DIFFUSION PHENOMENA IN STRONG MAGNETIC FIELDS

by

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INTRODUCTION

Many interesting things have been found by former investigators who conducted diffusion experiments in a strong magnetic field. It was found by S. S. Bhatnagar and K. N. Mathur that chemical reactions may be hastened or retarded by a magnetic field. Mr. Harold Frederick Wahl, in 1936 wrote his master's thesis at Oregon State College on "Behavior of Colored Ions in Electric and Magnetic Fields". He found that if a mixture of Windsor water colors is put in a strong magnetic field, certain color particles are attracted to the strongest part of the field. He gives the following list of effects:

Color combination	Color which migrates to field
Red-Green	Green
Blue-Chrome orange	Blue
Blue-Green	Green
Yellow-Vermilion	Vermilion
Blue-Vermilion	Blue
Yellow-Blue Green	Blue

On repeating some of this work, it was found that the green color traveled most rapidly to the field. It takes only 15 minutes for the green particles to cluster, especially

near the edges of the pole pieces. For the blue color it takes at least 1 or 2 hours for a few particles to migrate into the field while for vermilion a half a day will not suffice to make them visible. Possibly the pigments differed from Mr. Wahl's even though the container had the same label. The green color had a very small insoluble residue which was strongly magnetic. The composition of the pigment is not known.

Mr. Wahl also showed that the time of diffusion of a gold sol is increased in the magnetic field and that the Liesegang phenomenon has an abnormal appearance in a magnetic field. But he has not explained why. It is the purpose of this thesis to search for some explanation of these peculiar phenomena in a magnetic field.

APPARATUS

The magnetic field was produced by an electro-magnet originally made for an old Edison bi-polar machine. To this was affixed a set of holders for several pairs of pole pieces. The pole pieces were held in position by clamp rings as shown in Fig. 1. The gap distance of the pole pieces could be adjusted by moving the rings to any desired position. The current could be reversed rapidly by means of a special quick-break switch.

Three pairs of Swedish iron pole pieces were provided, each pole piece being about 4 inches long and 2 3/4 inches in diameter. The ends were turned down at an angle of 45° until, in one pair, the diameter of the face was 1 inch, and in another pair 1/2 inch. The third pair had one inch faces pierced by a 3/8 inch axial boring.

During this investigation, the 1/2 inch pole pieces were used almost entirely so as to obtain the maximum possible field. The field strength was measured by a Grassot flux-meter connected to a special test coil of 25 turns. The calibration curves are shown in Fig. 2.

It is interesting to note that there is a slight temperature effect (see curve D, Fig. 2). The jump of 60 gauss there indicated is due to running the lower portion with an increasing, and the upper portion with a decreasing current. A similar effect is mentioned by Ashworth: an increase of

temperature causes a decrease in the intensity of magnetization. This effect is not of sufficient magnitude to enter into the discussion of the present experiments.

