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A STUDY OF TRANSPARENT PLASTICS FOR USE ON AIRCRAFT

By Benjamin M. Axilrod and Gordon M. Kline
National Bureau of Standards

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SUMMARY

Various transparent organic plastics, including both commercially available and experimental materials, have been examined to determine their suitability for use as flexible windshields on aircraft. The properties which have been studied include light transmission, haziness, distortion, resistance to weathering, scratch and indentation hardnesses, impact strength, dimensional stability, resistance to water and various cleaning fluids, bursting strength at normal and low temperatures, and flammability.

The two types of transparent plastics which are now in use on aircraft, namely, cellulose acetate and acrylate resin, were found to have certain defects which, it is believed, can be overcome in part by suitable modification of the composition and processing of the plastic.

Cellulose acetate plastic was found to have excellent impact strength, bursting strength, and flexibility, but the products sold at present vary considerably in their resistance to weathering and are subject to marked shrinkage in one year's time. This shrinkage causes warping and sets up strains in the plastic sheets, which cause them to craze and crack. This is believed to be the cause of the spontaneous cracking of cellulose acetate windshields after they have been in service for six months or longer. This is particularly true of windshields which are exposed to low temperatures, as by ascent to high altitudes, thereby introducing additional strains in the windshield because of thermal contraction. Our tests have shown a great deal of variation in the weathering resistance of cellulose acetate sheets received from different manufacturers, and also in the case of different lots of the material prepared by a given firm. Further tests on modified samples are in progress to determine whether more uniformly durable products than have been on the market to date can be made available to the aircraft industry.

The acrylate resin was found to be remarkably transparent, more stable to light and weathering and more resistant to scratching than cellulose acetate, but its impact strength and flexibility are much poorer than is the case for cellulose acetate. Surface crazing of the acrylate resins was noted after one year's exposure on the

roof and also in the case of some samples kept in storage. Further samples have been submitted by the manufacturers of this type of plastic for our examination to determine whether modifications which they have made in the material have eliminated this tendency to craze.

Other transparent plastics, such as cellulose nitrate, ethylcellulose, vinyl chloride-acetate resin and vinyl acetal resins, failed in resistance to weathering after approximately three months. Glyceryl-phthalate, styrene and phenol-formaldehyde resin plastics discolored markedly on exposure to sunlight or ultraviolet light from a carbon arc lamp, and were also lacking in the flexibility which is desirable for aircraft windshield products. A sample of cellulose acetobutyrate was practically unchanged after 12 months' exposure, but this material is not available commercially in sheet form. With the exception of the cellulose nitrate, cellulose acetate, and acrylate resin plastics, the materials tested were of an experimental nature and were not recommended for use on aircraft. Many of the undesirable properties observed for these experimental materials will undoubtedly be eliminated in the course of the development of these plastics and it is not improbable that some of them will later become available in a form suitable for windshield use.

I. INTRODUCTION

Although it is true that no organic plastic has yet been developed that possesses both the qualities and the low price of glass, nevertheless, plastic materials are now serving as windows on many airplanes. Two properties of fundamental importance in the use of transparent materials on aircraft, namely, weight and flexibility, have brought about this invasion of a field generally limited to glass. The organic plastics are approximately one-half as heavy as glass, a distinct advantage for aeronautical purposes. Flexibility is desirable in order to permit the use of curved transparent enclosures which offer minimum wind resistance.

The plastic sheets which are in use in this country for aircraft windows (fig. 1) are made from cellulose acetate, known commercially under such trade names as "Fibestos", "Lumarith", and "Plastacele", or from polymerized esters of acrylic and methacrylic acids, designated in the trade as "Lucite" and "Plexiglas". Cellulose nitrate transparent sheet is also employed to a limited extent; this type of product is variously designated as "Celluloid", "Fiberloid", "Pyralin", and the like by its manufacturers. A transparent synthetic resin made from glycerol and phthalic anhydride has been used in England as a window material on aircraft, but the particular product involved does not possess the flexibility characteristic of the cellulose derivatives. These organic plastics do not possess the surface hardness typical of glass, and the abrasive action of sand, dust, dirty rags, and flying insects soon impairs the transparency of the original product. For this reason a laminated product, made by sandwiching a plastic material between two layers of glass and commonly called "safety glass," is used in locations where clear and undistorted vision is continuously demanded, as through the windshield directly in front of the pilot. These parts must be designed for flat pieces, however, since the commercial production of laminated glass in curved shapes is very costly and difficult to achieve, although it has been accomplished experimentally.

Although the cellulose acetate sheets have been found to be more satisfactory with respect to weathering than the nitrate product, they are very susceptible to scratching and have also been observed to develop a surface cracking after a few months in service. These factors, of course, lead to an impairment of vision through such material. Recognizing that there is a real need for an improved flexible material for use in curved windows on aircraft, the National Advisory Committee for Aeronautics established a project at the National Bureau of Standards to study the available transparent plastics with regard to their suitability for such purpose.

The following types of transparent plastics were found to be available commercially or experimentally for examination in connection with our investigation: cellulose nitrate, cellulose acetate, cellulose acetobutyrate, ethylcellulose, acrylate (which term is used to include the polymerized esters of both acrylic and methacrylic acids), vinyl chloride-acetate, vinyl acetal, glycerylphthalate, styrene, and phenol-formaldehyde. Laminated glass for use on aircraft is made at the present time with four different plastic materials as binders, namely, cellulose nitrate, cellulose acetate, acrylate resin, and vinyl acetal resin. Samples of these various products were obtained for our investigation through the courtesy of the respective manufacturers.

The properties of transparent plastics which are of primary importance in their use on aircraft and which are reported on herein are as follows: light transmission, freedom from haze, surface imperfections and constituents which reduce or distort vision, resistance to weathering, resistance to surface abrasion, impact strength, dimensional stability, resistance to the action of water and cleaning fluids, bursting strength at normal and low temperatures, and flammability. Other properties of interest, such as tensile strength, thermal coefficient of expansion, mechanical strength at low temperatures, and resistance to high velocity impacts, and the problem of modifying the formulation and processing of the transparent plastics to obtain improved aging qualities are being investigated in the further work which is under way on this project.

II. CLARITY

The clarity of plastics is generally considered to be dependent upon two factors, light transmission and scattering of light by particles or by surface imperfections. Distortion caused by wavy surfaces and nonhomogeneous material is also an important factor in visibility through windshield materials and will be considered in a later section. The military services generally specify that the plastic sheet shall transmit at least 68 percent of white light when tested within 30 days of the date of manufacture and shall be free from wrinkles, bubbles, scratches, pits, or depressions. The light transmission is usually measured with a visual or photoelectric photometer, in the latter case with a photoelectric cell which is sensitive mainly to the visible portion of the spectrum. The transparent plastics now in use generally transmit more than 85 percent of the incident light. The haziness has been measured by several methods, including visual inspection with or without a background of light from Cooper-Hewitt lamps, comparison of the plastic sheet with samples of varying degrees of haziness, attempts to count the "star dust" visible in a small area under the microscope, and determination of a small portion of the light scattered when the sample is placed at a suitable angle with relation to the light source and photometer. Although the latter method has the desirable feature of utilizing one instrument for measuring both light transmission and haziness, it presents some difficulty because of the possibility of introducing considerable error in measuring only a small portion of the scattered light.

A photometer of simple construction, called the "hazeometer", which can be used effectively to measure the haziness of a plastic as well as the light transmission, was developed in the course of this investigation.

1. Description of Hazeometer

A photograph of the photometer is shown in figure 2:

A 6-volt automobile-type bulb is mounted in front of a reflector. A cylindrical shield, blackened inside and with a circular aperture b in the center of the base, causes an approximately parallel beam of light to be radiated toward the photoelectric cell. A blackened disk with a circular aperture a, is mounted in front of the photoelectric cell. In the instrument as built for experimental purposes the two openings a and b, are each 1 inch in diameter and are spaced 18 inches apart. The photoelectric cell is of the Weston photronic type. The spectral response of this cell deviates considerably from the luminosity curve of the eye, and hence the light transmission obtained is not the same as would be measured with a visual photometer but is a close approximation to such value for samples with little or no dye. A filter can be obtained from the manufacturer which will approximately correct the response of the cell to that of the eye. The meter has an internal resistance of 50 ohms and a range of 100 microamperes. Spring clamps are fastened to the frame at each aperture to hold the plastic in place. A 6-volt storage battery is used to operate the lamp. All the parts are housed within a wooden box finished in a dull black which reduces reflections to a minimum. The lid of the box is closed during measurements to keep rays of light from outside sources from reaching the photoelectric cell. This instrument is only applicable for measuring the haze in sheets which have approximately parallel surfaces and are free from imperfections which act as lenses or prisms.

2. Test Procedure and Definitions

To obtain a measure of the light transmission of the plastic, the light is adjusted in intensity so that a current of 100 microamperes is obtained from the photoelectric cell. A flat sample is then placed in front of the cell at aperture a. Of the light incident on the sample, a fraction is transmitted undeviated, and a fraction is scattered by the surfaces and the interior of the sample. The photoelectric cell receives the undeviated fraction of the light and that part of the scattered light which is not deflected at angles greater than about 90°. The light transmission of the plastic is defined as the fraction of the original light received by the photoelectric cell which continues to reach the sensitive element when the plastic is placed over the aperture a at the photoelectric cell.

To obtain a measure of the haziness of the plastic, the sample is placed at aperture b, 18 inches distant from aperture a. The photoelectric cell still receives the undeviated fraction of the light but collects only that small portion of the scattered light which is confined to the small solid angles subtended by aperture a at points in opening b. The difference between the photoelectric current with the sample at a and at b is a measure of the light scattered, assuming that a linear relation exists between the photoelectric current and the total light incident upon the sensitive element of the cell. The current is practically proportional to the total incident light for no external resistance; the deviation is only slight for the 50-ohm resistance in the microammeter used. Haziness is defined as the percentage of the total light transmitted at position a which is scattered when the sample is placed at position b.

3. Results of Measurements of Clarity

The initial white-light transmission and haziness of the materials submitted by manufacturers cooperating with us were measured with the hazeometer; the results are presented in table I. Each value in the table represents the average for three specimens, each 1-1/4 by 2-1/2 inches. Measurements of light transmission and haziness were also made on several varieties of plain and laminated glass (table II) to afford a comparison with the results obtained for plastics.

a) Light transmission.- It will be noted that the white-light transmission of all of the plastics tested exceeds the 68-percent requirement formerly specified by the military services. The highest values were obtained with samples of acrylate resins, the percentage transmission varying between 93.6 and 94.2 for these materials. The samples of cellulose acetate which gave whitesion varying between 93.6 and 94.2 for these materials. The samples of cellulose acetate which gave white light transmissions exceeding 90 percent did not contain blue dye, whereas those which gave values varying between 77 and 83 percent were very obviously colored blue. The effect of the addition of blue coloring on the transmissivity is shown in table II for the glass products and in table III for a special series of cellulose-acetate transparent plastics. Because of this pronounced lowering of percentage light transmission, the practice of adding blue dye to cellulose-acetate transparent sheet has been discontinued by some manufacturers. For undyed materials approaching the transparency of polished glass, most of the loss is due to reflection at the two surfaces and can be approximately calculated from the refractive index.

b) Haziness.- The haze values for two of the acrylate samples, namely, 1.8 and 1.9 percent, compare favorably with measurements made on laminated safety glass and were the lowest of any of the plastics studied. The values for the cellulose-acetate products show considerable variation. Apparently a minimum of about 4 percent haze for sheets up to 100 mils thick is the best that can be done and for thicker sheets this would be somewhat higher. The fog or cloudiness present in sheets with haze values of this order is quite easily detected by the eye and is a much more serious defect than the lowering of white-light transmission by blue dye. The cause is probably inherent in the fibrous nature of the raw material, cellulose, rather than in the chance inclusion of foreign matter. The values recorded in table I for the materials other than cellulose nitrate, cellulose acetate, and acrylate resin, were obtained on experimental samples only, such products not being available in sheet form for aircraft-windshield use at the present time.

III. INDEX OF REFRACTION

The index of refraction is of interest in considering the light-transmission characteristics of plastics. This property was measured by means of an Abbe refractometer on the same samples used in the light transmission and haze tests. Two contact liquids, bromnaphthalene and mercuric iodide, were employed in order to guard against incorrect values resulting from reaction between the sample and the contact liquid. The data obtained are presented in table I. The refractive indices for the materials studied range from 1.47 to 1.58.

IV. DISTORTION TESTS ON PLASTICS

Distortion tests were made on 12- by 12-inch sheets of the various materials in accordance with the procedure suggested by the American Standards Association for laminated safety glass. A line is projected with a lantern so as to fall midway between two parallel lines marked on a screen, these lines being one inch apart. The test specimen is 25 feet from the screen and the lantern is adjusted so that the center 10- by 10-inch square fills the beam. The sample in a suitable frame is moved across the beam and the movement of the projected line observed; the safety glass specification requires that the projected line shall not deviate more than 1/2 inch as the sheet is moved across the beam. Several materials were tested but none failed to meet the specification. Then measurements were made on each sample of the deviation of the projected line as the square was moved an inch at a time across the beam. This measurement was made at the top, center, and bottom of the screen for the sample normal to the incident light; this was repeated just at the center of the screen for angles of 75°, 60°, 45°, and 30°. The data did not prove suitable for giving an estimate of the visibility because a specimen with many relatively small ripples simply causes the projected line to move back and forth rapidly as well as causing it to get out of focus; a sample which is slightly wedge-shaped or one with a large wave in its surface, might cause the line to deviate as much or more, yet it would be far superior as regards distortion.

The above considerations led to the following method for evaluating the distortion of the transparent plastic sheets. A projection lantern is focused on a screen 40 feet distant; the specimen is placed in front of and parallel to the screen. The sample is moved toward the light and its shadow observed. When light and dark patches begin to appear in the shadow, the distance of the specimen from the screen is noted and is taken as a measure of the relative distorting characteristics of the sheet. The better the material, the greater is the distance at which the shadow becomes nonuniform. Observations were made by three individuals on 12- by 12-inch samples of the plastics. The results are shown in table IV. The acrylate resin sheets are found to be considerably better than other plastic materials in this test.

V. RESISTANCE TO WEATHERING

Samples of transparent plastics 7 by 7 inches were prepared for weather-exposure tests by fastening them in brass frames curved cylindrically to a radius of 5 inches. Most of the materials were flexible enough to bend to the curvature of the frame without special heat treatment and could be drilled in the flexed position without cracks forming at the holes. Two samples of the acrylate resin sheets, J2 and K1, were softened in water warmed to about 60° C, for 15 minutes and then bent and drilled. Another acrylate sample, K3, was softened by heating for 10 minutes at 70° C. in an oven. One manufacturer of these resinous sheets has recently recommended bending them by warming at 90° to 125° C., depending on the thickness, using as the heating medium either hot water or preferably hot air, pressing the sheet around a wood or metal form covered with rubber or glove cloth, and allowing it to cool in the bent position. Initial white-light transmission and haze determinations were made on the specimens in the frames before placing them on the roof. In addition the light transmission was measured with red, green, and blue filters in order to follow any color changes in the various materials during exposure. The frames were fastened to exposure racks on the roof of the Industrial Building of the National Bureau of Standards, the racks facing south and being inclined at an angle of 45° to the horizontal. The samples were placed on the roof during March 1936, and the changes in clarity after 1, 2, 3, 6, 9, and 12 months were determined quantitatively. The samples were cleaned with lens paper soaked in tap water and for some of the materials in kerosene.

The data for light transmission and haze measurements made on the transparent plastics are given in tables V, VI, and VII. The condition of the samples after 12 months' exposure on the roof is shown in figures 3 to 6. Examination of the photographs indicates clearly that the samples of acrylate resins, numbers 15, 16, 17, and 18, are in the best condition after the year's exposure. This same conclusion is reached from a consideration of the light-transmission data in tables V and VI and the haze data in table VII. The surfaces of three of these samples, however, had begun to craze and crack. These cracks are not readily visible when viewed by directly transmitted light, but become very pronounced when illuminated so that the light scattered by them can be observed. Figure 7 shows panels 16, 17, and 18 taken at a suitable angle to show this cracking. It should be kept in mind that these frames are curved and that the cracks which show up at the center portion of panels 16 and 18 are present throughout the whole sheet. Sample 17 (K1) did not show any evidences of cracking; however, it contained a plasticizer which resulted in a slight yellowing of the sheet upon exposure. This discoloration is particularly indicated by the results of the light transmission measurements using a blue filter, shown in table VI. Some samples of acrylate resin which had been kept in storage for approximately 18 months have developed similar crazing, as shown in figure 8. One of the manufacturers of this type of plastic has informed us that they have modified their product so as to avoid this failure. Tests on these new samples are in progress.

The cellulose acetate transparent sheets tested are shown in figures 3 and 4, panels 1 to 9, after 12 months' exposure. The products of different manufacturers and of different samples from the same manufacturer varied considerably in their behavior upon weathering. Panels 1 to 3 had crazed badly, discolored, and become practically opaque. Panels 4 and 5 were in the best condition of any of the cellulose acetate samples after 1 year on the roof. Even these had become considerably more hazy and in one case had cracked at the top of the frame because of shrink age. These two samples tend to become coated with a frosty layer when left untouched for several weeks. This surface coating was readily removed with lens paper soaked in kerosene, and would be constantly eliminated by normal cleaning in service. Panel 6 was a sample submitted as a supposedly improved product, but it is quite apparently inferior to panels 4 and 5, made by the same firm. Panels 7 and 8 were beginning to show large surface cracks after one year and their surfaces had become roughened or "pebbled," thereby resulting in distortion of vision through them. Panel 9 had become practically opaque after one year; the cracking which caused this had taken place fairly regularly over the period of exposure as indicated by the haze values in table VII.

It is well known that cellulose nitrate is decomposed by ultraviolet light. Samples 10 and 11 show how completely opaque this plastic becomes after one year's exposure to sunlight. Table VII indicates that the major portion of the breakdown occurred between the 3- and 6-months period, namely, during June, July, and August.

The condition of these samples after 3 months' exposure is shown in figure 9. The crazing which occurs is confined to the outer surface of the material, the back remaining smooth and transparent.

The ethylcellulose sheets tested were among the first samples of this plastic which became available in this country. As indicated in table VII, figure 9 (panel 12 after 3 months) and figure 5 (panel 14 after 12 months), these materials were not resistant to exposure on the roof. A marked increase in the haziness of two of the samples took place within 3 months; the third sample deteriorated rapidly during the following three months. It is our understanding that manufacturers of these materials have improved the stability of ethylcellulose sheets during the interval which has elapsed since these materials were received. New samples are being tested to determine whether a grade which would be suitable for airplane use has been developed.

None of the vinyl resin sheets tested, all of which were experimental samples, had satisfactory resistance to weathering. The polyvinyl chloride-acetate sheets (panels 19 and 20 in fig. 6) discolored rapidly, becoming dark purple. This purple discoloration was entirely a surface layer effect and extended only one-fifth of the way through the sample, the remainder being apparently unaffected. The vinyl acetal samples (panel 22 in fig. 6 after 12 months and panel 24 in fig. 4 after 9 months) did not discolor but became opaque and showed evidences of surface cracking.

The sheet of cellulose acetobutyrate (panel 23 in fig. 6) was cast from a solution in various organic solvents. The bubbles which are seen were present in the sheet as it was received. As indicated in tables V, VI, and VII, no marked changes in the light transmission and haze characteristics took place during the exposure period. The streak which is present on one side of the picture of panel 23 is an optical effect only, no cracks having appeared in the exposed sample.

The sample of glyceryl-phthalate resin which was received was too brittle to be bent to the 5-inch radius of curvature of the test frames. Accordingly, a flat piece was exposed on the roof and is shown in figure 6 (number 26) after nine months. No cracking or crazing is evident but the material has discolored considerably.

The possible effect of the bolting of the materials in a stressed state in the test frames on crazing was studied by exposing flat sheets of cellulose acetate and cellulose nitrate simultaneously with the same materials fastened in the curved panels. Figure 10, which was taken after 9 months' exposure on the roof, indicates that the crazing took place equally rapidly under the two conditions. The crack down the middle of panel 30 was the result of strain caused by shrinkage due to loss of volatile material.

