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Research Report

PHYSICAL FACTORS AFFECTING THE CRACKING OF HOUSE PAINTS

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PHYSICAL FACTORS AFFECTING THE CRACKING OF HOUSE PAINT

INTRODUCTION:

The durability of exterior coatings on wood is often limited by cracking of the coating. In the development of water-borne emulsion house paints, good crack resistance has been attained over new wood, and over properly prepared and primed repainted wood surfaces. Some emulsion paints, however, have shown poorer crack resistance than high quality oil-base paints when applied directly over weathered, cracked oil-base paint on pine siding. The causes of this type of cracking failure, and the film properties required for crack resistant coatings are the concern of the present work. This program is an extension of studies made at the Marshall Laboratory over the past ten years to relate the crack resistance of emulsion paints to film properties.

OBJECTIVES:

Develop improved accelerated tests for predicting the crack resistance of latex house paints applied over weathered cracked paint, investigate the mechanism of cracking, and establish the relationships between measurable physical properties and crack resistance.

SUMMARY AND CONCLUSIONS:

The cracking behavior of a variety of latex paints and oil paints has been related to physical properties of free films combined with adhesion of the films to the substrate. The film properties important for crack resistance are: dimensional stability when subjected to climatic variations, low water permeability, high elongation, retained tensile strength of weathered stretched films, and good adhesion.

An improved accelerated test for crack resistance over cracked weathered paint has been developed. The most recent outdoor exposure data on house paints have been analyzed, and confirm the validity of the accelerated test for predicting cracking. Test panels are exposed in a newly developed accelerated weathering cycle which provides wet and dry periods, sunlamp irradiation, and panel temperatures ranging from 40°F to 130°F. Crack resistance ratings of paints applied to cracked weathered substrates can be obtained within one week.

The accelerated cracking test has been run on the experimental accelerated weathering machine (AWC-I), which has a limited panel capacity and is needed for experimental purposes. The new service cycle (AWC-3) closely follows the conditions of the experimental cycle, and appears promising for routine crack testing. The AWC-3 cycle is being evaluated for testing the crack resistance of house paints applied to cracked substrates, as well as for the production of uniformly weathered and cracked substrates.

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Despite the complex interaction of many variables, the basic mechanism of cracking is not complicated. The cracks result from the expansion and contraction of the substrate as moisture content and temperature vary. On substrates of cracked weathered paint, localized expansions in excess of 100% are commonplace.

Observations with the accelerated weathering cycle indicate that the condition warm and dry following a wet interval, produces cracking failure. The localized cracks in weathered substrates open up during drying (while the bulk of the wood is contracting), placing the film under strain. The stretched film then suffers further stresses due to contraction when warmed, and at the same time may lose toughness (elongation and/or tensile strength). This concept is contrasted with the old idea that the condition cold and wet causes cracking, but both conditions can lead to film failure under particular circumstances.

A test for evaluating the crack resistance of stretched free films exposed in the accelerated weathering cycle was developed. The stretch test is a useful screening test for evaluating the performance of latex films, and provides data independent of substrate variables.

The following equation has been developed for the relationship between crack resistance and measurable physical properties:

$$R = 10e^{-\frac{5000\,P(D + 0.2)\,A}{ETS\,(A + 1)^2}}$$

where:

R = Crack resistance, 0-10 scale, with 10 = most crack resistance

e = Base of natural logarithms = 2.718...

P = Permeability, mg-mm/cm^2 - 24 hrs.

D = Dimensional change, %

A = Adhesion, 0-10 scale, with 10 = greatest adhesion

E = Elongation at 77°F, %

T = Tensile strength at 77°F, lbs./$in.^2$

S = Stretch test factor, with two possible values:

1 = failure or intractable

2 = pass

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The equation meets the known boundary conditions, as well as the experimentally determined relationships between physical properties and crack resistance. The equation gives calculated crack ratings in good agreement with actual exposure experience, and shows the magnitude of property changes needed to reach a given level of crack resistance.

ACTION TAKEN:

The house paint research group has been informed of developments under this project. The experimental accelerated weathering cycle has been used to evaluate new formulations for crack resistance over cracked weathered paint, and to screen new latices using the free-film stretch test.

PATENT SITUATION:

No patent action is planned at the present time.

PUBLICATION PROPOSAL:

Publication is not currently contemplated.

ACKNOWLEDGEMENTS:

Valuable discussions, background information, and samples have been obtained through the cooperation of M. J. McDowell, D. R. Strehlau, J. E. Oyler, T. B. Hill, E. R. Werner, and others associated with house paint development. G. P. Bartow ably carried out the experimental program.

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DISCUSSION:

The present study deals with the cracking of house paint applied to old weathered paint which is badly cracked. The cracked old paint used for most testing was #40 Outside White, applied to southern yellow pine siding, and exposed for two years or more at the Texas exposure station. Ideally, such substrates showed uniform and extensive cracking, but little flaking or peeling. (Figure 1 illustrates the cracking appearance). Southern yellow pine is the least dimensionally stable of the common woods used in construction, and in conjunction with the cracked weathered paint, gave a substrate which accelerated the cracking of topcoats.

The type of cracking under study is often referred to as grain cracking, since the cracks follow the grain of the wood. We are not dealing with shrinkage cracking, cold cracking, or mud cracking, which are due principally to stresses developed within the coating itself. In these forms of cracking, a checkered pattern of failure is typical, with cracks running at right angles. In grain cracking, the cracks run in the same direction, with little or no branching.

Literature Review:

The cracking of house paint has been studied for some time at the Marshall Laboratory, particularly in connection with the development of water-borne emulsion outside house paints. The following is a review of the significant laboratory literature from 1952 to the present. Graves, in 1954, ascribed the poor crack resistance of a butyl methacrylate paint to its high permeability and poor adhesion:

"When the wet wood dries out, cracks open up which rupture the paint film. The entry of water through the cracks accelerates the breakdown of adhesion bonds"(1). Similar ideas were indicated for polyvinyl acetate paints (2,3). Werner measured dimensional changes in films, and the uptake and release of water from emulsion house paint films (4,5). No significant features were found which related to cracking performance. In setting the specifications for an ideal house paint primer, LaBerge recognized the requirements of impermeability to water, elongation great enough to withstand the dimensional changes of wood, and good adhesion(6).

Fasolino, in 1957, studied the cracking of polyvinyl acetate and linseed oil house paints (7). The properties of latex paints believed to cause inferior crack resistance with respect to linseed oil paint were: incomplete coalescence, a low wet elongation at cold temperatures, and insufficient swelling when wet. McDowell recognized high permeability and lack of swelling when wet as contributing to the cracking of emulsion paint, but felt that the most important physical property for improved durability

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was high low-temperature elongation retained after weathering (8). The factors affecting elongation and other properties were studied further by McDowell (9). The effects of temperature, weathering, moisture, and strain rate on elongation were examined. Properties considered important for film integrity included high elongation at low temperatures, good wet adhesion, greater swelling when wet, and reduced permeability.

Peters (10,11) studied the correlation between physical properties and durability for PVAc emulsion paints. The only film property which gave good correlation with durability was elongation. Permeability of PVAc emulsion paints was shown to be much greater than that of conventional paints, and was indicated as being a possible factor affecting cracking.

The effect of pigment packing on elongation of emulsion paints was studied (12). As the packing index of the pigmentation was increased, the elongation increased significantly at 77°F, but only slightly at 30°F. The chemical changes in Rhoplex AC-33 acrylic emulsion on exposure to ultraviolet radiation were investigated by W. T. M. Johnson (13). Cracking failure was attributed to loss of elongation and tensile strength due to photodegradation, inability of the paint film to be plasticized by water, and poor adhesion.

An accelerated test for the cracking of emulsion house paint over old paint was developed by W. F. Singleton (14, 15). The test involved exposure on the AWC-2 accelerated weathering cycle of wooden panels where the substrate was cracked old paint. The poor crack resistance of #50 acrylic white (AC-33 emulsion) was attributed to high permeability, permitting water to penetrate the film and swell the wood, and low elongation at 30°F after weathering.

Additional reports on house paint developments stressed the need for formulations with high retained low-temperature elongation (16, 17, 18, 19, 20, 21, 22, 23). Low water permeability and good initial wet adhesion were other factors regarded as desirable for a house paint resistant to cracking and peeling. D. R. Strehlau (20) analyzed the crack resistance of a series of acrylic emulsion house paints. No clear correlation between crack resistance, elongation, and water permeability was found.

Extensive work on the mechanism of deterioration of house paint has been done at the Forest Products Laboratory, Madison, Wisconsin. F. L. Browne (25), dealing principally with oil-base paints, attributed chemical deterioration to water, in conjunction with ultraviolet light. Shrinking and swelling caused by water and temperature changes (26) stress and disrupt paint films, Browne stated. He regarded cracking as caused more by

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stresses developed within the coatings themselves than by differences in movement between wood and coating. Browne's viewpoint has been found to be untenable for the problem of cracking over old weathered paint (27). Paint coatings do not "commit suicide" (26) in the situation with which we are dealing. (Latex paints of AC-33 quality or better do not crack when applied to metal substrates, for example.) Browne was thinking in terms of rather small dimensional changes in the wood substrate, representative of overall, rather than local effects. Recent work at the Forest Products Laboratory by V. P. Miniutti and J. M. Black (28) has emphasized that large local strains can develop in the wood surface, regaining the perspective that dimensional change in the wood substrate is an important factor in paint film cracking.

Crack Resistance:

Substrate Effects

The substrate plays a dominant role in the cracking of house paint. Because of substrate variability, the cracking performance of paint films is also variable. When the substrate is old weathered paint, its properties, as well as the properties of the wood, influence topcoat performance.

The substrate affects not only the rate at which cracking develops, but the relative ranking of a series of topcoats, as well. If Topcoat A is more crack resistant than Topcoat B over one substrate, the reverse may be true when another substrate is used. This source of variability has clouded some of the published results and conclusions on house paint performance, and makes precise test results difficult to obtain.

Table 1 indicates how the crack performance of topcoats was affected by the type of substrate that was used. Free films, or films brushed on metal, glass, or other dimensionally stable substrates did not crack within the time scale of our testing. (This was true for all the commercially acceptable house paints that were tested. Some paints will develop shrinkage cracking(29), mud cracking, or cold cracking when drying or during exposure, but these types of internal-stress cracking are not being discussed here.) When applied to southern yellow pine panels painted with #40 Outside White which was cracked from 2 + years exposure at the Texas Test Fence, AC-33 paint, for example, failed rapidly while #42 Outside White did not. Over similarly cracked Stucco, Shake & Shingle paint, the performance of #42 became as poor as that of the AC-33 paint. Over chalky crack-free #40, no cracks developed in any of the topcoats, while direct to bare wood, some slight cracking developed.

