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ACCELERATED AGING OF PHENOLIC-BONDED HARDBOARDS AND FLAKEBOARDS--ETC(U)
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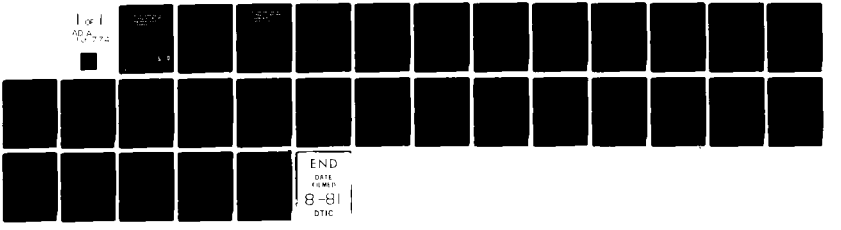

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Accelerated Aging of Phenolic-Bonded Hardboards and Flakeboards

Abstract

This report is the second on results of a continuing series of investigations that establish an information base on durability of new exterior-type, wood-based panel products. Four nominal 1/2-inch-thick commercial hardboards were exposed to various accelerated aging treatments; results were compared with results from an earlier study of flakeboards, plywood, and solid wood exposed to the same treatments. Actual values for original properties and properties retained after aging were generally lower for the flakeboards and the hardboards than they were for the plywood; however, for the best performing boards degradation rates and percentages of original property retained were comparable to those of plywood. The conclusion is the best performing flakeboards and hardboards are suitable for long-term exterior applications.

Acknowledgment

The laboratory exposure of hardboards and much of the testing was conducted by Anne Slack, a student trainee. E. A. Okkonen of the Laboratory staff assisted with testing and performed the data processing.

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Accelerated Aging of Phenolic-Bonded Hardboards and Flakeboards

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Introduction

The variety of structural panel products produced from wood increases yearly, spurred by the increasing use of a wider variety of particle geometries, board designs, manufacturing processes, and adhesive systems. Information about the durability of these new products is important to all segments of the building industry. This report describes the second of a series of investigations designed to obtain basic information on durability of exterior-type, wood-based panel products. In this work, results of the behavior of four exterior-type hardboard materials are compared to those of solid wood, plywood, and structural flakeboard in a previous investigation *(2)*.[2]

All materials were exposed to four regimes for aging the boards: (1) Cyclic boil-dry; (2) cyclic vacuum-pressure, soak-dry; (3) ASTM D-1037 accelerated aging; and (4) outdoor weathering. Degradation was evaluated by changes in: (1) Modulus of rupture (MOR), (2) modulus of elasticity (MOE), (3) internal bond strength (IB), and (4) thickness. The results are presented in the form of fitted regression lines of each property versus the number of aging cycles and in histograms that present comparisons of the initial value of each property with the value after 80 cycles of boil-dry or soak-dry aging. Results of outdoor weathering will be summarized in a later report.

Background

The principal factors in bond degradation are heat, moisture, and stress; most laboratory aging tests consist of some sequence of these factors. Although to suppose laboratory aging exposures can quantitatively duplicate an actual service environment is unreasonable, many artificial exposures have been found to degrade weather-resistant materials at a rapid rate. These exposures are useful for a quick comparison of the performance of new products to that of products with a history of successful service. By these comparisons, materials can be ranked, and their service lives estimated.

The prescribed test for durability of type-2, mat-formed wood particleboard is described in ASTM Method D-1037 *(1)*. The aging exposure consists of six cycles of soaking, steaming, freezing, and drying for a 12-day period. Some people feel the test effects are the equivalent of 50 years of aging, but no actual data support this. Researchers at the West Coast Adhesive Manufacturers Association (WCAMA) studied effects of various portions of the ASTM D-1037 cycle *(14)*. They found two cold-water soak swell-shrink treatments were not as deleterious as two boil treatments in each D-1037 cycle. But the study also showed the freeze treatment in each D-1037 cycle was relatively ineffective. In a followup to this study, the researchers at WCAMA found a simplified test requiring only 6 days and consisting of vacuum-pressure-soak, boil and dry (WCAMA method 6.1) correlated with 5-year test fence results as well as those of more complex ASTM D-1037 test *(13)*. Shen and Wrangham *(12)* have presented an accelerated-aging test using a 2-hour boil followed by wet testing as defined in the German Standard DIN 68761 *(7)* for determining change in internal bond strength. This treatment has

[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.
[2] Italicized numbers in parentheses refer to Literature Cited at end of report.

also been included in the Canadian Standard CSA-0188-75 *(3)*, and is applied to bending specimens.

None of these exposure sequences provides a means to follow aging or deterioration of a board. Instead, they are "torture tests" that provide only a comparison of the mechanical properties before and after the treatment. They do not provide an indication of the various rates at which degradation will proceed during the life of a product.

Actual testing of particleboard performance in outdoor exposure has been limited. The most information is from work reported by Hann, Black, and Blomquist *(8, 9)*, Jokerst *(10)*, and Geimer, Heebink, and Hefty *(6)*. Investigations have also been reported by the WCAMA *(13, 14)* and by Clad and Schmidt-Hellerau *(5)*. In summary, the results of these investigations showed a pattern of rapid loss of strength and stiffness during the first and second year followed by a much slower rate of loss in ensuing years.

Baker and Gillespie *(2)* in the first report of this series compared the behavior of phenolic-bonded flakeboard with that of solid wood and plywood exposed to four accelerated-aging exposures: (1) Up to 80 cycles of boiling and drying at elevated temperature, (2) up to 40 cycles of vacuum-pressure soaking and drying at an intermediate temperature, (3) the six-cycle, ASTM D-1037 exposure, and (4) continuous outdoor weathering at Madison, Wis. The first and the second tests revealed the pattern of degradation and the rate of degradation, which are new dimensions in estimating service life of particleboard. The initial strength and the initial stiffness of the flakeboards were lower than those of both plywood and solid wood. Many flakeboards exhibited the same rapid initial loss of properties noted in outdoor weathering, but the rates of property loss after the initial drop were comparable between the flakeboards and the plywood. The authors concluded the phenolic-bonded flakeboards were suitable for structural applications in which conventional wood products are used.

Another class of exterior-grade panel products are thick hardboards of the type commonly used for house siding. Their durability, however, has not been compared to other exterior panel materials.

Experimental

Materials

Four nominal 1/2-inch-thick (12.7 mm) commercial hardboards were selected, and were assigned the alphabetical identifications S, T, U, and V. No information about their manufacture was available except a phenolic binder was used; all material of a given type was from a single panel. S, T, U, and V and other materials are listed in table I (also with alphabetical identifiers); the other materials are from the first investigation *(2)*.

Specimens

Each panel was cut into bending specimens 2 inches by 12 inches (50 x 305 mm) with the 12-inch dimension parallel to the long axis of the panel. After the bending test, internal bond specimens 1/2 inch by 2 inches by 2 inches (12.7 x 50 x 50 mm) were cut from one end of each bending specimen. For mounting the specimens on racks, 1/4-inch (6.35 mm) holes were drilled in the opposite end of each bending specimen. Specimens were stored at 80° F (27° C), 65 percent relative humidity until exposure. During exposure, the specimens were spaced 1/4 inch (6.35 mm) apart on the racks.

Exposures

The equipment and procedures were the same as those described by Baker and Gillespie *(2)* and will only be briefly summarized:

Controls.—Ten specimens of each type were conditioned to equilibrium at 80° F (27° C), 65 percent relative humidity, and tested to provide control data.

Boil-dry exposure.—Thirty specimens of each type were initially saturated with water by vacuum-pressure soak, which consisted of 30 minutes under 29-inch (735 mm) mercury vacuum followed by 30 minutes under 60 pounds per square inch (420 kPa) pressure while immersed in water, then subjected to the required number of cycles of the following treatment (the vacuum-pressure soak treatment was applied only before the first boil-dry cycle): 10 minutes in boiling water followed by 3-3/4 hours of drying in an air-circulating oven at 225° F (107° C). Five randomly selected specimens of each panel type were removed for testing after 1, 5, 10, 20, 40, and 80 boil-dry cycles.

Vacuum-pressure, soak-dry exposure.—Twenty-five specimens of each type were subjected to cycles consisting of the vacuum-pressure soak described in the preceding paragraph, then 23 hours of drying in an air-circulating oven at 180° F (82° C). Five randomly selected specimens of each type were removed for testing after 1, 5, 10, 20, and 40 cycles.

ASTM D-1037 accelerated-aging exposure.—Five specimens of each board type were subjected to six cycles of the following treatment:

1. Soaking in water at 120° F (49° C) for 1 hour.
2. Spraying with steam and water vapor at 200° F (93° C) for 3 hours.
3. Storing at 10° F (-12° C) for 20 hours.
4. Drying at 212° F (100° C) for 3 hours.
5. Spraying with steam and water vapor for 3 hours.
6. Drying at 212° F (100° C) for 3 hours.

After exposure, all of the specimens were removed for testing.

Weathering.—Thirty specimens of each type were placed on exposure at an angle of 60° above horizontal, facing south at the outdoor exposure site of the Forest Products Laboratory, Madison, Wis. The angle was chosen arbitrarily to prevent water from upper specimens dripping on lower specimens. Five random specimens of each type will be removed for testing after 1 year and at five intervals of approximately 1 year thereafter.

Conditioning, Measurements, and Testing

After removal from exposure, specimens were reconditioned to equilibrium at 80° F (27° C), 65 percent relative humidity. Thickness, width, and weight were measured before testing. Each specimen was then tested to obtain the bending load-deformation curve; internal bond strength (IB) was determined by the procedures outlined in ASTM D-1037 and from those described in the previous report *(2)*.

Data Analysis

In this work, modulus of rupture (MOR) and modulus of elasticity

(MOE) were calculated on the basis of the dimensions measured after reconditioning at 80° F (27° C), 65 percent relative humidity after exposure. This is in contrast to the calculations in the first report *(2)*, which were based on the dimensions before exposure.[3] For comparison here, data from the first study were also recalculated using dimensions after exposure. The specimens used in this work were smaller than those specified in ASTM D-1037 for determining MOR and MOE of 1/2-inch-thick (12.7 mm) specimens.

Further analysis of the data from the cyclic boil-dry and soak-dry exposures was carried out using the Minitab II Statistical Computing System *(11)*. The change in MOR, MOE, IB, and the percent thickness swelling of each specimen compared to the average of the control specimens was determined for each test interval (1, 5, 10, 20, 40, 80 cycles). Then these changes expressed as "percent" or "percent retained" were fitted to each of the following regression models using the number of aging cycles as the independent variable, X, and the percent or percent retained as the dependent variable, Y.

Linear: $Y = A_O + A_1X$ (1)

Hyperbolic: $Y = A_O + A_1X + A_2/X$ (2)

Log: $Y = A_O + A_1 \log X$ (3)

In the earlier report, Baker and Gillespie used the linear model (1).

Analysis of variance (ANOVA) was conducted to test two hypotheses: First, that the variability explained by the regression of the observed property (MOE, MOR, etc.) was not significantly greater than the variability (error) expected from the choice of the regression model and pure error; and second, that the error attributable to the choice of the regression model was not significantly greater than expected from pure error (natural material variability and experimental error).

The format of the ANOVA table was the following:

	S.S.	d.f.	M.S.	F
Regression				
Residual				
Lack of fit				
Pure error				
Total				

where: S.S. = sum of squared deviations of observed property value from property value predicted by regression model.

d.f. = degrees of freedom

M.S. = S.S. ÷ d.f.

F = ratio of M.S.

Note: Residual S.S. = Lack of fit S.S. + Pure error S.S.

The F value is calculated for each hypothesis as:

Hypothesis 1

F = Regression M.S. ÷ Residual S.S.

Hypothesis 2

F = Lack of fit S.S. ÷ Pure error S.S.

The calculated F is evaluated against the value of *F* that can be expected solely on the basis of pure error and one of the following conclusions drawn:

Hypothesis 1: Slope = 0

N.S.—Hypothesis is accepted. No relationship exists between observed property and number of aging cycles.

*—Hypothesis is rejected. A relationship exists between observed property and number of aging cycles at 95 percent level of confidence.

**—Hypothesis is rejected. A relationship exists between observed property and number of aging cycles at 99 percent level of confidence.

