DEVELOPMENT OF FABRIC-BASED MATERIALS FOR SPACE APPLICATIONS

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ABSTRACT

This project was designed to produce new and improved coated fibrous structure materials for rigidizable expanded structures for future aerospace uses. Woven fiberglas is coated with polymeric compositions designed to retain flexibility until rigidization is required. Two techniques involving removal of part of the coating (normally a plasticizer) are evaluated and found satisfactory for producing a rigid structure. Inflatable structures are used to demonstrate the methods. A third procedure for rigidization is outlined from a theoretical viewpoint only.

The investigation is restricted to continuous-filament glass yarn and coating compounds based on polyvinyl chloride and polyurethane polymers. The effects of yarns, weaves, and coating composition are investigated with respect to their rigidization capability. Criteria used to determine the relative merit of a coated fabric matrix are buckling strength under compression loading and modification of the standard stiffness test for plastics. Relative rates of rigidization are measured for several candidate materials.

INTRODUCTION

Previous efforts to develop materials for the space environment have been concentrated in two areas: (1) the measurement of physical characteristics of materials, and (2) the development of a specific material having certain physical characteristics considered desirable. Excellent information has been compiled in these areas but very little work has been done in combining the knowledge of materials to produce complexes suitable for the space environment. As a starting point, we have concentrated on new and improved fibrous structure materials for rigidizable expanded structures.

The development of a rigidization capability for coated fabric matrices will provide a means of deploying large, shape-retaining structures in space from a relatively small packaged volume. The selection of glass as the basis for fabrics is intended to supply inherent dimensional stability (by virtue of its high modulus) to maintain the desired shape. The resins used for coating exhibit rigidization capability under the proper environmental conditions while retaining sufficient flexibility for packaging in the "as coated" state.

The practical aspects of developing a rigidizable fibrous structure require that the matrix remain flexible for any intended packaging application with inflation and rigidization taking place on command. It is our intent to provide information which will help minimize the number of possible choices in meeting a requirement of this type.

The effort was divided into two major phases: (1) the development and demonstration of rigidization techniques and (2) the evaluation of fibrous-structure materials to which the techniques could be applied. Commercial vinyl-coated glass fabric was used in both areas as a starting point to provide a basis for the evaluations conducted.

The presentation of data is separated as defined above for the sake of clarity but, in actual fact, both phases were carried on simultaneously.

RIGIDIZATION CONCEPTS

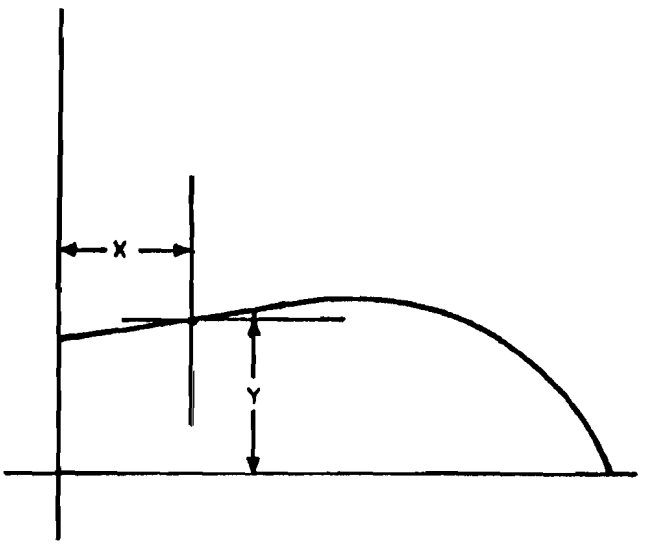
Rigidization of a coated fabric may be accomplished by a number of methods most of which are variations of three basic concepts. In general, since it is required that the fabric, as coated, be flexible enough to handle and package, the choice of polymer used must be one which, with suitable additives such as plasticizers, will be relatively soft and limp. Simultaneously, the polymer, without additives, must produce a coherent, rigid film. The procedures for rigidization take advantage of the properties of the polymer and the additives used, utilizing the fabric as a shape control mechanism. Briefly, the three methods are:

a. Solvent Extraction of the Additive. In this case, immersion of the coated fabric in a solvent, such as toluene, leeches out the plasticizer leaving behind a film of rigid resin. The solvent will act as a temporary plasticizer but the fabric complex must be kept wet.

b. Vaporization of the Additive. Here, the coating formulation deliberately incorporates a high-vapor-pressure plasticizer which will be held within the film long enough to permit handling and packaging. Rigidization may be accomplished by the application of heat or by exposure to high vacuum. The limitation to this method is elapsed time from original coating to deployment.

c. Conversion of the Additive to Rigid Structure. This method is the most complex but seems likely to provide the most reliable results. It is dependent on selective polymerization with respect to its environment. For example, a catalyst system is chosen so that one portion is reactive under atmospheric conditions, producing a soft, flexible film. Upon exposure to heat and/or vacuum, the remaining portion of the catalyst is activated so that the coating system becomes rigid.

Since our chief objective was that of rigidization under controlled and repeatable conditions, the research emphasis with respect to yarns, weaves,



X	Y
0.00	5.00
2.50	5.10
5.00	5.68
7.50	6.38
10.00	7.03
12.50	7.37
15.00	7.50
17.50	7.28
20.00	6.65
21.25	6.15
22.50	5.35
23.75	4.10
25.00	0.00

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Figure 1. Gore Template 1/4 Section of Pattern No. 4
Ovals of Cassini

Having satisfactorily demonstrated the principle, the evaluation was switched to a study of yarns, weaves, and coatings and, after considerable testing, the best of each was combined to provide a rigidizable matrix. It was decided that coated yarns laid out in various patterns would yield more information than specifically coated fabrics. Therefore, a 15-inch oblate paraboloid was constructed of 1/2-mil mylar to provide a surface for yarn application. Mylar was chosen for visibility while the oblate construction would yield information on a shape other than spherical. One half of the paraboloid included a 0.0035-inch laminated layer of aluminum foil as a radar-reflective surface. The method of calculation used for construction of this shape is shown in figure 3, while the values used in building the template are shown in figure 4.