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The substrate variations indicated in Table 1 are particularly significant because of the changing performance of AC-33 paint (the original #50 Outside White, 310-095) relative to #42, the oil-base paint regarded as a control goal for #50. Over the #40 substrate, cracked by exposure in Texas, the crack resistance of AC-33 paint was poor compared to #42, while over the other substrates the crack performance was good.

The substrate influences cracking primarily as a result of dimensional changes and adhesion. The basic driving force for grain cracking is dimensional change in the substrate, especially localized surface movements due to wetting and drying of the wood. When the substrate is dimensionally stable, cracks do not form. A weathered #40 film, which is intact and impermeable, offers dimensional stability. When cracked, however, large local strains can develop.

The cause of the cracking difference between the cracked weathered #40 and the cracked weathered Stucco, Shake & Shingle substrate in Table 1 was adhesion. #42 had good adhesion to #40, and poor adhesion to Stucco, Shake & Shingle. Poor adhesion permitted increased moisture penetration and wider cracks, resulting in poorer crack resistance ratings.

New wood is more dimensionally stable than wood which has been on exposure and is covered with cracked paint. The exposed wood is usually laced with small cracks which open and close with moisture content. Paints are crack resistant over new bare wood as a result of good adhesion and the absence of large local strains. However, just a few weeks weathering of bare wood will significantly reduce the durability of an applied paint film (30).

Large changes in the widths of cracks on weathered substrates were found to occur during exposure. Using a microscope and filar eyepiece, we measured crack dimensions during cycling on the accelerated weathering machine (AWC-1). Cracks were usually wide when dry, and narrow when the panel was wet. Changes in crack widths amounting to more than 400% from wet to dry were observed in cracked weathered #40 panels from Texas exposure. Dimensional changes of 100% to 400% were not uncommon. These local strains are substantially larger than the overall dimensional changes in wood due to water absorption. Southern yellow pine swells about 5% in the direction of the grain when taken from dry to wet, and 10-15% across the grain (31). The summerwood bands swell more than the springwood bands.

Large local "microstrains" at the wood surface have also been reported (28) as a result of grain raising. In old weathered wood siding the local dimensional changes are further emphasized, because the differential swelling of the springwood and summerwood bands leads to the development of cracks in the surface of the wood.

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The paint film applied to the cracked weathered old paint substrate is under greatest strain when the substrate becomes dry after a period of wetness. This is because the expansion and contraction of the cracks in the weathered panels is opposite to the overall expansion and contraction of the wood. When wet, the wood swells and the local cracks close. When dry, the wood contracts as a whole, and the local cracks open, stretching the applied paint film.

The usual view has been that house paints are under greatest strain when the wood is wet. This is true only for the overall dimensional strain, amounting to 5-15%. Brittle films will crack under this condition. But the major problem in repainting cracked weathered substrates is the large local dimensional changes in the substrate due to wet-dry cycling. These place the topcoat under greatest strain when the wood is dry, and can be many times greater than the average strain, often 100-400%.

These large local strains in old weathered substrates make the development of a completely crack-free house paint a difficult problem. The basic property requirements for a crack resistant house paint are:

(1) Impermeability, to prevent moisture from reaching the substrate,

(2) High elongation over a wide temperature range to withstand local strains,

(3) Tensile strength, to distribute local stresses,

(4) Good adhesion, to prevent peeling, and to prevent an interfacial path for moisture penetration,

(5) Dimensional stability, to reduce internal stresses, and

(6) Retained tensile strength of weathered stretched films.

These properties are reviewed in more detail in later sections, and combined into an equation for calculating crack resistance.

Accelerated Crack Test:

House paints usually have to be exposed outdoors for 1-3 years before meaningful evaluations of crack resistance can be made. To provide information in less time, an accelerated weathering test was developed by W. F. Singleton (14). The test was based on exposing suitably prepared panels on the AWC-2 accelerated weathering machine (service cycle). We have developed an improved version of the test using the AWC-1 experimental weathering machine, which gives significant crack ratings over cracked weathered paint within one week. With the AWC-1 machine, we have also been able to experiment with exposure conditions in order to establish the effect of weathering variables.

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In the improved AWC-1 cycle, the exposed panels dry out completely before being re-wet by the water sprays. In the AWC-2 service cycle, the panels remain wet, and this is apparently the reason for the slower cracking rate. The substrates for the test were yellow pine blocks painted with #40 Outside White which was uniformly cracked from two or more years of outdoor exposure (usually at the Texas Test Fence). A measured amount of topcoat was brushed over the cracked substrate, and the back and edges of the block were sealed with aluminum paint against the entry of water.

Due to the variable nature of the wood and the cracked weathered paint, substrates were selected for uniform appearance. Adequate controls were also necessary, and several replicates were exposed in order to obtain statistically significant results.

The accelerated test consistently showed #42 linseed oil house paint to be superior to #50 Acrylic, made with AC-33 Latex. This is in agreement with outdoor exposure data, both on houses and test fences. In other crosschecks between accelerated weathering and outdoor exposure involving a variety of emulsion paints, no significant differences in ranking were found between outdoor and AWC-1 exposure. Table 2 summarizes an analysis of recent outdoor exposure data, and shows that the paints are ranked in the same order in crack resistance as by the accelerated test.

With the back and edges of the test panels sealed against moisture penetration, the permeability of the topcoat determines to what extent moisture affects the wood. An oil paint, with low permeability, appears more crack resistant in such a test than a permeable latex paint such as #50 (AC-33). Because this result agrees with house test exposure experience, the use of sealed panels is justified. If panels are not sealed, but are allowed to soak up water from the back, the advantage of low permeability in stabilizing the substrate is lost. In such a soak test, the linseed oil paint will crack more severely than the latex paint (9, 14), in disagreement with field test experience.

Effect of Exposure Conditions

Using the experimental accelerated weathering machine, AWC-1, we varied the exposure conditions in order to find out how various weathering factors affected cracking over old paint.

Water was found to have a dominant role in cracking failure. When the AWC-1 machine was operated with the sunlamps on, but all water sprays turned off, no cracking occurred. (The test conditions were maintained for one week. Normally some cracks would develop within one day.)

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When exposures were made with the sunlamps turned off, and the water on, cracking developed within one day. Different paints cracked in the same order as on the complete weathering cycle, and the appearance of the cracking was the same. This result showed that UV embrittlement was not essential to cracking.

The effect of water temperature was also investigated. A jet of cooled water was directed onto the test panels before they were exposed to the sunlamps on the AWC-1 machine, to simulate the action of cold rain. The temperature of the water was varied from 40°F to 70°F. The temperature of the water spray did not affect the rate of cracking or the relative cracking rank of test paints.

From the above results, one should not rule out the effect of sunlight and water temperature on the ultimate durability of house paints. Rather, the results point out the dominant role of wet-dry cycling in the cracking of topcoats applied over old paint that is badly cracked and flaked. Here the local dimensional changes in the substrate brought about by moisture are large enough to crack permeable paint films with relatively high initial elongation. Neither UV embrittlement nor low temperatures appear necessary for cracking to occur under these conditions.

Accelerated Cracking Tests with the AWC-3 Machine

To provide a means for the routine testing of crack resistance, the new AWC-3 accelerated weathering machine was evaluated. The AWC-1 machine which we used, has a limited panel capacity and is needed for experimental purposes, so that the adaptation of a larger machine for service work is desirable. Preliminary tests indicate that the present AWC-3 machine (X-30 cycle) acdelerates cracking in the same way as the AWC-1 cycle, and correlates with outdoor exposure results.

We have also investigated use of the AWC-3 machine for producing artificially cracked substrates to use for topcoat tests. The most satisfactory cracked weathered panels obtained in the past have come from the Texas Test Fence, and require at least two years of exposure to attain the desired cracked appearance. It would be advantageous to obtain cracked substrates in a shorter time, with uniform cracking developed under controlled exposure conditions in order to reduce substrate variability. Preliminary exposures on the AWC-3 of southern yellow pine panels painted with #40 Outside White have appeared promising. With one-coat application, the film showed cracking after two months, although some difficulty with erosion was indicated. With two-coat application, the development of cracks was slower, and excessive peeling developed. Evaluation of the AWC-3 machine is continuing.

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Artificially Produced Cracks

To avoid the problem of having to use weathered substrates, attempts have been made to form artificial cracks in a substrate. Most simply, this involved taking a panel painted with #40, and cutting lines or patterns in the surface. With the film cut through to the substrate, one hoped to simulate a crack in the film. This procedure was found not to work, because the artificial cracks did not undergo the dimensional variations that affect natural cracks during exposure. Natural cracks develop along grain boundaries where the wood undergoes its largest local dimensional change. The artificial cuts do not necessarily coincide with the lines of natural strain concentration. Also new wood is more stable than exposed wood to local dimensional changes.

Other Effects on Crack Resistance

The crack resistance of a coating depends upon its thickness. We found that the thicker the film, the slower was the cracking rate over old cracked paint. Figure 3 shows the dependence of crack rating on film thickness for two emulsion paints and one oil paint. The general trend to greater crack resistance for thicker films was shown by these paints. Thicker films are less permeable, and this is probably the main factor leading to greater crack resistance. In addition, strains at the substrate interface will not be transmitted throughout a thick film as much as a thin film.

The direction of brushing has been reported to determine the direction of cracking of house paints (32). When acicular pigment particles are present, they become oriented in the brushing direction. The film may then be weaker in the direction at right angles to brushing, and prone to crack along brushmarks. Since paint is customarily applied with the last strokes in the direction of the wood grain, this may lead to the mistaken belief that the direction of cracking is determined by the grain of the wood (25). We tested this hypothesis, and found no significant effect of brushing direction on cracking over cracked old paint, for the series of paints under study.

Appearance of Cracks

Observations of the cracking during accelerated weathering brought out several points of importance. Cracks developed mostly during the sunlamp portion of the exposure cycle, when the panels became warm and dry. Also, when cracks were examined closely, the edges were not sharp, as would be the case for brittle fracture. Instead, the cracks in their early stage had a taffy-like appearance, with threads of paint film bridging the cracks. The appearance of the cracks is illustrated in Figure 2. These observations support the view that the cracking mechanism over weathered cracked paint is not one of low temperature, low-elongation brittle failure, but rather one of failure when the film is warm, and with rubber-like elasticity.

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Physical Properties, and Correlation with Crack Resistance:

Numerous physical properties of house paints were measured, and examined for correlation with crack resistance. No single or simple correlation was found, but rather a number of different properties affected crack resistance. In some cases the correlation studies did not give conclusive results because of interactions between variables. Independent experiments were valuable in defining the important properties.

As indicated before, the basic property requirements for a crack resistant house paint were found to be:

(1) Impermeability, to prevent moisture from reaching the substrate,

(2) High elongation over a wide temperature range to withstand local strains,

(3) Tensile strength, to distribute local stresses,

(4) Good adhesion, to prevent peeling, and to prevent an interfacial path for moisture penetration, and

(5) Dimensional stability, to reduce internal stresses.