The effect of one year's exposure out of doors on the light transmission and haziness of laminated and ordinary glass is shown in table VIII. No marked breakdown of these products took place during this period. The laminated glass made with an acrylate plastic gives somewhat erratic results in the measurement of haze because the plastic tended to squeeze out at the edges, thereby leaving the product slightly wedge-shaped. However, there was no apparent change at the end of one year on the roof in the clarity or appearance of this type of laminated glass.

VI. ACCELERATED AGING

Accelerated aging tests were conducted on samples 6 inches by 1-1/2 inches, in a Weather-O-Meter having a carbon arc light. A portion of the sample was covered with aluminum to obtain a ready comparison of exposed and unexposed material. The samples were rotated about the carbon arc at a distance of 2 feet, making one revolution every 20 minutes. Tap water was sprayed on the plastics at one location in the Weather-O-Meter; the duration of its application to each sample was about 15 seconds. The samples were removed and tested after 500 and 1,000 hours. The results of these tests are shown in table IX. Figure 11 shows the condition of the samples after 1,000 hours' exposure. The unexposed portion is at the top of the samples in the photograph.

The cellulose acetate materials in general were improved in regard to light transmission, because of bleaching of the blue dye added to the original plastic. The samples were held only by light spring clamps and many of the acetate samples warped during the test. The nitrate samples were less affected by 1,000 hours in the Weather-O-Meter than by three months' (March, April, and May) exposure out of doors. One sample of ethylcellulose was in a very friable state after 1,000 hours' exposure to the carbon arc light. The acrylate resins were practically unchanged after this treatment. The effect of the carbon arc light on the polyvinyl chloride-acetate samples was very pronounced, converting them from the transparent condition to purplish-colored opaque masses. This chane was confined to a thin layer at the surface of the sample, indicating practically complete absorption of the harmful light radiation. The styrene and vinyl acetal samples were rapidly attacked by the carbon arc light. The cellulose acetobutyrate was practically unaffected. Salt deposited during the alternate wetting and drying cycles prevented accurate determination of haze changes.

A second group of samples was subjected to the light from the carbon arc lamp without using a water spray so that haze measurements could be made. The samples were subjected to a somewhat higher temperature in this test, approximately 55° C. compared to 40° C. when the water spray was employed. Examination of the light transmission data after 500 hours' exposure in tables IX and X indicates that the cellulose nitrate and vinyl chloride-acetate resin samples are deteriorated more rapidly in the drier and warmer condition. Sample J1, an acrylate resin, was quite markedly affected by the higher temperature, becoming translucent rather than transparent because of surface roughening. Comparison of the haze values in tables VII and X show that the results of the accelerated test do not indicate the same relative order of stability as is found upon exposure out of doors. Thus, the two cellulose nitrate samples became clouded at about the same rate on the roof whereas E1 breaks down more rapidly in the accelerated test. Similar discrepancies are noted for the ethylcellulose and vinyl acetal resins. The amount of discoloration of the samples by the carbon arc light can be judged from the data in table XI for light transmission using various color filters. There was a considerable drop in the light transmitted using the green and blue filters in the case of the cellulose nitrate samples and the glyceryl-phthalate resin O1. A slight drop is also noted for acrylate resin K1. On the other hand, the light transmission using the green filter showed a marked increase after the 500 hours' exposure to ultraviolet light for those samples which contained blue dye, notably in the case of cellulose acetate T1.

VII. SCRATCH RESISTANCE

The comparative ease with which transparent organic plastics are scratched is a major obstacle to their substitution for glass in many applications where their toughness and nonsplintering characteristics would be advantageous. However, the plastics vary considerably among themselves in scratch resistance, and it is desirable to have a method of measuring this property. The effect of tumbling with sand of a standard grade was tried but, after a short period, a polishing action produced by fine fragments tended to undo the action of the coarse grains of sand. It was also very difficult to remove the fine dust from the samples preparatory to determining the amount of abrasion by measuring the light transmission of the abraded materials.

These difficulties are avoided by the use of a sclerometer to produce a band of scratches on the sample, from which the relative resistance of the material can be judged by determining the average width of the scratches. Various types of sclerometers have been developed for use in making scratch tests on metals. These were discussed in detail by O'Neill (reference 1).

1. Description of Apparatus

The instrument used in this work on plastics was developed by Bierbaum and is called the "microcharacter" (fig. 13). The cutting diamond is in the form of a corner of a cube, mounted so that the diagonal of the cube is normal to the test surface and one edge is in line with the direction of the scratch. The diamond is suspended from a balanced arm pivoted on sapphire bearings. One end of the arm is provided with a spirit level and the other with a 3-gram weight which constitutes the standard load for the diamond point. The diamond is mounted at the small end of a tapered steel spring; the other end of the spring is fastened to the lower side of the suspension area. A vertical rack is provided for raising and lowering the bracket that carries the cutting tool. This bracket is attached to a microscope mechanical stage provided with suitable clamps and screw mechanism to permit the specimen to be moved slowly under the diamond point. The width of the scratch (fig. 14) is measured with a microscope having a calibrated filar micrometer eyepiece. The plastics were conditioned at 21° C. and 65 percent relative humidity for at least 24 hours, and the test was conducted under these same conditions. The scratch resistance is reported numerically as the quotient of the load in kilograms divided by the square of the scratch width in millimeters.

2. Results of Scratch Width Measurements

The data obtained with the Bierbaum microcharacter on various plastics are shown in table XII. Each value was computed from the averaged result of the measurement of the widths of five scratches at three locations on each scratch. The speed of the diamond point relative to the specimen was approximately 0.2 millemeter per second. To determine whether or not a material was anistropic, bands of scratches were ruled both parallel and perpendicular to the length of the sample. A few cellulose acetates, notably samples A3, B5, and C2 give some indication of anisotropism. The results show that most of the materials are isotropic as far as scratch resistance is concerned.

The scratch resistance of cellulose acetate varied with the products of different manufacturers, presumably because of differences in types and amount of plasticizer present. The acrylate resins were found to be the most resistant to scratching of the materials studied.

A value of 14.8 for the scratch hardness of acrylate resin sample K1 was obtained when a 6-gram load on the diamond point was used. Comparison of this value measured with a 6-gram load with the one in table XII obtained with a 3-gram load, namely, 15.0, shows that the calculated scratch resistance value is substantially independent of the load used. This would be expected to be true, since the diamond tool is of such shape that the scratches made with different loads are geometrically similar. The width of the microcuts obtained with the 3- and 6-gram loads for this acrylate resin were, respectively, 14.2 and 20.3 microns.

VIII. INDENTATION HARDNESS

A number of indentation tests previously developed for use with metals have been applied to the determination of the so-called hardness of plastics, including the Brinell, Martens, Rockwell, Vickers, and Shore machines. Table XIII presents the results of measurements made on unconditioned samples of plastics with some of these instruments. There is relatively good agreement between the degrees of hardness indicated by the Vickers, Rockwell, and Brinell machines. The Shore Scleroscope is not considered very satisfactory because the hardnesses indicated for the plastics were in all cases much higher than those for a mild steel specimen, whose Brinell hardness was about ten times that of the plastics. The data in the last two columns in table XIII show the effect of time of application of the load on the hardness values obtained. For the relatively soft plastics very little increase in indentation is noted, but in the case of the materials above Brinell No. 15 a considerable effect on the area of the indentation is noted.

The Vickers hardness testing machine (fig. 15) uses a square pyramid as an indenting tool, the value obtained therewith being substantially independent of the testing load. The length of the diagonals of the indentation (fig. 16) made with this tool are more readily measured than the diameter of the indentation made by a spherical tool. The Vickers hardness testing machine was, therefore, used for making a more detailed study of indentation hardness of plastics. The tool in this instrument is a square pyramid, having an angle between opposite faces of 136°. A load of 5 kilograms was used. The machine is constructed so that the load is applied slowly and progressively to the test specimen, remains applied for a predetermined time, and is then automatically removed. A special measuring microscope is then swung into position, locating itself exactly over the impression. The lengths of the diagonals of the indentation are measured by means of a micrometer ocular in the microscope. The Vickers hardness number is the quotient of the applied load in kilograms divided by the pyramidal area of the impression in square millimeters. The plastics were conditioned at 21° C. and 65 percent relative humidity for at least 24 hours prior to testing.

The effect of variation in the time of application of full load on the values obtained for Vickers hardness numbers is shown in table XIV. Just as in the case of Brinell numbers, it is seen that this is an important factor in the measurement. A more extensive examination of the Vickers hardness of the transparent plastics which were available was made on the same samples used for the scratch hardness test. A full load time of 10 seconds was selected. In some cases the values obtained which are shown in table XV, differed somewhat from those recorded in table XIV.

This can be attributed in large part to lack of uniformity in the sheet. Each value given in tables XIV and XV is the average of four determinations.

The glyceryl-phthalate resin was the most resistant to indentation of the materials tested; the cellulose derivatives were indented more readily than the resins with the exception of the vinyl acetal sheets, one of which was very soft. Some evidence was also obtained in measurements of the indentation diagonals that a few of the cellulose acetate sheets were anisotropic, but the variations in the two directions were not large enough to warrant reporting in detail.

It is interesting to compare the Vickers hardness values in table XV with the scratch-resistance data in table XII. Good correlation is evident for the cellulose nitrate, ethylcellulose, and acrylate resin plastics. However, the scratch-resistance values for the vinyl and styrene resins are much lower than the indentation values. In the case of the cellulose acetate samples, the two coefficients are not similar. It is, therefore, believed to be impractical to substitute the better known and more rapid indentation hardness measurement for scratch-resistance data obtained with a sclerometer.

IX. IMPACT STRENGTH

1. Charpy Test

The resistance of the transparent plastics to impact was determined with a Charpy impact machine and also by a falling-ball method. For the Charpy tests, two sets of notched specimens 0.5 inch by 2.5 inches were prepared. The notch, located at the center of the specimen, was 0.1 inch deep and was produced with an ordinary 60° triangular file. One set was tested for impact strength at 70° F., and the other at about 25° F. The samples were broken individually and not as a composite specimen. The capacity of the Charpy machine (fig. 17) was 2.9 foot-pounds, while its striking velocity was about 8 feet per second. The results of these tests are shown in table XVI. The cellulose nitrate, cellulose acetate, ethylcellulose, and vinyl acetal samples have relatively high impact strength at 70°, whereas the vinyl chloride-acetate and acrylate resins were relatively weak. At 25° F. the cellulose acetate samples had from 15 to 50 percent of their strength at 70° F.; the cellulose nitrate had about 55 percent of their original strength; the vinyl resins had approximately 30 percent of their impact strength at 70° F. For the acrylate resins and ethylcellulose, the loss in strength at the subfreezing temperature was only about 20 percent.

2. Falling-Ball Test

In tests made by the falling-ball method to determine the impact resistance of the plastics, it was found to be impractical to use the 12- by 12-inch frame employed for testing laminated safety glass in which the specimen is not clamped at the edge. In such a frame a cellulose acetate sample, 94 mils thick, failed only on the 24th impact from a ½-pound steel ball falling 65 feet. A nitrate specimen 64 mils thick pulled through the frame on the first impact. The following test procedure was, therefore, adopted. A steel ball weighing ½ pound was dropped from various heights on a disk 6½ inches in diameter held firmly between rubber gaskets in a metal frame (fig. 18) which had a circular opening of 5½ inches diameter. The test was continued until the sample was penetrated by the ball. The results are given in table XVI. The cellulose plastics failed when the ball dropped 50 to 65 feet, some requiring several impacts from the latter height. All of the acrylate-resin samples failed when the ½-pound ball was dropped 10 feet. The vinyl chloride-acetate resin samples received failed at 8 feet, whereas a vinyl acetal resin now being developed particularly for safety-glass construction broke on the average only after 11½ impacts with the steel ball from 65 feet.

In order to determine the comparative effect of impacts of elastic and inelastic bodies on the plastic, a tennis ball partially filled with one pound of shot was used in a series of tests. Results of tests on a few acetate samples indicate that a given sample will withstand three times as many impacts from the 1-pound shot-filled tennis ball as from a ½-pound steel ball. The study of the impact strength of these plastics and of laminated glass is being continued to determine the type of windshield which would be required to resist the impact of a bird during flight.

X. SHRINKAGE

The shrinkage which transparent plastics undergo in service is an important factor in their durability. Excessive shrinkage causes buckling and in some cases cracking of the plastic sheet.

The shrinkage of trasnparent plastics occurring during exposure on the roof and also as a result of accelerated aging was studied. Samples approximately 11 inches by 1 inch were conditioned at 21° C. and 65 percent relative humidity and gage lengths of 10 inches were marked off. One set of samples was placed on a roof-exposure rack while a second set was subjected to accelerated aging in an oven with circulating air at 70° C. After various periods the samples were removed to the conditioning room and the change in length measured. The results are presented in tables XVII and XVIII.

When the shrinkage is accelerated by heating at 70° C. in an oven, the decrease in length after four days ranged between 70 and 100 percent of the value obtained after two weeks at the same temperature. For cellulose-acetate plastics the shrinkage after two weeks was about 1 percent for 120-mil stock, and 2 percent for the 60-mil material; after two months these values had increased to approximately 2, and 3 percent, respectively. The lowest shrinkage of all the cellulose-acetate samples was undergone by sample B12, a 60-mil-thick sheet, the change in length being 1.2 percent for two months. The two cellulose-nitrate samples had decreased 0.5 percent in length after two weeks, and 1 percent in two months. The acrylate-resin plastics which were first submitted, shrunk almost 2 percent after two weeks at 70° C., and did not change appreciably thereafter. A later sample of this type of resin identified as K5, which was given a final heat treatment by the manufacturer to drive off volatile solvents, shrunk approximately 0.3 percent in two weeks, after which no further change in the length was observed. A sample of unplasticized acrylate resin, J2, decreased in length only 0.2 percent after two weeks, but showed 0.7 percent shrinkage after two months. The greatest shrinkage during the two months' heating at 70° C. occurred with a vinyl chloride-acetate resin; the decrease in length being 8.2 percent. A glyceryl-phthalate resin, O1, gave the least shrinkage, namely, 0.1 percent; another sample of this resin, made by a different company, decreased 0.7 percent in length.

The shrinkage tests made by exposing samples on the roof, gave somewhat different results from the accelerated tests. In general, the outdoor shrinkage of the synthetic resins was small compared to that of the cellulose plastics. Reasonably good correlation was observed between the shrinkages for the various cellulose derivatives on the roof and heated at 70° C. The cellulose-acetate samples had decreased in length from 0.7 to 3.1 percent after nine months on the roof, whereas these same samples gave 2.0- to 3.4-percent shrinkage when heated for two months at 70° C. The cellulose-nitrate samples averaged 0.5-percent shrinkage for nine months on the roof, and 1-percent for two months' heating at 70° C. The ethylcellulose plastics deteriorated rapidly on the roof, making measurements impossible after approximately six months. They had shrunk up to 2.0 percent at the end of three months on the roof compared with an average value of about 3 percent for the accelerated test. The acrylate resins had decreased in length only about 0.2 percent after nine months on the roof; the preshrunk resin had shrunk approximately 0.05 percent after six months, which was the latest data available for this particular sample. The greatest disparity between the natural and accelerated aging was noted in the case of the vinyl chloride-acetate resin which, although it shrunk 8.2 percent in two months at 70° C., had decreased in length less than 0.05 percent after nine months on the roof.

Presumably it would be possible to reduce the shrinkage of the cellulose plastics by heat treatment during the process of manufacture, as was done for the acrylate-resin sample K5. The impact strength of sample K5 as measured on the Charpy apparatus was the same as that for the ordinary acrylate stock. As indicated in tables XII and XV, the values of scratch and indentation hardnesses are higher for the preshrunk than for the ordinary acrylate. Samples of ordinary cellulose acetate and cellulose nitrate were preshrunk by heating at 100° C. for 4- and 24-hour periods. Impact measurements were made at 21° C. with the Charpy apparatus on both the original and heated materials. The decrease in length was also determined; the specimens used to measure shrinkage were placed on the roof to detect further shrinkage. The results are given in table XIX. The impact strength of the cellulose-acetate sample was decreased only 5 percent by heating for four hours; the same treatment halved the impact strength of the nitrate and caused it to discolor. It would seem therefore that this method of driving off the volatile solvent residue, which is in large part responsible for the shrinkage of the acetate plastics, would yield a much improved acetate sheet for windshield purposes.

XI. RESISTANCE TO WATER, ALCOHOL, AND KEROSENE

Resistance to water and to various organic solvents with which it is likely to come in contact, is an important property of a transparent plastic which is to be used as an airplane windshield. Data were therefore obtained as to the amount of water, alcohol, and kerosene absorbed by the various plastics and also as to the effect of these chemicals on the condition of the surface and appearance of the samples. The results of these tests are presented in tables XX to XXII. It will be noted in table XX that the absorption of water is particularly pronounced in the case of the cellulosic plastics, with the exception of cellulose acetobutyrate. Two of the three ethylcellulose samples become cloudy when exposed to water for 48 hours. This behavior would be very objectionable in a material for windshield use. The resinous materials absorb very little moisture, with the exception of the vinyl-acetal sample M1, which is a vinyl-acetate polymer which has been hydrolyzed and condensed with formaldehyde. This resin also becomes cloudy when wet and warps badly. The acrylate and vinyl resins are not attacked by water.

The data in table XXI indicate that alcohol attacks to a very considerable extent, all of the transparent plastics studied with the exception of the vinyl chloride-acetate resin. It has a dissolving action on the cellulose plastics and causes their surfaces to become roughened. A similar action of alcohol on the acrylate resinous sheets was noted. It is, therefore, apparent that alcohol should not be used to clean the surfaces of these transparent plastics.

The absorption of kerosene was negligible in the case of all the plastics except ethylcellulose, according to the results shown in table XXII. The three samples of ethylcellulose differed markedly in their affinity for kerosene. However, no impairment of transparency or roughening of the surface on any of these samples was noted. Kerosene is, therefore, a very suitable reagent for cleansing the surfaces of plastic windshields. It was found to be very effective in removing a frosty appearing layer which accumulated on the surface of some of the cellulose-acetate samples, and which was not fully removed by washing with water.

XII. BURSTING STRENGTH

Tests of bursting strength were made on a few specimens of cellulose acetate, cellulose nitrate, and acrylate resin. Seven-inch circular disks of the various materials were cut out and conditioned at 21° C. and 65 percent relative humidity. In the testing apparatus the specimen was held between steel clamping rings having an opening 5 inches in diameter. Hydraulic pressure from a hand pump was applied to one side of the disk and the maximum pressure withstood, observed. The tests were repeated with the specimen protected from the steel rings by 1/16-inch thick rubber gaskets.

All specimens except the acrylate resins were greatly deformed by the test, the portion not clamped having a domelike appearance. The results are presented in table XXIII. Figure 19 shows samples of cellulose acetate (G) and acrylate resin (I) after the bursting strength determination. Without rubber gaskets most of the samples failed by shearing at the clamping rings. However, when protected by the rubber gaskets, only the acrylate resin and one cellulose-acetate sample failed by shearing. The other specimens failed in lateral tension, that is, along radial lines. The gaskets had very little effect on the numerical value obtained for bursting strength.

A circular membrane under uniform pressure deforms to the shape of a paraboloid of revolution. The lateral and radial tensile stress are maximum and equal at the center, the expression being:

$$S_t = \frac{p\ a^2}{4h\ d}$$

for maximum bilateral stress where a = exposed radius, d = deflection at center, h = thickness of the skin, and p = pressure. Computations for a few samples were made with this formula. The deflection at the center was measured only for the 57-mil thick cellulose acetate; for the other samples, the permanent set was used in place of deflection under load. Since the elastic recovery was small compared to permanent set, this approximation will be satisfactory for obtaining an estimate of the stresses involved. The shearing stress at the edge was also calculated:

$$S_s = \frac{pa}{2h}$$

The calculated values for maximum tensile and shear stresses are presented in table XXIV.

The effect of cooling one surface of the plastic to -30° F. on the bursting strength, was also determined. The cooling was accomplished by application of a mixture of solid and liquid ethylene dichloride, which freezes at -31° F.; dry ice was used to maintain solid ethylene dichloride in the mixture. Cellulose acetate (fig. 19,H), 125 mils thick, burst at 174 pounds per square inch (average of 2 samples), whereas at room temperature a bursting strength of over 400 pounds per square inch was observed. An acrylate resin, K5, of 70 mils thickness (fig. 19,J), cracked before an appreciable load was applied, whereas previous tests at room temperature had shown a bursting strength of 26 pounds per square inch for this material. Examination of the specimen indicated minute crazing of the cooled surface, apparently caused by stresses set up by the thermal contraction. It is concluded that the spontaneous cracking of cellulose-acetate windshields, which has been reported to occur on airplanes which have ascended to high altitudes, is due to loss in strength of the particular product because of poor aging characteristics rather than because of inherent weakness of the original cellulose-acetate sheet.

