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DIVISION OF BUILDING RESEARCH

DBR INTERNAL REPORT NO. 430

WATER VAPOUR PERMEATION THROUGH CLEAR COATINGS

by M. Yaseen and H.E. Ashton

Checked by: P.J.S. **Approved by:** L.W.G. **Date:** July 1976

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PREFACE

In most climates exterior coatings are exposed to a considerable amount of rain and water vapour in service. Consequently, the permeability of these coatings to water vapour is one of the more important properties because it affects their performance. Change in permeability with increasing relative humidity and temperature is also important not only because it indicates how a material may behave in practice but also because it gives an insight into the molecular structure of the material.

Although the permeability of plastic films has been studied in great detail, owing to their use as vapour barriers, the permeability of organic coatings, and its change with temperature and relative humidity, has not received as much attention.

The report describes the permeability studies made with clear finishes intended for exterior wood. The effects of the two variables on permeation and on the permeability coefficient are discussed. It is shown that the results can be related to the composition of the coatings.

Ottawa
July 1976

C.B. Crawford
Director
DBR/NRC

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by

M. Yaseen and H.E. Ashton

INTRODUCTION

The protection provided by an organic coating depends on many factors, one being its resistance to permeation by gases, vapours, liquids and ions.⁽¹⁾ The phenomenon of permeation begins when a diffusant in contact with the coating gets imbibed in it. Depending on the forces of interaction between diffusing molecules and the components of the coating, the diffusant moves within the coating in the sorbed state. This process results in gradual absorption of vapour until a state of dynamic equilibrium is reached. At this stage the difference in vapour pressure between the two sides of the coating causes the permeation of vapour through it. Hence, permeation of vapour through a coating occurs in three steps: absorption of vapour on the surface, followed by its diffusion through the film, and then desorption or evaporation at the lower vapour pressure side.⁽²⁾

Generally, coatings are used because they act as barriers to the free access of gases, vapours, liquids and ions to metal surfaces. While it is believed that no organic coating is completely impervious, they do provide the substrate with considerable protection from corrosive agents.⁽³⁾

Permeability characteristics of coatings are important in assessing their performance in practical use. They are dependent mostly on the molecular structure and chemical nature of groups present in the material and their affinity towards diffusants. Permeability, is basically governed by the vapour pressure and temperature of the surroundings. The permeability properties of coatings also affect their adhesion to metallic substrates by controlling the changes in osmotic pressure at the interface.⁽⁴⁾

It is sometimes observed that exterior coatings that might be expected to last for years develop blisters and peel within a relatively short period, thus suffering premature failure. This may be related to the low permeability of the coating which still allows some moisture to diffuse through when given enough time. During exterior exposure vapour that condenses at the coating substrate interface

develops high pressure in the heat of the day because of the low permeability of the coating. When the vapour pressure built up at the interface exceeds the force of adhesion (at those conditions), it pushes the coating away at weak spots in the form of blisters, which may lead to peeling. On the other hand, if a coating allows vapour to permeate through it freely, it does not act as a protective coating especially for metal substrates which may corrode.⁽⁵⁾ It is, therefore, desirable that the coating should be moderately permeable to maintain a fairly low vapour pressure at the interface so that the adhesion of the coating to the substrate is not affected.

THEORETICAL

Equations for Permeation

At a steady rate of permeation the quantity of vapour Q transmitted through a coating of thickness ℓ and area a in time t at vapour pressure differential Δp is expressed by:

$$Q = P \cdot \frac{at}{\ell} \Delta p \quad \text{or} \quad P = \frac{Q\ell}{a t \Delta p} \quad (1)$$

where P is a proportionality constant known as the permeability coefficient.

Fick's treatment of permeation is based on the assumptions that permeation takes place in a steady state, the concentration gradient in the film is uniform and permeation proceeds in one direction. In such a case the rate of vapour transfer F is given by:

$$F = P \frac{(p_1 - p_2)}{\ell} \quad (2)$$

The integrated form of Fick's equation, $F = D \cdot dc/dx$,⁽⁶⁾ is:

$$F = D \frac{(c_1 - c_2)}{\ell} \quad (3)$$

The relationship suggested by Henry's law is applicable if there is equilibrium between the vapour and the first layer of the coating:

$$c = Sp \quad (4)$$

Therefore:

$$F = DS \frac{(p_1 - p_2)}{\ell} \quad (5)$$

and

$$P = DS \quad (6)$$

Here p and c are pressure and concentration of the vapour; D and S are the coefficients of diffusion and solubility of the coating for the vapour.

Effect of Temperature and Vapour Pressure on the Permeability Coefficient

Rate dependent phenomena are naturally affected by changes in temperature. A rise in the temperature activates the molecules and creates voids by the movement of polymer segments which in turn are occupied by diffusing in the vicinity thus providing the vapour with an easy means of movement.⁽⁷⁾ Permeation of vapours through polymers is a thermally activated process and the temperature dependence over small changes can be given by an Arrhenius type equation.⁽⁸⁾

$$P = P_0 e^{-E_p / RT} \quad (7)$$

P_0 , the pre-exponential factor, can be related to the openness of the polymer structure and the appearing-disappearing and reforming of voids due to movements of segmental chains in the activated state. E_p is the apparent energy of activation for permeation.

The pressure dependence of the permeability coefficient of a polymer for a vapour is governed basically by the size and shape of the penetrating molecule and also by its activity and solvent power. Ideal gases, because of their low activity and solvent power, do not cause swelling, strain or other rearrangements in the structure of polymers. Consequently, permeability coefficients of polymers for such gases are not affected by concentration at a constant temperature. In the case of water vapour, the activity of sorbed vapour increases with concentration and may have a plasticizing effect on the molecular structure of the polymer thus promoting the rate of permeation. The deviations of permeation from Fickian behaviour with concentration or vapour pressure arise as a consequence of the finite rates by which changes take place in the structure of the polymer due to stresses imposed upon it before and during the sorption - diffusion - permeation processes.⁽⁹⁾

It has been observed in water vapour permeability tests that under a steady state of permeation, the distribution of the vapour sorbed in the coating equilibrates so that the vapour pressure gradient is linear through the film. Because of the low interaction between water and most organic polymer molecules, the permeability coefficients of polymers are not greatly affected by relative humidity⁽¹⁰⁾ or thickness of the film.⁽¹¹⁾

Some of the observations made at DBR/NRC on the effect of temperature and humidity gradients on moisture transmission through organic building materials have been reported earlier.⁽¹²⁾ It was felt, however, that little information was available on the effect of vapour pressure and temperature on the rate of permeation of water vapour through coatings such as phenolic varnishes and alkyds. It was considered worthwhile, therefore, to study the properties of such coating materials and the results of this investigation are now reported.

EXPERIMENTAL

Materials

Twelve paraphenylphenolic resin varnishes previously described⁽¹³⁾ were used. The proportion of oil, resin and solvents in each varnish are summarized in Table 1. Five orthophthalic short, medium and long alkyds, six isophthalic long and very long alkyds, and two medium alkyds prepared in the laboratory were also tested. The compositions of the commercial alkyds listed in Table 2 are based upon information given by the manufacturers in the technical literature.

Commercial cardanol and cashew nut shell liquid (CNSL) were first condensed with hexamine individually and one of the reaction products, cardanol-hexamine condensate or CNSL-hexamine condensate, incorporated in some of the oils, phenolic resin varnishes and commercial alkyds. The compositions of the modified coatings are described in Table 3.

Free Films

Coatings of uniform thickness were drawn down by a machine-driven film applicator on tin foil and air dried for 3 weeks in a dust-free room controlled at 50 ± 5 per cent R.H. and 73 ± 3.5 °F (23 ± 2 °C). The free film obtained by amalgamation of the tin were dried in the same room for at least another 3 weeks before using them.

Permeability Measurements

The steady rate of permeation of water vapour through free films of the clear finishes was determined using a modification of the well-known cup method. Film samples cut to the size of the cup were placed carefully on thin cardboard rings soaked in molten wax. They were first equilibrated with vapour at the desired R.H. and temperature and then placed over the cup which had been filled to the top with anhydrous magnesium perchlorate, taking care that the granules did not touch the film. The cup was sealed with wax in such a way that a known area of film covering the desiccant in the cup was exposed for the transmission

of vapour. (14) Sealing of cups with the films was carried out at the temperature of the experiment so that the films would not bulge or contract due to changes in the temperature of the experimental surroundings. Triplicate specimens were prepared for each type of film and separate sets were used for the variation of temperature and of R.H.

