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No. 881

APPLICATION AND TESTING OF TRANSPARENT PLASTICS
USED IN AIRPLANE CONSTRUCTION

By K. Riechers and J. Olms

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APPLICATION AND TESTING OF TRANSPARENT PLASTICS USED
IN AIRPLANE CONSTRUCTION*

By K. Riechers and J. Olms

Transparent plastics are used in airplane construction principally to replace silicate glass, having recently become indispensable in the construction of the gunner's cockpit for increasing the field of view. The advantages of the artificial material are its low specific gravity, and the absence of the great brittleness characteristic of ordinary glass. The fracturing of silicate glass is always accompanied by the formation of dagger-shaped, very sharp-edged splinters (fig. 1) that may cause severe or even fatal injuries. The disk shown in figure 1 was tested for its resistance to a high pressure on one side by being subjected to a bursting test through the application on one side of high pressure air. Similar disturbance phenomena arise whenever impulsive stresses are set up as, for example, occur in difficult landings.

In general, two types of dangerous conditions may arise:

1. If the disk is fractured as a result of the impact, the splinters may be hurled against the occupants of the airplane and may lead to cuts and eye injuries. Eloquent testimony of this are the automobile accident lists, for example, in the newspapers.
2. The occupants may be hurled against or even through the windshield, in which case - while the glass breaks away at the point of collision - there generally remains a ring of sharp-edged splinters in the frame, with the result that serious and even fatal arm and throat injuries may hardly be avoided.

*"Verwendung und Prüfung durchsichtiger Werkstoffe im Flugzeugbau." Luftwissen, vol. V, no. 6, June 1938, pp. 197-202.

It was attempted to meet both of these defects of normal glass either by preventing formation of the large dagger-shaped splinters or by binding the splinters so as to prevent their scattering. These attempts led to the development of the so-called laminated safety glass of one or several layers.

SINGLE-LAYER SAFETY GLASS

In the so-called hard-glass type, ordinary plate glass is subjected, by heat treatment, to large inner stresses which, when released during fracture, give rise to small crumbly fragments as shown in figure 2. These small fragments are generally not very sharp-edged, and so cannot lead to the same type of injuries as the splinters of normal glass; besides, there never remain in the frame those extremely dangerous knife-like splinters. Nevertheless, the occupants may be covered by numerous small fragments and thus possibly suffer light injuries. If the disk, in breaking, remains in the frame, the visibility through an obliquely set windshield becomes seriously impaired.

MULTILAYER SAFETY GLASS

By the above type of safety glass is generally meant the type consisting of two glass sheets which are firmly attached by means of a transparent elastic layer, sandwiched in binding, being thus a combination of normal and artificial glass. The sandwiched layers are products of cellulose nitrates, cellulose acetates, and polymerization products, the oldest in use being cellulose nitrate. Disadvantages are the strong discoloring and formation of bubbles and haziness. Moreover, the binding force of the cellulose-nitrate layer weakens considerably by the dispersive precipitations in ageing, so that the protective action is diminished. Safety-glass panes with celluloid layer as binder, acquire after some time the appearance shown in figure 3. If safety glass with a cellulose acetate layer is used, there is likewise observed after weathering for some time, a slight discoloring which, however, only affects the appearance. Great progress has been made with the highly polymerized plastics which are not sensitive to weathering and moisture.

In the above binding materials the silicacare glass is always used as a thin cover sheet, the object being to save weight since the specific weight of silicate glass is 2.6 as compared with 1.4 of the artificial materials.

TRANSPARENT PLASTIC RESINS

The transparent plastics in use are celluloid, cellulose acetate, mixtures of polymers and esters of polyacrylic acid. In the following paragraphs these materials will be considered in more detail.

A. Celluloid

The starting material for celluloid is cellulose nitrate, which is developed according to the scheme of figure 4. The production of celluloid is as follows: The cellulose nitrate is dissolved in alcohol and camphor, gelatinized in kneading machines, during which process a part of the alcohol evaporates so that a doughy mass results. The latter is again strongly kneaded under heated rollers, colors in some cases being added. There is thus obtained a homogeneous mass in the form of thin, now completely gelatinized, plates. The latter are put up in layers and compressed while still warm into blocks and, to remove entrapped bubbles, are baked for several hours at high temperatures. The blocks are then cut up by suitable machines into the desired shapes (sheets, plates, rods, etc.). The alcohol still remaining (up to about 15 percent) is driven off by drying.

