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MATERIALS FOR SLACK DIAPHRAGMS

By Traute Puschmann

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MATERIALS FOR SLACK DIAPHRAGMS

By Traute Fuschmann

So-called slack diaphragms made of rubber, leather, etc. - more recently also of synthetic materials - are frequently employed in measuring instruments and for purposes of regulation and control. Up to now, no systematic experiments have been carried out on the suitability of such materials for work of this kind, so that in many cases it is very difficult to choose the proper material for a particular purpose. The author first investigates the conditions under which such slack diaphragms are employed and then describes a number of instruments most commonly used for the testing of the materials.

SUMMARY

The present report deals with systematic experiments carried out on five diaphragm materials with different pretreatment, for the purpose of ascertaining the suitability of such materials for slack diaphragms. The relationship of deflection and load, temperature and moisture, was recorded. Of the explored materials: synthetic leather, balloon cloth, goldbeaters skin, Igelit and Buna, synthetic leather treated with castor oil is the most suitable material for the small pressure range generally required (20 to 50 mm water). Balloon cloth is nearly as good, while goldbeaters skin, Igelit and Buna were found to be below the required standards.

Weather- exposure tests proved that temperature and humidity changes had little effect on the zero-point travel (diaphragm unloaded) of synthetic leather and balloon cloth, particularly, in contrast with goldbeaters skin. By rising temperature and humidity the zero-point travel is counterdirectional and, in part, is canceled.

*"Werkstoffe für schlappe Membranen." Forschung auf dem Gebiete des Ingenieurwesens, vol. 11, no. 1, January-February 1940, pp. 35-42. (Dissertation)

For practical purposes a number of simplified test methods for ascertaining the climatic effects and the elastic behavior of diaphragms, are given.

1. INTRODUCTION

Although slack diaphragms (reference 1) have been employed for a long time for a multitude of purposes, there is a lack of test data concerning the properties of the material of which such diaphragms are made. The investigation was made in the laboratory of the Askania Co., Berlin-Friedenau (reference 2).

The material is generally classified as follows:

1. For metal diaphragms: copper, brass, phosphor bronze, beryllium copper, monel, steel, or aluminum.
2. For slack diaphragms: rubber, leather, bacterial leather, duprene, goldbeaters skin, balloon cloth, cellophane, glass cloth, asbestos, etc.

The metal diaphragms, provided with several concentric grooves, are particularly suitable for pressure suction and differential pressure gages up to around ± 5000 mm water = 0.5 atmosphere. Instruments of this kind are used extensively in laboratories and industrial concerns. Of course, there are other suitably dimensioned metal diaphragm pressure meters which range up to 200 atmospheres. Their usual diameter is about 150 millimeters. Slack diaphragms are especially suitable for picking up weak impulses or low pressures and can be made with much greater diameter (300 mm or more), which is an important factor for sensitive measuring or control instruments (reference 2), and therefore much preferred for quantitative measurements of gases (reference 3). They are also used extensively for regulating (for example, domestic and station-gas regulators) and control (for instance, automatic directional controls) purposes.

2. REQUIREMENTS FOR AN "IDEAL" SLACK DIAPHRAGM

Slack diaphragms for regulating, measuring, or control purposes should meet the following requirements:

1. Linear ascent of deflection by increasing load.
2. Adequate reproducibility of values (maximum departure from theoretical value generally not in excess of 2 percent of recorded value).
3. A minimum of hysteresis (i.e., lag between the upwardly and downwardly measured values).
4. Recording and operating range must, with sufficient accuracy, lie within the strength limits of the diaphragm.
5. Constancy of indication by humidity changes within a certain range.
6. Constancy of indication by temperature changes within a certain range.
7. Constancy of zero point (no so-called zero-point travel).
8. Diaphragm material of domestic raw materials wherever possible.
9. Cheap enough to compete with other diaphragm materials.
10. The materials should be available in ready form or available for manufacturing, so as to maintain uniformity of quality with safety.

As regards the last requirement, it is to be noted that the organic materials such as leather, rubber, etc., frequently disclose unavoidable defects, while synthetic materials are easier to manufacture in uniform quality.