Free films of the vehicle also need to pass the special free-film stretch test, which combines the factors of retained tensile strength of weathered stretched films, and the contractive forces in a stretched elastomeric network that are developed by heating.

The significant physical property data are summarized in Tables 3-5, along with ratings of crack resistance over cracked weathered #40 paint. Table 3 gives data for latex paints and Table 4 for non-latex (oil and alkyd) paints. Table 5 shows the physical properties of many of the vehicle clears that were studied as a guide to the performance of the pigmented systems. The properties that were measured will be discussed separately, and then combined into a single equation for calculating crack resistance.

Permeability

We measured the permeability of free films to liquid water, using the inverted Payne cup technique (14, 15). The initial permeability of latex paints, Table 3, is in general ten to 50 times greater than the permeability of oil paints, Table 4. The low permeability of oil paints is an important factor in their resistance to cracking.

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Permeability, like all the other properties under consideration, is not constant but is a function of film history, temperature, and other conditions of measurement. During weathering, paint films become less permeable. Figure 4 shows how the permeability of two latex and two oil paints changed during exposure on the AWC-1 accelerated weathering machine. Initially, the latex paints were about 50 times more permeable than the oil paints. During exposure the permeability of the oil paints did not change much, while the permeability of the emulsion paints decreased, probably as a result of leaching of water-sensitive groups. After 48 hours of exposure the latex paints were about 10 times more permeable than the oil paints, and dropped to about two times more permeable after 200 hours of exposure. Normally, on AWC-1 exposure over cracked old paint, cracks developed in the topcoat within one day for the poorer crack-resistant emulsion systems, at a time when the permeability was near the initial high level.

Because of higher solids, the oil paints are generally applied in thicker films than the water emulsion paints. This gives the oil paints a further advantage over the emulsion paints in blocking water penetration.

Permeability is also a function of temperature, being lower at colder temperatures. Figure 5 shows curves of permeability versus temperature for paints made with AC-33 and AC-34 latex (#50 acrylic house paint), and #40 and #42 oil paints. The oil paints have substantially lower permeability than the latex paints at all temperatures (in the range 40°F to 120°F). The ratio of the permeability of the latex paints to that of #42 was about 25-30 from 77°F to 120°F and increased to more than 100 at 40°F.

The effects of humidity, film thickness, liquid water versus water vapor transmission, and water absorption have been studied before (10, 11, 14).

Because wood is a porous substrate, we thought that the permeability of films on a porous substrate might be different from that of films cast on smooth polyethylene or glass, as a result of differences in penetration or other factors. To test this possibility, films were drawn down on filter paper, and the water permeability of the filter paper/paint film combination was measured. The porous substrate was found to have no significant effect on permeability.

We examined the effect of humidity at the time of film preparation on free film properties. The permeability of films prepared at 33% R.H. to 83% R.H. was not significantly different. The effect of stretching on permeability was measured for free films of AC-33 and AC-34 latex. Stretching the films up to 200% elongation had no significant effect on the permeability to water. This result removed the possibility that one or both of these latices might become more permeable when stretched due to flaws within the films.

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Dimensional Change

The effect of temperature and moisture on the shrinking and swelling of free films was measured. Measurements of this type have been made by others (7, 10, 25, 26), but our results and conclusions differ in some important respects from previous work. Dimensional changes are time dependent, particularly swelling due to water absorption. Our emphasis has been on relatively short-time effects, with a time scale of one hour or so, similar to the rate of cycling during accelerated weathering. Dimensional changes measured on this time scale are consistent with dimensional changes noted directly on free films during AWC-1 exposure, and are supported by the evidence of agreement between accelerated weathering and outdoor exposure.

Free film dimensions were measured in the temperature range from 35°F to 120°F, and with the films completely wet (soaked in water) and completely dry (desiccated). The maximum dimensional change occurring under these conditions was determined, and values for various paints are recorded in Table 3 and Table 4. In general, the oil paints have lower dimensional change than the latex paints. This is contrary to the usually reported result that oil paints swell more than latex paints when wet (7, 10, 25). After three or more days of water immersion, oil paints do swell more, but initially water has a greater effect on latex paints, probably as a result of their higher permeability.

In a statistical analysis of our data made by S.C.Horning of the relationships between physical properties and crack resistance, the single factor showing the most significant correlation with crack resistance was found to be dimensional change. Low dimensional change correlated with good crack resistance. Dimensional stability is advantageous because it reduces interfacial stresses during exposure, and helps prevent peeling. The tendency of some topcoats to strip off old paint from the substrate is usually a result of dimensional changes.

The effect of accelerated weathering exposure on free film dimensions was also measured. No significant dimensional changes were produced by exposure on the AWC-1 cycle for a length of time sufficient to cause cracking failure in crack test panels. The major weathering factors in dimensional change were therefore found to be temperature and moisture, rather than the long term effect of sunlamp irradiation.

Contraction of Stretched Free Films

The effect of temperature on dimensional changes is quite different in stretched films than in the unstretched films which are usually tested. Because latex house paints are elastomeric above their second order transition temperature (approx. 50°F), their stress-strain behavior is described by rubber elasticity theory (33). Unstrained elastomers expand slightly when

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heated. In the stretched state, however, elastomers contract when heated, and the magnitude of the contraction increases with the elongation of the film. The contraction can be much greater than the normal thermal expansion, e.g. 25 times greater (33).

With rubber-like paint films, including the acrylic house paints in general, we have directly observed the contraction due to warming. Precise measurements proved difficult however, as a result of creep which also occurred during heating. For making measurements, a load was applied to the free film to elongate it. The creep rate was fast at first, but soon an equilibrium length was reached. The film was then warmed by radiant heating. At high elongations, the film contracted noticeably as soon as it was heated. This was followed by further elongation due to creep at the increased temperature. Contractions of 5-10% against a tensile stress of 30 lbs./in.^{2} and at elongations of about 100% were observed for both emulsion paint films and clear latex films.

The technique proved valuable mostly for permitting direct observation of the contraction of elastomeric films when warmed. The interactions between temperature, time, creep, and contraction effects did not permit satisfactory quantitative results. Effective evaluation of the response of stretched films to temperature was obtained from Instron stress-strain data and the special free-film stretch test, to be described later. Contraction upon heating appears to play an important role in the cracking of latex paints. As stated before, our observations during accelerated weathering cycling showed that cracks in weathered substrates widened when the panels were dried under sunlamp irradiation following a period of wetness. Thus the topcoat became stretched and warmed under the sunlamps. Contractive forces due to warming would have placed the elastomeric film under further stress and increased the possibility of topcoat cracking.

Elongation

By elongation, we mean the elongation at break for free films measured in uniaxial tension on the Instron tensile tester. Elongation is not a constant value, but is a function of temperature, humidity, rate of testing, and film history (age, weathering exposure). Values of percent elongation at three different temperatures are tabulated for the samples in Tables 3, 4 and 5. The test conditions were controlled: rate of strain of 20% per minute, samples aged and weathered under the same conditions, and conditioned at 77°F and 50% R.H. before testing.

The measurements show that the elongation of the non-latex house paints (oil and alkyd types) is relatively independent of temperature over the range 30° to 130°F. The latex paints and clears, on the other hand, have elongations which increase markedly from 30° to 77°F. This is a result of the second-order transition

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temperatures falling within this temperature range, so that the films are "glassy" at 30°F and "rubbery" at 77°F. Data at 130°F were obtained because house paints reach that temperature during accelerated weathering and outdoor exposure in the sun on a hot day. The 130°F elongation data for clear latex films have particular significance for the free-film stretch test, to be described later.

Our results showed no clear-cut correlation between elongation and crack resistance over old paint. While there has been evidence to support a relationship between high elongation and crack resistance (10), contradictions have also been reported before (20, 23). Elongation is an important property, but it is not the only property influencing crack resistance. The importance of elongation is most evident in the poor performance of brittle films (elongation less than 2% or so at 77°F) on wood. The cracking of more elastic films has usually been attributed to brittleness at low temperatures, since films with elongations of 20% or more at room temperature were believed able to withstand any dimensional changes in the substrate at room temperature. However, the observations of localized dimensional changes of 100-400% in substrates of weathered cracked paint indicated that film elongations much higher than 20% would be required.

For permeable paint films on new wood, elongations greater than 20% at 77°F should withstand the dimensional changes in wood due to moisture. At low temperatures, less elongation can be tolerated because of reduced dimensional variations in wood at low temperatures, and the decrease in permeability with decreasing temperature. Over badly cracked old paint, however, the topcoat elongation would have to exceed 400% in order to assure crack resistance on the basis of elongation alone. None of the house paint films that we tested had elongations that high.

Figure 6 shows how elongation depends upon temperature, for some water emulsion and oil solution paints. Elongation is plotted on a logarithmic scale, so that differences look less dramatic than on a linear plot. The elongations of the emulsion paints approach the oil paints at low temperature, but at room temperature and above, the emulsion paints have more than 10 times the elongations of the oil paints.

Prolonged contact with water tends to plasticize paint films, and increase their elongation. Linseed oil paints have about four times their initial elongation after several days of soaking in water, while latex paints are less affected, by a factor of about one-half to two times (7, 9, 10). The plasticization of the oil paints would be expected to help crack resistance under prolonged wet conditions, where low permeability loses its advantage. However, for cracking over old paint on the AWC-1 accelerated weathering machine, wet elongation has been found not to play a significant role. The short periods of wetness do not significantly modify the elongation of free films. In addition, cracking was noted to occur when the panels became dry, not wet.

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During exposure the elongation of paint films gradually decreases. The embrittlement may be due to photochemical degradation (chain scission) or to loss of plasticizer (by leaching or evaporation), or other factors. The embrittlement resulting from weathering has commonly been regarded as a major factor in the poor crack resistance of some latex paints (8, 9, 10, 14). This is certainly the case sometimes, especially with respect to long-term durability over well-prepared substrates. For paints applied to weathered cracked substrates, however, we found that the topcoats cracked sufficiently early so that not much embrittlement had occurred. The elongation values in Tables 3-5 are for films weathered approximately 100 hours in the AWC-1 cycle, long enough to have cracking in the latex paints with poor crack resistance over cracked weathered paint. Thus elongation retained after long exposure is not directly involved in the type of cracking we are dealing with here, and this is bolstered by the correlation between AWC-1 exposure and outdoor tests.

Figure 7 shows the effect of weathering on elongation at three different temperatures for several latex and oil paints. The effect of temperature on elongation is greater than the effect of weathering. Since AC-33 paint cracks over cracked old paint within several days of AWC-1 exposure, with temperatures at or above room temperature at all times, while #42 paint does not crack under similar conditions, it is evident that factors other than elongation are involved.