Hypothesis 2: Model fits

N.S.—Hypothesis is accepted. Error due to lack of fit of model to data is not significant compared to pure error; model is adequate.

*—Hypothesis is rejected. Error due to lack of fit of model to data is significantly greater than expected pure error at 95 percent level of confidence.

**—Hypothesis is rejected. Error due to lack of fit of model to data is significantly greater than expected pure error at 99 percent level of confidence.

Results and Discussion

Comparison of Degradation Model Equations

The average properties of unexposed specimens are listed in table 1. The percent retention of each property as a function of the number of aging cycles was fitted to each regression model. The capability of each model to accommodate the data was judged on the basis of the R^2 statistic and the "lack of fit" test. (R^2, the correlation coefficient squared, may also be interpreted as the fraction of the variation in the property that can be explained by the regression equation.) Subjectively, the hyperbolic model was distinctly better (higher R^2's and fewer "lack of fit" indications) than the linear model and was from somewhat to distinctly more satisfactory than the log model. For uniformity, all of the comparisons in the results are based on the hyperbolic model. The coefficients of the fitted equations plus the R^2 values and the "lack of fit" test results for each equation are shown in tables 2 *through* 9.

Four categories of R^2 and "lack of fit" were evaluated: (1) Lack of fit (NS) and R^2 (high), (2) lack of fit (* or **) and R^2 (high), (3) lack of fit (NS) and R^2 (low), and (4) lack of fit (* or **) and R^2 (low). Of these, the first category is the most desirable. The second is also desirable because the R^2 in this case is generally very high and the "lack of fit" indication results only from the error term of the regression being very small. One hundred and eight regression equations were fitted; 45 of the regressions fell into categories 1 and 2; and 51 fell into category 3. Category 3 can be interpreted as meaning the data are so scattered almost any model will fit the data. All but two (18 of 20) of the regressions for solid wood and plywood fell in category 3. This probably reflects the greater natural variability of solid wood compared to that of the more homogeneous particleboards and fiberboards. Twelve regressions fell in category 4, significant lack of fit and low R^2. A better fit

[3] In this work, MOR and MOE were evaluated primarily as measures of degradation. Both properties are more sensitive and less variable if calculated using thickness after aging. It is understood designers prefer MOR and MOE calculated using original, or unaged thickness. These values can be approximated from the data in this Report by the equation:

$$MOR' \text{ or } MOE' = \frac{V_O \times R_N [t_O (1 + S_N)]^2}{t_O^2}$$

where V_O = unaged MOR or MOE from figs. 9, 13, or 10, 14.

R_N = pct retention of MOR or MOE after N cycles from figs. 1, 5, or 2, 6.

t_O = the unaged thickness from table 1.

S_N = pct swelling after N cycles from figs. 4 or 8.

may be possible for these regressions, but again the data are scattered and not worthy of a model more elaborate than that of the hyperbolic equation.

Hyperbolic Model for Degradation

The aging behavior of bonded wood products frequently is characterized by a rapid initial property loss (occasionally gain), a transition zone, and a prolonged linear rate of loss (occasionally gain) for the major portion of the life of the product. These stages of degradation are evident in the plots of the fitted equations shown in figures 1 through 8.

The hyperbolic model provides a coefficient descriptive of each stage in the aging process. The A_0 term of the hyperbolic equation is related to the rapid initial property change; its size reveals both magnitude and direction of initial change. The A_2 term describes transition from the fast initial rate to the slower prolonged rate; its size indicates the abruptness of the transition and its sign, the direction of change. A large A_2 coefficient indicates a gradual transition. A positive coefficient indicates the curve is concave upward. The A_1 coefficient describes the slower rate of property change during the major portion of a material's serviceable life; a negative A_1 coefficient indicates the property is decreasing.

Variability of Regression Equations

The standard deviations of the fitted hyperbolic equations are listed in tables 10 and 11. The fitted equations for plywood (P) and solid wood specimens (W and X) generally had the largest standard deviations for mechanical properties among all of the boards and the lowest standard deviations for thickness swelling. The high variability of mechanical properties should be expected from the variability of size and distribution of solid wood defects. The low standard deviation for thickness swelling should be expected from the higher degree of bonding in solid wood than in reconstituted wood panels. In most cases the fitted equations for hardboard mechanical properties had small standard deviations. They were consistently smaller than were the standard deviations for particleboards after the vacuum-pressure, soak-dry treatment. However, the difference was less pronounced after the boil-dry treatment. The smaller standard deviations for hardboard might be expected because of small size and homogeneity of defects in the hardboards. Among the mechanical properties, MOE had the lowest average standard deviation (7.47 pct in boil-dry; 7.14 pct in soak-dry) for all boards. (Standard deviations for thickness swelling equations were by far lower, but they are not comparable because the equations for thickness are based on the percent of swelling that never exceeded 30 percent, whereas the equations for mechanical properties are based on percent remaining that varied from about 100 to 30 percent.) Equations for internal bond strength had the highest average standard deviations (13 pct) for all boards.

Change of Properties After 80 Cycles of Aging

Figures 9 through 16 (computer histograms) show the initial values of three mechanical properties and the magnitude of the changes in the properties caused by 80 cycles of boil-dry or soak-dry treatment. Examination of the histograms reveals the best performing flakeboards and hardboards are comparable to plywood for MOR retained after 80 cycles of the aging treatment. However, they are less comparable for MOE retained. The best performing flake and hardboards retain their internal bond strength as well as or better than does plywood, and surprisingly, better than solid Douglas-fir in the soak-dry treatment. The thickness swelling of the best performing hardboards compares favorably to swelling of solid wood and plywood, especially in the soak-dry treatment.

Hardboards U and V were initially slightly thinner than were boards S and T and the flakeboards, but the specific gravities, or densities, of boards U and V, at 0.89 and 0.83, were significantly higher than were boards S and T and most flakeboards; none of the flakeboards exceeded 0.71 specific gravity (table 1). It would be reasonable to think boards U and V might swell more than would the other materials, on the contrary, they swelled less. Boards U and V probably had a higher resin content or bonding conditions were better.

Effect of Aging Treatments on Degradation Rate

Inspection of figures 1 through 8 shows that the boil-dry treatment caused slower rates of degradation as indicated by the A, coefficient than did the vacuum-pressure, soak-dry treatment and that rates among the various boards were more uniform in the boil-dry treatment than they were in the vacuum-pressure, soak-dry. This is summarized in table 12, which shows that generally the degradation rates for mechanical properties were approximately 1.5 times greater in the vacuum-pressure, soak-dry treatment than they were in the boil-dry. Secondly, the coefficients of variation of the degradation rates range from 1.2 to almost 4 times greater in the vacuum-pressure, soak-dry treatment than in the boil-dry. No difference is apparent in the means of the rates of thickness swelling between the treatments; however, the coefficients of variation of rates of the vacuum-pressure, soak-dry treatment are again about twice those of the coefficients of variation of the boil-dry.

Carroll reported differences in effects between boil-dry and cold-water soak-dry treatments on phenolic-bonded plywood *(4)*. One difference is attributed to completion of cure of undercured phenolic adhesives in the boil-dry treatment compared to no further cure in the soak-dry treatment. If all bonds reach complete cure by boiling, then degree-of-cure is removed as a cause of variability among the various products. Differences in amount of rapid initial loss are probably caused by differences in degree-of-cure and residual internal stresses from bonding. After these factors have been equalized by the first boil-dry cycle, the degradation proceeds at a uniform rate with small differences caused by species, adhesive formulation, particle size, and board density.

Large differences in amount of rapid initial loss are also apparent after the first cycle of the vacuum-pressure, soak-dry treatment, but because elevated temperature is not part of the treatment, differences in adhesive cure among boards remain during the entire exposure. This must account for the great differences in degradation rates (A, coefficients) noted in the vacuum-pressure, soak-dry treatment.

Comparison of ASTM D-1037 with Boil-Dry and Soak-Dry Treatments

In figures 1, 2, 5, and 6, values of MOR and MOE retained after the ASTM D-1037 exposure are plotted on the corresponding boil-dry and vacuum-pressure, soak-dry degradation rate curves. The dangers of the ASTM test not providing any indication of the rate of degradation can be seen in the figures. It is evident some degree of correspondence exists between the MOR or the MOE retained after ASTM exposure and the other cyclic exposures. However, very little correspondence is seen in the number of cycles to produce the same amount of degradation. For example, figure 2 shows only two boil-dry cycles of board U were required to produce a loss of MOR equivalent to the loss caused by the six-cycle ASTM exposure. By contrast, 65 boil-dry cycles of board B were required to produce loss equivalent to that in the ASTM exposure. Furthermore, misleading conclusions can be drawn by assuming a board with a higher retention after the ASTM test will last longer than a board with a lower retention. The danger is not knowing each board's current degradation rate and position on the curve. For example, in figure 2, board Z has a higher ASTM retention than board L, but the board Z ASTM value is far to the right and its degradation rate is faster; therefore, it will certainly reach zero strength before board L does. (A fair assumption is that respective rates will remain constant in late stages of degradation.) Similar examples are boards S and B in figure 5 and boards 0 and S in figure 6.

These results demonstrate that a test such as the ASTM D-1037 accelerated-aging test (or WCAMA test 6.1) can be useful for quality control but this type of test should never be assumed to predict long-term performance of exterior-type board products.

Conclusions

1. A simple hyperbolic equation, $Y = A_0 + A_1X + A_2/X$, provides a useful model for change in bending strength, modulus of elasticity, internal bond strength, and thickness swelling of panel products exposed to boil-dry or vacuum-pressure, soak-dry cycles (Y = property, X = number of cycles).

2. Degradation of most panel products is characterized by a rapid initial change in a property followed by transition to a much slower linear degradation.

3. Test data for hardboards were generally the least variable and gave the best fit to the model equations. Data for plywood and solid wood were consistently the most variable, and gave the poorest fit to all equations.

4. Long-term degradation rates from boil-dry exposures were much more uniform among all materials tested than were rates from vacuum-pressure, soak-dry exposures. The conclusion was the difference was caused by removal of the degree of resin cure as a source of variability in the boil-dry test

5. The best performing hardboards and flakeboards retained percentages of original properties after 80 cycles of exposure comparable to the percentages retained by plywood. Although the actual flakeboard and hardboard property values were lower than were those for plywood (or higher for thickness swelling), the data indicate some flakeboards and hardboards should perform very well in long-term exterior applications.

Table 1.—Properties of unexposed boards (average)

Board	Material	Specific gravity	Thickness	Bending strength	Bending stiffness	Internal bond strength
			In.	Lb/in.²	Lb/in.²	Lb/in.²
A	Laboratory flakeboard	0.64	0.51	4,930	677,000	164
B	Laboratory flakeboard	.61	.52	3,800	608,000	83
C	*Commercial waferboard*	.60	.53	2,660	508,000	69
D	Commercial overlaid particleboard[1]	.56	.64	1,570	260,000	74
F	Three layer commercial flakeboard[1]	.70	.53	6,580	997,000	112
L	Laboratory flakeboard	.63	.54	4,590	711,000	107
O	Laboratory flakeboard	.62	.52	4,890	670,000	125
P	Douglas-fir plywood	.47	.48	6,660	965,000	127
S	Commercial hardboard[2]	.71	.45	3,020	351,000	48
T	Commercial hardboard[2]	.66	.41	2,490	419,000	21
U	Commercial hardboard[2]	.89	.39	6,370	566,000	347
V	Commercial hardboard[2]	.83	.39	4,390	424,000	346
W	Douglas-fir lumber	.48	.50	14,350	2,007,000	372
X	Southern pine lumber	.52	.50	16,180	1,990,000	612
Z	*Commercial flakeboard*[1]	.65	.54	5,210	799,000	125

[1] Results from first investigation but were not in the earlier report *(2)*.
[2] New boards included in this investigation.

