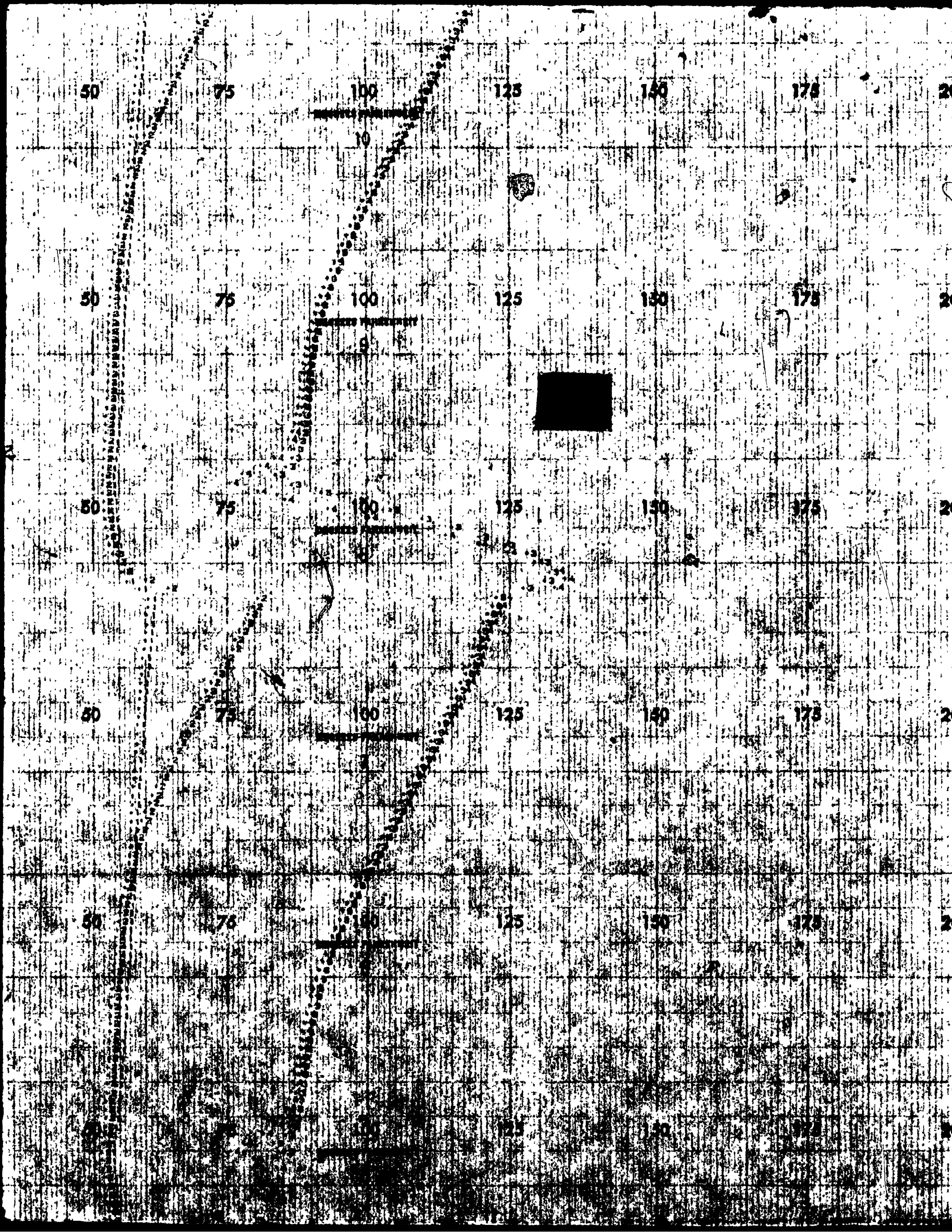
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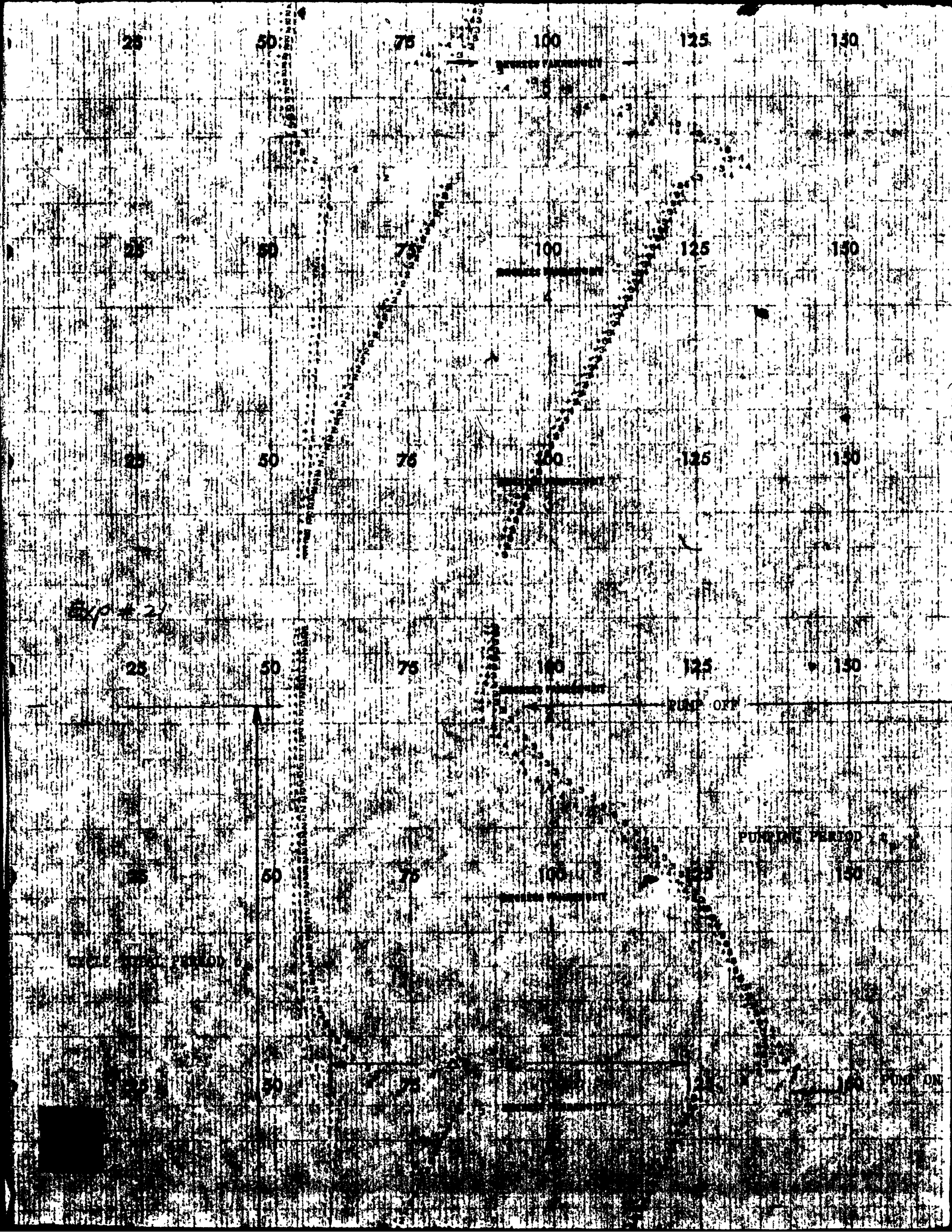
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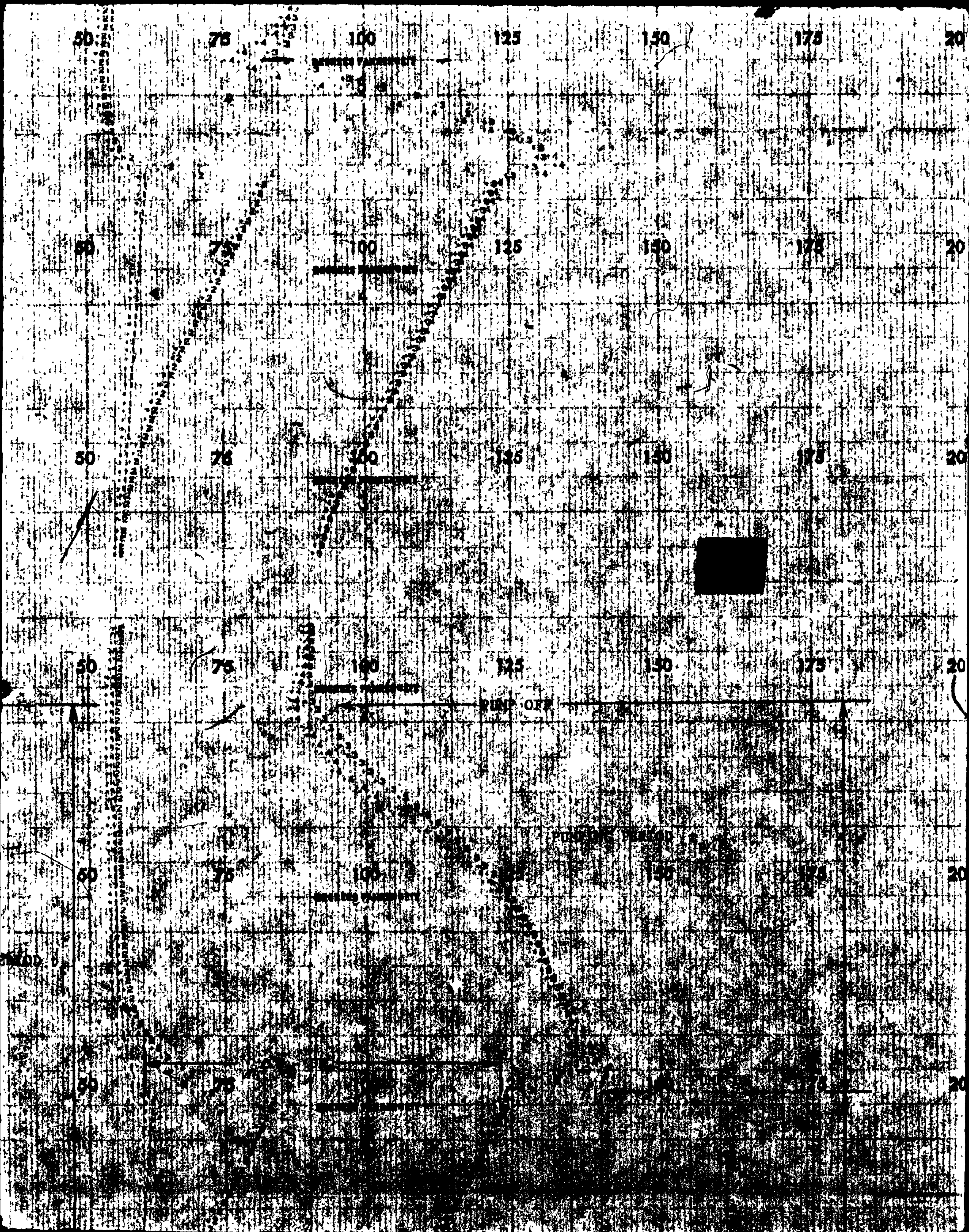
