WADC TECHNICAL REPORT 58-486
ASTIA DOCUMENT NO. 210225

EFFECTS OF VARIOUS METHODS OF WET CONDITIONING ON THE STRENGTH PROPERTIES OF SEVERAL GLASS-FABRIC-REINFORCED PLASTIC LAMINATES

BERT P. MUNTHE
ROBERT L. YOUNGS

FOREST PRODUCTS LABORATORY, FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE

MARCH 1959

MATERIALS LABORATORY
USAF CONTRACT NO. DO 33(616)-58-1
PROJECT NO. 7340

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

McGregor & Werner Midwest Corp., Dayton, O.
29-598-400-4-17-59

FOREWORD

This report was prepared by the U. S. Forest Products Laboratory under USAF Order No. 33(616)-58-1. Work here reported was initiated by the Materials Laboratory under Project No. 7340, "Rubber, Plastics, and Composite Materials," Task No. 73400, "Structural Plastics." It was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Mr. G. P. Peterson acting as project engineer.

Work here reported was conducted during the period August 1956 to April 1958.

ABSTRACT

This report presents the results of tests to evaluate the effects of various types and durations of wet exposure on the tensile, compressive, and flexural properties of epoxy, polyester, phenolic, and silicone laminates reinforced with 181 glass fabric that had various types of fabric finish. The tests were made after normal conditioning and after various periods of wet exposure. Wet conditions used were (1) immersion in water at 73° F., (2) exposure to an atmosphere at 100° F. and approximately 100 percent humidity, or (3) boiling in water.

Tensile strengths were reduced about equally by 30 days in water at 73° F. or by 2 hours in boiling water. Compressive strengths were reduced about the same amount by either 2 hours in boiling water, 30 days in water at room temperature, or 30 days at high humidity. Modulus of rupture was reduced about equally by equal periods of immersion in water at room temperature or exposure to high humidity at 100° F. At either of these conditions, the reduction after 30 days was generally similar to that observed after exposure in boiling water for 1/2 or 1 hour, but was generally less than that observed after exposure for 2 hours in boiling water.

The various laminates differed considerably in their response to the various wet exposure conditions. However, the results indicate that a 2-hour wet exposure in boiling water is a reasonable substitute for the standard 30-day immersion in water at room temperature. Any discrepancy is likely to be on the conservative side, with greater strength reduction after the 2-hour period in boiling water than after 30 days in water at room temperature.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

R. T. Schwartz
R. T. Schwartz
Chief, Organic Materials Branch
Materials Laboratory

TABLE OF CONTENTS

INTRODUCTION[1]

Data on tests of polyester laminates indicate that glass-fabric-reinforced laminate specimens that have been boiled in water for 2 hours show about the same reduction in strength properties as do those immersed in water at 73° F. for 30 days or exposed to 100 percent humidity at 100° F. for 30 days. The 30-day soak at 73° F. is considered a standard condition for evaluating the wet strength properties of laminates, but the 2-hour boil is often considered for use as an approximation of the standard wet condition at a considerable saving in time. However, this assumption of approximately equal effect for the three types of wet exposure is based on limited data confined largely to polyester laminates.

The purpose of this investigation was to compare the effects of the three types of wet exposure on the tensile, compressive, and flexural properties of various polyester, epoxy, phenolic, and silicone laminates of 181 glass fabric with different types of fabric finish.

PANEL FABRICATION

Ten panels, each 1/8 inch thick by 36 inches square, were fabricated at the U. S. Forest Products Laboratory from commercial resins and fabrics. Each of the panels was made up of 12 or 13 parallel-laminated plies of 181 glass fabric with these fabric finishes and resins:

Panel No.	Resin	Fabric finish
	Epoxy	
582	Epon 828 with Curing Agent CL	Volan A
	Heat-resistant polyester	
583	Laminac 4232	Garan
	Phenolic	
584	CTL-91LD	Volan A
585	CTL-91LD	Linde Y-1100
	Silicone	
586	DC 2106	112
587	DC 2106	T-31

[1] Manuscript released by author for publication as a WADC Technical Report July 1958.

	Polyester	
588	Paraplex P-43	T-31
589	Paraplex P-43	A-172
590	Paraplex P-43	OC-301
591	Paraplex P-43	Volan A

A detailed fabrication description is given in Appendix I. Average thickness, resin content, specific gravity, and Barcol hardness of each panel are listed in table 1.

PREPARATION AND EXPOSURE OF SPECIMENS

Ninety-six flexure, 96 compression, and 60 tension specimens were cut parallel to the warp direction from each of the ten laminated panels. Figure 1 is a cutting diagram that illustrates the position in the laminates from which the various test specimens were taken.

Eight groups of specimens (A through H), each consisting of 8 flexure, 8 compression, and 5 tension specimens, were selected by randomization from each of panels 582 through 590. Specimens were also selected by the same method for panel 591 (Paraplex P-43 laminate reinforced with 181-Volan A glass fabric), but tests were made only for groups A, B, D, and G.

A group of specimens from each laminate was exposed to the following conditions before they were tested at room conditions:

A. Controls -- conditioned at 73° F. and 50 percent relative humidity for at least 15 days.
B. Immersed for 30 days in distilled water at 73° F.
C. Immersed for 90 days in distilled water at 73° F.
D. 30 days at 100° F. and approximately 100 percent relative humidity.
E. 90 days at 100° F. and approximately 100 percent relative humidity.
F. Boiled in distilled water for 1/2 hour.
G. Boiled in distilled water for 2 hours.
H. Boiled in distilled water for 4 hours.

TESTING

The flexure specimens were 1/2 inch wide by 4 inches long by the thickness of the laminate. Method of testing conformed with the requirements of Method

1031.1 of Federal Specification L-P-406b. They were tested flatwise over a span of 2 inches at a testing machine head speed of 0.05 inch per minute. Tests were made on a mechanical-type testing machine equipped with a sensitive electronic weighing system that employed bonded-wire strain gages. Load-deflection data were plotted automatically on a graphic recorder, which was driven synchronously with respect to the crosshead. Center deflection of the specimen was also checked with a dial gage reading to 0.001 inch.

The compression specimens were 1/2 inch wide by 3-1/16 inches long by the thickness of the laminate. The ends were ground on a surface grinder to insure flat and parallel loading surfaces. Specimens were restrained from buckling by using a supporting jig of the type described in Method 1021.1 of Federal Specification L-P-406b. Specimens were tested in a hydraulic testing machine, which was equipped with a spherical loading head, at a head speed of 0.05 inch per minute. The maximum load was determined but no deflection data were taken.

The tension specimens were 3/4 inch wide, 8-7/8 inches long, and the thickness of the laminate. With the exception of the length, the specimens conformed to the requirements for the Type 2 specimen given in Method 1011 of Federal Specification L-P-406b. They were tested in a mechanical-type testing machine, which was equipped with Templin tension grips, at a head speed of 0.2 inch per minute. Maximum load was determined but no deflection data were taken.

STATISTICAL ANALYSIS

The individual test results of maximum strength in tension, maximum strength in compression, and modulus of elasticity and modulus of rupture in flexure were used in analyses of variance to determine the statistical significance of the observed exposure effects on each property. The effect of the random variable (the laminate) and interactions involving this variable, were tested for significance by the F-test based on the error variance. The effect of the fixed variable (the exposure) was tested for significance by the F-test based on the mean square of the first order interaction with the laminate variable.

In conjunction with this analysis, values of standard deviation and of least significant difference were calculated for each property of each laminate, as well as for the combined data for each property. The values of standard deviation thus calculated indicate the degree of scatter in the test results. The values of least significant difference were used to compare the effects of individual exposure conditions on the properties of each laminate, as well as on all the laminates taken together.

PRESENTATION OF RESULTS

Table 2 presents the average results of tension and compression tests conducted on specimens from each laminate after normal conditioning and after each type and duration of wet exposure. Also included are the standard deviation value for specimens from each laminate and the values of least significant difference at the 5 percent and 1 percent levels of probability for the individual mean values for each exposure for each laminate, as well as for the mean values for each exposure for all the laminates.

Table 3 presents the average values of modulus of rupture and modulus of elasticity from tests in flexure after normal conditioning and after each type and duration of exposure. Included also are values of standard deviation and least significant difference that correspond to those of table 2.

Table 4 presents values of moisture absorption measured in flexure specimens from each laminate after each type and duration of exposure.

A comparison of the effect of 30-day immersion in water at room temperature with that of other exposures is presented in Table 5.

Figures 2, 3, 4, and 5 illustrate the effect of the various conditions and durations of exposure on the maximum tensile strength, maximum compressive strength, modulus of rupture, and modulus of elasticity, respectively, of the individual laminates. Figure 6 illustrates the effect of the various conditions and durations of exposure, combined for all the laminates, on the above-mentioned mechanical properties. Present practice is to consider a 2-hour immersion in boiling water approximately equivalent in effect on strength to either 30 days' immersion in water at room temperature or 30 days' exposure at 100° F. and 100 percent humidity; therefore, the abscissa of each figure was set up to equate those three conditions of exposure on the time scale. An equivalent effect is thus indicated by a close proximity of the data points for the various types of exposures.