Table 2.—Regression equations percent MOR (modulus of rupture) retention versus number of cycles of boil-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		R^2
	A_0	A_1	A_2	Regression	Lack of fit	
A	63.6	−0.275	+12.3	**	**	0.70
B	52.0	−.259	+12.3	**	NS	.50
C	35.7	−.231	+20.2	**	*	.64
D	59.7	−.182	+18.6	**	NS	.45
F	60.8	−.183	+11.1	**	*	.50
L	52.8	−.182	+5.04	**	NS	.43
O	50.6	−.171	+10.6	**	NS	.58
P	88.8	−.308	+0.333	**	NS	.35
S	52.4	−.343	+16.6	**	*	.69
T	55.2	−.253	+8.31	**	NS	.81
U	70.3	−.185	+17.7	**	NS	.80
V	81.7	−.217	+10.7	**	*	.60
W	107	−.323	−9.32	*	NS	.23
X	87.5	−.226	+11.2	**	NS	.38
Z	59.0	−.181	+10.1	**	NS	.57

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)

Table 3.—Regression equations percent MOE (modulus of elasticity) retention versus number of cycles of boil-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		R^2
	A_0	A_1	A_2	Regression	Lack of fit	
A	62.7	−0.234	+3.29	**	**	0.63
B	49.6	−.193	+9.80	**	**	.60
C	35.6	−.263	+16.5	**	**	.80
D	57.8	−.157	+12.3	**	NS	.47
F	54.9	−.124	+12.0	**	NS	.61
L	61.6	−.255	−4.80	*	**	.26
O	51.0	−.124	+8.74	**	NS	.50
P	96.7	−.069	−1.04	NS	NS	.03
S	46.9	−.327	+12.0	**	**	.61
T	39.2	−.218	+9.64	**	**	.86
U	53.6	−.178	+20.8	**	NS	.86
V	68.7	−.177	+11.3	**	**	.64
W	98.1	−.028	+2.25	NS	NS	.02
X	94.9	−.064	+0.337	NS	NS	.02
Z	55.7	−.351	+10.3	**	NS	.82

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)

Table 4.—Regression equations percent IB (internal bond strength) retention versus number of cycles of boil-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		
	A_0	A_1	A_2	Regression	Lack of fit	R^2
A	58.2	−0.269	+34.5	**	NS	0.69
B	27.7	−.248	+24.2	**	NS	.66
C	12.2	−.138	+20.1	**	**	.55
D	47.4	−.320	+0.356	NS	NS	.19
F	52.8	−.352	+40.2	**	NS	.53
L	50.3	−.331	+27.4	**	NS	.65
O	48.2	−.303	+22.9	**	NS	.82
P	98.9	−.718	−3.29	**	NS	.40
S	44.3	−.293	+30.7	**	NS	.72
T	70.3	−.426	-6.52	**	NS	.81
U	13.0	−.028	+6.48	NS	NS	.08
V	27.7	+.067	+11.5	NS	**	.11
W	86.5	−.416	−14.2	*	NS	.21
X	97.5	−.712	−9.68	**	NS	.45
Z	29.8	−.362	+11.9	**	NS	.48

[1] $\hat{y} = A_0 + A_1X + A_2 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)

Table 5.—Regression equations percent thickness increase versus number of cycles of boil-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		
	A_0	A_1	A_2	Regression	Lack of fit	R^2
A	15.8	+0.018	−2.51	**	NS	0.41
B	25.4	+.008	−4.82	**	NS	.37
C	27.0	+.191	−9.26	**	NS	.66
D	14.5	+.009	−4.32	**	NS	.64
F	16.6	+.030	−2.80	**	NS	.36
L	22.0	+.001	−2.32	NS	NS	.12
O	27.2	−.015	−7.76	**	**	.57
P	3.19	+.003	−.563	NS	NS	.07
S	16.0	+.145	−3.58	**	*	.71
T	18.3	+.067	+1.43	**	NS	.35
U	11.1	−.005	−5.59	**	NS	.49
V	5.31	+.012	−2.52	**	**	.29
W	1.47	−.005	−.713	NS	NS	.14
X	1.53	+.013	−.548	NS	NS	.11
Z	22.5	−.013	−4.04	**	NS	.47

[1] $\hat{y} = A_0 + A_1X + A_2 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)

Table 6.—Regression equations percent MOR (modulus of rupture) retained versus number of vacuum-pressure, soak-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		
	A_0	A_1	A_2	Regression	Lack of fit	R^2
A	68.7	−0.323	9.91	**	NS	0.36
B	76.6	−.862	−10.1	NS	NS	.22
C	64.8	−1.05	7.94	**	**	.70
D[3]	—	—	—	—	—	—
F[3]	—	—	—	—	—	—
L	64.5	−.479	−3.47	NS	NS	.24
O	70.6	−.687	−3.50	**	NS	.50
P	76.0	−.120	12.3	*	NS	.29
S	50.1	−.061	23.7	**	NS	.65
T	32.8	−.306	37.7	**	*	.96
U	67.7	−.109	20.5	**	*	.78
V	77.6	−.135	4.16	**	NS	.35
W	100	−.059	−1.48	NS	NS	.0
X[3]	—	—	—	—	—	—
Z	57.1	−.115	8.26	*	NS	.27

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)
[3] No data.

Table 7.—Regression equations percent of MOE (modulus of elasticity) retained versus number of vacuum-pressure, soak-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		
	A_0	A_1	A_2	Regression	Lack of fit	R^2
A	66.1	−0.376	13.2	**	NS	0.62
B	55.5	−.268	9.46	**	NS	.38
C	58.5	−.775	16.4	**	NS	.73
D[3]	—	—	—	—	—	—
F[3]	—	—	—	—	—	—
L	62.0	−.413	1.89	**	*	.36
O	71.5	−.680	−4.86	**	**	.66
P	85.1	−.179	13.6	**	NS	.38
S	43.5	−.120	22.3	**	*	.73
T	28.1	−.411	34.7	**	**	.97
U	51.8	−.179	31.7	**	**	.87
V	62.9	−.035	12.6	**	**	.59
W	107	−.037	−2.98	NS	NS	.02
X[3]	—	—	—	—	—	—
Z	55.5	−.198	11.1	**	NS	.61

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)
[3] No data.

Table 8.—Regression equations percent IB (internal bond strength) retention versus number of cycles of vacuum-pressure, soak-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		R^2
	A_0	A_1	A_2	Regression	Lack of fit	
A	75.7	−0.274	12.2	NS	*	0.15
B	56.2	−.707	−12.5	**	NS	.42
C	40.1	−.749	8.15	**	NS	.50
D[3]	—	—	—	—	—	—
F[3]	—	—	—	—	—	—
L	84.3	−.752	−9.98	*	NS	.33
O	74.7	−.688	−6.22	NS	NS	.23
P	107	−.632	−11.4	NS	NS	.10
S	48.4	−.339	31.7	**	NS	.75
T	78.1	−.674	61.9	**	NS	.94
U	8.77	−.008	18.0	**	NS	.90
V	16.8	+.155	35.9	**	NS	.81
W	110	−1.34	−28.5	NS	NS	.20
X[3]	—	—	—	—	—	—
Z	35.5	−.156	22.5	**	NS	.55

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)
[3] No data.

Table 9.—Regression equations percent thickness *increase versus number of cycles of* vacuum-pressure, soak-dry treatment

Board	Equation[1] coefficients			ANOVA "F" test[2]		R^2
	A_0	A_1	A_2	Regression	Lack of fit	
A	12.5	+0.073	−1.56	**	NS	0.51
B	18.4	+.170	−2.18	**	**	.73
C	15.3	+.275	−2.75	**	NS	.54
D[3]	—	—	—	—	—	—
F[3]	—	—	—	—	—	—
L	16.2	+.141	−1.68	**	**	.50
O	17.6	+.145	−1.34	**	NS	.58
P	2.45	+.048	−1.17	**	NS	.61
S	15.8	−.146	−7.51	**	**	.49
T	23.8	−.001	−15.3	**	**	.76
U	11.9	−.174	−8.16	**	**	.73
V	8.42	−.185	−6.12	**	**	.68
W	1.16	−.004	−.774	NS	NS	.19
X[3]	—	—	—	—	—	—
Z	17.6	+.098	−2.99	**	*	.64

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/X$.
[2] *, Error caused by lack of fit is significant at 95 pct level of confidence; **, error caused by lack of fit is significant at 99 pct level of confidence; and NS, error caused by lack of fit of model to data is significant compared to error attributed to pure error; model is adequate. (Further explanation in Data Analysis section of text.)
[3] No data.

Table 10.—Standard deviations of $\hat{y}$ about regression line[1] (boil-dry treatment)

Board	y			
	Modulus of rupture	Modulus of elasticity	Internal bond strength	Thickness swelling
A	7.2	5.8	12.2	1.54
B	10.5	6.5	10.0	2.52
C	9.2	6.1	9.2	5.65
D	11.6	8.4	19.1	1.29
F	8.1	5.6	20.1	2.22
L	7.4	11.2	12.5	2.35
O	6.6	6.0	7.0	2.30
P	12.3	9.9	24.3	.97
S	9.5	9.8	10.8	3.16
T	4.6	3.5	5.3	2.32
U	5.1	4.6	7.2	2.04
V	7.3	6.0	10.2	1.80
W	14.8	11.7	20.1	.54
X	12.0	13.0	20.9	1.40
Z	5.3	3.9	9.3	1.58

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/x$.
where y = Modulus of rupture, modulus of elasticity, internal bond strength, or thickness swelling,
x = number of cycles of boil-dry treatment.

Table 11.—Standard deviations of $\hat{y}$ about the regression line[1] (vacuum-pressure, soak-dry treatment)

Board	y			
	Modulus of rupture	Modulus of elasticity	Internal bond strength	Thickness swelling
A	10.5	7.6	18.6	1.51
B	20.4	8.8	9.8	1.89
C	11.7	9.8	13.4	4.49
L	11.4	8.8	13.2	2.58
O	9.4	6.4	16.5	2.15
P	11.1	15.2	22.5	.84
S	7.2	6.2	9.2	2.36
T	3.5	3.1	8.3	3.40
U	4.8	5.4	2.4	1.55
V	4.5	4.4	6.2	1.56
W	11.5	10.5	31.6	.53
Z	7.3	5.3	9.4	9.45

[1] $\hat{y} = A_0 + A_1X + A_2\ 1/x$.
where y = Modulus of rupture, modulus of elasticity, internal bond strength, or thickness swelling,
x = number of cycles of boil-dry treatment.

Table 12.—Comparison of average and variability of degradation rates[1] caused by boil-dry and vacuum-pressure, soak-dry treatments

	Treatment	Mean rate of all boards	Standard deviation	Coefficient of variation
Modulus of rupture	Boil-dry	−0.235	±0.057	24
	Vacuum-pressure, soak-dry	−.359	±.339	94
Modulus of elasticity	Boil-dry	−.184	±.094	51
	Vacuum-pressure, soak-dry	−.300	±.245	82
Internal bond	Boil-dry	−.323	±.209	65
	Vacuum-pressure, soak-dry	−.514	±.407	79
Thickness swelling	Boil-dry	+.031	±.060	200
	Vacuum-pressure, soak-dry	+.037	±.145	392

[1] A, coefficient of hyperbolic model *(2)*.

