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Report on

Laminations in Plates - An Acoustical Method for Determination of.

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WASHINGTON DC

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Distribution:
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A B S T R A C T

The following report describes an acoustical method for detecting and locating laminations in steel plates. It is based on the fact that the stiffness of a plate is decreased over a laminated area and the resulting fact that the velocity of flectural waves is decreased across such areas. The presence of such defective areas is disclosed through sand patterns formed on the surface of the plate when it is vibrated at some resonant frequency.

In practice the vibrating forces are applied in a manner that will make the sand patterns on a perfect plate consist of straight parallel lines. Laminated areas are disclosed through distortion of the sand pattern from this simple form.

AUTHORIZATION

1. This problem was authorized by references (a) and (b). Other pertinent correspondence is listed under reference (c).

Reference: (a) Bu.Eng.ltr.JJ46-1(12-29-Ds) of 5 Jan. 1935.
(b) Bu.C&R ltr.JJ46-1(5)(S) of 29 Dec. 1934.
(c) NRL ltr. N8-12 of 29 April 1935.

STATEMENT OF PROBLEM

2. Laminations in steel plates do not greatly weaken riveted structures where angle irons and reinforcing strips give added strength to all joints. However, in case of modern welded construction, where such reinforcements are not employed, these defects may introduce weaknesses that are more serious. Thus arises the problem of developing methods and means for detecting laminations in steel plates.

3. Any method for detecting these lamination defects must be based on measurements of some physical characteristic or property of the plate that is affected by them. The method described herein is based on the effect that laminations produce on the stiffness of the plate, i.e. on its resistance to bending or flecture.

4. Both the presence and location of the defective or laminated areas are indicated by distortions in a standing flectural wave pattern set up in the plate similarly to the well known "Chladni's Figures". If the plate is vibrated in such a manner that the shape of the sand pattern can be definitely predicted, then the presence of laminations will be indicated by distortion of the sand pattern from the predicted form, i.e. from the form it would take on a perfectly uniform plate.

5. A lamination distorts the sand pattern through reduction of the stiffness of the plate across the laminated area. Such reduction of stiffness reduces the velocity of the flectural waves traversing the laminated area and this shifts the nodal lines from the position they would have taken on a perfect plate.

THEORETICAL CONSIDERATIONS

6. The effect produced by a lamination on the stiffness of a plate depends on its depth below the surface. Figure 1, Plate 1, represents a portion of a plate of thickness (a) with a lamination along dotted line (A-A) at a depth (X) from the top surface. Let (S_x), (S_{a-x}), (S_ℓ) and (S_a) represent respectively the stiffness of the metal above the lamination, below the lamination, laminated plate and solid plate. Then:

(1) $S_x = KX^3$, (where (K) is a constant depending on the material, etc.)

(2) $S_{a-x} = K(a-x)^3$

(3) $S_\ell = S_x + S_{a-x}$

(4) $S_a = K.a^3$

The stiffness (S_{ℓ}) of the laminated plate becomes,

(5) $S_{\ell} = S_x + S_{a-x} = K\{x^3 + (a-x)^3\} = K(a^3 - 3a^2x + 3ax^2)$

Dividing (5) by (4) gives (S_{ℓ}/S_a), the ratio between the stiffness of the laminated plate and that of the solid plate.

(6) $S_{\ell}/S_a = (a^2 - 3ax + 3x^2)/a^2$.

7. Curve 1, Plate 2, shows the relation between (S_{ℓ}/S_a) and (x). The minimum stiffness occurs when the lamination is centered between the faces of the plate where it equals one-fourth that of the solid plate. The curve shows that the stiffness of a laminated area remains less than half that of the solid portions of the plate so long as the lamination lies at a depth greater than about one-fifth of the plate thickness. Under such conditions, the distortion of the sand pattern should be sufficient definitely to indicate the presence and probably the location of the laminated area. A study of the end portions of the plot shows that the method becomes ineffective at an increasing rate as the lamination approaches the surface of the plate and fails entirely when it arrives at or very near to the surface.

8. Curve 2, Plate 3, is derived from Curve 1 and, as will be seen, applies more directly to the present subject.

9. The velocity of flectural waves in a plate is proportional to the square root of the stiffness, i.e. -

(7) $V = c.\sqrt{s}$

where (V) is the wave velocity, (s) the stiffness of the plate and (c) a constant depending on the material, etc. The velocity term can be replaced by ($N.\lambda$) through the well known relation

(8) $V = N.\lambda$

where (N) and (λ) represent frequency and wave-length respectively. This gives the relation

(9) $N.\lambda = c.\sqrt{s}$.

Since (N), the frequency at which the plate is vibrated, is constant over the whole plate, equation (9) states that the wave-length over any part of the plate is proportional to the square root of the stiffness across that area. It follows that the ratio of the wave-length (λ_{ℓ}) over a laminated portion to (λ_a) the wave-length over a solid portion of the plate is equal to the square root of the ratio of the stiffness over these respective portions.

10. The plot on Plate 3 shows how this ratio (λ_{ℓ}/λ_a) varies with (x), the depth of the lamination within the plate. If the lamination is located within the center three-fifths of the plate's thickness, this ratio will not exceed one-half and the sand pattern distortion should then be sufficient to definitely show the presence of lamination defects. It is probable that distortions will show for greater values of this ratio, i.e. when the lamination is still nearer to a surface, but they certainly will not be detectable when the lamination is very close to the surface.