3. EXPERIMENTAL SCHEDULE

Since all regulating, measuring, and control instruments operate on the principle of deflection of a diaphragm under load, the chief problem consists of exploring the relationship between the diaphragm deflection and the aforementioned practical operating conditions. Since a slack diaphragm collapses completely into its final position, even at very low pressure, its deflection cannot be taken as an indication of its load. They therefore operate usually in conjunction with helical or flat springs, to which the pertinent impulses or forces are transmitted.

The investigation included five kinds of diaphragm materials, each of which was subjected to different pre-treatments, or to close examination. These were:

1. Synthetic leather (American fishskin) -
 - a) treated with glycerin (hygroscopic) and, after drying, with watch oil;
 - b) pretreated with watch oil;
 - c) pretreated with castor oil.
2. Goldbeaters skin -
 - a) as delivered;
 - b) pretreated with watch oil, bone oil, or castor oil;
 - c) very thin (two-ply).
3. Igelit -
 - a) with web interlayer (manufacturer: Venditor, Troisdorf);
 - b) without web liner;
 - c) gray (manufacturer: Veritas, Berlin);
 - d) brown;
 - e) black;
 - f) very thin.
4. Buna "120" -
5. Balloon cloth -
 - a) cotton fabric, treated 18 times with synthetic rubber solution (manufacturer: Luftschiffbau A.G., Berlin-Tempelhof);
 - b) as before, then covered with aluminum powder.

Essentially, the problem consisted of establishing the dependence of the diaphragm deflection under loads up to 20 and 50 millimeters of water at different temperatures and relative air moisture. The materials were tested at 20°, 40°, and 60° C air temperatures and for a constant relative moisture of 30, 60, and 90 percent.

4. EXPERIMENTAL ARRANGEMENT

Diaphragm deflection.— Figure 1 illustrates diaphragm box a with a clamped diaphragm b of 150 millimeters diameter. Small rods h in the center of the diaphragm seat c transmit the deflection — first to a flat spring d fixed above, and then to the lever arm of a mirror pivoted on axis e. The temperature-resisting rods h (of Invar) pivoted loosely in agates at c, d, and the lever of the mirror, the whole being held together by tension springs f. In view of the smallness of the diaphragm loads, and hence the deflections, the need for an accurate reading as free as possible from inertia, was paramount, and this is best achieved by optical means with a light beam thrown on a mirror and reflected by it.

To check this test arrangement, air was pumped into the diaphragm chamber with a rubber ball at lead g and the light path observed, while the pressure was recorded with an Askania manometer (graduation 1/100 mm water). Special precautions to prevent slanting of the diaphragm were found to be necessary.

For calibration of the light path in millimeters of deflection, a micrometer screw substituted for the diaphragm, so that the conversion factor of the light path, measured in scale graduations, was immediately obtainable in millimeters of deflection.

The next problem after proving the practicability of the set-up in preliminary tests, was to provide a suitable method for a continuous record of the deflections under different loads; there the optical Askania multiple recorder was particularly suited. Its advantage over mechanically recording instruments (ink or carbon black) lies in the complete absence of erroneous test values caused by friction in the transmission rods and recording mechanism; besides, external accelerations and the location of the instrument, which was originally intended for aircraft use,

have no effect on the reading. One serious difficulty - that of making the whole experimental set-up completely lightproof - had to be overcome.

In the principal tests, a hydrostatic balance served for producing the pressure in the diaphragm chamber. One arm of the balance carried a bell dipped in a sealing liquid, the air space of the bell being connected with the diaphragm chamber by a hose. The other scale arm was loaded with weights.

Air conditioner (fig. 2). - The climatic chamber a is preceded by an atomizing chamber b. The compressed air, carefully cleaned by a filter of compressor oil before passing through the nozzle c, atomizes the water inducted from the bottom through pipe d, and is heated by gas burner e to approximately test temperature. Then, the thus-humidified air reaches the climatic chamber, where an adjustable electric heater f keeps it at constant test temperature. A guide plate g conducts the air past the diaphragm h, whence it is exhausted by fan i.