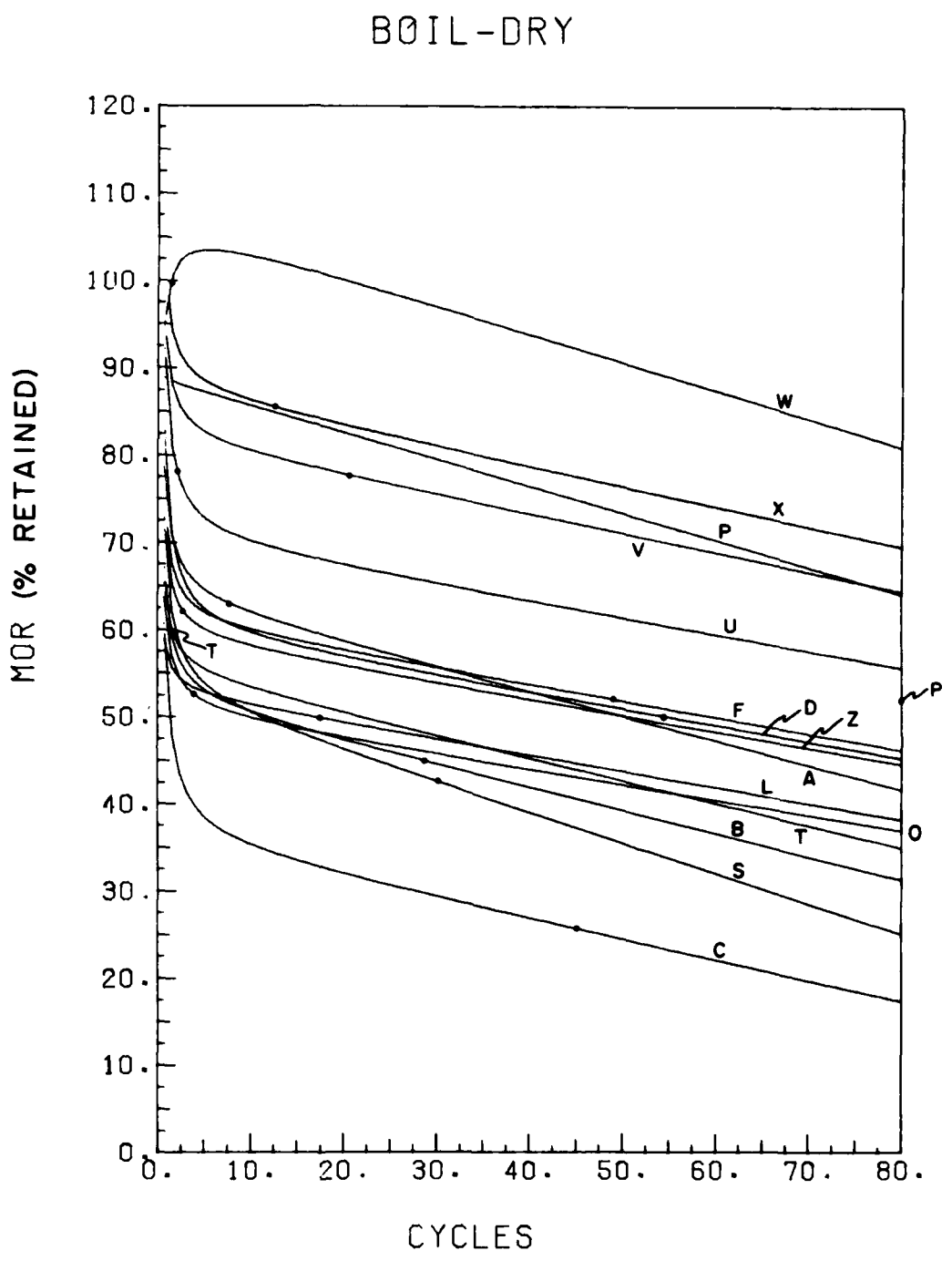

Figure 1.—Fitted hyperbolic equations for residual modulus of rupture (MOR) as function of number of boil-dry cycles. (ASTM D 1037 values, (●).)

(M 149 015)

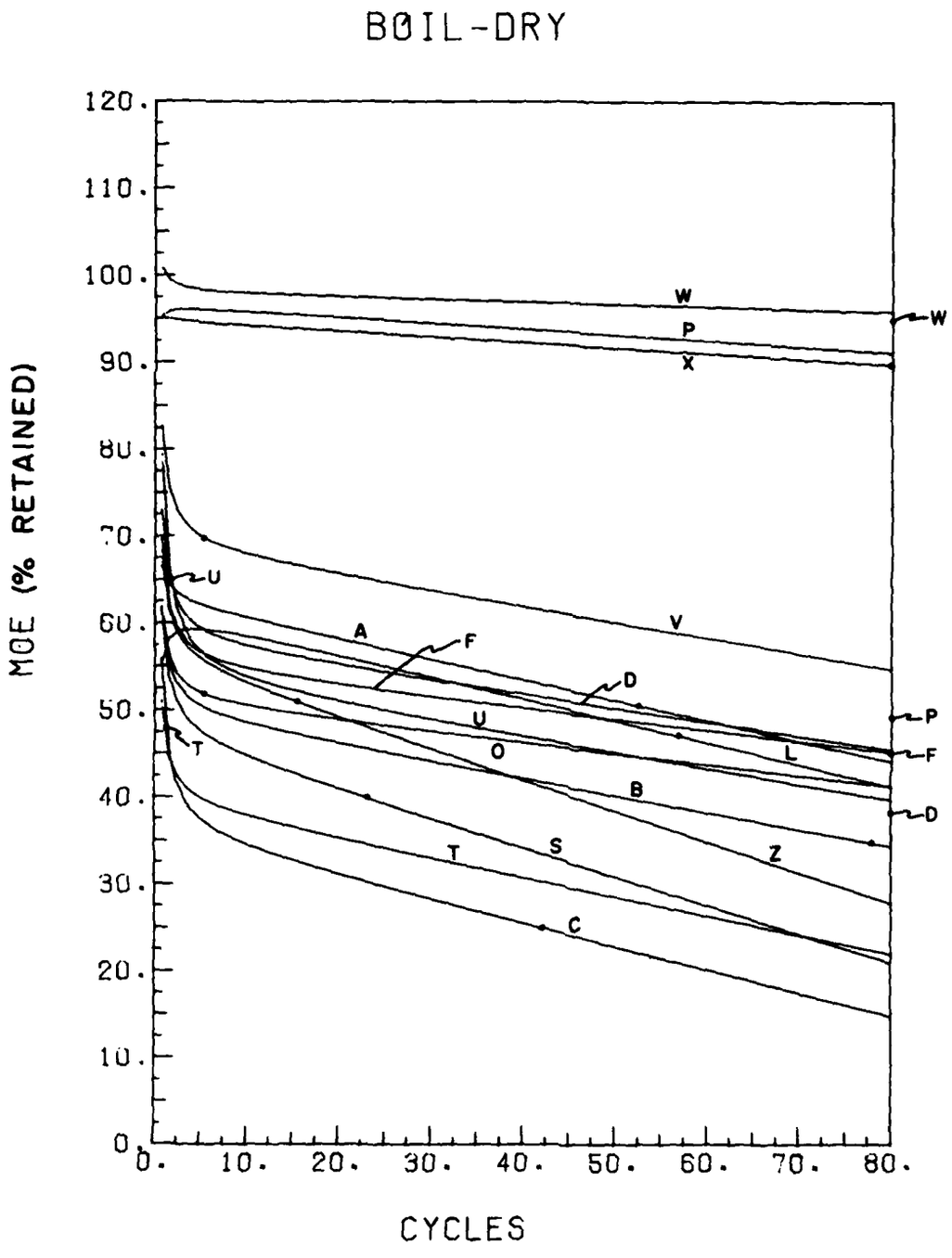

Figure 2.—Fitted hyperbolic equations for residual modulus of elasticity (MOE) as function of number of boil-dry cycles. (ASTM values, (●).)

(M 149 014)

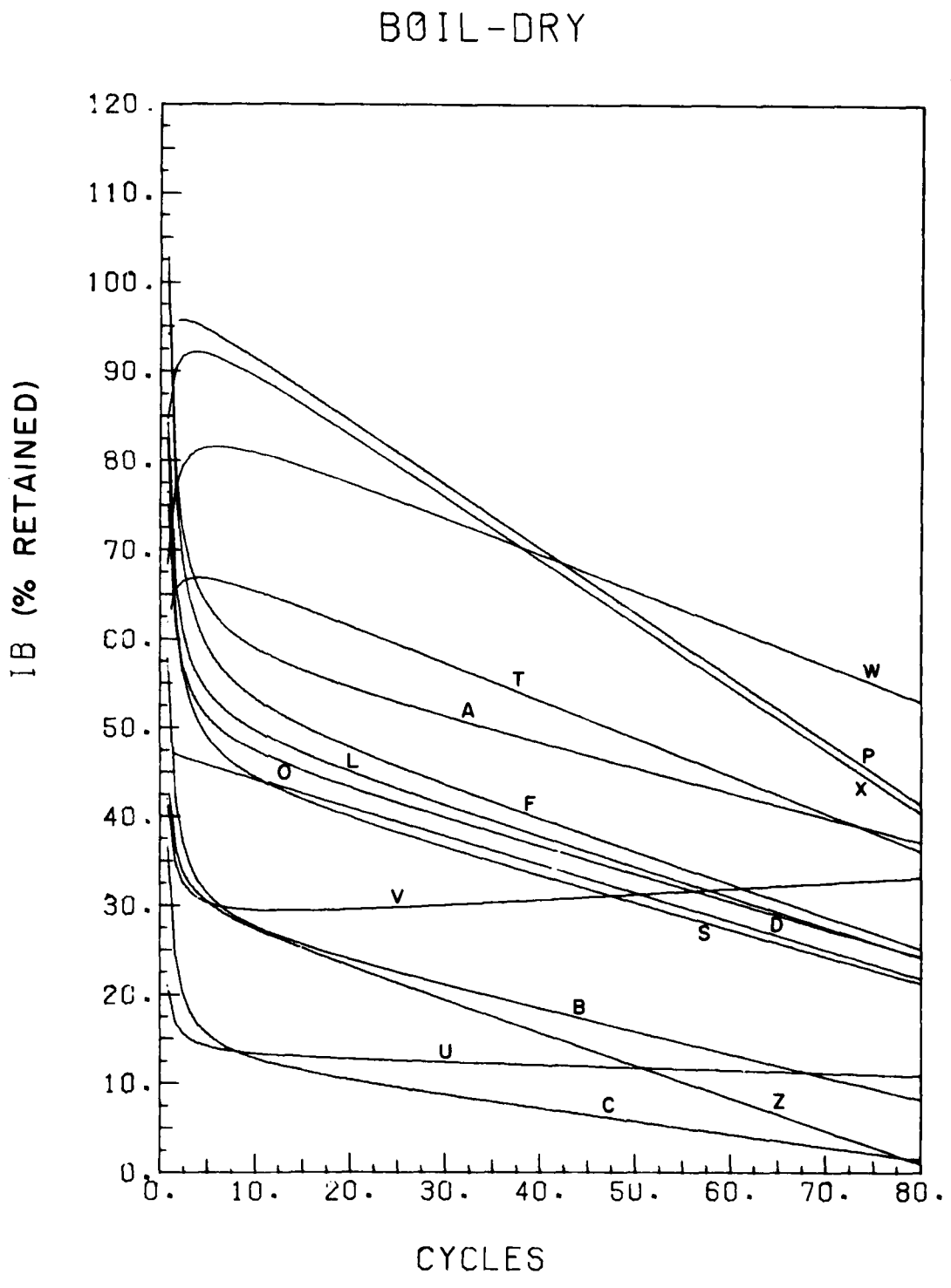

Figure 3.—Fitted hyperbolic equations for residual internal bond strength (IB) as function of number of boil-dry cycles.