11. It should be noted that plots (I) and (II) are derived on the assumption that the lamination along line (A-A), Fig. 1, Plate 1, offers a free shearing plane. Probably slag inclusions adhere to the metal surfaces sufficiently to prevent these curves for representing practical conditions. Such inclusions will not decrease the stiffness of the plate as much as will the free shearing plane assumed and as a result the sensitivity of the method in practice may be expected to be less than that predicted from these curves.

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METHODS

12. A plate set into flectural vibrations by bowing, as practiced by Chladni, automatically takes on one of its numerous natural or resonant frequencies. It then vibrates in a standing wave system and sand or powder sprinkled on the horizontal surface will collect along the nodal lines because there is no motion at these locations to scatter it elsewhere. If a plate is forced to vibrate by coupling it loosely to some mechanically driven member, it will take on a standing wave system only when the frequency of the driving force is adjusted to equality with one of its natural or resonant frequencies. Such adjustment of the driving frequency is readily made by noting the point at which sand sprinkled on the plate collects into clean-cut nodal lines.

13. Portions of the plate on opposite sides of a nodal line oscillate 180 degrees out of phase and as a result the plate is warped back and forth across these lines. Thus it is that the stiffness of the plate is brought into play. If the sand pattern is such that the nodal lines are parallel with one another, the perpendicular distance between two adjacent lines is a half wave-length. Therefore, for our purpose, it becomes desirable to vibrate the plate in a mode that will give parallel nodal lines.

Method Applied to Circular Plates

14. The nodal lines on a circular plate driven at its center are concentric circles and therefore parallel. Figures 1 and 3 of Plate 4 and 2 of Plate 5 show three different sand patterns formed on a circular aluminum plate driven at its center point. The driving element was a nickel tube, one end of which was brazed to a lug for screwing it to the center of the plate. This element was surrounded by a magnetizing coil supplied with A.C. current by an electron tube oscillator that could be uniformly tuned through a considerable range of frequency. Each figure represents a definite resonant frequency of the plate. Figure 15 of Plate 4 shows the bottomside of this plate. A strip of metal (M) has been cemented to the plate to serve as an artificial defect. Figure 14 shows the distortion it produced on the sand pattern. Here Figure 1 is the predicted pattern -- the pattern given by a perfect plate -- and Figure 14 is the test pattern. It gives convincing evidence that the plate is imperfect in the southwest quadrant, the quadrant containing the defect.

15. Figures 4, 5 and 6A of Plate 5 all refer to the same plate, a circle 12 inches in diameter cut from a supposedly laminated steel plate. The lack of symmetry in all three figures shows the plate to be defective in the lower left hand quadrant, while Figure 6A indicates that the defect carries across to the lower right hand quadrant. This diagnosis is substantiated by

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examination of the machined edge of the disk. There is definite evidence of a lamination extending from (1) to (2), and some evidence of faults along the arc subtended between (3) and (4) as marked on the margin of Figure 5.

Method Applied to Rectangular Plates

16. The various patterns taken on by a rectangular plate energized at its central point or, indeed, at any single point, are complicated and difficult to predict and in general the nodal lines are not parallel. Distortion of the nodal lines which the presence of a lamination might produce are less readily detectable in such a complicated wave pattern than they are in a simple pattern where the nodal lines are parallel. By driving a rectangular plate along a line extending the whole width, and preferably at the end of the plate, simple grid-shaped patterns can be produced such as are shown in Plate 5.

17. The scheme employed to drive the plate is shown in Figure 2, Plate 1, wherein numeral (1) represents a rectangular-shaped plate cut away except for the driven end; (2) the core of an electro-magnet built up of thin silicon steel punchings piled to a depth slightly greater than the width of the plates to be tested and properly aligned by inserting three small rods through the three punched holes (3, 4 and 5). An energizing coil (in part cut away) surrounds the right hand or larger portion of the core. It fits into slot (6) on the one side and rests on ledge (7) on the other.

18. The test plate forms an armature across the jaws of the magnet. A strip of felt (8) separates the plate from one jaw of the magnet, thereby leaving a thin air gap (9) between the plate and the other jaw. The magnetizing coil is supplied with D.C. current through a suitable choke coil for polarizing purposes and A.C. from a tunable power-tube generator. Figure 3, Plate 1, shows the wiring diagram schematically.

19. In practice, the end of the plate is subjected to bending strains when the coil carries D.C. current because the magnetic flux linkage between plate and magnet core tends to close the intervening gaps. The felt pad (8) takes this strain and therefore acts as a fulcrum with respect to the attractive force across gap (9). The bending strain on the plate across this fulcrum is steady so long as D.C. only traverses the magnet coil, but when A.C. also traverses this coil, the bending strain fluctuates in accordance with the frequency of the A.C. current. When this frequency is adjusted to a resonant frequency of the plate, the sand will form in nodal lines parallel to one another and parallel to the end of the plate, providing the plate is homogeneous

20. Theoretically, such a pattern will form for each driving frequency that makes the length of the plate a whole number of half wave-lengths. Therefore, starting at any resonant frequency of the plate, the next one above or below this frequency will respectively add or subtract one nodal line. The several figures of Plate 6 form such a series. Table 1 gives data referring to these figures.

21. These patterns were formed on a strip cut from a steel plate 9/16 inches thick. The strip was 5-1/3 feet long and 1 foot wide at the ends, but concave along the free edge, thereby making the width about 11.5 inches at the

center. In addition to this lack of true geometric form, the strip was bowed lengthwise and warped or twisted about its longitudinal axis. Moreover, the plate from which it was cut was suspected of carrying laminations. The fact that such regular and consistent sand patterns form on a plate that departs so much from a plane rectangle, as required by theory, argues that there should be no difficulty in producing such simple grid-shaped patterns on commercial plates.