The sealed cups were placed in a specially designed humidity cabinet which can be adjusted to any desired relative humidity at temperatures between 30 and 160 °F. The transmission of water vapour was determined by weighing the cup inside the humidity cabinet, the gain in the weight being followed as a function of time. In most cases a steady rate of vapour transfer was attained in 48 hours.

The rate of water vapour permeation through the free film was determined under steady state flow conditions at different relative humidities with constant temperature of 73 °F and at different temperatures with constant humidity of 50 per cent. Rates were calculated in terms of the quantity of vapour (g) permeating in one hour (h) through a film of unit area (m²) and unit thickness, 1 mil (25 μm).

RESULTS

Treatment of Results

The space in the cup under the film is filled with the desiccant to the extent that only a fairly small volume between the film and desiccant is left. In such a system the vapour permeating through the film is mostly absorbed by the desiccant thus having negligible pressure in the cup. For the purpose of calculating the coefficient of permeation, the vapour pressure inside the cup has been considered to be zero and the pressure differential, Δp, across the film equal to the vapour pressure corresponding to the relative humidity of the experiment.

The permeability coefficient of each coating formulation for water vapour was calculated using Equation (1) and expressed in the following units:

$$P = \frac{Q \times l}{a \times t \times \Delta p} \quad \frac{\text{gm cm}}{\text{cm}^2 \text{ sec mm Hg}} \quad (8)$$

Effect of Relative Humidity on Permeation

At constant temperature and a particular vapour pressure the flow of vapour through the coating attains a steady rate after about 48 hours. When the pressure difference across the film is changed to a different value the rate changes until steady conditions are again reached. The amount of water vapour sorbed by a coating varies with the R.H.; hence,

the plasticizing effect of the sorbed vapour on the transmission of vapour through the coating changes correspondingly. The increase in permeation rates with vapour pressure can readily be seen in all plots against R.H.

Permeation rates through phenolic varnishes (Table 4) increase linearly with water vapour pressure at lower relative humidities but at higher R.H. the increase is somewhat more than linear as shown in Figures 1 and 2. This may be due to an increase in sorbed water at higher R.H. that promotes permeation by acting as a plasticizer. Also as films swell due to sorbed water, there would be more space for diffusion to take place.

Permeation rates through alkyds (Table 5) are more affected by water vapour pressure than through phenolics. For example, at 50 per cent R.H. and 73 °F the permeation of water vapour through a medium linseed alkyd (NRP 1055) is 10 per cent lower than through a linseed phenolic (1021), whereas at 97 per cent R.H. it is 31 per cent more. For comparison of moisture content dependence, the permeation rates are plotted against R.H. in Figure 3 for a few alkyds having different oils and oil contents and also of two phenolics. In the one comparable case in Table 5 (E1 vs E5 and E6) it is seen that permeation through orthophthalic alkyds is greater than through isophthalic alkyds at higher R.H.

Because in the case of alkyds the permeation rates increase quickly and linearly with R.H. at around 80 per cent R.H. and above, it is concluded that the plasticizing action of the sorbed vapour on the internal structure of the coating is more effective and increases uniformly at higher R.H.

Of the phenolic varnishes, those prepared from semi-drying soya oil are relatively the most permeable to water vapour. Upon modification with the condensate of either cardanol or CNSL this property is changed considerably (Figure 4). Modified dehydrated castor oil phenolics also show lower permeation than the unmodified ones (Figure 5). The results also indicate that the CNSL condensate with hexamine reduces the permeability of phenolics and alkyds more than the cardanol condensate (Table 6).

It is evident from Table 6 that modification of the long and very long oil alkyds reduced their permeability significantly (E2 vs 1066, E6 vs 1065 and 913 vs 1067). The same degree of change in the permeability of a short alkyd (916 vs 1068) is not found (Figure 6). This is considered to be confirmation that in long and very long alkyds, the oil is not fully reacted with the resin⁽¹⁵⁾ so the cardanol or CNSL hexamine condensate forms cross-links with the partially reacted oil and improves the properties of the composition. In a short alkyd the degree of reaction is limited hence the modification can have less effect.

Effect of Temperature on Permeation

A certain amount of energy is needed to generate the thermal motion of coating molecules so that they are separated sufficiently to allow the diffusant molecules to move through the spaces created. The fairly low permeation rates of some varnishes at 63 °F show that the movement of water vapour through the coatings is very low due to the slow state of molecular activity. On the other hand a temperature increase of 40 °F activates the coating molecules so that the permeation rates of some phenolics are found to be more than 7 times faster (Table 7). These results indicate that a change in the environmental temperature has a marked influence on permeation rates of vapours through certain coatings. It is useful therefore to know the temperature dependence of permeation rates if the selection of coatings is to be made on the basis of permeability properties.

The results show that with phenolic varnishes the increase in permeation rates with temperature depends on the type of oil used because the increase is not proportional in all cases (Table 7). This feature can be noticed in the plots of permeation rates (Figure 7). For example, at 63 °F and 50 per cent R.H., the rate through 20-gal. soya phenolic (0.61 g/m²/h/mil) is one and a half times that of the same oil length tung phenolic (0.405 g/m²/h/mil) whereas at 103.6 °F it is double (soya - 4.64; tung - 2.36). In the case of varnishes with the same oil but different oil contents, the permeation rates of coatings with high oil content increase relatively fast with temperature (linseed oil phenolics: 1021, 902, 903 and 905 in Figure 7).

The permeation rates of several alkyds and 3 phenolics are plotted in Figure 8. Comparison of plots for alkyds and phenolics (1055 vs 1021, 1056 vs 1022 and 915 vs 1024) shows that the temperature dependence of permeation rates of alkyds is more than for phenolics. Among alkyds the increase in rates with temperature is greater in the case of orthophthalic alkyds than the isophthalic ones (913 vs E5 in Table 8). Plots, E2 vs E3 show the difference in the permeability properties of soya and safflower oils. It is thought that the effect of temperature on permeation properties of alkyds can be correlated with the degree of cross-linking, the inter-molecular spacings and the total free energy levels in their molecular structures.

The effect of temperature on permeation rates through modified alkyds and phenolics is illustrated in Figure 9 and presented in Table 9. After modification there is less difference between dehydrated castor and soya (1058 vs 1060) than with the original varnishes. The large difference between a modified coating and its original counterpart shows the improvement in temperature resistance properties due to the reaction. Modification of the 40-gal. soya phenolic results in lower permeability for 1062 than the unmodified 20-gal. varnish. Even soya oil modified by cardanol condensate (1064) transmits less water vapour than unmodified

very long oil alkyds at higher temperatures. The difference in temperature dependence between unmodified and modified alkyds is small for short oil lengths (916 vs 1068) but increases with increasing oil content (913 vs 1067 and E2 vs 1066).

Effect of R.H. On Permeability Coefficient

The permeability coefficients at different R.H. are given for phenolics in Table 10 and are plotted in Figure 10. While higher humidities had a large effect on permeation rates (Figures 1 and 2) the phenolic permeability coefficient plots are almost flat with respect to the R.H. axis. Although the direction away from the axis indicates some dependence on moisture content, it is concluded that the permeability coefficients of phenolics for water vapour are little affected by an increase in moisture content.

The permeability coefficients of alkyds are found to increase with R.H. rather more than phenolics (Figure 11 and Table 11).

The R.H. dependence of permeability coefficients of some modified alkyds and phenolics is illustrated in Figure 12. The plot for modified alkyd 1067 shows the extent of the decrease in permeability coefficient and its dependence on R.H. in comparison with the unmodified alkyd 913. A remarkable decrease in the R.H. dependence of the permeability coefficient of very long isophthalic alkyd E2 can be seen after its modification (1066). Modified phenolics show some decrease in the R.H. dependence of their permeability coefficients in the case of those which were affected the most in the unmodified form (Tables 10 and 12).

Effect of Temperature on Permeability Coefficient

The change in permeability coefficient with temperature provides an insight into the mechanism of permeation and the nature of the coating. Owing to the low activity of ideal gases towards polymers, $\log P$ is a linear function of $1/T$ over a wide temperature range above the glass transition temperature. By contrast, the permeation of water vapour through any amorphous polymer, such as a coating, is affected by temperature because of the increased activity of water. Nevertheless, the permeability coefficients of coatings for water vapour are linearly related to the inverse of temperature over small temperature changes.

In the case of phenolics it has been seen that their permeability coefficients are almost independent of R.H. at lower relative humidities but they are found to increase with temperature. The temperature dependence of the permeability coefficients of phenolics as a function of the types of oils and of oil contents can be seen in Figure 13 and Table 13.