(M 150 038)

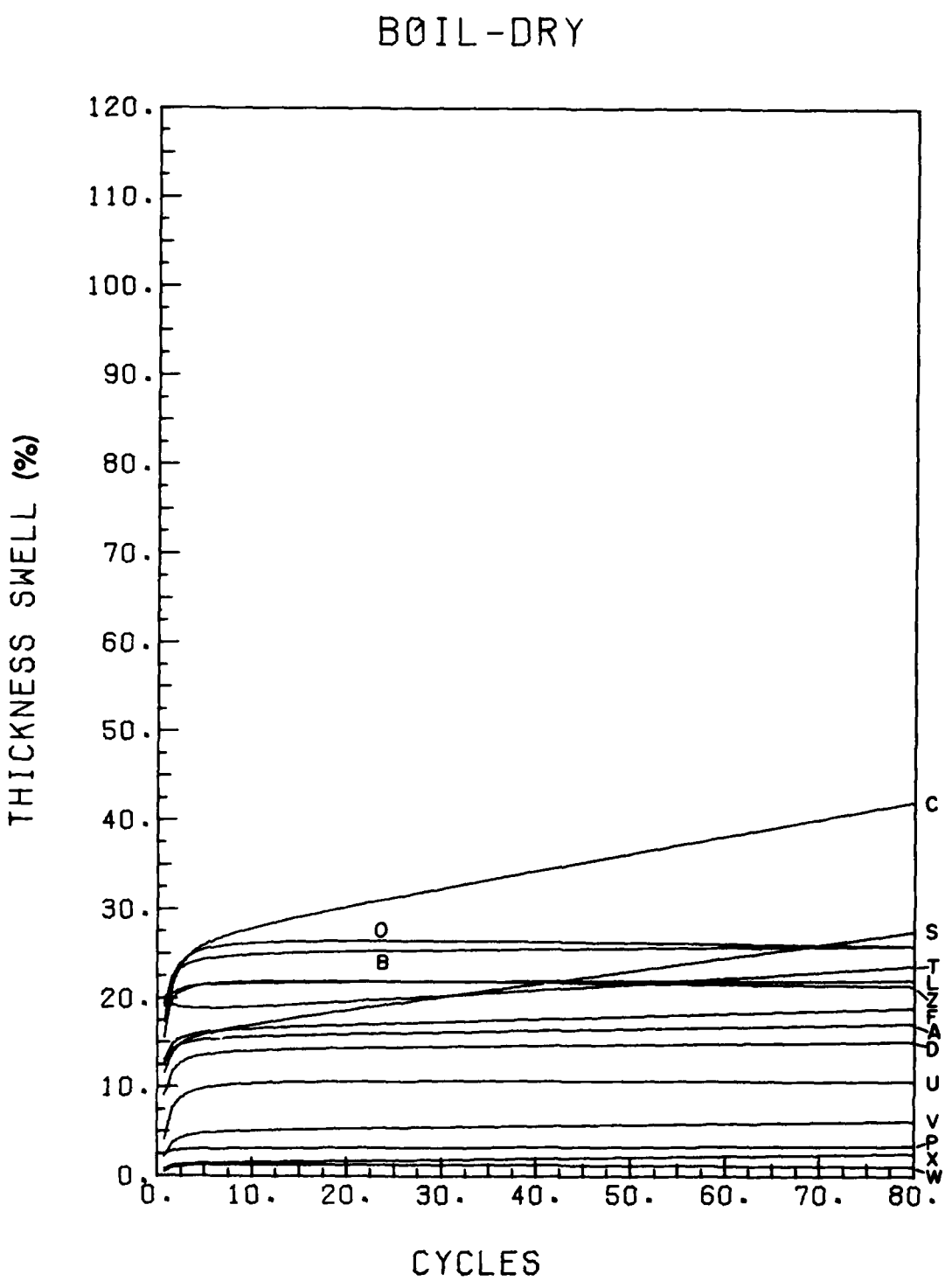

Figure 4.—Fitted hyperbolic equations for residual thickness swell as function of number of boil-dry cycles.

(M 150 038)

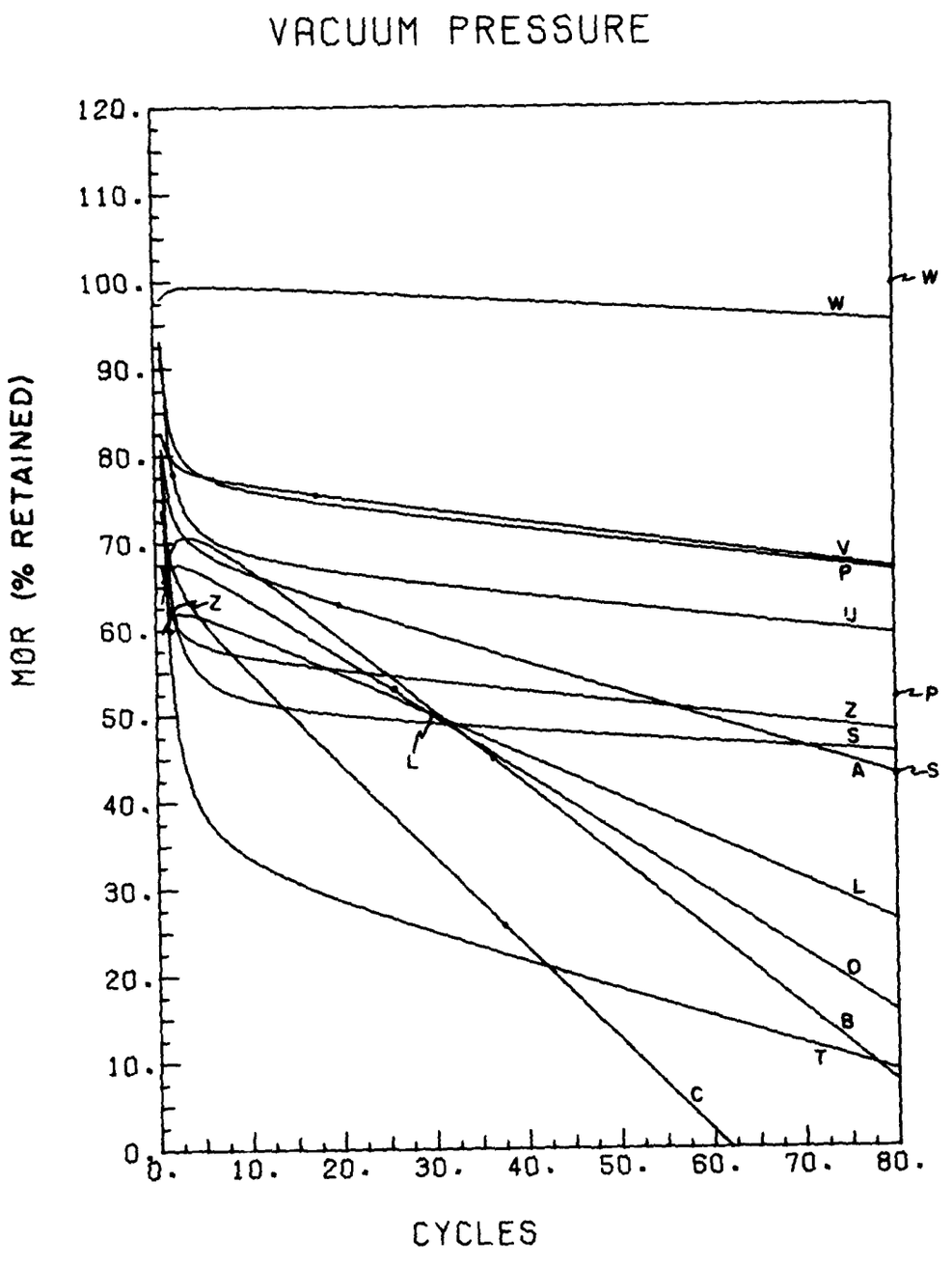

Figure 5.—Fitted hyperbolic equations for residual modulus of rupture (MOR) as function of number of vacuum-pressure, soak-dry cycles. (ASTM values, (●).)

(M 149 013)

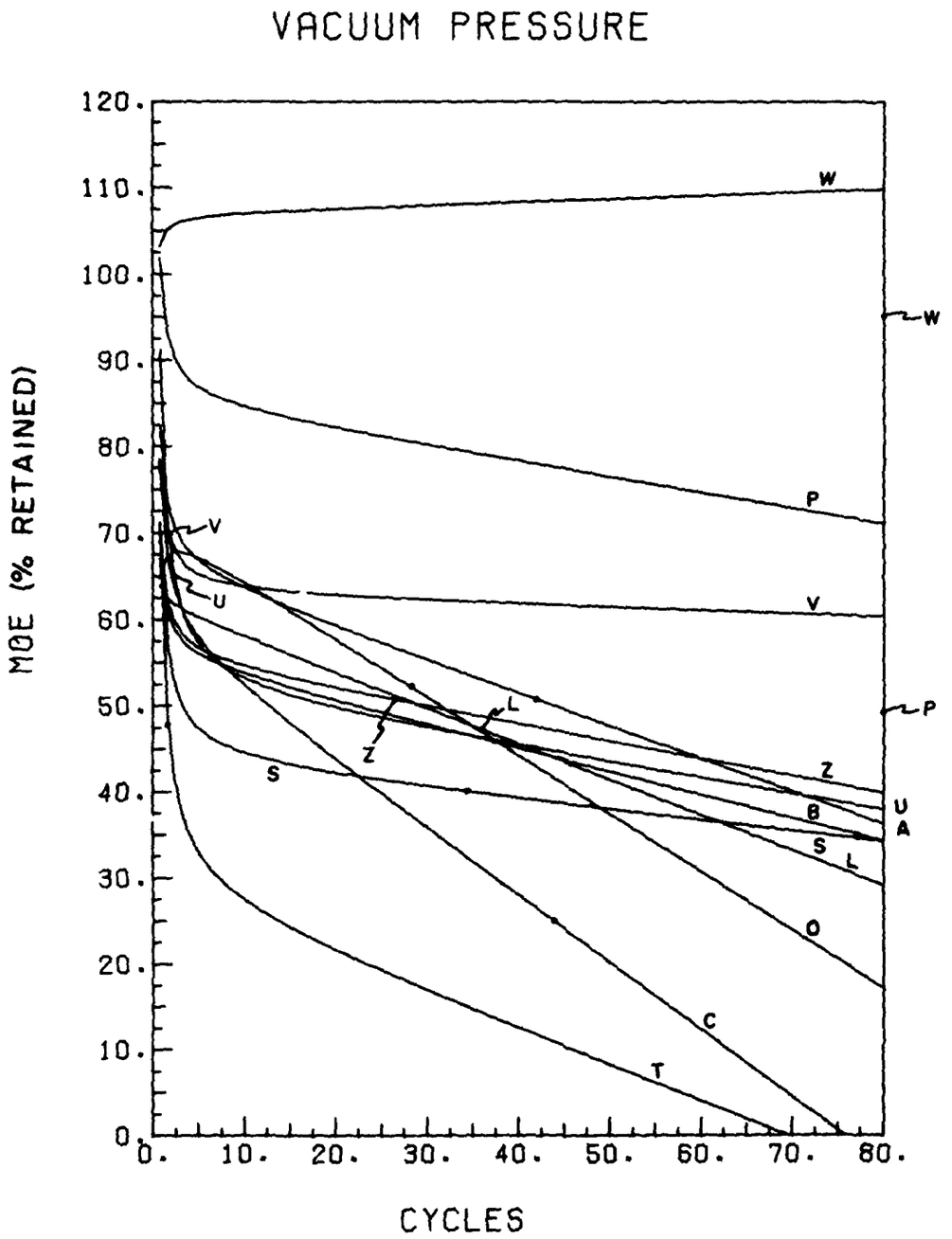

Figure 6.—Fitted hyperbolic equations for residual modulus of elasticity (MOE) as function of number of vacuum-pressure, soak-dry cycles. (ASTM values, (●).)

(M 149 012)