Previous data on modulus of rupture as a function of exposure time at 100° F. and approximately 100 percent humidity[2] indicate that the relationship up to about 180 days can be fairly well characterized by a linear plot on a semilogarithmic scale (strength versus log time). Similar treatment of the average values from this investigation and replotting on a uniform scale gives the curves shown in Figure 6 for each of the properties.

[2] Werren, Fred. Effects of Fabric Finish and Wet Exposure on Strength Properties of Glass-Cloth Polyester Laminates. WADC Technical Report No. 53-483, March 1955, and Supplement I, June 1957.

DISCUSSION

It is apparent from the average test values listed in Tables 2 and 3 and from the graphical presentation of the results in Figures 2, 3, 4, and 5 that there were marked differences among the laminates in their response to the various conditions and durations of exposure investigated. Statistical confirmation of this difference in behavior is indicated by the high degree of significance of the interaction between exposures and laminates in the analysis of variance for each property.

Much of the difference in response on the part of the individual laminates can, of course, be attributed to the differences in type of fabric finish and in type of resin. Moreover, the values of laminate characteristics in Table 1 indicate that there was considerable variability among the laminates as to resin content. This is true not only between the various resin types, where differences in resin content are to be expected, but also between laminates made with the same resin type. While this probably reflects the effect of various fabric finishes in allowing different degrees of resin flow under similar laminating conditions, it may also be due to differences in void-freeness, which would have some effect on the behavior of the laminates after exposure to wet conditions. However, an effort was made to produce void-free panels, and general observation of the polyester laminates indicated that they were essentially void free.

Another readily apparent difference in the behavior of the various laminates is the amount by which strength properties of all exposed material, taken as a whole, were lower than those of the normally conditioned material. For some laminates, such as the laminate of P-43 polyester resin and fabric with T-31 finish, the difference between the exposed material and the normally conditioned material is quite marked. For other laminates, such as the one of P-43 polyester resin and fabric with A-172 finish, the difference between properties of exposed and unexposed material is relatively small.

The question then arises as to whether or not the response of the various laminates to the exposure conditions investigated is essentially similar, once the difference between exposed and unexposed material has been eliminated from consideration. It is apparent from Figures 2 through 5 that a consideration of the individual laminates, including only the exposed material, indicates a considerably higher degree of uniformity than when the normally conditioned material is also considered. There are still appreciable differences between the individual laminates, however. Statistical testing of these differences on an overall basis was accomplished by repeating the analysis of variance with the values for normally-conditioned material excluded. The results of such analysis confirmed that the values for normally conditioned material contributed a very high proportion of the sum of squares for treatment (exposure); they also indicated that the laminates differed significantly as to their response to the various exposure conditions, though the level of significance was appreciably reduced.

It is thus apparent that considerable caution must be exercised in arriving at any overall conclusions as to the effects of the various exposures and their comparability. Rather, individual cases must be considered as to their similarities and differences when any such conclusions are drawn.

Two chief difficulties are encountered in attempting to compare either the responses of individual laminates, as presented in Figures 2 through 5, or an overall response based on all laminates, as in Figure 6. The first difficulty is the lack of sufficient data points to establish, with any degree of certainty, the relationship between strength and duration of exposure to any of the three types of exposure -- water immersion, 100 percent humidity, or boiling water. The second difficulty is in the apparent inconsistencies indicated by the test results of many individual laminates and, to a lesser extent, by their overall relationship.

Maximum Tensile Strength

When the effect of the various exposures on maximum tensile strength is combined for all the laminates to give an overall effect of each type and condition of exposure, there is good agreement between the effect of 30 days of water immersion and that of 2 hours of boiling. However, the overall strength reduction after 30 days at 100° F. and 100 percent humidity was significantly greater than that observed after either 30 days of water immersion or 2 hours of boiling. It is interesting to note that, while there are statistically significant differences between the effects on maximum tensile strength of the various exposure conditions, there are no significant differences between the effects of the exposure times investigated for any of the exposure conditions. This indicates that tensile strength was affected more by the condition of exposure than by the time of exposure for all times investigated.

In view of the fact that marked differences in response between the individual laminates have been shown to exist, it is not sufficient, and may be misleading, to consider only the overall effect. Some consideration must also be given to the behavior of the individual laminates.

Tension test specimens from the epoxy laminate were affected almost equally by 30 days of water immersion and 1/2 hour of boiling. Exposure to high humidity at 100° F. reduced tensile strength considerably more than water immersion at room temperature.

Specimens from the heat-resistant polyester laminate were affected about equally by all the exposure conditions investigated.

The tension test specimens from the phenolic laminates and those from the silicone laminates were affected in much the same manner by comparable exposure conditions. Fabric finish appeared to make little difference in the response to the various exposure conditions. Although strength was reduced slightly more after 2 hours of boiling than after 30 days' immersion in water, Table 5 indicates that this difference is generally not statistically significant. The one instance of significance, the phenolic laminate reinforced with fabric having Y-1100 finish, is marked by a 30-day water immersion value that is greater than that for unexposed material; hence, it casts some doubt on the accuracy of the observed difference.

Although the effect of boiling on the tensile strength of specimens from the polyester laminates varied somewhat with respect to the other types of exposure, these specimens differed from those of the other laminates investigated in generally showing a greater strength reduction after water immersion at room temperature than after comparable periods of exposure to high humidity at 100° F. This difference was most pronounced after 30 days and negligible after 90 days. In each instance the strength reduction after 2 hours in boiling water was significantly less than that after 30 days' immersion in water at room temperature. The observed differences in effect of boiling on tensile strength are somewhat erratic; they give some indication that strength was actually increased by boiling specimens for periods of greater than a half hour. If this is true, perhaps the increased strength is caused by additional resin cure that results from the heat of the boiling water.

Maximum Compressive Strength

In considering the effect on maximum compressive strength of all laminates at all exposures, it is apparent that there is a higher degree of similarity between the effects of the various exposure conditions than was the case for maximum tensile strength. It is also apparent that the effects of the various exposures are somewhat more severe than were their effects on tensile strength. There was no statistically significant overall difference between 30 days of water immersion, 30 days of 100 percent humidity, and 2 hours of boiling in their effect on compressive strength. As was the case for tensile strength, agreement between the effects of 30-day immersion and 2-hour boil was better than that between either of those and 30 days at high humidity. The differences were much less than for the effects on tensile strength, however.

Figure 3 indicates that most of the individual laminates were also characterized by relatively more uniform and more severe effects of exposure on compressive strength than was evident for tensile strength of the same laminate. Compressive strength of test specimens from the epoxy laminate was affected similarly by 30 days of water immersion and 2 hours of boiling in water, with no significant difference between the results. The average compressive strength values for all other exposures were significantly different from that for 30 days of water immersion.

Specimens from the heat-resistant polyester laminate showed very close agreement in the effects of 30 days of water immersion, 30 days of high humidity, and 2 hours of boiling, with a slightly greater strength reduction observed after longer exposure to high humidity.

The phenolic and silicone laminates showed consistently good agreement between the effects on compressive strength of equal periods of exposure to water immersion at room temperature or 100 percent humidity at 100° F. The effect of exposure was more pronounced on the phenolic laminates than on the silicone laminates. Possible differences in effects of fabric finish were indicated by the fact that a significantly greater strength reduction was observed after 2 hours or more of boiling than after 30 days' immersion in water in compression specimens from two laminates. These two were the phenolic laminate reinforced with fabric having a Volan A finish, and the silicone laminate reinforced with heat-cleaned (112) fabric. The corresponding phenolic and silicone laminates reinforced with fabric having Y-1100 or T-31 finish did not show such an effect.

The compressive strength of polyester laminates tested did show a consistently similar effect for 30 days' immersion in water and 30 days' exposure to high humidity. In most instances the agreement with the effect of 2-hour boil was also good. The single laminate that did not exhibit such agreement was the one reinforced with fabric having T-31 finish; here the compressive strength-time relationship in boiling differed from that of most other laminates in showing a pronounced decrease in strength after more than 2 hours of boiling. For most laminates the difference in effect between 2 hours of boiling and 4 hours of boiling was quite small.

Modulus of Rupture

The modulus of rupture of flexural specimens was generally affected about equally by equal periods of either water immersion at room temperature or exposure to high humidity at 100° F. However, the reduction of modulus of rupture after 2 hours of boiling was consistently more than that after 30 days at either of the other types of exposure, with one exception. There was generally better agreement between the effects of the 1/2-hour boil or the supplementary 1-hour boil, and the 30-day immersion or high humidity exposures, than between the 2-hour boil and the 30-day immersion or high humidity exposures.