A few samples of laminated glass and plate glass were tested at 25° C. in the same bursting-strength apparatus used for the plastic sheets. The results of these tests are presented in table XXV, and the condition of the laminated glass products after test is shown in figure 20. It will be noted that the bursting strengths of these materials are considerably less than those observed for the cellulose-acetate plastic sheets.

XIII. FLAMMABILITY

Two types of flammability tests for transparent plastic sheet were made on specimens 6 inches long and 0.5

inch wide. In one test the specimen is suspended from a hook by a hole drilled 1/8 inch from one end, an alcohol flame is kept in contact with the bottom edge for 10 seconds, and the time required for the sample to fall from the hook or the flame to extinguish, is noted. A Navy specification requires that the sample shall not fall from the hook or become completely enveloped in flames in less than 40 seconds from the time the flame was first applied. In the other test the sample is clamped at one end in a horizontal position longitudinally and at an angle of 45° to the horizontal laterally, ignited at the free end with an alcohol flame in contact with it for 10 seconds, and the time required to burn 3 inches or for the flame to extinguish, is determined. An Army specification requires that the time to burn 3 inches shall not be less than $1\frac{1}{2}$ minutes.

The results of these tests are shown in table XXVI. It will be noted that for most of the materials, two values are given. The first set of data was obtained after the samples had been conditioned 24 to 48 hours at 21° C. and 65 percent relative humidity, whereas the second set of samples had been in the conditioning room for approximately 30 days when tested. The latter samples in general tend to extinguish more quickly or burn at a slightly slower rate than those conditioned for the shorter time. The cellulose acetate, cellulose acetobutyrate, vinyl chloride-acetate resin, glyceryl-phthalate resin, and phenol-formaldehyde resin samples passed the above requirements for both the horizontal and vertical tests. Some of the acrylate resin strips were enveloped in flames in less than the 40 seconds specified for the vertical test, but this is a very difficult value to estimate. Only one acrylate specimen burned faster than the rate of 2 inches per minute, allowed for the horizontal test. One vinyl acetal and the ethylcellulose samples, all of which were relatively thin materials, burned in the horizontal test at a somewhat greater rate than the 2 inches per minute. However, none of these plastics was found to approach the degree of flammability of cellulose nitrate, which burned at a rate of about 17 inches per minute when held in a horizontal position.

There is considerable question regarding the practical value of flammability tests of this type. The differences in ease of ignition of melting points greatly influence the results. Some samples tend to melt and separate the burning portion from the rest of the sample. The manner in which the strip is mounted for the test also is a controlling factor in the rate of burning. Data on the rates of burning in horizontal and vertical positions of plastics clamped in a metal frame (fig. 21) are presented in table XXVII. All of the plastics, including the cellulose nitrate, burn more slowly under these conditions. The cellulose-acetate samples contain flame-retarding plasticizers which cause them to extinguish in many of the tests shown in tables XXVI and XXVII. Sample B5 and apparently D1 did not contain this type of plasticizer.

Tests made with incendiary bullets are of interest in connection with the establishment of specifications for the fire resistance of these materials. Tracer bullets of 30- and 50-caliber were fired through the samples at ranges of 100 and 600 yards. None of the plastics, which included cellulose nitrate, cellulose acetate, vinyl chloride-acetate, and acrylate acid resin, was ignited. It is, therefore, apparent that, considered from the viewpoint of military requirements, the safe limits for the flammability of these materials should be based on storage and handling problems rather than on the danger of ignition from tracer bullets. The break caused by the impact of the bullet afforded useful information on the relative toughness of these materials. Some samples were merely penetrated, leaving a small hole with no radial cracks, while others were completely shattered by the larger caliber bullets. These effects of tracer bullets on transparent plastics are clearly shown in figures 22 to 30. Figures 31 and 32 show the type of break which is obtained when laminated glass made with cellulose-acetate and acrylate-resin plastics, respectively, are penetrated by tracer bullets.

XIV. CONCLUSION

Pending the results of further tests on samples of cellulose acetate, acrylate resin, and other plastics, which have been prepared by the manufacturers using modified compositions and methods of processing to overcome the defective behavior noted during the course of this investigation, it is concluded that the problem of choosing between cellulose-acetate and acrylate-resin plastics for aircraft windows at present, appears to be one of impact-strength requirement. If a relatively high impact strength is necessary, the cellulose-acetate sheets are much superior to the acrylate-resin in this respect. However, if high impact strength is not essential, then the superior clarity and weathering resistance of the acrylate resin makes it the most desirable material. Both the cellulose acetate and the acrylate resin, of course, have the advantages of being lighter in weight than glass and of being readily fitted to curved openings.

National Bureau of Standards,
Washington, D. C., May 12, 1937.

REFERENCE

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LEGENDS

FIGURE 1.- Transparent plastic covering on turret and cockpit of a bomber.

FIGURE 2.- Hazeometer.

FIGURE 3.- Exposure panels after one year out of doors.

FIGURE 4.- Exposure panels after one year out of doors (sample 24 exposed for 9 months only).

FIGURE 5.- Exposure panels after one year out of doors (sample 25 exposed for 9 months only).

FIGURE 6.- Exposure panels after one year out of doors (sample 26 exposed for 9 months only).

FIGURE 7.- Acrylate resin samples after one-year exposure, showing crazing.

FIGURE 8.- Acrylate resin samples after approximately one year in storage, showing crazing.

FIGURE 9.- Exposure panels after 3 months out of doors.

FIGURE 10.- Exposure samples of cellulose acetate and cellulose nitrate after 9 months out of doors.

FIGURE 11.- Condition of samples after exposure to carbon arc light for 1,000 hours with intermittent water spray.

FIGURE 12.- Condition of samples after exposure to carbon arc light for 500 hours without water spray.

FIGURE 13.- Bierbaum scratch-resistance apparatus.
Above: Diamond tool in scratching position.
Below: Diamond tool swung aside and microscope in position to measure scratch width.

FIGURE 14.- Scratches on cellulose acetate plastic (X150).

FIGURE 15.- Vickers hardness testing machine.

FIGURE 16.- Pyramidal indentations on vinyl resin plastic (X70).

FIGURE 17.- Apparatus for determining Charpy impact strength.

FIGURE 18.- Frame used to hold plastics in the falling-ball impact test.

FIGURE 19.- Samples of transparent plastics after bursting-strength tests.

G. Cellulose acetate burst at about 25° C.
H. Cellulose acetate burst when one surface was cooled with ethylene dichloride at -31° C.
I. Acrylate resin burst at about 25° C.
J. Acrylate resin burst when one sample was cooled with ethylene dichloride at -31°.

FIGURE 20.- Samples of laminated glass after bursting-strength tests.

K. Glass bonded with cellulose nitrate plastic.
L. Glass bonded with cellulose acetate plastic.
M. Glass bonded with vinyl resin plastic.
N. Glass bonded with acrylate resin plastic.

FIGURE 21.- Apparatus for determining rate of burning.

FIGURE 22.- Effect of tracer bullets on transparent plastics: Cellulose acetate, A2,0.095" thick; three tracer bullets caliber 30, M1, at 100 yards; one tracer bullet caliber 30, M1, at 600 yards.

FIGURE 23.- Effect of tracer bullets on transparent plastics: Cellulose acetate, C2, 0.095" thick; three tracer bullets caliber 50, M1, at 100 yards.

FIGURE 24.- Effect of tracer bullets on transparent plastics: Cellulose acetate, B3, 0.066" thick; three tracer bullets caliber 50, M1, at 100 yards.

FIGURE 25.- Effect of tracer bullets on transparent plastics: Cellulose nitrate, F1, 0.062" thick; three tracer bullets caliber 30, M1, at 100 yards; two tracer bullets caliber 30, M1, at 600 yards.

FIGURE 26.- Effect of tracer bullets on transparent plastics: Cellulose nitrate, E1, 0.066" thick; three tracer bullets caliber 50, M1, at 100 yards.

FIGURE 27.- Effect of tracer bullets on transparent plastics: Acrylate resin, K1, 0.113" thick; three tracer bullets caliber 30, M1, at 100 yards.

FIGURE 28.- Effect of tracer bullets on transparent plastics: Acrylate resin, K9, 0.067" thick; three tracer bullets caliber 50, M1, at 100 yards.

FIGURE 29.- Effect of tracer bullets on transparent plastics: Vinyl chloride-acetate resin, L3, 0.100" thick; two tracer bullets caliber 30, M1, at 100 yards.

FIGURE 30.- Effect of tracer bullets on transparent plastics: Vinyl chloride-acetate resin, L3, 0.100" thick; two tracer bullets caliber 50, M1, at 100 yards.

FIGURE 31.- Effect of tracer bullets on laminated glass; Plate glass bonded with cellulose acetate plastic, X5, 0.188" thick; two tracer bullets caliber 30, M1, at 100 yards.

FIGURE 32.- Effect of tracer bullets on laminated glass: Plate and sheet glass bonded with acrylate resin plastic, Y5, 0.238" thick; one tracer bullet caliber 50, M1, at 100 yards.

FIGURES 3 to 12. Identification of materials:

1.	Cellulose	acetate	A1
2.	"	"	A2
3.	"	"	A3
4.	"	"	B1
5.	"	"	B2
6.	"	"	B3
7.	"	"	C1
8	"	"	C3
9	"	"	D1
10.	Cellulose	nitrate	E1
11.	"	"	F1

LEGENDS (Cont.)

FIGURES 3 to 12. Identification of materials (Cont.)

12.	Ethylcellulose	G1
13.	"	H1
14.	"	I1
15.	Acrylate resin	J1
16.	"	J2
17.	"	K1
18.	"	K2
19.	Vinyl chloride-acetate resin	L1
20	" " " "	L2
21.	Styrene	R1
22.	Vinyl acetal resin	M1
23.	Cellulose acetobutyrate	S1
24.	Vinyl acetal resin	N1
25.	Acrylate resin	K3
26.	Glyceryl-phthalate resin	O1
27.	Cellulose nitrate	E1
28.	" "	E1
29.	Cellulose acetate	B6
30.	" "	B6
31.	Phenol-formaldehyde resin	U1
32.	Cellulose acetate	B9
33.	" "	B4
34.	" "	B5
35.	Acrylate resin	K5
36.	Glyceryl-phthalate resin	T1

Table I.- Optical properties of transparent plastics

Material	Sample number	Thickness	White light transmission	Haze value	Index of refraction
		mils	percent	percent	$n_D^{21°}$
Cellulose acetate	A1	64	88.8	3.9	1.500
" "	A2	95	85.9	6.1	1.500
" "	A3	133	83.0	7.6	1.501
" "	B1	63	91.4	7.1	1.501
" "	B2	93	90.6	5.1	1.502
" "	B3	64	91.7	4.0	1.500
" "	B4	98	89.1	4.0	1.495
" "	B5	101	88.7	3.9	1.498
" "	C1	56	88.2	6.1	1.500
" "	C3	125	81.8	10.4	1.501
" "	D1	162	77.1	6.7	1.475
Cellulose acetobutyrate	S1	41	92.3	6.0	1.494
Cellulose nitrate	F1	64	85.0	4.1	1.501
" "	E1	67	91.6	3.7	1.501
Ethylcellulose	G1	57	82.1	27.2	1.479
"	H1	29	86.1	9.8	1.472
"	I1	38	91.1	7.0	1.483
Acrylate resin	J1	66	93.6	4.6	1.496
" "	J2	76	93.7	4.2	1.492
" "	K1	117	94.1	1.9	1.496
" "	K2	88	94.2	1.8	1.483
Vinyl chloride-acetate resin	L1	56	82.5	5.3	1.525
" " " "	L2	100	79.2	7.2	1.529
Vinyl acetal resin	M1	62	88.8	5.4	1.509
" " "	N1	126	84.4	11.5	1.490
Glyceryl-phthalate resin	P1	159	86.2	4.8	1.578

Table II.- Optical properties of glass windshield products

Type of glass	Type of plastic lamination	Sample number	Thickness	White light transmission	Haze value
			mils	percent	percent
Thin plate	none	X1	85	86.9[1]	0.9
Thin plate safety	Acetate	X5	186	82.8[1]	1.3
10 oz sheet	none	X2	53	93.2	1.2
10 oz sheet safety	Acetate	X6	130	91.3	1.2
1/4" plate	none	X4	225	91.0	0.9
Micro safety	Acrylate	Y1	107	92.8	1.2
Featherweight safety	Acrylate	Y2	130	92.4	1.2
Plate safety	Acrylate	Y3	248	89.4	1.2
Plate safety	Nitrate	Z1	234	73.7[1]	1.8
Plate safety	Vinyl	Z2	261	71.6[1]	1.4
Sheet safety	Vinyl	Z3	144	92.0	1.6

[1] Blue color added to glass

Table III.- Light transmission and haziness values of transparent cellulose acetate plastics with and without the addition of blue dye

Thickness	Dye	Light transmission		Haziness value
		Sample at photoelectric cell (A)	Sample 18 in. from photoelectric cell (B)	$\left(\frac{A-B}{A}100\right)$
mils		percent	percent	percent
53	Blue	86.3	83.9	2.8
53	Blue	86.2	83.7	2.9
67	None	90.7	87.6	3.4
68	None	91.2	87.5	4.1
65	None	91.0	85.8	5.7
67	None	90.7	85.3	6.0
67	None	90.7	85.2	6.1
85	None	89.7	84.0	6.4
31	Blue	4.2	3.8	9.0
35	Blue	86.7	78.4	9.6
35	Blue	86.7	77.6	10.5
105	Blue	75.0	64.3	14.3
105	Blue	75.1	63.8	15.0

Table IV.- Measurements of distortion of light by transparent plastics

Material	Sample number	Distance where shadow becomes spotty
		inches
Acrylate resin	K4	26
Vinyl chloride-acetate resin	L1	10.7
Cellulose nitrate	F1	6.8
Cellulose acetate	A2	4.7
Vinyl acetal resin	N1	4.2
Cellulose acetate	C2	3.8
" "	B7	2.3
" "	D1	0.3

Table V.- Effect of outside exposure on light transmission

Material	Sample number	Initial	Light transmission 3 months	 6 months	 9 months	 12 months	Remarks on condition at last test period
		percent	percent	percent	percent	percent	
Cellulose acetate	A1	88.2	90.6	83.4	85.5	77.1	Crazed;discolored
" acetate	A2	85.2	88.2	81.7	81.2	71.1	" "
" "	A3	82.2	86.4	84.9	83.5	72.9	" "
" "	B1	90.8	91.6	91.2	91.3	91.3	Surface roughened cracked
" "	B2	89.9	90.7	90.5	90.7	90.7	" " "
" "	B3	90.7	90.7	90.5	90.4	88.8	Crazed
" "	C1	87.1	87.6	88.7	89.2	89.3	Pebbled;crazed at edge
" "	C2	81.1	83.1	83.5	84.7	84.6	" " " "
" "	D1	76.6	87.9	86.7	80.9	57.4	Crazed and cracked
Cellulose acetobutyrate	S1	92.0	92.2	92.2	92.1	92.2	Unchanged
Cellulose nitrate	E1	91.0	84.8	43.2	37.0	35.1	Surface crazed; opaque
" "	F1	83.7	79.1	39.0	34.2	32.2	" " "
Ethylcellulose	G1	79.7	51.8	-	-	-	Opaque;cracked
"	H1	85.3	86.2	-	-	-	Cracked loose from frame at 6 months
"	I1	90.3	89.8	60.2	24.0	-	Opaque;friable
Acrylate resin	J1	92.9	92.7	92.9	92.6	92.3	Roughened; crazed
" "	J2	93.2	93.0	93.1	92.8	92.6	Crazed
" "	K1	93.3	92.7	91.7	91.7	91.4	Slightly discolored
" "	K2	93.2	93.7	93.6	93.5	93.1	Roughened; crazed
" "	K3	93.5	93.5	93.3	92.6		Slight crazing
Vinyl chloride-acetate resin	L1	81.6	77.4	30.0	33.4	36.0	Discolored; crazed
" " "	L2	78.9	70.2	4.1	3.9	4.4	Discolored; opaque
Vinyl acetal resin	M1	88.0	87.1	78.7	57.1	52.3	Crazed;opaque
" " "	N1	84.3	69.4	53.6	43.8		" "
Glyceryl-phthalate resin	O1	85.5	-	82.8	82.4		Slightly discolored

Table VII.- Effect of outside exposure on haziness of transparent plastics

Material	Sample number	Haze Value Initial	 3 months	 6 months	 9 months	 12 months
		percent	percent	percent	percent	percent
Cellulose acetate	A1	4.1	4.7	14.4	24.1	38.5
" "	A2	6.0	6.9	14.5	21.4	30.8
" "	A3	7.7	7.5	11.5	20.6	24.3
" "	B1	6.7	7.5	8.3	8.3	9.3
" "	B2	4.7	5.0	7.2	7.9	7.9
" "	B3	3.6	3.8	5.1	6.4	10.0
" "	C1	6.4	7.5	11.5	10.4	11.3
" "	C2	9.4	9.7	12.2	11.9	12.5
" "	D1	7.2	11.8	16.5	33.0	56.4
Cellulose acetobutyrate	S1	5.4	4.7	4.6	4.6	6.0
Cellulose nitrate	F1	4.2	7.5	84.8	97	98
" "	E1	3.2	7.8	83.8	96	97
Ethylcellulose	G1	26.0	78.8	-	-	-
"	H1	9.0	17.0	-	-	-
"	I1	5.8	7.2	86.3	99	-
Acrylate resin	J1	4.4	4.7	5.3	5.3	5.2
" "	J2	3.5	4.5	4.8	4.7	4.4
" "	K1	2.7	2.8	2.5	3.2	3.7
" "	K2	2.6	3.2	3.4	3.1	3.8
" "	K3	1.3	1.7	2.8	4.0	
Vinyl chloride-acetate resin	L1	6.3	7.2	11.1	18.2	25.9
" " " "	L2	10.6	15.0	38.	55	64
Vinyl acetal resin	M1	3.2	10.3	74	95	96
" " "	N1	8.4	27.8	90	94	
Glyceryl-phthalate resin	O1	7.7	-	9.4	10.0	

Table VI.- Effect of outdoor exposure of transparent plastics on light transmission using various color filters