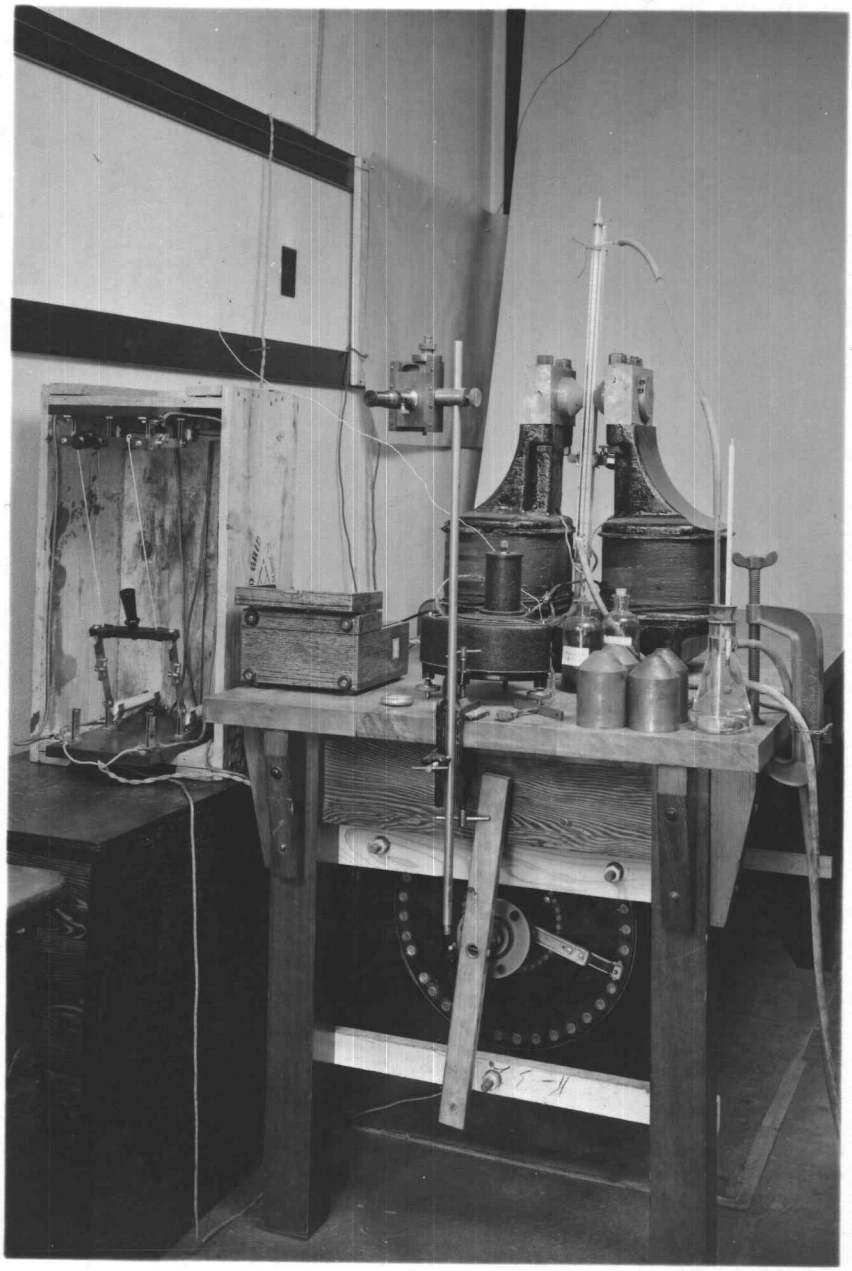
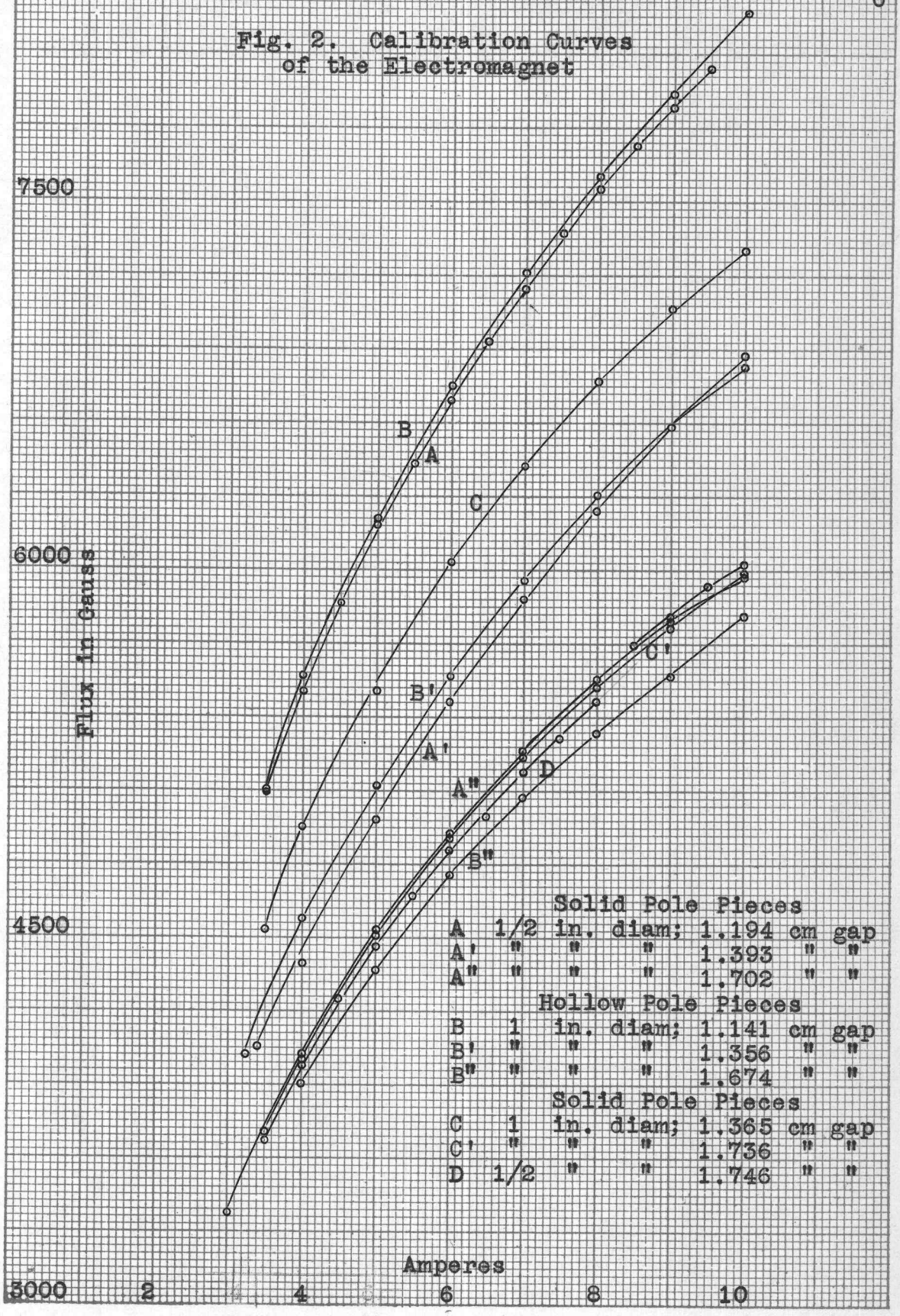


Figure 1. General View of Apparatus.