To assure ourselves that elongation was being measured under meaningful conditions, we studied the influence of some additional variables on elongation. Films were dried in a desiccator and tested in a desiccated atmosphere, and no significant deviations from the usual measurements of films conditioned at 50% relative humidity were noted.

The effect of humidity at the time of film preparation was examined. Relative humidity in the range of 33% to 83% did not significantly alter the elongation of latex paint films, or #42 oil-base films.

The effect of biaxial stress was also studied by means of measurements at different width/length ratios of free films on the Instron tensile tester. The wider the film with respect to the gauge length, the more biaxial stress is developed. A high width/length ratio is also characteristic of paint films strained by the widening of substrate cracks. No significant trend of biaxial stressing on tensile properties was found, for width/length ratios from 0.4 to 6.0.

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The effect of film thickness on elongation was investigated. For unweathered films, elongation was not significantly affected by variations in film thickness. However, the elongation at 77°F of films weathered for 100 hours on the AWC-1 machine dropped roughly one-half as film thickness went from 4 to 2 mils. The low temperature elongation (30°F) was not significantly altered. The greater embrittlement of the thin films at 77°F probably contributes to the poorer crack resistance of thin films, along with the factors of greater moisture penetration and higher stress concentrations due to dimensional variations in the substrate.

During tensile testing, the emulsion paint films frequently developed holes before finally breaking in two. These were mostly evident in tests at room temperature or higher, where the films were rubbery, and had high elongation. The holes developed as a result of flaws in the film, and usually did not noticeably affect the tensile force. Flaws were observed in many films of good as well as poor crack resistance, and no relationship between flaw formation and crack resistance was evident.

The possibility exists that free-film tests may not give a complete story on film properties because of interactions between the topcoat, old paint, and wood substrate. Oil or water may absorb into the substrate, and cause a change in film properties. This possibility will be discussed later under penetration and wicking rate. Another aspect of interaction might be plasticization of the old paint by the new topcoat. Some high-spot tensile tests were run on two-coat free films consisting of #40 Outside White plus various topcoats. The elongations were about the same for the different topcoats, at 30°F and 77°F, and were nearly the same as for #40 alone. No correlation with crack resistance was evident.

Tensile Strength

One might expect that high tensile strength contributes to crack resistance, although there is no conclusive evidence to support this view for house paints. In general, free-film tensile data showed an inverse relationship between tensile strength and elongation: high elongation was accompanied by low tensile strength, and vice versa. To increase tensile strength with no decrease in elongation means increased toughness (or greater energy to break).

Tables 3-5 give tensile strength data on latex paints, oil and alkyd paints, and clears. The oil paints have higher tensile strengths than the latex paints at 77°F and 130°F, but this follows from the lower elongations of the oil paints.

Tensile strength increased with increased weathering time and decreased temperature. The trend was therefore opposite to that shown for elongation in Figure 7. The effects of biaxial stress, 2-coat free films, humidity, film thickness, etc. discussed in the previous section apply also to tensile strength.

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Adhesion

Adhesion plays a dual role in the cracking of house paints. First, an adhesive bond is necessary to transmit the dimensional changes of the substrate to the topcoat. We found that films with zero adhesion (unstretched free films, or films laid onto a substrate but not sticking to it) did not crack. Secondly, adhesion affects the development and propagation of cracks. In this case, good adhesion is needed for crack resistance in order to prevent widening and peeling, and to prevent water penetration along interlayer boundaries.

Ratings of adhesion to weathered chalky #40 panels are given in Tables 3-4. Good adhesion correlated with good crack resistance. This conclusion is not so evident from the composite tables, but is based on the results of experiments with different weathered substrates discussed in the earlier section on substrate effects. Adhesion is the property affecting cracking that encompasses the interaction between topcoat and substrate. Accelerated crack tests with different weathered paints as the substrate provided a variation in adhesion with the other topcoat properties being unaltered. Decreased adhesion was accompanied by increased cracking. Table 1, discussed before, illustrates the variation in crack rating due to the degree of adhesion to different substrates.

We cannot be certain that wet adhesion is any more important to cracking performance than dry adhesion. Because wet and dry adhesion of the same system may be different, we feel that both must be measured, and that adhesion wet and dry must be good for good crack resistance.

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Free-Film Stretch Test

A test was developed to evaluate the "cracking" resistance of free films. Films were stretched in special holders, and held at fixed elongation as unsupported free films during exposure on the AWC-1 accelerated weathering machine. Some films ruptured when exposed this way, while others did not. The test showed dramatic differences between clear films of different latices, and has served as a useful screening test for house paint latices.

The stretched free films showed the same kind of failure that occurred in films painted on cracked weathered substrates and exposed on the AWC-1 accelerated weathering cycle. The cracks formed with threads of film bridging the gap, similar to the behavior shown in Figure 2 for paints on weathered cracked substrates. Figure 8 is a photograph of two stretch test films, one (AC-34 latex) with no sign of failure after exposure, and the other (AC-33 latex) with rupture developing after only one cycle of weathering on the AWC-1 machine. Continued exposure caused the AC-33 film to break in two, while the AC-34 film remained intact.

In the free film stretch test, the adhesion variable is absent, and conditions are better defined than on wood. On wooden panels the film stretch is applied by expansion of the wood, while in the free film test the stretch is applied by the operator, and the percent elongation can be directly measured.

The rupture of the stretched free films was found to occur during the sunlamp portion of the AWC-1 cycle, when the films were warm and dry. Similar rupture also occurred when the films were warmed with hot air. Numerous cyclic conditions were also tried, involving water sprays, cold temperatures (to -40°F), and heating. In all cases film failure occurred only during warming above room temperature, rupture developing slowly near 77°F and rapidly at 130°F. Latex films were usually stretched 200% at room temperature for the tests. Unstretched free films showed no signs of rupture under any of the exposure conditions.

When the stretched latex films were warmed, movement within the film was visible, indicative of contractive stresses. This behavior was due to the property of contraction when heated exhibited by stretched elastomers (33). Rupture then occurred if the stresses exceeded the strength of the film. Low elongation or tensile strength at 130°F usually predicted stretch test failure. In some borderline cases, however, stress-strain data did not reflect stretch test performance. In these cases the strength of the stretched films was thought to be degraded more by sunlamp irradiation than the unstretched films normally exposed for stress-strain data. Less photo energy should be required for chain scission as a result of the mechanical work done in stretching the films.

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Some of the results obtained with the free film stretch test were especially interesting because unanticipated differences between latices were found. In particular, imination generally improved the stretch test performance as well as the adhesion of the latex. Referring to Table 5, sample RC-W-65248 (non-iminated IE polymer) failed the stretch test, while RC-W-65255 (iminated IE polymer) did not fail. The iminated film had significantly higher elongation at 130°F and was more insoluble than the non-iminated film (Table 6). Imination may slightly crosslink the film to give improved stretched film durability, as well as promote adhesion.

Similar behavior was shown by Rhoplex AC-33 and AC-34 (Rohm and Haas acrylic latices). As shown in Figure 8, AC-33 ruptured in the stretch test, while AC-34 did not. The AC-34 film had significantly higher elongation at 130°F and less solubility than AC-33 (Tables 5 and 6).

Environmental stress cracking can also arise from more subtle factors than temperature or photodegradation. Examples are the ozone cracking of rubber tires and the recently reported effect of zinc salts on stressed acrylic plastics (34). Tests with stretched house paint films did not uncover any significant effect due to zinc salts. Results on the cracking of stretched films invariably appeared to be dominated by the effect of heat on the film.

Other Properties

The solubility of free films was determined by measuring the time for the film to break when the film was submerged in solvent under a light tensile load. Pronounced differences were noted between AC-33 and AC-34 films, and between some iminated and non-iminated films. Some of the differences in solubility may have been due to the formation of crosslinks. Representative solubility times are given in Table 6 for clears and pigmented films in two solvents: xylene and ethyl acetate. The differences between AC-33 and AC-34, and iminated and non-iminated IE, for the paints as well as the latices, are evident.

Stress relaxation and cyclic strain tests were run on free films using the Instron tensile tester. No significant features were found which correlated with crack resistance. Second order transition temperature, Tg, was determined but could not be related to crack resistance. While Tg is valuable for defining the temperature dependence of mechanical properties, it involves measurement under small strain, and does not necessarily reflect behavior at the high extensions involved in cracking. Elongation and tensile strength as a function of temperature provided a more significant description.

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Rheological properties of house paints were also examined to see if there was a relationship between flow behavior and crack resistance. Good leveling, for example, might improve crack resistance because of more uniform flow over the rough cracked substrates and reduced brushmarks. No correlation between leveling and cracking was found, however. Values of wicking rate (35) and the factors such as surface tension, viscosity, and drying rate which affect penetration into porous substrates, were also determined for a variety of house paints. Some large differences between paints were noted, but no pattern relating to crack resistance was observed.

Equation for Crack Resistance

Because of the number of variables involved in the cracking of house paints, and the interaction of these variables, it has not been obvious how the physical properties are quantitatively related to crack resistance. Computer calculation of multiple regression equations is a straightforward means for handling data in a form similar to Tables 3 and 4, but such equations have been found to have limited validity, because the tabulated data did not tell the computer all we know about house paint cracking, and because of the limitations of the multiple regression approach, where the variables are treated as being independent and additive.

Basically, we want to obtain an equation for calculating the crack resistance of a paint from measurable physical properties. Conversely, with such an equation, one could calculate the values of physical properties needed for a given level of crack resistance. We have derived an equation which is reasonably simple, and with a minimum of arbitrary constants, which is especially noteworthy considering the number of variables involved. The equation was developed to meet the known boundary conditions, as well as the empirically established relationships between physical properties and crack resistance.

The equation is:

$$R = 10e^{-\frac{5000P(D + 0.2)A}{ETS\ (A + 1)^2}}$$

or in logarithmic form:

$$\log_{10} R = 1 - 2170\ \frac{P(D + 0.2)A}{ETS(A + 1)^2}$$

where:

R = Crack resistance, 0-10 scale, with 10 = most crack resistance

e = Base of natural logarithms = 2.718...

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P = Permeability, mg-mm/cm^2-24 hrs.

D = Dimensional change, %

A = Adhesion, 0-10 scale, with 10 = greatest adhesion

E = Elongation at 77°F, %

T = Tensile strength at 77°F, lbs./in.^{2}

S = Stretch test factor, with two possible values:

1 = failure or intractable

2 = pass

The equation meets the following boundary conditions:

No cracking (R = 10; or the exponent equals zero) when any one of the following is true:

Permeability = 0

Elongation = ∞ (500% may be large enough)

Tensile Strength = ∞ (50,000 lbs./in.^{2} may be large enough, based on shear strength of pine)

Adhesion = 0 (free films do not crack)

Crack resistance improves when the exponent approaches zero, that is with:

Decreasing permeability

Decreasing dimensional change

Increasing adhesion for A greater than 1 (decreasing adhesion for A less than 1)

Increasing elongation

Increasing tensile strength

Passing stretch test.