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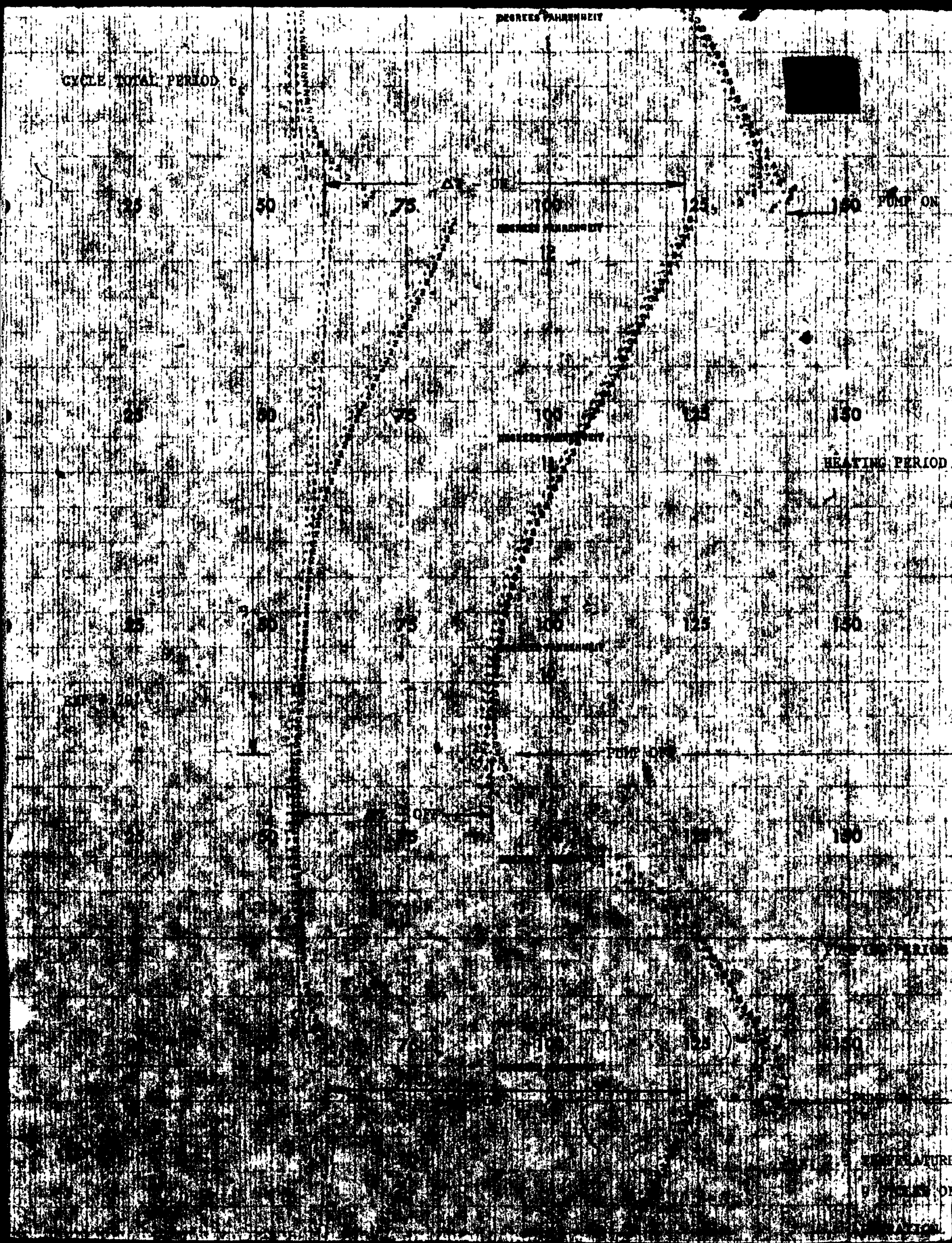
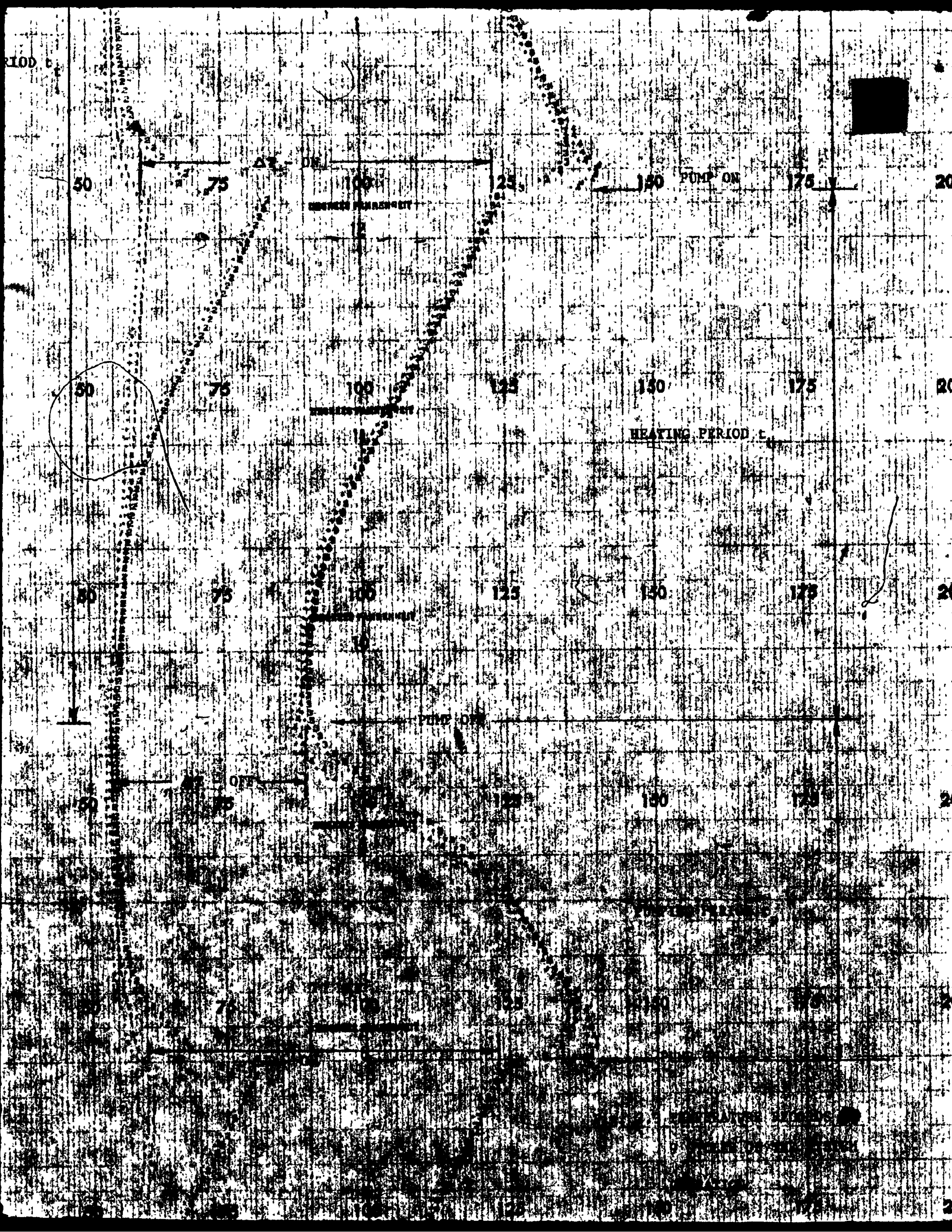
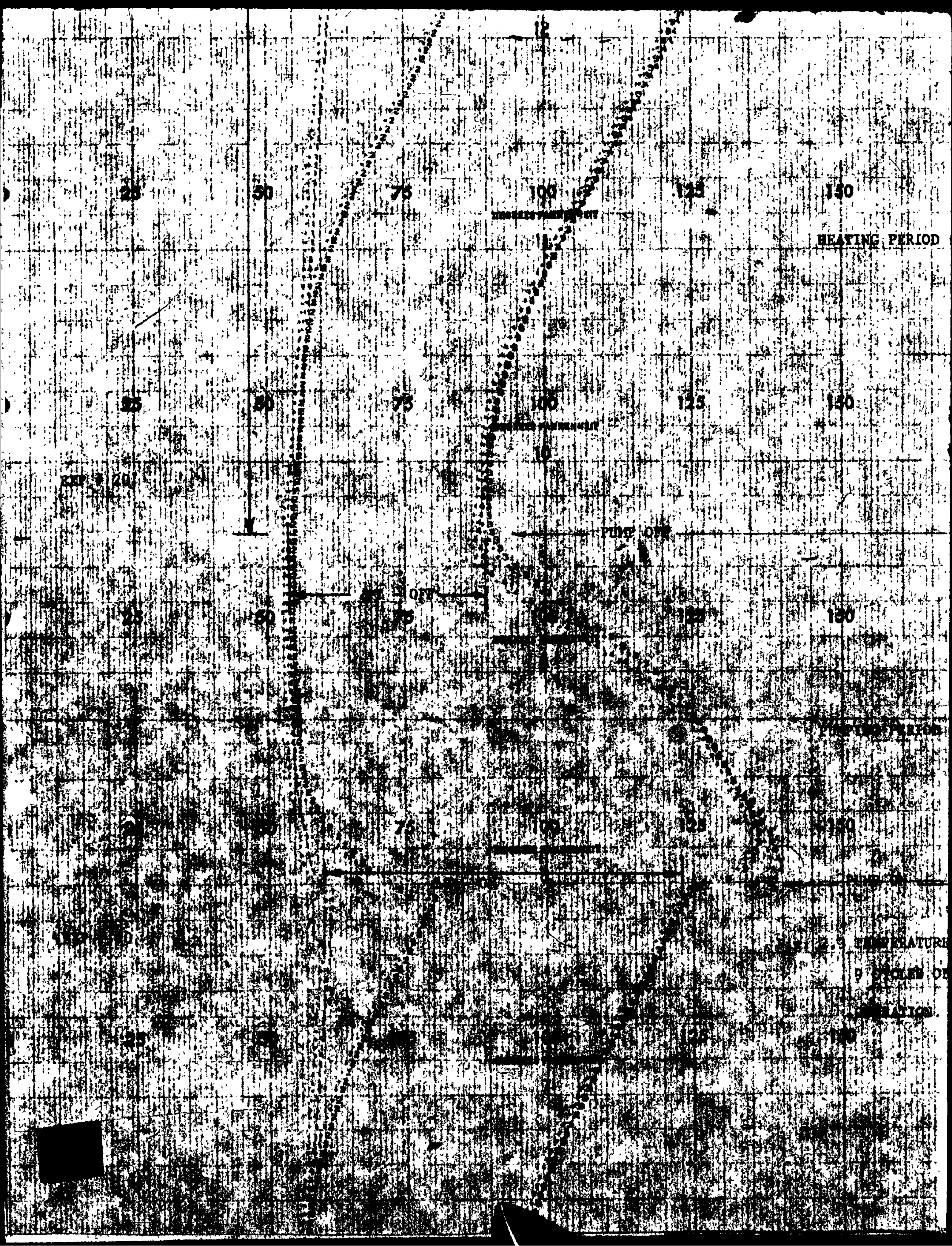
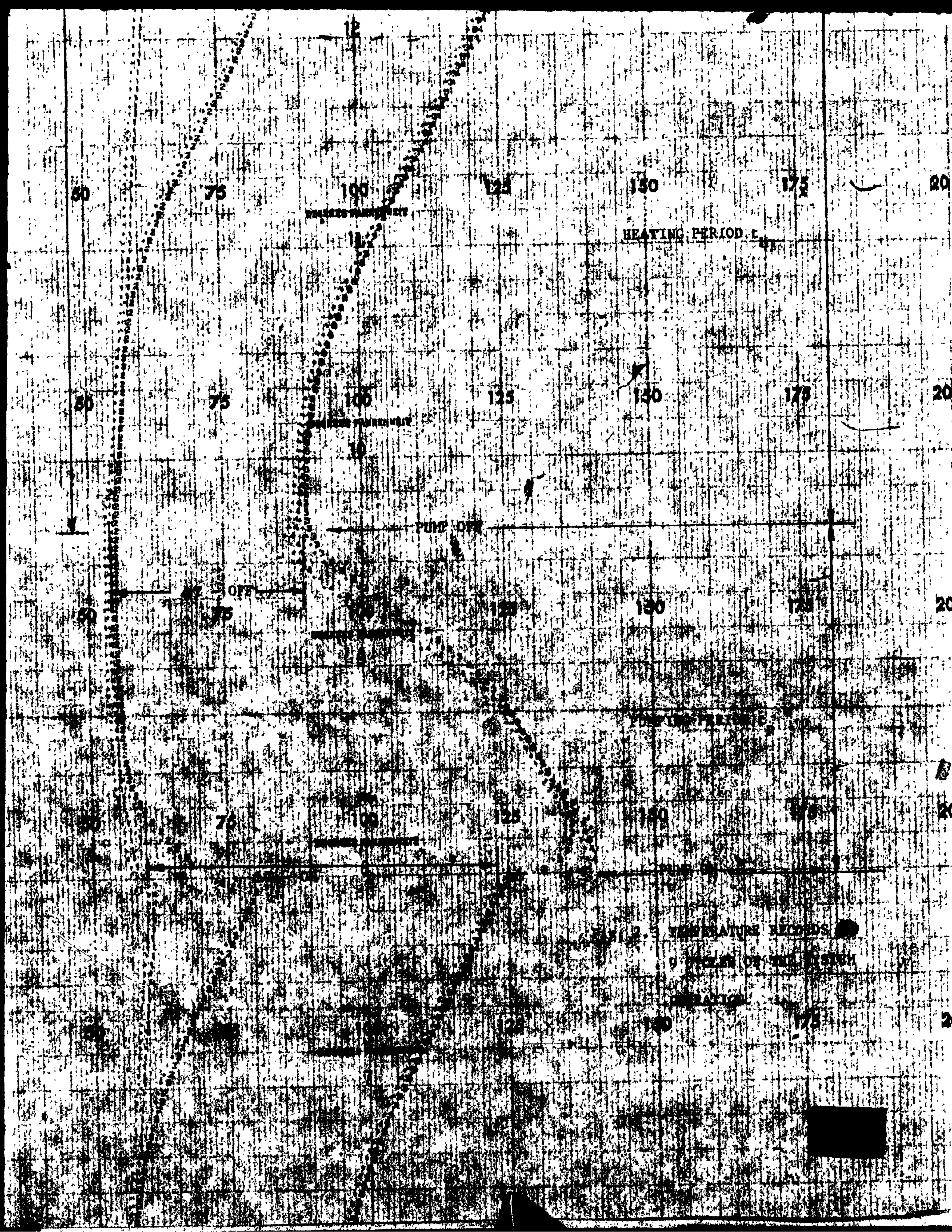
PUMP OFF
PUMPING PERIOD