The increase in permeability coefficients of alkyds with temperature is relatively higher than phenolics (Figure 14, 1055 vs 1021 and E6 vs 1022). The temperature dependence of permeability coefficients of orthophthalic alkyds is greater than that of iso alkyds at comparable oil lengths. The difference due to oil type is evident in Table 14 by comparing 1055 with 1056 for an ortho alkyd and E2 with E3 for an iso alkyd.

The plots of permeability coefficients of modified alkyds and phenolics as a function of temperature in Figure 15 show that the modifications affect the temperature dependence of the permeability coefficients (Table 15).

Effect of Composition on Permeation of Water Vapour

From the results previously presented it can be seen that, in general, the higher the oil content in either phenolic varnishes or alkyds, the greater the permeability and the more permeation rates and coefficients are affected by temperature and relative humidity.

In phenolic varnishes the rate of permeation decreases with increasing resin content with all four oils studied. Also the changes in permeation and permeability coefficient with both increasing R.H. and temperature are smaller with varnishes containing less oil (Figures 1, 7, 10 and 13). It is also evident that tung oil varnishes are less permeable to water vapour than linseed followed by dehydrated castor and soya. Again, the effect of R.H. and temperature on permeation rate and permeability coefficient is in the same order.

Alkyds are more permeable to water vapour than phenolics. To obtain the same permeation rate at 73 °F as the 20-gal soya varnish which contains 67 per cent oil it is necessary to use a soya alkyd with an oil content less than 60 per cent. Within the alkyd group there is the same relationship between oil content and permeability although NRP 914 appears to be out of line. There are not sufficient resins containing the same amount but different types of oil to reach firm conclusions about the effect of oil type. It appears, however, that as with the phenolics, linseed alkyds are less permeable than soya or safflower alkyds. Isophthalic alkyds are less permeable than orthophthalic resins of comparable oil length. For example, E6 with 67 per cent soya transmits 1.3 g/m²/hr/mil while 913 with 62.5 per cent oil transmits 1.4 g at 73 °F.

The effect of modification with cardanol or CNSL hexamine condensate is to reduce the permeation rate at a given set of conditions and the effect of R.H. and temperature on permeation and permeability coefficients. The latter can be seen in Table 16 where some of the changes in rate and coefficient are summarized. It is also evident that CNSL causes a greater change in permeability characteristics than cardanol.

DISCUSSION

The water molecule is relatively small and has a tendency to form hydrogen bonds with other water molecules in either the liquid or solid state as well as with polar groups present in the material of contact. Hence water vapour sorbed in a coating forms hydrogen bonds with hydrophilic or polar groups of the polymer and permeation is followed by the spatial movement of the vapour from high to low pressure levels. Apart from the heat of solution the sorbed vapour needs energy for moving from one position to the other. This energy is principally supplied by the thermal motion of the polymer molecules. Structural configuration and inter-molecular forces contribute to a polymer's total free energy which consequently is of a different magnitude for each polymer. Since a change in temperature generates different thermal motions in different polymers a vapour with a definite amount of free energy faces different degrees of resistance in permeating through them.

This difference in energy requirement for the permeation of vapour is related to the degree of cross-linking in the polymer as well as to the size of the penetrating molecule. In a highly cross-linked product the randomness due to the movement of segmental chains and formation of spacings is restricted. In such a system the movement of the penetrant is impeded and the rate of diffusion and consequently the permeation is dependent upon the degree of cross-linking.⁽¹⁶⁾ The energy of activation required for the permeation of vapour through a coating can be correlated with the degree of cross-linking.

The results reported here on the permeation of water vapour through coatings based on semi-drying and drying oils support the qualitative relationship between permeation and the degree of cross-linking in coatings. Resin in the composition not only forms cross-links with the oil but also physically reinforces the coating. This is illustrated in the differences between phenolics and alkyd coatings. Phenolics have a more highly condensed structure which is reflected in the lower permeability and higher tensile strength of varnishes made with them.

Conversely the oil portion of coatings has a much more open structure resulting in relatively low resistance to water transmission and low tensile properties. Tung oil, because of its high degree of conjugated unsaturation forms more cross-links with resins and with itself than do the other oils. Consequently, tung-based varnishes are not only less permeable to water but also stronger mechanically than varnishes made with other oils.

CONCLUSIONS

Permeation rates and permeability coefficients of coatings for water vapour reported here differ greatly from each other in magnitude. This feature of the permeability properties of coatings can be explained on

the basis of the general characteristics of the materials used in the formulation and also their structural arrangement. Poor symmetrical or unsymmetrical molecules interfere with molecular packing within a material. Consequently, the molecular structure develops openings with sufficient spacings so that permeating molecules can diffuse through them easily which results in high permeability. This is the reason that amorphous polymeric coatings generally have higher permeation rates than crystalline ones.

The low permeation rates and permeability coefficients that are less affected by R.H. and temperature indicate that phenolics have better symmetry and a relatively high degree of cross-linking. The decrease in permeability coefficients of the modified formulations is also due to molecular changes. The study of the R.H. and temperature dependence of permeability coefficients of coating materials for water vapour can be used as an index of the degree of cross-linking in their molecular structures when they are prepared from known components.

The cup method used for the determination of permeation of water vapour through coatings can produce useful results when necessary precautions are taken in the course of preparing the test cups and also while conducting the determinations.

The determination of the energy of activation for permeation of water vapour through these coatings, the effect of natural weathering on permeation rates and also the changes which may take place in permeation rates when the coating is exposed to a variety of experimental conditions for a longer period, will be described in later publications.

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TABLE 1

COMPOSITION OF PARAPHENYLPHENOLIC VARNISHES

NRP Formula No.	Oil Content			% Volatile Content		Solution Characteristics	
	Type	Approx. length*	Per cent of Solids	Aromatic Solvents	Mineral Spirits	Per cent Solids	G - H Viscosity
1020	Tung	15	58.3	85.3	14.7	51	A - B
893	Tung	20	66.7	33.3	66.7	50	C
8894	Tung	30	75	10.0	90.0	50	D
901	Tung	40	80	-	100.0	50	B - C
1021	Linseed	15	58.3	49.4	50.6	49.5	D
902	Linseed	20	66.7	30.6	69.4	51	B - C
903	Linseed	30	75	20.2	79.8	49.5	D
905	Linseed	40	80	10	90	50	C - D
1022	Soya	20	66.7	28.6	71.4	50	B
1023	Soya	40	80	34.7	65.3	50	C - D
1024	Dehydrated Castor	20	66.7	33.3	66.7	50	C
1025	Dehydrated Castor	40	80	2.6	97.4	49	E

* Imp. Gal. per 100 lb. Resin

TABLE 2
COMPOSITION OF ALKYDS

NRP Formula No.	Oil Content		% Phthalic Content		Solution Characteristics	
	Type	Per cent of Solids	Isomer	Per cent of Solids	Per cent Solids	G - H Viscosity
912	Soya	59.4*	Ortho	25	50	A - B
913	Soya	62.5*	Ortho	24	50	A - B
914	Soya	56 *	Ortho	30	50	D - F
915	Soya	48 *	Ortho	35	42	E
916	Soya	39.6	Ortho	39	40	G - H
1055**	Linseed	54	Ortho	35	50	A - B
1056**	Soya	56.5	Ortho	31	50	A - B
E1	Safflower	70	Ortho	17	60	A ₁
E2	Safflower	83	Iso	9	60	A ₁
E3	Linseed-Soya	85	Iso	13	60	A ₁
E4	Soya	75	Iso	18	50	C - D
E5	Soya	72	Iso	20	50	C - D
E6	Soya	67	Iso	28	50	C - D

* Per oil content of alkyds marked with * calculated from reported fatty acid content. Other commercial alkyds are reported as oil content.