The diaphragm box with springs and mirror, as of figure 1, is solidly connected with the multiple recorder k. The part protruding into chamber a is sealed by rubber tape. The recorder, being mounted on an erstwhile lathe support l, could be moved horizontally and vertically. A dry- and a wet-bulb thermometer m served for moisture recording. In addition, the course of the moisture change was continuously recorded on a newly developed moisture recorder fitted with a hygroscopic membrane (Zapon film, trinitrocellulose). This is the first approved experimental design of the Bohnstedt-Askania moisture recorder and closely agreed with the hard-to-read hair-hygrometer (Fuess Co., Berlin).

The susceptibility of the zapon film to oil necessitated the aforementioned careful purification of the compressed air from the oil entrained by the compressor, quite apart from which a portion of the diaphragms were to be tested as received; i.e., without oil treatment.

The moisture recorder was compensated for temperature by a bimetallic strip and calibrated with the Assmann aspiration psychrometer.

For experimentation at low relative humidities, the dehumidification of the air was found to be necessary. In consequence, the atomization mechanism was removed and a

vessel filled with calcium chloride fitted in the connecting pipe (fig. 2) between chamber a and atomization chamber b.

Figure 3 is an interior view with front and side removed. Figure 4 is an external view, showing the shaped window a for the hygrometer and thermometer readings. Since the moisture coated the window, a windshield wiper b (fig. 3), was installed.

5. TEST PROCEDURE

Sealing test.— Each diaphragm, after being mounted to the brass box, was tested first for tightness. The pressure drop within 5 minutes was not to exceed 2 percent of the final value. The sealing compound was Guro mastic or ideal rubber and cement glue.

Tests with unloaded diaphragm.— These tests are fundamentally important in order to ascertain whether zero indication was preserved under temperature and humidity changes, for without adequate zero-point constancy it is impossible to achieve a reliable instrument. For these experiments the box with diaphragm mounted was screwed to the upright wall of chamber a (fig. 3), and the mechanical connection between slack diaphragm and mirror (fig. 1) was established by insertion of rods h and return springs f. The zero point of the luminous beam was adjusted for a normal temperature of around 20° C and 60 percent relative humidity, and the movement of the zero point observed at different temperatures and relative humidities.

Tests with diaphragm loaded.— The pressure line g (fig. 1) is connected to the hydrostatic balance. As soon as pressure is applied to the diaphragm, it is necessary to check the correct movement of the light spot on the scale (focusing screen) and also to ascertain the maximum value at which the light spot still remained on the scale - which has the same height (120 mm) as the film paper. It was found expedient to record first the related scale values of the light spot on the screen for certain equal pressure stages - say, every 2 mm, water - and then to decide on the basis of the obtained values as to whether a photographic record was advisable. The pressure stages in all tests were adjusted by weights on the hydrostatic bal-

ance which at the same time give an indication for the pressure in the diaphragm box and for the diaphragm load - starting from zero to maximum value and back again in equal stages to zero, in order to ascertain whether the test points assume the same position on going forward and backward, and to gage eventual discrepancies. The steady state must be awaited before the respective diaphragm deflection or light spot is photographed. This stage was found to have been reached after a few seconds, although the new setting of the stages was effected at intervals of about 30 seconds. Depending on the type of test material, the pressure range chosen varies from 0 to 16 and 0 to 50 millimeters of water.

Photographs of the pressure stages disclose curves of the type shown in figures 5 and 6, where the ordinates give the light-spot path for the diaphragm deflection in scale divisions (Skt) at the individual pressure stages. The pressure at the separate stages is given in millimeters of water.

In principle, every material tested was first photographed at 20° C room temperature and 60 percent relative humidity. For measurement at higher temperatures (40° and 60° C), the electric heater is used and the humidity adjusted. The fan was an absolute necessity in every test. Obviously, care must be taken in the mounting of thermometer, hygrometer, and humidity recorder, so that the readings actually correspond to the true temperature and humidity on the diaphragm. According to preliminary tests, the readings of three thermometers of the same type differed 1° C at the most, and the readings of two identical hygrometers, 5 percent, which still may be considered permissible. No measurement was started until the instrument reading had remained constant at least 30 minutes - a time interval long enough for the diaphragm to assume the desired attitude.