22. It will be noted that two patterns are missing from the series, one carrying 23 and the other carrying 26 nodal lines. The reason can be deduced from Figure 9, Plate 6, showing the presence of two wave systems, one carrying 22 nodal lines lengthwise and another carrying 4 nodal lines crosswise on the plate. If the length and width of the plate happen to be such that the half wave-length for some frequency is a common divisor of both dimensions, then the two wave systems can and usually do exist simultaneously. The sand pattern then becomes small dots defining the corners of squares. It might well be termed a "checker-board pattern". Such patterns tend to form when the half wave is not exactly a common divisor of length and breadth and then show more or less distortion from the pure checker-board pattern. Figure 9 is such a pattern. At frequencies where the half wave lacks too much from being a common divisor of length and width of the plate to permit both wave systems to exist but does not lack enough to permit either system to exist free of reaction from the other, then neither system can be established. Such conditions doubtless account for the two missing patterns.

23. As stated, the large plate from which our test strip was cut was suspected of carrying lamination defects. However, it was not known that this particular portion was defective. The sand patterns show no irregularities that would indicate lamination defects. Starting with Figure 6, both end lines show distortion. Figure 7 shows distortion of three lines at each end of the plate and Figure 8 shows distortion of at least seven lines. Finally, the double wave system (where all lines are distorted) appears in Figure 9. The increasing distortion as the frequency is raised to give these successive figures is due to the increasing tendency of the cross-directed wave system to form. And these distortions affect more and more of the lines at each end of the plate as the frequency is raised because, as stated, the ends are wider than the center. The point to note is that the distortions in each case are symmetrical with respect to a cross-line half-way between the ends of the figure. A defective plate should not exhibit such symmetry. If this plate carries laminations, either the areas which they separately cover must have dimensions at least as small as the wave-lengths disclosed on the sand patterns or else the laminations do not appreciably affect the stiffness of the plate.

24. The figures of Plate 7 refer to a rectangular strip 1' x 6.5' cut from a defective plate 5/32" thick. The distorted patterns definitely indicate a large defective area between cross-lines (1-1) and (2-2) which is judged to extend across the full width of the plate. Its presence is indicated by the shorter wave-lengths (closeness of the nodal lines) as compared with other portions of the plate area. And the fact that these closer packed nodal lines extend the full width of the plate argues that the lamination covers the whole width. This argument is strengthened by the presence of a lamination showing on each edge over this section. A cut made later across this area proved that the lamination covered the whole width as predicted.

25. A possible second defective area lies between the cross-lines (3-3) and (4-4). Its presence and boundaries are indicated by lack of nodal lines on Figure 5 and distortion of the nodal lines surrounding this area. The patterns, particularly those of Figures 5 and 6, indicate that the defect does not extend to the edge of the plate on either side. Examination of the edges opposite this area showed no laminations.

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26. So far as determining whether or not the plate is defective, any one of the several figures indicates that it is defective because none of the patterns are symmetrical about a cross-line midway between the ends of the plate. They have no center or line of symmetry.

27. Determination of the location and extent of the defect is less definite. In most of the figures the nodal lines are bent and distorted over the whole plate area. These figures differ so much from the simple grid-shaped patterns of a perfect plate that they cannot be interpreted as to the cause of the distortion. Some figures, however, such as (5), (6) and (7) retain sufficient of the grid-pattern to indicate more or less accurately the location and extent of the defect.

28. Such interpretable figures are given for any frequency that will give a standing wave system for both the plate as a whole and for the defective area as a whole. The grid pattern then tends to form over both the perfect and defective areas of the plate and the location and area of the defect is indicated by crowding of the nodal lines over the defective area and distortion of those adjacent to this area. Since such figures require a frequency that resonates both the whole plate and the defective areas they will be noticeably less numerous than is the case for a perfect plate. Indeed, it may sometimes prove that no such figures will be formed on a plate carrying several defective areas. In such a case, the plate can definitely be judged as defective through lack of symmetry of the patterns but the location and extent of the defects will not be clearly indicated.

CONCLUSIONS AND RECOMMENDATIONS

29. Theoretical considerations lead to the belief that:

(a) Laminations in steel plates can be detected through the resulting reduction of the stiffness of the plate over the defective areas.

(b) The relative stiffness across all increments of the plate area can be deduced from sand patterns formed when the plate is vibrated at one or more of its resonant frequencies.

(c) The presence, location and extent of lamination defects can be predicted with most assurance if the plate is vibrated in a way to give simple sand patterns wherein the nodal lines are parallel.

30. These predictions have been proved in practice. Circular plates driven to oscillate from the center point give circular parallel nodal lines. Such geometrically perfect patterns on a perfect plate are markedly distorted by an artificial defect such as pasting a small strip of metal on the back of the plate. Another circular plate known to carry a lamination defect clearly showed distortion of the nodal lines from the

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true circles that would form on a perfect plate.

31. Rectangular plates one foot wide and of various lengths and thicknesses have been resonated to give simple grid-shaped patterns wherein the nodal lines are parallel and directed crosswire of the plate. One plate known to carry lamination defects gave highly distorted patterns and another plate suspected of carrying defects gave wholly normal patterns.