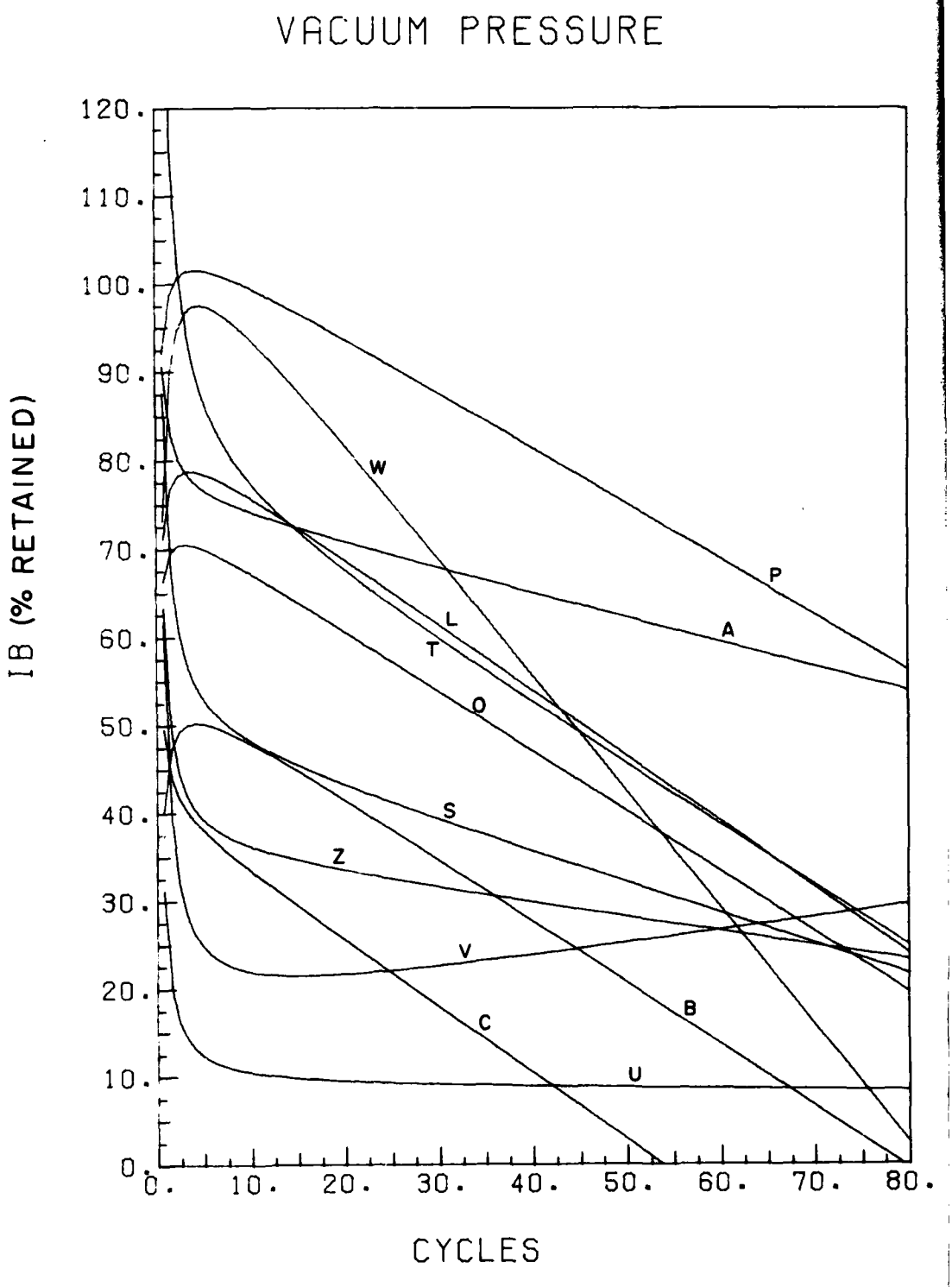

Figure 7.—Fitted hyperbolic equations for residual internal bond strength (IB) as function of number of vacuum-pressure, soak-dry cycles.

(M 150 037)

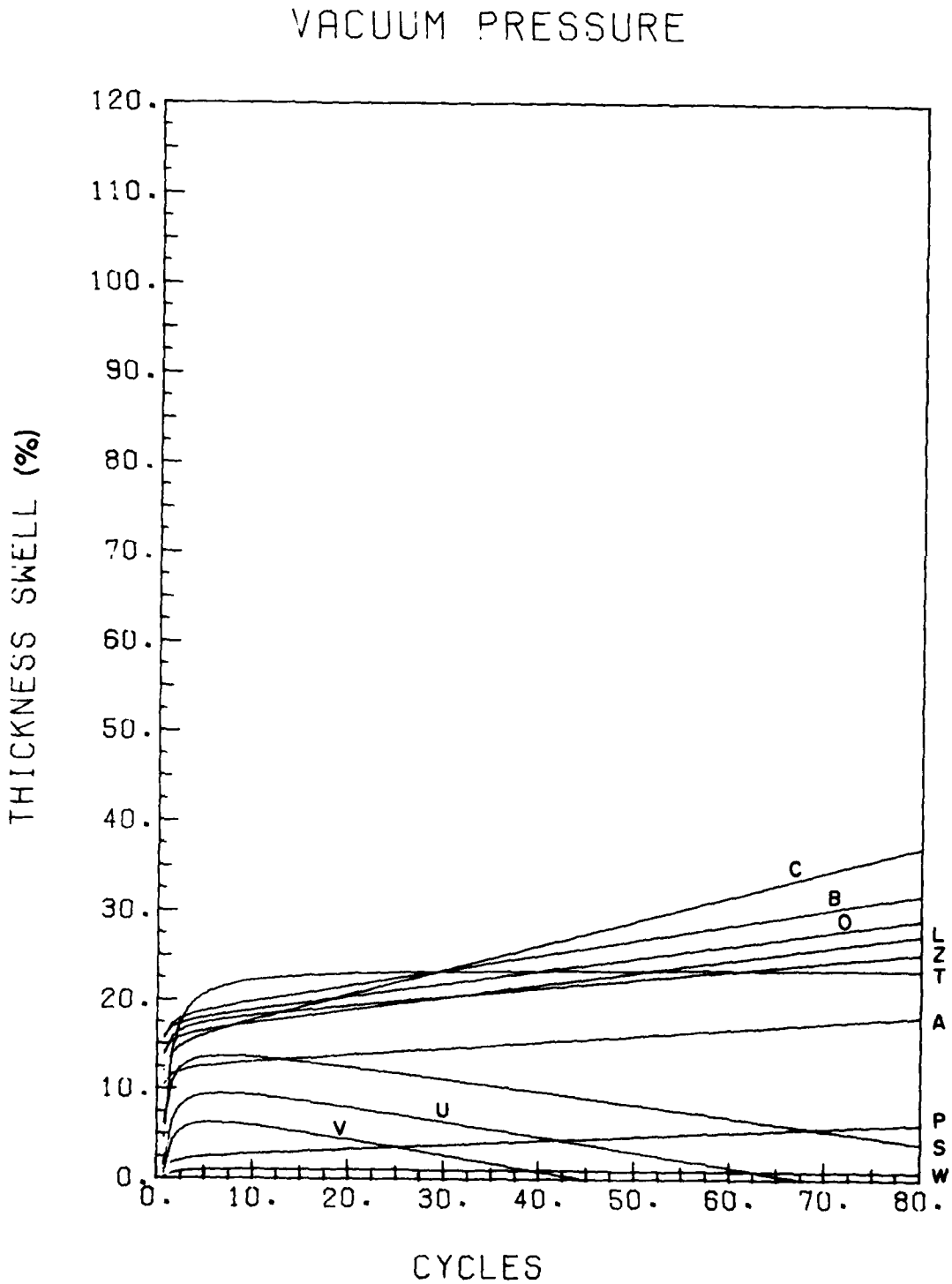

Figure 8.—Fitted hyperbolic equations for residual thickness swell as function of number of vacuum-pressure, soak-dry cycles.

(M 150 039)

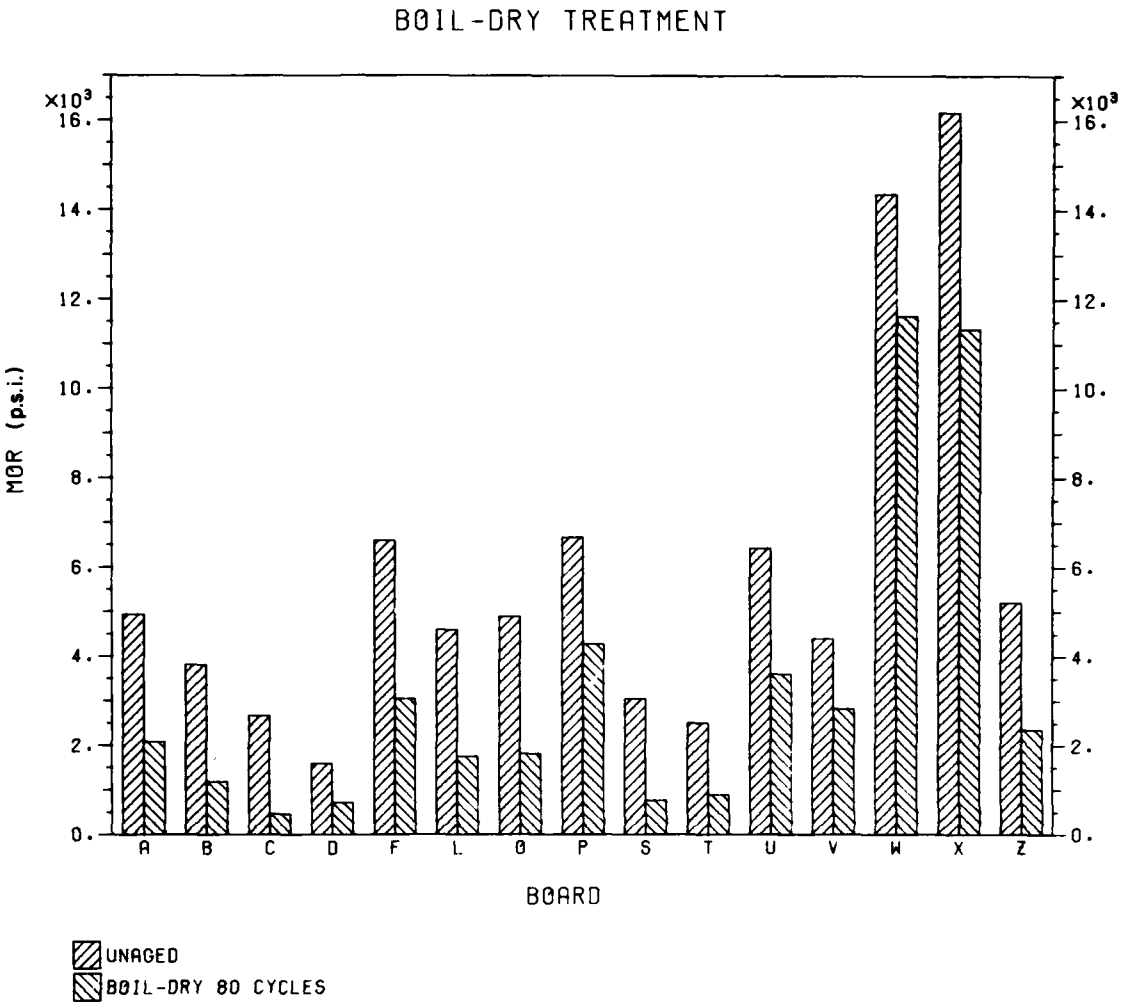

Figure 9.—Original modulus of rupture (MOR) and residual modulus of rupture (MOR) after 80 cycles of boil-dry treatment.

(M 149 011)

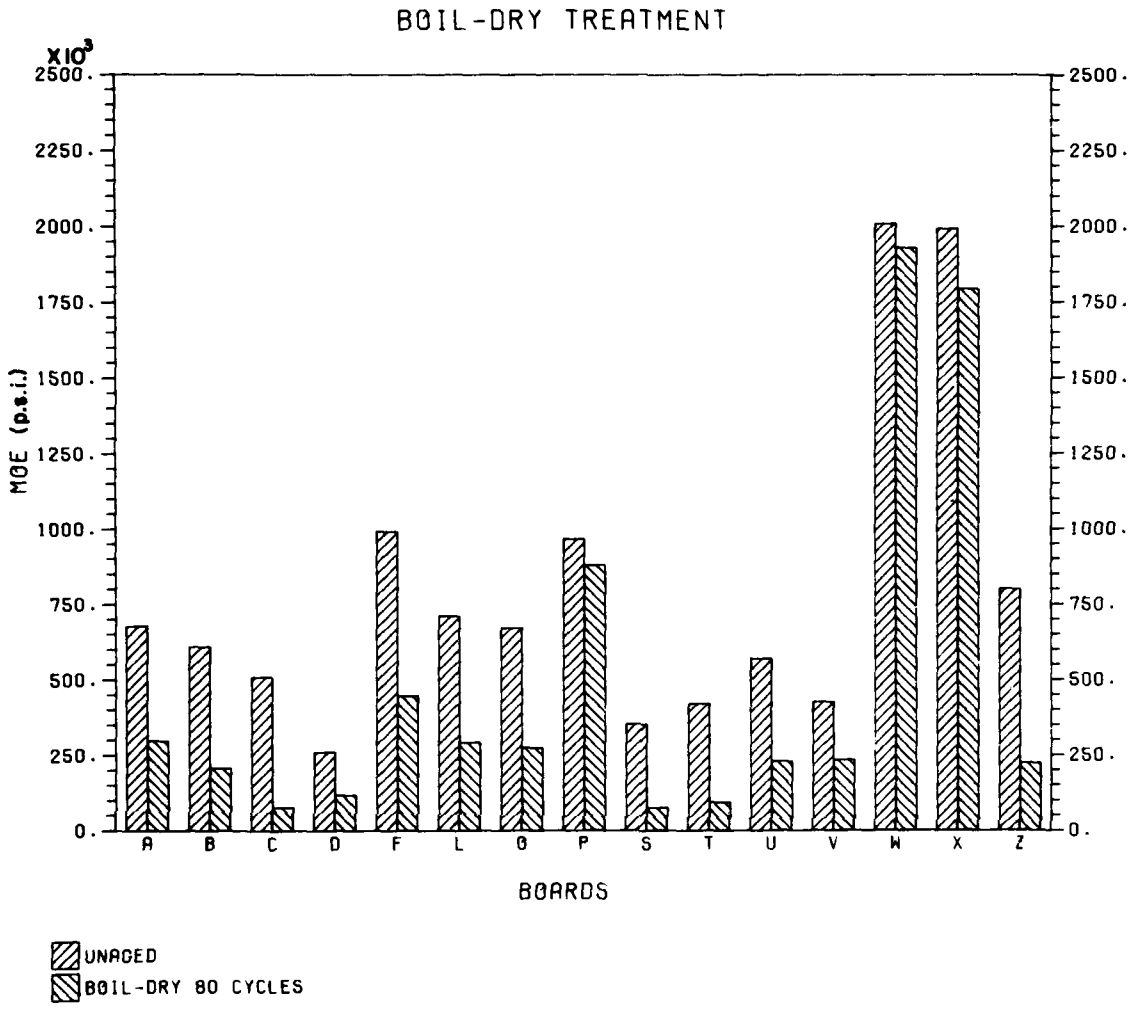

Figure 10.—Original modulus of elasticity (MOE) and residual modulus of elasticity (MOE) after 80 cycles of boil-dry treatment.

