Navy Department - Office of Research and Inventions

FR-2676

NAVAL RESEARCH LABORATORY
Washington, D.C.

* * *

CHEMISTRY DIVISION - PROTECTIVE COATINGS SECTION

1 November 1945

First Report
on
INVESTIGATION OF THE CONDUCTING
PROPERTIES OF FILMS PIGMENTED WITH
COPPER

by
Robert Benemelis - Bobetta Sidlow -
J. E. Huskey - Allen L. Alexander

- Report P-2676 -

* * *

Approved by:

Allen L. Alexander - Head, Protective Coatings Section

Dr. P. Borgstrom
Superintendent, Chemistry Division

Commodore H. A. Schade, USN
Director, Naval Research Laboratory

Preliminary Pages	a-d
Numbered Pages	12
Plates	6 11
Distribution List	d

NRL Problem No. P-90

TABLE OF CONTENTS

ABSTRACT

Some evidence exists that organic films containing metallic copper pigment sometimes may be expected to perform similarly to a metallic conductor. The present investigation was designed to uncover evidence to clarify this point of view. A number of experiments are described in which efforts have been made to study the electrical conductivity of anti-fouling paint compositions covering a wide range of pigment volumes. The data indicate that at high pigment volume the conductivity of the film is of a sufficiently high order as to accelerate the corrosion of steel to which it is coupled through a metallic conductor. Further evidence is presented to show that paint films which provide cathodic areas blister and fail more rapidly than non-conducting films. Additional experiments are recommended to expand this investigation to include cuprous oxide paints.

INTRODUCTION

A. Authorization

1. This study was authorized by Bureau of Ships letter S19-1-(3)(336) dated 2 December 1944.

B. References

2. (a) Bureau of Ships letter S19-1(3)(336) of 2 December 1944.
   (b) Bureau of Ships letter S19-1(3)(60177)(336) of 9 March 1944.
   (c) Woods Hole Oceanographic Institution Monthly Report dated 1 September 1944.
   (d) International Nickel Company's Report on Specimens Removed from Sea Water Tests at Kure Beach, N. C., May 1944.
   (e) Young, G. H., Seagren, G. W., Zehner, J. C., Ind. Eng. Chem. 37, No.5 pp 461-4, 1945.
   (f) Woods Hole Oceanographic Institution, Monograph on the Fouling of Ships' Bottoms, Chapter 9 (in preparation).

C. Statement of Problem

3. From observations on the rate of corrosion of steel in contact with paint containing copper, some evidence appears that certain anti-fouling paints rich in copper flake, perform somewhat as a metallic conductor. Reference (a) requested this Laboratory to undertake a study to determine the degree of conductivity of a number of anti-fouling paints containing copper flake pigment. It is felt that a better understanding of the behavior of copper pigment in organic matrices during immersion in sea water will go far in helping the formulators to produce more efficient anti-fouling paints.

D. Known Facts Bearing on the Problem

4. The galvanic corrosion of steel hulls induced by contact with metallic copper has been known for a long time. Numerous instances of damage have been recorded where ships with hulls of copper sheathing have been coupled accidentally with ships whose hulls were made of steel. The accelerated corrosion of the steel was phenomenal, resulting in severe damage. As a result, maritime laws have governed strictly the mooring of copper-bottomed ships in close proximity of steel hulls.

5. Until recently, cuprous oxide was the principal active ingredient of the most successful anti-fouling formulations used by the Navy. Due to the greatly expanded building program of both Navy and Maritime Commission, the supply of cuprous oxide was inadequate and a search was inaugurated for additional toxic ingredients. The most readily available materials turned out to be copper flake and copper powder, which were known to provide adequate protection against the accumulation of fouling organisms. However, their use had long been shunned for fear

of inducing galvanic corrosion. In some instances there was evidence to indicate that loss of fouling resistance resulted when anti-fouling paints containing high volumes of metallic copper were placed in contact with steel. It has been pointed out in refererence (c) that steel strips, when bolted to either steel or wooden panels painted with copper flake anti-fouling formulations, reduce markedly the anti-fouling properties of the film. This phenomena is analogous to the performance of a sheet of metallic copper employed in a like role. Additional evidence recorded in references (e) and (f) indicate that this effect extends for a distance of several feet from the point of metallic contact, the distance and intensity being proportional to the ratio of metallic copper to the resinous constituents of the formulation.

6. Data reported in reference (d) indicate that copper paints increase the corrosion of bare steel areas above that caused by control paints containing no copper. It was also observed that near the edges of bare areas intense fouling occurs. Some efforts have been made (reference (e)) to investigate the electrical conductance of metallic copper paints on the assumption that they possess sufficiently low resistance to support galvanic action. The results have pointed to the fact that while accelerated corrosion does occur and fouling resistance is impaired, the conductivity of the film is so low that accurate measurements have been difficult.

7. From the references cited above, it is clear that some type of electrical contact exists between the pigment particles of highly pigmented anti-fouling paints and steel areas adjacent thereto. The effects of such contacts have been observed and reported in a number of instances. Several theories have been proposed as to the mechanism by which the observed phenomena has occurred. One theory (reference (e)) holds that copper, whether present in the paint film as cuprous oxide or as the metal, passes into solution in sea water from which it subsequently plates out in the form of metallic copper on the surface of the metal beneath the paint film. This immediately sets up a galvanic couple, the nature of which is well known. It is the purpose of this study to investigate the properties of paint films containing copper metal and its various oxides in their several forms with a view of further explaining observed phenomena.

METHODS AND DATA OBTAINED

A. Materials

8. The steel used in panel preparation consisted of 1/16" cold rolled bright plate. Care was taken to use only clean steel free from rust and pits. Each panel was assembled and then solvent cleaned and sand blasted. Steel rods (1/4") used for support of the panels were silver soldered to the panel surface. The silver solder-steel junction undoubtedly set up galvanic action, but this action is entirely local and does not affect the performance of the large steel-copper cell.

Copper sheet was used for the preparation of all copper panels, to which copper rods were soldered.

9. In order to study the properties of paint films when applied to a nonconducting medium, lucite panels 1/8" or 1/4" thick were used. Lucite was chosen because of its excellent insulating properties and workability. All paints studied adhere well to lucite, which was an added advantage.

10. For making electrical contact with the edges of the paint films, duPont's Colloidal Silver Conducting Paint No. 4133 was used. Films of this paint possess resistance of 0.5 ohms when measured longitudinally across a 2.0 x 0.8 inch strip at a thickness of 0.002 to 0.003 inch.

11. All resistance measurements above 75,000 ohms were made with a Megohm Bridge manufactured by the General Radio Corporation. This bridge is operated by alternating current and is capable of measuring resistances from 87,000 ohms to 1,000,000 megohms. Resistance values between 87,000 ohms and 1,000 megohms are accurate within 1.2%; those from 1,000 megohms to 1,000,000 megohms are accurate within 4.5%. The A.C. voltage impressed across the resistance to be measured can be set at 100 or 500 volts. For our purpose the 100 volt potential was chosen and used in all measurements.

12. For measuring resistance values below 87,000 ohms a Weston ohmmeter Model 665 was employed. Accuracy of readings made by this instrument, which employs a potential of approximately 10 volts, does not vary more than 1% over the entire range.

13. Since no fresh sea water is available at this Laboratory for exposing specimens of this sort, resort was made to a bath containing artificial sea water prepared according to a standard Navy formula. A welded steel tank, size 60" X 30" X 18" was lined with 1/4" uncured neoprene and cured in place. All seams were carefully sealed to insure that no contact existed between the water and steel. The tank was filled with approximately 150 gallons of sea water prepared according to the following formula:

TABLE I

Constituent	% by Weight
Sodium Chloride Crystal	2.45-2.55
Magnesium Chloride Crystal ($MgCl_2 \cdot 6H_2O$)	1.08-1.12
Calcium Chloride Crystal ($CaCl_2 \cdot 2H_2O$)	0.155-0.165
Sodium Sulfate Anhydrous	0.390-0.410
Distilled Water	Balance

A gear pump having a capacity of 20 gallons per minute was used to circulate the water from one end of the tank to the other. At a point just behind the output end of the circulatory system a stream of air was injected into the water to insure a continuous supply of dissolved oxygen. The circulating pump was allowed to run continuously during some exposures, and was shut off during others. The complete set-up is illustrated in Plate II.

B. Experimental

14. For descriptive purposes the experimental work may be divided conveniently into three parts as follows:

(a) A study of the effect of sea water on the surface conductivity of anti-fouling paints pigmented with copper flake.

(b) A determination of the galvanic effect of a standard anti-fouling paint (AF-23) when coupled directly with bare steel panels submerged in artificial sea water.

(c) A study of the effect on the surface conductivity of a copper bearing anti-fouling film when immersed in sea water and coupled with bare steel.