6. RESULTS OF TESTS

Zero-point travel by unloaded diaphragm. - A 20° C air temperature and a 60-percent relative humidity constitutes an acceptable standard condition; departures due to changes in moisture and air temperature are determined by light-beam observation. All diaphragms registered a rise in zero point by constant humidity and temperature rise. A retrogressive motion of the zero point occurred by constant

temperature and rise in humidity; hence temperature and humidity effects act in opposite directions. The order of magnitude of the changes was practically the same in both cases for all the diaphragms explored. The worst conditions occurred at 20° C and 90-percent relative humidity; and again at 60° C and 30-percent relative humidity. Table I gives the zero-point travel between these two stages for the different materials (fig. 3).

TABLE I

Zero-point travel	Synthetic leather treated with castor oil	Goldbeaters skin		Igelit, very thin	Balloon cloth with aluminum powder	Buna "120"
		thin	thick			
In scale divisions	2	30	44	22	5	8
In mm of diaphragm deflection	0.022	0.34	0.49	0.25	0.056	0.09

Goldbeaters skin and Igelit are very inferior under greatly varying humidity and temperature effects. Synthetic leather treated with castor oil, and balloon cloth coated with aluminum powder, appear to be the most suitable materials, with a zero-point travel of 2 and 5 scale divisions for the whole test range of 20° to 60° C, and 30 to 90 percent humidity which, by a conversion figure of 89, is equivalent to an additional diaphragm deflection of 0.022 and 0.056 millimeter, respectively. The maximum changes for synthetic leather, as for balloon cloth, are still within safe limits.

Pressure-stage tests.— On connecting the corners of the stepped curve (figs. 5 and 6), it can readily be seen if the diaphragm deflection changes linearly under load or does not change. A comparison of the ascending with the descending stepped curve further indicates that the diaphragm deflection at the same load stages lags behind on the descending curve. Figure 5, plotted for synthetic leather, discloses the favorable behavior of this material: linear ascent and descent of the stepped curve; the hysteresis of the descending curve itself is small. The behavior of

Igelit (fig. 6) is very unsatisfactory, as is seen when the loads (pressure stages) are plotted against the related diaphragm deflection as effected in figures 7 and 8 for the stepped curves of figures 5 and 6 (curve 1). The ascending and descending curves form a hysteresis loop, which is not closed, however, since the descending curve does not return to the zero point (zero point deflection rather than zero point travel!) but shows the greatest divergence at this point. The small hysteresis area of figure 7 is typical of the favorable attitude of synthetic leather as diaphragm material in contrast with Igelit (fig. 8). The diagrams further show the hysteresis for extreme temperature and humidity changes. The lower hysteresis refers to low temperature and high relative humidity; the upper hysteresis to high temperature and low humidity. In most cases the height h of the stepped curves (figs. 5 and 6) changed fairly little, hence the hysteresis due to heat and humidity effect was merely shifted parallel (figs. 7 and 8).

The characteristic quantities for the appraisal of the suitability of diaphragm material are as follows:

TABLE II

Material	Height h of stepped curve at 20°C and 60 percent rela- tive hu- midity Skt	Load range mm of water	Hysteresis 0 point deflection percent	Height change of stepped curve percent	0 point travel percent
Synthetic leather	98	20	2	2	2
Balloon cloth	91	20	2	5	5
Goldbeaters skin, thin	90	20	2	5	30
Goldbeaters skin, thick	85	20	2	5	50
Igelit, very thin	110	30	4	15	20
Buna "120"	76	50	5		20

The percent values refer to the normal height of the stepped curve, second column, and represent averages obtained from the photographic records (altogether 81, with 4 to 6 stepped curves each).

The height h of the stepped curves also changed under the effect of humidity and temperature; the changes are small for synthetic leather and never very considerable for any of the other materials except Igelit. The zero-point travel also favors synthetic leather and balloon cloth, but none of the other materials. Accordingly, synthetic leather treated with castor oil rates highest (table II), with balloon cloth (with aluminum powder) as second best. The zero-point travel for goldbeaters skin was particularly great. Igelit and Buna also were unsuitable for the present purposes because of their unfavorable characteristics.

In this connection the externally visible actions on the different materials during the climatic tests, might be mentioned.