Preliminary tests using solvent extraction as the rigidizing mechanism resulted in high distortion of the mylar substrate indicating the possibility of unusual stress distribution in a finished, rigidized structure. The coating system was then shifted to one based on a fugitive plasticizer which could be rigidized by the application of moderate heat. The patterns tested are shown in figure 5. Note the area where no yarns are applied.

coating, and construction techniques was oriented primarily around the first method. Toward the end of this phase of the work, some coatings were designed to fit the second method and rigidization capability was demonstrated.

RIGIDIZATION OF INFLATED STRUCTURES

A commercially coated vinyl-fiberglas fabric was repeatedly extracted with toluene to determine whether sufficient stiffness could be imparted to the cloth to provide shape-retaining characteristics. Stiffness measurements (using a Tinius Olsen Stiffness Tester) indicated that the bending stiffness was increased ten-fold for this fabric. While the method was crude, the results were promising enough to build inflatable structures to test the validity of the procedure as well as shape-retaining characteristics.

Since the fabric used in each case is glass, the shapes constructed were designed with an objective of precise contour and shape control. Mathematically, the sphere is the simplest to construct and all but the most recent work is in this area.

To minimize the effect of seaming on contour stability, the mathematical concept known as the Ovals of Cassini was used as a starting point. The equation

$$(x + a)^2 + y^2 (x - a)^2 + y^2 = K^4$$

defines all possibilities with respect to oval formation as dependent on the values for a and k. Some value of a and k must be selected so that only one oval, shaped like one half a baseball cover, results. This means that $K^2 > a^2$ for if $K^2 < a^2$, two ovals result and if $K^2 = a^2$ a lemniscate (two separate ovals just touching) occurs.

This formula, with established values for a and k (for 60-inch circumference in this case), will approximate a spherical shape when two sections are joined. Cutting in the flat, rather than on a curved form, combined with the inability of the glass to make gross adjustments in load dispersion caused the first three attempts to be somewhat less than round. This expected condition occurred even though the fabric was cut on the bias to provide maximum load-distribution capability. The original template was cut down by trial and error until sphericity resulted on the fourth attempt. This pattern is shown in figure 1 with the values for selected points.

Several spheres of this type were built as well as one using a standard gore pattern. These were solvent extracted with toluene and rigidized by (1) exposure to vacuum or (2) application of internal pressure until the toluene had completely evaporated. (NOTE: The extracted sample must be kept wet with solvent until rigidization is desired.) Figure 2 shows the vacuum-rigidized sphere with a hole cut in it to show the measure of shape-retaining ability.