15. The surface conductivity specimens were prepared for immersion as follows: Lucite sheets size 3" X 3" X 1/4" were masked 1/2" along each edge after which they were given two spray coats of the anti-fouling formulations. After drying, the masking tape was removed leaving a 2" square of paint film exactly in the center of each panel. No attempts were made to hold the film thickness constant although the spraying technique was identical in each case. To obtain dimensionless resistance values, perfect squares of paint surface were examined. When thoroughly dry, two opposite edges were covered with the silver conducting paint which served as contact points for measuring resistance. The copper paints used varied in pigment volume ratio from 5% to 45% as shown in Table II. The matrix consisted of a chlorinated rubber-rosin blend commonly employed in cold plastic anti-fouling formulations. The exact composition of the vehicle is as follows:

	% by Wt.
Rosin	45
Hercolyn	3
Pliolite	12
Varsol	18
Turpentine	22

16. All panels prepared as described above were permitted to reach equilibrium in a constant temperature-humidity room maintained at 25° C., and relative humidity of 50%. Duplicates were prepared for each panel and conductivities were determined daily until a constant value was reached. The data of Table II represents averages of duplicate determinations. An average period of between one and two weeks was required for equilibrium.

TABLE II

SURFACE RESISTANCE (OHMS) OF CuFLAKE A-F PAINT

P. V. Ratio	Set 1		Set 2		Set 3		Set 4		Set 5	
	I	45 hours	I	96 hours	I	144 hrs.	I	168 hrs	I	216 hrs.
5%	Inf.	Inf.	Inf.	1.50×10^{11}	Inf.	1.0×10^{11}	Inf.	1.5×10^{11}	Inf.	1.75×10^{11}
10%	"	1.25×10^{11}	"	1.0×10^{11}	"	6.0×10^{10}	"	1.5×10^{11}	"	1.25×10^{11}
15%	"	7.5×10^{10}	"	3.0×10^{10}	"	3.5×10^{10}	"	2.8×10^{10}	"	1.7×10^{10}
20%	1.3×10^{10}	1.0×10^{10}	7.0×10^{9}	5.5×10^{9}	3.5×10^{10}	1.0×10^{10}	1.7×10^{10}	1.1×10^{10}	1.5×10^{10}	1.0×10^{10}
25%	8.0×10^{8}	1.1×10^{9}	2.0×10^{9}	1.5×10^{9}	1.5×10^{9}	1.5×10^{9}	1.5×10^{9}	1.5×10^{9}	9.0×10^{8}	7.0×10^{8}
30%	3.0×10^{8}	2.6×10^{8}	3.75×10^{8}	3.3×10^{8}	5.0×10^{8}	7.0×10^{8}	4.5×10^{8}	8.0×10^{8}	3.1×10^{8}	6.3×10^{8}
35%	5.0×10^{7}	3.0×10^{8}	4.0×10^{7}	4.0×10^{8}	1.0×10^{8}	6.0×10^{8}	9.5×10^{7}	4.1×10^{8}	7.1×10^{7}	1.95×10^{8}
40%	2.4×10^{8}	8.6×10^{8}	1.5×10^{8}	9.0×10^{8}	3.2×10^{8}	1.5×10^{9}	2.5×10^{8}	1.7×10^{9}	1.8×10^{8}	1.35×10^{9}
45%	1.0×10^{8}	5.25×10^{8}	4.0×10^{6}	7.5×10^{8}	1.5×10^{8}	8.5×10^{8}	2.0×10^{8}	1.4×10^{9}	2.0×10^{8}	1.00×10^{9}

17. Five sets of identical panels were prepared in order to provide for removal at varying periods. The first set was removed from the sea water tank after 45 hours with the others following at the intervals indicated in Table II. Upon removal all panels were thoroughly washed with distilled water to dislodge any loosely adhering salt particles, and were returned to the constant temperature-humidity room where they were allowed to come to equilibrium, at which time conductivity measurements again were made. Measurements were repeated until constant conductivity values were obtained.

18. The second phase of this investigation (see (b) of paragraph 14 above) consisted of a study of the galvanic effect produced by coupling panels coated with standard copper anti-fouling paint with steel immersed in sea water. As a point of reference, steel and copper panels of equal surface area were coupled and immersed simultaneously. A series of panels was prepared using anti-fouling paint No. AF-23 pigmented with two varieties of copper flake as designated in Table III. In order to avoid any uncontrolled factors which might be introduced by the presence of a conducting panel, two lucite panels were painted and coupled to steel in exactly the same manner as the copper sheet and painted steel specimens.

19. The steel panels were carefully sand blasted, after which they received two medium coats of AF-23 paint. Supporting steel rods in contact with the panels were heavily waxed over their entire length to insure that no bare steel was exposed to the sea water. The lucite panels were given no treatment prior to application by spray of two coats of AF-23 Anti-Fouling Paint. Once the paints had dried thoroughly, a copper strip 1/2" in width was bolted across the top of the panel with care being taken to insure good electrical contact with the paint. A copper rod was soldered to the copper strip, after which all metal parts of the system were given one coat of aluminized spar varnish and then heavily waxed to seal completely all metal parts from contact with the sea water.

20. The painted panels, along with the bare copper controls were coupled to a bare steel panel through a 10 ohm resistor. The galvanic or corrosion current of the couple was determined by measuring the IR drop across the resistor. From this value the current was calculated readily. The 10 ohm resistor was selected as providing a convenient value to be measured with equipment readily available. A more accurate measure of the current might be obtained with the use of smaller resistors but the IR drop would become so small as to require the use of much more elaborate apparatus.

21. The current produced by the couples was measured periodically, results of which are plotted in Plates I through VIII. Duplicate couples were prepared for each paint as shown in Table III. While the shapes of the curves produced for each set of couples are not exactly duplicated, a good general agreement is in evidence. As noted on each plate, two sets of data were obtained, with and without aeration and agitation.

TABLE III

DESCRIPTION OF COUPLES INVESTIGATED

Couple No.	Panel Materials	AF-23 Pigments
I, II	Steel	Cu Flake MD 750
III, IV	Steel	Cu Flake MD 8224
V, VI	Cu Metal	None
VII, VIII	Lucite	CuFlake MD 750

22. The third phase of the experimental work consisted of a study of the effect on the conductivity of a copper bearing anti-fouling film when immersed in sea water and coupled directly with the steel. As in the foregoing experiments lucite panels size 5" X 5" X 1/4" were masked 1/2" on three sides and given two spray coats of an anti-fouling paint prepared at varying pigment-volume ratios. The pigment-volume values are shown in Table V, and the vehicles were the same as that described in paragraph number 15. After thorough drying the masking tape was removed and a copper strip 1/2" in width was bolted carefully along the edge of the panel which had not been masked. A copper rod had been soldered to the copper strip to serve as a means of support as well as a conductor. After final assembly all metal parts were covered thoroughly with two coats of aluminized spar varnish followed by a thick coat of heavy wax to insure against any electrical contact between metal parts and the sea water. A film of the silver conducting paint was applied to the edge of the panel opposite the copper strip to serve as the other contact point for measuring resistance across the 4" square of paint. The assembly of all the panels described in the three sections of the experimental work is illustrated in Plates 9 and 10. The silver-copper paint junction is entirely local and any galvanic effect would not appear in the measurement of the large cell.

23. Five sets of copper paint-steel couples were prepared and immersed in the sea water bath along with an uncoupled control. The couples were prepared in duplicate for each paint through a 10 ohm resistance. Pigment-volume ratios varied between 15% and 35%, as earlier experiments had indicated that a critical value affecting the resistance of the film occurred somewhere within this range. Currents resulting from the couples were determined periodically by measuring the IR drop across the known resistance. Measurements were made over a total interval of 114 hours at which time no couple prepared from a paint having pigment-volume ratio below 30% showed any indication of producing a measurable current. The two sets of couples prepared from paints of 30% and 35% pigment-volume ratio, respectively, reacted as indicated in Table IV.

TABLE IV

GALVANIC CURRENT OF PAINT-STEEL COUPLES

Couple Number	P/V Ratio	Current in milliamps after soaking as indicated: 6 hours	23 hours	28 hours	45 hours
11	30%	0	0	0	0 (No current after 114 hours)
12	30%	0	3.0	3.2	1.2
14	35%	0	2.8	3.8	1.5
15	35%	0	3.2	5.2	1.5

24. At the end of 114 hours all panels were removed from the immersion bath. Adhering salt particles were removed from the paint films with distilled water and the panels returned to the constant temperature-humidity room where they were allowed to stand until constant resistance values were obtained. These values are shown in the last column of Table V. Figures showing the original resistance before immersion are included for reference.