Material	Sample number	COLOR TRANSMISSION											
		Red Filter[b]				Green Filter[c]				Blue filter[d]			
		Initial	After 3 months	After 6 months	After 1 year	Initial	After 3 months	After 6 months	After 1 year	Initial	After 3 months	After 6 months	After 1 year
		percent	percent	percent	percent	percent	percent	percent	percent	percent	percent	percent	percent
Cellulose acetate	A1	91.2	91.6	84.5	75.1	87.1	89.1	80.6	72.3	88.3	88.0	78.6	71.1
" "	A2	89.1	89.6	83.6	68.9	83.8	85.7	78.4	65.1	85.4	84.8	75.3	64.1
" "	A3	87.5	87.9	87.1	71.7	80.0	83.6	82.0	66.8	83.0	83.1	79.0	65.7
" "	B1	91.3	91.7	91.5	91.7	89.5	90.0	90.2	90.3	89.2	90.3	89.4	90.1
" "	B2	90.8	90.8	90.8	91.1	88.4	89.0	89.4	89.6	87.9	89.3	88.5	89.3
" "	B3	91.6	91.8	91.7	88.8	89.8	89.1	89.0	87.2	89.4	88.2	86.7	86.0
" "	C1	89.3	89.0	89.6	90.2	85.4	85.2	87.2	87.5	86.4	86.4	86.9	88.0
" "	C2	85.4	85.8	86.2	87.7	78.0	78.9	81.3	82.6	80.2	81.5	81.3	83.6
" "	D1	84.4	87.7	86.2	52.6	75.1	85.0	84.1	49.4	80.9	86.1	83.7	50.2
Cellulose acetobutyrate	S1	92.2	92.2	92.4	92.4	91.2	91.0	91.6	91.1	90.9	91.2	91.3	90.9
Cellulose nitrate	E1	91.6	87.0	40.3	29.8	90.0	80.3	31.8	23.3	89.1	76.7	31.5	24.0
" "	F1	83.3	79.9	35.0	25.4	84.7	76.8	29.4	20.9	85.0	73.3	27.2	20.7
Ethylcellulose	G1	82.7	44.2	-	-	74.7	41.7	-	-	72.6	42.4	-	-
"	H1	86.5	86.2	-	-	83.3	83.9	-	-	81.8	83.2	-	-
"	I1	91.2	90.0	57.9	-	89.2	87.7	53.3	-	88.5	87.7	51.6	-
Acrylate resin	J1	92.9	92.5	92.7	92.9	92.2	91.7	92.5	92.3	92.1	91.6	91.6	91.8
" "	J2	93.2	92.8	93.1	93.6	92.5	92.0	92.4	92.7	92.4	92.0	91.8	92.6
" "	K1	93.1	93.0	92.6	93.1	92.7	91.1	90.3	90.5	92.6	90.1	87.9	88.7
" "	K2	94.1	93.4	93.5	93.5	93.0	92.7	92.9	93.0	93.2	92.8	92.8	93.1
" "	K3	93.7	93.3	92.5[a]		93.1	93.0	91.5[a]		93.2	92.2	91.5[a]	
Vinyl chloride-acetate resin	L1	86.5	82.7	52.2	54.3	83.3	72.7	19.8	22.4	84.9	74.7	33.2	37.4
" " " "	L2	85.1	77.4	12.0	13.3	76.9	62.8	6.2	4.4	76.6	65.4	15.2	15.1
Vinyl acetal resin	M1	89.0	87.3	79.2	48.0	86.6	84.7	74.9	40.3	85.8	84.2	73.1	41.2
" " "	N1	85.6	71.8	42.4[a]		81.2	65.3	35.0[a]		79.6	64.1	36.5[a]	
Glyceryl-phthalate resin	O1	87.7	-	87.0[a]		80.2	-	78.5[a]		79.3	-	77.7[a]	

[a] After 9 months

[b] Pyrometer red filter (Corning Glass Works)

[c] No. 61 Wratten filter (Eastman Kodak Company)

[d] No. 47 Wratten filter (Eastman Kodak Company)

Table VIII.- Effect of outdoor exposure on light transmission and haziness of glass windshield products

Type of glass	Type of plastic lamination	Sample number	Thickness	Light transmission		Haze value	
				Initial	After 12 months	Initial	After 12 months
			mils	percent	percent	percent	percent
Thin plate	None	X1	85	86.7	86.8	1.3	1.2
Thin plate safety	Acetate	X5	186	81.6	82.5	1.5	1.7
10 oz sheet safety	Acetate	X6	130	91.2	92.0	1.1	1.3
12 - 14 oz sheet	None	X3	67	93.1	93.1	1.0	1.2
12 - 14 oz sheet safety	Acetate	X7	152	91.2	91.9	1.4	1.3
1/4" plate	None	X4	225	91.2	91.1	0.9	0.8
1/4" tempered plate	None	X8	248	92.5	91.7	1.4	1.1
Micro safety	Acrylate	Y1	107	92.8	92.0	0.9	1.3
Featherweight safety	Acrylate	Y2	130	92.6	92.2	1.4	1.1
Plate safety	Acrylate	Y3	248	89.5	89.2	1.1	0.6
Plate and micro safety	Acrylate	Y4	228	91.3	90.7	1.2	1.0
Plate and sheet safety	Acrylate	Y5	238	89.9	89.3	0.9	1.0
Plate safety	Nitrate	Z1	234	73.3	73.0[a]	1.5	1.4[a]
Plate safety	Vinyl	Z2	261	71.4	71.2[a]	1.5	1.7[a]
Sheet safety	Vinyl	Z3	144	91.8	91.5[a]	1.6	1.4[a]

[a] After 9 months exposure

Table IX.- Accelerated aging of transparent plastics by carbon arc light with intermittent water spray

Material	Sample number	White Light Transmission			Remarks on condition after 1000 hours
		Initial	500 hr	1000 hr	
		percent	percent	percent	
Cellulose acetate	A1	88.2	90.2	89.2	Warped, cracked and slightly clouded
" "	B1	91.3	92.3	91.7	Surface roughened
" "	B3	91.4	92.6	91.8	Warped, and slightly clouded
" "	C1	87.9	89.0	89.6	Warped
" "	C3	81.7	84.6	84.8	Slightly warped
" "	D1	76.8	82.5	86.0	Cracked and bleached
Cellulose acetobutyrate	S1	92.2	92.2	92.2	Slightly warped
Cellulose nitrate	E1	91.2	91.5	87.6	Warped, discolored and slight crazing
" "	F1	84.7	86.0	86.7	Discolored
Ethylcellulose	G1	82.3	81.3	-	Opaque at 800 hr; friable
"	H1	85.0	85.0	85.0	Warped, and cloudy
"	I1	91.3	89.6	78.3	Warped; surface frosty
Acrylate resin	J1	93.3	93.4	93.3	Surface pitted
" "	J2	93.4	93.3	92.7	No marked change
" "	K1	93.6	93.1	92.5	No marked change
" "	K2	94.0	93.9	93.3	No marked change
Vinyl chloride-acetate resin	L1	82.4	82.7	17.1	Discolored purple
" " "	L2	79.2	59.2	0.7	Discolored purple; opaque
Vinyl acetal resin	M1	89.0	88.3[a]	-[b]	Warped and cloudy
Styrene	R1	74.7	72.8	59.8	Darkened and cracked

[a] 163 hr

[b] Too warped to measure

Table XXVII.- Rate of burning of transparent plastics

Material	Sample number	Rate of burning of test strips 3/4" x 3"			Rate of burning of test strips 1 1/4" x 3"		
		Horizontal strip ignited at one end	Vertical strip ignited at bottom	Vertical strip ignited at top	Horizontal strip ignited at one end	Vertical strip ignited at bottom	Vertical strip ignited at top
		in./min	in./min	in./min	in./min	in./min	in./min
Cellulose acetate	C1	0.93	a	a	a	1.86	a
" "	C3	0.35	a	a	-	-	-
Cellulose nitrate	E1	3.75	9.75	2.22	4.28	9.90	2.12
" "	F1	3.96	8.55	2.12	5.00	10.30	2.08
Ethylcellulose	G1	1.24	2.81	0.75	2.10	3.00	1.25
Acrylate resin	J1	0.41	0.94	0.31	0.52	0.84	0.31
" "	J2	0.28	0.61	0.20	0.51	0.62	0.23
" "	K1	0.21	0.30	0.16	0.31	0.53	0.18
Vinyl acetal resin	M1	0.53	0.88	0.29	0.83	1.41	0.38
Styrene resin	R1	0.54	0.58	0.41	-	-	-

[a] Extinguished before burning 3 inches

Table X.- Accelerated aging of transparent plastics by carbon arc light without water spray

Material	Sample number	White light Transmission		Haze value		Remarks on condition at 500 hr
		Initial	500 hr	Initial	500 hr	
		percent	percent	percent	percent	
Cellulose acetate	A1	89.2	90.8	3.8	4.4	Surface slightly roughened
" "	B1	91.5	91.8	7.4	8.4	No marked change
" "	B3	91.7	91.9	3.6	4.0	Surface slightly roughened
" "	B4	89.1	87.6	4.5	5.5	Surface slightly roughened
" "	B5	88.3	87.0	4.4	5.0	do; discolored yellow
" "	B6	91.3	91.8	3.2	4.0	Surface slightly roughened
" "	B8	90.6	90.8	3.8	4.1	Surface slightly roughened
" "	C1	88.5	90.2	6.0	6.0	Surface slightly roughened
" "	C3	82.3	84.3	10.0	10.0	Surface slightly roughened
" "	D1	77.4	86.6	7.0	9.3	Blue dye faded; cracked
Cellulose acetobutyrate	S1	92.8	91.8	5.5	4.1	Warped; no marked change
Cellulose nitrate	E1	91.7	81.4	3.8	6.9	Discolored brown; cracked
" "	F1	85.2	73.2	3.6	4.1	Discolored brown;
Ethylcellulose	G1	82.7	83.1	26.6	29.6	Cracked badly and discolored
"	H1	85.6	84.4	9.9	10.2	No marked change
"	I1	91.4	90.6	6.1	a	Cracked badly and became friable
Acrylate resin	J1	93.7	93.7	6.1[b]	10.6[b]	Surface badly pebbled
" "	J2	93.7	93.3	6.1[b]	4.7[b]	No marked change
" "	K1	94.0	93.1	3.6	3.5	Slightly yellowed
" "	K2	94.4	94.3	1.4	1.9	No marked change
" "	K5	94.2	93.8	1.6	1.4	No marked change
Vinyl chloride-acetate resin	L1	82.6	ca. 0	5.0	–	Opaque; discolored purple
" " " "	L2	80.3	ca. 0	8.7	–	Opaque; discolored purple
Vinyl acetal resin	M1	88.7	85.5	3.9	7.8	Discolored yellow
" " "	N1	85.6	83.0	9.5	10.8	Surface roughened; discolored yellow
Glyceryl-phthalate resin	O1	85.8	81.0	5.2	5.8	Discolored brown
" " "	T1	66.2	65.0	c	c	Discolored yellow

[a] Specimen broke before these values could be determined

[b] Specimen slightly prismatic, making haze measurement doubtful

[c] Surfaces of specimen unpolished

Table XI.- Effect of accelerated aging of transparent plastics by carbon arc light without water spray on light transmission using various color filters

Material	Sample number	Color transmission					
		Red Filter[b]		Green Filter[c]		Blue Filter[d]	
		Initial	500 hr	Initial	500 hr	Initial	500 hr
		percent	percent	percent	percent	percent	percent
Cellulose acetate	A1	91.3	91.6	87.3	89.5	89.4	90.6
" "	B1	91.7	92.1	89.3	90.5	89.8	91.2
" "	B3	92.3	92.2	90.2	90.8	90.0	91.4
" "	B4	89.1	88.8	86.2	85.7	86.2	86.6
" "	B5	89.6	88.7	87.0	84.7	87.4	85.6
" "	B6	92.1	92.1	89.8	90.6	89.6	91.4
" "	B8	91.1	91.3	91.4	89.2	89.0	90.2
" "	C1	90.6	91.2	86.3	88.5	87.8	89.6
" "	C3	86.7	87.5	78.7	81.3	81.8	84.4
" "	D1	84.9	88.2	75.7	84.0	82.6	84.6
Cellulose acetobutyrate	S1	92.8	91.8	91.2	90.7	91.4	90.6
Cellulose nitrate	E1	92.0	90.7	89.8	74.2	89.4	72.0
" "	F1	83.8	82.8	84.9	66.7	85.8	65.6
Ethylcellulose	G1	86.1	86.2	78.2	80.3	76.6	80.8
"	H1	86.7	86.0	82.7	82.6	81.6	82.4
"	I1	92.2	a	89.7	a	89.6	a
Acrylate resin	J1	93.3	92.9	92.3	92.7	92.8	92.8
" "	J2	93.5	93.2	92.4	92.3	92.4	92.4
" "	K1	93.2	93.3	92.6	91.7	92.6	91.4
" "	K2	93.9	93.7	93.0	93.4	93.4	93.4
" "	K5	93.7	93.3	93.0	92.7	93.2	92.6
Vinyl chloride-acetate resin	L1	87.5	ca. 0	83.8	ca.0	87.2	ca. 0
" " " "	L2	86.3	ca. 0	77.3	ca.0	79.2	ca. 0
Vinyl acetal resin	M1	89.3	88.3	86.2	82.3	85.6	80.4
" " "	N1	86.8	85.7	82.4	80.3	81.4	78.6
Glyceryl-phthalate resin	O1	88.5	86.6	81.2	74.8	80.6	76.4
" " "	T1	69.3	70.3	57.2	58.8	62.4	63.0

a Specimen broke before these values could be determined

b Pyrometer red filter. c No. 61 Wratten filter. d No. 47 Wratten filter.

Table XII.- Scratch hardness of transparent plastics measured with the Bierbaum Microcharacter

Material	Sample number	Thickness	Scratch Hardness		Average
			Scratches ruled parallel to length of sample	Scratches ruled perpendicular to length of sample	
		mils	kg/sq mm	kg/sq mm	kg/sq mm
Cellulose acetate	A1	62	9.9	9.9	9.9
" "	A2	90	11.9	11.8	11.9
" "	A3	125	11.1	9.2	10.2
" "	B1	60	8.3	8.1	8.2
" "	B3	60	8.2	8.1	8.2
" "	B4	100	9.3	9.2	9.3
" "	B5	100	5.6	6.9	6.3
" "	B6	60	7.3	7.9	7.6
" "	C1	60	7.6	7.1	7.4
" "	C2	90	8.1	7.0	7.6
" "	C3	125	7.7	7.3	7.5
" "	D1	150	5.7	5.0	5.4
Cellulose acetobutyrate	S1	40	4.5	4.5	4.5
Cellulose nitrate	E1	60	10.0	9.9	10.0
" "	F1	62	10.3	9.9	10.1
Ethylcellulose	G1	60	5.6	5.5	5.6
"	H1	30	6.3	6.2	6.3
"	I1	40	4.0	4.5	4.3
Acrylate resin	J1	70	15.0	15.0	15.0
" "	J2	65	18.4	18.1	18.3
" "	K1	120	15.1	14.9	15.0
" "	K5	120	16.8	16.4	16.6
Vinyl chloride-acetate resin	L1	50	10.3	10.1	10.2
" " " "	L2	100	9.8	9.6	9.7
" " " "	L3	100	10.7	10.6	10.7
Vinyl acetal resin	N1	100	7.0	7.0	7.0
Glyceryl-phthalate resin	O1	125	14.0	-	14.0
Styrene	R1	80	10.6	10.4	10.5

Table XIII.- Hardness of transparent plastics as measured by various instruments

Material	Sample	Thickness	Shore scleroscope number[a]	Vickers number[b]	Rockwell number[c] (15-T scale)	Brinell number[d] (30 sec)	Brinell number[e] (3 min)
		mils		kg/sq mm		kg/sq mm	kg/sq mm
Cellulose acetate	A1	62	57	8.7	15.1	13.0	12.4
" "	B1	60	58	11.0	16.2	13.1	12.6
" "	B2	90	61	8.4	16.0	13.9	12.3
" "	C1	60	53	7.0	9.9	11.5	11.4
" "	C3	125	54	6.2	11.2	10.9	11.0
Cellulose nitrate	E1	60	63	12.7	29.7	16.6	15.8
" "	F1	62	60	11.7	23.2	15.8	15.0
Ethylcellulose	G1	60	50	6.3	7.7	10.6	10.6
Acrylate resin	J1	70	73	18.4	39.5	17.5	14.7
" "	J2	65	84	24.0	81.6	27.4	20.9
" "	K1	120	75	15.0	31.5	16.0	14.5
Vinyl chloride-acetate resin	L1	50	62	16.2	32.7	16.4	14.0
Vinyl acetal resin	M1	63	45	3.0	f	f	f
Styrene resin	R1	80	65	20.0	65.0	20.0	16.4
Phenol-formaldehyde resin	U1	125	80	12.6	15.5	15.8	15.3
Plate glass	X1	85	121	-	-	-	-
Mild steel	-	1000	25	159[g]	-	159[h]	-

[a] Rebound, measured on an arbitrary scale of 140, of a hammer with spherical diamond striking point falling freely from a height of approximately 3/4 inch. Model D instrument.

[b] 5 kg load applied on a diamond pyramid for 7 seconds.

[c] 15 kg load applied on ball of 1/16 inch diameter for 30 seconds. Rockwell Superficial Hardness Tester.

[d] 15 kg load applied on ball of 1/16 inch diameter for 30 seconds. (usual Brinell time)

[e] 15 kg load applied on ball of 1/16 inch diameter for 3 minutes.

[f] Too soft to measure.

[g] 50 kg load.

[h] 3,000 kg load on ball of 10 mm diameter.

Table XIV.- Variation of Vickers hardness with time of loading

Material	Sample number	5 kg load applied for 10 seconds	inches 5 kg load applied for 30 seconds	inches 5 kg load applied for 90 seconds
		kg/sq mm	kg/sq mm	kg/sq mm
Cellulose acetate	A1	6.3	5.8	5.9
" "	B1	7.2	6.7	6.7
" "	B2	6.8	6.3	6.3
" "	C1	5.6	5.2	4.8
" "	C3	5.2	4.6	4.2
Cellulose nitrate	E1	11.7	11.2	10.5
" "	F1	10.5	10.4	9.3
Ethylcellulose	G1	5.2	4.9	4.8
Acrylate resin	J1	14.0	12.1	11.2
" "	J2	18.9	17.2	15.4
" "	K1	14.1	12.7	11.3
Vinyl chloride-acetate resin	L1	14.9	14.7	13.4
Styrene	R1	20.1	18.7	16.6
Phenol-formaldehyde	U1	13.0	11.3	9.3

Table XVI.- Charpy and dropped ball impact tests on transparent plastics

Material	Sample	Thickness	Charpy impact strength (Notched)		Ball impact strength	
			70°F	25° F	Ball Height	Average No. of balls required for failure
		mils	ft lb/in of notch	ft lb/in of notch	ft	
Cellulose acetate	A1	65	2.8	0.51	65	2.5
" "	A2	96	3.2	0.37	50	7
" "	A3	135	2.1	0.25	50	9
" "	B2	94	1.9	0.33	65	6
" "	B4	98	3.0	1.51	65	2.5
" "	B5	100	3.6	1.33	65	10
" "	B6	67	2.7	0.89	65	1
" "	B7	95	2.4	1.16	65	6
" "	B9	92	2.3	0.29	65	5
" "	C1	57	2.8	1.02	65	3
" "	C3	125	2.4	0.84	65	9
" "	D1	165	2.3	0.30	50	6
Cellulose nitrate	E1	66	3.8	2.13	65	4
" "	F1	63	4.4	2.60	65	4.5
Ethylcellulose	G1	59	3.1	2.49	-	-
Acrylate resin	K1	117	0.46	0.33	3	2
" "	K4	88	0.45	0.26	-	-
" "	K7	222	0.44	0.37	10	2
" "	K8	218	0.40	0.36	10	3
Vinyl chloride-acetate resin	L3	102	0.4	0.15	8	2
Vinyl acetal resin	N1	122	2.9	0.65	65	11.5

Table XV.- Vickers indentation hardness numbers of various transparent plastics (Samples conditioned at 21° C and 65% relative humidity; 5 kg load applied for 10 seconds)

Material	Sample number	Thickness	Vickers number
		mils	kg/sq mm
Cellulose acetate	A1	62	6.9
" "	A2	90	7.7
" "	A3	125	7.1
" "	B1	60	7.9
" "	B2	90	6.6
" "	B3	60	6.8
" "	B4	60	7.0
" "	B5	60	4.3
" "	B6	60	6.2
" "	B9	60	6.6
" "	C1	60	5.6
" "	C2	90	5.5
" "	C3	125	5.2
" "	D1	150	7.0
Cellulose acetobutyrate	S1	40	4.8
Cellulose nitrate	E1	60	11.6
" "	F1	62	10.5
Ethylcellulose	G1	60	5.6
"	H1	30	8.0
"	I1	40	4.6
Acrylate resin	J1	70	15.4
" "	J2	65	19.2
" "	K1	120	13.6
" "	K6	120	16.7
Vinyl chloride-acetate resin	L1	50	15.3
" " " "	L2	100	15.0
" " " "	L3	100	15.0
Vinyl acetal resin	M1	63	ca. 0.5
" " "	N1	100	11.0
Glyceryl-phthalate resin	O1	125	27.1
Styrene resin	R1	80	19.8
Phenol-formaldehyde resin	U1	125	13.0