The diaphragm of glycerin-treated synthetic leather remained soft even after the tests were completed, while the synthetic leather treated with bone oil became hard and brittle. Admittedly, the highly hygroscopic glycerin, serving as impregnator, has the disadvantage of making the diaphragm very susceptible to moisture. Since castor oil had stood up best, it was then used in all subsequent test series for synthetic leather. Goldbeaters skin as delivered (not treated) gradually became pervious during the measurement, especially at the sealing ring of the diaphragm seat. Impregnation with different kinds of oil (watch oil, bone oil, castor oil) resulted in very taut, almost parchment-like diaphragms, and disclosed an individual characteristic which excluded them as slack diaphragms within the required small test range. Very thin (two-ply) goldbeaters skin showed up no better. Several samples of the little-tested new synthetic material, Igelit, were subjected to a four-hour heat test at 75° C, without manifesting any changes. Buna "120" of 1-millimeter thickness appeared considerably stiffer than any other material tested. A 12-day heat treatment in a drying oven at 45° C disclosed no change in the diaphragm material, nor in the test values. Buna "120" should be especially suitable for high pressures. It can be summarily loaded up to 2000 millimeters of water, according to rigidity tests.

Balloon cloth was available in two versions - with and without a protective coating of fine aluminum powder to prevent sticking. Following a 12-day-drying process at 45° C in a drier, the balloon-cloth diaphragm was again measured in the optical multirecorder and air conditioner. The results showed no changes, i.e., no measurable effect of the protracted heat treatment.

7. SIMPLIFICATION OF TESTS FOR PRACTICAL PURPOSES

The measurements in the optical multirecorder are predicated on an elaborate experimental set-up. It seemed, therefore, most important to first develop some experimental device for obtaining rough estimates, making it possible to separate the fit from the utterly unfit of a large number of unknown materials, quickly and dependably, so as to avoid unnecessary and time-consuming experimental labor. To begin with, it was necessary to gain a survey of the zero-point travel caused by climatic effects. Next came the elasticity tests. It is in the nature of the "slack" diaphragm to have little or no elasticity, or stretch, under load. The elasticity effect or, as it is expressed, the individual characteristic of the diaphragm, is the real reason why the stepped curves are nonlinearly distorted.

The climatic and elasticity effects finding joint expression in the stepped curves and in the derived hysteresis, it is important that these effects be amenable to separate analyses with simple experimental arrangements.

Strip tests for predicting the climatic effect. - A test strip 30 millimeters wide and 100 millimeters long cut from the material, is clamped in a supporting plate of glass (low-temperature coefficient) and loaded in the center with a light weight (0.8 to 2.0 g), so as to secure an unequivocally defined neutral position (fig. 9). A pointer - the setting of which is read on a millimeter scale with the cathetometer - indicated the change in the strip deflection: once for variable moisture content and constant temperature (fig. 10a), then for variable temperature and constant humidity (fig. 10b). The deflection in both cases was approximately linear except with opposite prefix, as already established in the previously discussed climatic tests.

To check the homogeneity of the material in all directions, samples were cut lengthwise and crosswise and tested separately.

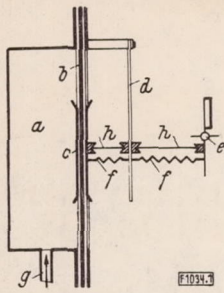
Elasticity tests.— The deflection in relation to the load under normal temperature and moisture conditions was determined with a diaphragm box similar to that used in the principal test, but much smaller (34 mm diameter). The deflection was transmitted by means of a metal band to a pivoted mirror and the light path read on a scale (conversion factor, 13). In this manner the same materials as before were tested with the exception of Buna. Figure 11 shows the elasticity - i.e., the relation of diaphragm deflection and load. This was increased to 120 millimeters of water first, because the measurement of smaller pressure stages is experimentally more difficult, whereas the test method was to be simplified; secondly, in order to obtain - beyond the required small test range - some information concerning any possibly existent undesired elastic elongation of the material. The best qualities again were first, those of synthetic leather, and then balloon cloth, whose curve was the same.