DEGREES FAHRENHEIT
CYCLE TOTAL PERIOD C
25
50
75
100
125
150
PUMP ON
HEATING PERIOD
OFF


RIOD t
ΔT - ON
50
75
100
125
150
PUMP ON
175
HEATING PERIOD t
PUMP OFF
OFF


12
25
50
75
100
125
150
HEATING PERIOD
10
PUMP OFF
OFF
TEMPERATURE
CYCLES OF
OPERATION.


12
50
75
100
125
150
175
HEATING PERIOD
10
PUMP OFF
OFF

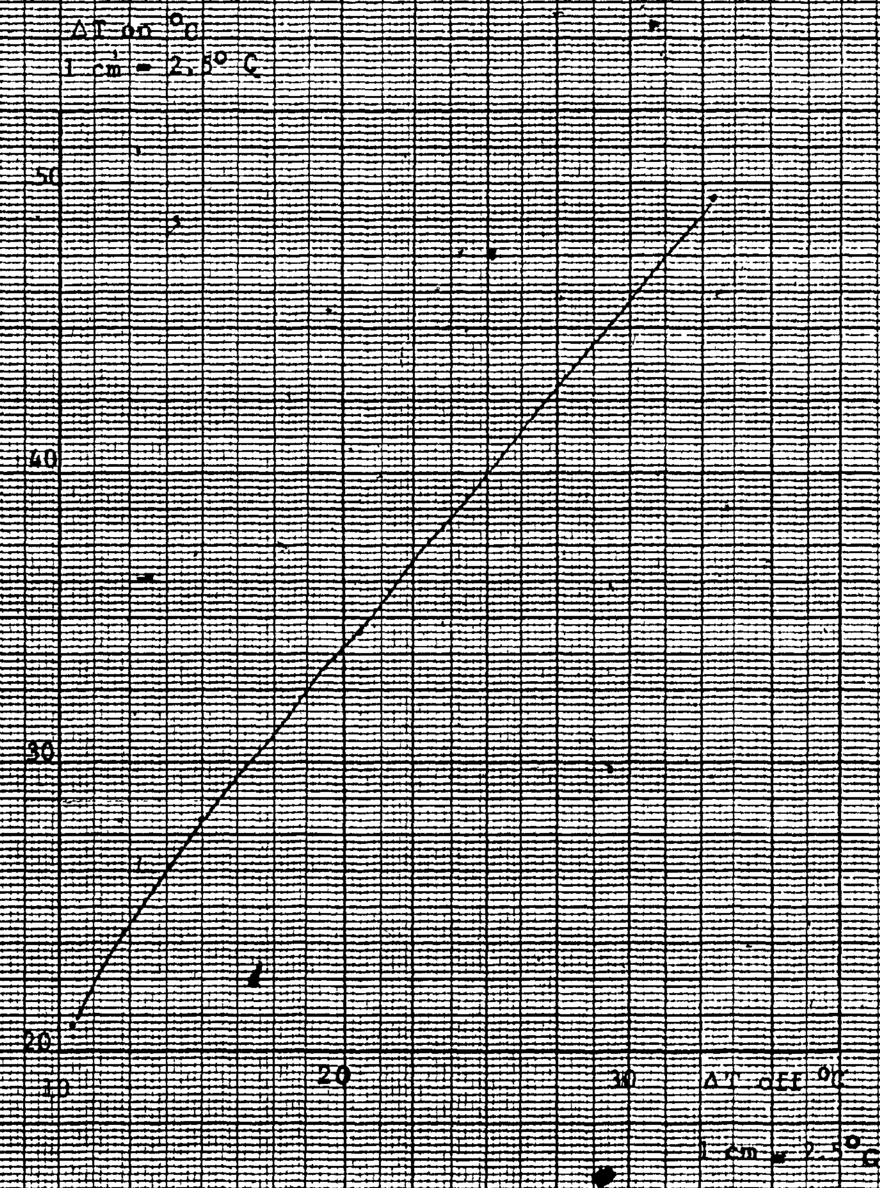


Fig. 5.1 CHARACTERISTICS OF CONTROLLER

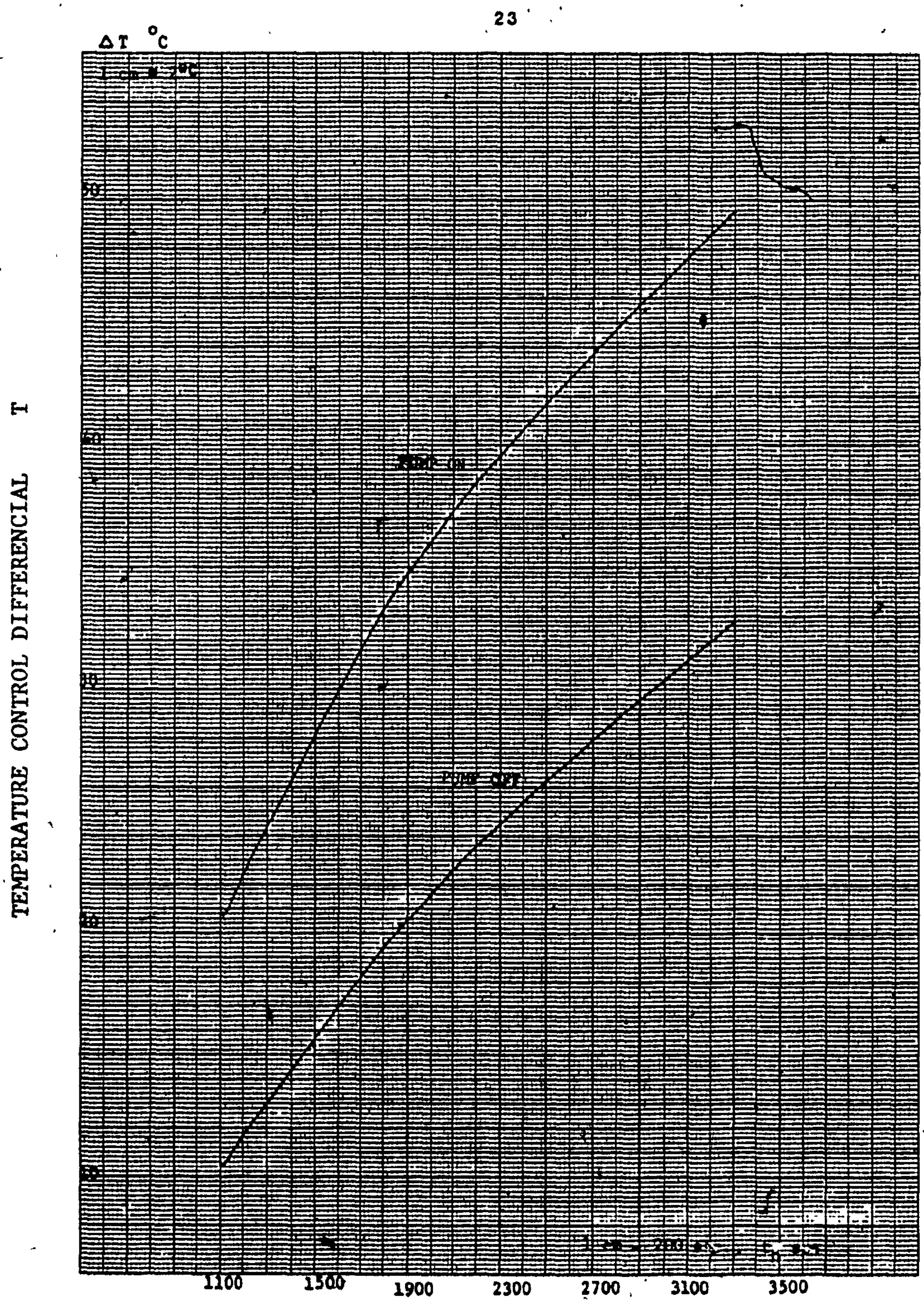