Fig. 2. Calibration Curves of the Electromagnet



		Solid Pole Pieces			
A	1/2	in. diam;	1.194	cm	gap
A'	"	" "	1.393	"	"
A"	"	" "	1.702	"	"
		Hollow Pole Pieces			
B	1	in. diam;	1.141	cm	gap
B'	"	" "	1.356	"	"
B"	"	" "	1.674	"	"
		Solid Pole Pieces			
C	1	in. diam;	1.365	cm	gap
C'	"	" "	1.736	"	"
D	1/2	" "	1.746	"	"

EXPERIMENTS

A. Diffusion of dye solutions in water.

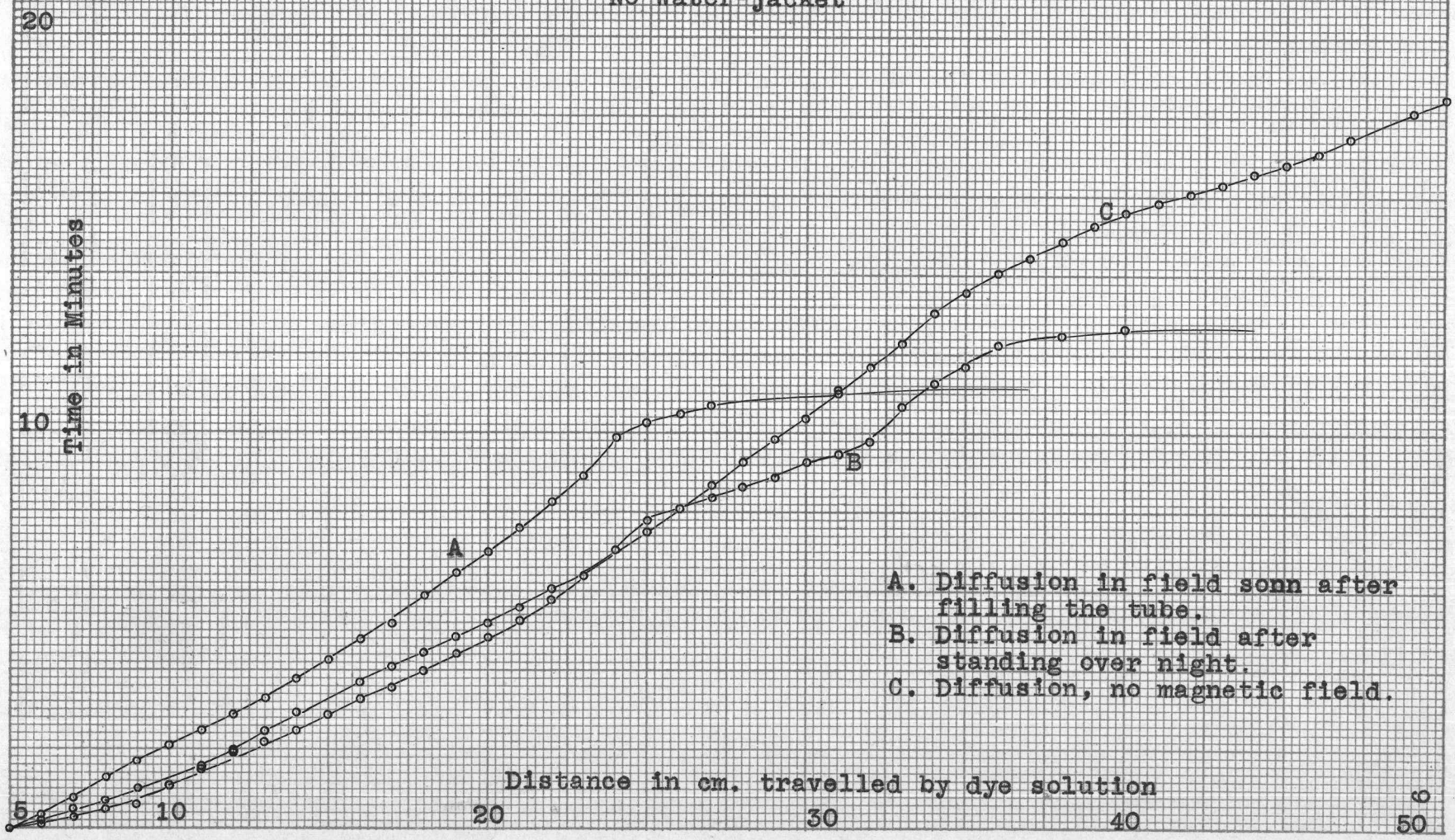
Diffusion experiments on dyes in liquids, but not in a magnetic field, have been performed by many investigators; among these may be mentioned Raymond Haskell, W. A. Patrick, B. W. Allen, and L. J. Burrage. In all of these experiments the influence of gravity was eliminated by causing the diffusion to take place against gravity. According to their descriptions it takes one or two months to run only one diffusion experiment. As the expense of performing experiments of this type in a strong magnetic field would be prohibitive, the diffusion in the present experiments was aided by gravity.