The hysteresis of neither material is excessive. The ascent of the deflections under increasing load approaches a constant value, after which the curve changes to a straight line. Igelit shows considerable extensibility; goldbeaters skin, fairly little. There was no perceptible deflection below 16 millimeters of water in any of the four diaphragms, hence no values below 16 millimeters of water could be recorded.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

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- a diaphragm box
- b fixed diaphragm
- c diaphragm seat
- d flat spring
- e mirror axis
- f tension springs
- g lead
- h rod

Figure 1.- Diaphragm box with mechanism transmitting the diaphragm deflection on a rotating mirror.

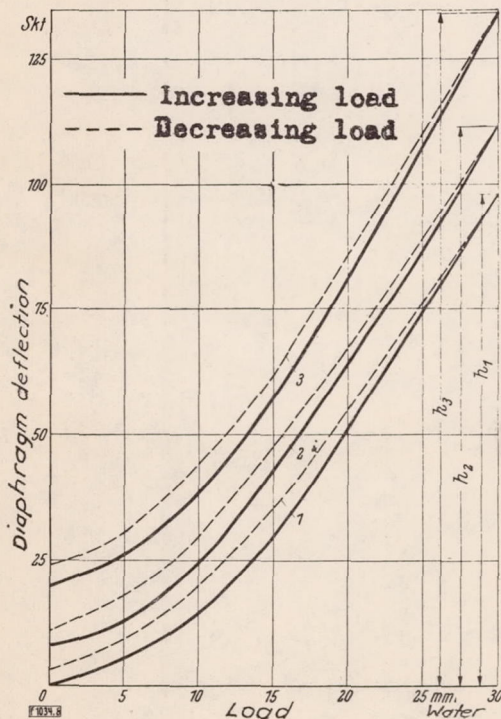
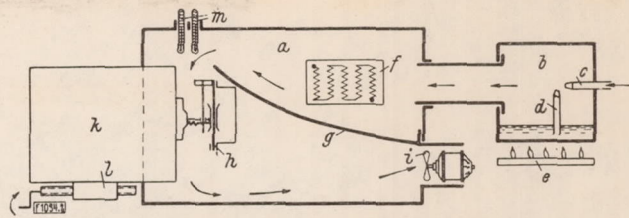


Figure 8.- Hysteresis for Igelit under different climatic conditions.
 Curve 1: air temp. 20°C, rel. humidity 45%
 " 2: " " 27°C, " " 95%
 " 3: " " 63°C, " " 38%
 Conversion factor: 89



- a air condition chamber
- b atomizing chamber
- c compressed air nozzle
- d water induction pipe
- e gas burner
- f electric heater
- g guide plate
- h diaphragm
- i fan
- k opt. multi-recorder
- l lathe support
- m wet and dry-bulb thermometer

Figure 2.- Experimental arrangement.

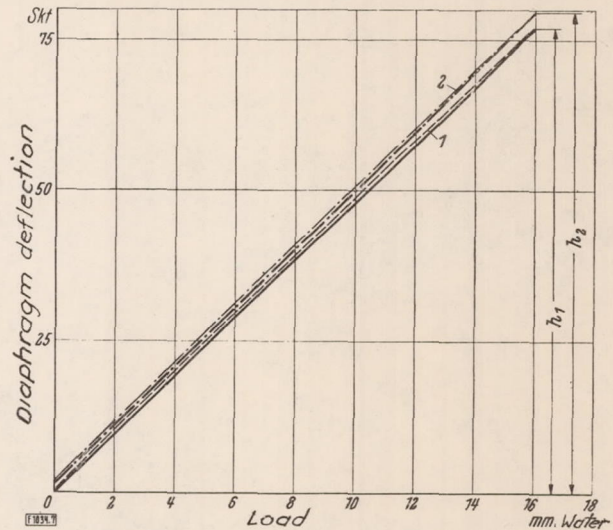
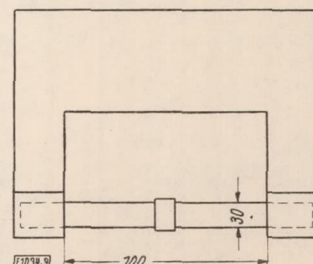
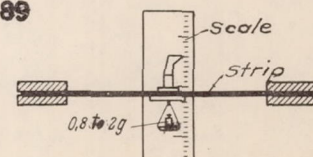


Figure 7.- Hysteresis for synthetic leather under different climatic condition
 Curve 1: air temp. 60°C, rel. humidity 85%
 " 2: " " 60°C, " " 33%
 Conversion factor: 89

Figure 9.- Simple test setup for strip measurements.