** Alkyds prepared in the laboratory.

TABLE 3

COMPOSITION OF MODIFIED PHENOLICS AND ALKYDS

NRP Formula No.	Content of Varnish, Oil or Alkyd		Content of Hexamine Condensate		Solution Characteristics	
	Type	Per cent of Solids	Type	Per cent of Solids	Per cent Solids	G - H Viscosity
1057	20-gal DH Castor	60.0	Cardanol	40.0	50	B
1058	20-gal DH Castor	60.0	CNSL	40.0	50	B
1059	20-gal Soya	60.0	Cardanol	40.0	50	A - B
1060	20-gal Soya	60.0	CNSL	40.0	50	A - B
1061	40-gal DH Castor	50.0	Cardanol	50.0	50	C - D
1062	40-gal Soya	50.0	Cardanol	50.0	50	B - C
1063	DH Castor Oil	66.7	Cardanol	33.3	50	A - B
1064	Soya Oil	66.7	Cardanol	33.3	50	A - B
1065	Alkyd No. E6	58.8	CNSL	41.2	50	B - C
1066	Alkyd No. E2	58.8	Cardanol	41.2	50	A
1067	Alkyd No. 913	58.8	CNSL	41.2	50	A - B
1068	Alkyd No. 916	58.8	Cardanol	41.2	50	D

TABLE 4
 EFFECT OF RELATIVE HUMIDITY ON RATE OF PERMEATION THROUGH PHENOLIC VARNISH FILMS
 AT 73°F

		Rate of Permeation of Water Vapor - $\text{g/m}^2/\text{h}/\text{mil}$ (25 μm)*														
Per cent R.H.	15-gal. Varnishes				20-gal. Varnishes				30-gal. Varnishes				40-gal. Varnishes			
	1020 Tung	1021 Linseed	893 Tung	902 Linseed	1022 Soya	1024 DH Castor	894 Tung	903 Linseed	901 Tung	905 Linseed	1023 Soya	1025 DH Castor				
50.0	0.54	0.58	0.67	0.75	1.11	0.92	0.80	0.79	1.12	1.21	1.46	1.20				
57.5	0.62	0.67	0.78	0.86	1.27	1.07	0.92	0.92	1.31	1.39	1.69	1.39				
70.0	0.76	0.82	0.94	1.06	1.57	1.30	1.12	1.13	1.59	1.71	2.06	1.70				
80.0	0.92	0.98	1.07	1.21	1.86	1.50	1.35	1.38	1.85	2.02	2.41	2.05				
87.0	1.02	1.08	1.20	1.33	2.09	1.67	1.55	1.57	2.10	2.28	2.65	2.37				
97.0	1.17	1.27	1.39	1.60	2.37	1.93	1.79	1.83	2.38	2.61	3.05	2.73				

* Thickness of Film.

TABLE 5

EFFECT OF RELATIVE HUMIDITY ON RATE OF PERMEATION THROUGH ALKYD FILMS AT 73°F

Per cent R.H.	Rate of Permeation of Water Vapor - g/m ² /h/mil (25 μm)*												
	Ortho-phthalic Alkyds - Commercial						Iso-phthalic Alkyds - Commercial					Lab Prepd. Alkyds	
	912 Soya	913 Soya	914 Soya	915 Soya	916 Soya	E1 Saf-flower	E2 Saf-flower	E3 Lin-seed Soya	E4 Soya	E5 Soya	E6 Soya	1055 Lin-seed	1056 Soya
50	0.99	1.42	1.03	0.86	0.73	1.46	2.05	1.82	1.87	1.55	1.30	0.52	1.07
65	1.38	2.00	1.41	1.19	1.01	2.04	2.94	2.49	2.52	2.12	1.76	0.73	1.46
80	2.00	3.11	2.17	1.85	1.57	3.19	4.21	3.72	3.75	3.20	2.40	1.17	2.19
90	2.47	3.67	2.54	2.21	1.85	3.81	5.05	4.33	4.36	3.72	2.88	1.40	2.59
97	2.86	4.26	2.97	2.55	2.13	4.43	5.74	4.91	4.96	4.17	3.31	1.66	2.98

* Thickness of Film

TABLE 6

EFFECT OF RELATIVE HUMIDITY ON RATE OF PERMEATION THROUGH MODIFIED PHENOLIC, OIL
AND ALKYD FILMS AT 73°F

Per cent R.H.	Rate of Permeation of Water Vapor - g/m ² /h/mil (25 μm)*											
	Modified 20-gal. Phenolics				Modified 40-gal. Phenolics		Modified Oil		Modified iso-phthalic Alkyds		Modified o-phthalic Alkyds	
	1057 Card.** DH Castor	1058 CNSL*** DH Castor	1059 Card. Soya	1060 CNSL Soya	1061 Card. DH Castor	1062 Card. Soya	1063 Card. DH Castor	1064 Card. Soya	1065 CNSL Long Soya	1066 Card. Very Long Saf- flower	1067 CNSL Long Soya	1068 Card. Short Soya
50	0.76	0.61	0.86	0.69	0.80	0.95	0.93	1.51	0.96	1.51	1.02	0.85
64	0.98	0.78	1.11	0.89	1.03	1.22	1.20	1.98	1.25	1.96	1.43	1.10
80	1.25	1.01	1.48	1.16	1.40	1.63	1.55	2.61	1.69	2.62	1.98	1.46
90	1.45	1.16	1.68	1.31	1.60	1.84	1.80	3.02	1.94	3.04	2.32	1.71
97	1.61	1.29	1.87	1.47	1.77	2.06	2.01	3.38	2.19	3.42	2.62	1.93

* Thickness of Film

** Card. = Cardanol

*** CNSL = Cashew Nut Shell Liquid

TABLE 7

EFFECT OF TEMPERATURE ON RATE OF PERMEATION THROUGH PHENOLIC
VARNISH FILMS AT 50% R.H.

Temperature °F	Rate of Permeation of Water Vapor - g/m ² /h/mil (25 μm)*											
	15-gal. Varnishes		20-gal. Varnishes				30-gal. Varnishes		40-gal. Varnishes			
	1020 Tung	1021 Lin- seed	893 Tung	902 Lin- seed	1022 Soya	1024 DH Castor	894 Tung	903 Lin- seed	901 Tung	905 Lin- seed	1023 Soya	1025 DH Castor
63.0	-	-	0.41	0.41	0.61	0.50	-	-	0.61	0.68	-	-
73.0	0.54	0.58	0.67	0.75	1.11	0.92	0.80	0.79	1.12	1.21	1.46	1.20
84.0	0.88	0.84	1.01	1.15	1.91	1.46	1.39	1.38	1.76	1.92	2.28	2.10
94.6	1.41	1.36	1.59	1.89	3.04	2.33	2.28	2.14	2.83	3.04	3.84	3.52
103.6	2.26	2.28	2.38	2.91	4.64	3.56	3.35	3.41	4.36	4.80	6.27	5.46

* Thickness of Film

TABLE 8

EFFECT OF TEMPERATURE ON RATE OF PERMEATION THROUGH ALKYD FILMS AT 50% R.H.

Temperature °F	Rate of Permeation of Water Vapor - g/m ² /h/mil (25 μm)*												
	ortho-phthalic alkyds - commercial						iso-phthalic alkyds - commercial					Lab. Prepd. Alkyds	
	912 Soya	913 Soya	914 Soya	915 Soya	916 Soya	E1 Saf- flower	E2 Saf- flower	E3 Lin- seed Soya	E4 Soya	E5 Soya	E6 Soya	1055 Lin- seed	1056 Soya
73	0.99	1.42	1.03	0.86	0.73	1.46	2.05	1.82	1.87	1.55	1.30	0.52	1.07
83	1.64	2.39	1.68	1.45	1.24	2.41	3.22	2.93	2.98	2.51	2.12	0.86	1.71
92	2.47	3.63	2.64	2.41	2.09	3.65	5.22	4.32	4.38	3.71	3.15	1.33	2.62
102	4.32	6.46	4.35	3.79	3.44	6.29	-	-	7.39	6.27	5.44	2.41	4.51

* Thickness of Film

TABLE 9

EFFECT OF TEMPERATURE ON RATE OF PERMEATION THROUGH MODIFIED PHENOLIC, OIL
AND ALKYD FILMS AT 50% R.H.