Table XVII.- Accelerated shrinkage tests at 70° C of transparent plastic

Material	Sample number	Thickness	Decrease in length			
			4 days	2 weeks	1 month	2 months
		mils	%	%	%	%
Cellulose acetate	A3	133	0.9	1.0	1.3	2.2
" "	A1	64	1.2	1.5	1.6	3.4
" "	A2	95	1.0	1.1	1.5	b
" "	B2	93	1.0	1.1	1.3	2.0
" "	B3	64	1.3[a]	2.1	-	-
" "	B4	96	1.1	1.5	1.8	1.7
" "	B5	100	2.0	3.5	4.2	4.8
" "	B6	66	1.7	2.0	2.5	3.1
" "	B9	89	1.4	1.8	2.2	2.3
" "	B10	63	1.1	1.6	2.2	2.4
" "	B11	64	1.0	1.6	2.2	2.5
" "	B12	61	0.8	1.1	1.2	1.2
" "	C3	125	0.9	1.0	1.3	1.9
" "	D1	169	1.1	1.4	1.5	2.3
Cellulose acetobutyrate	S1	41	2.5	3.1	3.5	4.0
Cellulose nitrate	E1	67	0.4	0.4	0.6	1.1
" "	F1	64	0.5	0.5	0.7	0.9
Ethylcellulose	G1	53	1.2	1.5	1.9	2.4
"	H1	29	0.4	0.5	-	-
"	I1	38	0.5	0.6	0.8	3.5
Acrylate resin	J1	66	2.2	b	b	b
" "	J2	76	0.2	0.2	0.2	0.7
" "	K1	124	2.0	2.0	2.0	-
" "	K2	88	1.8	1.8	1.8	2.0
" "	K3	71	1.5	1.6	1.7	1.7
" "	K5	118	0.2	0.3	0.3	-
" "	K9	60	1.9[a]	1.9	-	-
Vinyl chloride-acetate resin	L1	64	4.2	4.3	4.6	8.2
Vinyl acetal resin	M1	63	0.2	0.8	1.0	1.5
" " "	N1	127	0.4[c]	0.6[c]	0.6[c]	0.9[c]
Glyceryl-phthalate resin	O1	162	0.1	0.1	0.1	0.1
" " "	T1	290	0.7	0.7	0.7	0.7
Phenol-formaldehyde resin	U1	170	1.0	1.4	1.6	1.9

[a] 3 days

[b] Warped

[c] Increase in length

Table XVIII.- Outdoor shrinkage tests of transparent plastics

Material	Sample number	Decrease in length				
		1 month	2 months	3 months	6 months	9 months
		%	%	%	%	%
Cellulose acetate	A1	1.3	1.8	2.5	2.7	3.1
" "	A2	0.5	0.6	1.1	1.1	1.4
" "	A3	0.4	0.6	0.9	1.0	1.1
" "	B2	0.4	0.4	0.6	0.6	0.7
" "	B3	0.8	1.2	1.6	1.8	2.1
" "	C3	0.5	0.7	1.1	1.2	1.3
" "	D1	0.6	0.9	1.4	1.4	1.6
Cellulose acetobutyrate	S1	0.5	0.7	0.9	1.0	1.0
Cellulose nitrate	E1	0.2	0.3	0.4	0.4	0.4
" "	F1	0.2	0.3	0.4	0.4	0.5
Ethylcellulose	G1	0.6	1.1	1.5	a	a
"	H1	1.0	1.5	2.0	a	a
"	I1	0.8	1.1	1.4	1.8	a
Acrylate resin	J1	0.05	0.1	0.1	0.1	0.1
" "	J2	0.0	0.0	0.0	0.0	0.0
" "	K1	0.0	0.2	0.2	0.2	0.2
" "	K2	0.06	-	-	0.1	0.1
" "	K6	0.0	-	0.0	0.05	
" "	K9	0.04	0.1	0.2	0.2	0.2
Vinyl chloride-acetate resin	L1	0.0	0.0	0.0	0.0	0.03
Vinyl acetal resin	N1	0.4	a	a	a	a
Glyceryl-phthalate resin	O1	0.0	-	-	0.1[b]	0.1[b]
" " "	T1	0.0	0.0	0.0	0.1	0.1
Phenol-formaldehyde resin	U1	0.8	1.0	1.2	1.4	1.5

[a] Gauge lines obliterated by deterioration of sample

[b] Increase in length

Table XIX.- Effect of heating cellulosic plastics at 100° C on impact strength and shrinkage

Material	Sample number	Thickness	Charpy impact strength on notched specimen			Shrinkage	
			Original	After 4 hours at 100° C	After 24 hours at 100° C	After 4 hours at 100° C	After 24 hours at 100° C
		mils	ft lb/in. of notch	ft lb/in. of notch	ft lb/in. of notch	percent	percent
Cellulose acetate	C5	92	1.9	1.8	1.4	2.0	3.3
Cellulose nitrate	W1	93	3.6	1.8	1.8	1.6	2.0

Table XX.- Water absorption by transparent plastics at 70° F

Material	Sample number	Thickness	Gain in weight			Remarks
			After 2 hr	After 24 hr	After 7 days	
		mils	percent	percent	percent	
Cellulose acetate	A1	66	0.63	2.39	3.25	
" "	B1	64	0.59	2.02	2.40	
" "	B3	62	0.52	1.82	2.19	
" "	C1	58	0.68	2.10	2.08	
" "	D1	165	-	-	3.34	
" "	C3	126	0.38	1.32	-	
Cellulose nitrate	E1	66	0.19	0.73	1.23	
" "	F1	63	0.25	0.88	1.33	
Cellulose acetobutyrate	S1	36	0.43	0.85	0.76	
Ethylcellulose	G1	58	0.56	1.91	2.91	Cloudy at 48 hr
"	H1	29	3.25	8.71	9.32	
"	I1	35	2.50	3.21	3.61	Slightly cloudy at 48 hr
Acrylate resin	J1	79	0.05	0.21	0.51	
" "	J2	70	0.06	0.29	0.79	
" "	K1	116	0.04	0.14	0.43	
" "	K2	88	0.07	0.27	0.40	
Vinyl chloride-acetate resin	L1	57	0.02	0.05	0.07	
" " " "	L2	100	0.01	0.03	0.04	
Vinyl acetal resin	M1	61	0.59	2.45	5.70	Cloudy after 2 hr

Table XXI.- Absorption of ethyl alcohol (95%) by transparent plastics at 70° F

Material	Sample number	Gain in weight			Remarks
		After 2 hr	After 24 hr	After 7 days	
		percent	percent	percent	
Cellulose acetate	A1	4.08	15.72	10.68	Surface rippled. Slightly cloudy
" "	B1	2.41	10.72	6.64	" " " "
" "	B3	2.95	12.57	7.34	" " " "
" "	C1	3.13	11.14	4.85	" " " "
" "	C3	1.49	6.58	7.91	" " " "
" "	D1	1.52	6.84	14.99	Quite cloudy
Cellulose nitrate	E1	3.21	36.5	-	Surface roughened in 2 hr; swollen after 1 week
" "	F1	4.98	-	-	Surface roughened in 2 hr; swollen after 24 hr
Cellulose acetobutyrate	S1	6.43	6.02	3.79	No effect on appearance
Ethylcellulose	G1				Dissolves
"	H1				"
"	I1				"
Acrylate resin	J1	0.22	8.51	16.49	Surface pitted
" "	J2	-0.02	9.67	9.65	" roughened
" "	K1	0.00	3.23	20.92	" " after 2 hr; smooth at 1 wk
" "	K2	10.15	80.90		Softened in 2 hr; swollen after 1 wk
Vinyl chloride-acetate resin	L1	-0.01	-0.03	0.00	No attack
" " " "	L2	-0.01	-0.01	0.04	" "
Vinyl acetal resin	M1	5.70	18.16	11.79	Milk-white and opaque at one week

Table XXII.- Kerosene absorption by transparent plastics at 70° F

Material	Sample number	Gain in weight After 2 hr	Gain in weight After 24 hr	Gain in weight After 7 days
		percent	percent	percent
Cellulose acetate	A1	-0.12	-0.22	-0.38
" "	B1	0.01	-0.03	-0.14
" "	B3	-0.06	-0.10	-0.22
" "	C1	-0.14	-9.31	-0.59
" "	C3	-0.08	-0.17	-0.36
" "	D1	-0.04	-0.11	-0.23
Cellulose acetobutyrate	S1	-0.14	-0.22	-0.44
Cellulose nitrate	E1	0.00	-0.03	-0.06
" "	F1	-0.01	0.00	-0.04
Acrylate resin	J1	0.00	-0.01	-0.05
" "	J2	0.01	0.01	-0.09
" "	K1	-0.02	-0.04	-0.09
" "	K2	0.01	0.01	0.01
Vinyl chloride-acetate resin	L1	0.00	0.02	-0.02
" " " "	L2	-0.03	-0.04	-0.06
Ethylcellulose	G1	0.09	0.67	2.00
"	H1	0.42	1.82	5.04
"	I1	3.82	15.24	20.12
Vinyl acetal resin	M1	0.00	-0.03	-0.08

Table XXIII.- Bursting tests on transparent plastics

Material	Sample number	Thickness	Maximum pressure	Type of failure
		mils	lb/ sq in	
A. Without rubber gaskets				
Cellulose acetate	B2	93	295	Shear
" "	B3	65	200	Lateral tension
" "	C1	57	165	Shear at edge
" "	C3	125	400	Lateral tension
Cellulose nitrate	W1	93	375	Shear
Acrylate resin	K10	98	46	Shear
Vinyl acetal resin	N1	49	100	Pinhole developed between center and edge
" " "	N1	49	115	Shear
B. With rubber gaskets				
Cellulose acetate	C1	56	190	Lateral tension
" "	C3	125	430	Lateral tension
" "	B2	93	340	Shear at edge (slipped in grips)
Cellulose nitrate	W1	93	380	Lateral tension
Acrylate resin	K10	97	44	Shear in grips

Table XXIV.- Calculated maximum tensile and shear stress for bursting tests on transparent plastics

Material	Sample number	Maximum tensile stress	Maximum shear stress	d	p	Failure
		lb/sq in.	lb/sq in.	inch	lb/sq in.	
Cellulose acetate	C1	4000	3600	1.14	165	Shear
" "	C3	3600	4000	1.4	400	Tension
Cellulose nitrate	W1	5000	5000	1.25	375	Shear
Acrylate resin	K10	---	590	--	46	Shear

Table XXV.- Bursting strength of laminated and plate glass

Type of glass	Type of plastic lamination	Sample number	Thickness	Bursting strength
			mils	lb/sq in
Micro safety	Acrylate	Y1	106	12
Sheet safety	Vinyl	Z3	117	19
Plate safety	Cellulose nitrate	Z1	196	33
Sheet safety	Cellulose acetate	X6	129	32
Thin plate	None	X1	83	12
1/4" plate	None	X4	225	60

Table XXVI.– Flammability tests on transparent plastics

(Table XXVII with tables VIII, XIX)

Material	Sample	Thickness	VERTICAL TEST					HORIZONTAL TEST		
			Self-extinguishing materials		Non-extinguishing materials			Self-extinguishing materials		Non-extinguishing materials
			Burning time of sample	Burning time of sample and drippings	Time at which sample was enveloped in flames	Time at which sample fell off hook	Total burning time of sample	Burning time of sample	Length of sample burned	Time for burning 3 inches of sample
		mils	sec	sec	sec	sec	sec	sec	inch	sec
Cellulose acetate	A1	64	13 11					18 11	0.6	
" "	A2	94	12 12					12 11	0.4	
" "	A3	131	12 11					23 14	0.4	
" "	B1	63	16 16					24 13	0.5 0.5	
" "	B2	94	23 24					38 11		
" "	B3	65	19 16	49				24 16	0.6	
" "	B5	100			45 41	65 57	120 77			237 196
" "	B13	123	40 33					41 11	1.0	
" "	C1	54	18 26	41				23 75	0.7 1.8	
Cellulose acetate	C2	94	30 28	48				89	1.2	217
" "	C3	124	51 40	111 84				49 147	1.0 2.1	
" "	D1	150			80	79 82	229 169			171 199
Cellulose acetobutyrate " "	S1	40	11 14	41				17 18	0.8	
Cellulose nitrate " "	E1	66			5	7				8 10
" "	F1	63			4	7 8				10 12
	W1	94			4	10 11				13 11
Ethylcellulose "	G1	58			36	39 45	49 50			60 75
"	H1	31			45	40 51				49
Acrylate resin	J2	80			36	49 54	349 319			86 118
" "	J3	135			42	63 68	303 373			104 109
" "	K1	99			35	95 63	305 250			117 117
Acrylate resin	K2	88			35	63 59	223 276			120 93
" "	K3	61			28	81 51	151 142			92 96
" "	K6	113			47	112 81	292 237			174 140
Vinyl chloride-acetate resin	L2	98	Would not ignite " " "					Would not ignite " " "		
Vinyl acetal resin	N1	119			78	64 90	136 157			118 108
" " "	N2	52			55	44 68	51 78			80 77
Glyceryl-phthalate resin	O1	161			160	270 230	430 423			441 282
Phenol-formaldehyde resin	V1	260	Would not ignite					Would not ignite		

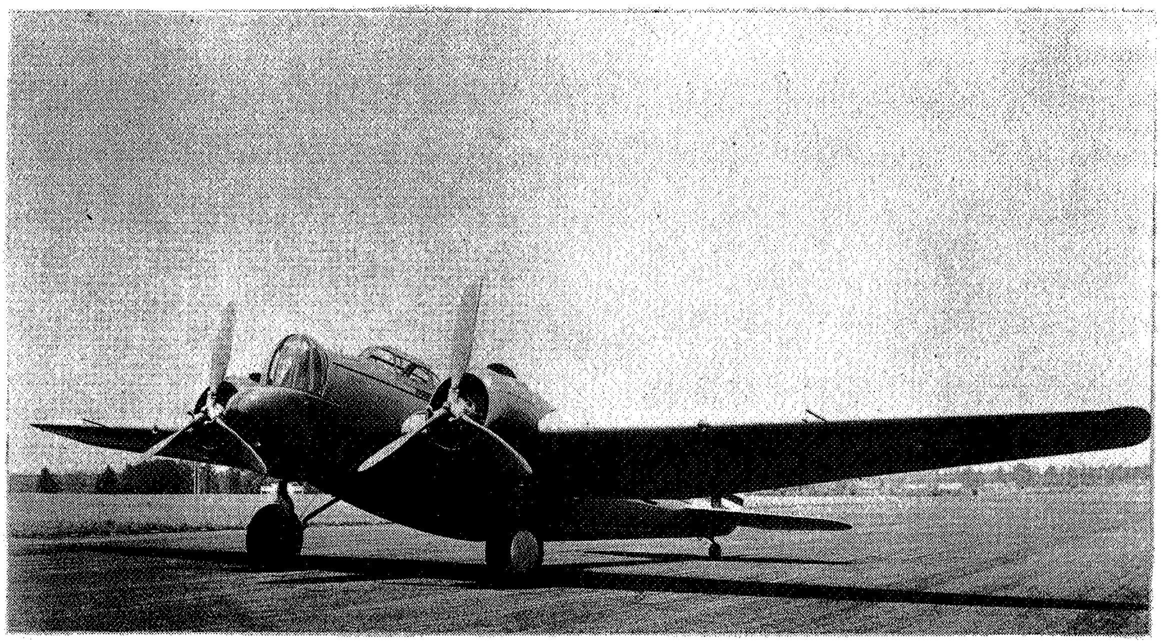


Figure 1. Transparent plastic covering on turret and cockpit of a bomber.

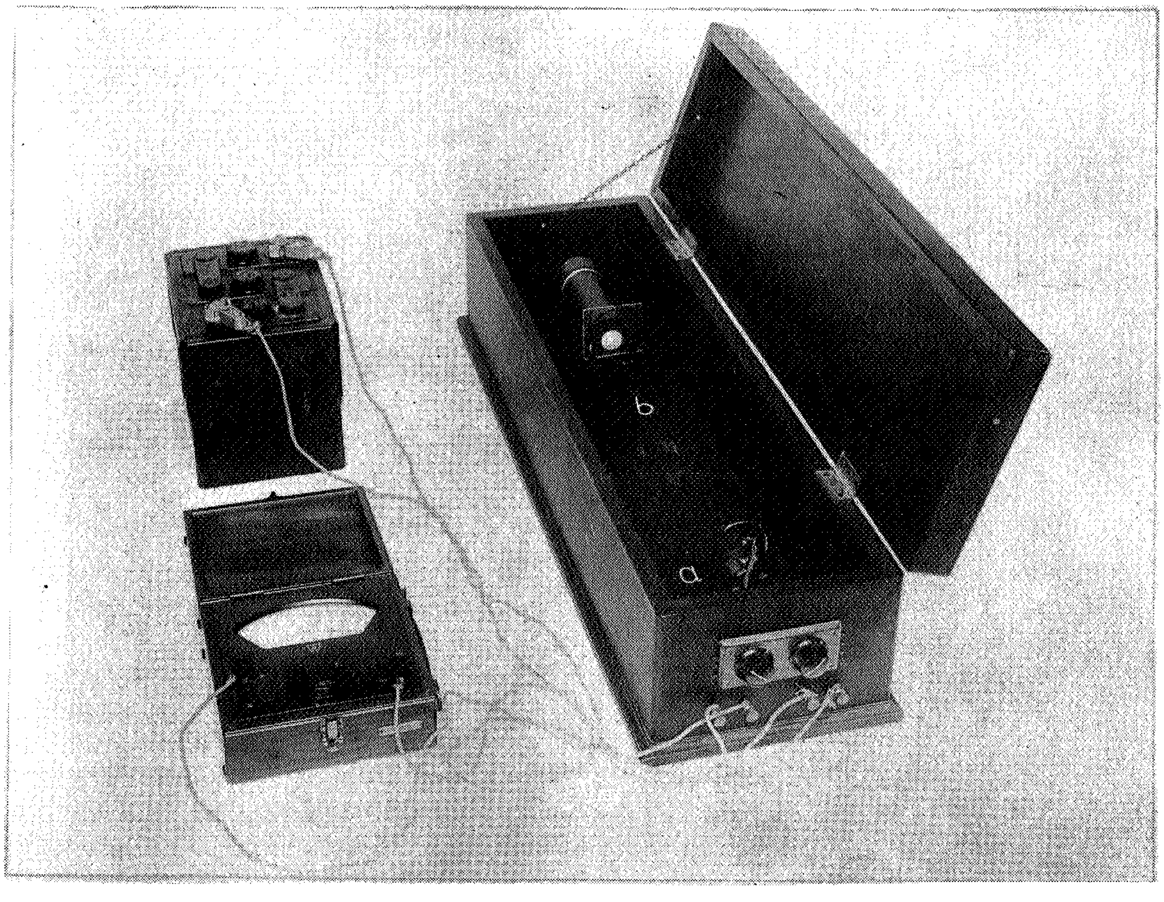


Figure 2. Hazeometer.

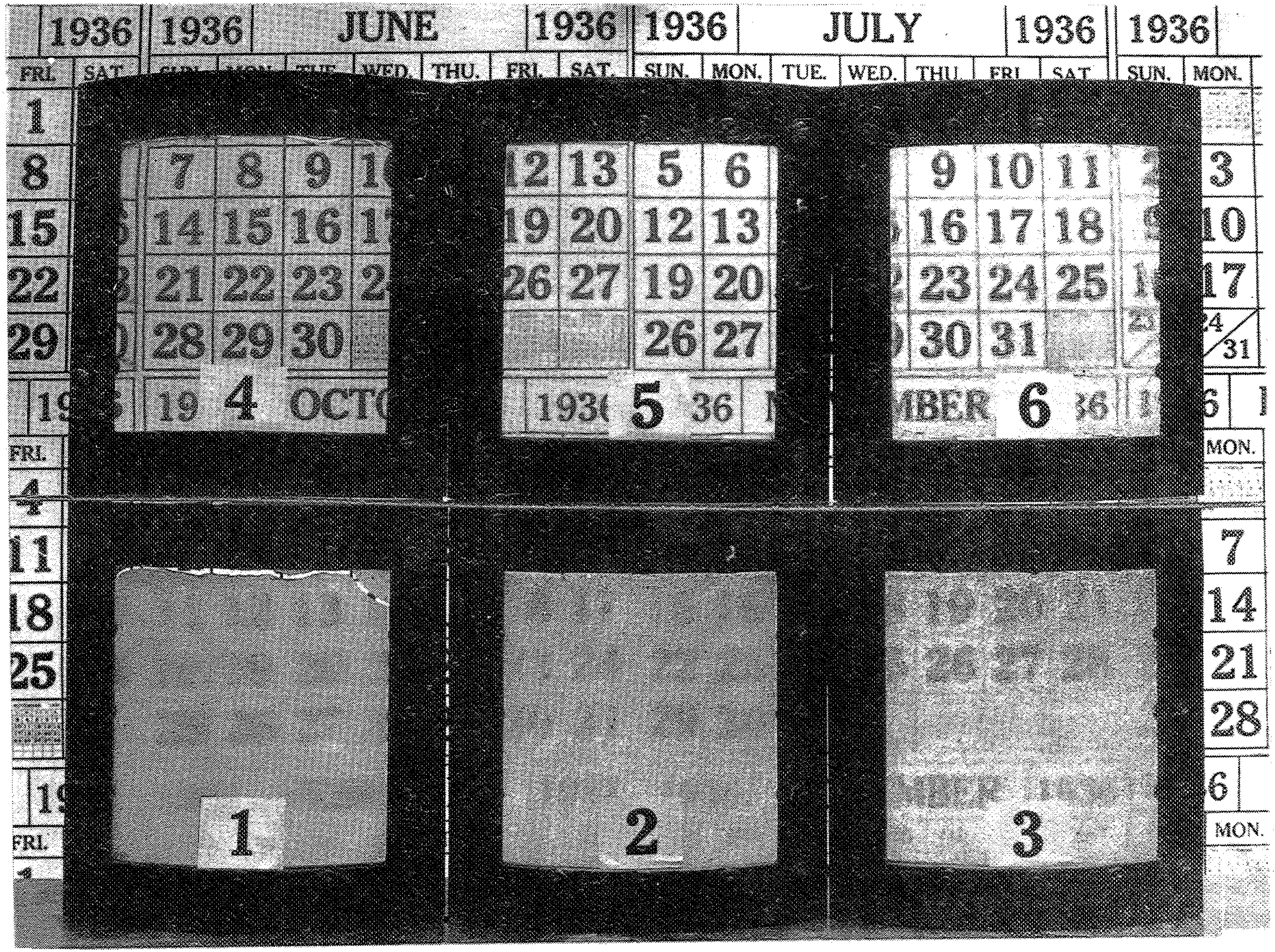


Figure 3.- Exposure panels after one year out-of-doors.