Fig. 5·2 EFFECT of ΔT on t_h HEATING PERIOD t_h

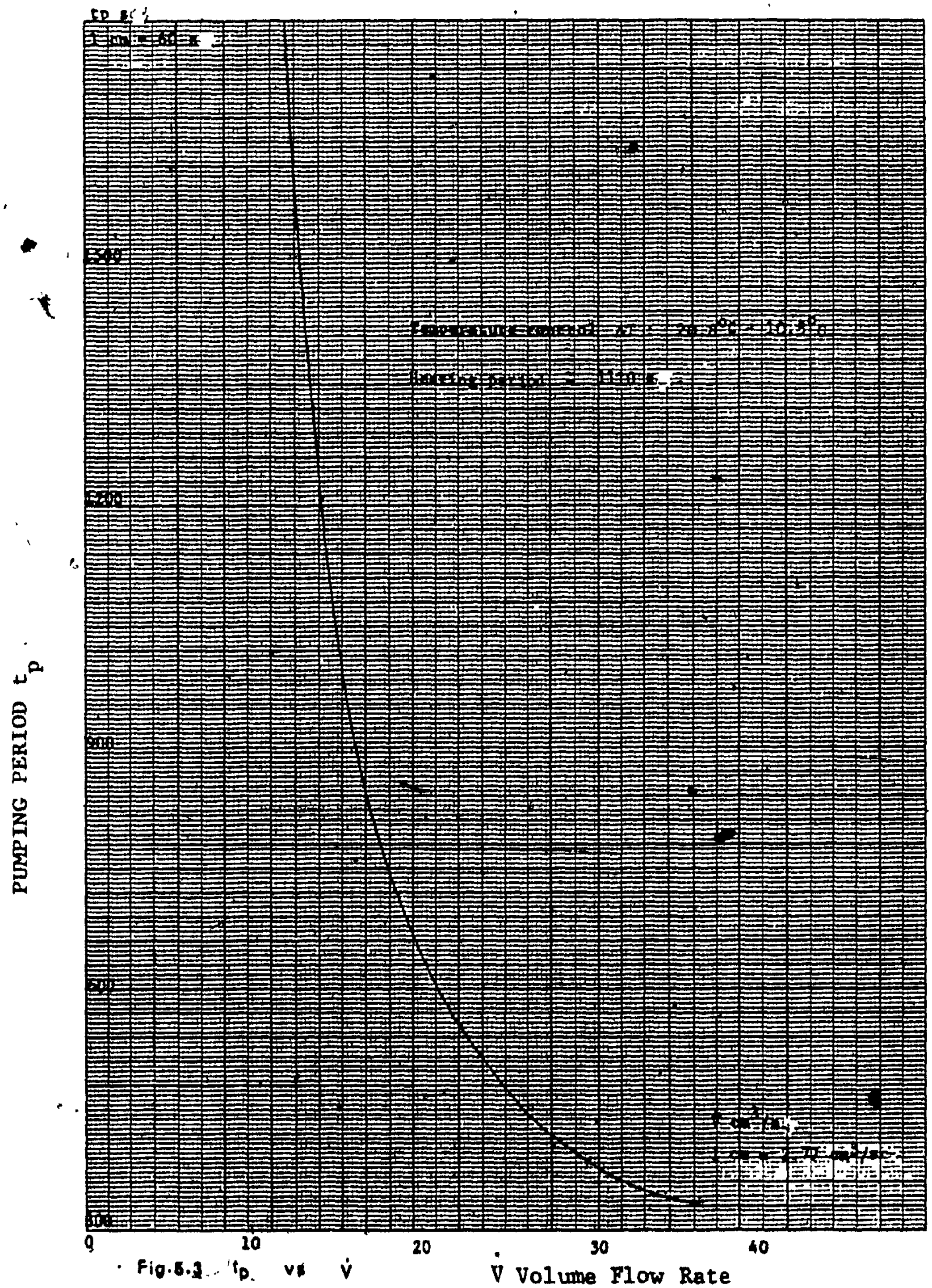


Fig.5.3 t_p vs $\dot{V}$

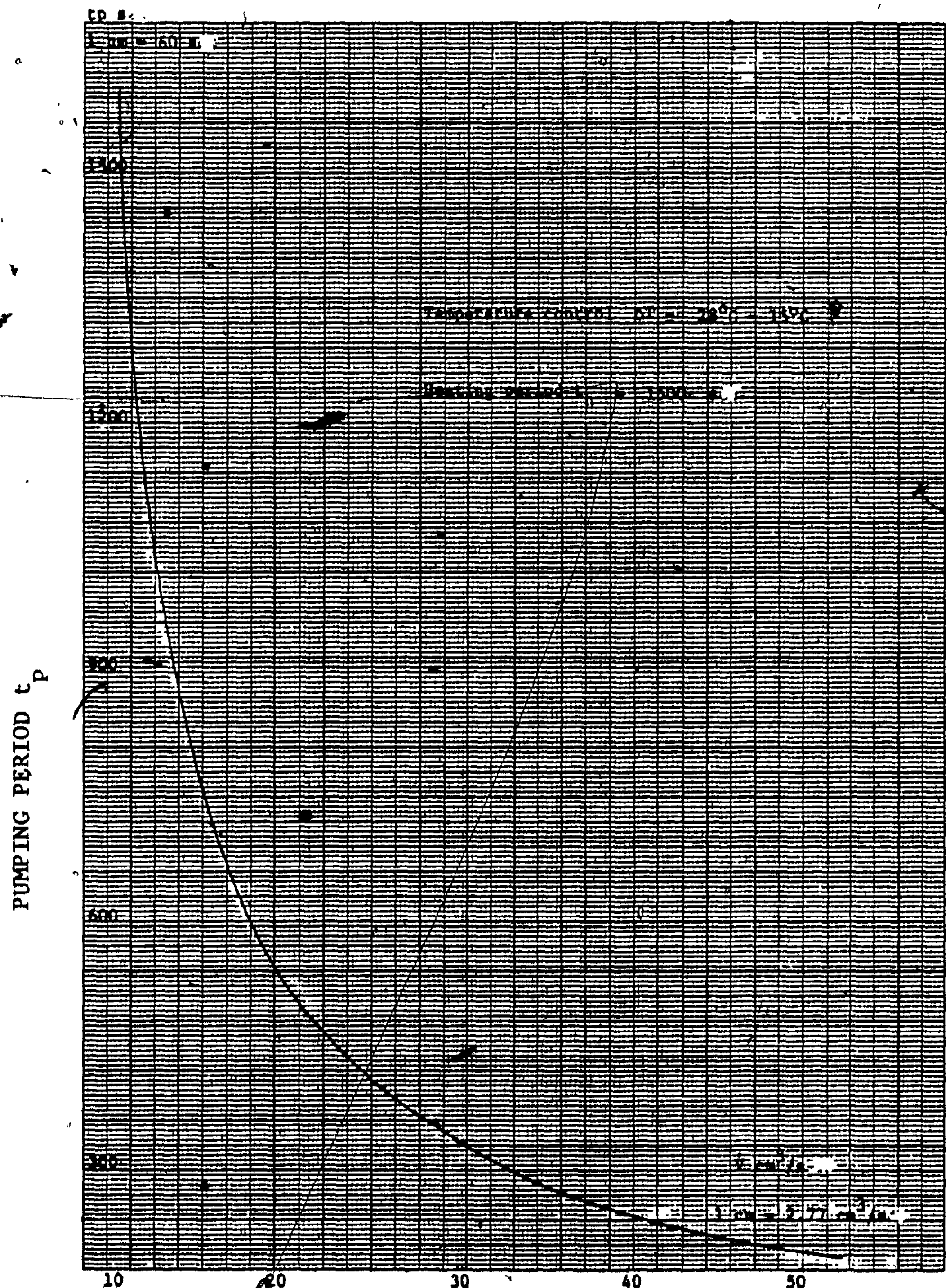


Fig.5.4 , tp vs $\dot{V}$ $\dot{V}$ Volume Flow Rate

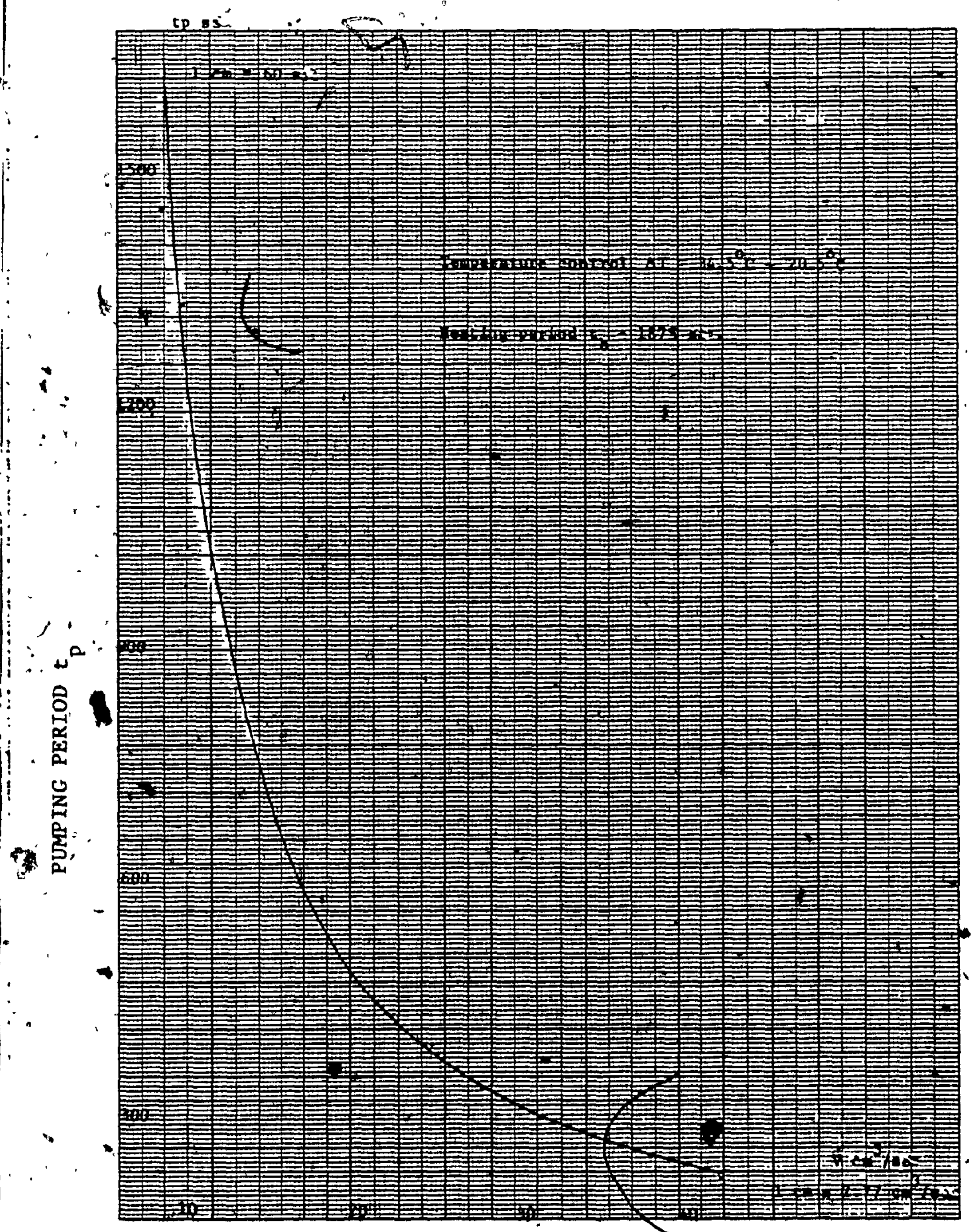


Fig. 5.5 t_p vs $\dot{V}$

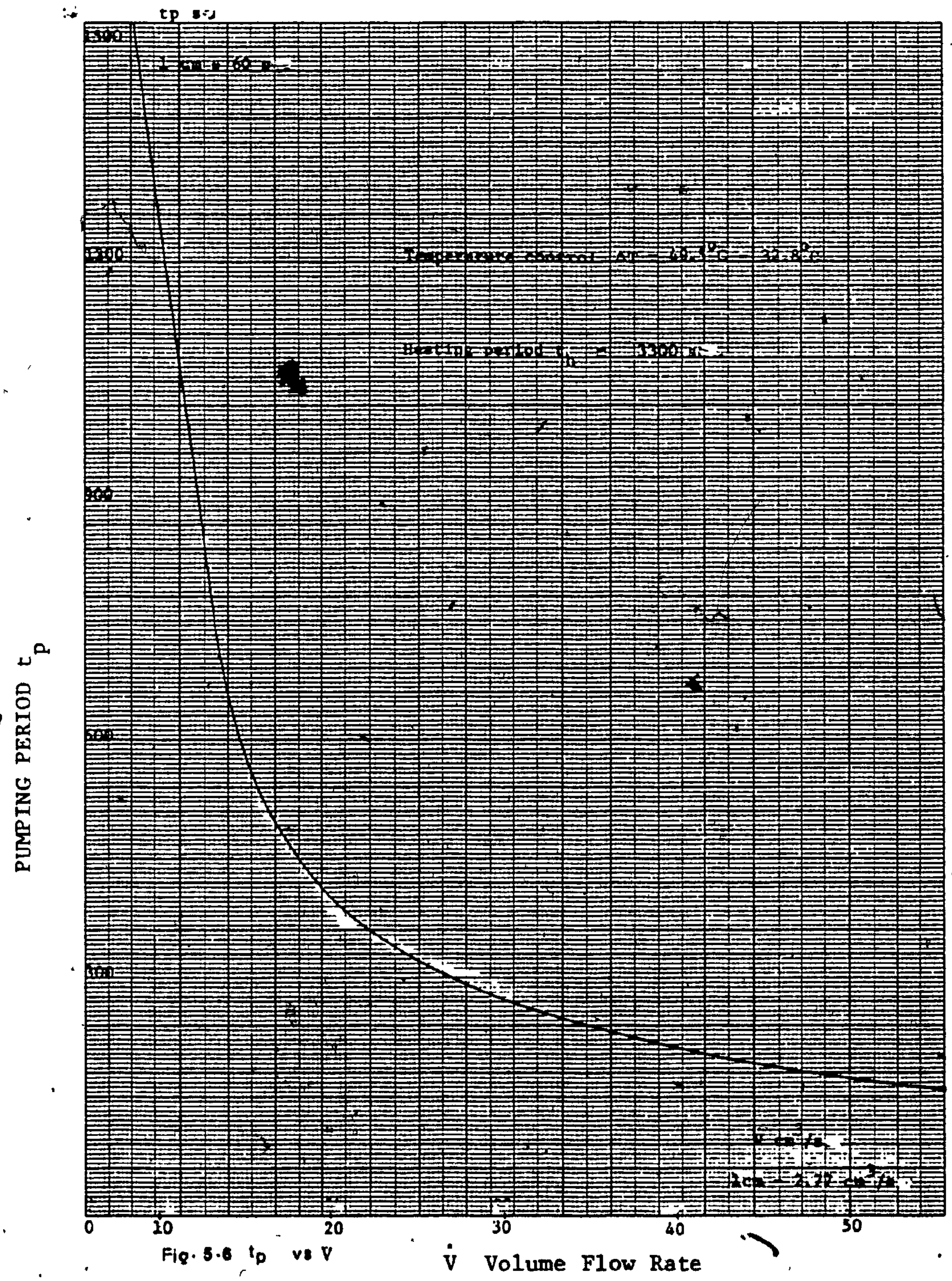

tp s
1300
1200
900
600
300
PUMPING PERIOD t_p
Heating period t_h = 3300 s
0
10
20
30
40
50
$\dot{V}$ Volume Flow Rate