By further working of the rough material, as, for example, rolling and pressing, the final product is obtained. Plates which are to receive a high surface polish are pressed between highly polished, chromed layers.

Principal Properties of Celluloid

Specific weight	1.38
Tensile strength	600-700 kg/cm ²
Bending strength	600 kg/cm ²
Elasticity modulus . . . up to	30,000 kg/cm ²

Impact bending strength . . .	100-200 cm kg/cm ²
Heat resistance according to Martens, about	40° C.
Expansion coefficient . . .	100 × 10 ⁻⁶

B. Cellulose Acetates

In the year 1907 the gelatinizing of cellulose acetate was successful, and it thereby became possible to work this material in exactly the same manner and with the same apparatus used in the manufacture of celluloid. Instead of alcohol, however, a mixture of benzol and alcohol is used. These cellulose nitrates, while not inflammable to the same degree, have properties similar to those of celluloid. The production of cellulose acetate is shown schematically in figure 4.

Principal Properties of Cellulose Acetate

Specific weight	1.3
Tensile strength, about	500 kg/cm ²
Bending strength, about	550 kg/cm ²
Elasticity modulus . . .	30,000-60,000 kg/cm ²
Impact bending strength . . .	100-200 cm kg/cm ²
Heat resistance according to Martens, about	35° C.
Expansion coefficient . . .	110 × 10 ⁻⁶

The artificial materials to be described next, namely, the polymers, were first developed in recent years. In spite of a different chemical basis, they are similar to celluloid and acetate sheets in their properties without, however, possessing their disadvantageous properties

C. Mixture of Polymers

The polymerized plastics are thermoplastic materials which do not consist of cellulose nitrate or acetate but are built up of water, carbon, and chalk (fig. 5). By mix-

ing various of these polymers, it becomes possible to obtain definite properties of these mixtures. Their behavior in fluids may be seen from the following table:

		Behavior in liquid	Change in weight after six months
Alcohols		Stable	±0 percent
Benzine		"	+0.1 "
Acetic acid,	10 percent	"	+0.5 "
" "	30 "	"	+0.45 "
" "	concentrated	"	+0.5 "
Solution of sodium hydro- chloride,	10 percent	"	+0.4 "
" "	20 "	"	+0.22 "
" "	30 "	"	+0.19 "
" "	50 "	"	+0.03 "
Palatine oils,		"	+0.1 "
Mineral oils,		"	--
Plant oils,		"	--
Animal oils,		"	--
Nitric acid,	10 percent	"	+0.5 "
" "	30 "	"	+0.45 "
Hydrochloric acid,	10 "	"	+0.35 "
" "	30 "	"	+0.3 "
Sulphuric acid,	10 "	"	+0.4 "
" "	35 "	"	+0.18 "
" "	concentrated	"	+0 "
" "	concentrated at 45°	"	unchanged after 45 days

		Behavior in liquid	Change in weight after six months
Solution of soda,	10 percent	Stable	+0.5 percent
"	30 "	"	+0.5 "
Acetone,		Disintegrates	--
Ether,		Unstable	+16.5 percent
Benzol,		"	+51 "
Full mixture,		"	+12.3 "
Chlorated hydrocarbons,		Disintegrates or dissolves	--
Cyclohexane,		Dissolves	--
Ethyl acetate,		Disintegrates	--
Nitrous acid,		Unstable	+8.3 percent (after 4 months)

Principal Properties of the Polymer Mixtures

Specific weight	1.34
Tensile strength, about	600 kg/cm ²
Bending strength, about	1,000 kg/cm ²
Compressive strength, about	800 kg/cm ²
Elasticity modulus	32,000 kg/cm ²
Impact bending strength	up to 450 cm kg/cm ²
Heat resistance according to Martens, about	60° C.
Expansion coefficient	78 × 10 ⁻⁶

D. Polyacrylic acid esters

Plates of acrylic acid esters are formed by casting into various shapes and in thicknesses of 0.5 to 10 mm.

Principal Properties of Polyacrylic acid esters

Specific weight	1.18
Tensile strength	750 kg/cm ²
Bending strength, about . . .	1,100 kg/cm ²
Elasticity modulus	28,000 kg/cm ²
Impact bending strength . . .	15-30 cm kg/cm ²
Heat resistance according to Martens, about	60° C.
Expansion coefficient . .	130 x 10 ⁻⁶

WORKING OF THE MATERIALS

The four artificial materials indicated above, namely, cellulose nitrate, cellulose acetate, polymer mixtures, and polyacrylic acid esters may be worked in almost the same manner. In the case of celluloid, however, particular caution must be applied on account of its inflammability.