The epoxy laminate differed from most of the other types of laminates in showing a significantly greater reduction in modulus of rupture after 30 days' exposure to high humidity than after 30 days' water immersion. This was characteristic of the epoxy laminate for all the properties investigated, with the exception of modulus of elasticity. The other laminate showing the same type of behavior with regard to modulus of rupture was the phenolic laminate reinforced with fabric having Volan A finish. It may be significant that the epoxy laminate was also reinforced with fabric having Volan A finish.

The heat-resistant polyester laminate showed a greater reduction in modulus of rupture after any of the three standard exposure conditions (immersion in water at room temperature for 30 days, in boiling water for 2 hours, or exposure to high humidity at 100° F. for 30 days) than was observed for either tensile strength or compressive strength. However, the agreement between effects of those three exposure conditions on modulus of rupture was good, just as it was for the other strength properties.

The phenolic laminates also showed a greater reduction in modulus of rupture after exposure than in other strength properties. All three exposure conditions produced significantly different effects on the modulus of rupture of specimens from the laminate reinforced with fabric having Volan A finish. The specimens from the other phenolic laminate, which was reinforced with fabric having Y-1100 finish, showed good agreement between the effects of 30-day soaking and 30 days at high humidity, but a significantly greater effect for all boiling periods greater than 1/2 hour.

The two silicone laminates resembled each other under all conditions and times of exposure. Agreement between the results of tests on specimens exposed for 30 days in water at room temperature and those exposed for 30 days at high humidity at 100° F. was very good, but a much greater strength reduction resulted from even 1 hour of boiling.

The polyester laminates differed considerably among themselves in the effect of the various exposures on modulus of rupture. Most of the laminates were less affected by exposure to high humidity than by equal duration of immersion in water. Except for the polyester laminate reinforced with T-31 finished fabric, most laminates were also affected more by 2 hours of boiling than by 30 days under either of the other exposure conditions.

The observed differences between modulus of rupture and strength in tension or compression in the effects of boiling, as compared to soaking at room temperature or high humidity at 100° F., may be partially explainable on the basis of two interrelated factors. One factor is the distribution of moisture and heating effects throughout the cross section of the test specimens. The other is the differences in stress distribution between specimens under direct stress and those subjected to bending stress. Since moisture diffuses into these laminates rather slowly and the laminates were not conditioned long enough to reach equilibrium, there must have been a rather steep moisture gradient in the specimens at the time they were tested, with higher moisture content near the surface than in the interior. This effect should be particularly pronounced in the boiled specimens, where the time allowed for moisture diffusion was much shorter than for the other types of exposure.

In tension or compression testing, a direct stress is applied to the entire cross section and would be resisted by both the outer weakened portion of the specimen and the stronger central portion. In flexure testing, however, the stresses are greatest near the surface of the two broad faces of the specimen, and thus coincide with the location of greatest weakening under a steep moisture gradient. It is conceivable, therefore, that in 1/2 hour or 1 hour of boiling, sufficient moisture could be absorbed in the outer layers of the laminate to produce the same weakening as 30 days of water immersion at room temperature or exposure to high humidity; this could occur with a smaller take-up of moisture.

For the epoxy and polyester laminates, it was generally true that the amount of moisture absorbed by flexural specimens in boiling was relatively small with respect to the resulting strength reduction, by comparison with strength reduction-moisture absorption relationships for the other types of exposure. For the phenolic and silicone laminates, however, the greater reduction of modulus of rupture by boiling flexural specimens was accompanied by greater moisture gain than was the case for the other exposure conditions.

Although most of the laminates showed a tendency toward negative correlation between modulus of rupture and moisture absorption, the degree of correlation was generally low. The silicone laminate reinforced with fabric having 112 finish and the polyester laminate reinforced with fabric having T-31 finish showed a higher degree of negative correlation than did the other laminates.

The relative effects on modulus of rupture of the various types of exposure differed somewhat from the relative effects observed on modulus of rupture of polyester laminates in a previous study.[2] In that investigation it was observed that exposure to an atmosphere at 100° F. and 100 percent humidity caused a greater strength reduction than did a similar period of immersion in water at room temperature. Further, there was generally good agreement between the effects on modulus of rupture of 2 hours of boiling and of 30 days of water immersion at room temperature. Such discrepancies between the results of different investigations indicate that undetermined factors have an important bearing on the response of glass-fabric-reinforced plastic laminates to various types of wet conditioning.

Modulus of Elasticity

Modulus of elasticity of flexural specimens was generally affected less, percentagewise, by water immersion at room temperature and high humidity at 100° F. than were other mechanical properties. However, the effect of boiling, which was more severe than that of other exposures, reduced the modulus of elasticity to a percentage of the normal that corresponds quite closely to the effect of similar exposure on maximum strength in tension.

Although Table 5 indicates several instances of statistical significance of differences in effect between 30 days of immersion in water and the other exposure times and conditions employed in this investigation, most of the differences are less than 7 percent and are probably so small as to be of little practical significance. The outstanding exception is the polyester laminate reinforced with fabric having A-172 finish. Modulus of elasticity of boiled specimens from that laminate was about 15 percent less than that of specimens immersed in water at room temperature for 30 days.

Also contributing to the large number of statistically significant differences indicated in Table 5 was the rather small amount of variability inherent in the data, as compared with the variability of data on other properties. For most of the individual laminates, as well as for the laminates as a whole, the coefficient of variation for modulus of elasticity was less than that for other properties. With the exception of the laminate made with the heat-resistant polyester resin, neither water immersion nor high humidity had any appreciable effect on modulus of elasticity. Boiling for periods of 1 hour or more did, however, significantly reduce modulus of elasticity of half of the laminates investigated. This may have been due to the effects discussed under the section dealing with modulus of rupture.

There was generally better agreement between the effect of 30 days of water immersion and that of 1/2 hour of boiling than between the effect of 30 days of water immersion and 2 hours of boiling. The laminate made with heat-resistant polyester resin differed from the others in showing a significant decrease in modulus of elasticity after all of the exposures, but no significant difference between the effects of any two of them.

CONCLUSIONS

Tensile, compressive, and flexural tests were made after various conditions and durations of wet exposure of epoxy, polyester, phenolic, and silicone laminates reinforced with 181 glass fabric having various types of fabric finish. On the basis of the results of these tests, the following conclusions may be drawn:

(1) Glass-fabric-reinforced plastic laminates made with different resins and different fabric finishes are likely to respond quite differently to comparable exposure conditions. This difference is less pronounced, but still evident, when comparisons are drawn between the effects of various exposures rather than between exposed and unexposed material.

(2) Under the exposure conditions investigated, compressive strength and modulus of rupture are most severely affected and modulus of elasticity is affected only slightly.

(3) Pooled data from all laminates indicate good agreement between the effects of 30 days in water at room temperature and those of 2 hours in boiling water on maximum tensile strength and maximum compressive strength. Pooled data also indicate good agreement between the effects on flexural properties of 30 days in water at room temperature and of 1/2 hour or 1 hour in boiling water, with greater reduction after 2 hours in boiling water.

Pooled data indicate that maximum tensile strength and flexural properties are reduced about the same amount by 30 days in water at room temperature as by 30 days at 100° F. and 100 percent humidity, but maximum compressive strength is reduced more by the high humidity exposure than by room-temperature water immersion.

However, the marked differences between laminates in their response to various types of wet conditioning indicate that considerable caution must be exercised in applying conclusions based on pooled data to describe or predict the behavior of individual laminates.

(4) A 2-hour wet exposure in boiling water appears to be a reasonable substitute for the standard 30-day immersion in water at room temperature. Any discrepancy is likely to be on the conservative side, with greater strength reduction after the 2-hour period in boiling water than after 30 days in water at room temperature.

APPENDIX I -- FABRICATION DETAILS

Panel No. 582

Resin: Epon 828 (Epoxy)
Curing agent: CL, 14-1/2 percent by weight (comment 1)
Fabric: 181-Volan A (comment 2)
No. of plies: 13
Method of impregnation: Resin poured over heated fabric and allowed to diffuse throughout the fabric (comment 3)
Initial resin impregnation: 60 percent
Diffusion period: 5 minutes
Curing time and temperature: 215° to 217° F. for 1 hour
Pressure in press: Contact pressure (7 minutes) followed by 25 pounds per square inch (53 minutes)
Parting film in press: 600 PC cellophane on both sides of laminate between 1/16-inch aluminum cauls
Cushion in press: 1 sheet of 0.027-inch chipboard on both sides between cauls and platens of press
Removal from press: Hot
Postcure: 1 hour at 400° F. in an oven
Comments: (1) Resin and curing agent were heated to 150° F. in separate containers in a hot-water bath at 160° F. The curing agent and resin were mixed for 4 minutes with a mechanical mixer.
(2) The fabric was heated in an oven at 200° F. for 30 minutes. The stack of fabric was then removed from the oven and placed in the center of a large sheet of cellophane immediately before impregnation.
(3) The hot resin mixture was poured on top of the stack of warm fabric and distributed evenly over the entire area. The resin was left to diffuse throughout the fabric for 4 to 5 minutes, and the layup was then covered with sheet of cellophane. The edges were rolled and sealed on all four sides to form a bag. This bag containing the impregnated fabric was turned over and air, along with excess resin, was removed with a squeegee. The assembly was turned once more to get the original top surface up, and the operation of removing air and resin was repeated. This operation of removing excess void and resin took about 10 to 12 minutes. The laminate was then ready to be cured in the hot press.