Fig. 5.6 t_p vs V

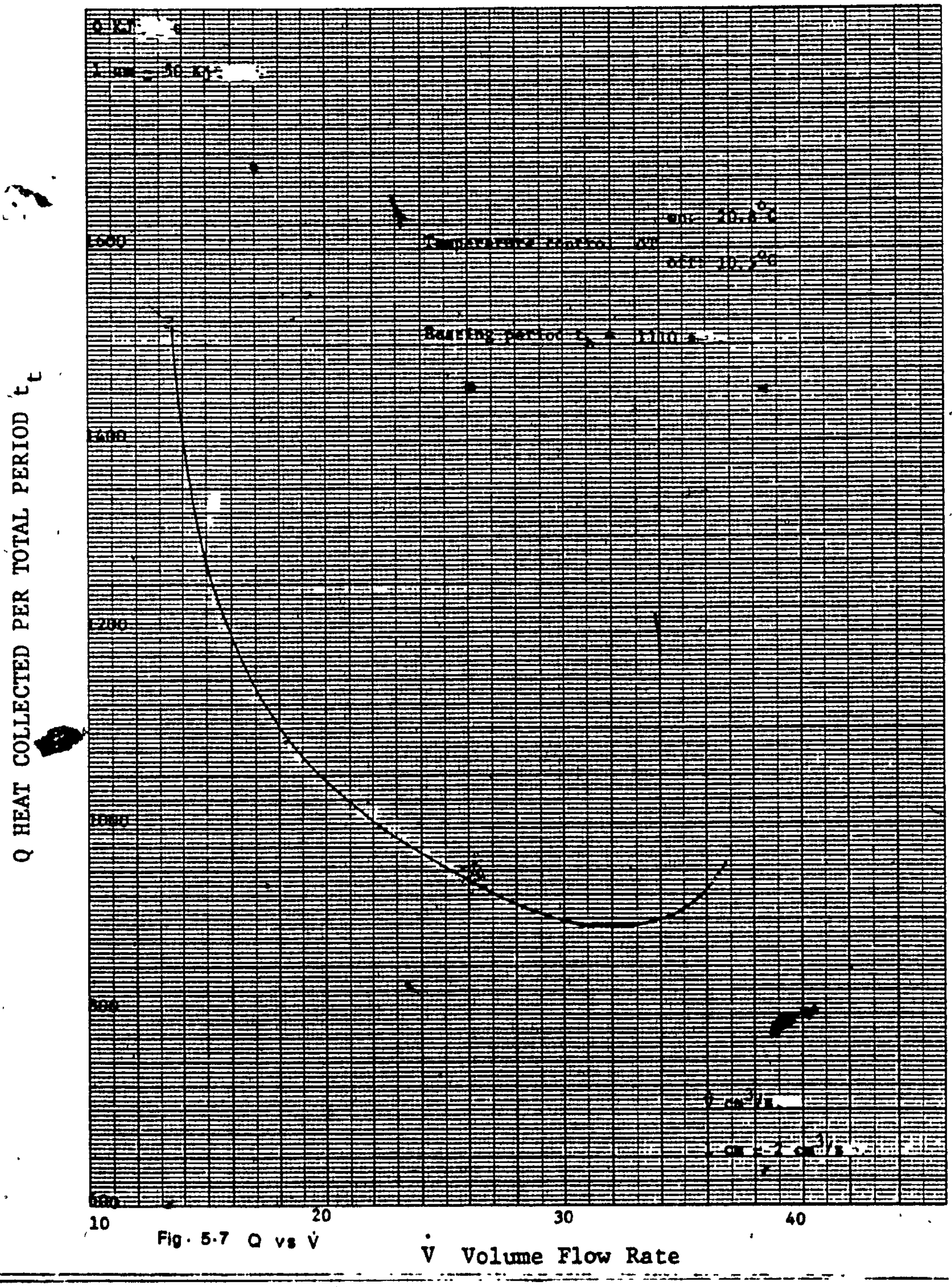


Fig. 5.7 Q vs $\dot{V}$

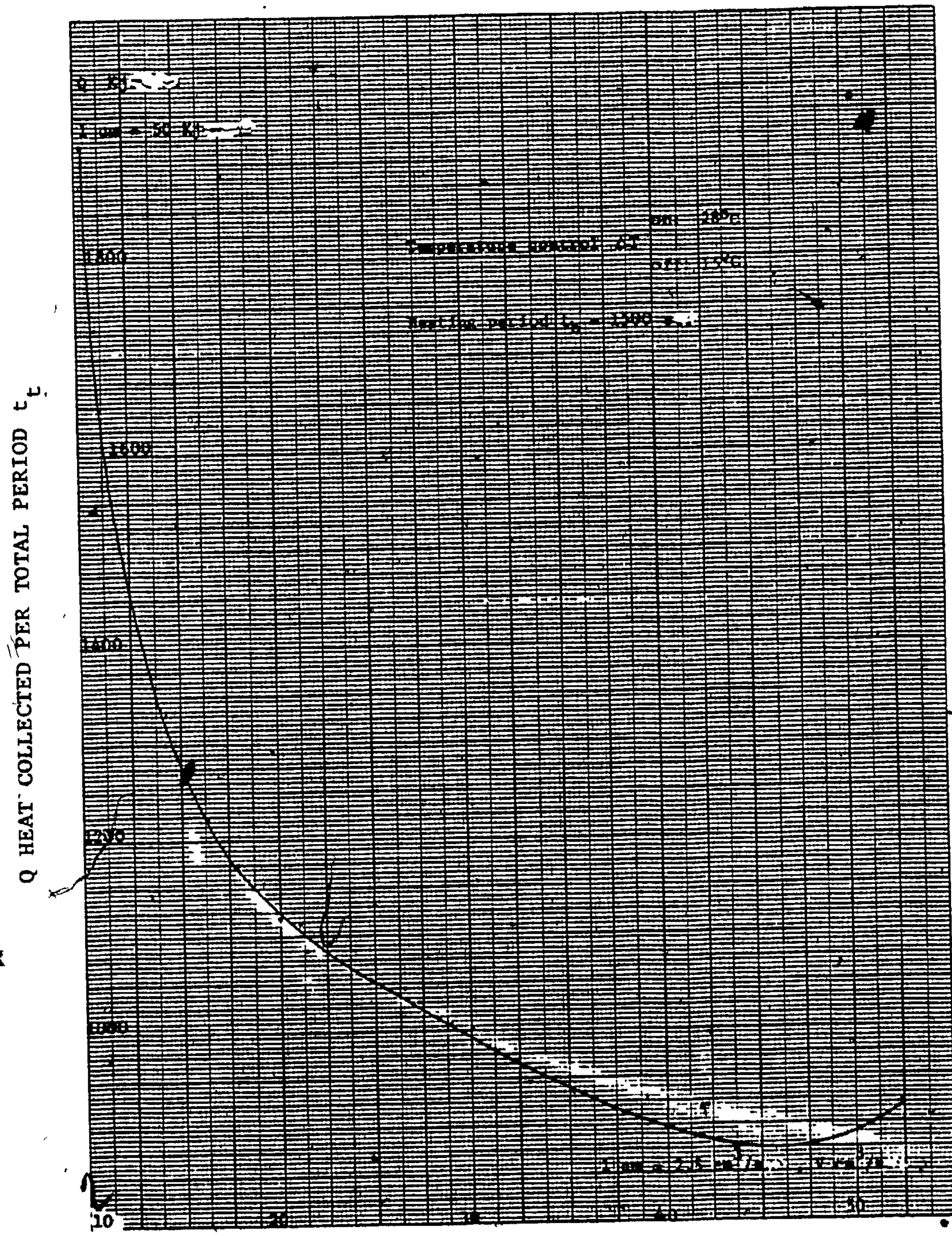


Fig.5.8 Q vs $\dot{V}$

$\dot{V}$ Volume Flow Rate

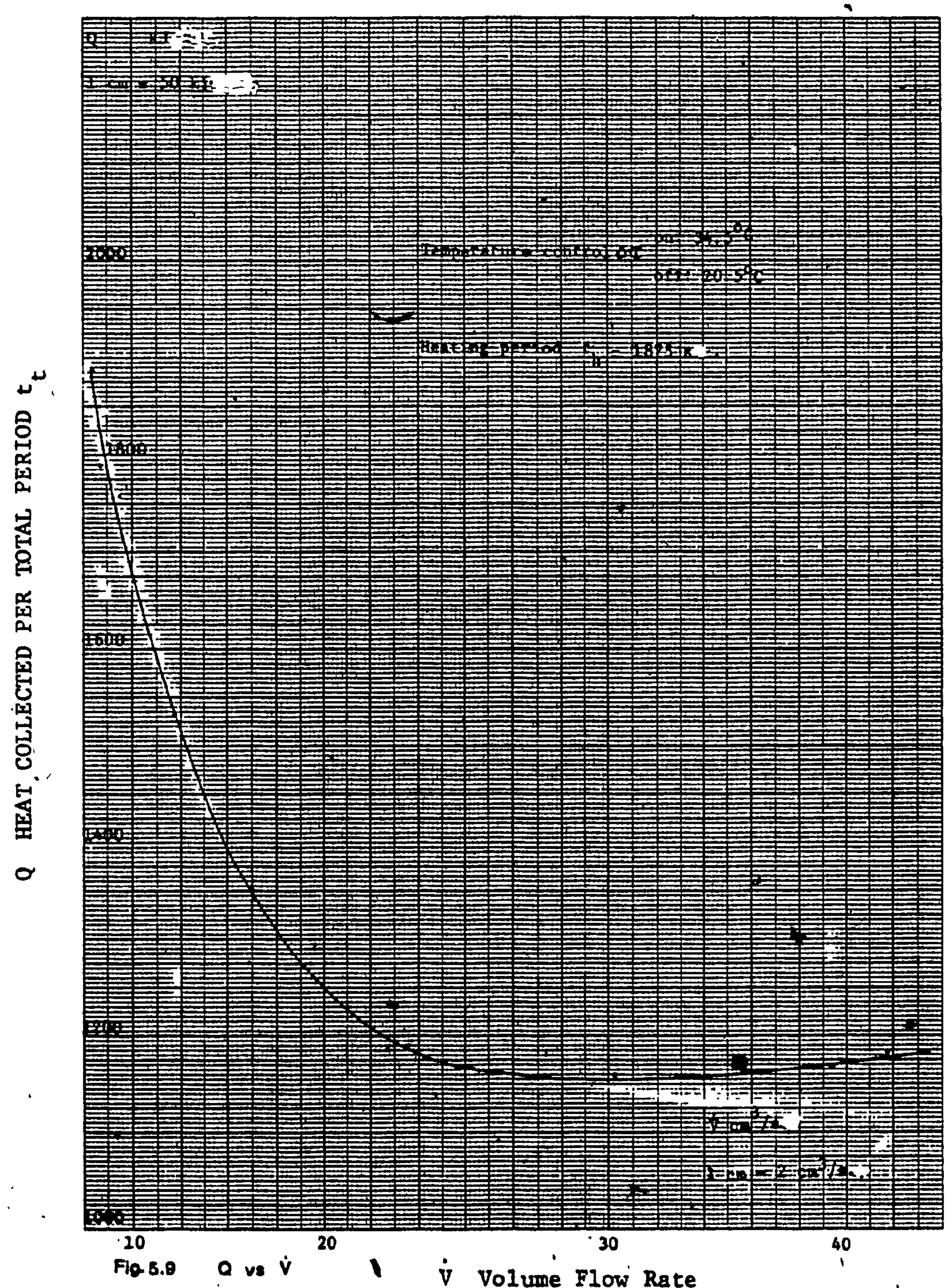


Fig. 5.9 Q vs $\dot{V}$