Fig. 4

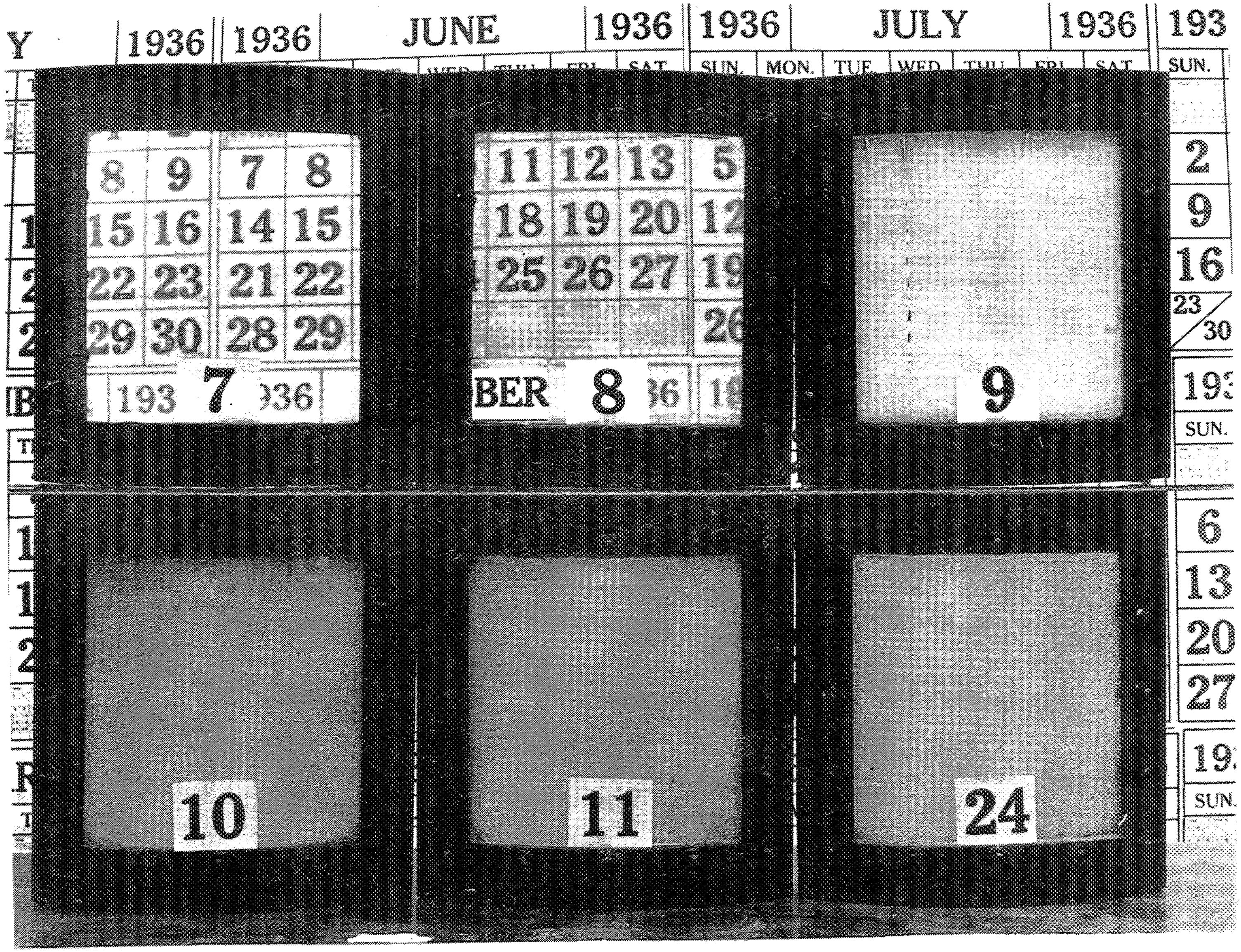


Figure 4.- Exposure panels after one year out-of-doors (sample 24 exposed for nine months only).

Figure 5.- Exposure panels after one year out-of-doors (sample 25 exposed for nine months only).

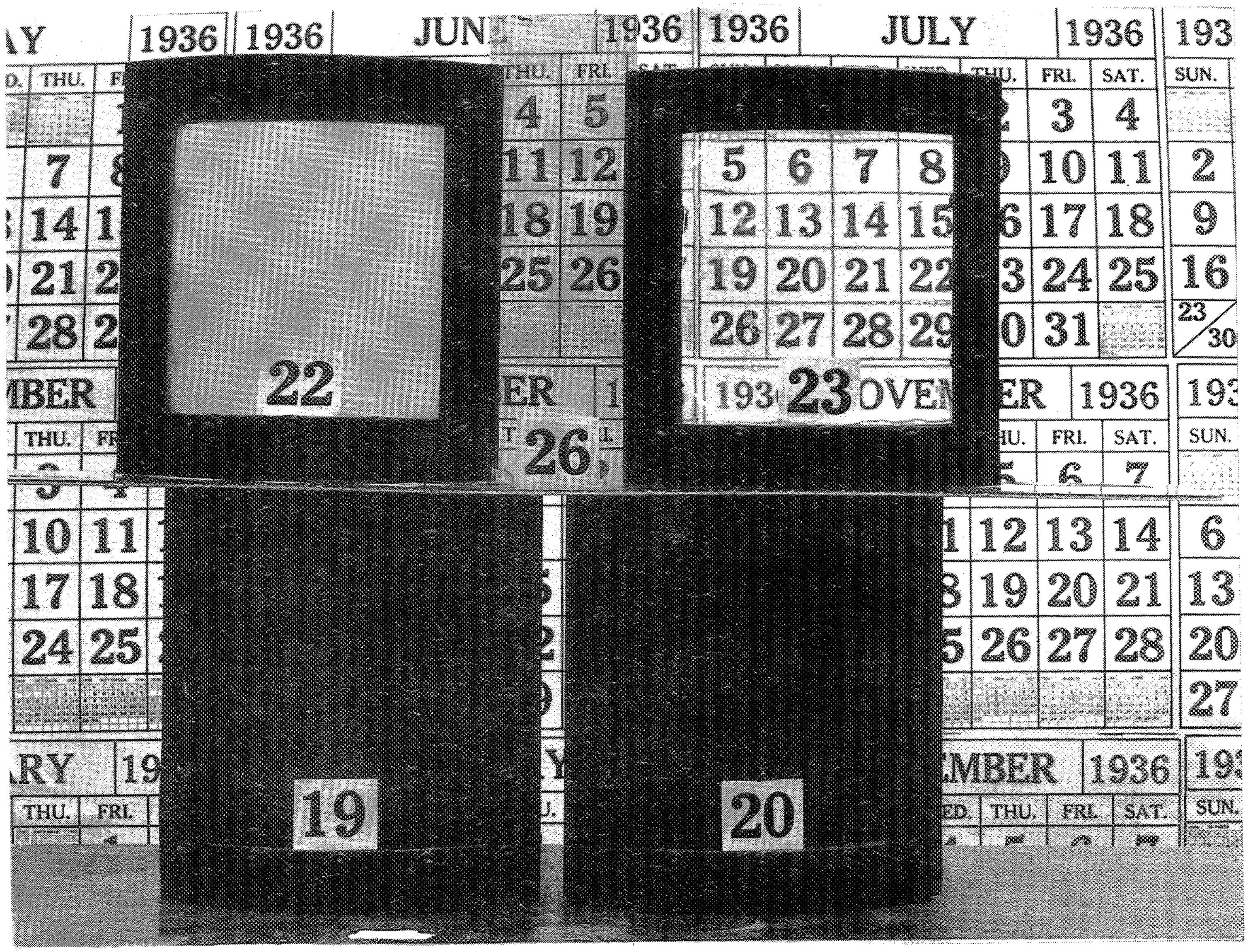


Figure 6.- Exposure panels after one year out-of-doors (sample 26 exposed for nine months only).

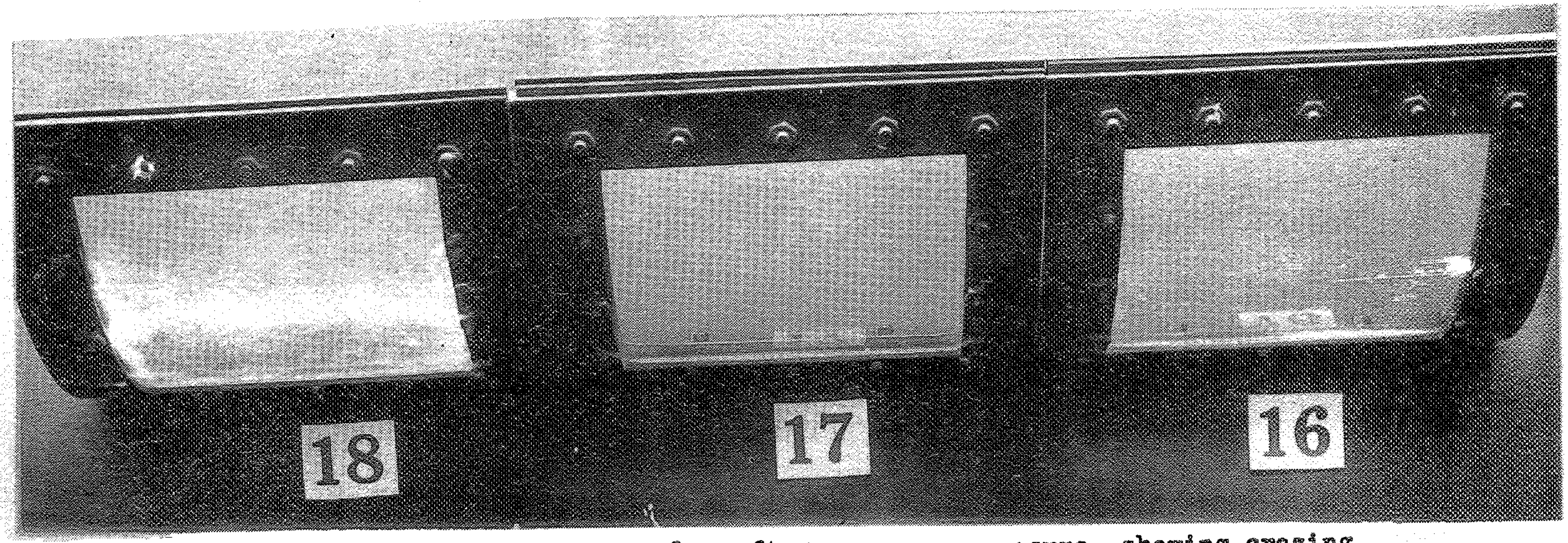


Figure 7.- Acrylate resin samples after one year exposure, showing crazing.

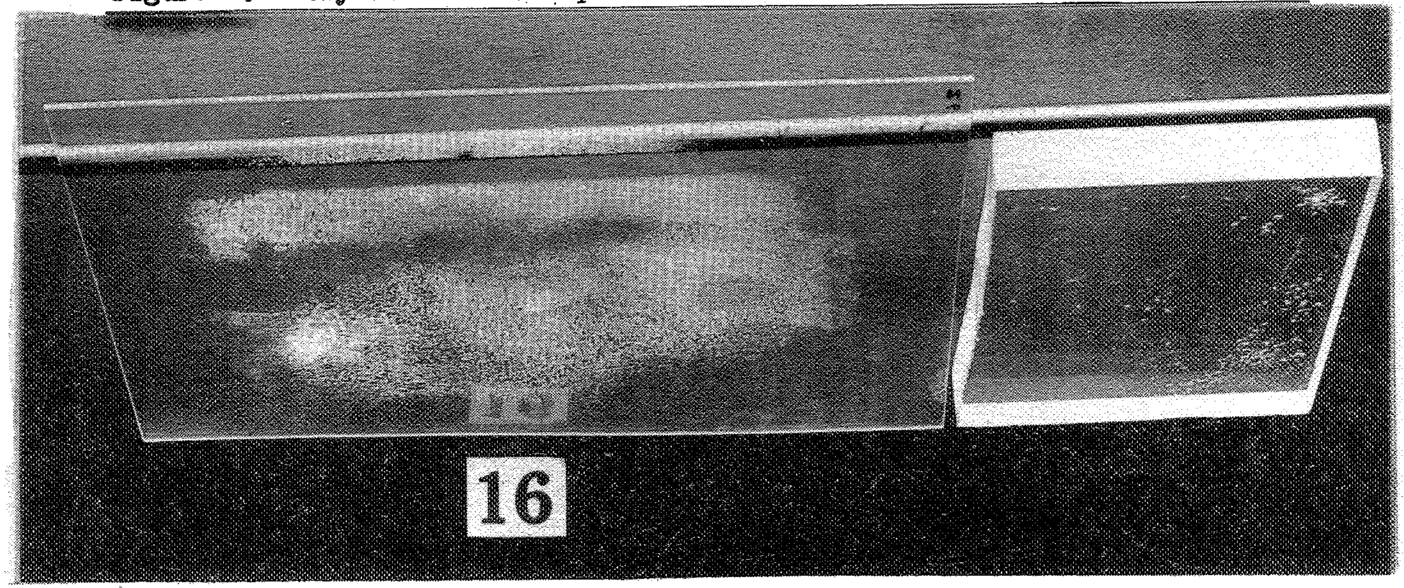


Figure 8.- Acrylate resin samples after approximately one year in storage, showing crazing.

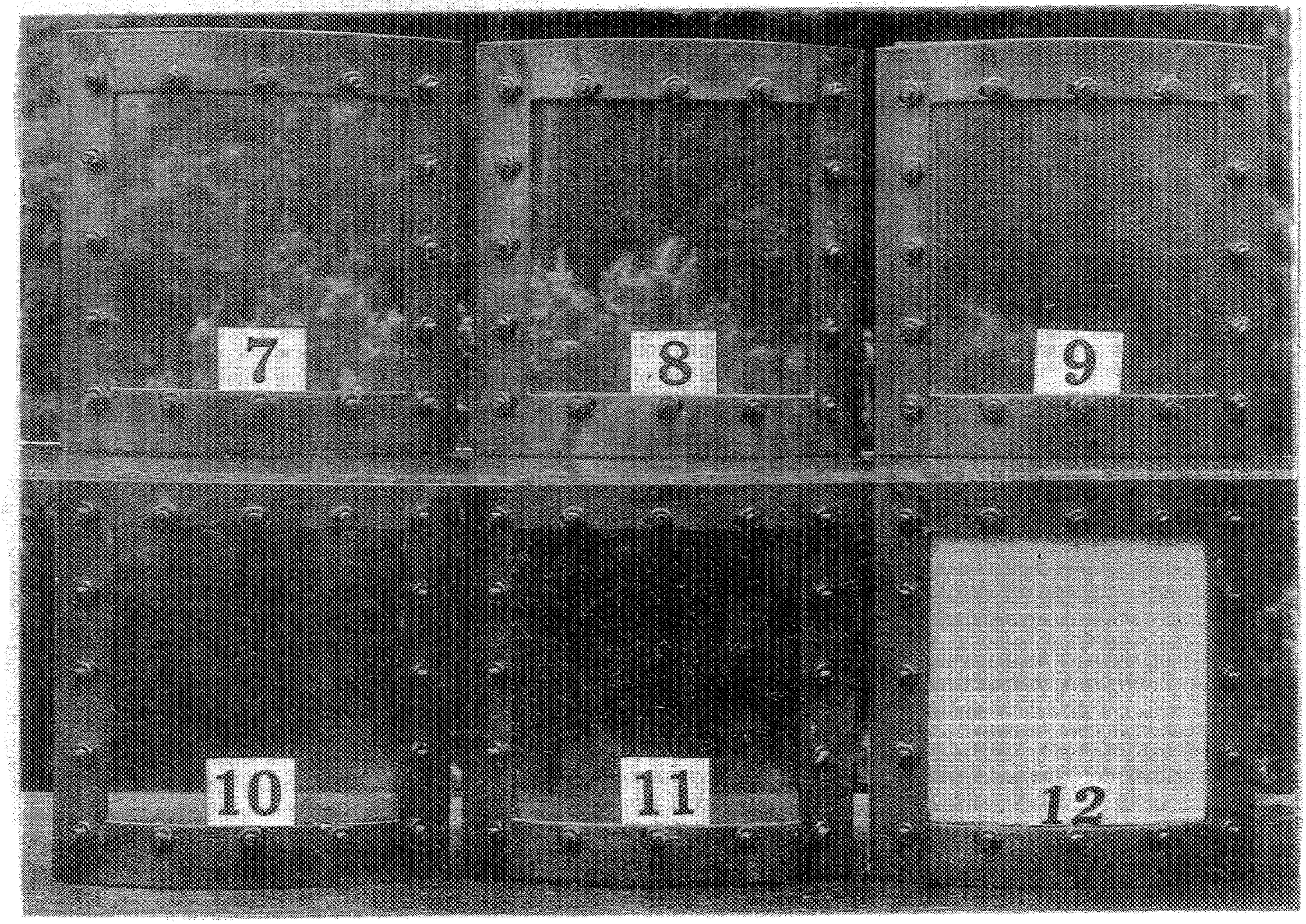


Figure 9.- Exposure panels after three months out-of-doors.