Panel No. 583

Resin: Laminac 4232 (heat-resistant polyester)
Catalyst: Benzoyl peroxide, 1.0 percent
Fabric: 181-Garan RS-49
Number of plies: 12
Method of impregnation: Hand pouring and spreading
Initial resin impregnation: 55 percent
Diffusion period: 2 hours, followed by removal of air and excess resin with a squeegee.
Curing time and temperature: A steam press was heated to 212° F. and allowed to cool to about 194° F. The laminate was placed in the press. Temperature was maintained at approximately 194° F. for 30 minutes by occasional reheating. The temperature was then raised to 212° F. and held for 30 minutes. Temperature was again raised to 230° F. and held for 30 minutes.
Pressure in press: 14 pounds per square inch
Parting film in press: 600 PC cellophane on both sides of laminate, between 1/4-inch aluminum cauls
Cushion in press: 2 pieces of 0.027-inch chipboard on both sides, between cauls and platens of press.
Removal from press: Hot
Postcure: 1 hour at 250° F.
1 hour at 350° F.
1 hour at 425° F.
3 hours at 500° F.
Comments: Turned brown in color during postcure.

Panels Nos. 584 and 585

Resin: CTL-91LD (heat-resistant phenolic)
Catalyst: None
Fabric: Panel No. 584 reinforced with 181-Volan A fabric
Panel No. 585 reinforced with 181-Y1100 fabric
Number of plies: 13
Method of impregnation: Resin thinned with methyl alcohol (35 percent by weight). Applied to fabric with brush. Impregnated fabric hung on line overnight to let alcohol evaporate.
Initial resin impregnation: 45 percent (dry weight)
Diffusion period: None. Assembled air-dried sheets on cellophane-covered aluminum caul, covered with cellophane, and sealed edges to form a bag.

Curing time and temperature: 33 minutes at 300° F.
Pressure in press: Contact pressure for 3 minutes with "bumping" of press 5 or 6 times, followed by 75 pounds per square inch pressure for 30 minutes.
Parting film in press: 600 PC cellophane on both sides of laminate between 1/4-inch aluminum cauls.
Cushion in press: 2 pieces of 0.027-inch chipboard on both sides between cauls and platens.
Removal from press: Hot
Postcure: 4 hours at 275° F.
1 hour at 300° F.
1 hour at 325° F.
1 hour at 350° F.
1 hour at 375° F.
1 hour at 400° F.
1 hour at 425° F.
1 hour at 450° F.
1 hour at 475° F.
2 minutes at 500° F.
Comments: Turned dark brown in appearance during postcure.

The laminates were made by procedures that are not in accordance with the latest recommendations of the resin manufacturer.

Panels Nos. 586 and 587

Resin: DC 2106 Silicone (silicone)
Catalyst: None added at time of fabrication
Fabric: Panel No. 586 reinforced with 12 plies of 181 heat-cleaned fabric
Panel No. 587 reinforced with 13 plies of 181-T31 fabric
Method of impregnation: Impregnated before it was received at Forest Products Laboratory
Curing time and temperature: 347° F. for 30 minutes
Pressure in press: 100 pounds per square inch for Panel No. 586
300 pounds per square inch for Panel No. 587
Parting film in press: 600 PC cellophane on both sides of laminate between aluminum cauls. For Panel No. 586, 1/16-inch aluminum caul on bottom and a 1/4-inch aluminum caul on top. For Panel No. 587, 1/4-inch aluminum caul on both sides.
Cushion in press: 1 piece of 0.027-inch chipboard on both sides between cauls and platens.
Removal from press: Cooled under pressure

Postcure: 16 hours at 195° F.
1 hour each at 250°, 300°, 350°, and 420° F.
100 hours at 480° F.

Comments: Barcol hardness before postcuring was 31 for Panel No. 586 and 49 for Panel No. 587. Barcol hardness increased after postcure to 56 for both panels.

Panels Nos. 588, 589, 590, and 591

Resin: Paraplex P-43 (polyester)
Catalyst: 1.0 percent benzoyl peroxide dissolved in an equal amount of styrene
Fabric: Panel No. 588 reinforced with 181-T31 fabric
Panel No. 589 reinforced with 181-A172 fabric
Panel No. 590 reinforced with 181-OC-301 fabric
Panel No. 591 reinforced with 181-Volan A fabric
Number of plies: 12
Method of impregnation: Hand pouring and spreading. Resin (thinned with 10 percent styrene) was poured on cellophane, a sheet of fabric laid on resin, and resin and fabric alternated until all plies were laid up.
Initial resin impregnation: 55 to 60 percent
Diffusion period: 1-1/2 to 2 hours
Curing time and temperature: 20 minutes at 220° F. followed by 70 minutes at 250° F.
Pressure in press: 14 pounds per square inch
Parting film in press: 600 PC cellophane on both sides of laminate between 1/4-inch aluminum cauls.
Cushion in press: 2 pieces of 0.027-inch chipboard on both sides between cauls and platens.
Removal from press: Hot
Postcure: None
Comments: Panels were essentially void free.

TABLE 1. AVERAGE THICKNESS, RESIN CONTENT, SPECIFIC GRAVITY, AND BARCOL HARDNESS OF PANELS PARALLEL-LAMINATED WITH 181 GLASS FABRIC

Panel No.	Resin	Fabric finish	Number of plies of fabric	Thickness	Resin content	Specific gravity	Barcol hardness
				In.	Percent		
582	Epon 828-CL	Volan A	13	0.115	31.4	1.87	67
583	Laminac 4232	Garan	12	.125	36.9	1.85	68
584	CTL-91LD	Volan A	13	.110	24.5	1.78	66
585	CTL-91LD	Y-1100	13	.113	21.0	1.73	56
586	DC 2106	112	12	.121	34.5	1.80	56
587	DC 2106	T-31	13	.124	34.6	1.91	56
588	Paraplex P-43	T-31	12	.118	34.6	1.83	66
589	Paraplex P-43	A-172	12	.134	40.8	1.75	62
590	Paraplex P-43	OC-301	12	.119	36.4	1.81	67
591	Paraplex P-43	Volan A	12	.117	35.7	1.81	68

M 114 222

TABLE 2. TENSILE AND COMPRESSIVE STRENGTH VALUES OF 181-GLASS FABRIC LAMINATES AFTER VARIOUS EXPOSURES[1]

Exposure Condition and time	Epon 828 CL with Volan A	Laminac 4232 with Garan	CTL-91LD with Volan A	CTL-91LD with Y-1100	DC 2106 with 112	DC 2106 with T-31	Paraplex P-43 with T-31	Paraplex P-43 with A-172	Paraplex P-43 with OC-301	Paraplex P-43 with Volan A	Average[2] for materials
TENSILE STRENGTH (P.S.I.)											
Normal	64,000	30,500	60,300	58,400	45,000	44,400	51,000	45,200	49,500	56,400	49,800
Immersed in water, 73° F., 30 days	62,400	27,300	58,300	59,800	43,800	42,100	44,200	42,600	46,000	52,200	47,400
Immersed in water, 73° F., 90 days	58,900	27,000	56,000	56,900	39,900	39,200	45,500	41,800	45,200	....	45,600
100° F., 100 percent humidity, 30 days	49,800	27,500	56,100	54,400	37,900	36,900	47,900	46,700	49,700	51,200	45,200
100° F., 100 percent humidity, 90 days	51,700	27,700	58,000	57,500	40,000	36,600	46,500	42,900	45,800	....	45,200
Boiled in water, 1/2 hour	62,800	26,100	60,400	58,800	43,600	40,600	49,900	43,000	49,200	....	48,300
Boiled in water, 2 hours	58,500	28,400	58,000	57,900	43,100	40,600	51,200	45,000	48,400	54,700	47,900
Boiled in water, 4 hours	57,800	27,400	57,000	56,800	40,800	38,600	49,800	46,200	46,800	....	46,800
Standard deviation	2,170	1,240	1,730	1,390	1,920	1,640	1,690	1,650	1,740	1,080	1,700
Least significant difference at 5 percent	2,790	1,600	2,230	1,790	2,480	2,110	2,180	2,130	2,240	1,440	2,000
Least significant difference at 1 percent	3,760	2,150	3,000	2,410	3,330	2,840	2,930	2,860	3,010	1,990	2,660
COMPRESSIVE STRENGTH (P.S.I.)											
Normal	59,100	29,200	43,700	44,000	25,500	25,800	44,900	43,600	49,900	48,600	40,600
Immersed in water, 73° F., 30 days	55,000	26,400	38,000	37,900	23,400	23,600	28,600	40,400	47,800	34,800	35,700
Immersed in water, 73° F., 90 days	51,600	25,000	36,200	37,700	22,200	23,400	28,900	39,200	45,800	....	34,500
100° F., 100 percent humidity, 30 days	51,200	25,800	37,100	38,500	24,100	23,900	30,100	41,100	47,400	35,400	35,500
100° F., 100 percent humidity, 90 days	46,900	22,700	37,500	35,900	22,400	23,300	28,300	38,700	44,200	....	33,300
Boiled in water, 1/2 hour	57,900	26,200	38,500	40,600	23,200	23,900	36,600	40,200	48,600	....	37,300
Boiled in water, 2 hours	54,300	26,100	36,000	37,900	21,800	24,000	34,100	40,500	47,800	33,700	35,800
Boiled in water, 4 hours	52,500	25,300	36,400	38,000	21,500	22,400	29,400	39,100	48,600	....	34,800
Standard deviation	1,810	1,770	1,440	2,030	1,030	1,480	1,680	1,680	1,980	1,580	1,680
Least significant difference at 5 percent	1,810	1,770	1,440	2,040	1,030	1,480	1,680	1,680	1,980	1,620	1,770
Least significant difference at 1 percent	2,420	2,360	1,920	2,710	1,370	1,970	2,240	2,230	2,640	2,190	2,350

[1] Tension values are average of 5 tests; compression values are average of 8 tests.