TABLE V

RESISTANCE OF SOAKED PAINT FILMS COUPLED WITH STEEL

Panel or Couple No.	P-V Ratio	Resistance in Ohms: Original	After Soaking
1*	15%	Infinite	$1.5x10^{11}$
2	15%	Infinite	$2.0x10^{11}$
3	15%	Infinite	$2.8x10^{10}$
4*	20%	$1x10^{10}$	$2.2x10^{9}$
5	20%	$1.1x10^{10}$	$1.35x10^{9}$
6	20%	$7.8x10^{9}$	$1.25x10^{9}$
7*	25%	$1.75x10^{8}$	$1.2x10^{8}$
8	25%	$1.90x10^{8}$	$1.45x10^{8}$
9	25%	$2.00x10^{8}$	$1.20x10^{8}$
10*	30%	$6.0x10^{7}$	$1.2x10^{10}$
11	30%	$6.0x10^{7}$	$9.0x10^{9}$
12	30%	$6.5x10^{7}$	2.5
13*	35%	$4.7x10^{7}$	$8.5x10^{7}$
14	35%	$6.8x10^{7}$	60
15	35%	$5.4x10^{7}$	3

* Uncoupled controls.

DISCUSSION OF RESULTS

25. The data of Table II gives rise to interesting speculation concerning the conductivity of highly pigmented films, particularly in view of the findings reported in reference (e), that all attempts to measure a finite resistance in the plane of the film of even the most conductive metallic anti-fouling paints were unsuccessful. Several conclusions are quite obvious from a close examination of our data. First, it is demonstrated that films of low pigment volumes, that is, below 15% are good insulators (infinite resistance) under the applied potential of 100 volts, before they are allowed to soak in sea water. However, after continuous immersion in artificial sea water for a minimum of 45 hours the resistance is reduced to such a point that it may be measured easily. Prolonged soaking does not change significantly the conductivity characteristics of the film. At pigment-volume concentrations above 20% soaking in artificial sea water does not reduce further the resistance of the film, but on the contrary a slight increase is noted. This may be attributed to the formation of corrosion products or salts from the pigment particles themselves.

26. At some pigment concentration between 20 and 25% the resistance of the film reaches a value that varies only slightly as the pigment volume is increased. A minimum value is attained around 35% pigment which is somewhere near the maximum employed in standard anti-fouling formulations. It should be noted that while some of the values shown vary considerably numerically, they are in fair agreement relatively (same order of magnitude) for values obtained by the described methods. It is significant that between 20 and 30% pigment volume, film resistance is reduced to a point at which some readily measurable currents might be expected to flow under potentials of a reasonably low value. It was at this pigment-volume concentration that the inactivating effect obtained by coupling steel bars to metallic paints applied to wood panels was noted by the Woods Hole investigators as reported in reference (c). This data therefore provides additional evidence that critical values for pigment volume concentrations of copper paints exists around the 20-30% level to insure adequate performance for continuing periods. Additional evidence is provided by an examination of other data discussed in the following paragraphs.

27. The curves shown in Plates 1 through 8 allow some interesting comparisons between the galvanic currents produced by coupling a film of highly pigmented copper flake paint (AF23, PV Ratio 37%) to a steel panel with similar currents that result from a copper-steel couple involving comparable areas. Data for the curves was derived in duplicate as indicated in Table III. Plates 1 and 2 report the galvanic currents produced on two independent couples prepared in exactly the same manner. The agreement obtained in the first set of experiments is excellent except during the first few hours of immersion. It should be noted that a relatively larger current was obtained in each case where the sea water was aerated and agitated. The slopes of the curves

of duplicate experiments are in close agreement. The currents produced during agitation shows a tendency to diminish at a more rapid rate, but the eventual slopes are almost identical.

28. Plates 3 and 4 represent repeat experiments in which the copper pigment was substituted as shown in Table III. The same generalizations apply as before except that current values obtained with the substitute pigment were somewhat lower throughout.

29. A comparison of Plates 5 and 6 with 1 through 4 shows a striking resemblance with the exception of the first few hours of immersion during which the current was increasing in the case of the copper paints. On plate 6 even this phenomenon is repeated by the copper steel couple. Inasmuch as the slopes, shapes, and magnitudes of the curves for the paint couples so nearly duplicate those for the copper-steel couples, it is difficult to evade the conclusion that the flakes of copper within the matrix above 25% pigment volume are in sufficiently close contact to perform as a conductor in somewhat the same manner as copper sheet.

30. The possibility may not be discounted that some contact was made vertically through the film to the steel plate beneath, thus bringing into the system the effect of steel in contact with the copper flake in the presence of sea water. At some points in this system areas could be set up which are anodic relative to the steel. In order to eliminate this possibility duplicate panels were prepared using lucite as a non-conducting base. Results obtained are in fair agreement with those from the copper steel couple (see plates 7 and 8) with the exception that a time lapse of 25 to 50 hours occurred in the case of the painted lucite before an appreciable current was produced. This indicates that some penetration of the film by the solution is necessary before the resistance between individual particles of copper is reduced to a point where a measurable current can be produced. It is also significant that in the case of the film of copper paint on lucite larger current values were obtained than with the copper steel couple. Since the lucite panel was painted on one side only the area of copper exposed to the sea water was twice that of the apparent areas of paint film. However, due to the flaky or uneven surface of the paint considerably more effective area was probably present resulting in the higher current values observed.

31. The assumption that individual pigment particles are in contact, thus providing straight line conductors throughout the plane of the paint film would provide immediate explanation for the facts observed. However, if this condition should occur one would expect resistance in the plane of the film to diminish to a value comparable to that of a sheet of copper. The values of Table II indicate that this does not happen. Reference (e) proposes the theory that when paints containing copper are submerged in sea water copper ion first leaches into solution from which it plates out, in, or beneath the paint film in which it was originally contained. Thus, the nature or source of the original copper in the paint assumes secondary importance as long as a sufficient quantity is present to continue this secondary action. Such a theory may offer an explanation for the lapse of approximately 50 hours which

occurs before the anti-fouling films applied to lucite begin to develop appreciable currents. During this interval copper is passing into solution and subsequently plating out into the paint film or beneath it.

32. The experiment described in paragraphs 22 through 24 serves in part to substantiate earlier observations that soaking in sea water lowers the resistance of paints with low pigment content, whereas, it serves to increase the resistance of paint films containing medium concentrations of pigment. The data of Tables IV and V, however, clearly indicate that at high pigment-volume concentrations the resistance of paint films reach such low values that appreciable currents are set up when coupled with steel that can be easily measured. Table IV presents data which indicates that copper flake anti-fouling paints pigmented above 30% produce films, which coupled to steel produce currents that are readily measured. Furthermore, the data indicates that the resistance of such films diminishes to values characteristic of good conductors.

33. Here, as in earlier experiments, a high pigment concentration must be obtained before low resistance values are reached. This critical value is approached by the AF 22-23 series of paints; however, it is not reached in the plastic type materials ordinarily used for ship bottom protection.

34. Of additional interest is the fact that the films showing high resistance and the passage of no current develop the characteristic green or brownish green color normally associated with films of this type immersed in sea water. Upon removal the films were firmly adhereing and were removed in the form of a powder when scraped with a knife edge. On the other hand the films showing low resistance and which developed appreciable currents when coupled with steel retained a bright metallic appearance and blistered, loosing their adhesion to the lucite panel. The film could be removed easily in the form of large flakes. The uncoupled controls behaved in exactly the same manner as the coupled films of lower pigment concentration.

35. Thus, the data presented in Tables IV and V lend further evidence to the theory that by increasing pigment concentration sufficiently a condition may be reached in which the conductance of the paint film becomes so great that it is capable of transmitting galvanic currents appreciable distances.

CONCLUSIONS

36. In the foregoing experiments it has been conclusively demonstrated that highly pigmented films possess a finite surface conductivity which can be measured over reasonable distances by means of instruments commonly used in the laboratory. On the other hand films of low pigment volume possess an infinite resistance when measured in the plane of the film.