Tem- pera- ture °F	Rate of Permeation of Water Vapor - g/m ² /h/mil (25 μm)*											
	Modified 20-gal. Phenolics				Modified 40-gal. Phenolics		Modified Oil		Modified iso-phthalic Alkyds		Modified o-phthalic Alkyds	
	1057 Card.** DH Castor	1058 CNSL*** DH Castor	1059 Card. Soya	1060 CNSL Soya	1061 Card. DH Castor	1062 Card. Soya	1063 Card. DH Castor	1064 Card. Soya	1065 CNSL Long Soya	1066 Card. Very Long Saf- flower	1067 CNSL Long Soya	1068 Card. Short Soya
73.0	0.76	0.61	0.86	0.69	0.80	0.95	1.13	1.51	0.96	1.54	1.02	0.85
83.0	1.31	1.06	1.50	1.20	1.46	1.67	2.23	2.44	1.65	2.71	1.76	1.54
93.0	1.93	1.55	2.22	1.83	2.19	2.49	4.11	3.84	2.40	4.03	2.78	2.23
103.0	2.95	2.45	3.36	2.81	3.25	3.76	6.91	6.14	3.51	6.03	4.24	3.43

* Thickness of Film

** Card. = Cardanol

*** CNSL = Cashew Nut Shell Liquid

TABLE 10

EFFECT OF RELATIVE HUMIDITY ON PERMEABILITY COEFFICIENTS OF PHENOLIC VARNISHES AT 73°F

Per cent R.H.	Permeability Coefficient to Water Vapor - $P \times 10^{12}$ g/cm/sec/mm Hg*											
	15-gal. Varnishes		20-gal. Varnishes				30-gal. Varnishes		40-gal. Varnishes			
	1020 Tung	1021 Lin- seed	893 Tung	902 Lin- seed	1022 Soya	1024 DH Castor	894 Tung	903 Lin- seed	901 Tung	905 Lin- seed	1023 Soya	1025 DH Castor
50.0	3.66	3.92	4.53	5.07	7.48	6.23	5.40	5.35	7.60	8.16	9.91	8.15
57.5	3.67	3.96	4.61	5.08	7.49	6.31	5.42	5.41	7.69	8.18	9.97	8.20
70.0	3.68	3.98	4.53	5.11	7.62	6.27	5.43	5.45	7.70	8.26	9.98	8.23
80.0	3.90	4.16	4.52	5.14	7.86	6.37	5.74	5.86	7.84	8.56	10.20	8.67
87.0	3.97	4.22	4.65	5.17	8.16	6.52	6.05	6.13	8.20	8.90	10.31	8.93
97.0	4.08	4.42	4.84	5.58	8.30	6.75	6.26	6.41	8.30	9.11	10.65	9.52

* Vapor Pressure

TABLE 11

EFFECT OF RELATIVE HUMIDITY ON PERMEABILITY COEFFICIENTS OF ALKYDS AT 73°F

Per cent R.H.	Permeability Coefficient to Water Vapor - $P \times 10^{12}$ g/cm/sec/mm Hg*													
	ortho-phthalic alkyds - commercial						iso-phthalic alkyds - commercial						Lab Prepd. Alkyds	
	912 Soya	913 Soya	914 Soya	915 Soya	916 Soya	E1 Saf-flower	E2 Saf-flower	E3 Lin-seed Soya	E4 Soya	E5 Soya	E6 Soya	1055 Lin-seed	1056 Soya	
50	6.71	9.60	6.96	5.80	4.91	9.88	13.93	12.36	12.64	10.49	8.54	3.52	7.23	
65	7.13	10.41	7.36	6.22	5.28	10.64	15.35	12.99	13.14	11.07	9.19	3.80	7.60	
80	8.48	13.17	9.20	7.82	6.66	13.53	17.84	15.75	15.91	13.55	10.16	4.97	9.29	
90	9.32	13.82	9.58	8.31	6.95	14.34	19.02	16.30	16.42	14.00	10.86	5.27	9.75	
97	10.01	14.90	10.36	8.93	7.43	15.46	20.06	17.17	17.33	14.56	11.57	5.80	10.40	

* Vapor Pressure.

TABLE 12

EFFECT OF RELATIVE HUMIDITY ON PERMEABILITY COEFFICIENTS OF MODIFIED PHENOLICS, OILS AND ALKYDS AT 73°F

Per cent R.H.		Permeability Coefficient to Water Vapor - $P \times 10^{12}$ g/cm/sec/mm Hg*										
		Modified 20-gal. Phenolics			Modified 40-gal. Phenolics		Modified Oils		Modified iso-phthalic Alkyds		Modified o-phthalic Alkyds	
50	1057 Card. ** DH Castor	1058 CNSL*** DH Castor	1059 Card. Soya	1060 CNSL Soya	1061 Card. DH Castor	1062 Card. Soya	1063 Card. DH Castor	1064 Card. Soya	1065 CNSL Long Soya	1066 Card. Very Long Saf- flower	1067 CNSL Long Soya	1068 Card. Short Soya
64	5.18	4.12	5.88	4.71	5.43	6.45	6.32	10.21	6.48	10.26	6.90	5.78
80	5.19	4.13	5.88	4.71	5.47	6.48	6.34	10.48	6.60	10.39	7.58	5.82
90	5.28	4.29	6.25	4.92	5.91	6.90	6.57	11.07	7.15	11.09	8.37	6.17
97	5.44	4.35	6.33	4.95	6.04	6.95	6.77	11.37	7.31	11.43	8.73	6.46
	5.63	4.52	6.52	5.14	6.19	7.18	7.01	11.80	7.64	11.96	9.17	6.73

* Vapor Pressure
 ** Card. - Cardanol
 *** CNSL = Cashew Nut Shell Liquid

TABLE 13

EFFECT OF TEMPERATURE ON PERMEABILITY COEFFICIENTS OF PHENOLIC VARNISHES AT 50% R.H.

Temperature °F	Permeability Coefficient to Water Vapor - $P \times 10^{12}$ g/cm/sec/mm Hg*											
	15-gal. Varnishes		20-gal. Varnishes				30-gal. Varnishes		40-gal. Varnishes			
	1020 Tung	1021 Lin- seed	893 Tung	902 Lin- seed	1022 Soya	1024 DH Castor	894 Tung	903 Lin- seed	901 Tung	905 Lin- seed	1023 Soya	1025 DH Castor
63.0	-	-	3.88	3.93	5.88	4.80	-	-	5.81	6.54	-	-
73.0	3.66	3.82	4.53	5.07	7.48	6.23	5.40	5.35	7.60	8.16	9.91	8.15
84.0	4.16	3.97	4.75	5.45	9.01	6.88	6.54	6.52	8.29	9.08	10.78	9.90
94.6	4.77	4.69	5.39	6.39	10.29	7.87	7.72	7.32	9.59	11.73	12.99	11.91
103.6	5.82	5.88	6.14	7.50	11.95	9.17	8.63	8.78	11.25	12.39	16.15	14.09

* Vapor Pressure

TABLE 14

EFFECT OF TEMPERATURE ON PERMEABILITY COEFFICIENTS OF ALKYDS AT 50% R.H.

Temperature °F	Permeability Coefficient to Water Vapor - $P \times 10^{12}$ g/cm/sec/mm Hg*												
	ortho-phthalic alkyds - commercial						iso-phthalic alkyds - commercial					Lab Prepd. Alkyds	
	912 Soya	913 Soya	914 Soya	915 Soya	916 Soya	E1 Saf- flower	E2 Saf- flower	E3 Lin- seed Soya	E4 Soya	E5 Soya	E6 Soya	1055 Lin- seed	1056 Soya
73	6.71	9.64	6.96	5.80	4.91	9.88	13.93	12.36	12.64	10.49	8.54	3.52	7.23
83	8.03	11.67	8.21	7.09	6.05	11.81	15.76	14.35	14.55	12.29	10.36	4.21	8.38
92	9.10	13.33	9.70	8.86	7.70	13.41	19.19	15.90	16.11	13.65	11.59	4.90	9.64
102	11.69	17.48	11.76	10.25	9.31	17.01	-	-	19.99	16.96	14.70	6.52	12.21

* Vapor Pressure

TABLE 15

EFFECT OF TEMPERATURE ON PERMEABILITY COEFFICIENTS OF MODIFIED PHENOLICS, OILS
AND ALKYDS AT 73°F

Tem- pera- ture °F	Permeability Coefficient to Water Vapor - $P \times 10^{12}$ g/cm/sec/mm Hg*										
	Modified 20-gal. Phenolics			Modified 40-gal. Phenolics		Modified Oils		Modified iso-phthalic Alkyds		Modified o-phthalic Alkyds	
	1057 Card.** DH Castor	1058 CNSL*** DH Castor	1059 Card. Soya	1061 Card. DH Castor	1062 Card. Soya	1063 Card. DH Castor	1064 Card. Soya	1065 CNSL Long Soya	1066 Card. Very Long Saf- flower	1067 CNSL Long Soya	1068 Card. Short Soya
73.0	5.18	4.12	5.88	5.43	6.45	7.69	10.21	6.48	10.26	6.90	5.78
83.0	6.41	5.17	7.36	7.16	8.18	10.90	11.92	8.09	13.24	8.58	7.53
93.0	6.88	5.50	7.90	7.80	8.84	14.60	13.67	8.53	14.35	9.89	7.91
103.0	7.76	6.45	8.84	8.57	9.90	18.20	16.18	9.25	15.89	11.15	9.03