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The adhesion function $A/(A + 1)^2$ accounts for the fact that free films (A = 0) do not crack since substrate strains cannot be transmitted to the film, while strong adhesion also helps crack resistance. A constant (0.2) is added to dimensional change, D, since there is no evidence that zero dimensional change gives perfect crack resistance. The constant 5000 (2170 in the log form) compensates for the greater magnitude of the values in the denominator.

With the equation, crack resistance ratings were calculated directly from the data given in Tables 3 and 4. The elongation and tensile strength values at 77°F were used because low temperature was found not to be a factor in AWC-1 cracking tests, while 130°F data was similar to that at 77°F. For adhesion, the lower value in the wet-dry rating was used.

The calculated crack resistance ratings for 12 different house paints are shown in Table 7. The agreement with actual exposure experience may be considered quite remarkable. The equation gives reasonable results with a minimum of arbitrary constants, and for wide variations in the six physical properties used in the calculation. The ranges of these variables are shown in Table 7.

Of the twelve paints in Table 7, the only one with a calculated crack rating particularly out of line with exposure experience is HF paint. Its calculated rating of 2.4 is too low; a value of 8-9 would be in better agreement with exposure data. HF was the softest, tackiest paint film tested, and as a result its low adhesion rating may be biased by cohesive failure and by its surface tack permitting greater peeling forces in the scotch-tape adhesion test. The measured dimensional change for HF may also be high as a result of the soft film elongating under its own weight.

A correlation coefficient of 0.69 was obtained between the calculated crack resistance ratings of Table 7 and exposure ratings from the AWC-1 cycle for cracking over weathered cracked oil paint. The correlation is significant,as a value of 0.58 was critical at the 95% confidence level.

The equation that we have derived for crack resistance is not dimensionally correct, but it could be made more rigorous and complete by including additional factors. In the interest of simplicity, we prefer the present form, however. One could introduce, for example, a substrate property, W = % local dimensional change per unit mass of water per unit time. A film thickness factor could also be included as well as factors for the exposure conditions. The equation as derived applies specifically to cracking over weathered cracked oil paint, with panels prepared and exposed in the specified manner.

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Calculation of Desired Properties

As is evident from the equation and the number of variables involved, the desirable limits for any one property can only be set when the other properties are specified.

To determine the magnitude of the changes required to improve crack resistance from our equation, we will illustrate with some examples for AC-33 paint (310-095). Calculations of crack resistance, R, show that:

1. Actual properties give R = 2.2.
2. Passing stretch test gives R = 3.3.
3. Increasing adhesion to 10 gives R = 5.1.
4. To improve to R = 8.0:

   decrease permeability to 1.4

   or decrease dimensional change to 0.6

   or increase adhesion to - not possible

   or increase elongation to 350%

   or increase tensile strength to 4900.

To improve IO paint from 8.9 to 9.9, calculations show that one needs to:

   decrease permeability to 0.7

   or decrease dimensional change to 0.01

   or increase adhesion to - not possible

   or increase elongation to 670%

   or increase tensile strength to 7200.

Smaller changes in the right direction in several properties would also accomplish the same result.

Statistical Analysis

An analysis of the physical property vs. cracking correlation was also made by S. C. Horning using the computer program for multiple regression. Seven paints were analyzed in this study: #42, #40, AC-33, AC-34, HG, HF, and HH. These paints were selected because a large amount of accelerated weathering and outdoor exposure data was available. Statistical analysis showed that all the formulations were significantly better than AC-33 paint in crack resistance, both outdoors and on the weatherometer. There was no significant difference between formulations other than AC-33.

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The multiple regression equation found for predicting crack resistance was:

$$Y_2 = 9.32 + .0877\ P - .502\ D - .0371\ E - .517\ T + .011\ A$$

where

Y_2 = Weatherometer (AWC-1) crack rating, adjusted

P = Permeability

D = Dimensional Change

E = Elongation 77°F

T = Tensile strength 77°F

A = Adhesion, wet.

In the above equation, adhesion was found to be non-significant, dimensional change very significant, and the others significant at the 95% level.

Since increasing values of Y_2 mean improved crack resistance, the multiple regression equation gives some misleading indications. The equation shows crack resistance to be helped by low dimensional change and high adhesion, which is correct; but also to be helped by high permeability, low elongation, and low tensile strength, which the weight of evidence indicates is incorrect. The difficulty is probably due to the interactions between variables, and the limited number of samples presented for calculation. The variables should be independent in order to apply the multiple regression technique, but the house paint properties cannot be considered independent. There is, for example, high correlation between tensile strength and elongation, or permeability and dimensional change.

EXPERIMENTAL DETAILS:

Free films were prepared using the automatic draw down machine fitted with a vacuum plate. Films were drawn down on polyethylene sheets, from which the dry film was subsequently peeled. Double drawdowns were used, with a 4.2 mil doctor blade, followed by a 5.6 mil blade. This procedure helped to reduce the effect of pinholes or other flaws which might be present in a single drawdown. All films were air dried in the laboratory for one week before exposure and testing.

To evaluate the crack resistance of topcoats applied to weathered substrates, uniformly cracked panels were selected for repainting. The standard substrate was southern yellow pine painted with two coats of #40 Outside White and weathered for two or more years in Texas at 45° South. On the average these panels

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had a rating of 4 to 5 for cracking. Controls of #50 and #42 were regularly exposed along with the other test paints. Blocks were cut to approximately 3 x 4 inches for accelerated weathering exposure. The test paints were applied by brush in one coat with a coverage of 1 gram of wet paint per 70 sq. cm. Edges and backs of the blocks were sealed with aluminum paint (165-5642). The painted panels were air dried in the laboratory for one week before exposure.

Most of the accelerated weathering data on crack resistance was obtained on the AWC-1 machine by us and on the AWC-2 service cycle by Strehlau and others (20). There were no significant discrepancies between the cracking performance of different paints on the accelerated weathering machines or outdoor exposure. Crack ratings were based on the scale 0-10, with the 10 rating corresponding to no cracking.

The AWC-1 machine was set up with the X-14 experimental accelerated weathering cycle (36), modified with a cold water stream and shortened cycle time. The cold water, at approximately 40°F, was directed onto the topcoat. The cycle time was 110 minutes. The panels became dry under the sunlamps before re-entering the water spray portion of the cycle. In the AWC-2 service cycle, the panels did not dry out at any time during exposure. The new AWC-3 accelerated weathering machine (36) more closely resembles the modified X-14 cycle, and initial exposure tests have shown good correlation with other cracking data.

The crack resistance rankings that we have reported were based on analysis of ten or more separate exposure series. Despite the use of control paints, the selection of uniformly cracked substrates, and the use of test panels from the same board, considerable variance could still occur in the exposure data (20). As a result, the within-series differences were analyzed from many exposure series.

Water permeability was measured by the inverted Payne cup method (15). Measurements of tensile strength and elongation were made on the Instron tensile tester, with a one-inch gauge length and a crosshead speed of 0.2 inches per minute. Dimensional changes were determined with a cathetometer, by measuring the distance between index marks on free films.

The free film stretch test was run by stretching films over a sheet metal bracket attached to a wooden block. Figure 8 is a picture of two stretch test panels. The panels fit on the AWC-1 accelerated weathering machine, so that the stretched film was exposed to the weathering cycle without contact with any substrate. In forming the stretched film, the sheet metal bracket (3" wide x 3-1/2" long) was first bent into a U-shape. A piece of free film, 2" wide, was placed across the ends of the bracket and taped firmly in position while flat and unstretched. The U-shaped

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bracket was then slowly bent open, putting a stretch in the film. The elongation of the film was determined by measuring the initial and final lengths across the bracket. For exposure tests on latex films, an elongation of 200% was used, with an initial span of one inch being increased to three inches.

Adhesion was evaluated with the scotch-tape peel test, knife scratches, and peel tests using a freed film end.

Solubility was determined by measuring the time for a free film to break, when the film was submerged in solvent under a light tensile load. The test was run on a film strip approximately 1-1/2" long and 1/4" wide. The strip was hung vertically, with the upper end supported in a clamp and the lower end loaded with a paper clip. The film was dipped into the solvent in a 100-ml graduated cylinder, and the time between the start of submersion and breakage of the film was measured. The test was stopped after 3 minutes if failure had not occurred by then.

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BIBLIOGRAPHY

1. S. Graves, Marshall Laboratory Research Report No. 1297 (March 11, 1954).

2. S. Graves, Marshall Laboratory Research Report No. 1342 (October 25, 1954).

3. S. Graves, Marshall Laboratory Research Report No. 1397 (August 29, 1955).

4. E. R. Werner, Jr., Marshall Laboratory Memorandum Report No. M-810 (November 1, 1955).

5. E. R. Werner, Jr., Marshall Laboratory Memorandum Report No. M-813 (November 7, 1955).

6. R. W. LaBerge, Marshall Laboratory Research Report No. R-56-7 (February 3, 1956).

7. L. G. Fasolino, Marshall Laboratory Research Report No. R-57-16 (March 5, 1957).

8. M. J. McDowell, Marshall Laboratory Research Report No. R-57-17 (March 7, 1957).

9. M. J. McDowell, Marshall Laboratory Research Report No. R-57-62 (September 24, 1957).

10. C. J. A. Peters, Marshall Laboratory Research Report No. R-58-3 (January 9, 1958).

11. C. J. A. Peters, Marshall Laboratory Research Report No. R-58-32 (May 9, 1958).

12. M. J. McDowell, Marshall Laboratory Research Report No. R-58-44 (June 24, 1958).

13. W. T. M. Johnson, Marshall Laboratory Research Report No. R-58-54 (August 5, 1958).

14. W. F. Singleton, Marshall Laboratory Research Report No. R-59-55 (September 21, 1959).

15. W. F. Singleton and C. H. Strolle, Marshall Laboratory Research Report No. R-61-7 (February 1, 1961).

16. J. R. Courtright, Marshall Laboratory Research Report No. R-60-50 (September 12, 1960).

DUP030010081

17. J. R. Courtright, Marshall Laboratory Research Report No. R-62-13 (January 26, 1962).

18. C. H. Strolle, Marshall Laboratory Research Report No. R-62-20 (February 16, 1962).

19. J. R. Courtright, Marshall Laboratory Research Report No. R-62-29 (April 12, 1962).

20. D. R. Strehlau, Marshall Laboratory Research Report No. R-62-35 (April 27, 1962).

21. T. B. Hill, Marshall Laboratory Research Report No. R-62-38 (June 12, 1962).

22. T. B. Hill, Marshall Laboratory Research Report No. R-63-10 (January 22, 1963).

23. T. B. Hill, Marshall Laboratory Research Report No. R-63-12 (January 30, 1963).

24. J. E. Oyler and D. R. Strehlau, Research Memorandum Report No. RM-61-12 (June 27, 1961).

25. F. L. Browne, "Understanding the Mechanisms of Deterioration of House Paint," Forest Products J. 9 417 (Nov. 1959).

26. F. L. Browne, "Thermal Expansion of Free Films of House Paint," Report No. 2204, Forest Products Laboratory, Madison, Wisc. (Dec. 1960).