A glass tube about 60 cm long and 1 cm in diameter was mounted on a narrow piece of board in front of a 50 cm paper scale so that the scale was visible through the tube. The tube had previously been cleaned with acid and alkali and the lower end was closed by a new cork. The tube was filled with distilled water up to an arbitrary zero scale mark and supported vertically with the 25 cm mark at the center of the pole pieces. 1 cc of the dye solution (say crystal violet) was then added slowly to the tube from a pipette. The current was kept constant. Due to the action of gravity, the solution will move downwards. At first it will form a very smooth lower boundary and will move slowly downwards.

When the lower surface has come down to about 4 or 5 cm above the pole pieces, it will slide down very fast on one side and then the solution will diffuse evenly throughout the whole tube. For different solutions the appearance is about the same. If a bigger tube is used, the solution will come down to the field and form a spiral around the field for some time before it drops down. On permitting the water to stand in the tube over night so that local currents may have time to cease entirely, the spiraling failed to appear. On carefully adding the dye, it moved down slowly at first; on reaching the field it traveled faster and then slowed down again after it passed through the field. At a fairly definite distance below the edge of the pole face, the lower surface of the solution dropped down very fast and spread out over the whole width of the tube. The solution seemed to slow down near the lower edge of the pole face and become more concentrated before it moved fast and diffused evenly. In check experiments performed without applying the field, the solution dropped down smoothly (regularly) but the boundary was not as sharp as before and the color of the solution was somewhat less pronounced.

The time for the solution to travel each cm was measured by a stop watch, (Fig 3) and curves were plotted with distance as abscissas and time as ordinate. No data were taken for the first few minutes of each experiment due to great irregularity resulting from the addition of the dye. All

Fig. 3. Diffusion Curves of Dye Solutions
in and out of a Magnetic Field;
No Water-jacket



curves taken with the field showed an irregularity near the 25 cm mark, where the pole pieces were. All check curves taken without the field are very smooth and slightly concave upward. This curvature may be due to the concentration of the dye solution, for in one trial with the solution diluted to one-half the usual concentration, the time became longer. The two curves may be made to almost coincide by doubling the time for the more concentrated solution (Fig. 4). The curves diverge only in the lower portion, where the boundary is no longer easily distinguished. The curvature is caused by the fact that as the solution travels downward, the concentration becomes less and thus requires more time. The rate of diffusion of dye solutions not in a magnetic field therefore appears to be proportional to the concentration of the solution.

To explain the peculiar phenomena of diffusion in the field, it seemed at first that the magnetic field accelerates the speed of diffusion. However, at the lower part of the tube, the field is almost zero, but the speed is so large that it cannot be measured by the method indicated.

Upon the completion of one experiment in which the solution was diffused quite evenly throughout the whole tube, the tube happened to be held in the hand for a considerable time. The solution very definitely showed the shape of the fingers by a decrease of the intensity of the color. Since the hand was warmer than the solution, it seemed possible