* Vapor Pressure
** Card. = Cardanol
*** CNSL = Cashew Nut Shell Liquid

TABLE 16

EFFECT OF R.H. ON PERMEATION RATE AND OF TEMPERATURE ON PERMEABILITY
 COEFFICIENT OF UNMODIFIED AND MODIFIED CLEAR FINISHES

Permeation Rate	R.H. Differ.	Phenolic Varnishes - 20 gal.					
		Dehydrated Castor			Soya		
	47%	Unmod.	Cardanol	CNSL	Unmod.	Cardanol	CNSL
		1.44	0.85	0.69	1.22	1.00	0.78
	47%	Phenolic Varnishes - 40 gal.					
		1.52	0.84	-	1.585	0.55	-
	47%	Alkyd Resins					
		Orthophthalic			Isophthalic		
		Short Soya		Long Soya		Long Soya	
		Unmod.	Cardanol	Unmod.	CNSL	Unmod.	CNSL
1.40		1.07	2.84	1.61	2.05	1.23	
Permeability Coefficient		Temp. Differ. °F	Phenolic Varnishes - 20 gal.				
	Dehydrated Castor			Soya			
	30.6	Unmod.	Cardanol	CNSL	Unmod.	Cardanol	CNSL
		2.93	2.58	2.33	4.47	2.97	2.70
	30.6	Phenolic Varnishes - 40 gal.					
		5.935	3.135	-	7.24	3.45	-
	30.0	Alkyd Resins					
		Orthophthalic			Isophthalic		
		Short Soya		Long Soya		Long Soya	
		Unmod.	Cardanol	Unmod.	CNSL	Unmod.	CNSL
4.39		3.25	7.84	4.25	6.16	2.77	