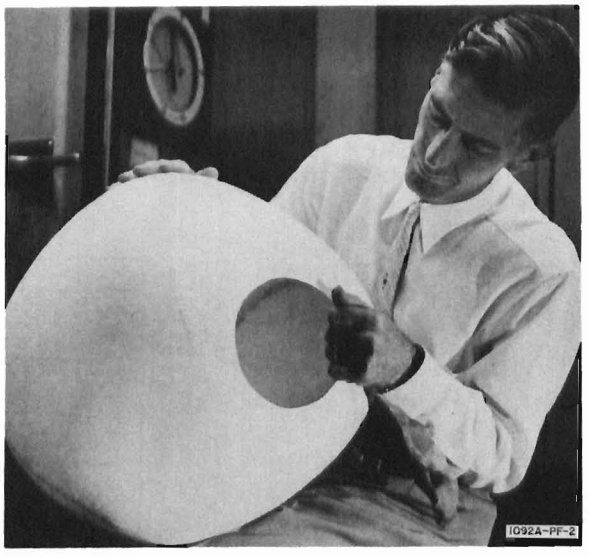


Figure 2. Vacuum Rigidized Sphere

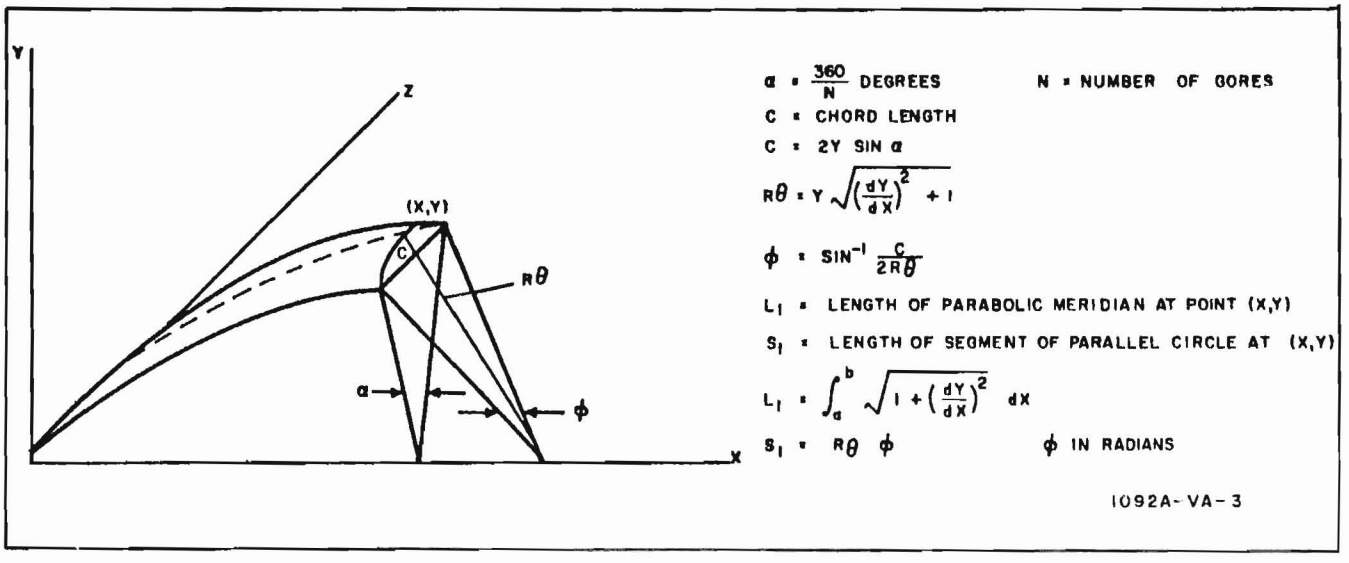
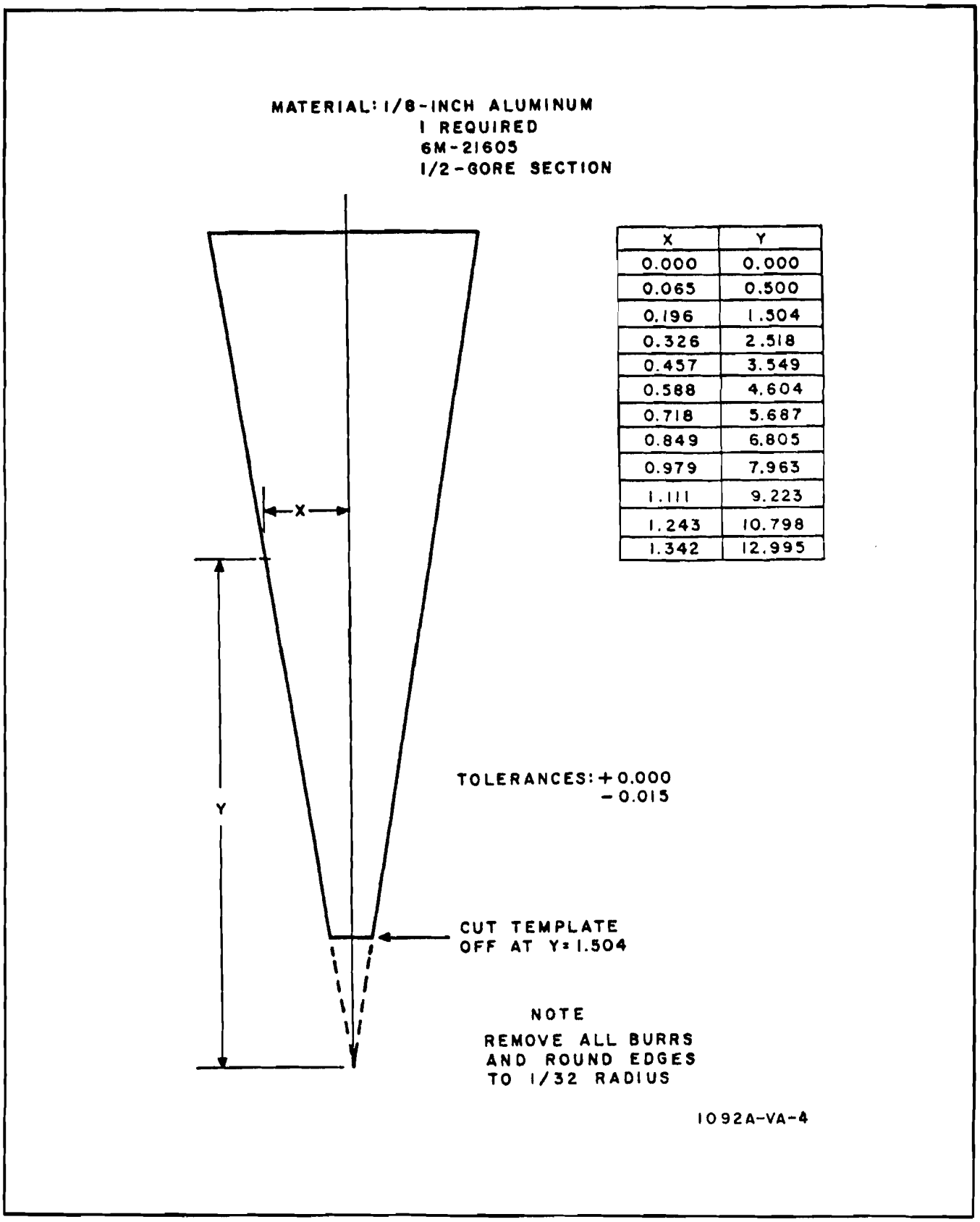


Figure 3. Calculation for 15-Inch Oblate

RIGIDIZATION RATES

It was originally intended to measure rates of rigidization by comparing weight loss with stiffness measurement at selected times during the rigidization procedure. Due to equipment limitations, this was not possible. However, it was determined that the governing factor for time to rigidization was the diffusion constant for the matrix under test.



X	Y
0.000	0.000
0.065	0.500
0.196	1.504
0.326	2.518
0.457	3.549
0.588	4.604
0.718	5.687
0.849	6.805
0.979	7.963
1.111	9.223
1.243	10.798
1.342	12.995