27. G. C. Bell to M. J. McDowell, Letter, File 1875, 2050 (May 28, 1963).

28. V. P. Miniutti, "Properties of Softwoods That Affect the Performance of Exterior Paints," Official Digest 35 451 (May 1963).

29. M. J. McDowell, Marshall Laboratory Memorandum Report No. RM-56-23 (Oct. 31, 1956).

30. M. Van Loo, "Exterior Finishes for Wood," paper presented at Engineering Institute, Univ. of Wisconsin, Nov. 30 - Dec. 1, 1961.

31. F. L. Browne, "Swelling of Springwood and Summerwood in Softwood," Forest Products J. 7 416 (Nov. 1957).

32. A. C. Elm, "Some Mechanical Properties of Paint Films," Official Digest 1953 751 (Nov. 1953).

33. P. J. Flory, Principles of Polymer Chemistry, Chap. XI, Cornell University Press, Ithaca, N. Y. (1953).

DUP030010082

34. P. Dunn, A.J.C. Hall, and T. Norris, "Failures in Stressed Nylons," Nature 195 1092 (Sept. 15, 1962).

35. B. S. Garrett, W. C. Prentiss, and J. D. Scott, "Factors Affecting the Levelling of Latex Paints," Official Digest, Feb. 1959.

36. M. P. Morse, Marshall Laboratory Research Report No. R-62-30 (April 18, 1962).

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TABLE 1

EFFECT OF SUBSTRATE ON CRACK RATING

SUBSTRATE	TOPCOAT PAINT		
	#50 (AC-33) 310-095	#50 (AC-34) 310-W-45927	#42 301-948
None, free films (unstretched)	10	10	10
Steel; glass	10	10	10
Bare wood, yellow pine	8	9.5	8
Weathered #40 (301-960) on pine siding, chalky, but not cracked	10	10	10
Weathered #40 (301-960) on pine siding, badly cracked	5	8	9
Weathered Stucco, Shake and Shingle (601-911) on pine siding, badly cracked	8	9	7

Crack rating after two weeks on AWC-1

Scale of 0 - 10:

10 = no cracking

7 = failure; extensive cracks

4 = approx. 50% of film area is cracked away.

TABLE 2

CRACK RATINGS FROM OUTDOOR EXPOSURE AND

ACCELERATED WEATHERING (AWC-1)

The ratings tabulated are the average differences obtained by substracting the AC-33 crack rating from the other ratings in each exposure series. Eleven series were averaged for the AWC-1 ratings. Eight series were averaged for the outdoor data, which included Delaware test fence and House Test results. These have been adjusted to compare with the AWC-1 ratings by adding the value 2.

CODE	NAME	OUTDOOR EXPOSURE	ACCELERATED WEATHERING
310-095	AC-33 #50	2.0	0.0
310-W-45927	AC-34 #50	3.0	2.7
310-W-46109	HG	3.0	3.4
310-W-12831	HF	2.9	2.3
310-W-37746	HH	3.8	3.0
301-948	#42	3.6	3.7
301-960	#40	3.3	3.5

All formulations are significantly more crack resistant than AC-33, and there is no significant difference between formulations other than AC-33. Average units better than AC-33:

3.1 for weatherometer

1.1 for outdoor exposure (small because exposure time was relatively short, 1 - 2 1/2 years)

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TABLE 3

PROPERTIES OF LATEX PAINTS

Code	Name	Crack Rating	Stretch Test (Vehicle)	Permeability (Water) (mg-mm/cm^2-day)	Dimensional Change (Max.%)	Elongation(%) 30°	77°	130°	Tensile Strength (Lbs./Sq.In.) 30°	77°	130°	Adhesion Wet	Dry
310-095	AC-33 #50	Poor	Fail	10	5.5	2	50	70	3800	700	180	3	9
310-W-45927	AC-34 #50	Good	Pass	10	3.5	2	60	70	3800	700	340	9	9
310-W-46109	HG	Good	Pass	16	2.8	4	120	140	1800	300	85	3	9
310-W-12831	HF	Good	Pass	13	5.4	8	120	90	1500	200	40	3	9
310-W-37746	HH	Good	Pass	0.5	1.8	20	80	90	1400	500	260	8	5
310-W-65275	IE	Good	Pass	14	2.2	7	130	190	2500	510	160	9	9
310-W-93935	IO	Good	Pass	8	2.2	7	60	100	2100	640	240	9	9
				± 10%	± 0.4			± 20%				±1	±1

Films were aged for one week at 77°F and 50% R. H., and weathered for 100 hours on AWC-1 accelerated weathering machine before testing.

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TABLE 4

PROPERTIES OF OIL & ALKYD PAINTS

Code	Name	Crack Rating	Stretch Test (Vehicle)	Permeability (Water) (mg-mm/cm^2-day)	Dimensional Change (Max. %)	Elongation(%) 30°	77°	130°	Tensile Strength (Lbs./Sq. In.) 30°	77°	130°	Adhesion Wet	Dry
301-948	#42	Good	*	0.2	0.8	3	5	12	2400	1000	700	10	10
301-960	#40	Good	*	0.3	1.2	3	5	10	2400	1000	700	10	10
87-894	Trim & Shutter	Good	*	0.3	1.4	6	70	50	4300	1500	600	10	10
601-911	Stucco, Shake & Shingle	Fair	*	0.6	2.2	2	3	4	2400	1500	1000	10	10
305-8010	Barn & Roof	Good	*	0.4	1.8	16	20	23	800	300	230	10	10
				±10%	±0.4			±20%				± 1	±1

Films were aged for one week at 77°F and 50% R. H., and weathered for 100 hours on AWC-1 accelerated weathering machine before testing.

*Free films were intractable.

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TABLE 5

PROPERTIES OF SOME LATEX CLEARS

LATEX	STRETCH TEST	PERMEABILITY (Water) (mg-mm/cm^2-day)	ELONGATION %			TENSILE STRENGTH (lbs./sq.in.)		
			30°	77°	130°	30°	77°	130°
AC-33	Fail	2.0	250	500	80	2500	300	16
AC-34	Pass	2.0	250	600	>750	2500	200	20
RC-W-17796 IO iminated	Pass	0.5	320	>750	>750	1800	160	10
RC-W-80026 IO non-iminated	Fail	0.5	230	600	>750	2400	660	20
RC-W-65255 IE iminated	Pass	2.2	340	>750	>750	2400	120	16
RC-W-65248 IE non-iminated	Fail	2.3	320	>750	380	2100	45	12
		±10%				± 20%		

Films were aged for one week at 77°F and 50% R. H. and weathered for 100 hours on AWC-1 accelerated weathering machine before testing.

TABLE 6

SOLUBILITY TEST FOR HOUSE PAINT FILMS

	Solubility Time (Seconds)	
Clears	Xylene H-583	Ethyl Acetate H-136
AC-34	>180	>180
AC-33	11	5
RC-W-17796 (IO iminated)	11	6
RC-W-80026 (IO non-iminated)	8	6
RC-W-65255 (IE iminated)	>180	8
RC-W-65248 (IE non-iminated)	6	2
Paints		
310-W-45927 (AC-34)	>180	>180
310-095 (AC-33)	32	20
310-W-93935 (IO iminated)	>180	>180
310-W-80026 (IO non-iminated)	>180	>180
310-W-65275 (IE iminated)	>180	>180
310-W-65268 (IE non-iminated)	36	16
301-948 (#42)	>180	>180

DUP030010089

TABLE 7

CALCULATED CRACK RESISTANCE RATINGS

CODE	NAME	CRACK RATING, R
301-948	#42	9.8
310-095	AC-33	2.2
310-W-45927	AC-34	8.2
310-W-46109	HG	5.3
310-W-12831	HF	2.4
310-W-37746	HH	9.9
310-W-65275	IE	8.9
310-W-93935	IO	8.9
301-960	#40	9.7
87-894	Trim & Shutter	10.0
601-911	Stucco, Shake & Shingle	8.7
305-8010	Barn & Roof	9.4

Property Ranges:	P	D	A	E	T	S
Maximum	16	5.5	10	130	1500	2
Minimum	0.2	0.8	3	3	200	1

FIGURE 1



CRACKED HOUSE PAINT

FIGURE 2



PHOTOMICROGRAPH OF CRACK IN HOUSE PAINT FILM.

NOTE THREADS OF PAINT ACROSS CRACK.