These materials can readily be shaped at low heat without introducing any stresses. The heating can be done by warm metal plates, hot air, or hot water - a temperature of 75° to 100° C. being required. The heated material is drawn over heated forms of sheet metal, wood, or glass and must be cooled in the form. The material can easily be bored, mechanical means being best suited for the purpose. Care must be taken in order to avoid the formation of scratches, soft layers, such as paper, being used under the materials. Turning is possible on any lathe. The materials can be cut along straight or slightly curved lines with a small band or fret saw, or in the same manner as glass, except that instead of the expensive diamond, a fine steel point may be used. The steel point must be applied with some pressure, and for thicknesses above 1.3 the scratching

must be repeated several times. For breaking narrow pieces flat-nosed tongs are used and wider specimens may be broken along the groove by hand. The rough edge on the scratch side of the broken piece is removed by drawing off with a file or with the blade of the scratcher as otherwise small grains may fall off from the rough edge and cause abrasions. The polyacrylic acid esters may be glued to wood, metal, textiles, and rubber with the aid of special putties. Care must be taken that those parts which are not to be glued do not come in contact with the solutions and glues, since they may attack the material and injure the surface. Machines used in grinding glass are also suitable for these artificial materials. The grinding is best done on emery disks and high-speed emery bands of medium grain. Polishing is done on felt disks under slight pressure with some pumice-stone powder and much water added. Strong heating is to be avoided. If the material is to be stamped, forms similar to those used for leather are used. Long heating or temperatures above 80° C. are to be avoided.

The small surface hardness that is always found with the artificial transparent materials, may give rise to scratches and abrasions at very sandy or dusty flying fields. By polishing, however, these scratches may easily be removed. Figure 6 shows a pane of polyacrylic acid ester which was set into the frame of a test airplane and exposed for 100 flying hours to the action of the most varied weathering conditions. No scratches or abrasions of any importance are observed, and the light transmission was in no way impaired.

A disadvantage is the very large expansion coefficient which in the case of the polyacrylic acid esters is 500 percent as great as that of aluminum; i.e., at 1-meter length the material will shrink, for a lowering of temperature by 40° C., about 5 millimeters whereas aluminum will change by only 1 millimeter. In mounting these artificial glass panes, care should therefore be taken that they are not rigidly fixed. In riveting, the orifices are to be bored 3 to 4 millimeters larger, making use of cover strips or washers. A very suitable method is framing in U-shaped edge strips. Further methods of attachment are illustrated in figure 7. In order to assure a uniform support, an intermediate layer of leather or rubber is, in all cases, advisable.

While the polyacrylic acid esters, from the point of

view of strength, are fairly resistant to heat and weathering, these two factors play a considerable part in the case of the cellulose acetates. In heating the latter to 60° C., there has been found a drop in tensile strength of 84 percent, and in cooling to -60° C., an increase was found of 53 percent (fig. 8). Six hundred hours of weathering resulted in complete warping, shrinking, and strong discoloration of the cellulose acetates (fig. 9), whereas the polyacrylic acid ester showed a slight discoloration when viewed parallel to the plane of the plate but none when viewed at right angles.

TEST PROCEDURE FOR WINDOW PLASTICS

The DVL conducts the following tests on safety glass and transparent plastics:

1. Optical testing.
2. Falling-ball test.
3. Testing for weathering resistance.
4. Bending stress.

For carrying out the optical investigations the 300- by 300-millimeter sheets are inclined about 35° to the horizontal and tested for light transmission at a distance of 1.5 meters. It is determined whether bubbles, milky haziness, discolored parts, schlieren, etc., are present. In the report of the test, it is noted whether visibility is impaired or the picture distorted.