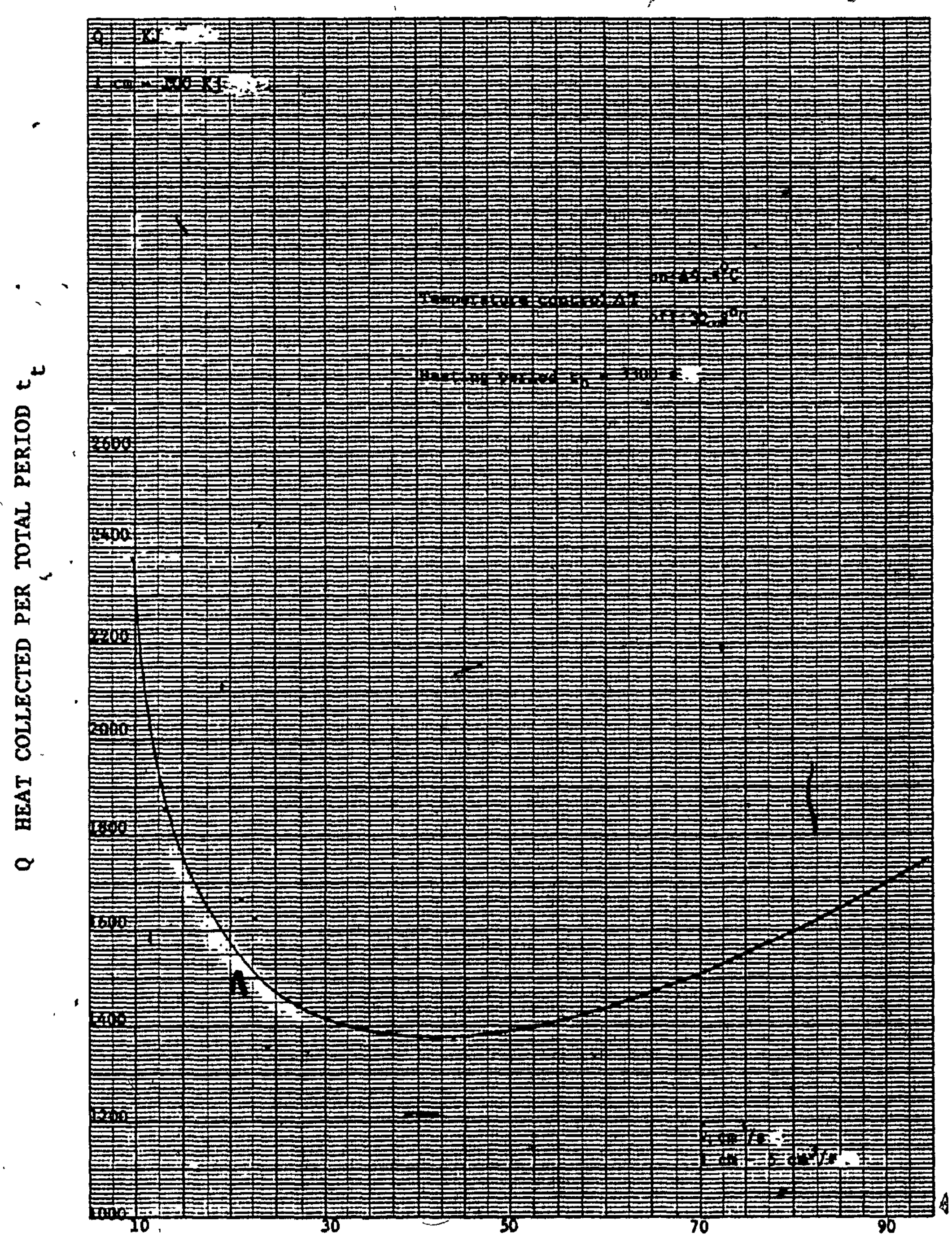


Fig. 5-10 Q vs $\dot{V}$

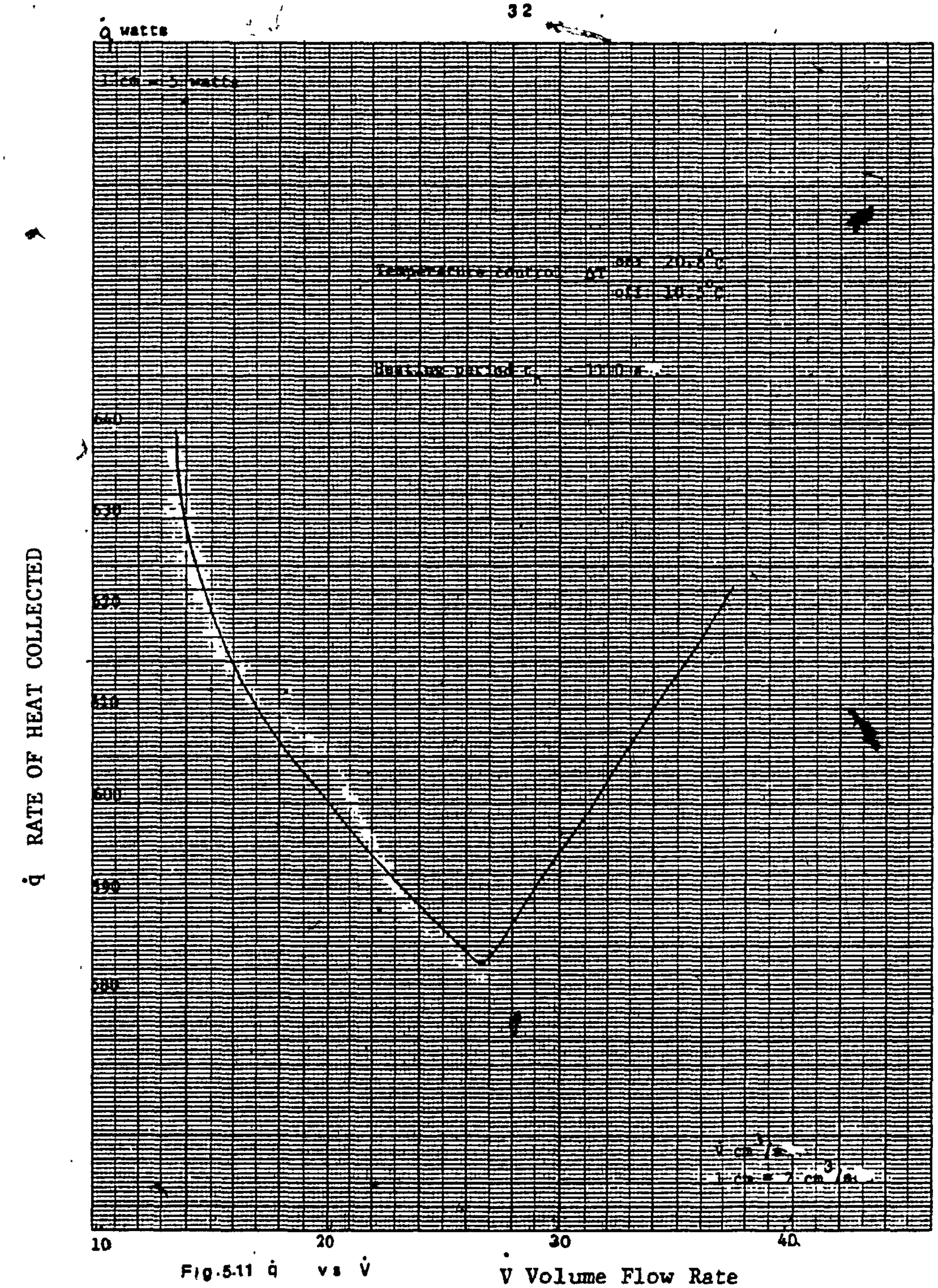


Fig.5.11 $\dot{q}$ vs $\dot{V}$

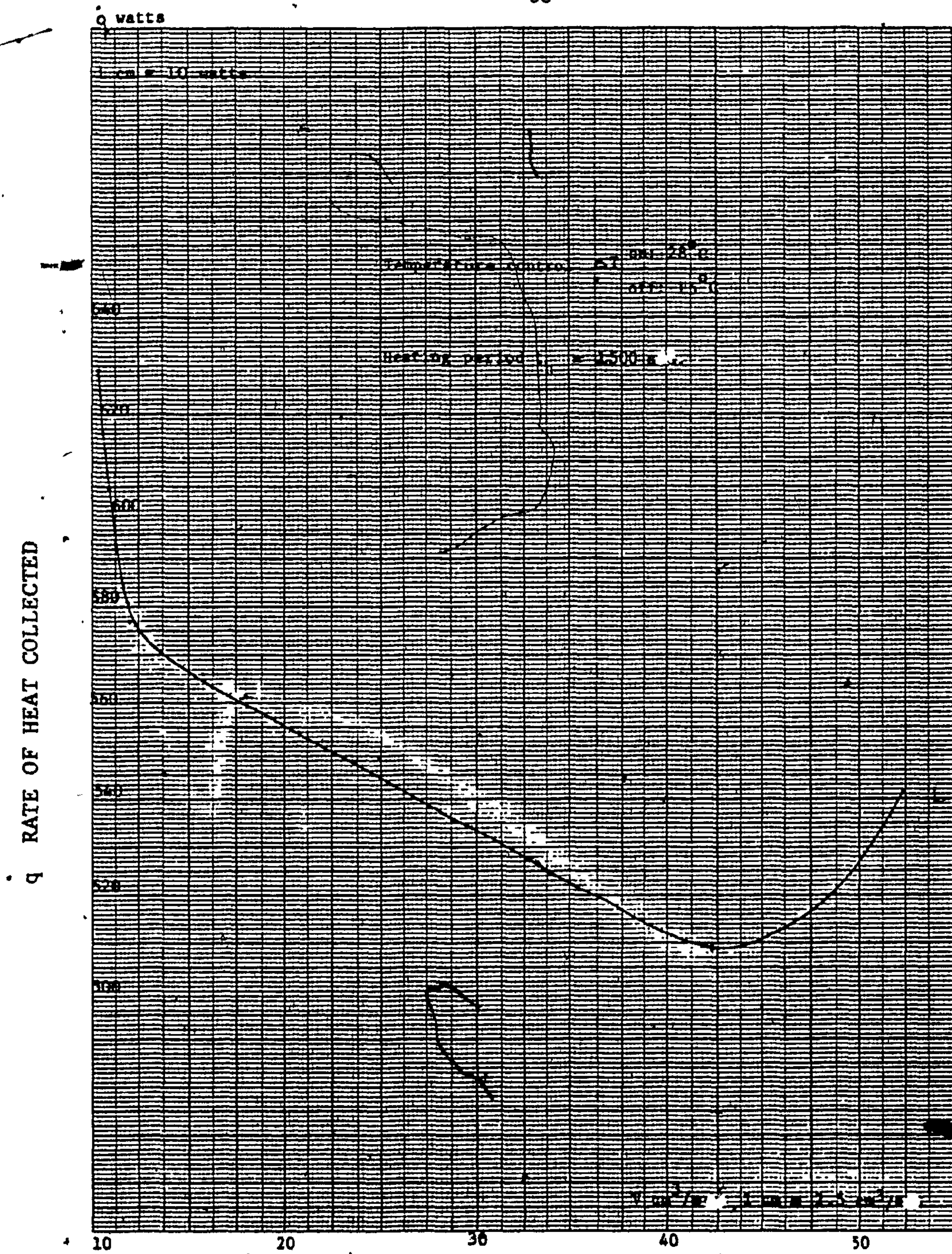


Fig.5.12 $\dot{q}$ vs $\dot{V}$

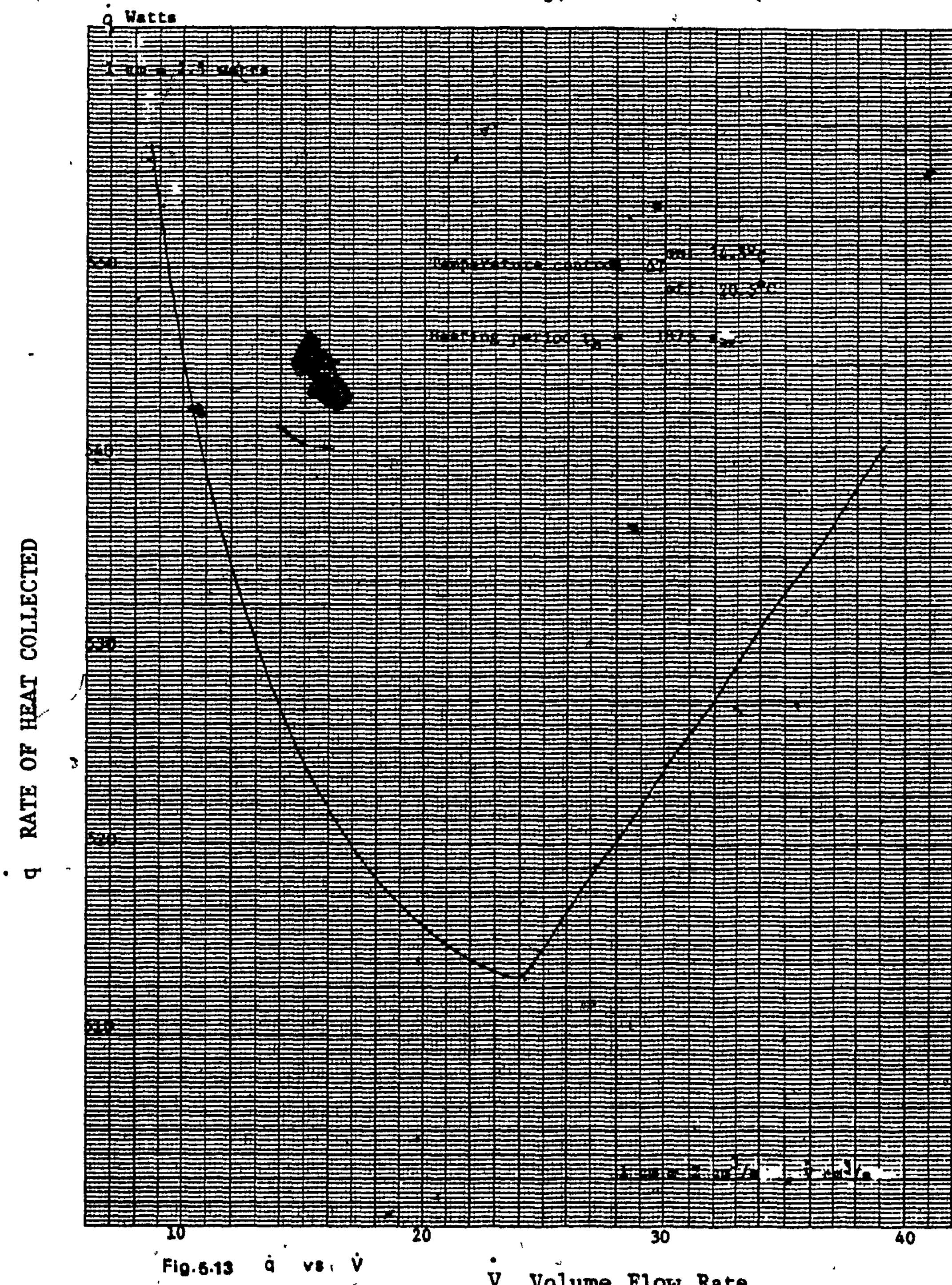