(M 149 010)

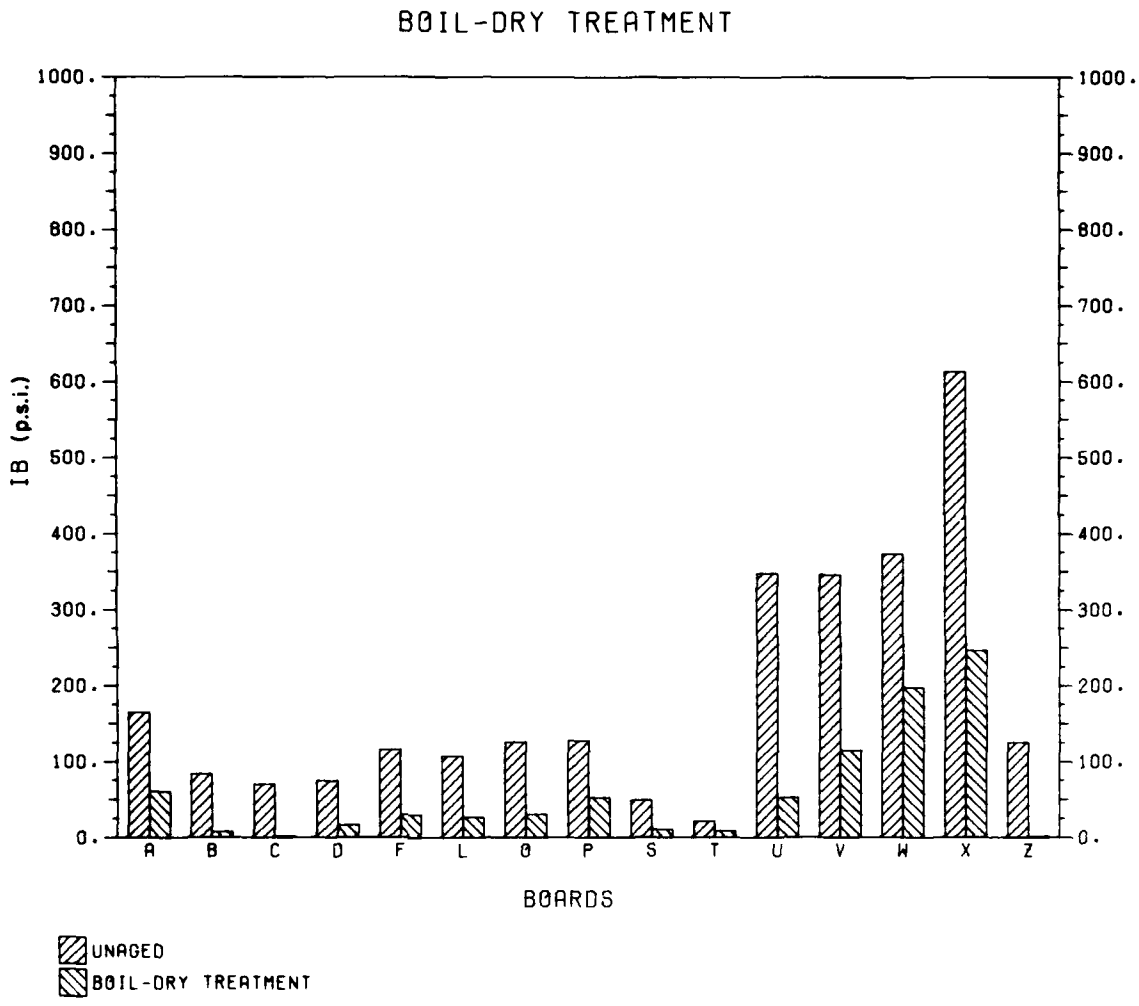

Figure 11.—Original internal bond strength (IB) and residual internal bond strength (IB) after 80 cycles of boil-dry treatment.

(M 149 009)

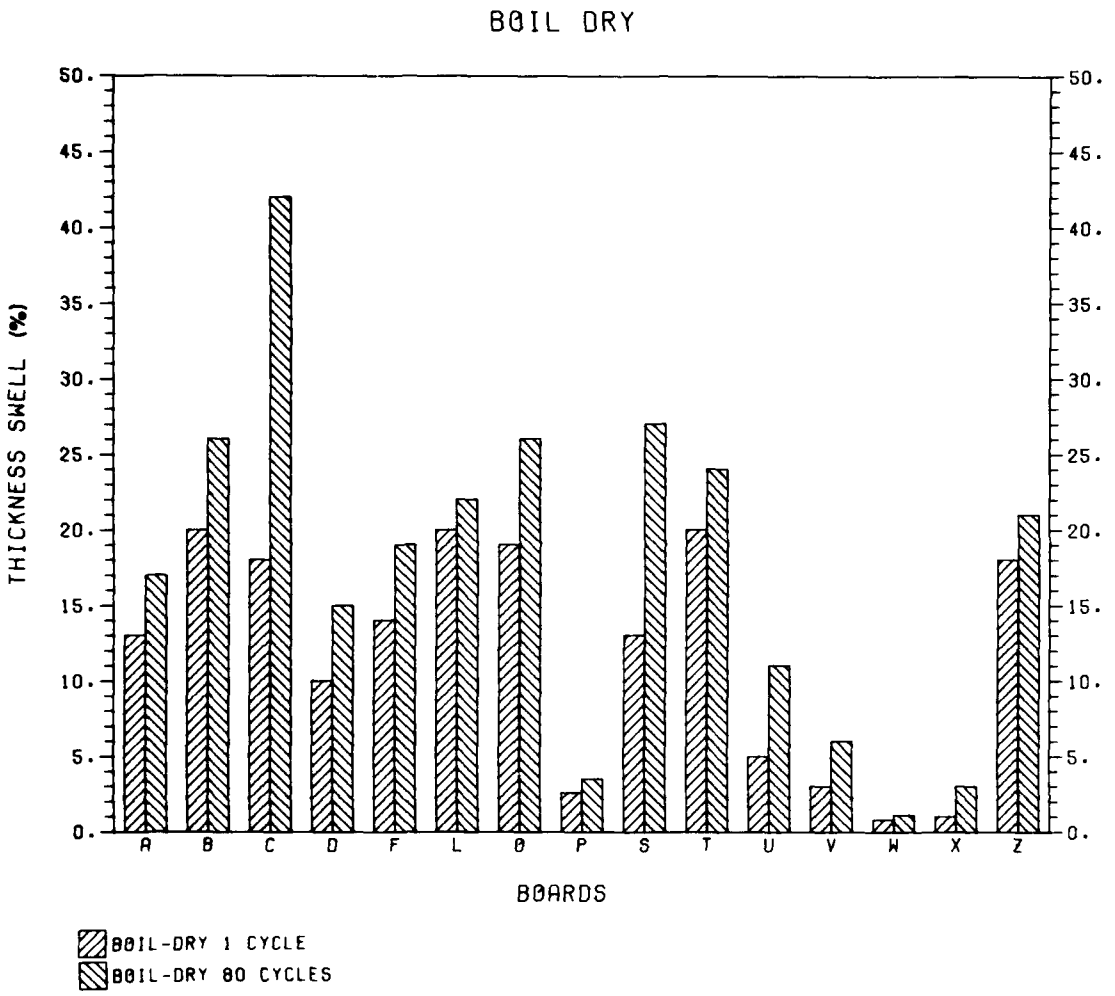

Figure 12.—Thickness swell after one boil-dry cycle and after 80 cycles of treatment.

(M 149 008)

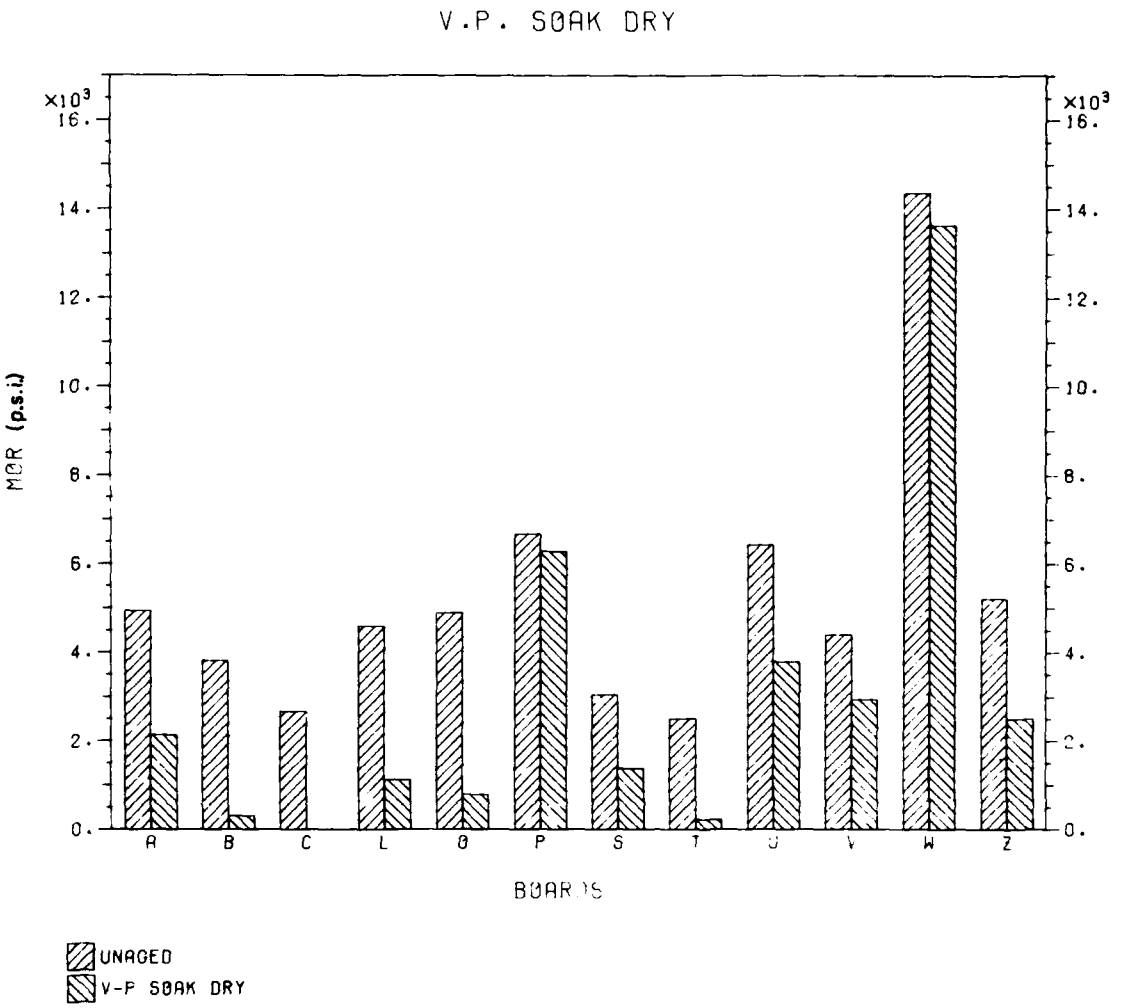

Figure 13.—Original modulus of rupture (MOR) and residual MOR after 80 cycles of vacuum-pressure (V.P.), soak-dry treatment.