Figure 4. Gore Template for 15-Inch Oblate

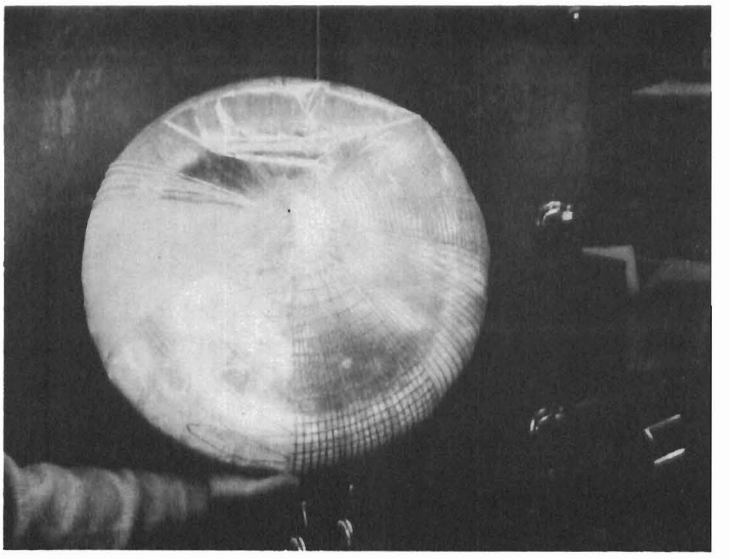


Figure 5. Polar View of Test Areas - Oblate Spheroid - Rigidized - No Air Pressure

Several tests made to determine the feasibility of using a fugitive plasticizer indicated that very long exposure times would be required to reach ultimate rigidization under moderate vacuum (50 to 100 microns). While a reduction in pressure would increase the evaporation rate, the efficiency would depend on the ability to keep the surfaces of fabric swept clean of accumulating vapors. If this can be accomplished, then the diffusion constant of the matrix will determine the speed with which rigidization takes place.

An experiment was designed to determine the effect of a series of reduced pressures on the rate of rigidization. Three samples were prepared as follows:

a. Solvent extracted commercially coated vinyl fiberglas.

b. Solvent extracted polyurethane-coated vinyl fiberglas.

c. Polyurethane composition containing a fugitive plasticizer coated on fiberglas.

NOTE: The fiberglas fabric in all cases was a 28 x 30 count using ECD 450 3/2 yarn in both directions.

Four techniques were employed, differing only in pressure level, to remove vapors from the surface of the samples.

a. The samples were mounted in front of a fan at room pressures (730 mm).

b. The samples were exposed to the house vacuum line (6 mm).

c. The samples were exposed to a mechanical pump (5 microns).

d. The samples were exposed to a diffusion pump (0.01 micron).

The pressures listed were essentially constant for each test. In each case, the convection currents created were adequate to keep the surfaces swept clean.

The fan used in a was a Westinghouse Model PA 1830 run at the slowest possible speed, while stationery (no pivoting or rotation). The samples were mounted in open air 6 inches from the fan blades and perpendicular to their plane of rotation.

Samples exposed to house vacuum and the mechanical pump were hung in a beaker so that all sides and edges were exposed. The beaker was placed in a glass dessicator (with no dessicant) and exposed to the vacuum in question. The line from dessicator to source included in this order: control valve, McLeod gage, liquid nitrogen trap, cutoff valve, and source. When samples were removed for weight measurements, these systems took approximately 1 minute to regain the pressure level.

The setup using the diffusion pump was identical to that used for the house vacuum except that a bell jar was substituted for the dessicator and a Philip gage for the McLeod.

The samples extracted with toluene lost weight at the same rate at all pressures except for minor discrepancies during the first few hours of the test. (This could be due to the excess solvent present. Samples were removed, shaken briskly to remove as much excess as possible, weighed, and the test started.) Differences are noticed for the samples containing triethylphosphate which were exposed to the fan. This probably is due to more rapid removal of the excess present at the beginning of the test. All tests were run for a 7-day period with readings being made hourly at the beginning and daily after the second day.

Since all toluene-extracted samples showed the same weight loss per unit time (except for the first several hours), a composite chart has been drawn for all four test conditions. Average values for the fugitive plasticizer coating are included for comparison in figure 6.

Figure 7 shows the relative differences for fugitive plasticizer with respect to the test condition.

Figure 8 is a plot of fractional weight loss versus the square root of time in days divided by fabric thickness in mils. A calculation of the diffusion constant is made on the figure for the toluene-extracted samples. Such a calculation for the fugitive plasticizer coating is not possible since the sample had not approached equilibrium at 7 days. (Theoretically, the weight loss should approach 12 percent for this sample.)