Fig.5.13 $\dot{q}$ vs $\dot{V}$

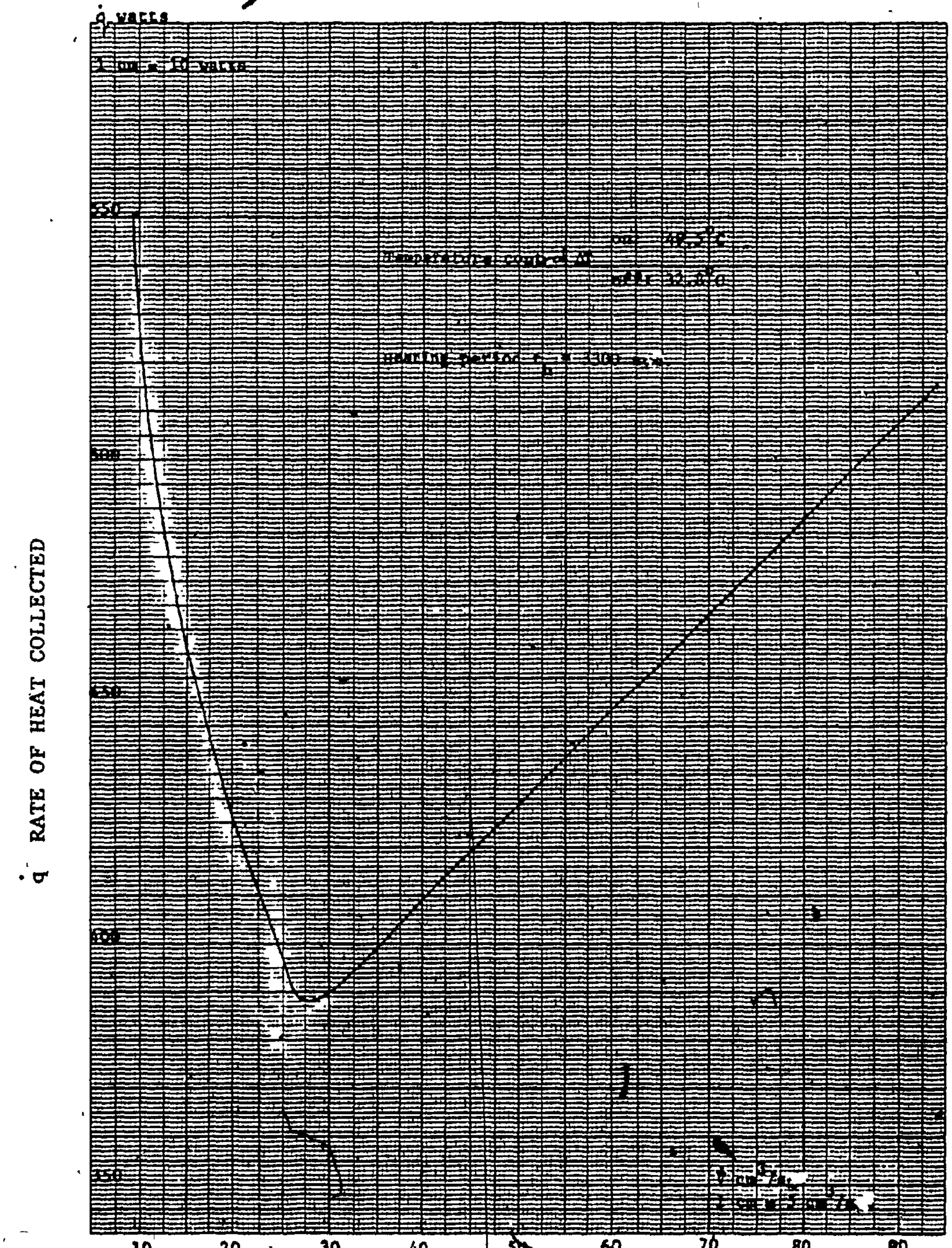


Fig 5.14 $\dot{q}$ vs $\dot{V}$

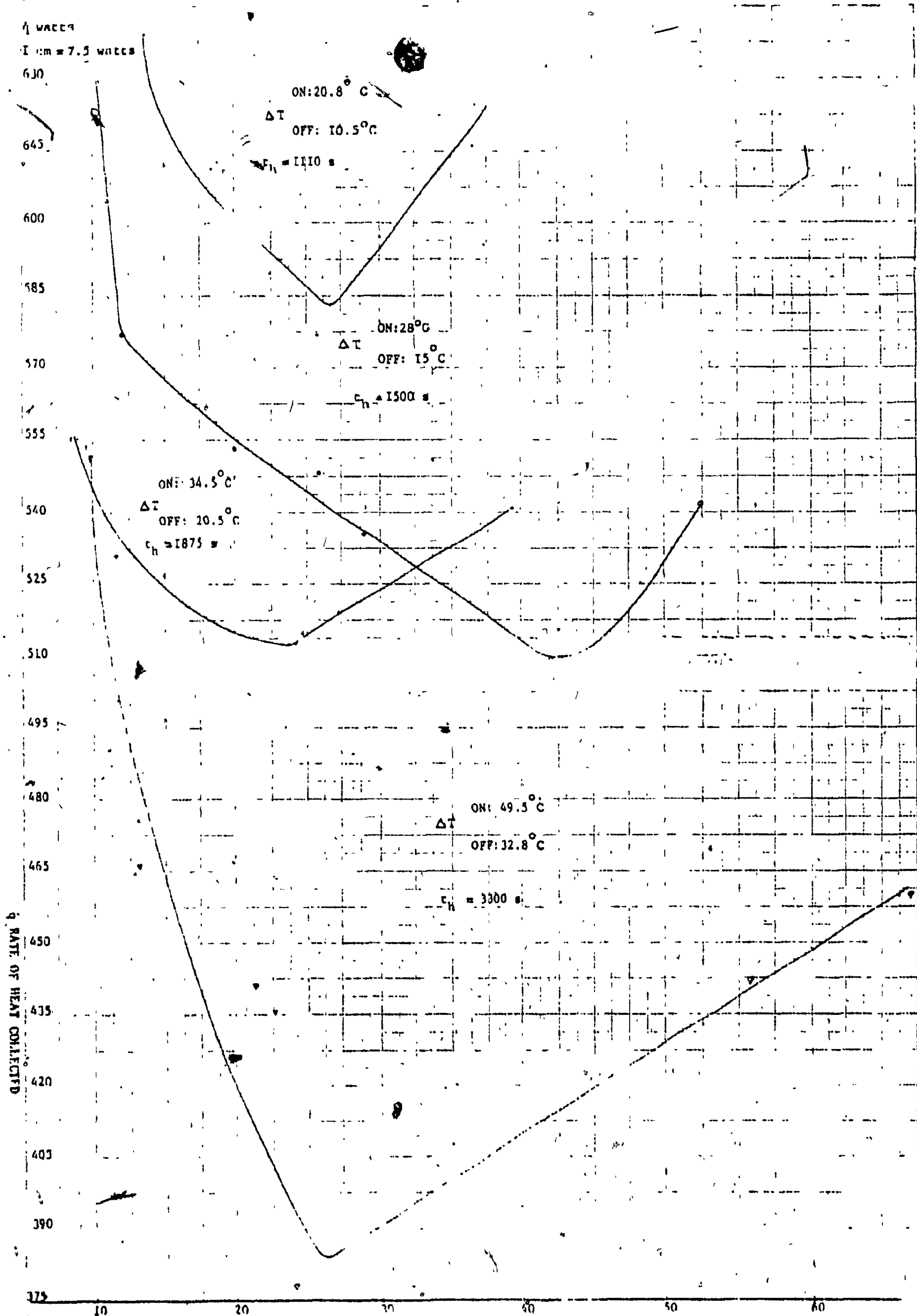


Fig. 5-15 $\dot{q}$ vs $\dot{V}$ for the four values of ΔT and t_h, I cm = 2.5 cm^3/s, $\dot{V}$ cm^3/s