For the falling-ball test, the test apparatus consists of a support, a release arrangement for the falling body, and a mounting device for the specimen. The steel support must have a base plate at least 20 millimeters thick, a column 2.5 meters high, and a cross head. For fixing the specimen, two square steel boxes of 260- by 260-millimeter inner dimensions are used. The lower box is 150 millimeters high, and the upper one 23 millimeters, the weight being 3 kilograms. The lower box stands on the 350- by 350- by 20-millimeter steel plate which must rest on an unyielding support. The falling body used is a 57.15-millimeter (= 2-1/4 inches) diameter ball of the kind used in commercial ball bearings, and weighs 769 ± 2

grams. The glasses of 4.5- to 5.5-millimeter thickness are tested by the DVL from a falling height of 1.5 meters, and those of over 5.5- to 6.5-millimeter thickness, from a height of 2 meters. The falling ball is magnetically released and must be allowed to fall perpendicularly over the center of the free surface. The ball may also be released by hand, in which case a suitable guide tube must be used. Before the test proper, the specimens are accurately weighed to 0.01 gram, brought to the test temperature, and set horizontally in the mounting. The room temperature during the test is $20^{\circ} \pm 2^{\circ}$. The test temperatures selected are -21° , -11° , 0° , $+20^{\circ}$, and $+40^{\circ}$. For this purpose the specimens are placed for at least 15 minutes in the following baths:

- -21° mixture of ice and cooking salt.
- -11° brine.
- 0° ice-water mixture.
- $+20^{\circ}$ air bath.
- $+40^{\circ}$ water bath.

After the specimens have been removed from the baths they are dried somewhat and placed in the test apparatus. The falling body is released after a definite time, depending in each case on the glass thickness and the test temperature. If the specimen is not penetrated the pieces, which in the case of the multilayer safety glasses are thrown off in the direction of the impact, are weighed as is also the pane freed from all the loose pieces, and the percent weight lost in the fragments is determined. At the same time the shapes of the pieces are noted. In case the specimen is penetrated, it is noted in what manner the bending layer has been ruptured and how many fragments result. The appearance of multiple-layer glass after the ball-falling test at -21° , -11° , and $+20^{\circ}$ may be seen from figure 9. Figure 10 shows how a multiple-layer safety glass is fractured in the test at -21° . Similarly, large fragments occur in the fracture of artificial glasses in the ball-falling test, but in this case the edges have no cutting action in contrast to the very sharp cutting edges of silicate glass.

For the weathering-resistance tests, the specimens are placed outdoors, inclined at 45° to the horizontal

and facing the south. The specimens lie unprotected, so that they are freely exposed to the action of heat and cold, sunlight and moisture. The data in table I, giving the mean ratios of effective sun exposure per day and month were used as a basis for the measurement of the duration of the exposure, since the principal action is that of the sun's rays. After a weathering of 300, 450, and 600 working hours, the specimens are tested at 20° by the falling-ball test.

For the bending-stress test, the specimens are placed on two supports and loaded in the center. Steel cylindrical rollers 50 millimeters in diameter and 300 millimeters long, ground as accurately as possible, serve to transmit the load. The distance between the supports is 200 millimeters. The bending strength is then computed from the formula

$$\sigma = \frac{P}{d^2} \text{ (kg/cm}^2\text{)}$$

where P is the load, and d the thickness of the specimen.

This test procedure, with some further details and explanations, is described in the DIN standard test-procedure sheet DVM 2302 "Safety glass for Vehicles, test Procedure."

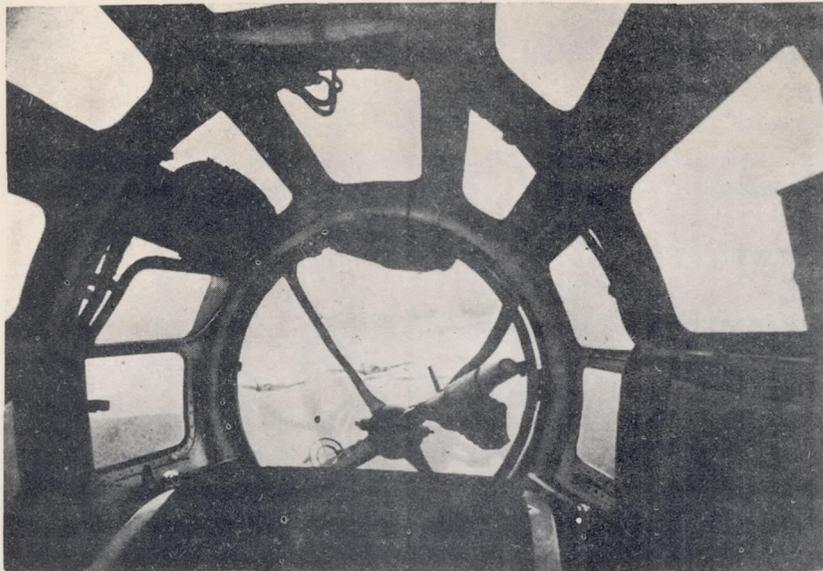
As may be seen from the foregoing brief discussion, the greatest efforts are being made to remove the source of danger to passengers, arising from the fracturing of silicate glass. The problem, of course, has not yet been completely solved with the artificial types of glass at present available, but the danger of serious injuries from broken glass has been considerably lessened by the application of the safety glasses. It is to the interest of the entire transportation industry - both airplane and automobile - to insure maximum safety to the lives of passengers entrusted to its care, and this idea has been gaining ground to an ever-increasing extent.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics