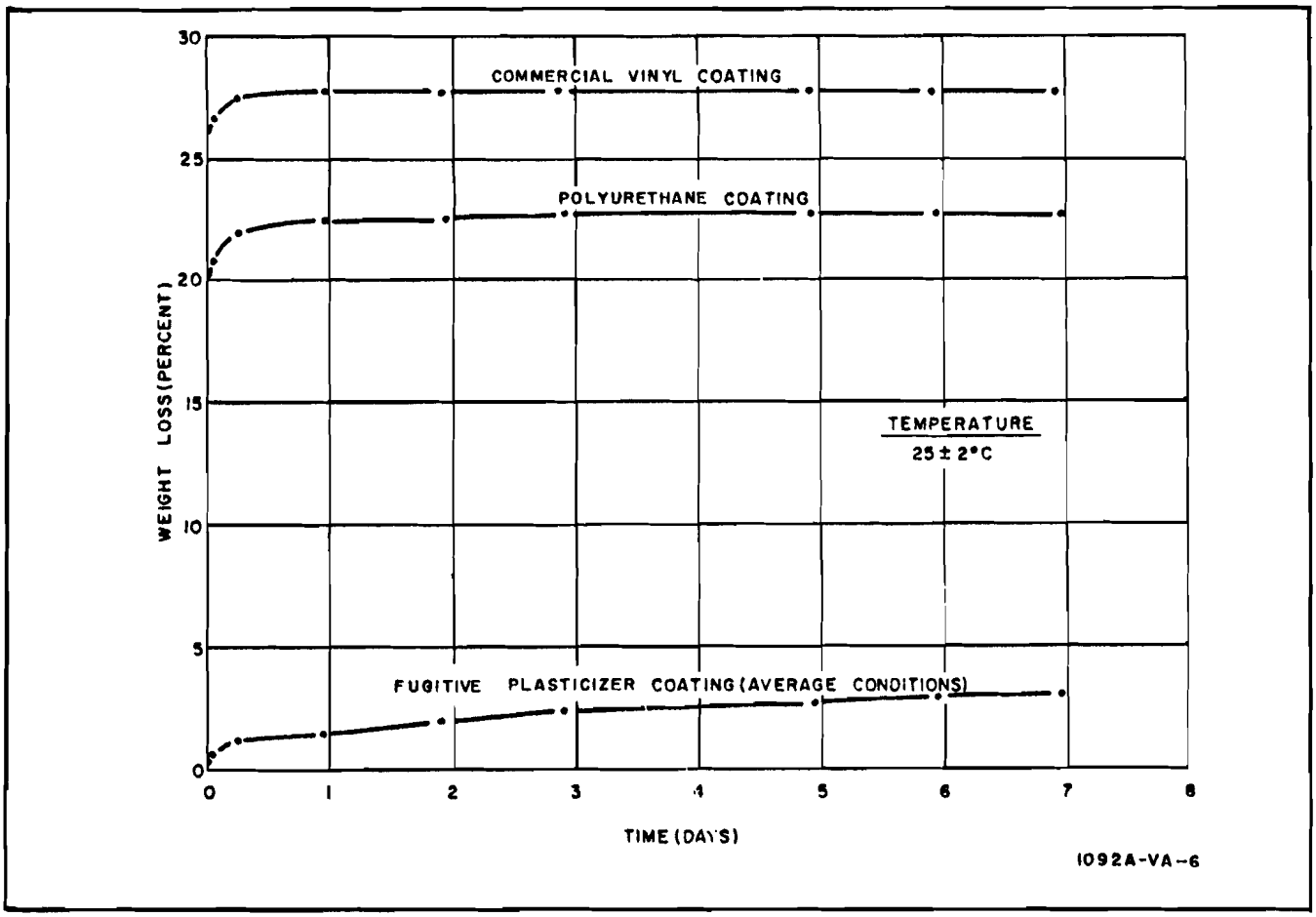


Figure 6. Composite of Weight Loss vs Time - All Conditions

The diffusion constant for the toluene-extracted samples is approximately 1.2×10^{-4} cm^2 per second which is quite large. Theoretically, if the coating had been solid and continuous, with no glass cloth included, it would have been 10^{-7} or less. In short, the loss of toluene is unexpectedly fast, due in part to the matrix tested and probably influenced by thick and thin sections throughout the sample.

In all cases where measurement of the rate of rigidization was attempted there was no pressure differential from one side of the fabric to the other nor were temperature variables incorporated. An evaluation of the effects of pressure and temperature gradients will be required before a precise time increment can be specified for a given matrix. However, it is obvious that the solvent extraction procedure more closely approaches the desired minimum time to rigid the structure.