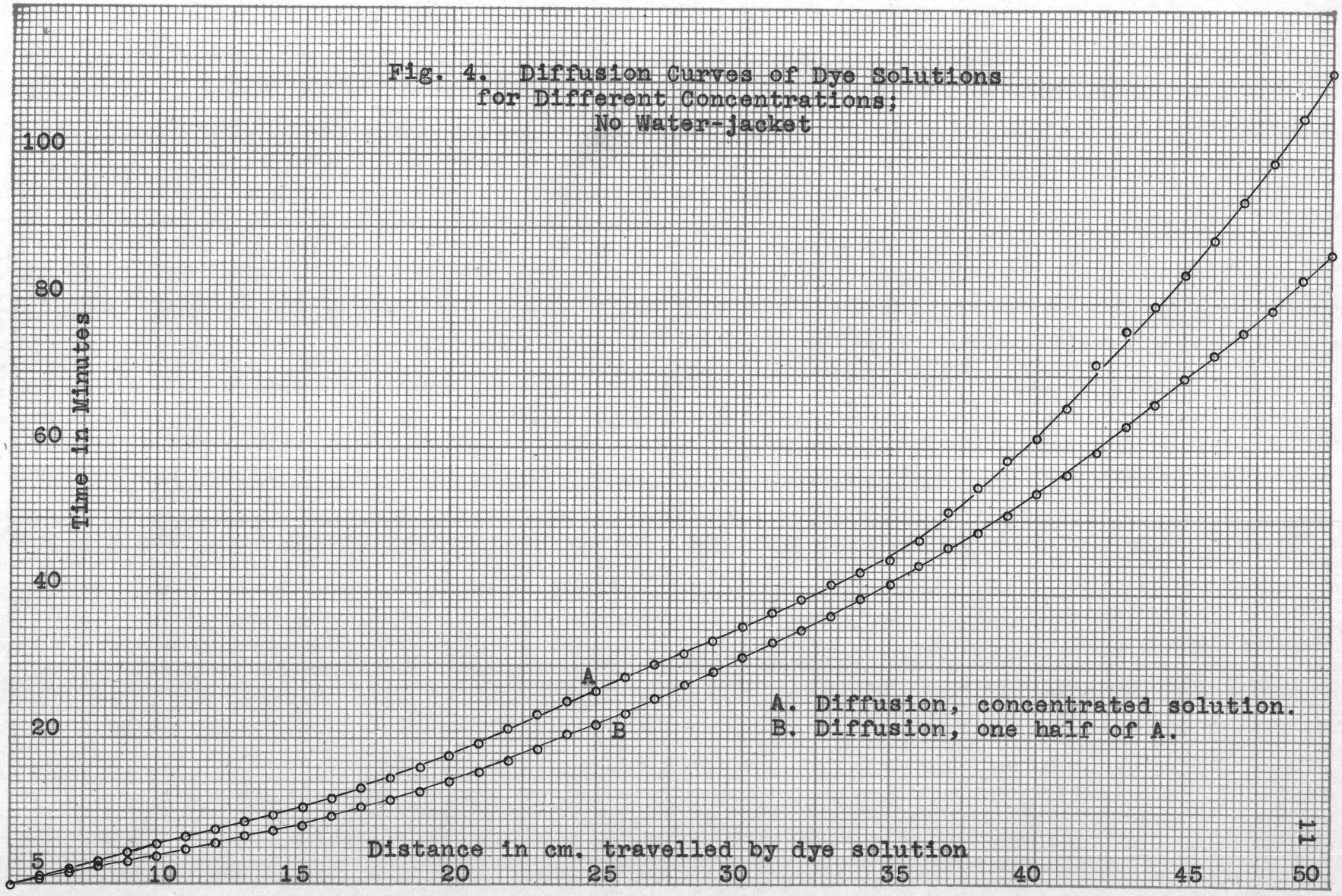


Fig. 4. Diffusion Curves of Dye Solutions
for Different Concentrations;
No Water-jacket
Time in Minutes
100
80
60
40
20
5
A
B
A. Diffusion, concentrated solution.
B. Diffusion, one half of A.
Distance in cm. travelled by dye solution
10
15
20
25
30
35
40
45
50

that this effect might be due to temperature. In fact, it seemed that the entire peculiar behavior in the field might be due to a difference in local temperatures. When the magnet has been run for some time, the pole pieces become warm. The lower end of the tube is near the coils and therefore at a higher temperature. In these two regions the diffusion is most rapid.

In order to test this explanation, it was decided to water-jacket the experimental tube and thus, with the aid of running tap water, to keep the temperature of the liquid practically constant. It was found that the solution traveled down regularly throughout the whole tube. When plotted, the data yield a smooth curve (Fig. 5) of the same form as the curve without any field; no peculiarity is shown either between the pole pieces or at the lower part of the curve. The slight difference in the curvature of the curves representing what happens (a) with and without the field in water jacket and (b) without either water jacket and field and with both water jacket and field (Curves A and B Fig. 5 and curve B Fig. 4) is probably due to slight differences in concentration and temperature. Data for one trial at a higher temperature show definitely (Fig. 6) that the solution travels faster at the higher temperature. Whether the speed of diffusion varies as the first power or second power has not been definitely determined, but it is evident that the rate of diffusion is an increasing function of temperature.