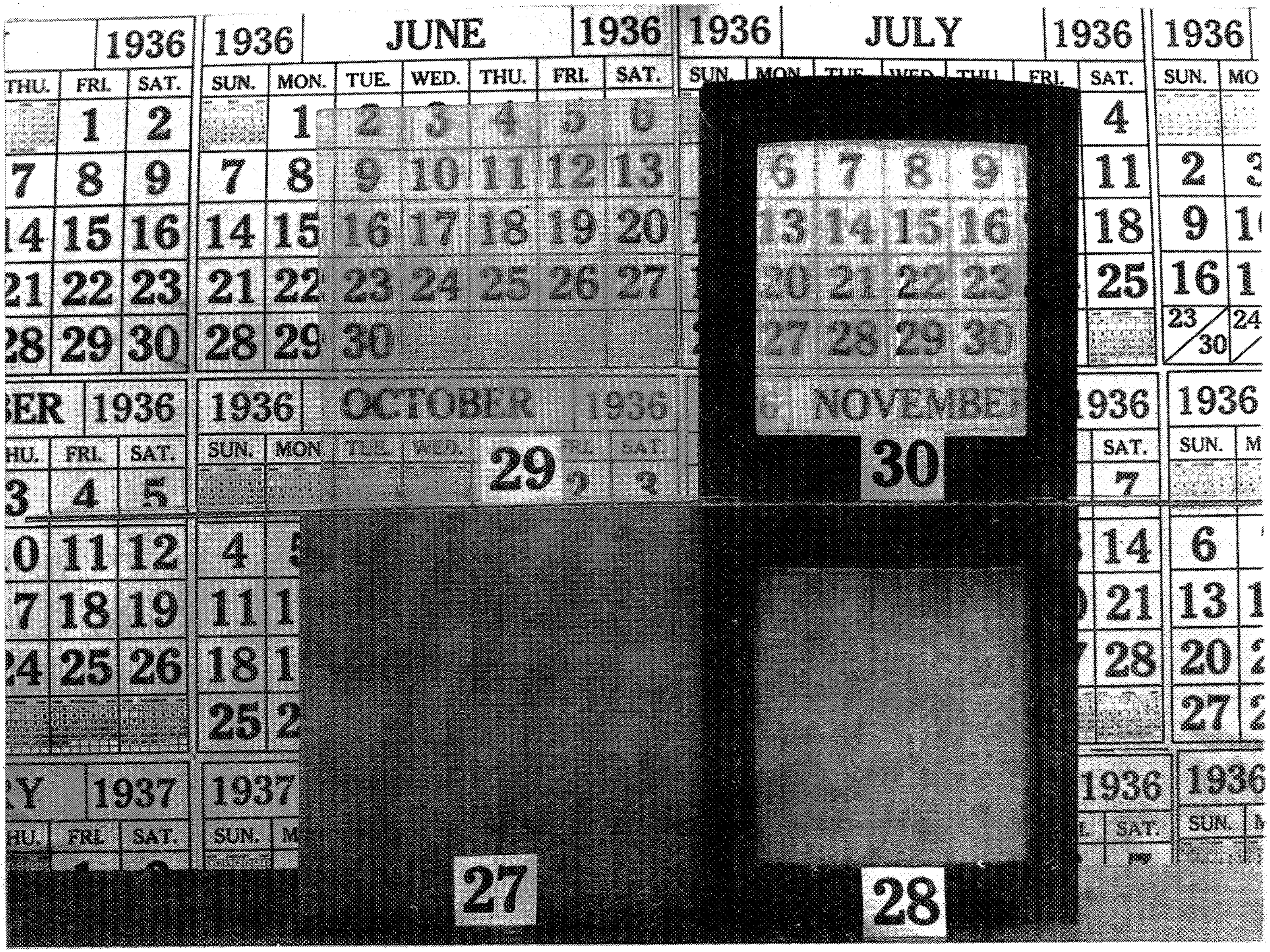


Figure 10.- Exposure samples of cellulose acetate and cellulose nitrate after nine months out-of-doors.

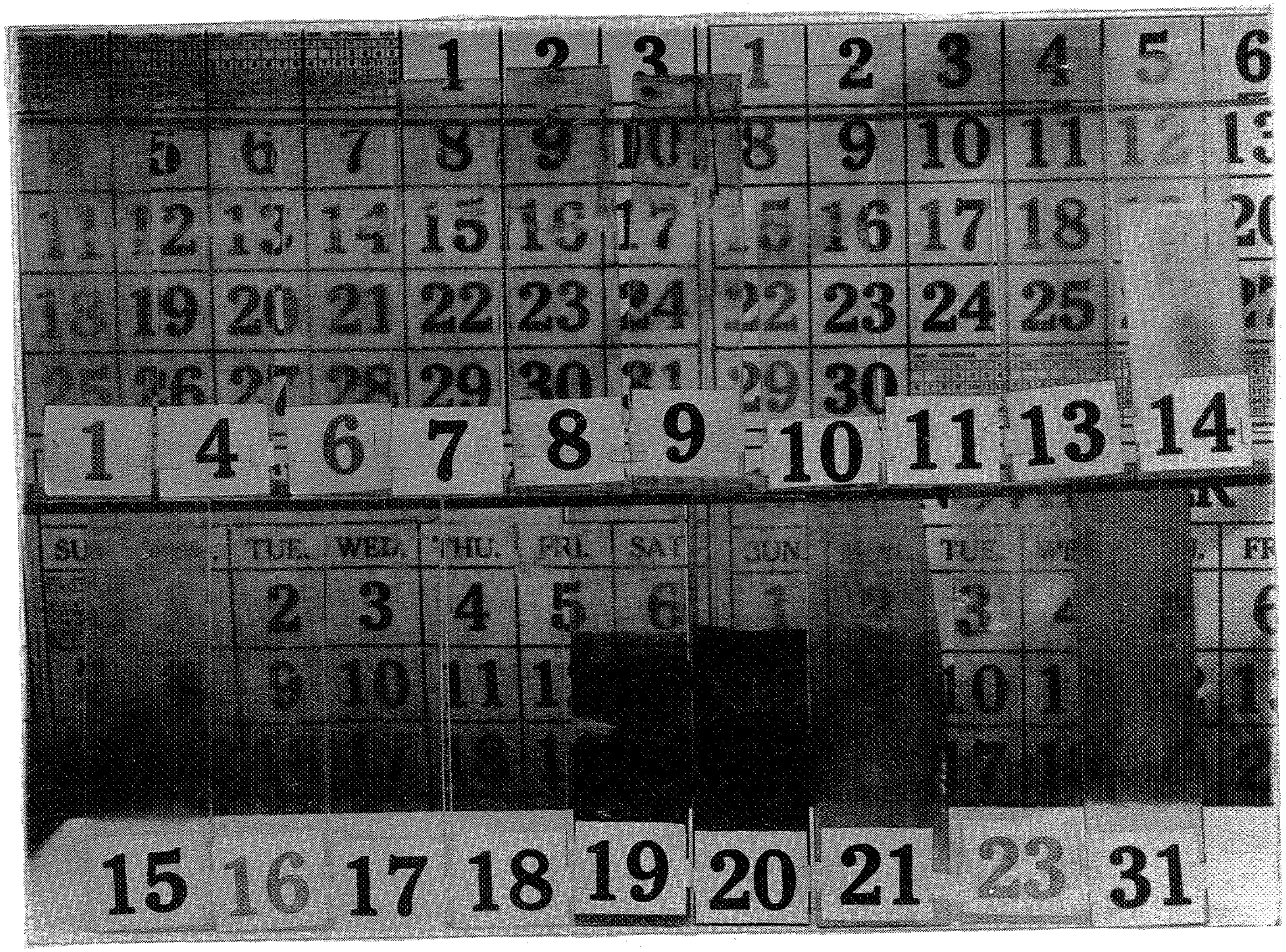


Figure 11.- Condition of samples after exposure to carbon arc light for 1,000 hr. with intermittent water spray.

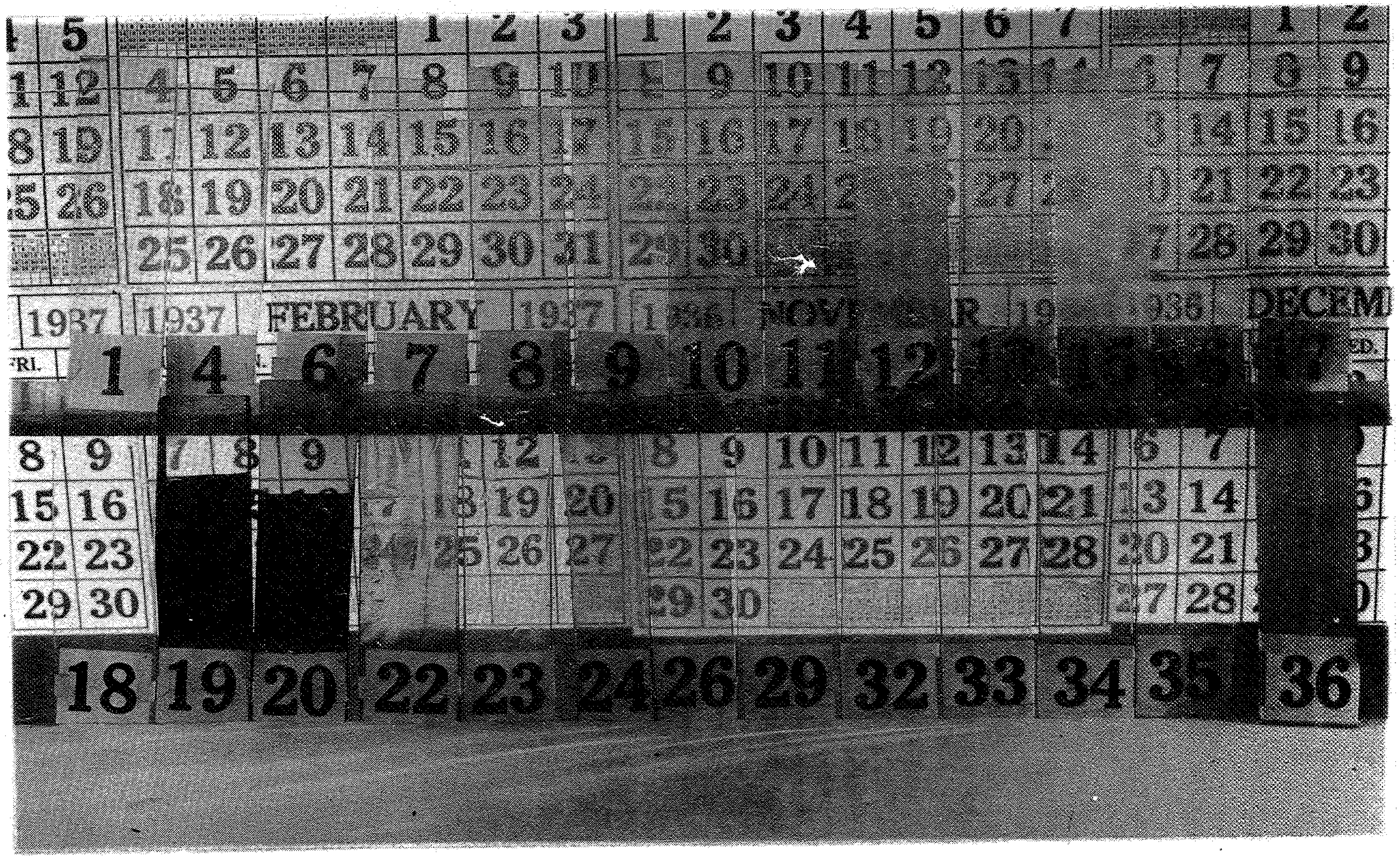
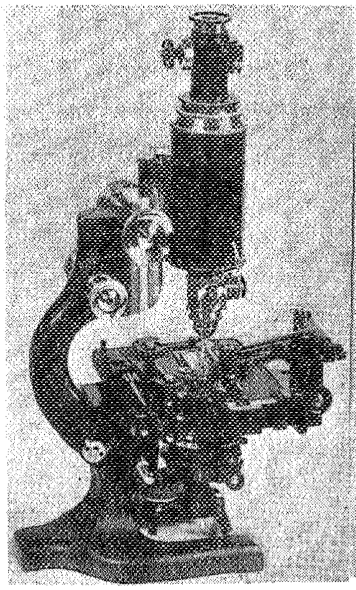


Figure 12.- Condition of samples after exposure to carbon arc light for 500 hr. without water spray.



Diamond tool in scratching position

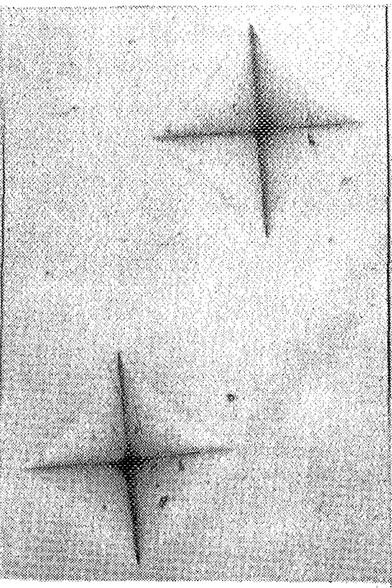
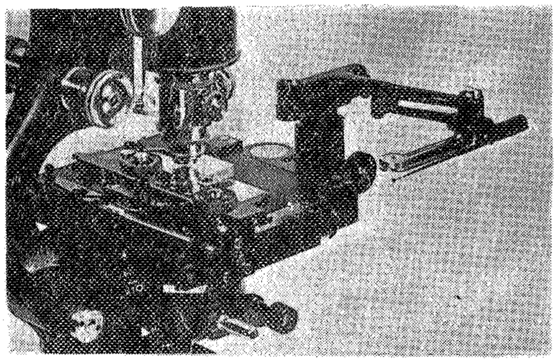


Figure 16.- Pyramidal indentations on vinyl resin plastic (X70)



Diamond tool swung aside and microscope in position to measure scratch width

Figure 13.- Bierbaum scratch-resistance apparatus.

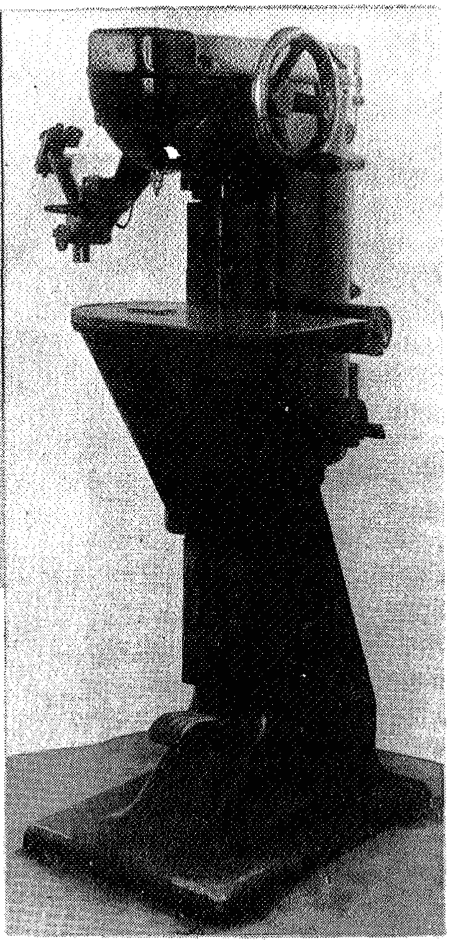


Figure 15.- Vickers hardness testing machine.

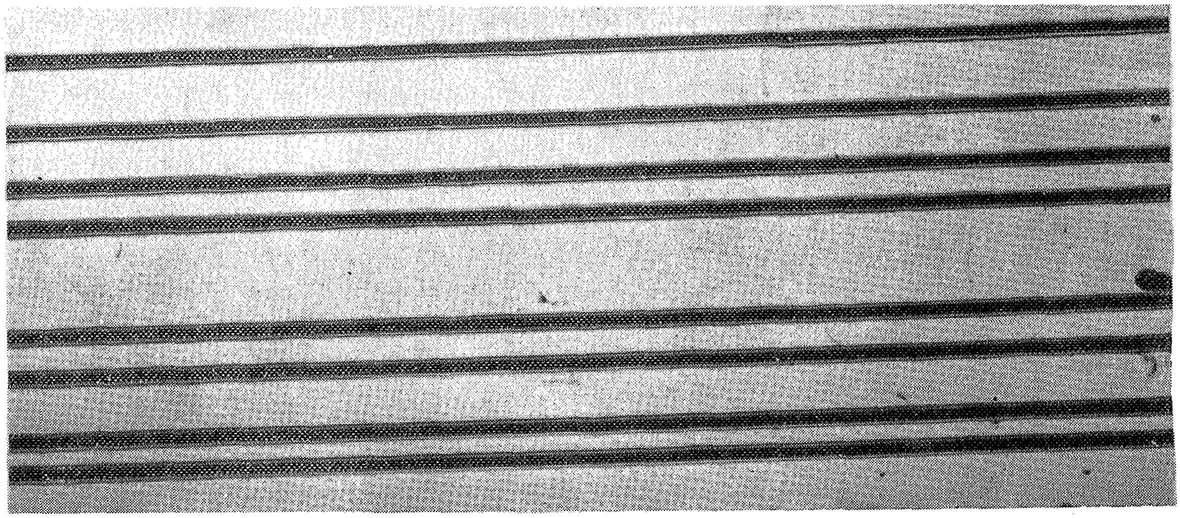


Figure 14.- Scratches on cellulose acetate plastic (X150)

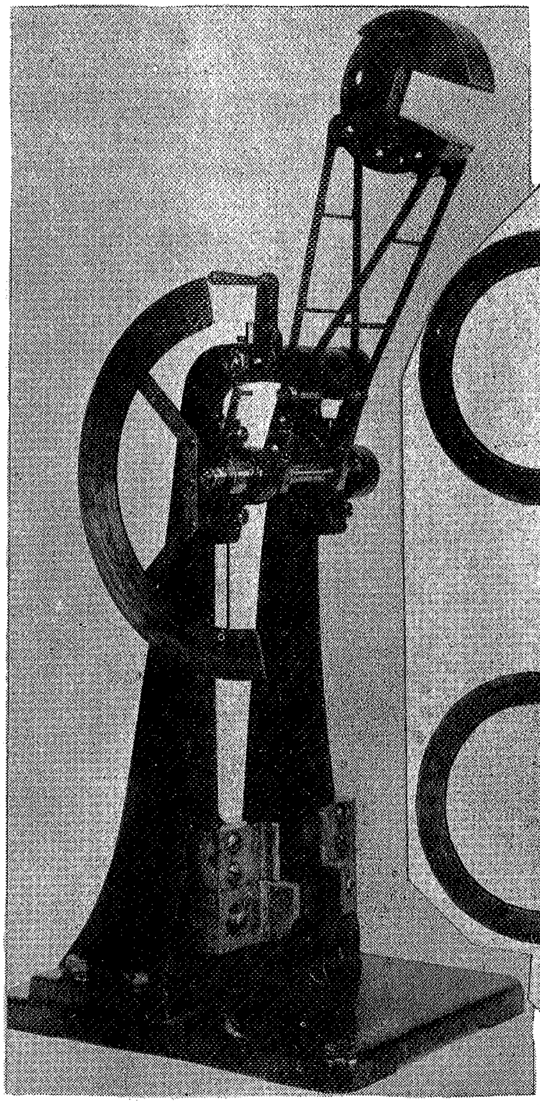


Figure 17. Apparatus for determining Charpy impact strength.

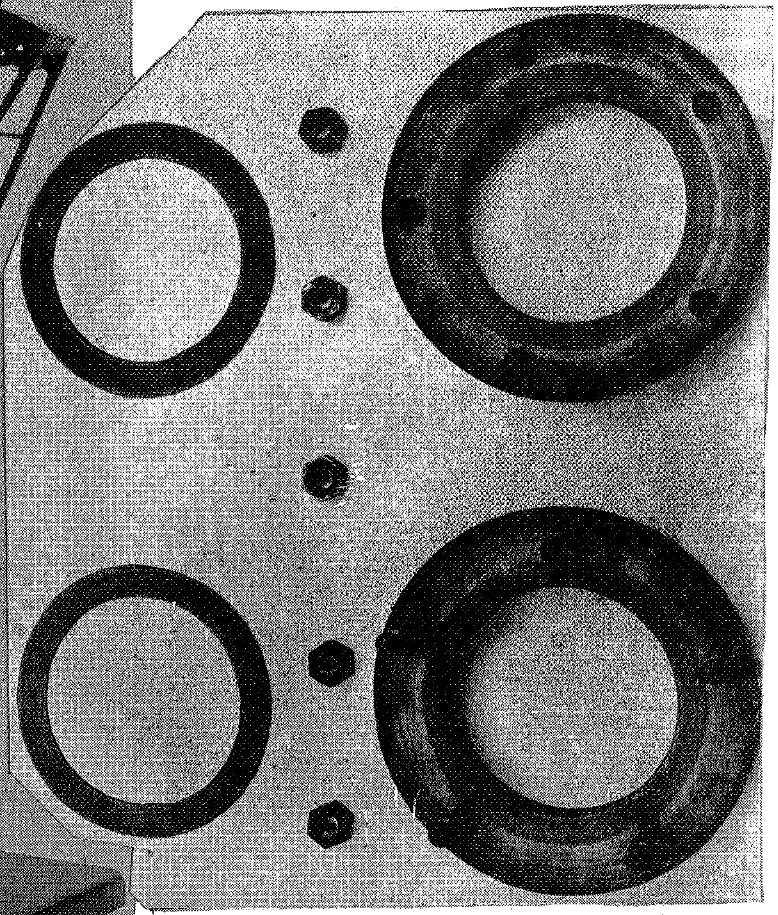


Figure 18. Frame used to hold plastics in the falling-ball impact test.