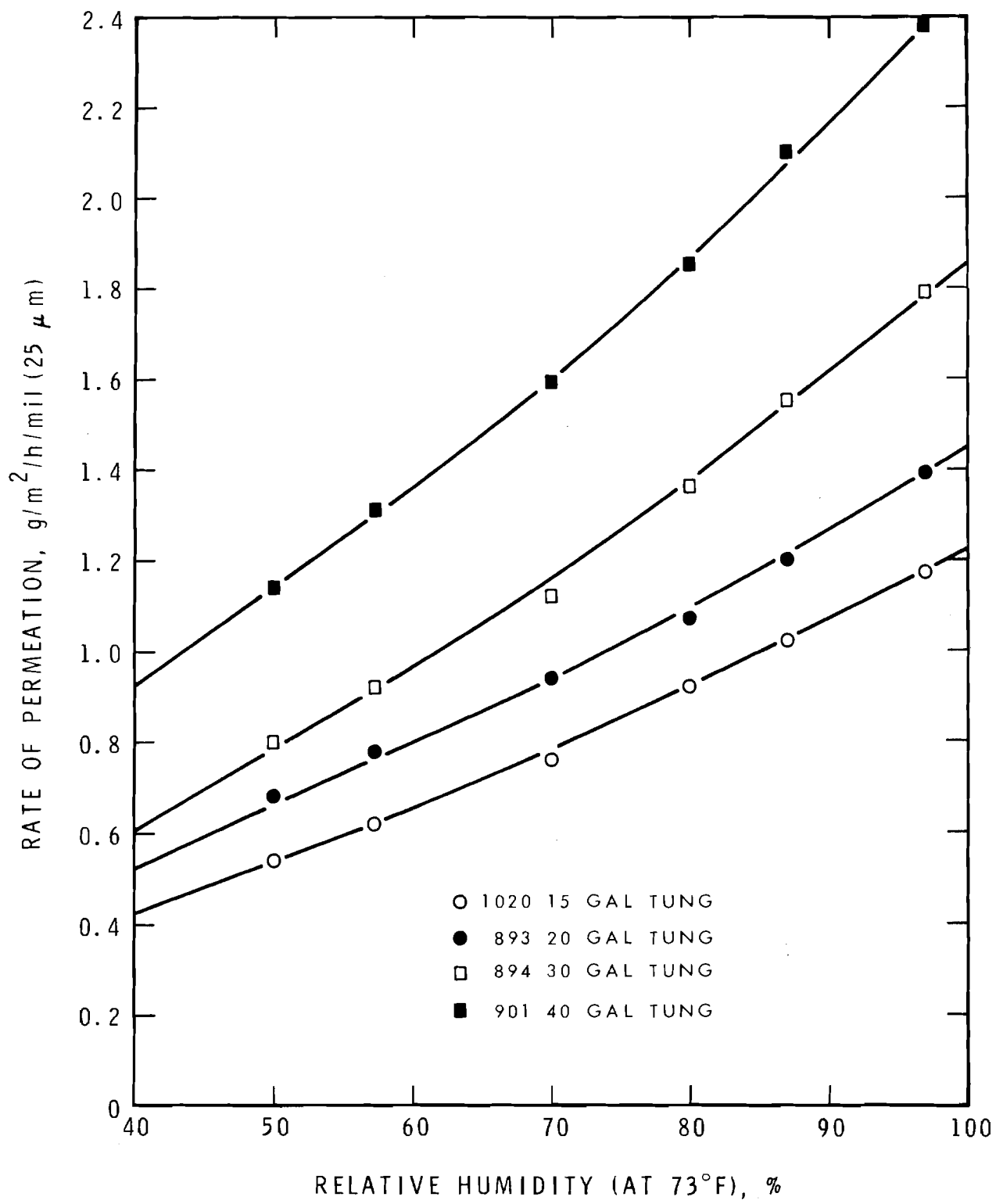


FIGURE 1

RATE OF WATER VAPOR PERMEATION THROUGH PHENOLICS WITH DIFFERENT OIL CONTENTS

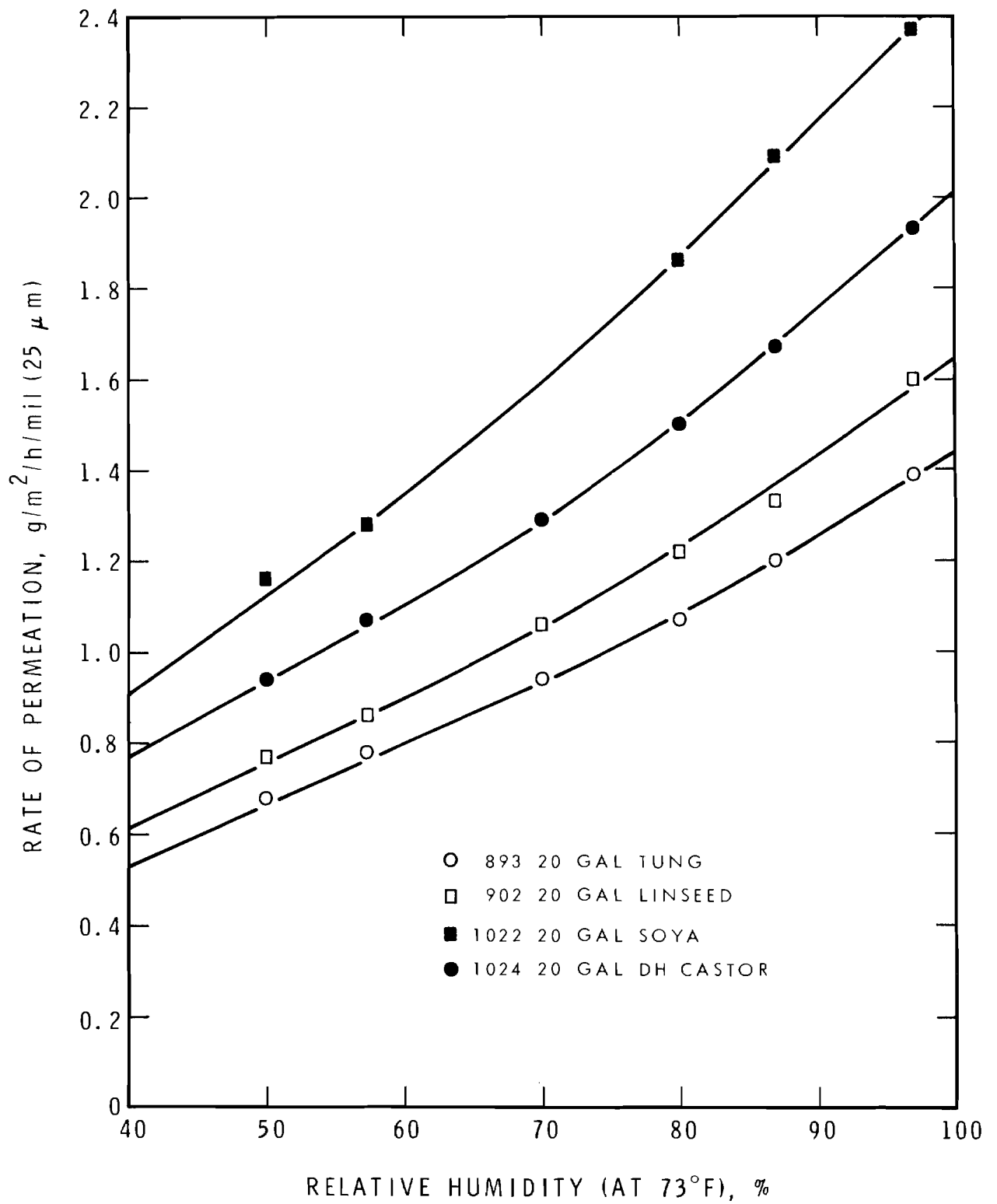


FIGURE 2

RATE OF WATER VAPOR PERMEATION THROUGH PHENOLICS WITH DIFFERENT OIL TYPES

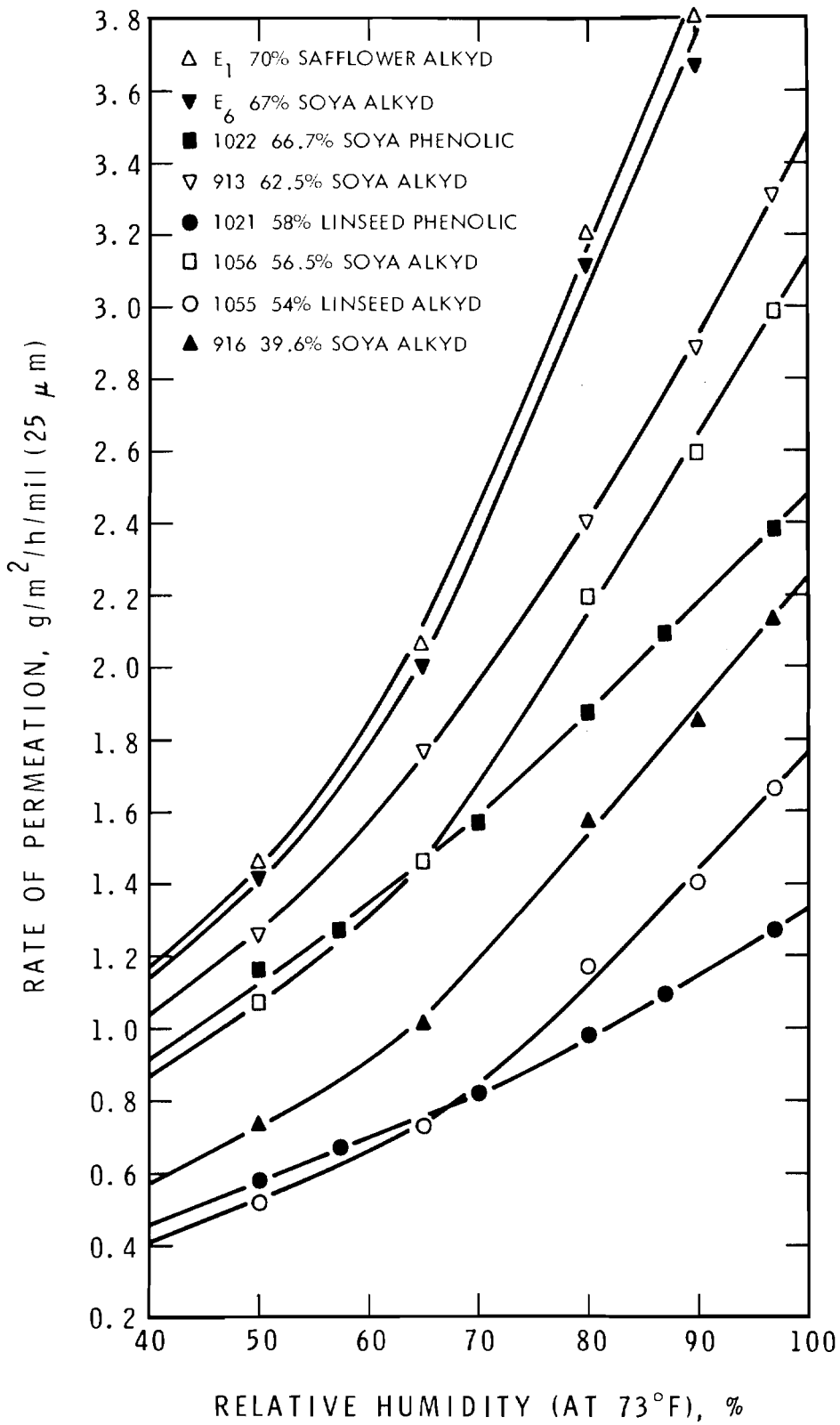


FIGURE 3
 RATE OF WATER VAPOR PERMEATION
 THROUGH ALKYDS