[2] Does not include P-43 Volan A laminate.

M 114 223

TABLE 3. MODULUS OF RUPTURE AND MODULUS OF ELASTICITY IN FLEXURE OF 181-GLASS FABRIC LAMINATES AFTER VARIOUS EXPOSURES[1]

Exposure Condition and time	Epon 828 CL with Volan A	Laminac 4232 with Garan	CTL-91LD with Volan A	CTL-91LD with Y-1100	DC 2106 with 112	DC 2106 with T-31	Paraplex P-43 with T-31	Paraplex P-43 with A-172	Paraplex P-43 with OC-301	Paraplex P-43 with Volan A	Average[2] for materials
MODULUS OF RUPTURE (P.S.I.)											
Normal	81,800	36,400	62,600	60,600	37,700	37,900	61,700	54,200	62,000	66,600	55,000
Immersed in water, 73° F., 30 days	79,900	26,200	54,300	52,800	36,100	36,300	44,000	55,500	58,400	51,700	49,300
Immersed in water, 73° F., 90 days	78,400	26,000	52,000	54,200	34,000	35,200	42,400	55,500	58,600	....	48,500
100° F., 100 percent humidity, 30 days	77,300	27,800	51,600	51,800	35,700	36,100	46,100	58,100	59,200	50,300	49,300
100° F., 100 percent humidity, 90 days	71,800	26,900	51,700	51,100	36,200	35,900	44,600	56,900	59,200	....	48,300
Boiled in water, 1/2 hour	79,400	26,600	55,700	51,300	35,200	33,200	54,100	53,400	58,700	....	49,800
Boiled in water, 2 hours	76,500	25,200	49,600	46,400	32,600	33,000	48,700	52,300	57,100	49,900	46,800
Boiled in water, 4 hours	76,000	26,900	48,800	50,000	33,900	32,600	45,300	53,100	58,600	....	47,200
Standard deviation	1,800	2,300	2,700	2,050	2,100	1,790	1,480	1,320	1,510	1,600	1,940
Least significant difference at 5 percent	1,800	2,300	2,700	2,050	2,100	1,790	1,480	1,320	1,510	1,670	2,460
Least significant difference at 1 percent	2,400	3,070	3,600	2,730	2,800	2,380	1,980	1,760	2,010	2,270	3,280
Normal[3]	78,700	36,200	61,900	59,200	37,200	36,600	61,000	54,100	60,300	....	53,900
Boiled in water, 1 hour[3]	75,200	25,000	50,700	49,600	32,800	31,700	48,500	52,000	58,800	....	47,100
Boiled in water, 1 hour (adjusted)[4]	78,100	25,200	51,300	50,800	33,200	32,800	49,000	52,200	60,400	....	48,100
MODULUS OF ELASTICITY (1,000 P.S.I.)											
Normal	3,650	2,510	3,700	3,640	2,590	2,480	3,100	2,500	3,190	3,190	3,040
Immersed in water, 73° F., 30 days	3,690	2,190	3,580	3,530	2,600	2,480	2,920	2,820	3,070	3,110	2,990
Immersed in water, 73° F., 90 days	3,760	2,210	3,670	3,700	2,570	2,540	2,880	2,670	3,220	....	3,020
100° F., 100 percent humidity, 30 days	3,780	2,260	3,550	3,550	2,540	2,500	2,940	2,700	3,160	3,230	3,000
100° F., 100 percent humidity, 90 days	3,720	2,220	3,580	3,610	2,630	2,530	2,930	2,660	3,180	....	3,010
Boiled in water, 1/2 hour	3,550	2,240	3,610	3,520	2,540	2,490	3,090	2,420	3,050	....	2,950
Boiled in water, 2 hours	3,470	2,170	3,330	3,350	2,440	2,450	3,030	2,400	3,170	2,920	2,870
Boiled in water, 4 hours	3,580	2,240	3,390	3,470	2,500	2,470	2,930	2,370	3,180	....	2,900
Standard deviation	83	101	112	78	80	75	61	84	64	62	83
Least significant difference at 5 percent	83	101	113	78	80	75	61	84	64	65	83
Least significant difference at 1 percent	111	135	150	104	107	100	81	112	85	88	111
Normal[3]	3,530	2,370	3,460	3,500	2,490	2,370	2,950	2,590	2,960	....	2,910
Boiled in water, 1 hour[3]	3,350	2,040	3,290	3,320	2,400	2,290	2,620	2,370	2,810	....	2,720
Boiled in water, 1 hour (adjusted)[4]	3,470	2,160	3,530	3,460	2,500	2,400	2,770	2,300	3,040	....	2,850

[1] Each value is an average of 8 tests.

[2] Does not include P-43 Volan A laminate.

[3] Supplementary data not included in original analysis.

[4] Adjusted value equals supplementary value $\left(\frac{\text{original normal}}{\text{supplementary normal}}\right)$.

M 114 224

TABLE 4. INCREASE IN WEIGHT OF FLEXURE SPECIMENS AFTER VARIOUS WET EXPOSURES[1, 2]

Exposure Condition and time	Epon 828 CL with Volan A	Laminac 4232 with Garan	CTL-91LD with Volan A	CTL-91LD with Y-1100	DC 2106 with 112	DC 2106 with T-31	Paraplex P-43 with T-31	Paraplex P-43 with A-172	Paraplex P-43 with OC-301	Paraplex P-43 with Volan A
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
Immersed in water, 73° F., 30 days	0.27	4.32	4.18	6.01	0.57	0.96	0.65	0.39	0.42	0.62
Immersed in water, 73° F., 90 days	.33	4.41	5.20	7.52	.72	.86	.93	.52	.43	....
100° F., 100 percent humidity, 30 days	.29	3.15	1.06	.96	.30	.34	.54	.48	.47	.64
100° F., 100 percent humidity, 90 days	.57	3.13	1.22	1.03	.23	.28	.68	.63	.56	....
Boiled in water, 1/2 hour	.06	3.67	6.75	8.72	1.56	.52	.16	.17	.18	....
Boiled in water, 2 hours	.11	4.20	7.38	9.19	1.97	1.11	.41	.33	.25	.46
Boiled in water, 4 hours	.16	4.04	6.71	9.02	1.91	1.62	.53	.39	.27	....

[1] Percent increase in weight = $\frac{\text{weight after wet exposure} - \text{weight before wet exposure}}{\text{weight before wet exposure}} \times 100.$

[2] All specimens were conditioned at least 2 weeks in a normal atmosphere before wet exposure, and were weighed immediately before and after wet exposure.