Figure 3

EFFECT OF FILM THICKNESS ON CRACKING

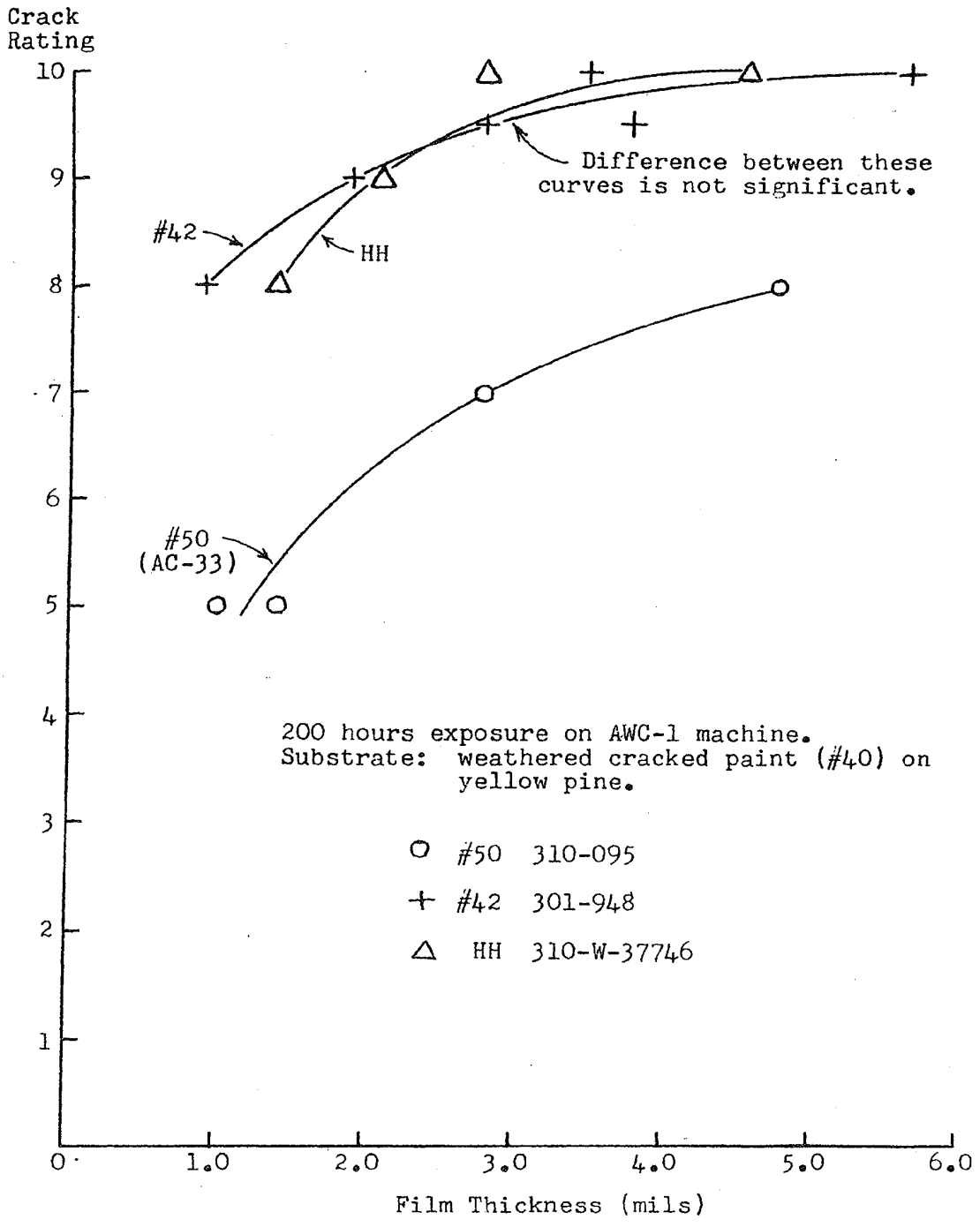

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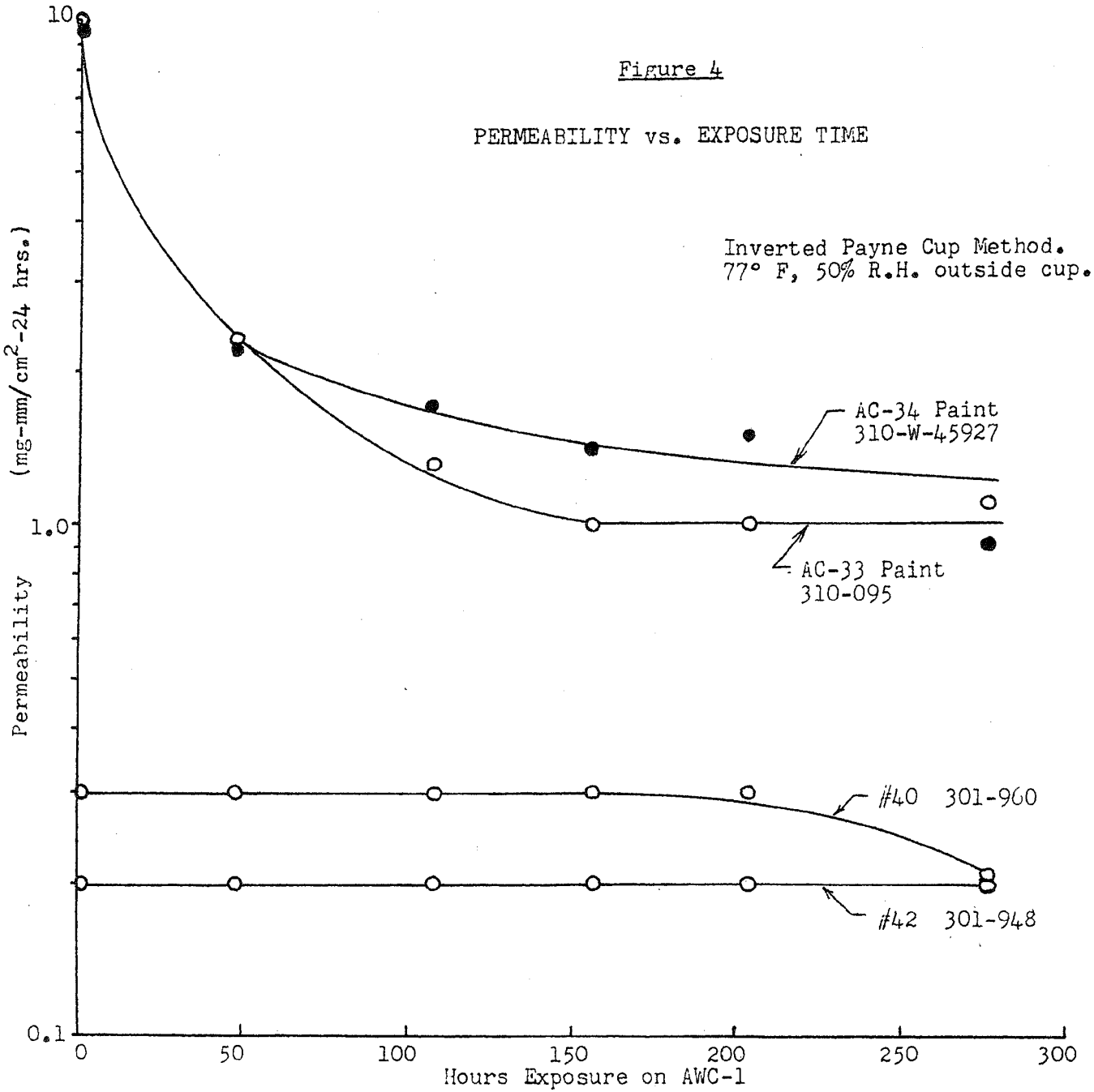
Figure 4

PERMEABILITY vs. EXPOSURE TIME



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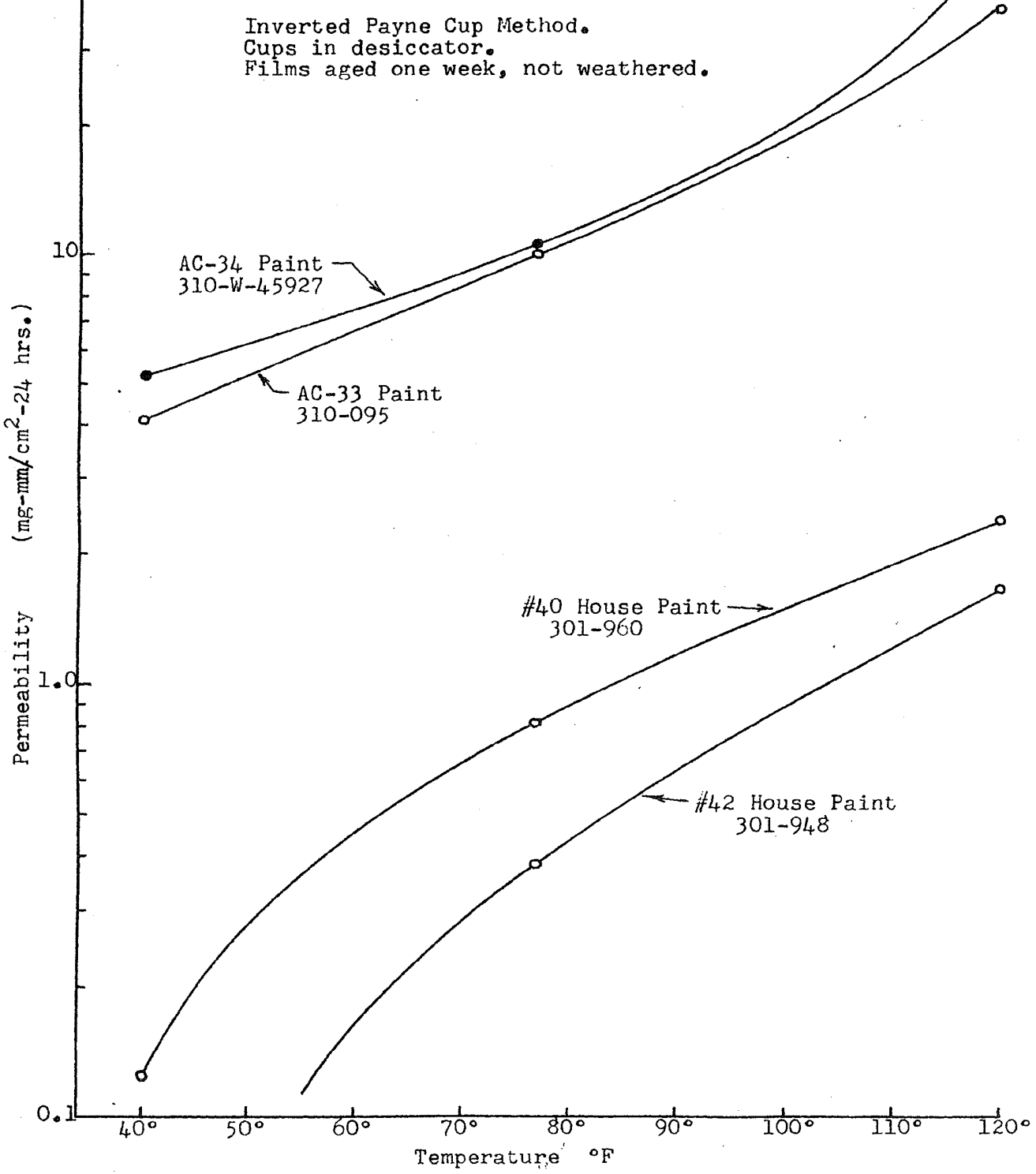