32. Tests on these and other plates seem to prove that:

(a) A perfect plate always gives a sand pattern that is symmetrical with respect to a cross-line that bisects the plate.

(b) Lack of such symmetry on any clean-cut pattern proves the plate to be defective, though it may not show the location and extent of the defect.

(c) Usually some one or more of the numerous possible patterns will serve to locate the defect and roughly determine its contour.

33. There is no obvious reason why the method cannot be applied to plates of any size. The nature of the magnet is such that it can be made to cover the width of any plate. Its flexibility allows it to fit the cross-contour even though the plate is considerably warped. The attraction between plate and magnet is sufficient to warp the magnet to fit the plate and thus leave a proper and uniform air-gap over its whole length.

34. Tests have shown that 50 watts of A.C. is enough power to oscillate a plate one foot wide and of any desired length or thickness. A 500-watt driver would serve for testing most plates. Two 500-watt power tubes in push-pull relation for amplifying the output of a master oscillator would make an ideal power source. It should be designed to tune through the frequency range -- 2-10 kilocycles. The magnet, of course, should be designed to match the impedance of the driver. The design as a whole represents a straightforward engineering problem that can be solved by any competent radio engineer.

35. It is recommended that one plate-testing apparatus of the nature described be purchased under contract carrying performance specifications prepared by this Laboratory.

SUMMARY AND DISCUSSION

36. The Sound Division of this Laboratory has conceived of a method for detecting laminations in steel plates and, as described herein, has devised and developed means whereby it can be put into practice. It is based on the effect that laminations have on the stiffness of the plate over their respective areas as compared with normal stiffness over other areas. This effect is registered through distortion of sand or dust patterns formed on the surface of the plate when it is set into resonant vibration.

37. Judging by laboratory tests on relatively small plates, the method will quickly and with considerable certainty tell whether or not a rectangular shaped plate carries lamination defects and will usually locate

and roughly outline the defects. A picture of the sand pattern showing a number painted on the plate furnishes a complete record of the test upon which acceptance or rejection of the plate can be based.

38. The apparatus employed by this method is rugged and simple in principle. It can be operated by personnel with but average technical ability.

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TABLE 1.

Number of Figure	Resonant Frequencies Kilocycles	Number of Nodal Lines	Wave-Length Inches	Remarks
6	4.20	19	7.0	Nodal line at each end distorted.
7	4.65	20	6.75	Three nodal lines at each end distorted.
8	5.00	21	6.50	Seven nodal lines at each end distorted.
9	5.60	22		All nodal lines distorted.
10	6.60	24	5.75	Slight nodal distortions on several lines.
11	7.20	25	5.50	Slight nodal distortions on several lines.
12	8.10	27	5.0	Slight nodal distortions on several lines.
13	8.85	28	4.87	Slight nodal distortions on several lines.

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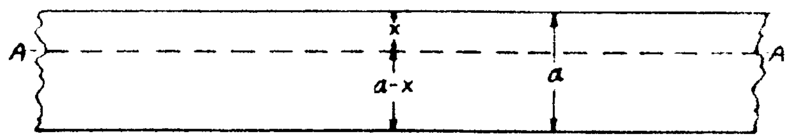