$\dot{V}$ Volume Flow Rate

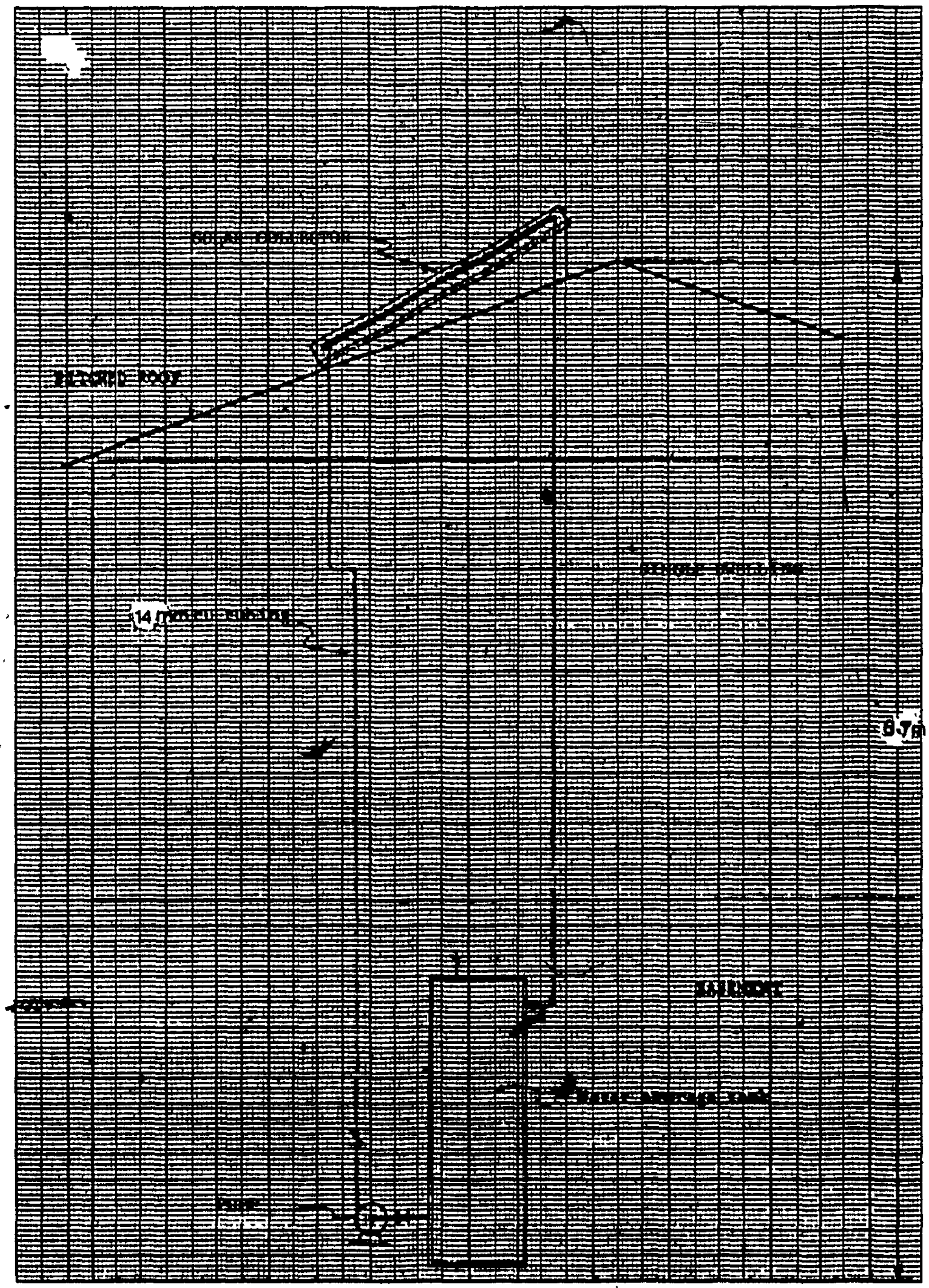


Fig. 5.16 Layout of a solar water-heating installation in a single dwelling

η THERMAL EFFICIENCY OF COLLECTOR

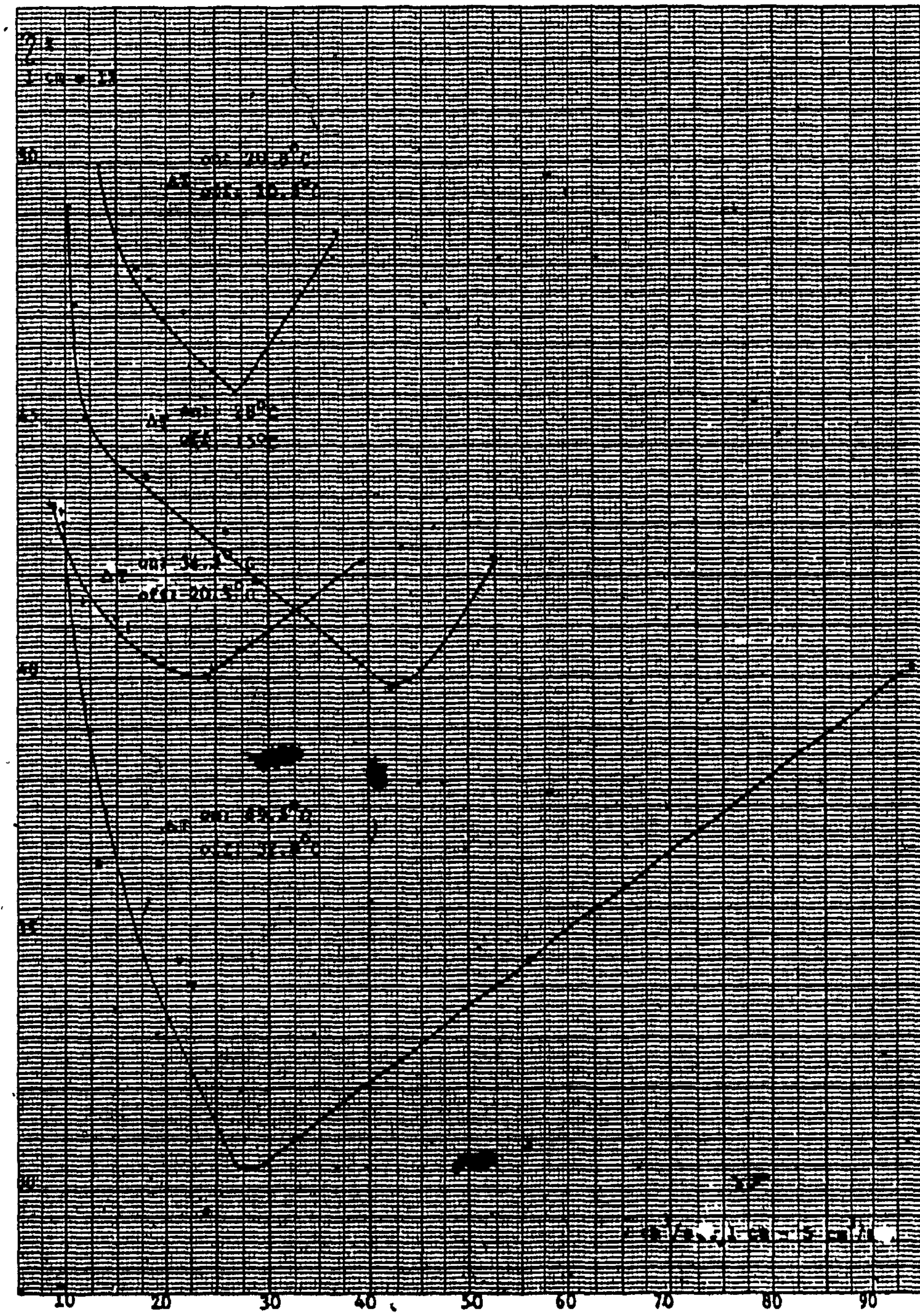


Fig. 5-17 η vs $\dot{V}$

$\dot{V}$ Volume Flow Rate

TABLE I SOLAR COLLECTOR PERFORMANCE   TEMPERATURE CONTROL AT ON 20.8°C OFF 10.5°C   HEATING PERIOD = 1110 s

Exp. #	$\dot{V}$ cm^3/s	M Kg	t_p s	t_t s	Tm °C	Ti °C	(Tm−Ti) °C	Q KJ	$\dot{q}$ Watts	$E_p \times 10^{-3}$ Watts	η %
9	13.60	16.94	1335.0	2373.0	32.8	11.4	21.39	1516.78	639.18	2.39	49.93
9'	15.02	15.59	1038.0	2073.0	30.8	11.4	19.44	1268.65	612.00	2.59	47.81
2	18.30	13.32	724.8	1760.0	31.5	12.2	19.31	1076.68	611.75	3.16	47.79
13	21.83	12.73	583.0	1693.0	32.5	13.3	19.17	1021.53	603.38	6.90	47.14
13'	22.34	12.42	555.0	1690.0	32.5	13.3	19.17	996.65	589.73	7.05	46.07
11'	26.75	12.14	453.0	1598.0	30.0	11.7	18.34	931.78	583.10	10.46	45.55
8'	30.02	11.71	390.0	1505.0	31.7	13.3	18.33	898.50	597.02	12.27	46.64
14	36.41	12.39	340.2	1532.0	29.9	11.7	18.20	943.93	616.14	18.54	48.14
14'	36.53	12.06	330.0	1520.0	30.1	11.4	18.75	946.56	622.74	18.77	48.65

TABLE 2 TEMPERATURE CONTROL AT ON 28°C / OFF 15°C HEATING PERIOD $t_h = 1500$ s

Exp #	$\dot{V}$ cm³/s	M Kg	t_p s	t_t s	Tm °C	Ti °C	(Tm−Ti) °C	Q KJ	$\dot{q}$ Watts	$E_p \times 10^{-3}$ Watts	η %
33	10.35	16.19	1560.0	3051.0	39.1	10.8	28.33	1919.61	629.17	1.09	49.15
34	10.92	14.87	1360.0	2859.96	38.3	10.6	27.78	1729.19	604.62	1.13	47.23
35	11.93	13.44	1128.0	2628.0	37.8	10.8	26.95	1516.20	576.94	1.21	45.07
36	17.98	11.17	622.8	2092.8	36.2	11.1	25.14	1175.49	561.68	2.41	43.88
43	19.94	10.59	531.0	2026.0	36.4	11.1	25.28	1120.55	553.10	3.63	43.21
37	25.87	10.43	403.0	1913.8	35.7	11.7	24.03	1049.45	548.36	6.36	42.84
38	28.77	10.25	356.0	1880.0	34.9	11.4	23.47	1006.72	535.50	7.87	41.84
40'	41.96	9.87	235.0	1735.0	32.5	11.1	21.39	883.39	509.16	14.41	39.78
39	52.37	10.26	196.0	1696.0	32.8	11.4	21.39	918.84	541.77	23.90	42.32

TABLE 3 TEMPERATURE CONTROL AT ON 34.5°C OFF 20.5°C HEATING PERIOD $t_h = 1875$ s

Exp. #	$\dot{V}$ cm^3/s	M Kg	t_p s	t_t s	Tm °C	Ti °C	(Tm-Ti) °C	Q KJ	$\dot{q}$ Watts	Ep x 10^{-3} Watts	η %
28	8.39	13.32	1562.8	3374.8	44.7	11.1	33.61	1874.01	555.30	.64	43.38
20	8.71	12.93	1386.0	3223.2	44.7	11.7	33.06	1789.37	555.15	.65	43.37
20'	9.53	12.70	1335.0	3172.2	44.7	11.7	33.06	1757.54	554.04	.76	43.28
23	11.67	11.37	972.0	2887.2	43.3	11.1	32.22	1533.51	531.14	.91	41.49
22	15.02	10.28	684.0	2563.8	42.8	11.4	31.39	1350.78	526.87	1.20	41.16
21	24.23	9.75	402.0	2277.0	40.0	11.4	28.61	1167.67	512.81	4.60	40.06
21'	24.67	9.64	390.0	2265.0	40.6	11.7	28.89	1165.80	514.70	4.63	40.21
25	27.26	9.41	345.0	2235.0	41.1	11.7	29.45	1160.04	519.03	5.32	40.55
24	39.38	10.16	258.0	2163.0	39.2	11.7	27.50	1169.57	540.72	11.12	42.24

TABLE 4 TEMPERATURE CONTROL AT ON 49.5°C OFF 32.8°C HEATING PERIOD = 3300 s

Exp. #	$\dot{V}$ cm^3/s	M Kg	t_p s	t_t s	Tm °C	Ti °C	(Tm-Ti) °C	Q KJ	$\dot{q}$ Watts	Ep $x10^{-3}$ Watts	η %
19	9.78	12.47	1275.0	4315.2	57.2	11.7	45.56	2378.21	551.12	1.29	43.06
16	13.12	9.26	705.0	3975.0	59.7	11.9	47.78	1852.07	465.93	1.39	36.40
15'	21.20	9.12	430.0	3775.0	56.1	12.5	43.61	1664.87	441.02	1.84	34.45
15	22.65	8.79	388.0	3733.0	56.4	12.2	44.17	1625.23	435.37	2.04	34.00
17	23.98	7.31	304.8	3574.8	56.4	12.2	44.17	1351.59	378.09	2.10	29.54
18	55.78	8.87	159.0	3199.2	50.8	12.8	38.05	1412.79	441.61	11.22	34.50
5	94.02	9.87	87.0	3387	54.4	12.2	42.22	1744.35	515.01	24.06	40.24