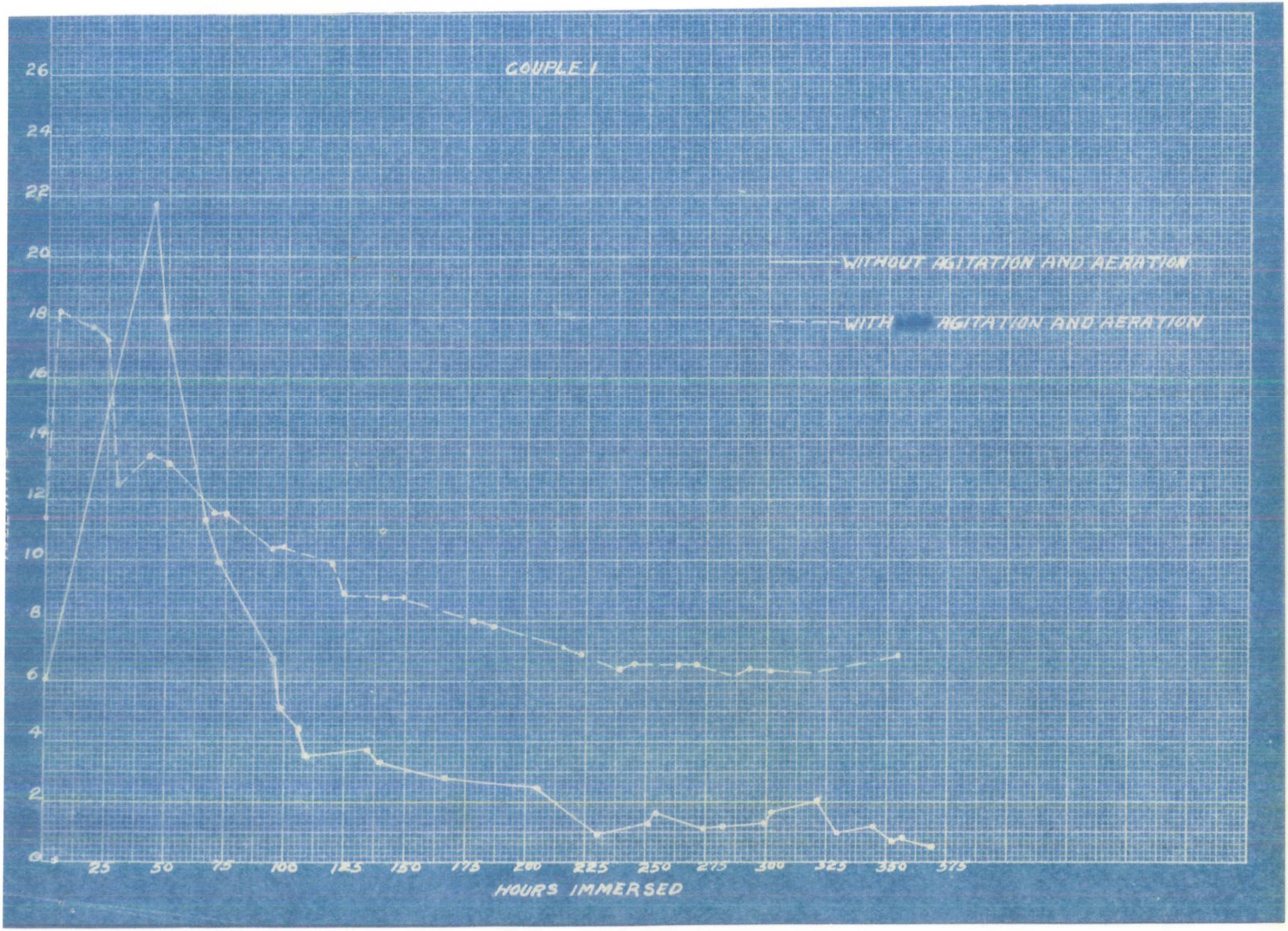
37. It has been shown that highly pigmented copper flake paints act as a cathode when coupled through a metallic contact with steel. Currents are produced which are of the same order of magnitude as those obtained for copper sheet involving comparable areas. Therefore, it may be concluded that highly pigmented films act in the same capacity as copper sheet when in electrical contact with steel over limited areas.

38. Additional evidence is provided to substantiate the view that highly pigmented copper films perform as electric conductors when coupled with steel. The evidence so far does not conflict with the proposed theory that copper first leaches from the film and subsequently plates out either beneath or in the plane of the film forming a deposit of metallic copper. Additional experiments will clarify further this view.

RECOMMENDATIONS

39. It is urgently recommended that these experiments be continued to develop data which will define more clearly the mechamism by means of which highly pigmented copper films appear to perform as metallic conductors. These experiments should include cuprous oxide pigment, in addition to copper powder.

40. Should additional laboratory experimentation appear to substantiate the theories proposed to explain the observed phenomena, it is recommended that panels prepared from copper-containing paint be coupled to steel in which sufficiently large areas will be involved in order that galvanic currents arising from such couples may be measured accurately.


COUPLE I
WITHOUT AGITATION AND AERATION
WITH [redacted] AGITATION AND AERATION
HOURS IMMERSED
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
2
4
6
8
10
12
14
16
18
20
22
24
26

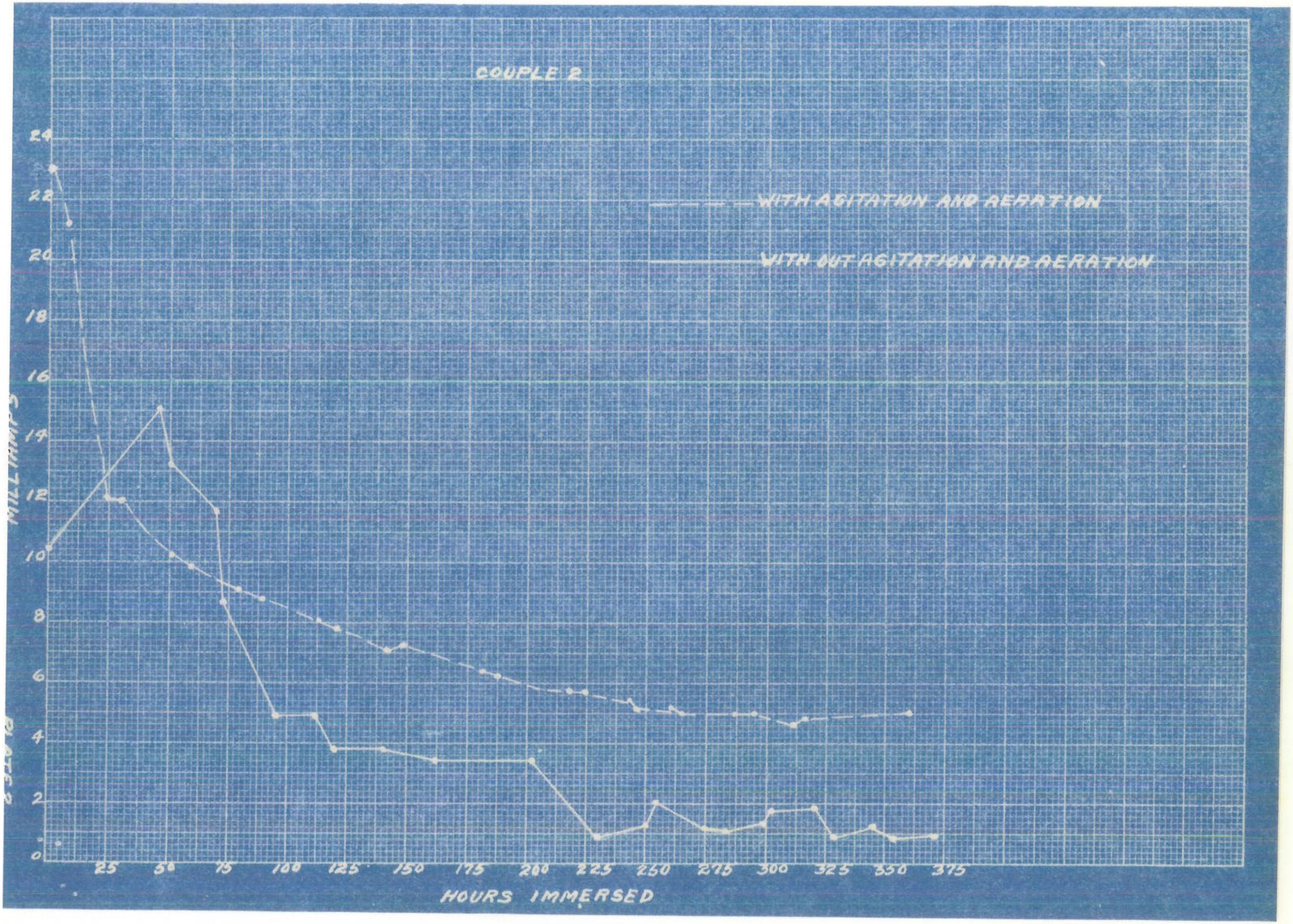


PLATE 2
COUPLE 2
MILLIAMPS
24
22
20
18
16
14
12
10
8
6
4
2
0
WITH AGITATION AND AERATION
WITH OUT AGITATION AND AERATION
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
HOURS IMMERSED