FIG. 1

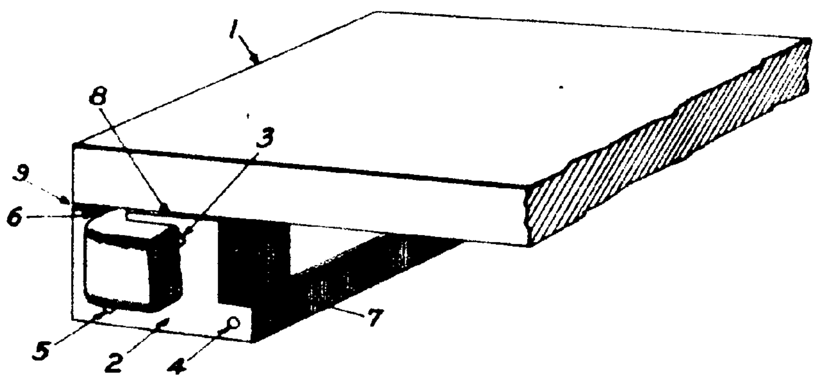


FIG. 2

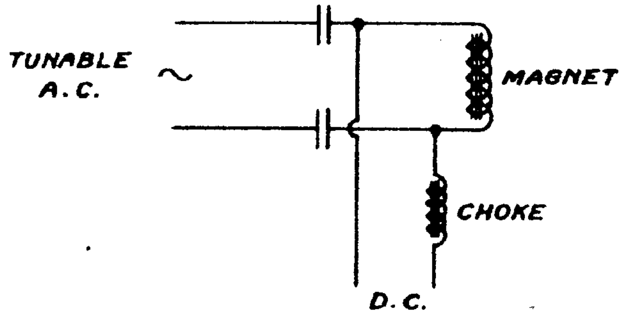
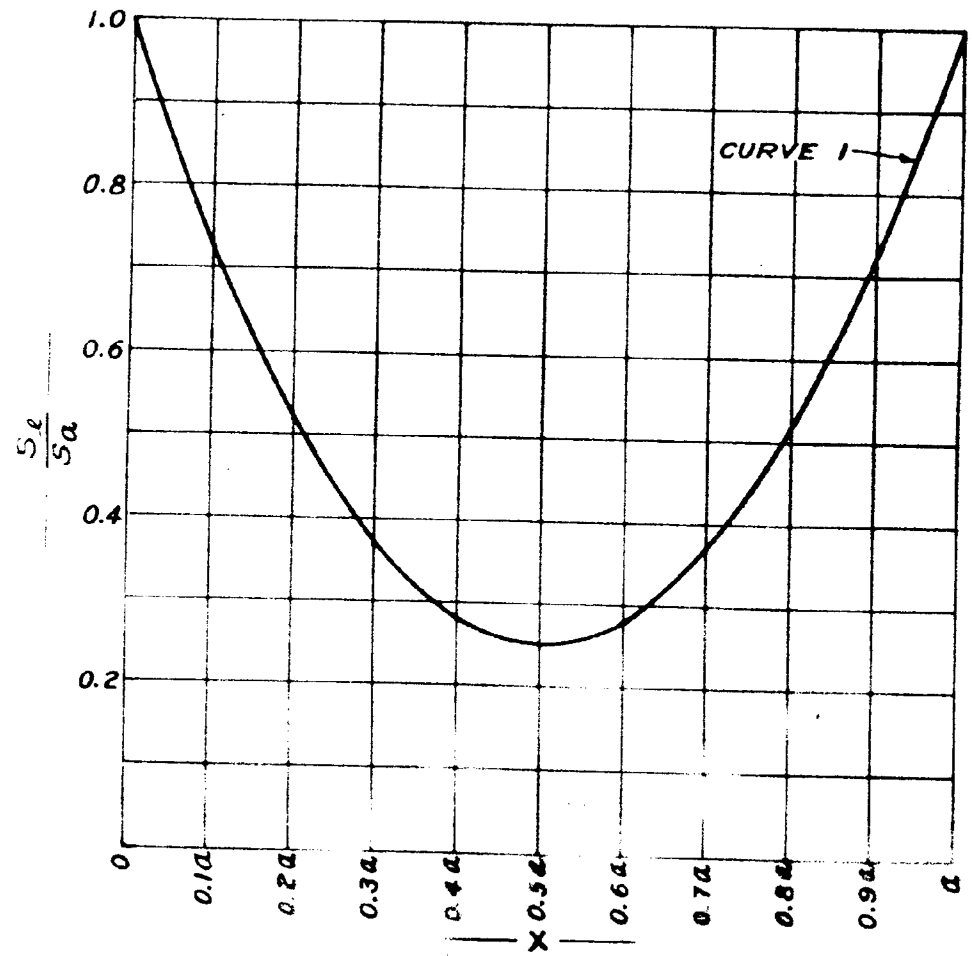


FIG. 3

PLATE 1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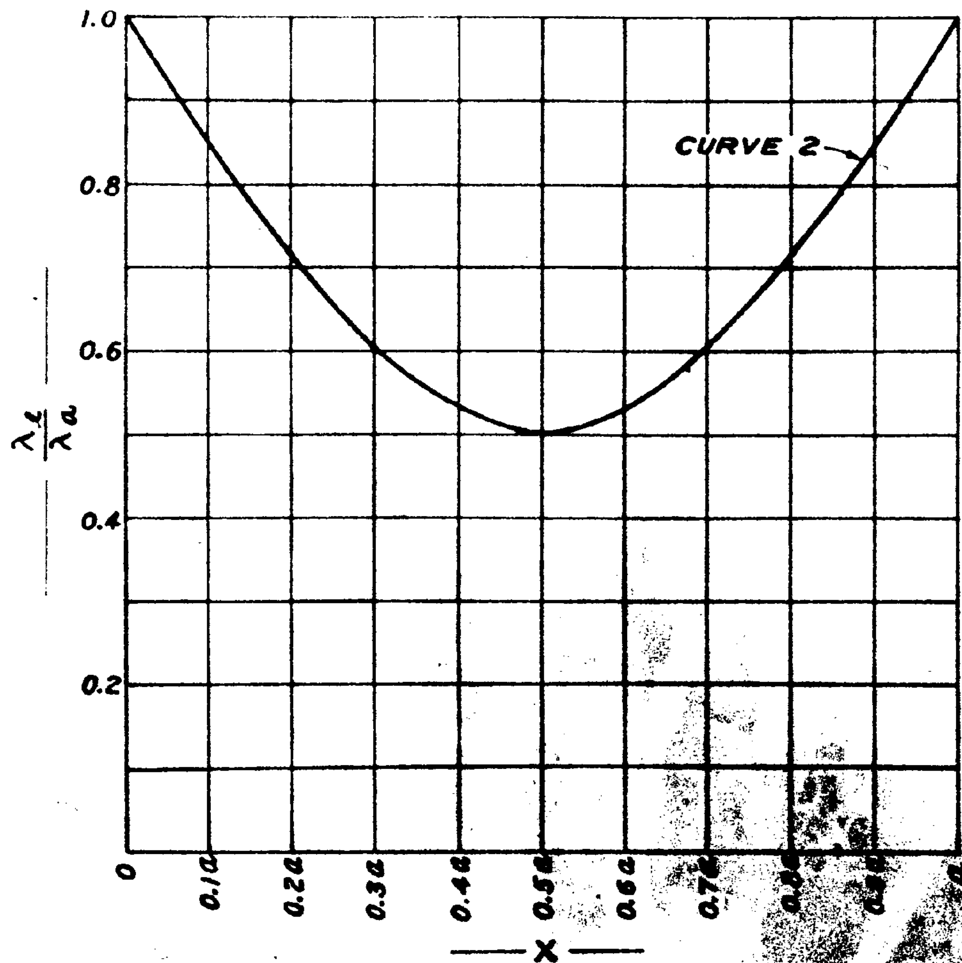
0.4a
0.5a
0.6a
0.7a
0.8a
0.9a
a
X