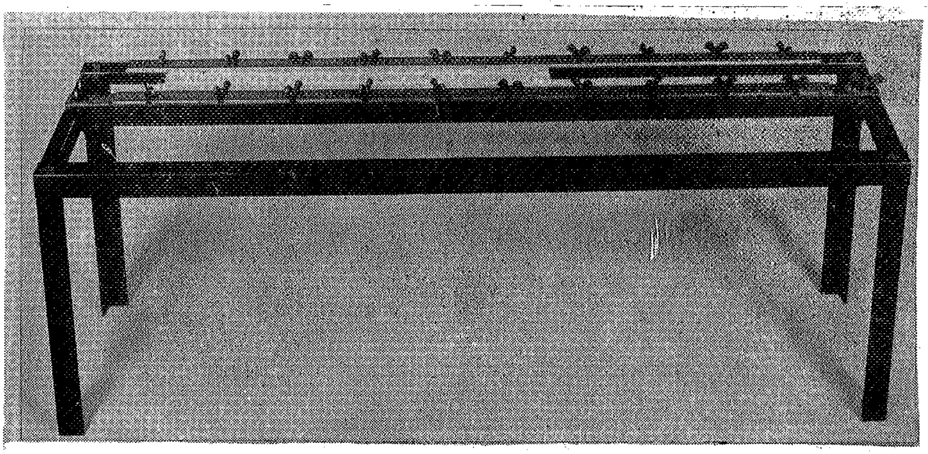
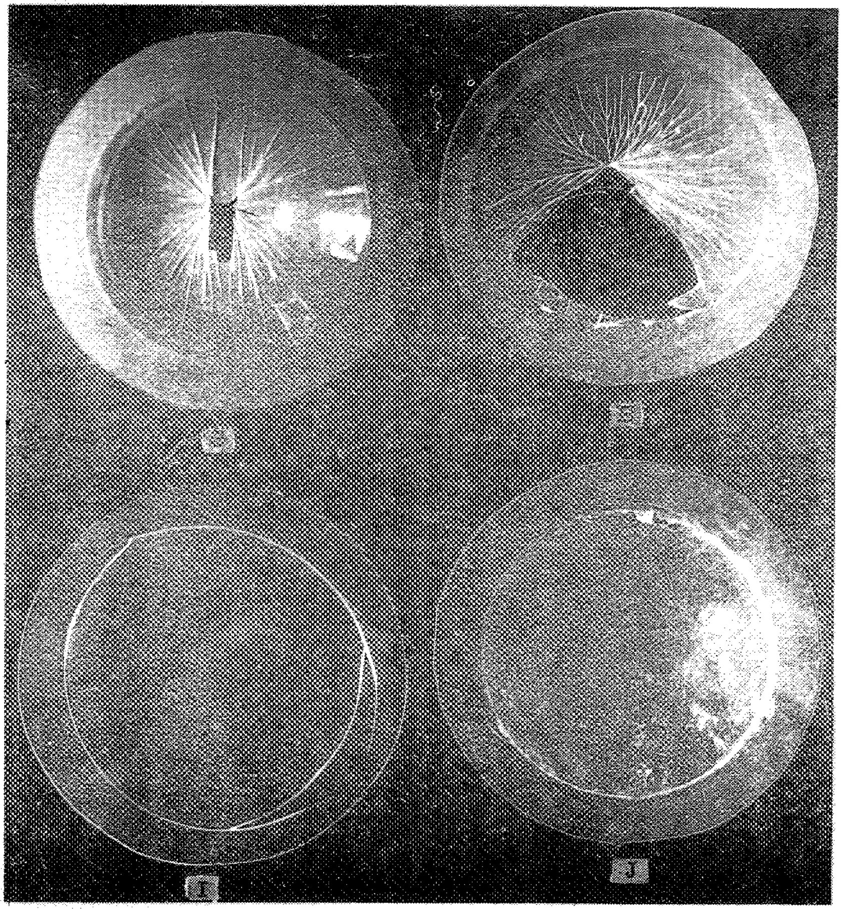
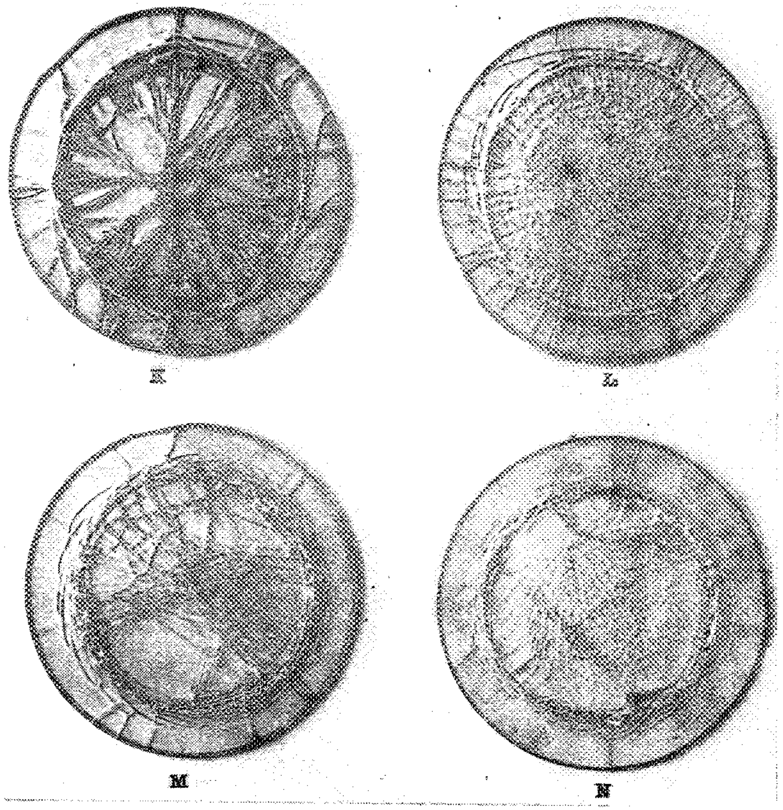


Figure 21. Apparatus for determining rate of burning.



G, Cellulose acetate burst at about 25° C
H, Cellulose acetate burst when one surface was cooled with ethylene dichloride at −31° C
I, Acrylate resin burst at about 25° C
J, Acrylate resin burst when one sample was cooled with ethylene dichloride at −31° C

Figure 19. Samples of transparent plastics after bursting strength tests.



K, Glass bonded with cellulose nitrate plastic
L, Glass bonded with cellulose acetate plastic
M, Glass bonded with vinyl resin plastic
N, Glass bonded with acrylate resin plastic

Figure 20. Samples of laminated glass after bursting strength tests.

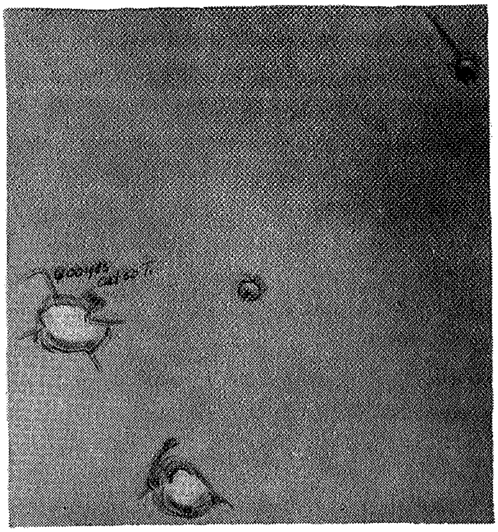


Figure 22. Effect of tracer bullets on transparent plastics. Cellulose acetate. A2. 0.095" thick: three tracer bullets caliber 30. M1. at 100 yards: one tracer bullet caliber 30. M1. at 600 yards.

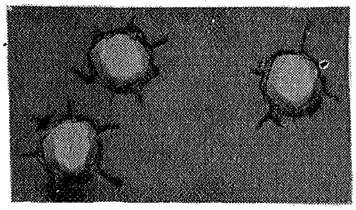


Figure 23. Effect of tracer bullets on transparent plastics. Cellulose acetate. C2. 0.095" thick: three tracer bullets caliber 50. M1. at 100 yards.

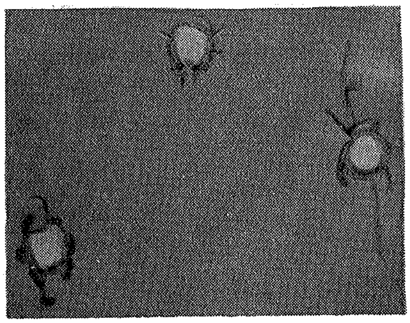


Figure 24. Effect of tracer bullets on transparent plastics. Cellulose acetate. B3. 0.066" thick: three tracer bullets caliber 50. M1. at 100 yards.

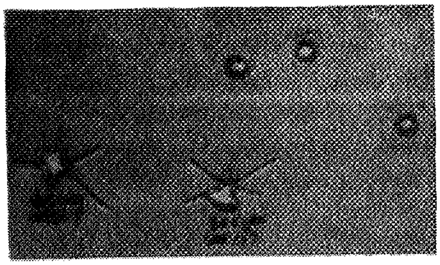


Figure 25. Effect of tracer bullets on transparent plastics. Cellulose nitrate. F1. 0.062" thick: three tracer bullets caliber 30. M1. at 100 yards: two tracer bullets caliber 30. M1. at 600 yards.

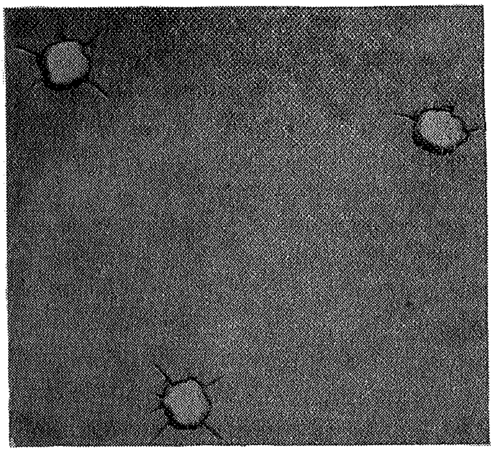


Figure 26. Effect of tracer bullets on transparent plastics. Cellulose nitrate. E1. 0.066" thick: three tracer bullets caliber 50. M1. at 100 yards.

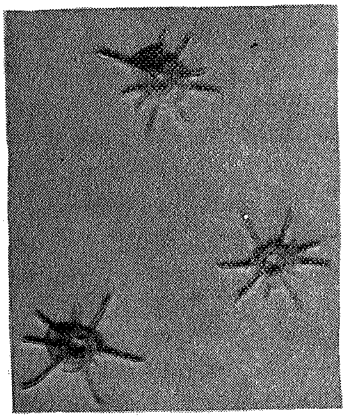


Figure 27. Effect of tracer bullets on transparent plastics. Acrylate resin. K1. 0.113" thick: three tracer bullets caliber 30. M1. at 100 yards.

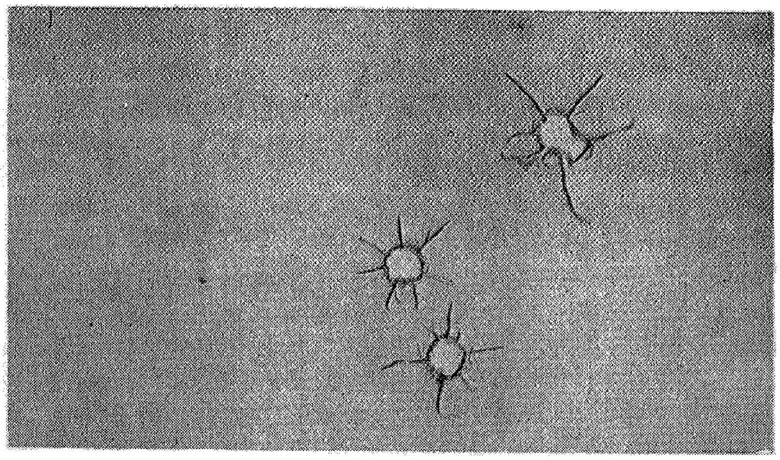


Figure 28.- Effect of tracer bullets on transparent plastics. Acrylate resin, K9, 0.067" thick; three tracer bullets caliber 50, M1, at 100 yards.

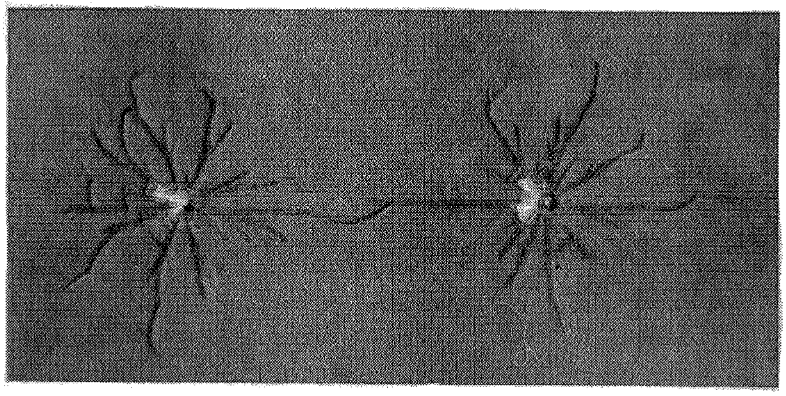


Figure 29.- Effect of tracer bullets on transparent plastics. Vinyl chloride-acetate resin, L3, 0.100" thick; two tracer bullets caliber 30, M1, at 100 yards.

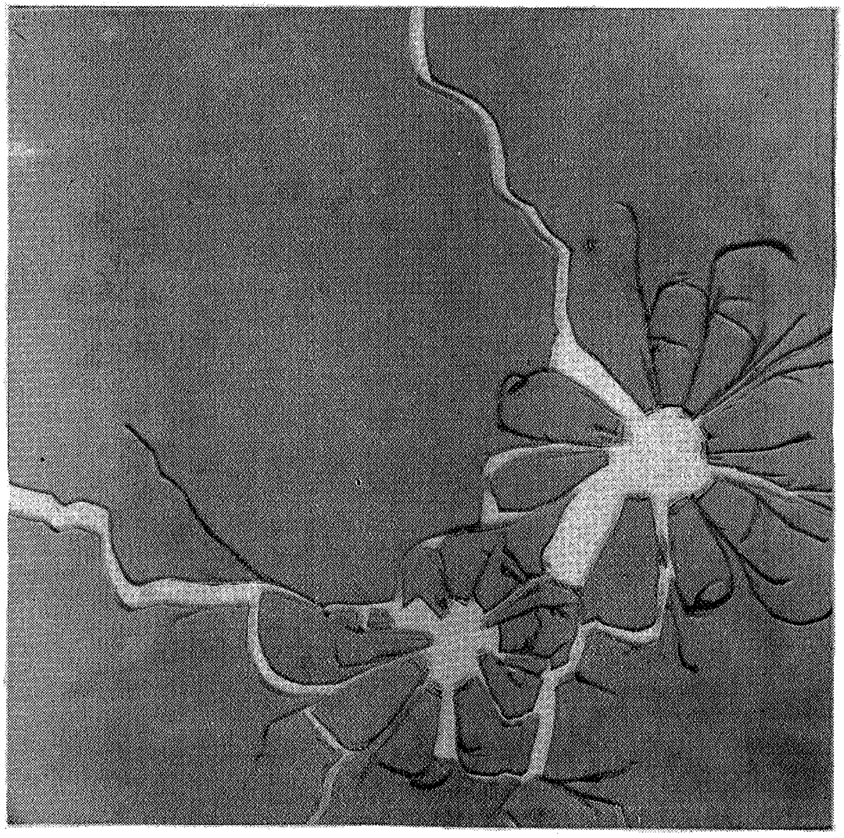


Figure 30.- Effect of tracer bullets on transparent plastics. Vinyl chloride-acetate resin, L3, 0.100" thick; two tracer bullets caliber 50, M1, at 100 yards.

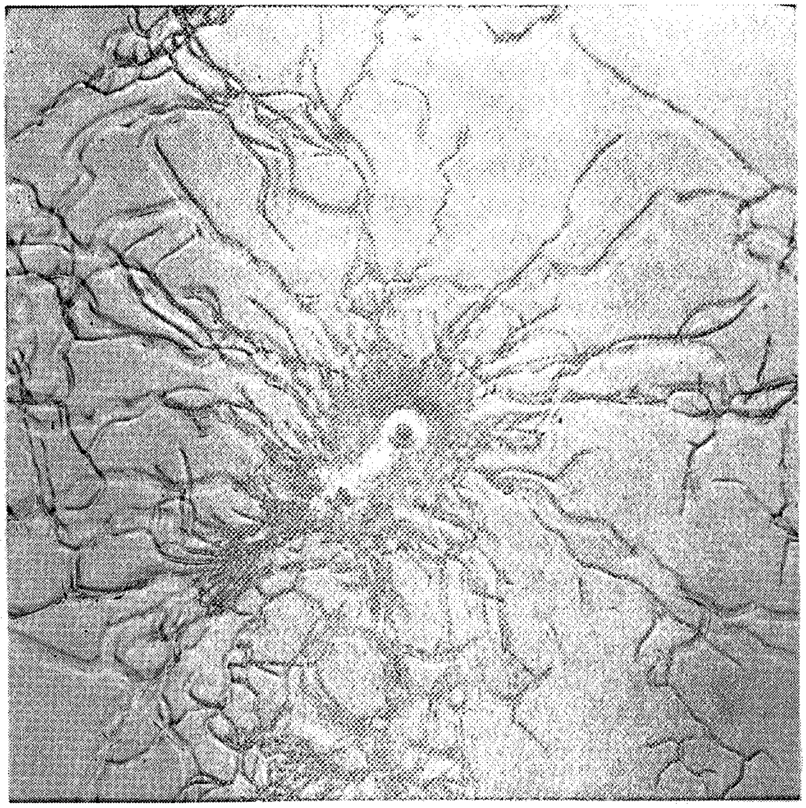


Figure 31.- Effect of tracer bullets on laminated glass. Plate glass bonded with cellulose acetate plastic, X5, 0.188" thick; two tracer bullets caliber 30, M1, at 100 yards.

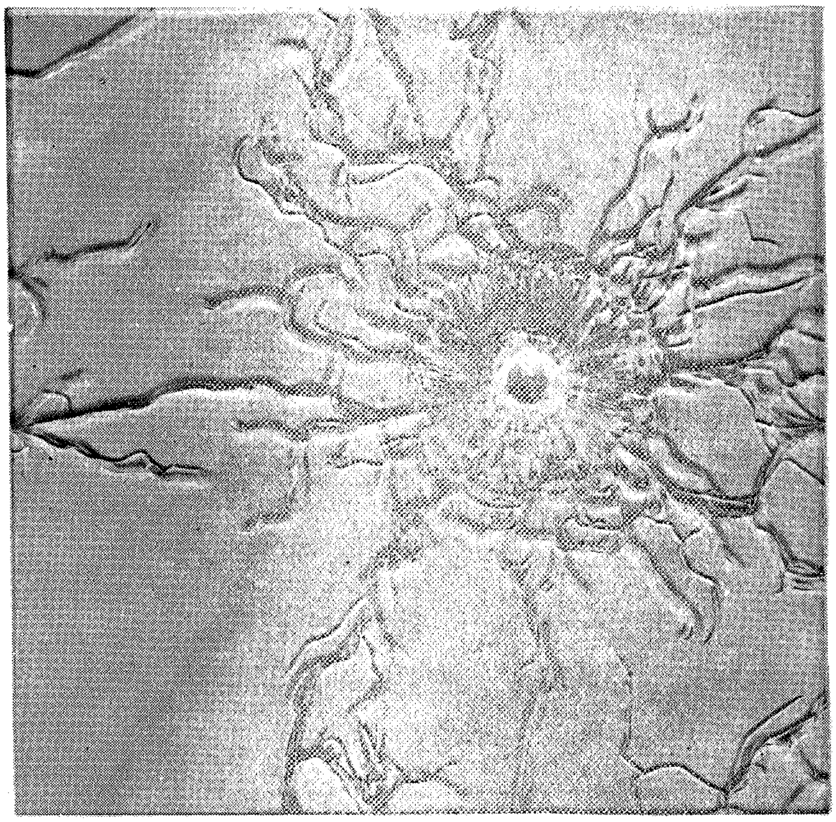


Figure 32.- Effect of tracer bullets on laminated glass. Plate and sheet glass bonded with acrylate resin plastic, Y5, 0.238" thick; one tracer bullet caliber 50, M1, at 100 yards.