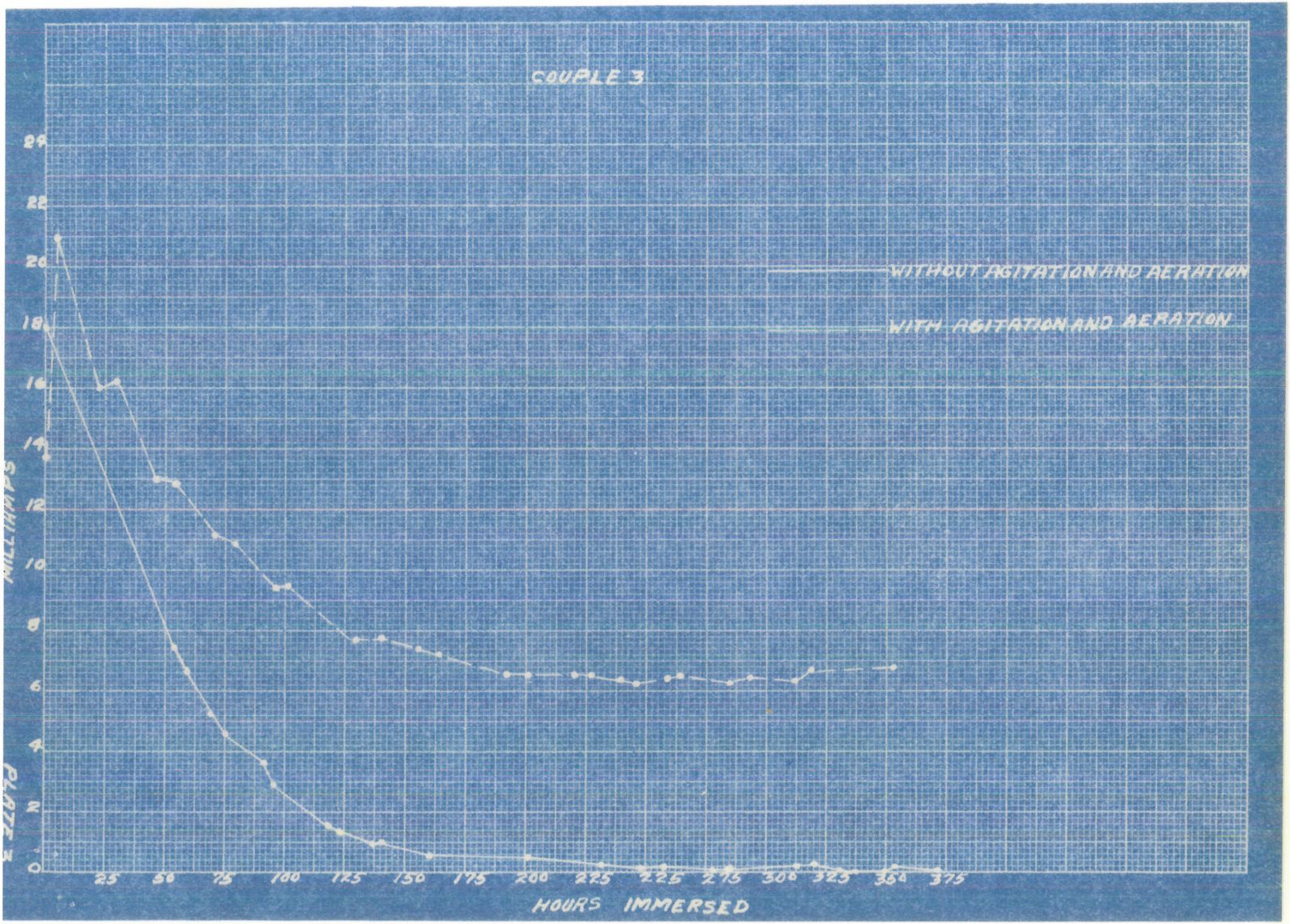
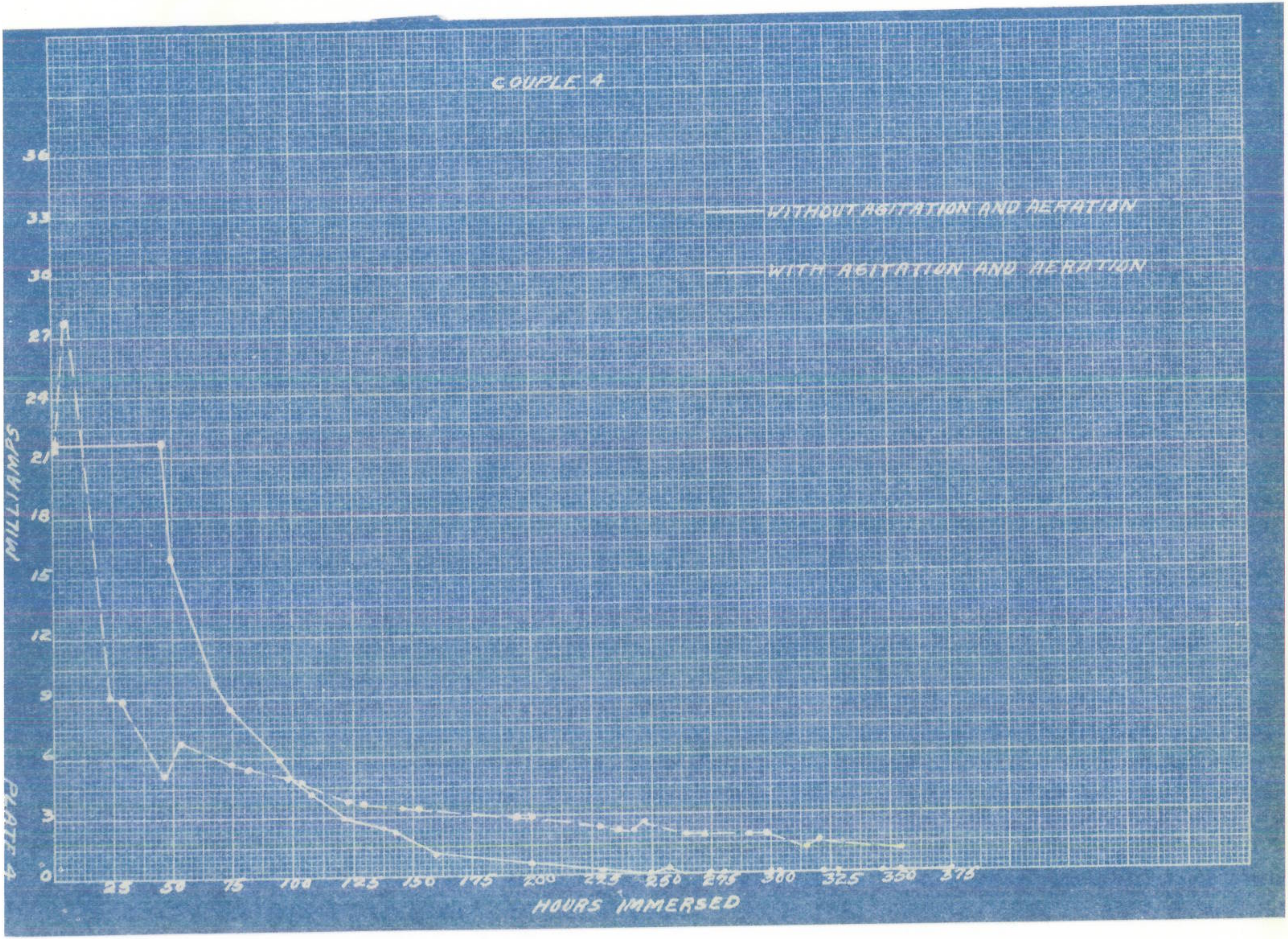