TABLE I

Daily and Monthly Effective Weathering Hours

Months	Average weathering hours	
	Daily	Monthly
January	0.8	25
February	1.5	42
March	2.5	78
April	3.2	96
May	4.4	136
June	5.0	150
July	4.8	149
August	4.5	140
September	3.8	114
October	2.0	62
November	1.1	33
December	.6	19



View through gunner's cockpit of a fighter plane provided with artificial glass of acrylate plastic.

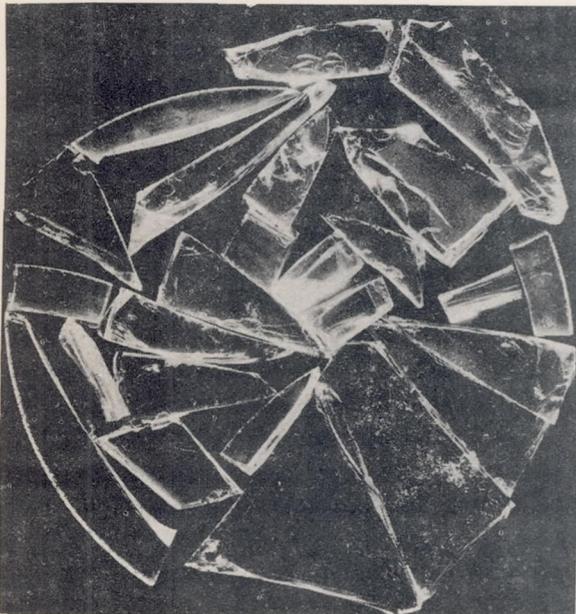


Figure 1.- Pieces of sheet silicate glass after testing for resistance against excess pressure on one side.

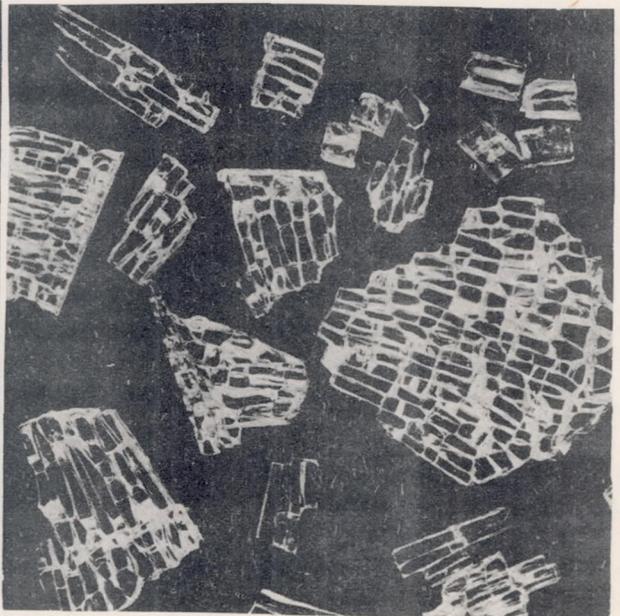


Figure 2.- Fragments of hard (heat treated) glass.

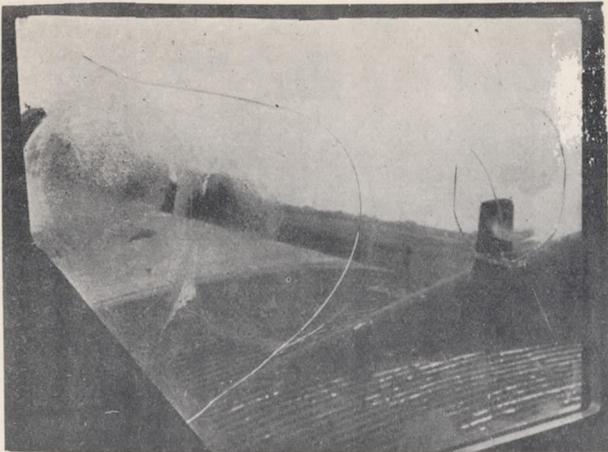


Figure 3.- Formation of bubbles in three-layer safety glass using cellulose acetate.