M 114 225

TABLE 5. COMPARISON OF EFFECT OF 30-DAY IMMERSION IN WATER WITH THAT OF OTHER EXPOSURE CONDITIONS: SIGNIFICANCE OF DIFFERENCE BETWEEN MEANS BASED ON VALUES OF LEAST SIGNIFICANT DIFFERENCE[1]

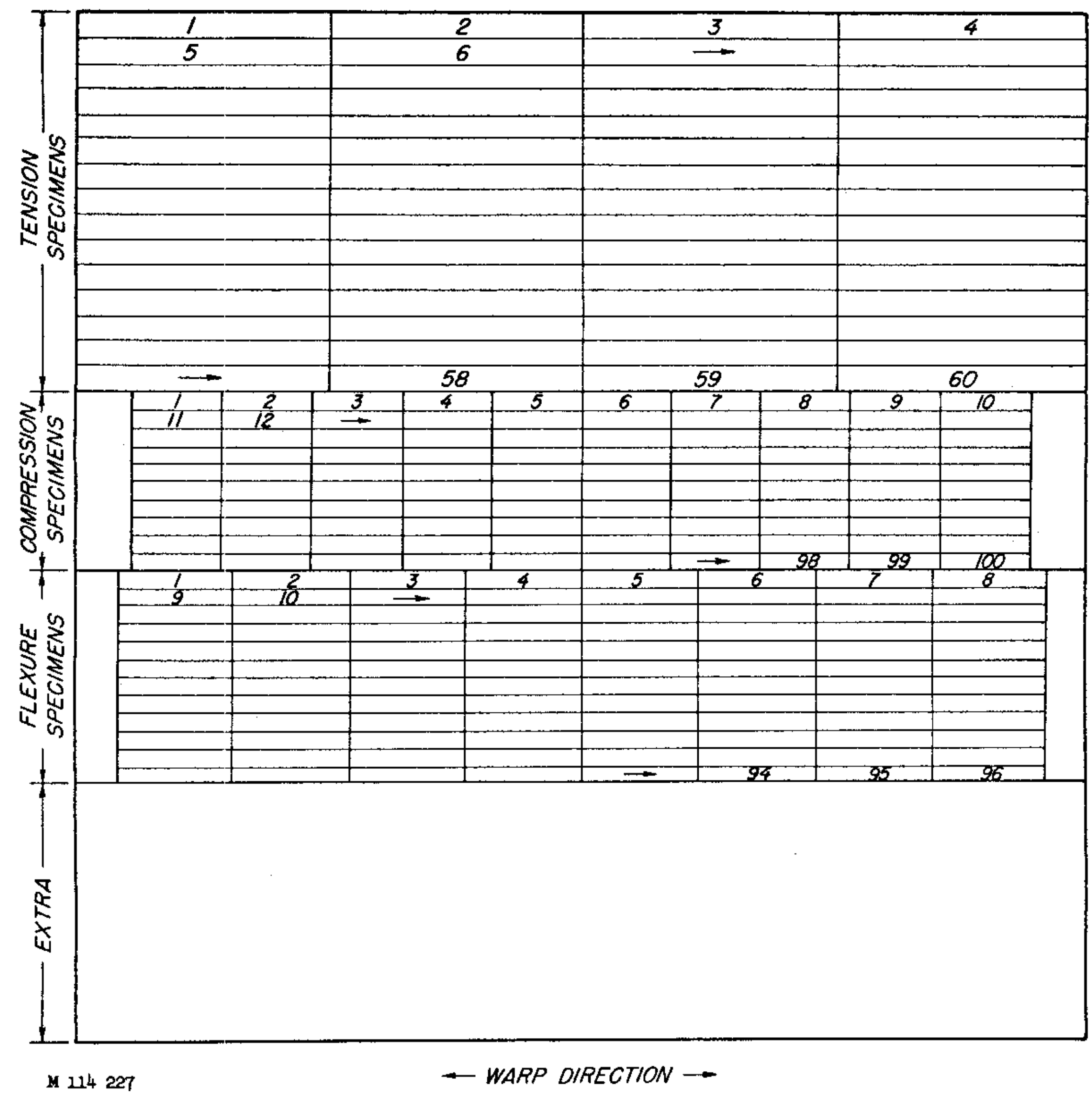
Exposure Condition and time	Epon 828 CL with Volan A	Laminac 4232 with Garan	CTL-91LD with		DC 2106 with		Paraplex P-43 with				Average for materials[2]
			Volan A	Y-1100	112	T-31	T-31	A-172	OC-301	Volan A	
MAXIMUM TENSILE STRENGTH											
Immersed in water, 73° F., 90 days	+5	+N	+5	+1	+1	+1	-N	+N	+N	....	+N
100° F., 100 percent humidity, 30 days	+1	-N	+N	+1	+1	+1	-1	-1	-1	+N	+5
100° F., 100 percent humidity, 90 days	+1	-N	+N	+5	+1	+1	-5	-N	+N	....	+5
Boiled in water, 1/2 hour	-N	+N	-N	+N	+N	+N	-1	-N	-1	....	-N
Boiled in water, 2 hours	+1	-N	+N	+5	+N	+N	-1	-5	-5	-1	-N
Boiled in water, 4 hours	+1	-N	+N	+1	+5	+1	-1	-1	-N	....	+N
MAXIMUM COMPRESSIVE STRENGTH											
Immersed in water, 73° F., 90 days	+1	+N	+5	+N	+5	+N	-N	+N	+5	....	+N
100° F., 100 percent humidity, 30 days	+1	+N	+N	-N	-N	-N	-N	-N	+N	-N	+N
100° F., 100 percent humidity, 90 days	+1	+1	+N	+N	+N	+N	+N	+5	+1	....	+1
Boiled in water, 1/2 hour	-1	+N	-N	-5	+N	-N	-1	+N	-N	....	-N
Boiled in water, 2 hours	+N	+N	+1	N	+1	-N	-1	-N	N	+N	-N
Boiled in water, 4 hours	+1	+N	+5	-N	+1	+N	-N	+N	-N	....	+N
MODULUS OF RUPTURE											
Immersed in water, 73° F., 90 days	+N	+N	+N	-N	+5	+N	+5	N	-N	....	+N
100° F., 100 percent humidity, 30 days	+1	-N	+5	+N	+N	+N	-1	-1	-N	+N	N
100° F., 100 percent humidity, 90 days	+1	-N	+N	+N	-N	+N	-N	-5	-N	....	+N
Boiled in water, 1/2 hour	+N	-N	-N	+N	+N	+1	-1	+1	-N	....	-N
Boiled in water, 1 hour[3]	+5	+N	+5	+N	+1	+1	-1	+1	-5	....	+N
Boiled in water, 2 hours	+1	+N	+1	+1	+1	+1	-1	+1	+N	+5	+5
Boiled in water, 4 hours	+1	-N	+1	+1	+5	+1	-N	+1	-N	....	+N
MODULUS OF ELASTICITY											
Immersed in water, 73° F., 90 days	-N	-N	-N	-1	+N	-N	+N	+1	-1	....	-N
100° F., 100 percent humidity, 30 days	-5	-N	+N	-N	+N	-N	-N	+1	-1	-1	-N
100° F., 100 percent humidity, 90 days	-N	-N	N	-5	-N	-N	-N	+1	-1	....	-N
Boiled in water, 1/2 hour	+1	-N	-N	+N	+N	-N	-1	+1	+N	....	+N
Boiled in water, 1 hour[3]	+1	+N	+N	+N	+5	+5	+1	+1	+N	....	+1
Boiled in water, 2 hours	+1	+N	+1	+1	+1	+N	-1	+1	-1	+1	+1
Boiled in water, 4 hours	+5	-N	+1	+N	+5	+N	-N	+1	-1	....	+5

[1] + indicates strength reduction greater than that after 30-day water immersion.
- indicates strength reduction less than that after 30-day water immersion.
1 or 5 indicate level of probability at which difference is significant.
N indicates no significant difference.

[2] Does not include P-43 Volan A laminate.

[3] Not included in original statistical analysis.

M 114 226



M 114 227

Figure 1.--Cutting diagram to show where specimens were cut from each laminated panel 1/8 by 36 by 36 inches in size.