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Figure 6

ELONGATION vs. TEMPERATURE

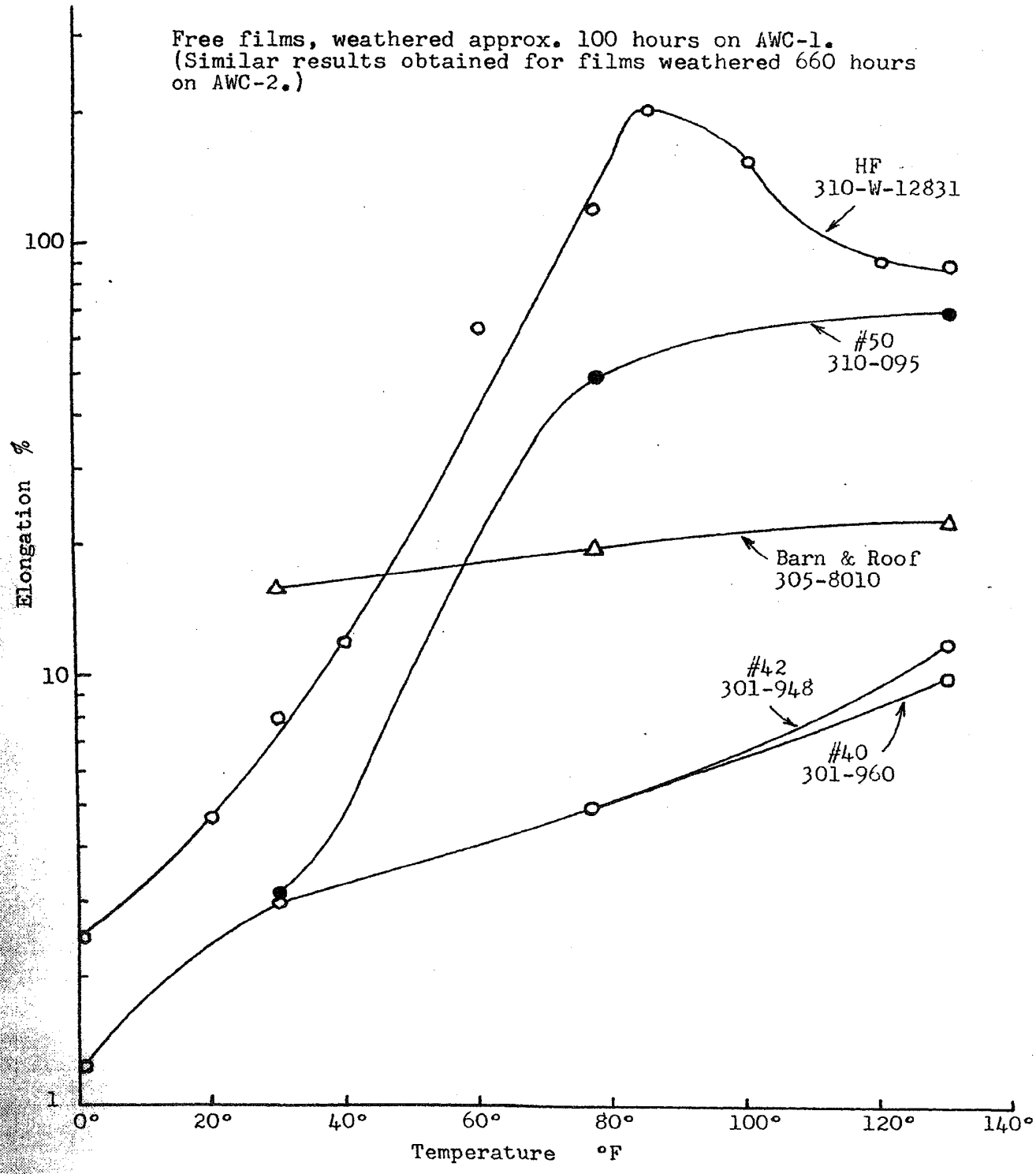

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Figure 7

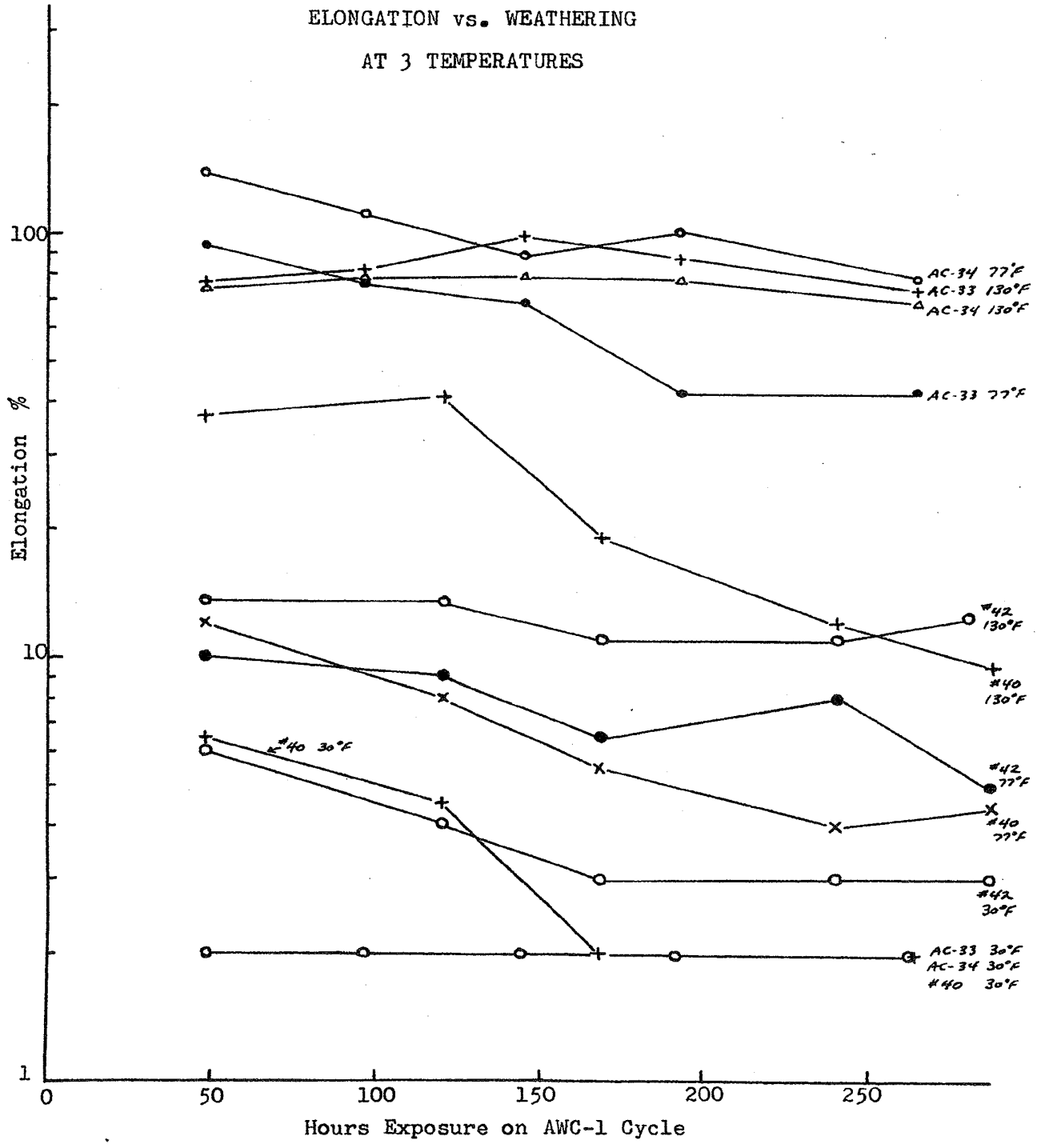
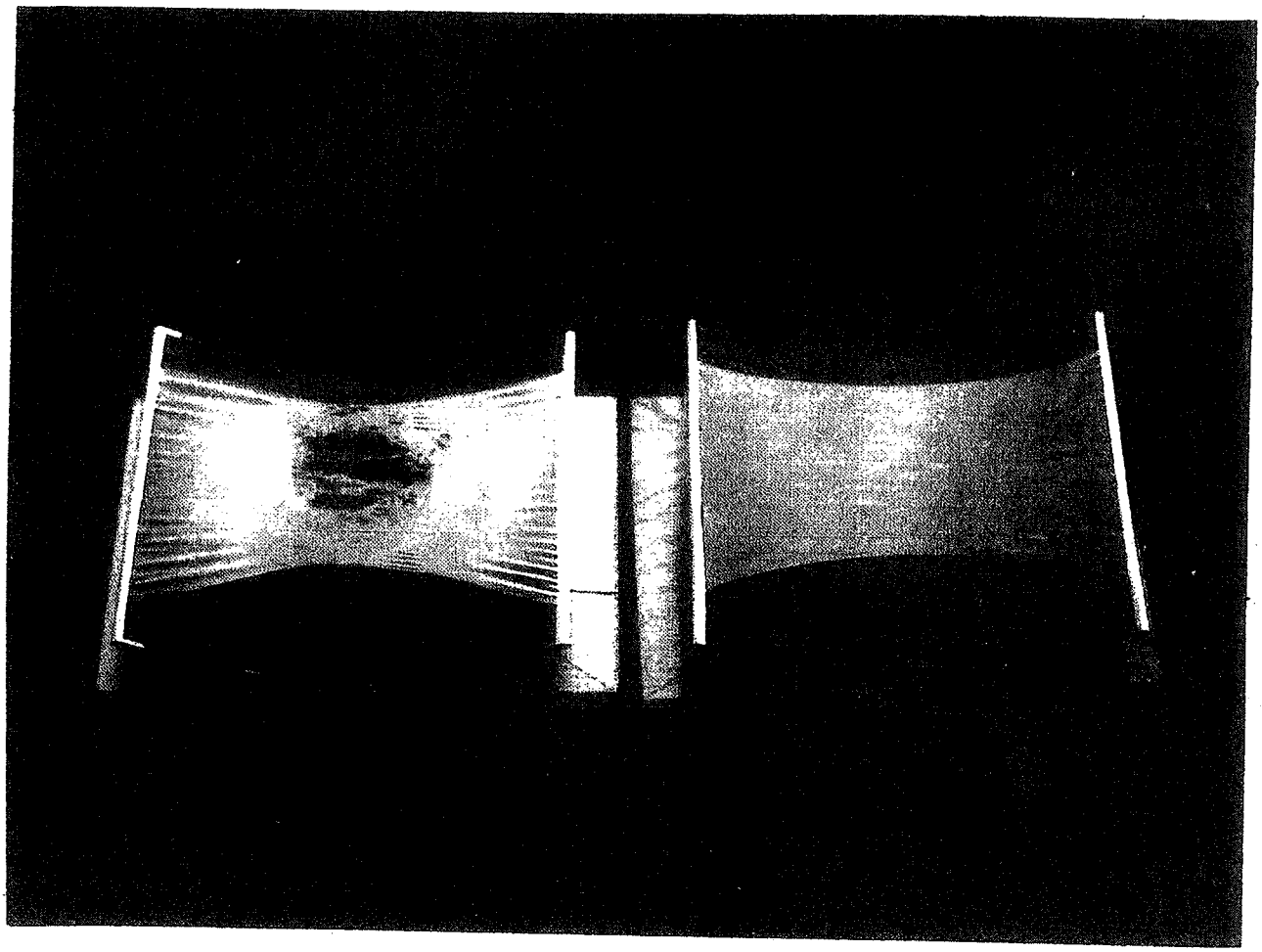

ELONGATION vs. WEATHERING
AT 3 TEMPERATURES
Elongation %
100
10
1
0
50
100
150
200
250
Hours Exposure on AWC-1 Cycle
AC-34 77°F
AC-33 130°F
AC-34 130°F
AC-33 77°F
#42 130°F
#40 130°F
#40 30°F
#42 77°F
#40 77°F
#42 30°F
AC-33 30°F
AC-34 30°F
#40 30°F

FIGURE 8



AC-33 LATEX (FAIL)

AC-34 LATEX (PASS)

FREE-FILM STRETCH TEST.

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