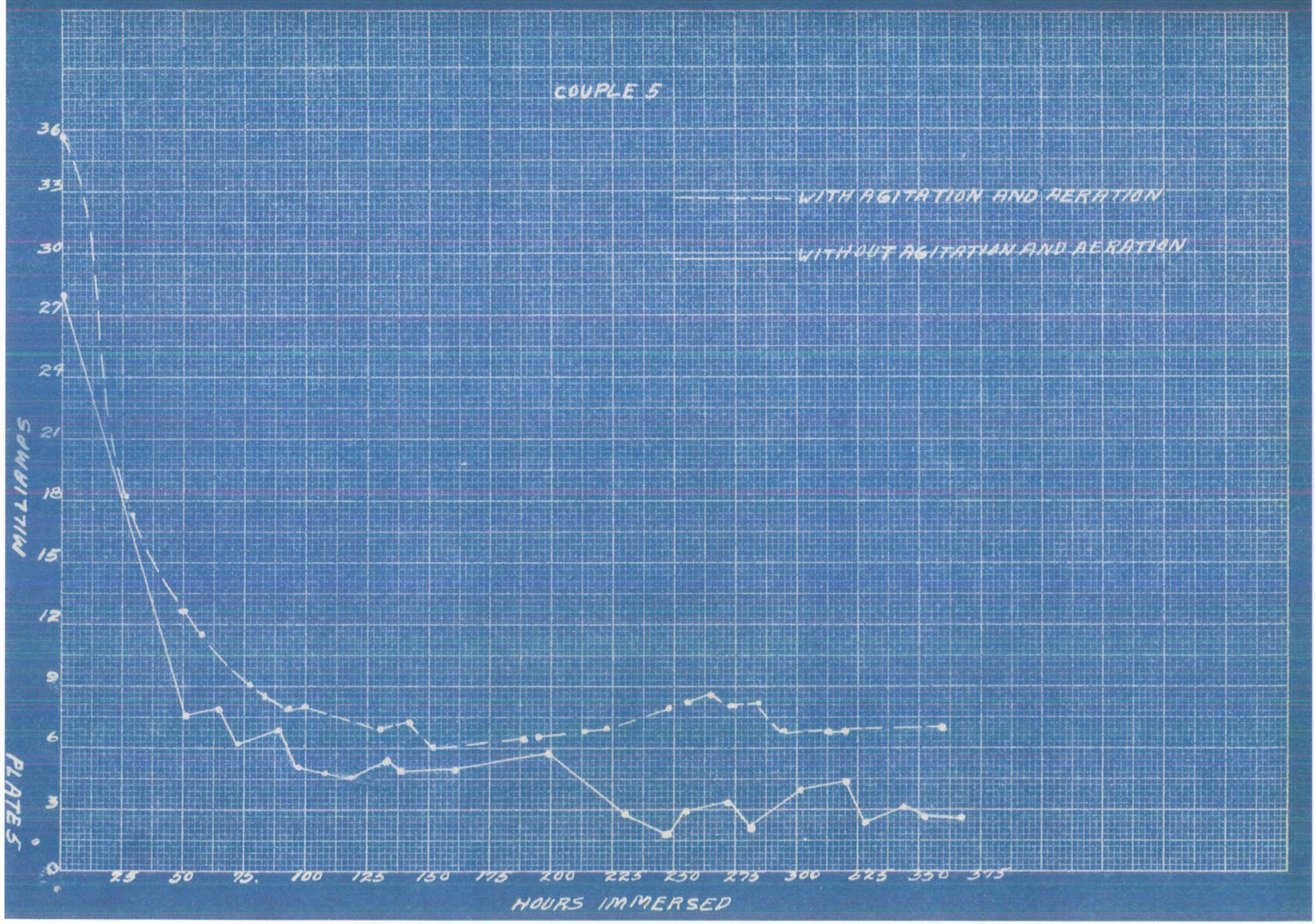
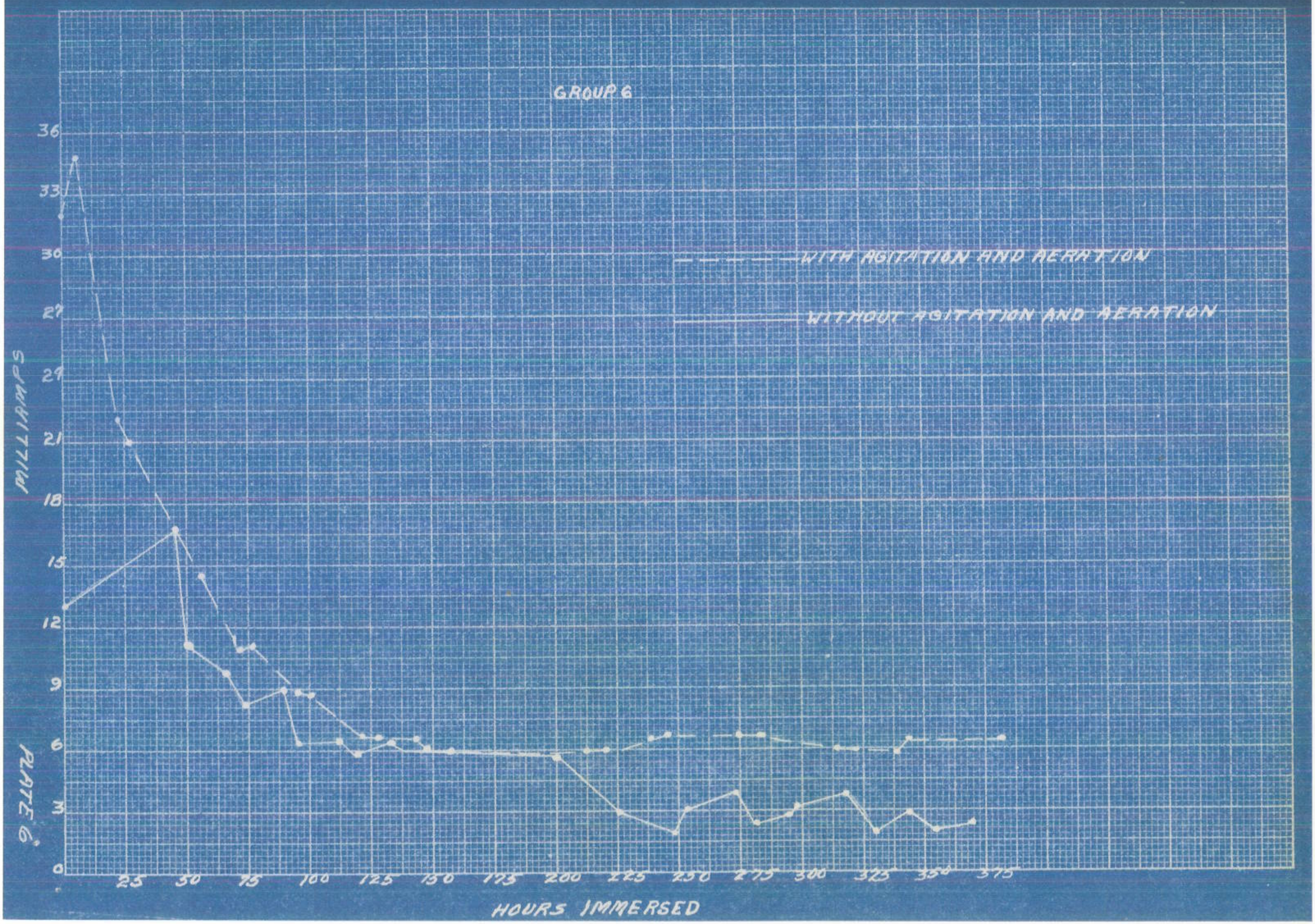