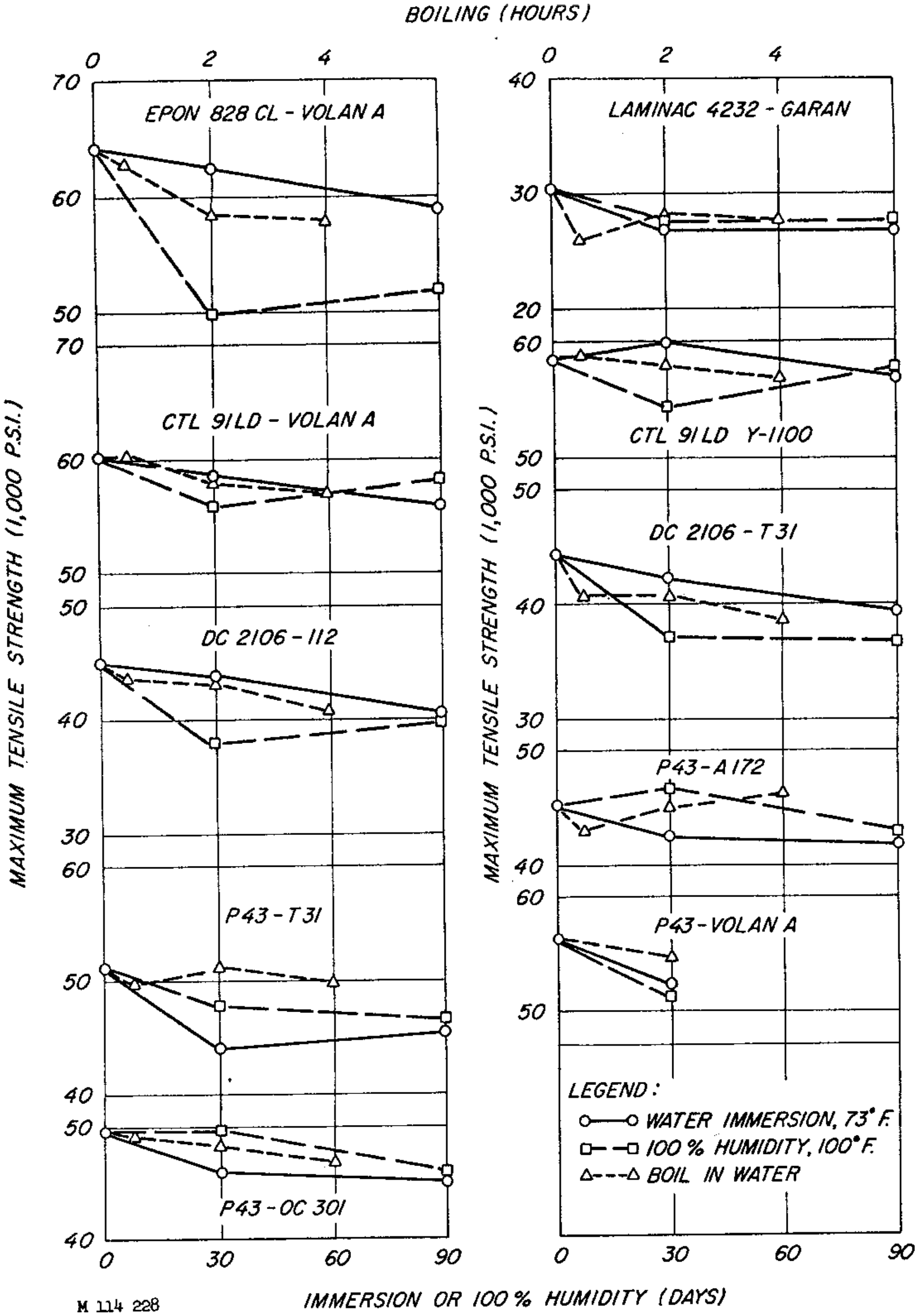


Figure 2.--Effect of various conditions and durations of exposure on the maximum tensile strength of laminates. Each point represents average of 5 tests.

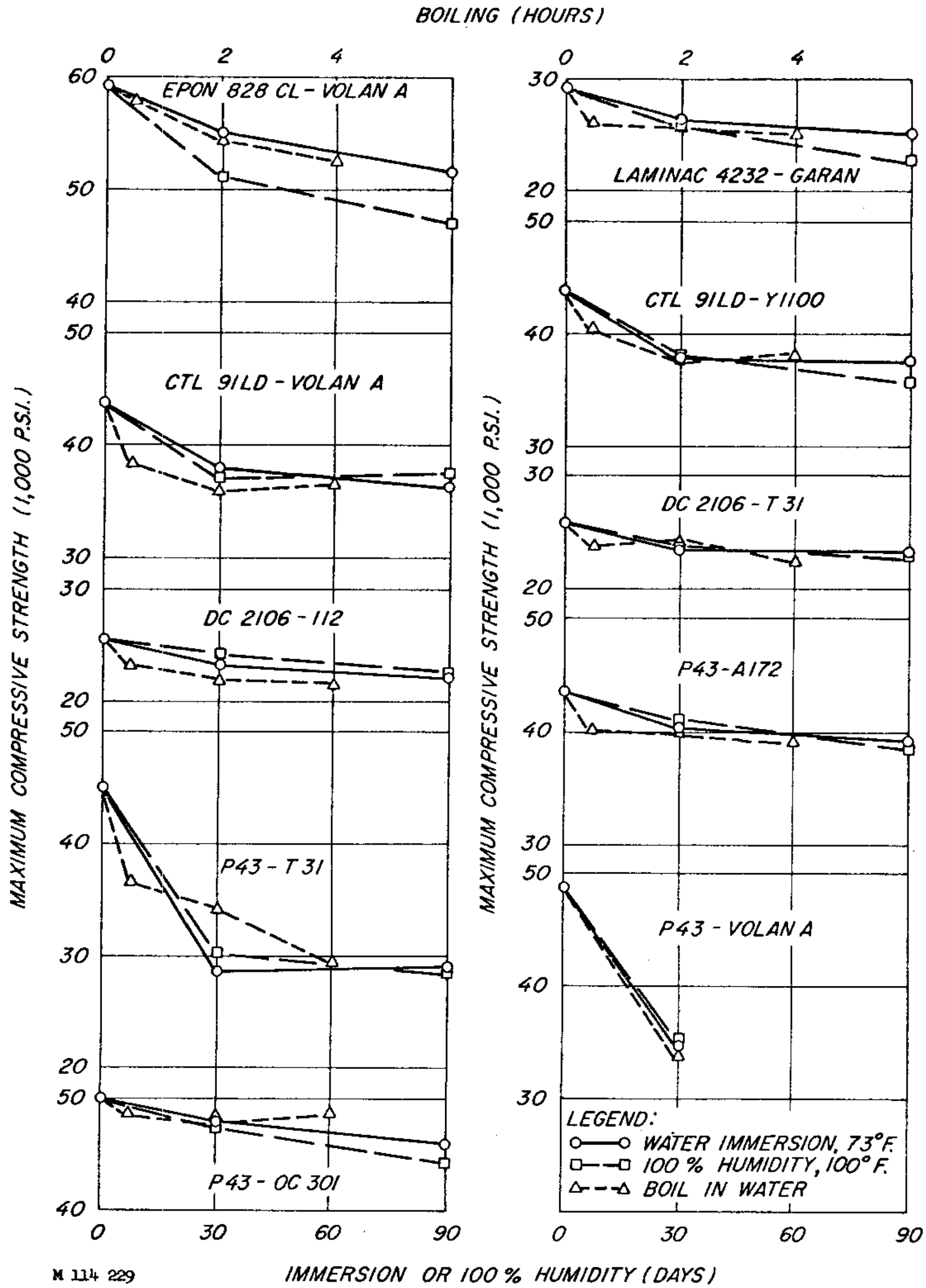


Figure 3. --Effect of various conditions and durations of exposure on the maximum compressive strength of laminates. Each point represents average of 8 tests.

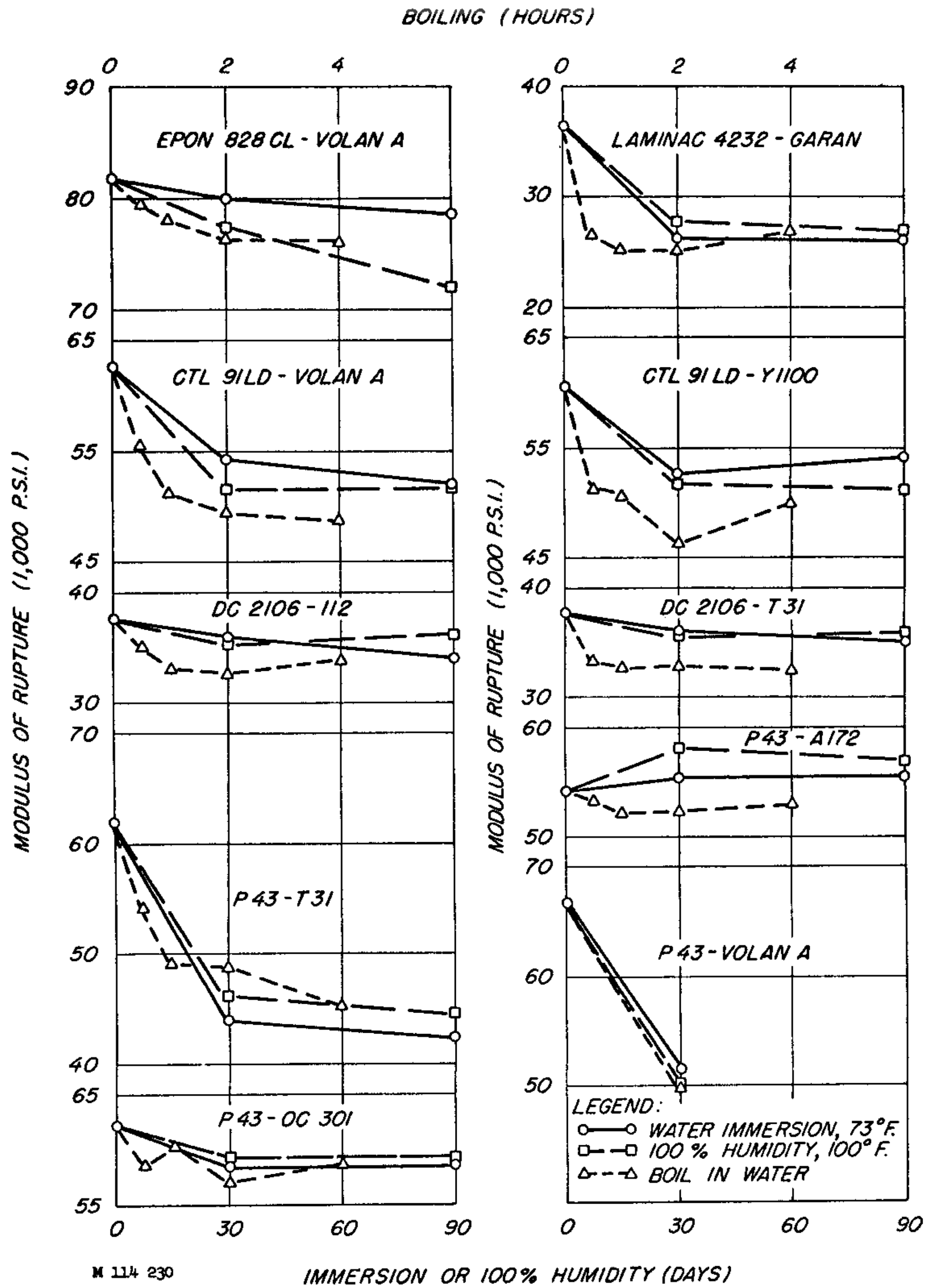


Figure 4.--Effect of various conditions and durations of exposure on the modulus of rupture of laminates. Each point represents average of 8 tests.