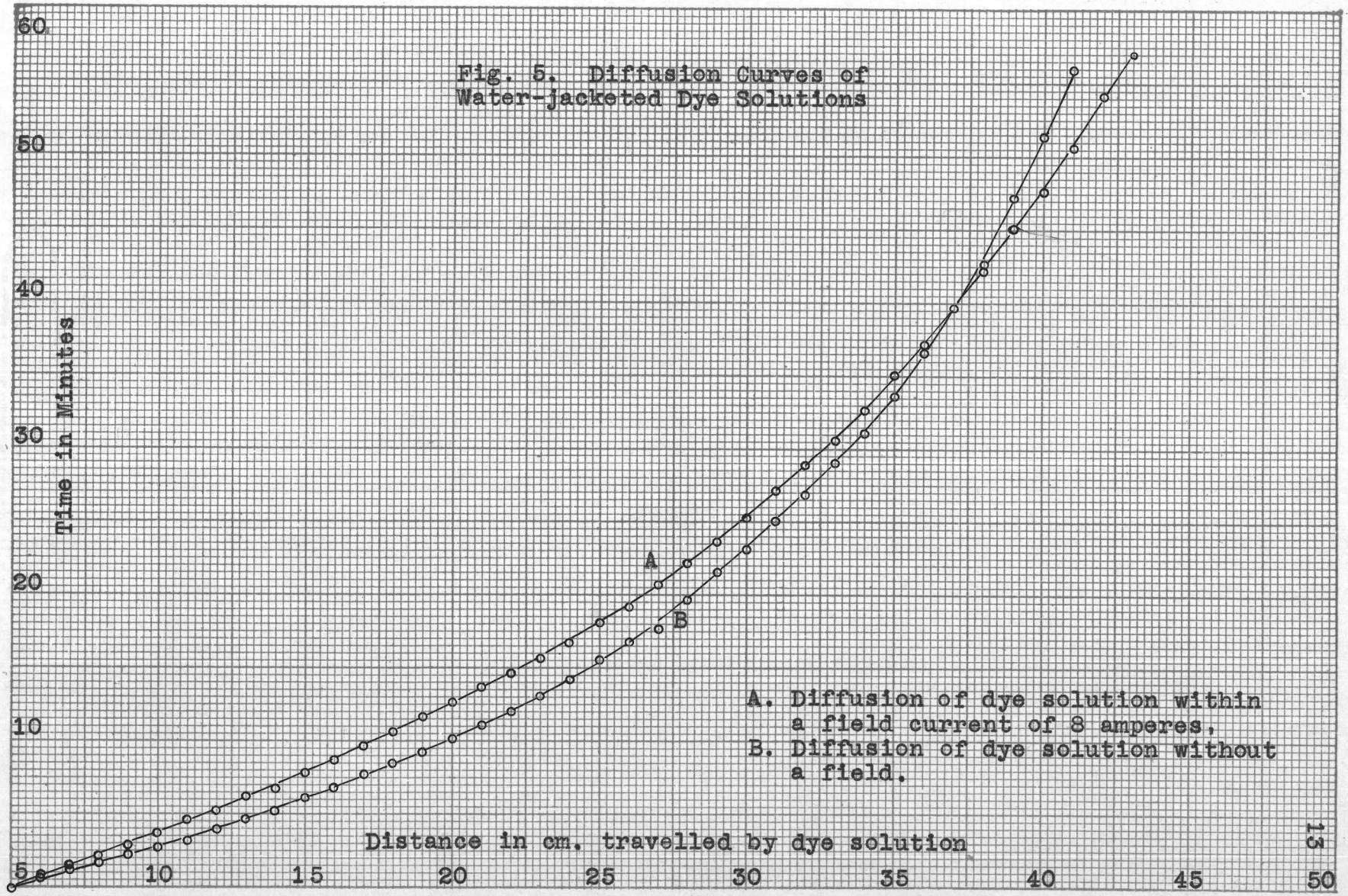


Fig. 5. Diffusion Curves of
Water-jacketed Dye Solutions
Time in Minutes
60
50
40
30
20
10
A
B
A. Diffusion of dye solution within
a field current of 8 amperes.
B. Diffusion of dye solution without
a field.
Distance in cm. travelled by dye solution
5
10
15
20
25
30
35
40
45
50