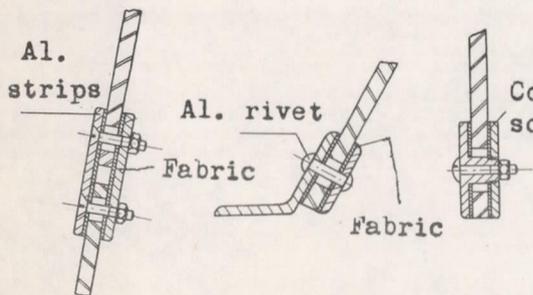


Figure 7.- Methods of attachment of transparent plastics.

Figure 6.- Sheet of polyacrylic acid ester after 100 flying hours. →

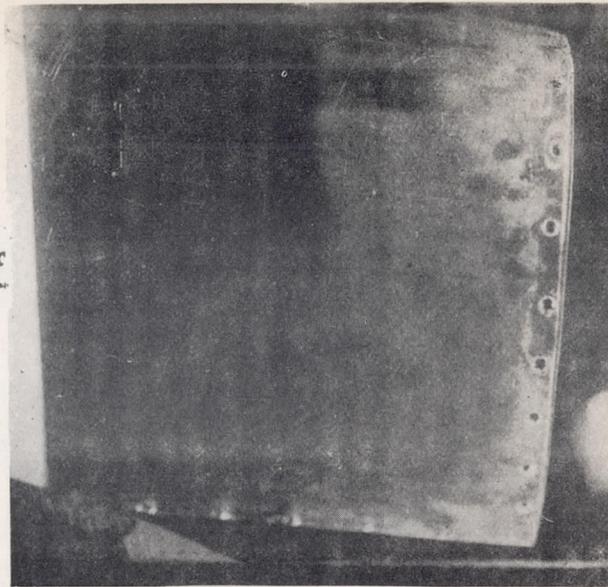
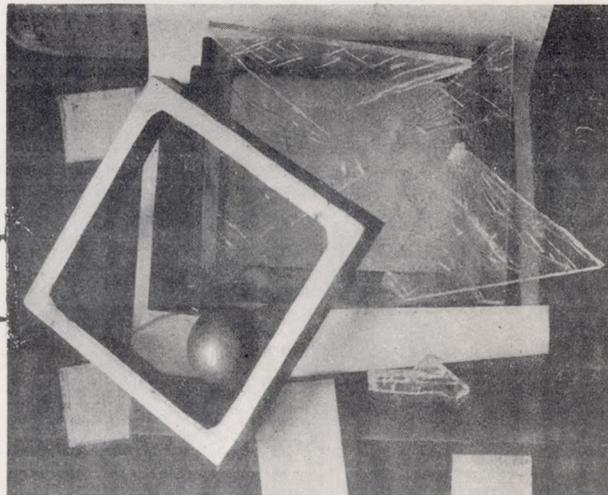


Figure 10.- Multilayer safety glass after the ball-dropping test at -21° . →



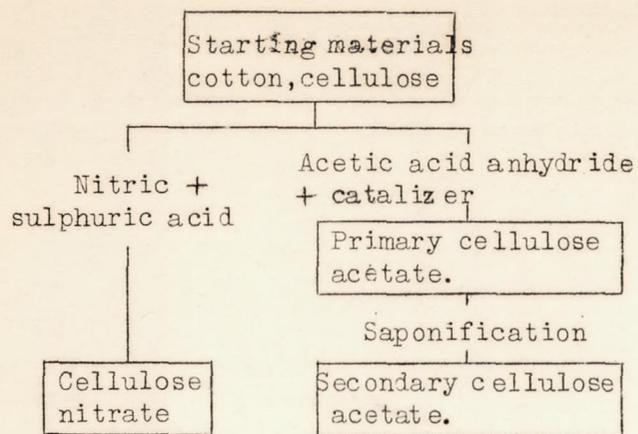


Figure 4.- Production of cellulose acetate and cellulose nitrate.