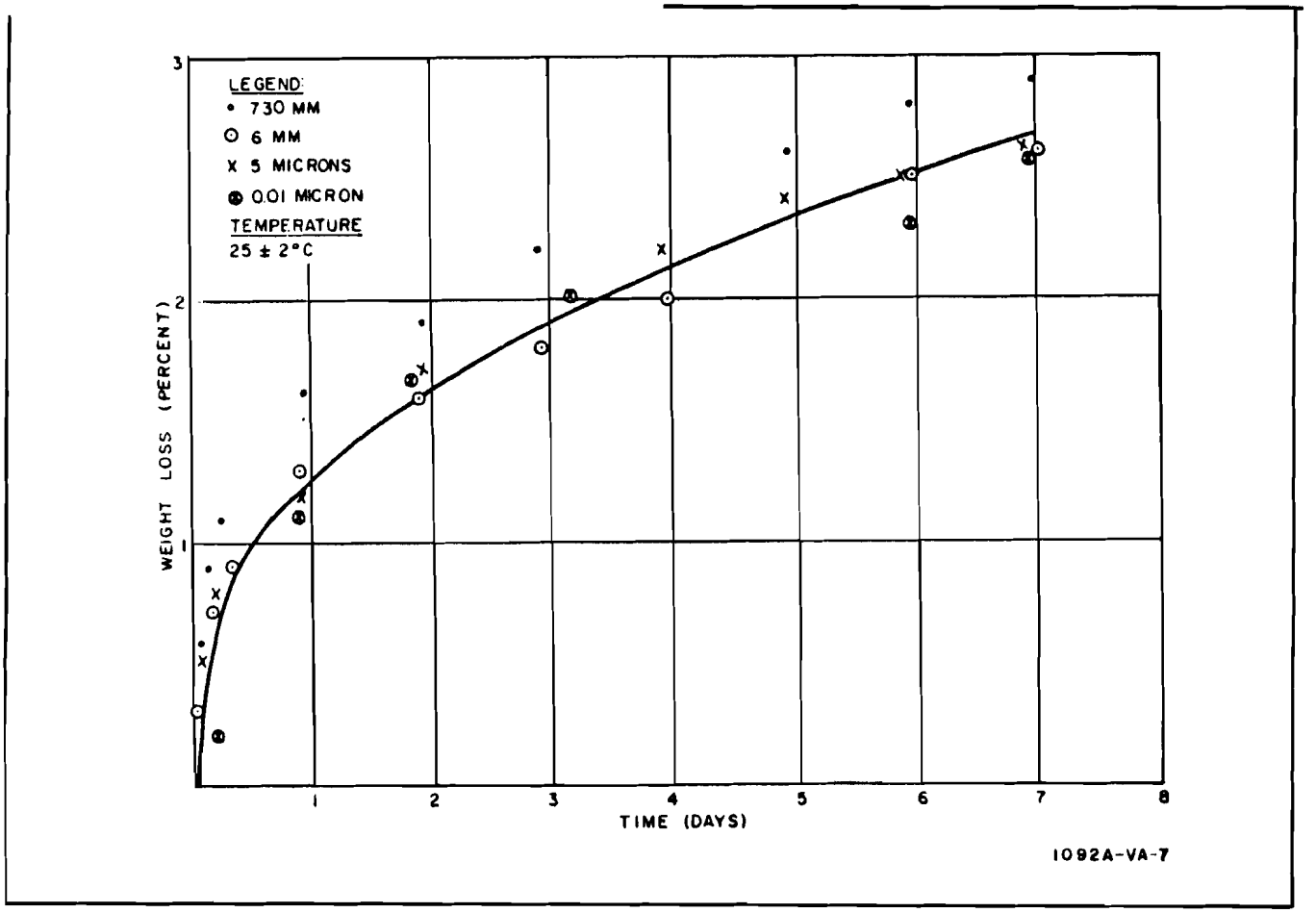


Figure 7. Weight Loss vs Time - Fugitive Plasticizer

YARNS

Original work on coated yarns was confined to plain filament glass (ECD 450 2/2 and ECD 450 4/0) and sodium silicate as an inorganic coating. It was impossible to plasticize the silicate, and all coatings were brittle. Inorganic coatings were discarded after a brief investigation.

Subsequent yarn coating was confined to polyurethane compositions with the investigation including solvent extractable and fugitive plasticizer types. The yarns were all continuous filament fiberglas and included varying degrees of texturization as well as plain constructions.

Work on plain yarns was subcontracted and was restricted to a polyurethane compound based on Adiprene LD-213 with MOCA as a catalyst and containing a high percentage of nonvolatile plasticizer. The subcontractor was requested to precoat yarns and weave a fabric with them so that an equivalent glass weight compared to the commercial fabric used as a standard was obtained. ECD 450 1/0

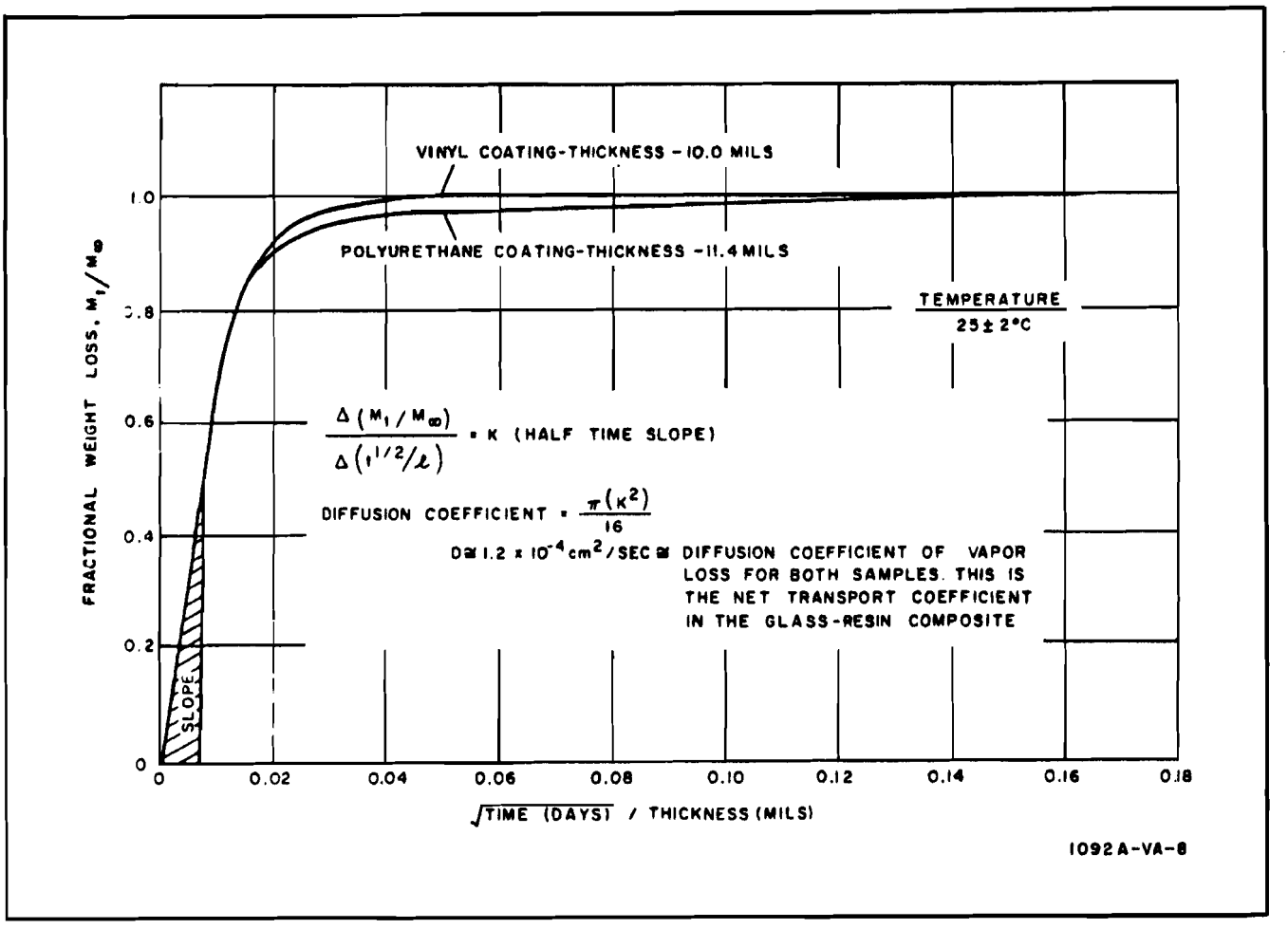


Figure 8. Diffusion Coefficient for Toluene Extracted Samples

with 2.0 TPIZ twist was used as the base yarn and two methods were employed to build up to a 6-yarn bundle. First, six ECD 450 1/0 yarns were coated as a bundle and woven into a 29 x 29 fabric. Second, ECD 450 1/0 yarn was coated separately and plied into a 3/2 bundle. Attempts to weave this bundle were limited to a 29 x 20 construction.