(M 149 007)

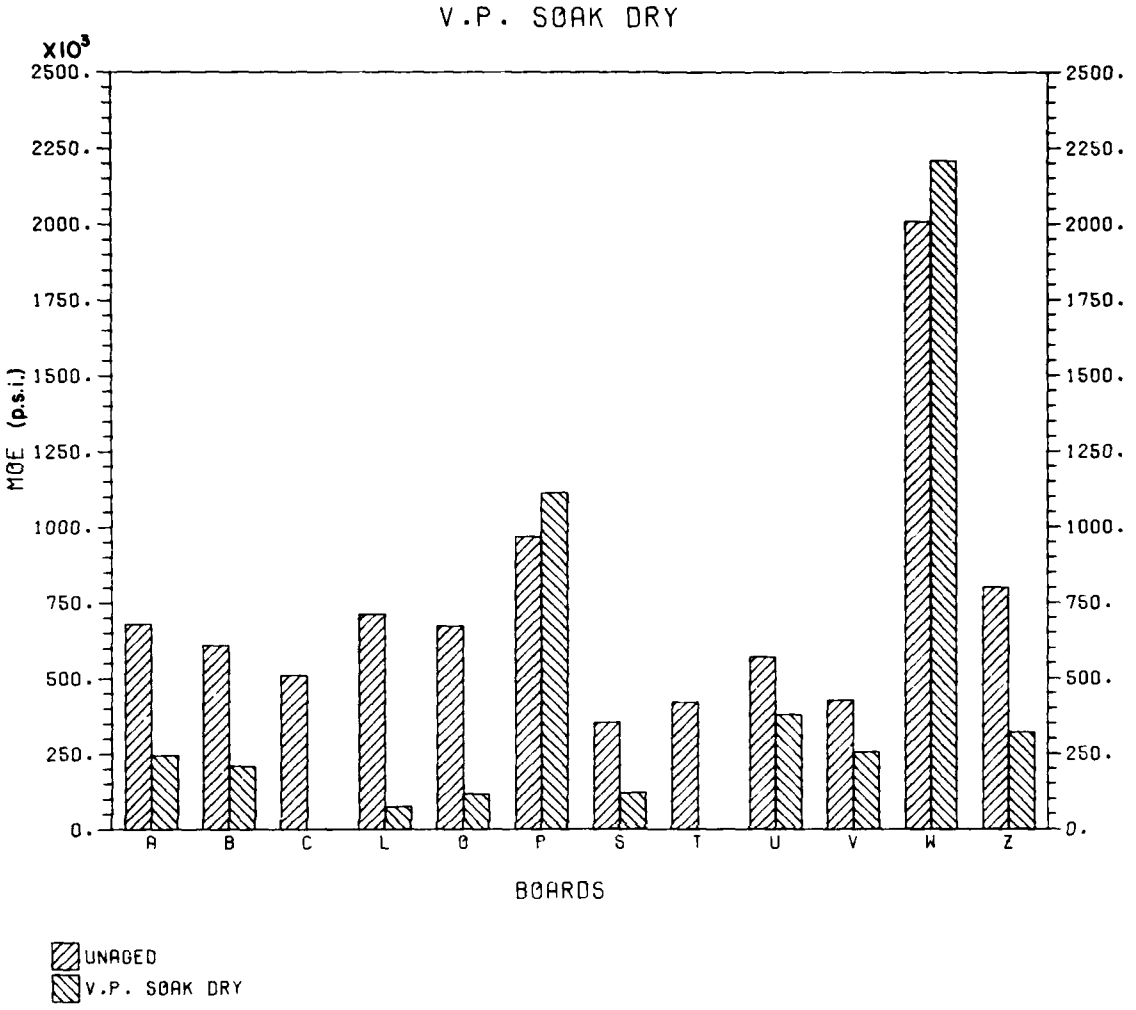

Figure 14.—Original modulus of elasticity (MOE) and residual MOE after 80 cycles of vacuum-pressure (V.P.), soak-dry treatment.

(M 149 006)

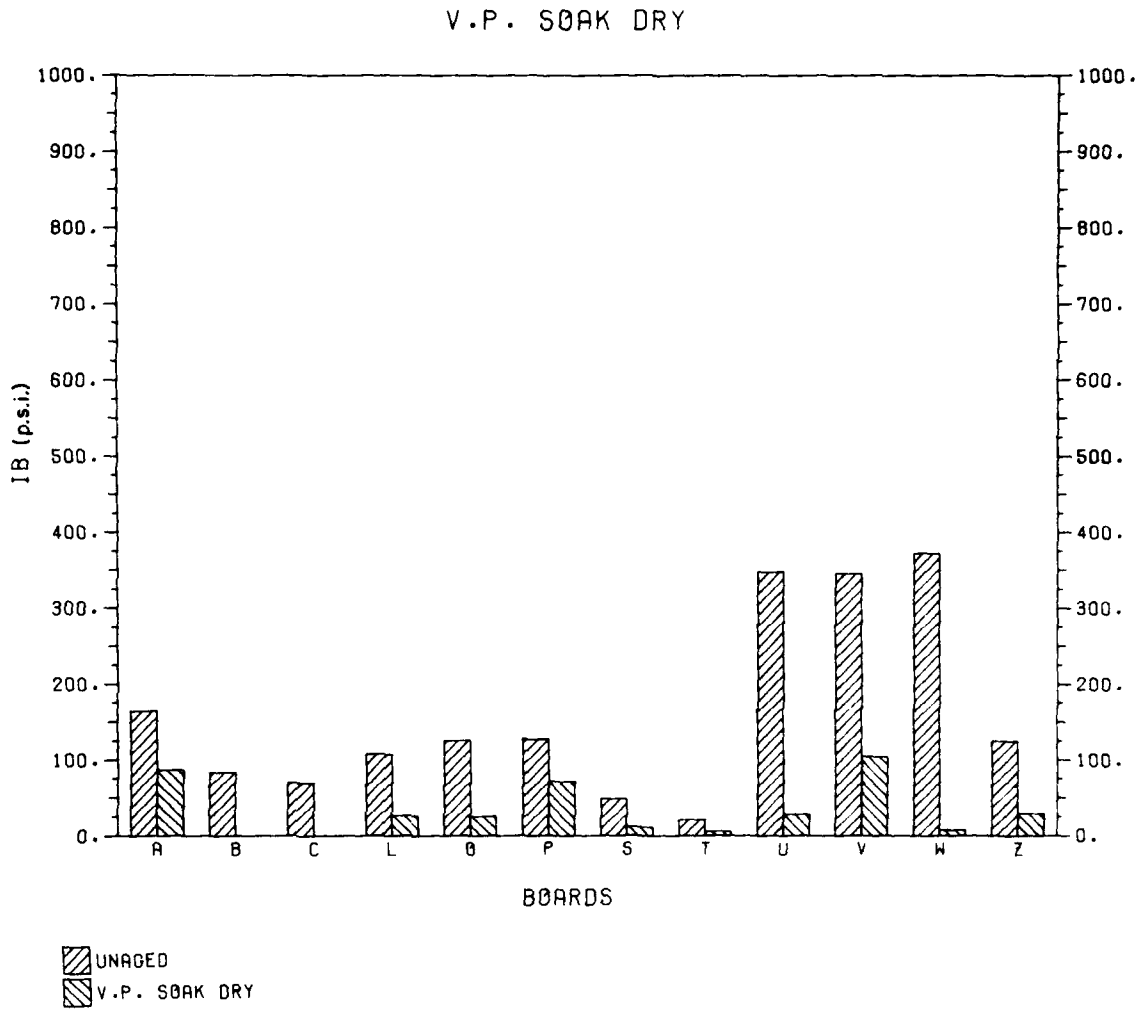

Figure 15.—Original internal bond strength (IB) and residual IB after 80 cycles of vacuum-pressure (V.P.), soak-dry treatment.

(M 149 005)

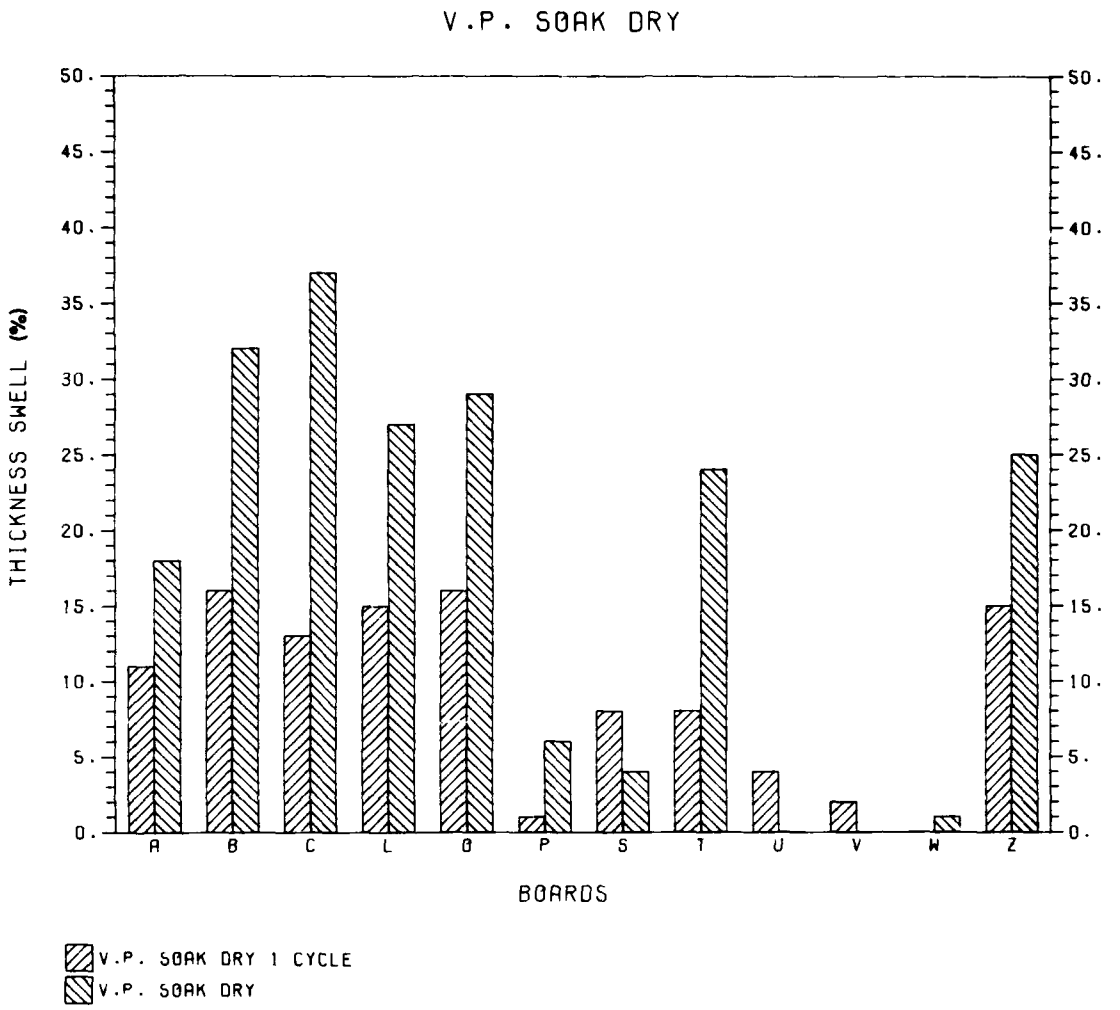

Figure 16.—Thickness swell after one vacuum-pressure (V.P.), soak-dry cycle and after 80 cycles of treatment.

(M 149 004)

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Second in a series of investigations to establish information base on durability of new exterior-type, wood-based panel products.