PLATE 2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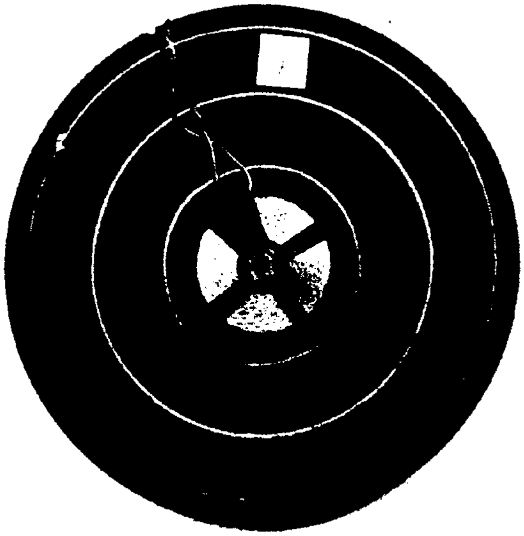
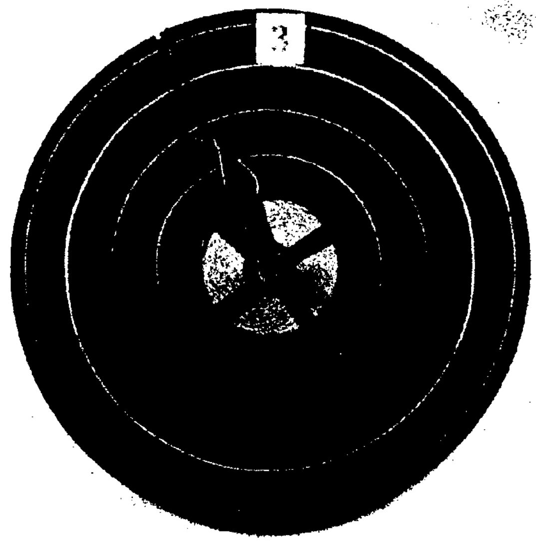
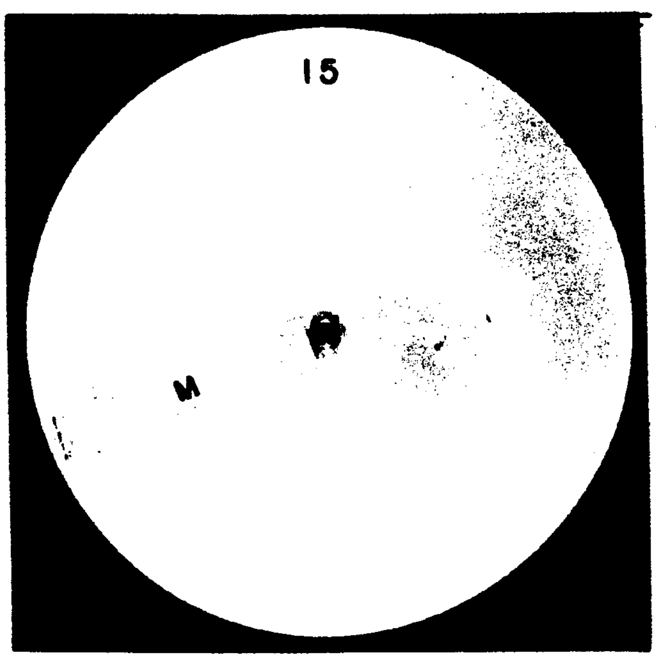
X