The woven samples were not satisfactory for the intended use because of poor fold resistance and relative stiffness. These characteristics are attributed to the cure cycle used (25 seconds at 460°F) which drove off essentially all the plasticizer. Solvent extraction of the cloth made from 6 ends coated as a bundle gave a 1.2-percent weight loss while the second sample showed no weight loss at all. Theoretically, weight loss by solvent extraction should approach 40 percent for these samples.

A short term fold test confirmed the suspicion that yarns coated in this fashion would not meet our requirements. Table 1 lists breaking strength before and after fold for these fabrics.

TABLE 1

FOLD TEST-PRECOATED YARNS, BREAKING STRENGTH, POUNDS PER INCH

Designation	As Received		2 Week Fold*		Count
	Warp	Fill	Warp	Fill	
(1)	242	235	7	14	29 x 29
(2)	179	168	24	6	29 x 20

* With 1-pound-per-inch load.

(1) Fabric woven from 6 ends ECD 450 coated as bundle.
(2) Fabric woven from 3/2 construction from single end coated ECD 450 1/0.

While these results are not encouraging, it is felt that the underlying theory is correct and that, with proper care and control, fabric can be produced with the desired properties. An attempt was made to saturate a similar glass cloth with the same coating, air drying instead of baking the finish. However, since no effort was made to adjust viscosity, the coating bridged the yarns in places. The results obtained were very erratic but consistently higher than those in table 1. This work is being repeated in an effort to produce uniform test values.

TEXTURIZED YARNS

Experiments with vinyl coated glass cloth containing texturized yarns indicated that a considerable improvement in compression strength was possible when tested in the texturized direction. Stiffness measurements also were somewhat higher in the texturized direction. Since these characteristics point toward improved rigidization capability, a series of texturized yarns was examined and the most likely candidates were selected for further work.

Standard Aeracor DE 150 1/2 with 15-percent texturizing was selected for use in pattern testing since the basic yarn weight was equivalent to the plain yarn and contained the highest degree of texturizing we could obtain. The choice was governed in part by the desire to see the maximum difference possible in terms of rigidization capability. It was compared to plain yarn with two different coating systems being used.

WEAVES

All experimental coating work was confined to plain weaves W-1 and W-4 (listed in table 2) which were procured as raw cloths. All the fabrics in the table were also procured as commercially coated vinyl fabrics. W-2 and W-3 were used exclusively for fold damage determinations while the remainder provided

TABLE 2

GLASS FABRIC DESIGNATIONS AND CONSTRUCTIONS

Sample	Type Weave	Count		Yarn Identification	
		Warp	Fill	Warp	Fill
W-1	Plain	28	30	ECD 450 3/2 (Not Text.)	ECD 450 3/2 (Not Text.)
W-2	Crimpless	28/28	28	1-ECD 450 1/5 Glass, 10 TPIZ with Balanced S-Twist, 1-40 Denier Dacron	ECD 450 1/5 Glass, 10 TPIZ with Balanced S-Twist
W-3	Crimpless	28/28	28	1-ECD 450 2/4 Glass, 6 TPIS 1-70 Denier Semi-dull Dacron	ECD 450 2/4 Glass, 6 TPIS
W-4	Plain	54	30	ECD 450 1/2 (Not Text.)	ECD 150 1/4 (9 percent texturized)
W-5	Plain	28	22	DE 150 1/3 Text. (45-9-87)*	DE 150 1/3 Text. (45-9-87)
W-6	Plain	34	28	DE 150 1/2 Text. (45-6-87)	DE 150 1/2 Text. (45-9-87)
W-7	Plain	34	18	DE 150 1/2 Text. (45-6-87)	DE 150 2/2 Text. (60-12-87)
W-8	Plain	34	16	DE 150 1/2 Text. (45-6-87)	DE 150 2/2 Text. (60-12-87)
W-9	Plain	34	24	DE 150 1/2 Text. (45-6-87)	DE 150 1/3 Text. (45-9-87)
W-10	Plain	34	26	DE 150 1/2 Text. (45-6-87)	DE 150 1/3 Text. (45-9-87)
W-11	Plain	34	28	DE 150 1/2 Text. (45-6-87)	DE 150 1/3 Text. (45-9-87)

*First No. - Airline Pressure, psi
Second No. - % Texturized
Third No. - Take up Speed, yds/min.

stiffness and compression data which served as a guide in the selection of the proper complex to use for rigidization capability. W-7 and W-8 are identical in construction but were prepared on separate occasions.

FOLD DAMAGE

Since compensation for fold damage to glass fabrics is normally reflected in breaking strength requirements and a concurrent weight penalty, we investigated some methods to reduce or eliminate the loss of strength. The unique crimpless constructions (W-2 and W-3) offer the advantage of evaluating the effects of tension and compression separately.

In fold tests conducted over a 3-month period on W-2 (using a 1-pound-per-inch of fold load, all compression samples showed severe loss while tension values were within experimental error of the values for unfolded specimens. Bias folding at 45 degrees eliminated the loss entirely, but small angle increments showed no improvement. The heavyweight construction (W-3) was somewhat better than plain weave and considerably better than the lightweight version. The poor performance of W-2 is attributed to either the yarn ply or excessive loading for this weight of fabric.

COATING SYSTEMS

This effort was designed primarily as a study of the mechanical aspects of fibrous structure materials. Since the study implies coated fabrics, the coatings considered were deliberately limited to polyurethane polymers using an amine cure and commercial vinyl coated glass fabrics. The commercial vinyl-coated fabrics were used as standards and to develop an understanding of the capabilities of a variety of glass fabrics.