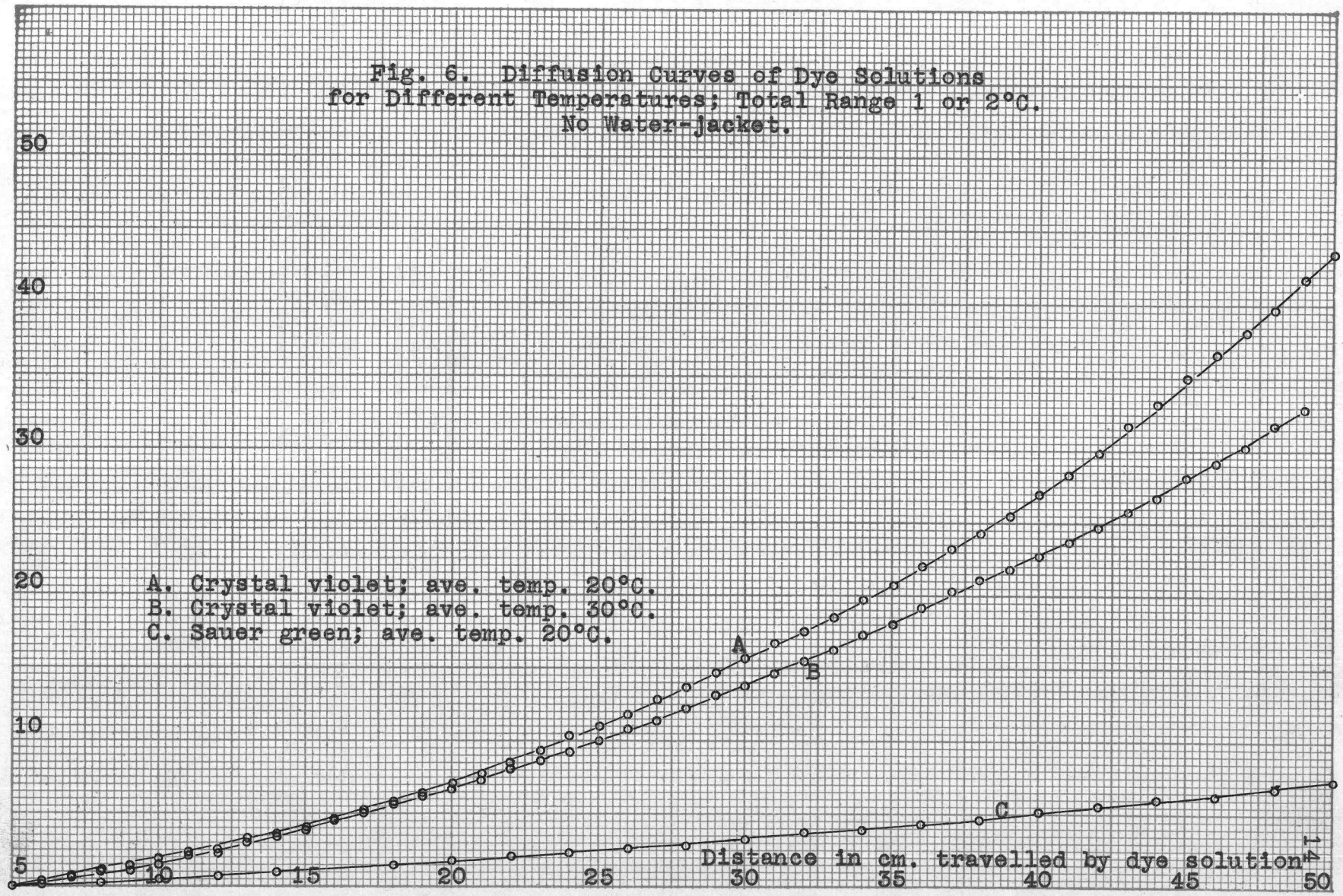


Fig. 6. Diffusion Curves of Dye Solutions
for Different Temperatures; Total Range 1 or 2°C.
No Water-jacket.
50
40
30
20
10
5
A. Crystal violet; ave. temp. 20°C.
B. Crystal violet; ave. temp. 30°C.
C. Sauer green; ave. temp. 20°C.
A
B
C
5
10
15
20
25
30
35
40
45
50
Distance in cm. travelled by dye solution in 4 hr.

With a different solution, the slope of the curve differs but remains of the same form. The diameter of the tube (except for a capillary tube) and the amount of solution used, has no effect in the rate of diffusion.

This part of the work may be summed up by saying that the rate of diffusion of dye solutions in water is not affected by the presence of a magnetic field, but does depend on the concentration of the solution and the temperature at which the experiment is performed. The rate of diffusion is directly proportional to the concentration and is an increasing function of temperature. Note: It appears from these experiments that in all probability when dying clothes, hot water will cause the dye to move faster and more evenly throughout the whole piece of cloth, and when washing colored clothes, cold water will prevent a rapid motion of the dye from the cloth to the water.

B. The Liesegang Phenomenon.

When a concentrated silver nitrate solution is allowed to diffuse into gelatin containing a small amount of potassium chromate, a band of red silver chromate precipitate is found at the boundary. The band will grow thicker if it is allowed to stand for some time. The reaction is

$$2\ AgNo_3 + K_2CrO_4 \quad Ag_2CrO_4 + 2KNO_3$$

Mr. Wahl found that if the diffusion is allowed to take place in a strong magnetic field, the diffusion boundary will

eventually break. He states that this breaking of the boundary is a magnetic and not a temperature effect. It will be shown in this paper that it is after all a temperature effect.

The experiment was repeated using a 4% gelatine solution in cold water, adding 3% potassium chromate (K_2CrO_4), and heating to near the boiling point. A clean pyrex glass tube about 15 cm long and 1.2 cm in diameter provided with a new cork stopper at its lower end, was partially filled with this solution, using a pipette so that none of the solution could adhere to the sides of the tube above the level of the liquid in the tube. The tube was chilled until the gelatin was set. It was then supported in the magnetic field with the upper surface of the gelatin at the center of the pole faces. The magnet was energized and an 8% silver nitrate solution carefully introduced on top of the gelatin. The amount of diffusion is measured at equal time intervals by a traveling telescope. Mr. Wahl's results were checked; the boundary breaks after a certain time, the time being somewhat longer than he found. On increasing the field strength, the time required for the break to appear is shorter.

In one experiment, the pole pieces were somewhat widely spaced, and the tube was not placed symmetrically between them. The break started at the side nearest the pole piece, and the silver chromate gel went directly down to the bottom of the tube. However, on decreasing the current after the boundary was broken, the silver chromate traveled slowly down

to the lower edge of the pole pieces and stopped there to form a new band. This behavior again indicated a possible temperature effect, since the melting point for gelatin is not definite. Mr. Wahl states:

"The temperature at which a gelatin solution solidifies or melts depends upon the rate of temperature change; the slower a gel is warmed, the lower the temperature at which it melts".

During the present work, the following data were obtained. The temperatures were taken by merely placing a thermometer near the pole pieces. These data indicate

Current in field coils	Temp. of break	Change in Temp.	Change in Time	Average rate of change of Temperature
4	28.2	5.6	120	.0466
6	29.2	9.8	85	.0892
8	31.5	13.2	57	.1623