PLATE 3
COUPLE 3
MILLIAMPS
HOURS IMMERSED
WITHOUT AGITATION AND AERATION
WITH AGITATION AND AERATION
0
2
4
6
8
10
12
14
16
18
20
22
24
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375

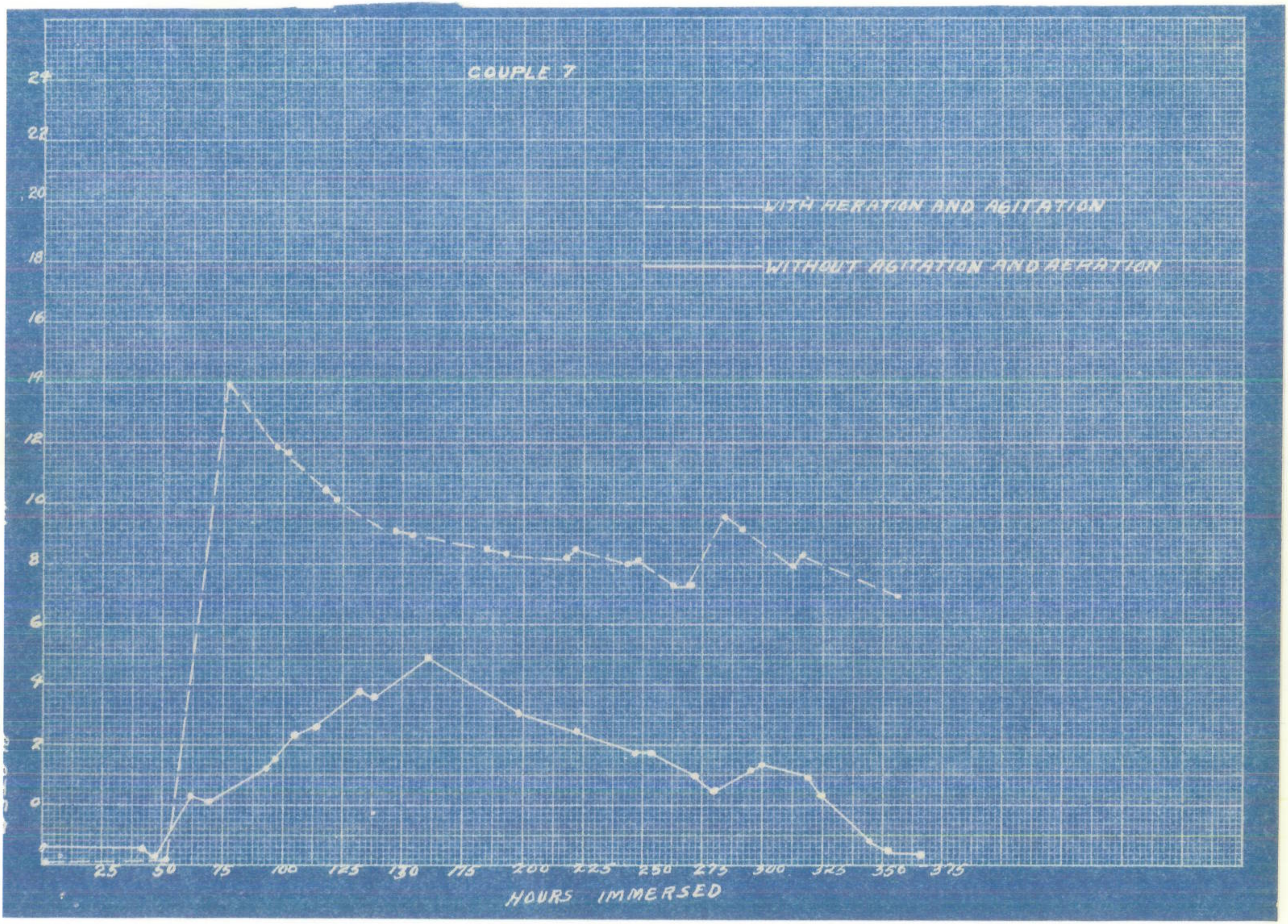

COUPLE 4
WITHOUT AGITATION AND AERATION
WITH AGITATION AND AERATION
MILLIAMPS
0
3
6
9
12
15
18
21
24
27
30
33
36
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
HOURS IMMERSED
PLATE 4


COUPLE 5
WITH AGITATION AND AERATION
WITHOUT AGITATIAN AND AERATION
MILLIAMPS
0
3
6
9
12
15
18
21
24
27
30
33
36
25
50
75.
100
125
150
175
200
225
250
275
300
325
350
375
HOURS IMMERSED
PLATE 5

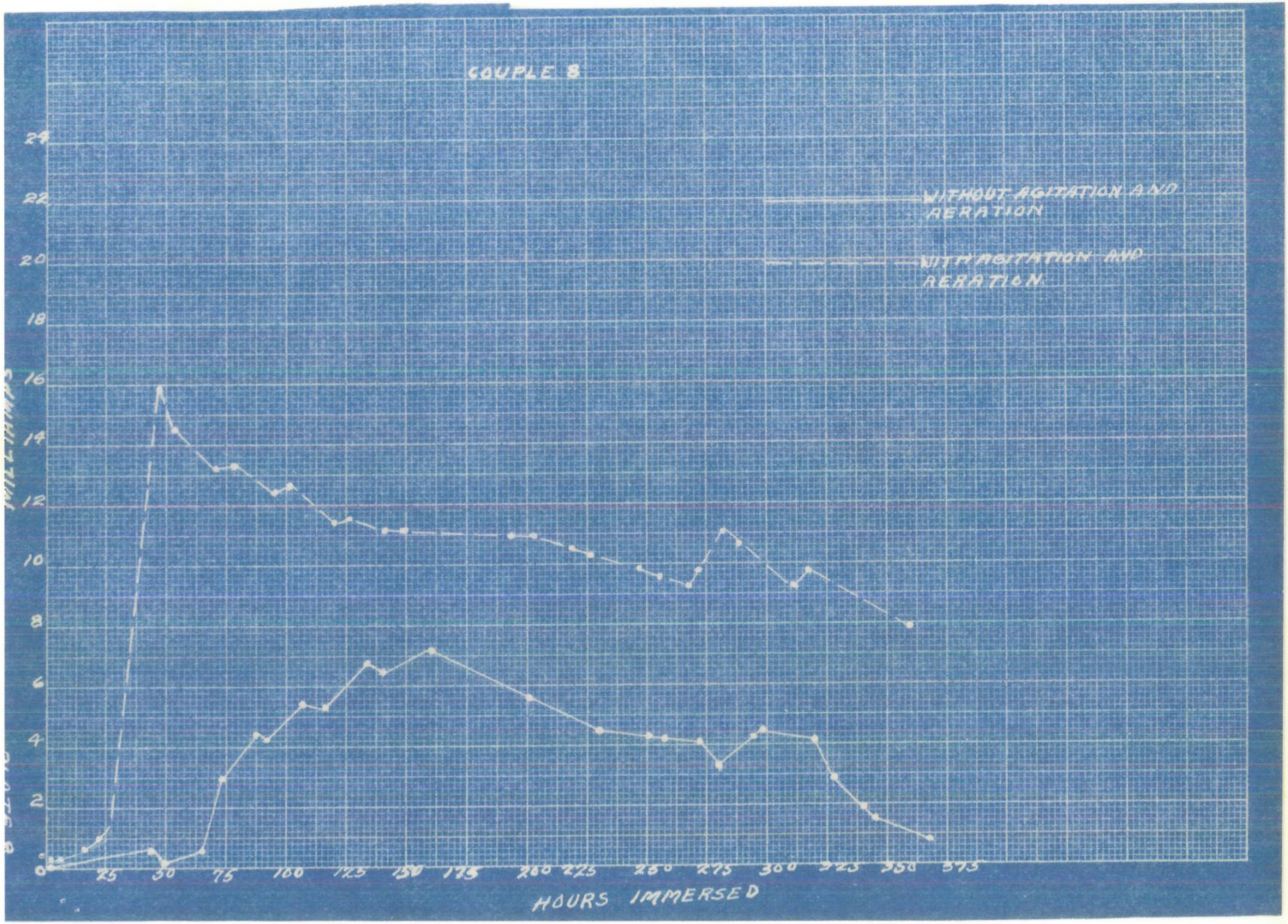


GROUP 6
WITH AGITATION AND AERATION
WITHOUT AGITATION AND AERATION
MILLIAMPS
0
3
6
9
12
15
18
21
24
27
30
33
36
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
HOURS IMMERSED

PLATE 6



COUPLE 7
WITH AERATION AND AGITATION
WITHOUT AGITATION AND AERATION
24
22
20
18
16
14
12
10
8
6
4
2
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
HOURS IMMERSED


COUPLE 8
WITHOUT AGITATION AND AERATION
WITH AGITATION AND AERATION
MILLIAMPS
HOURS IMMERSED
0
2
4
6
8
10
12
14
16
18
20
22
24
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375