The development of a polyurethane compound which would remain flexible after coating and yet rigidize when properly treated required employment of some unusual formulation procedures. For example, an amine cure normally sets up very quickly; yet, an amine was necessary to provide the desired rigidization capability.

The initial work was an investigation of possible plasticizers and curing agents other than MOCA (4, 4' methylene - bis - 2 - chloroaniline) which would provide the desired characteristics. Polar plasticizers, such as trioctylphosphate and tricresylphosphate, were satisfactory, with increased polarity tending to extend pot life to a useful level. Effort during this stage of development was concentrated on rigidization by solvent extraction of the plasticizer.

It was soon realized that, by using a more volatile plasticizer such as triethylphosphate, a compound might be prepared which would rigidize on exposure to high vacuum or heat. As it has turned out, vacuum rigidization would require a very long time, but rigidization is accomplished very readily with the application of heat.

The effect of additives to the compound was studied by adding hollow glass spheres (Eccospheres-R) to the more promising compositions. This does not seem to aid stiffness characteristics, but does produce a marked effect on compressive load bearing capability.

COMPRESSION TESTING

Rigidization capability can be measured, in part, with a test which produces a load-bearing limit for a given matrix. A cylindrical shape was chosen for test since this, theoretically, will produce the highest strength-to-weight ratio in compression testing.

Initial testing was confined to the standard coated fabric to determine whether height or diameter had a significant effect on the buckling load. This series included both fabric directions and, allowing for imperfections, verified the mathematical assumption that the cylinders would behave as thin-wall homogeneous structures. Construction techniques apparently have a greater effect than other variables such as weight and thickness. Significant differences occur with changes in weave and/or coating. For example, the average buckling load for the standard weave with either commercially coated vinyl or an unfilled polyurethane is approximately 30 pounds. The same coatings applied to a texturized weave (W-5) average 55 pounds. The addition of Eccospheres-R as a filler greatly increases the buckling load giving values in excess of 100 pounds on texturized cloth.

A mathematical procedure for predicting the range of buckling was developed based on the assumption that these cylinders behave as thin wall homogeneous structures. Experimental values for bending stiffness (S_b) are derived from the slope attained from zero through the straight-line portion of an Olsen stiffness test graph. This is a measurement of the percentage of load scale reading divided by the angular deflection in radians.

Values for stiffness in compression are measurements of the change in load with respect to the change in deflection (S_c). These values are determined experimentally on the Instron Tester for the cylinder in question. The buckling load range is given by:

$$1.44 \quad S_c \, S_b < P < 2.17 \quad S_c \, S_b$$

where:

S_c = compression stiffness
S_b = bending stiffness
P = local buckling load

It should be noted that the calculated buckling load ranges tend to be slightly high, which is attributed to imperfections in the constructed cylinder.

STIFFNESS TESTING

All stiffness testing was done with a Tinius Olsen Stiffness Tester designed for use with plastics. The plot of load scale reading versus angular deflection provides a convenient method of calculating modulus of elongation in stiffness if the thickness of the specimen is known. Bending stiffness, which ignores thickness and has a different constant, is also readily available. A "figure of merit" for modulus and stiffness incorporates the weight of the cloth to help minimize misinterpretation due to wide variance in applied coating. However, all comparisons of fabrics using figure of merit must be confined to one characteristic at a time since one includes thickness while the other does not.

These values are defined by the following equations:

$$E = \frac{4\,(S)}{(W)\,(d)^3} \cdot \frac{(M)\,(LSR)}{(100)\,(\phi)}$$

$$S_b = \frac{6\,(S)}{W} \cdot \frac{(M)\,(LSR)}{(100)\,(\phi)}$$

$$\text{Figure of merit (modulus)} = \frac{E}{\text{weight of fabric in ounces per square yard}}$$

$$\text{Figure of merit (stiffness)} = \frac{S_b}{\text{weight of fabric in ounces per square yard}}$$

where:

E = modulus of elongation in stiffness
S_b = bending stiffness
S = span over which deflection is measured
W = width of test sample
d = thickness of test sample
M = moment weight
LSR = load scale reading
ϕ = angular deflection in radians

Results on repetitive samples were inconsistent due to hidden variables in sample preparation as well as to different effects contributed by the instrument when the moment weight of span was changed.

Because of the uncertainties inherent in the data obtained, no broad statements (based on stiffness measurements) can be made in terms of fabric or coating except, perhaps, that a texturized cloth provides more stiffness than a plain weave.

CONCLUSIONS

Relative merit of a given, rigidized coated-fabric matrix can be determined by buckling strength under compression loading. The stiffness test for plastics may provide additional data on each fabric provided certain precautions are taken in comparing samples.

Buckling strength is improved by the use of texturized fabrics. Considerable increase in this characteristic can be realized by the incorporation of Eccospheres-R in the coating.

Polyurethane coatings can be formulated so that rigidization takes place by solvent extraction or by evaporation of plasticizer. The removal of fugitive plasticizer from the coated fabric is more rapid by heat application than by exposure to vacuum, although this type can also be solvent extracted.

Toluene extracted Adiprene LD 213-MOCA systems tend to be stiff in the extraction medium. Preliminary work indicates that a properly balanced solvent choice can minimize or eliminate this condition.

Rates of rigidization are controlled by the diffusion coefficient of the matrix under test, provided the surface of the fabric is continuously swept clean of vapor until equilibrium is reached. The time to rigidization can be estimated by weight-loss measurements used in calculating the diffusion coefficient although the results would be more positive if the change in modulus could also be measured throughout the rigidization procedure.

Efforts to reduce fold damage on coated glass fabrics were not successful for the weaves tested. Changes in construction, including ply and twist modifications, may produce better results than those reported here.

Where the expected improvement in resistance to fold damage by weaving yarns precoated with polyurethane did not materialize, the failure is attributed to the lack of flexibility in the yarn coating rather than to the concept being incorrect.