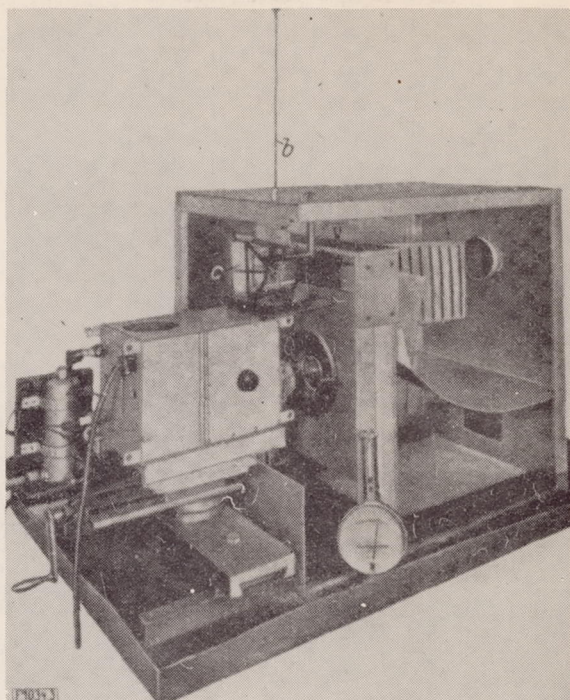
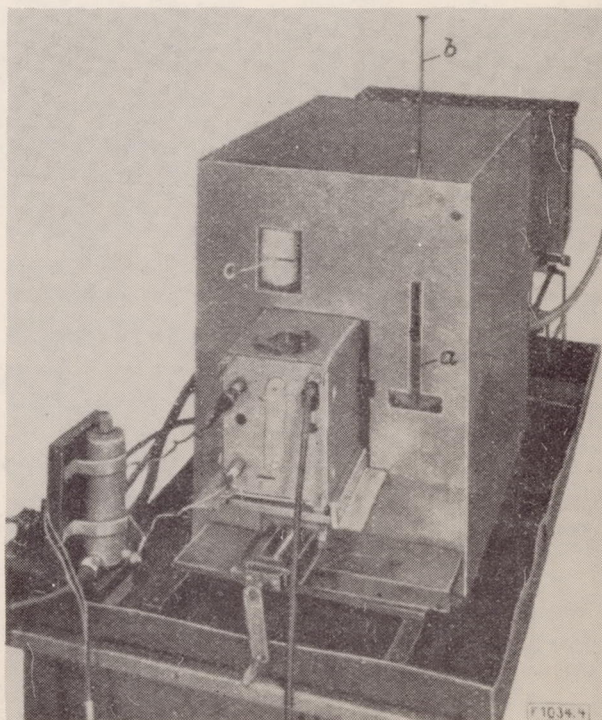


Figure 3.- Inside view, showing climatic chamber.



a L shaped window for hygrometer and thermometer reading;
b rod with window wiper; c humidity recorder.

Figure 4.- View of instrument closed.