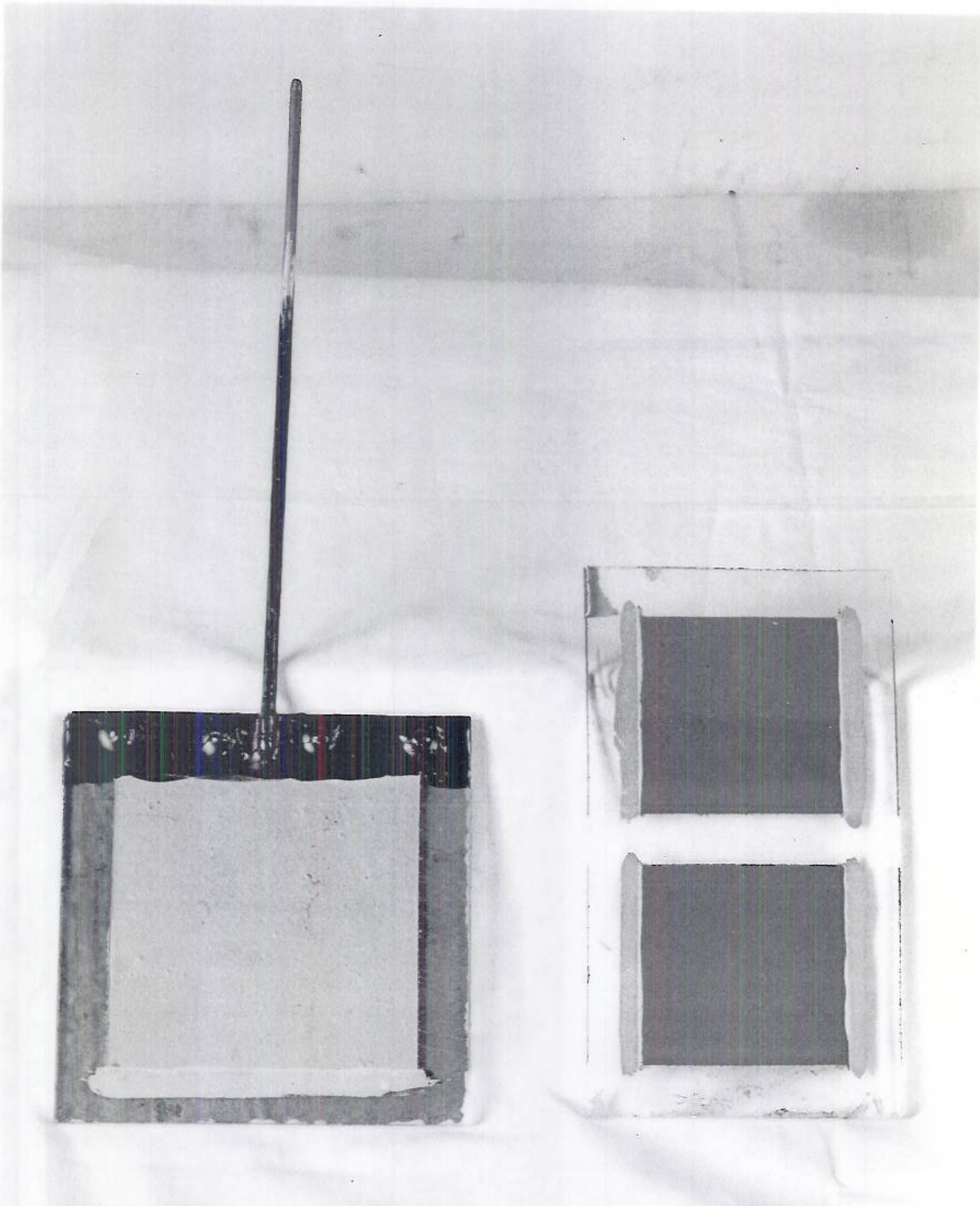


PLATE 9

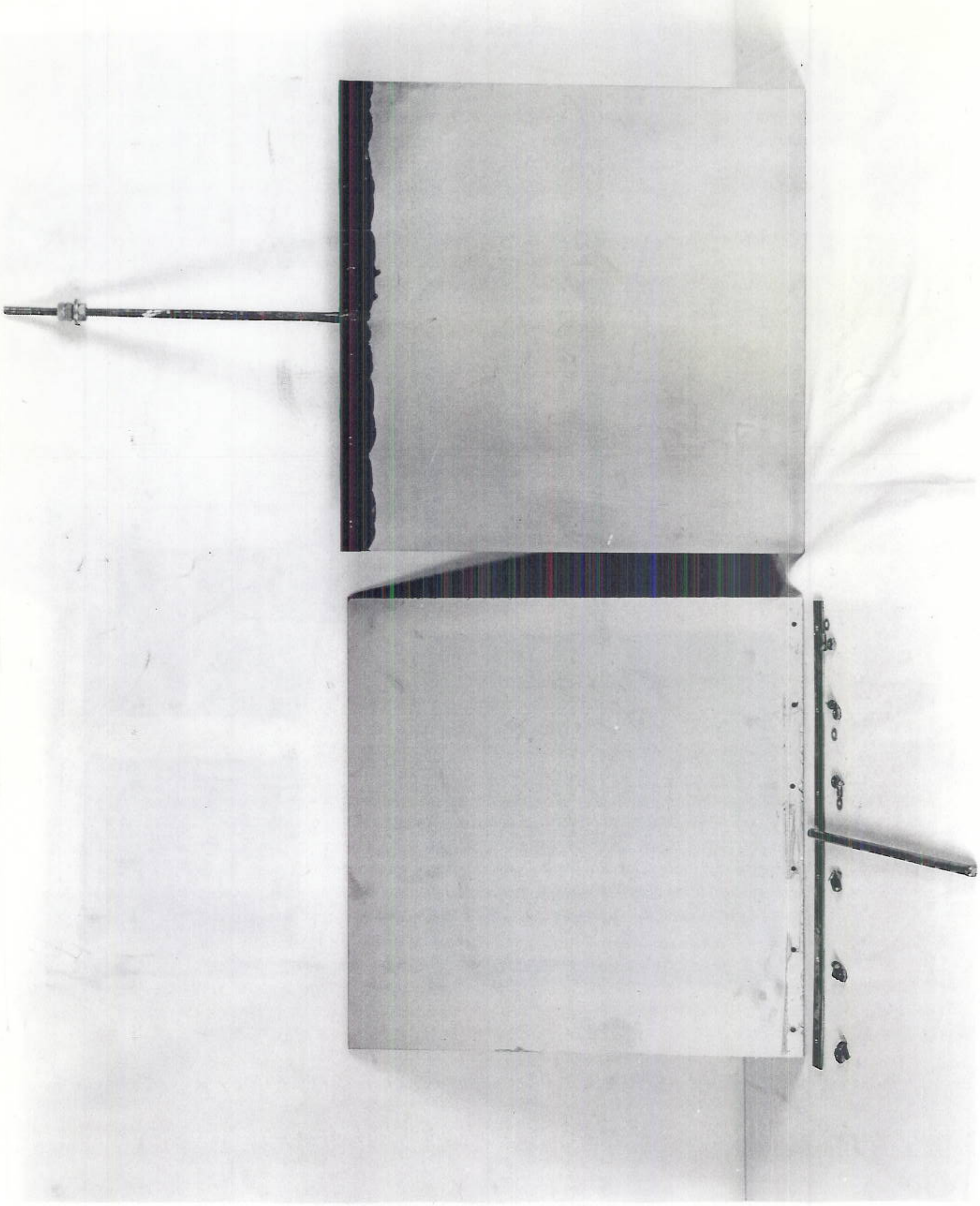


PLATE 10

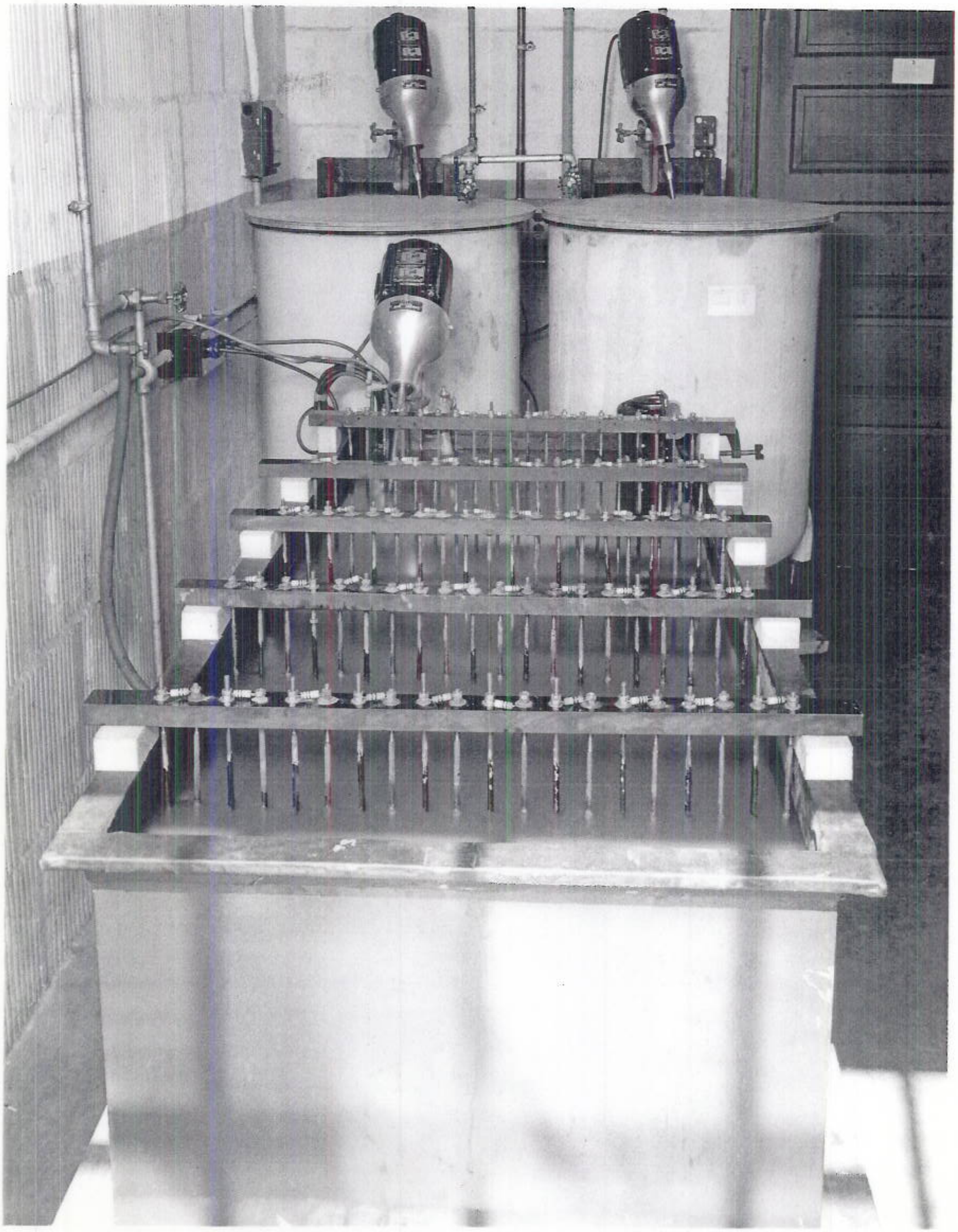


PLATE II