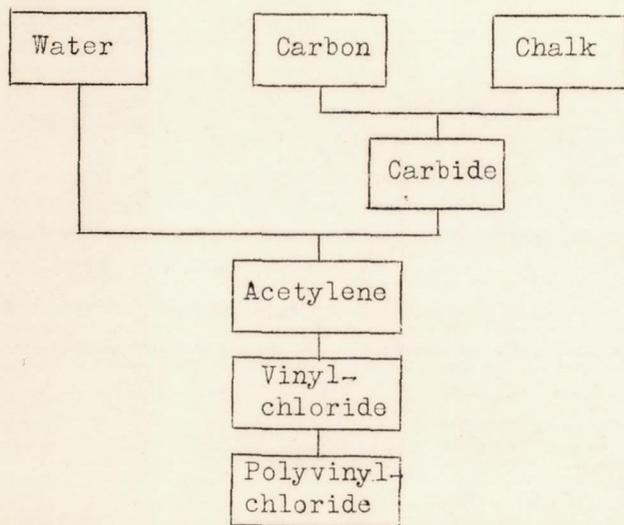


Figure 5.- Production of polyvinylchloride.

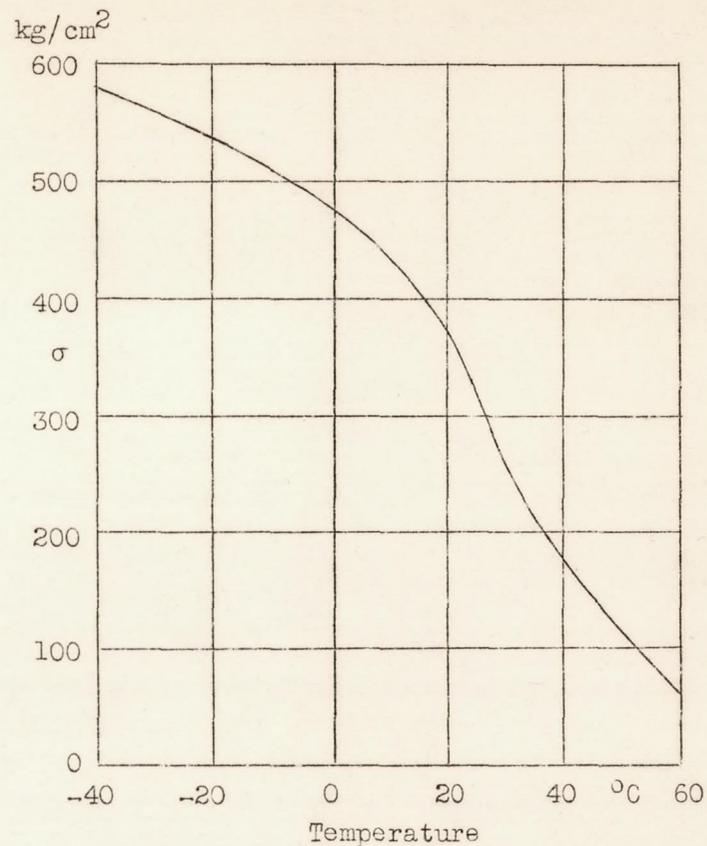


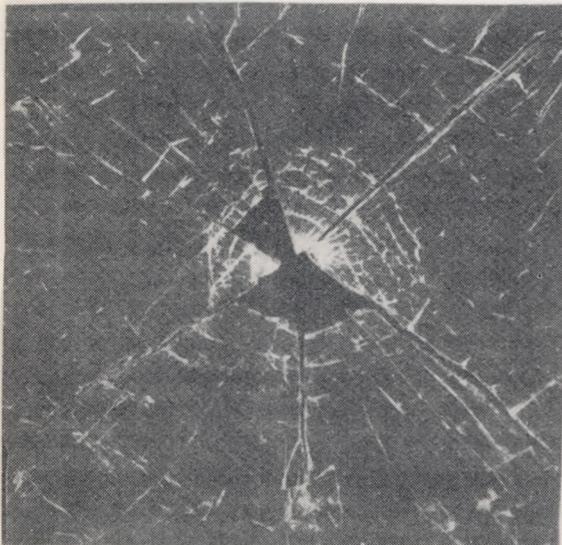
Figure 8.- Tensile strength of cellulose acetates as a function of the test temperature.



20°



-11°



-21°

Figure 9.- Three-layer safety glass
after the ball-dropping
test at 20°, -11°, and -21°.