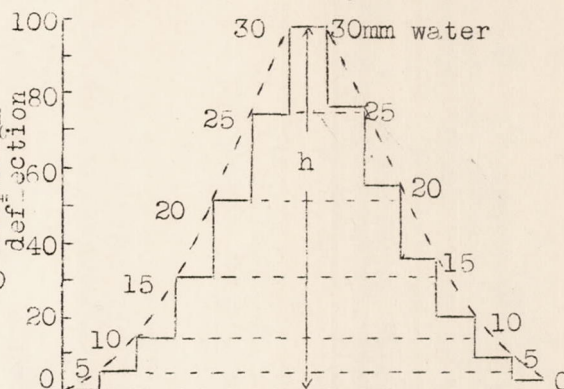
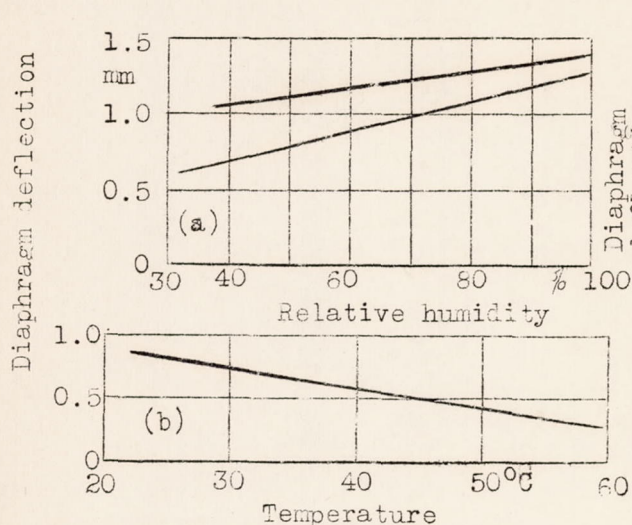


Figure 6.- Photographic record of stepped curve for Igelit.

Figure 10(a,b) Top-Diaphragm deflection at constant temp (19-21°C), variable relative humidity. Curve 1-Sample strip cut crosswise, load 2g. Curve 2-Sample strip cut lengthwise, load 0.8g. Bottom- Deflection at constant relative humidity of 15%, and variable temperature.

Strip tests on synthetic leather

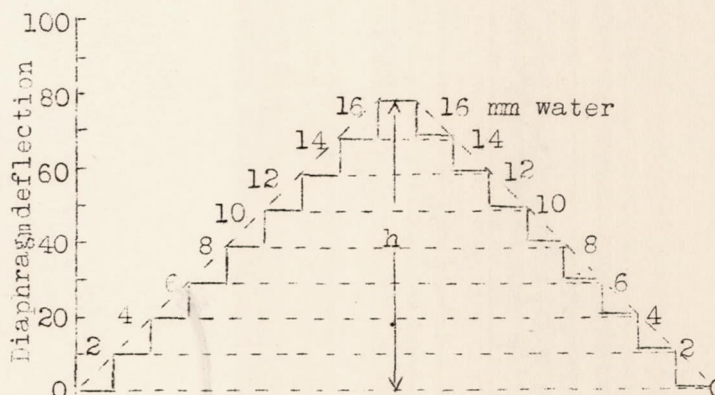
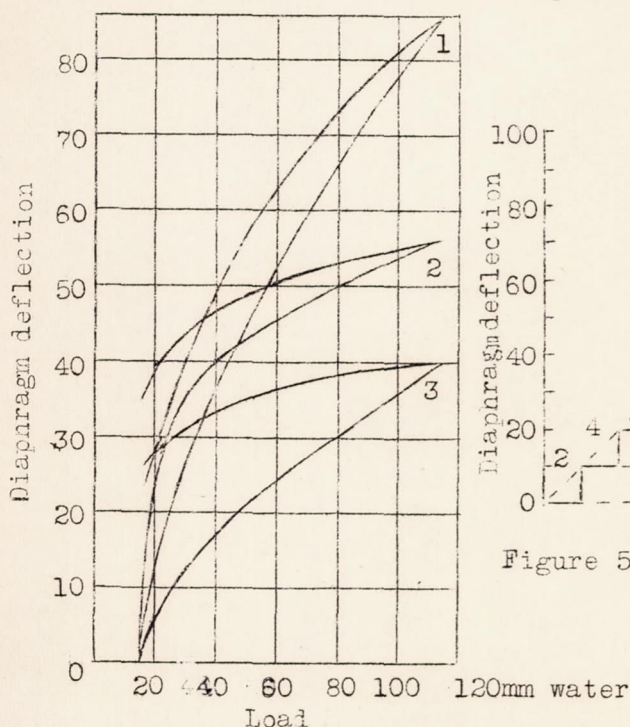


Figure 5.- Photographic record of stepped curve for synthetic leather.

Figure 11.- Extensibility and hysteresis of different diaphragm materials.

Curve 1.-Igelit, very thin.

Curve 2.-Synthetic leather, treated with castor oil.

Curve 3.-Gold beater's skin, thin, as received.

Conversion factor 23.