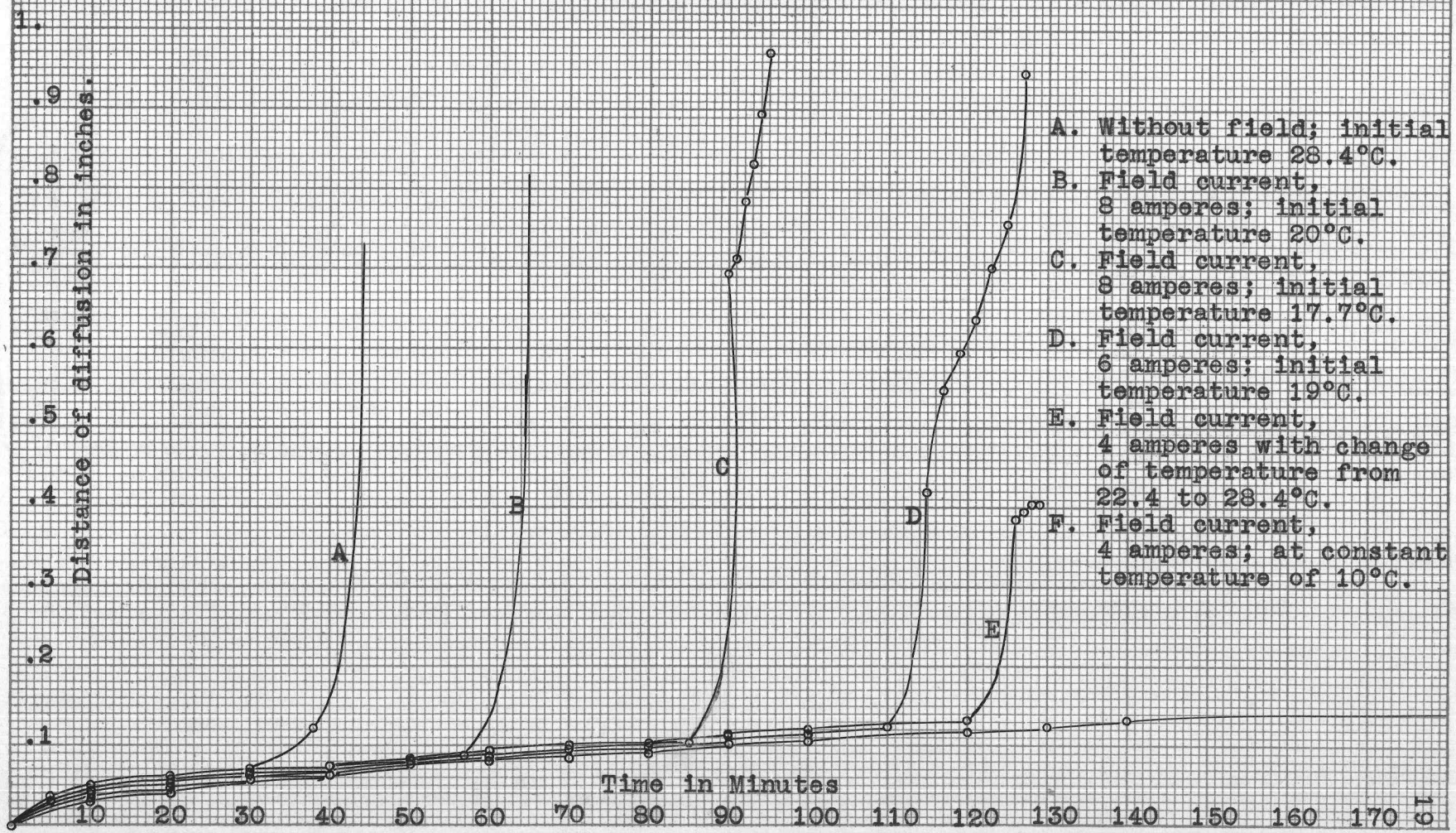
that if the rate of change of temperature is less, the temperature of the break is lower. That means the temperature of the break may be the melting temperature of the gelatin. Mr. Wahl showed that the heating and cooling curves of potassium chromate gel and silver chromate gel are identical in the field and without the field. This means that both gels have the same melting temperature. Hence both gels melt at the same time under the same conditions and the banding breaks down. If the melting point of the two gels were different, the break would probably not occur until

the higher melting point had been reached.

The time needed for the break to appear depends on the initial temperature of running the experiment. A series of experiments were performed using the same magnetising current but starting at different temperatures. The elapsed time for the break to occur is shorter for the higher initial temperatures. In all such cases the rate of change of temperature is about the same and the temperature at the break is also the same. When the temperature and current are kept constant, no break occurs, as shown in Curve F. Fig. 7. If the initial temperature is high, the time it takes for the break to appear may be very short and the necessary change of temperature very slight. Mr. Wahl probably used the last mentioned set of conditions.

From all the above considerations it seems probable that breaking of the silver chromate band in a strong magnetic field is due to the melting of the gelatin rather than to the magnetic field.

Fig. 7. Diffusion Curves of Silver Nitrate in Potassium Chromate Gel.



CONCLUSIONS

The experimental work leads to the following conclusions:

(1) The attraction of green colored particles of water color solution to the stronger part of a magnetic field is due to a paramagnetic substance contained in the color.

(2) The peculiar effects seen when an aqueous solution of a dye diffuses into pure water in a strong magnetic field are due to temperature changes caused by the magnetising current. The velocity of the diffusion is directly proportional to the concentration and is an increasing function of temperature.

(3) The peculiar break in the bands of the Liesegang phenomenon of diffusion of silver nitrate into potassium chromate gelatin seen when the bands are formed in a strong magnetic field, is due to the melting of the gelatin rather than to the magnetic field itself.

DISCUSSION

Since this research on properties of substances in a strong magnetic field shows that the elimination of temperature changes of the substance being investigated is of prime importance, and since water cooling the specimen of necessity reduces the field strength, it is suggested that in future work of this type the magnet rather than the specimen be water cooled.

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