PLATE 3







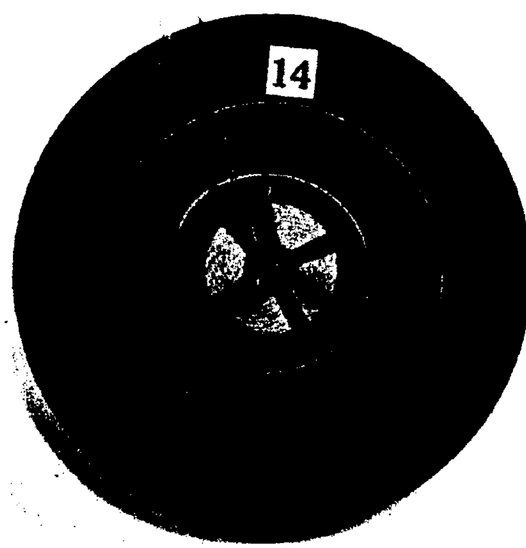


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Plate 4

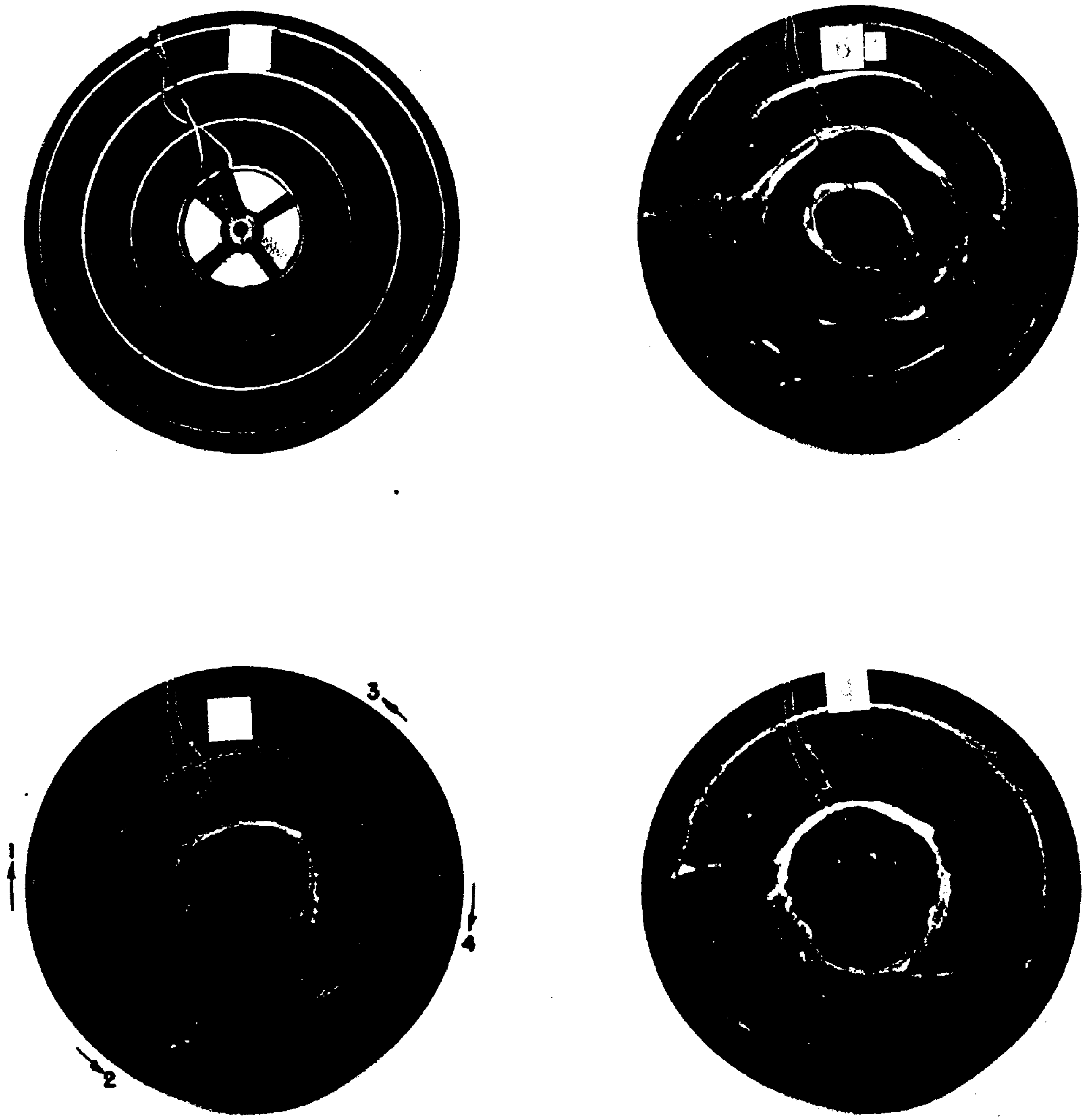
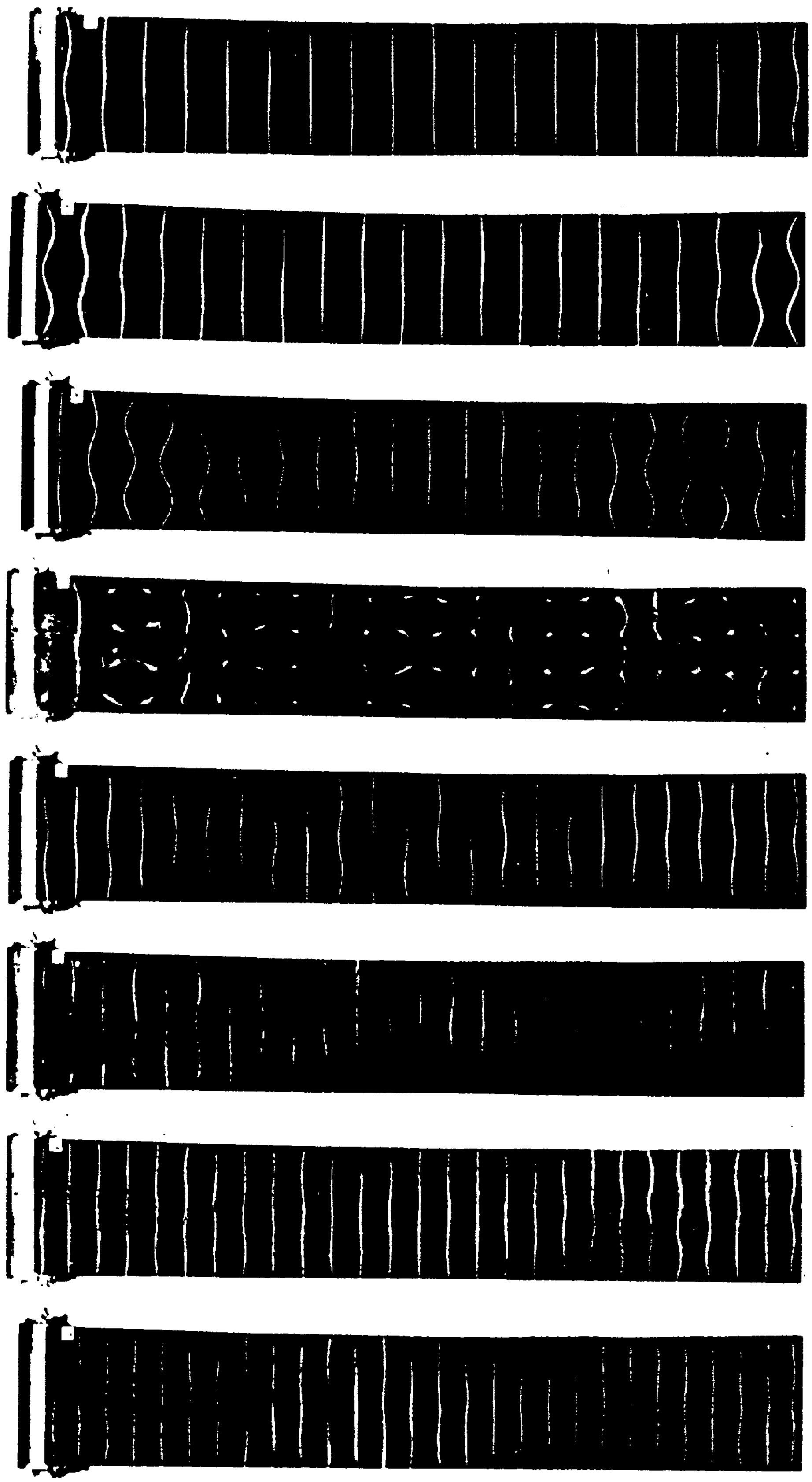