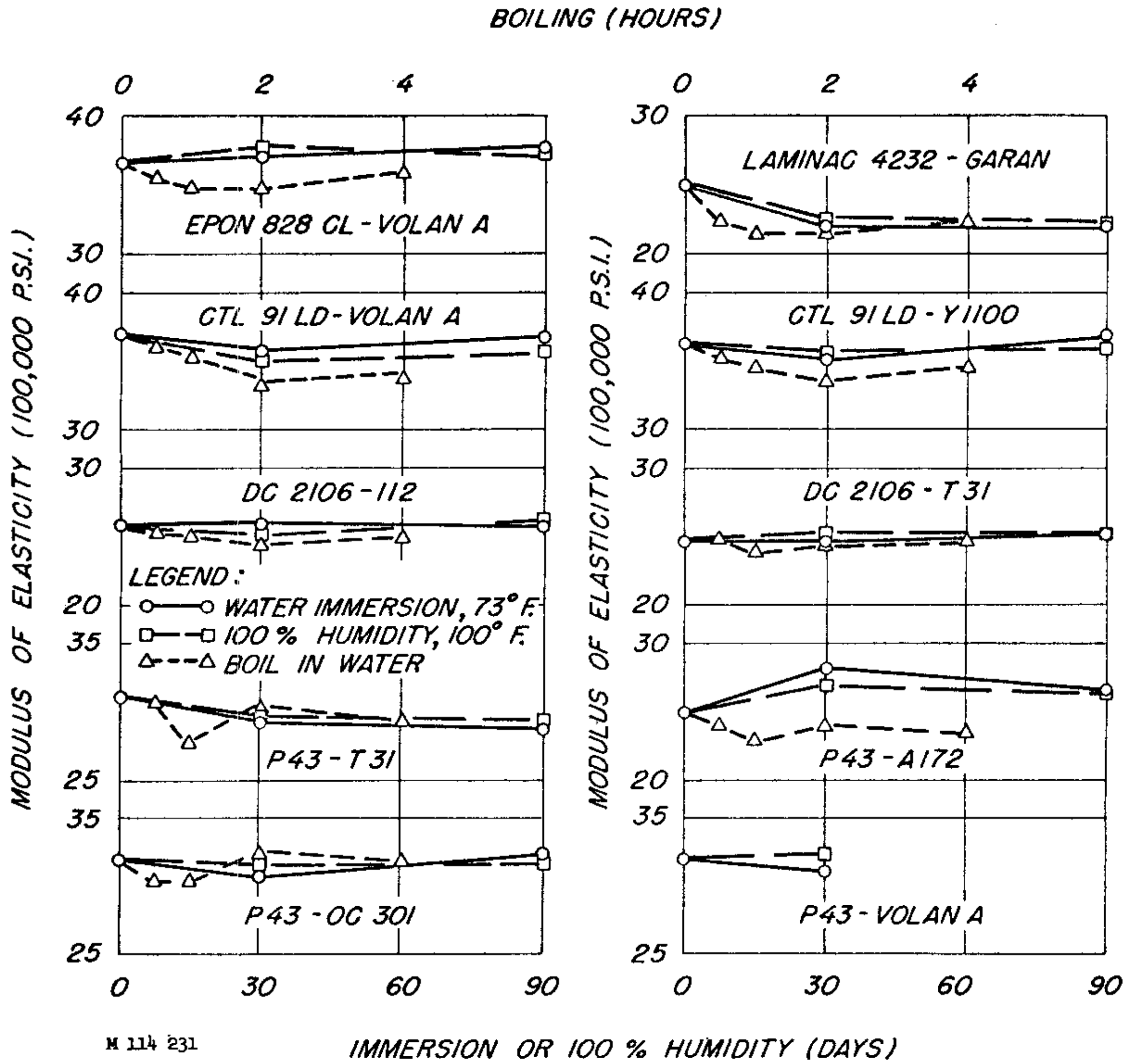
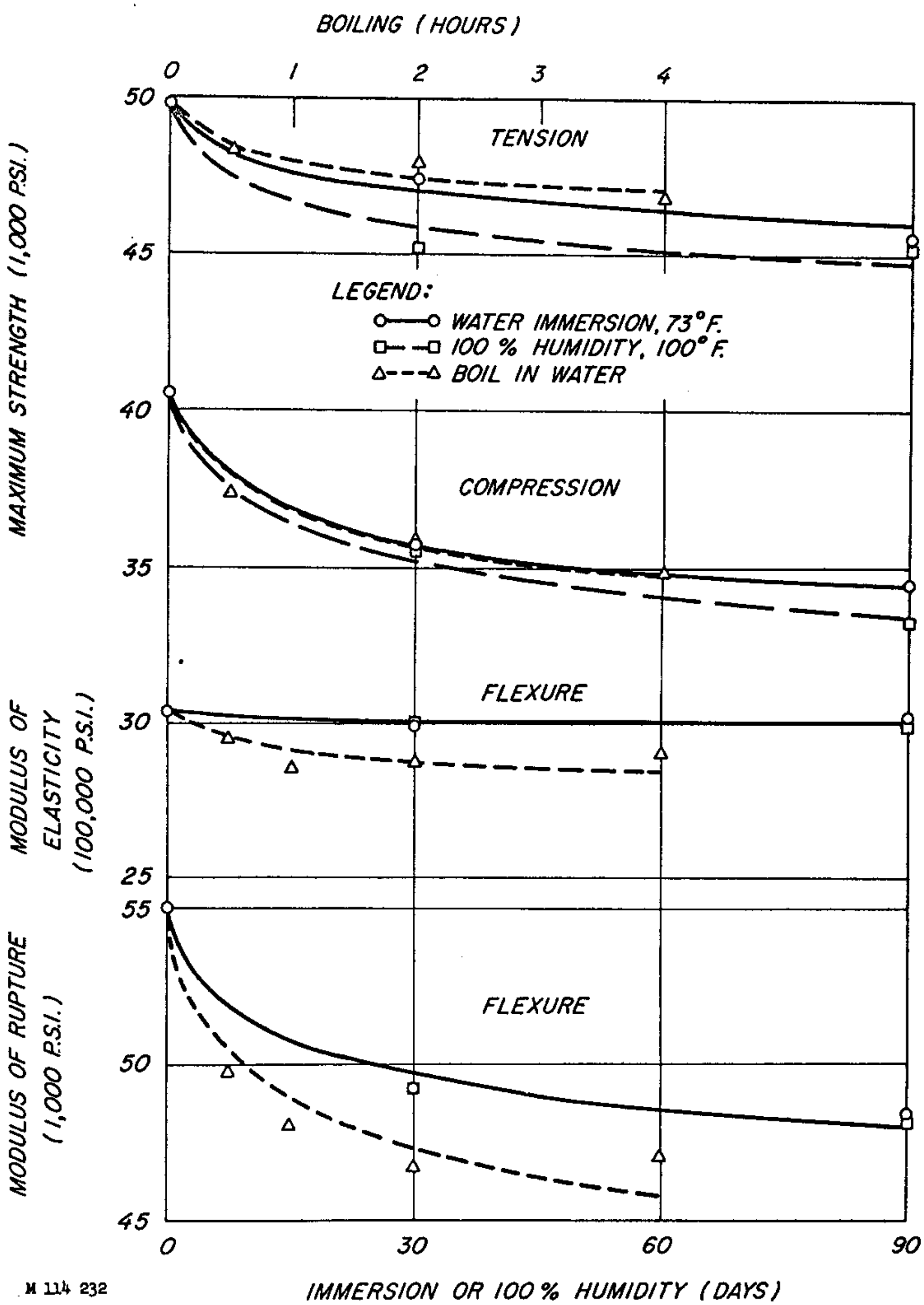


Figure 5. --Effect of various conditions and durations of exposure on the modulus of elasticity in flexure of laminates. Each point represents average of 8 tests.



M 114 232

Figure 6. --Effect of various conditions and durations of exposure on the overall average for each property, averaged over all laminates except P-43 Volan A. Exponential curve used to smooth relationship for each set of data.