Plate 5



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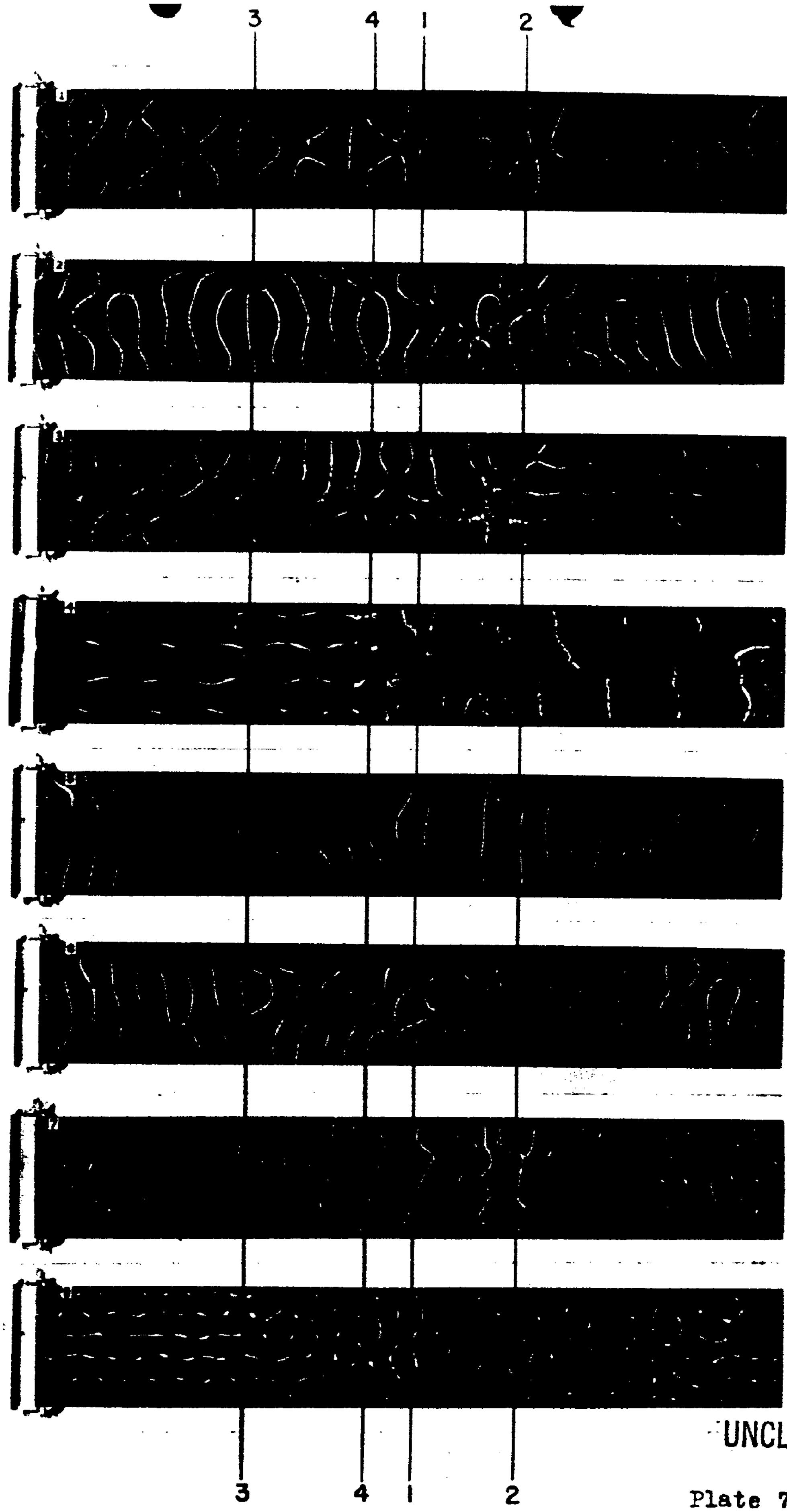

Plate 7

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