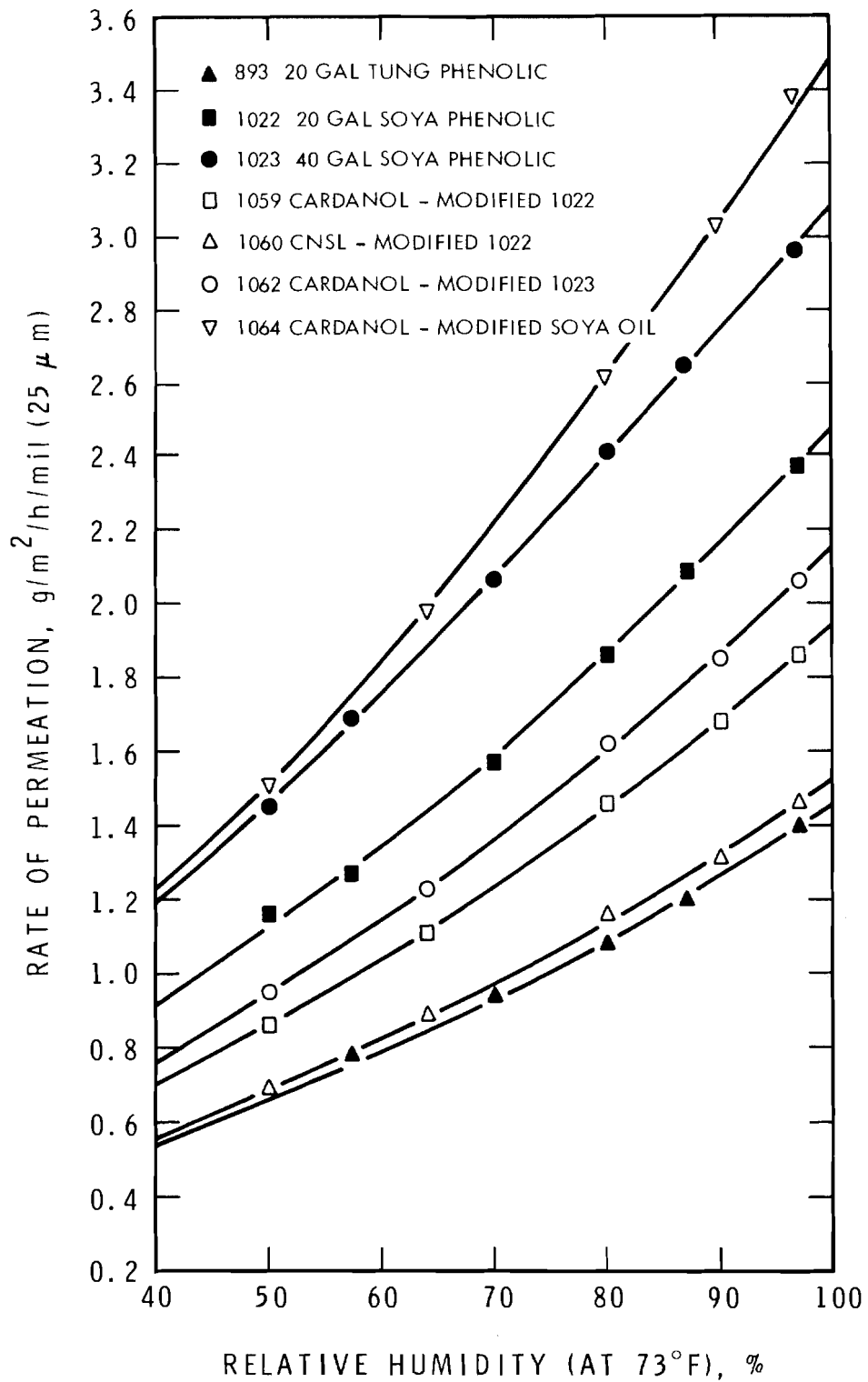


FIGURE 4

RATE OF WATER VAPOR PERMEATION
THROUGH MODIFIED SOYA-PHENOLICS

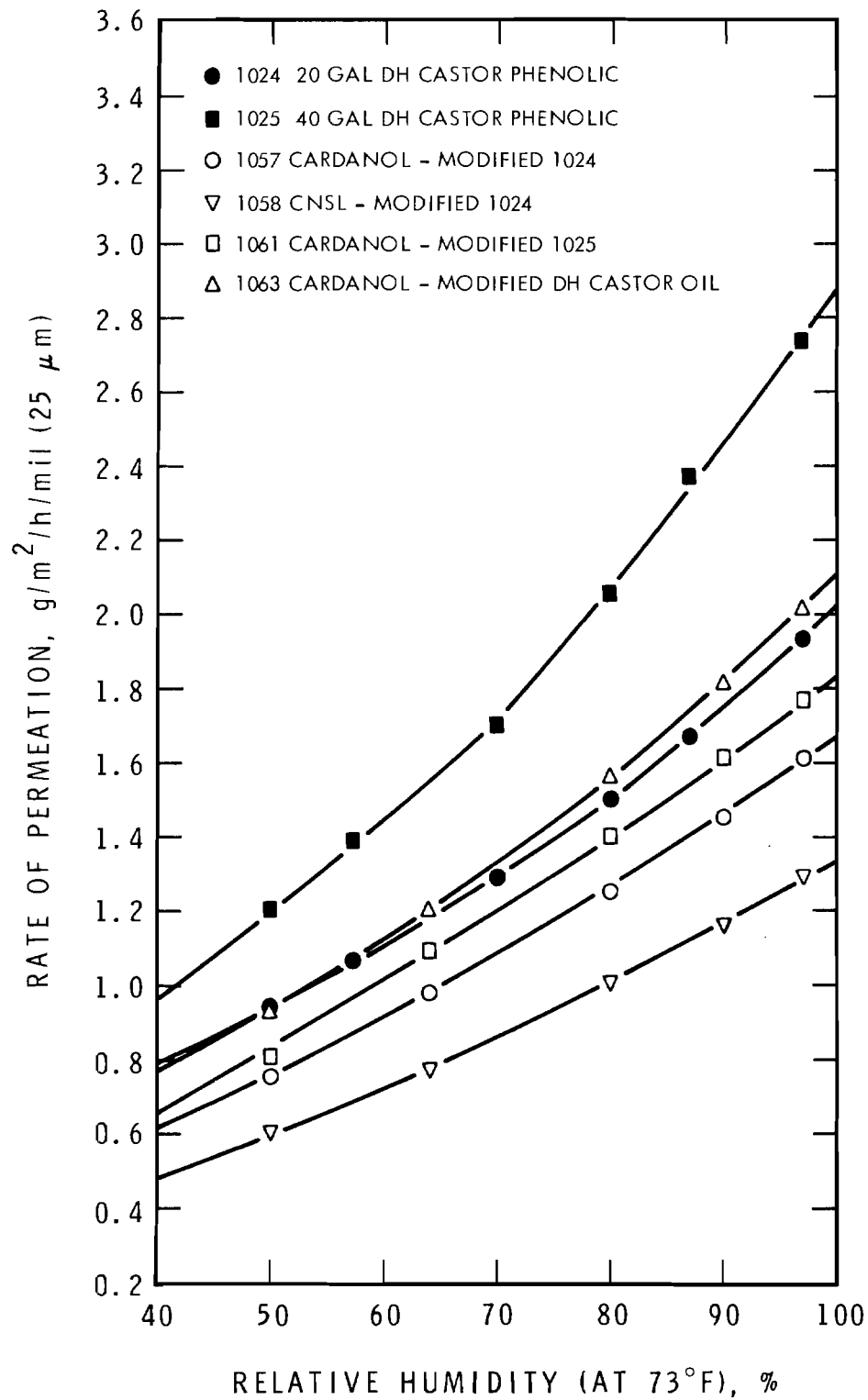


FIGURE 5
 RATE OF WATER VAPOR PERMEATION THROUGH
 MODIFIED DH CASTOR PHENOLICS

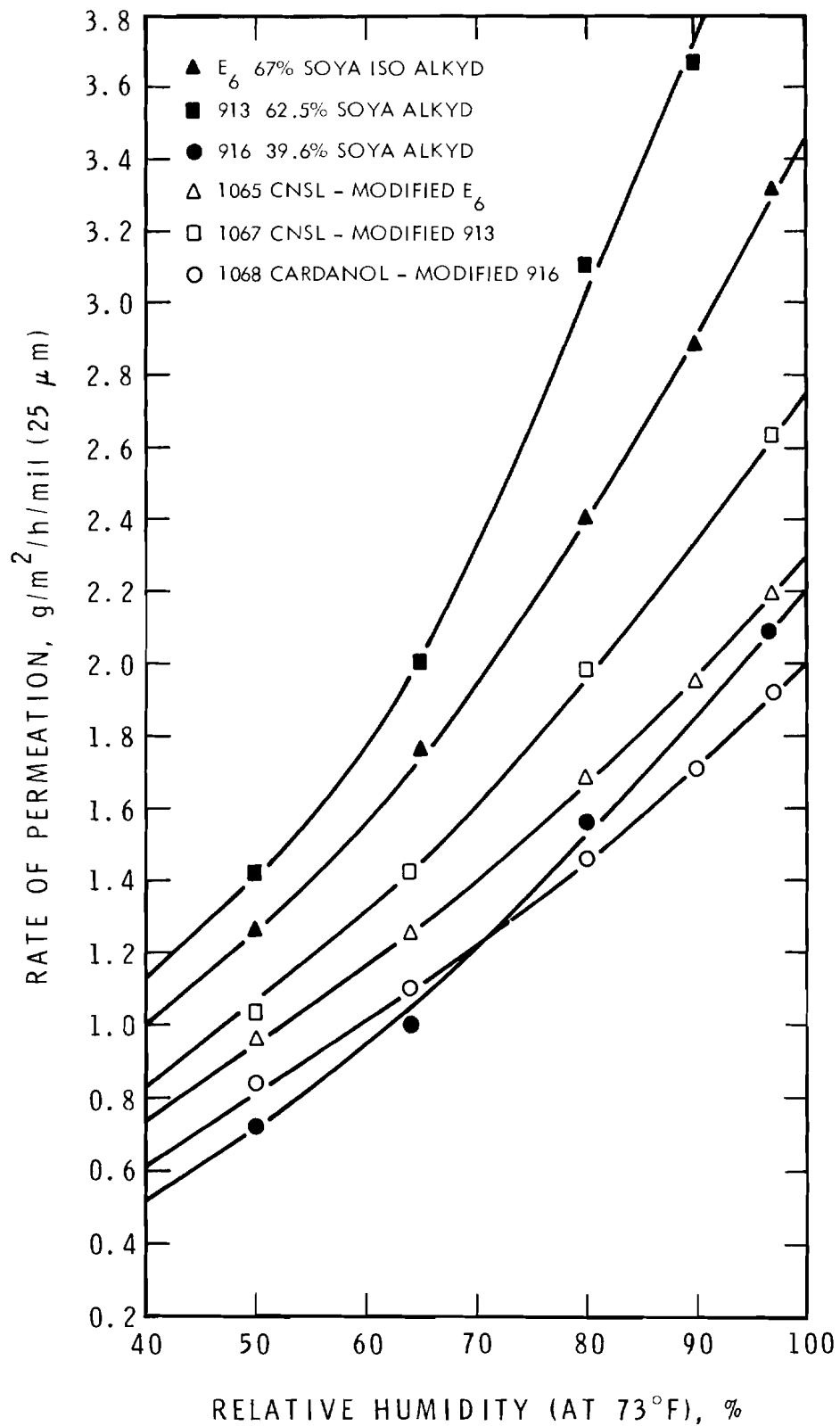


FIGURE 6

RATE OF WATER VAPOR PERMEATION
THROUGH MODIFIED ALKYDS

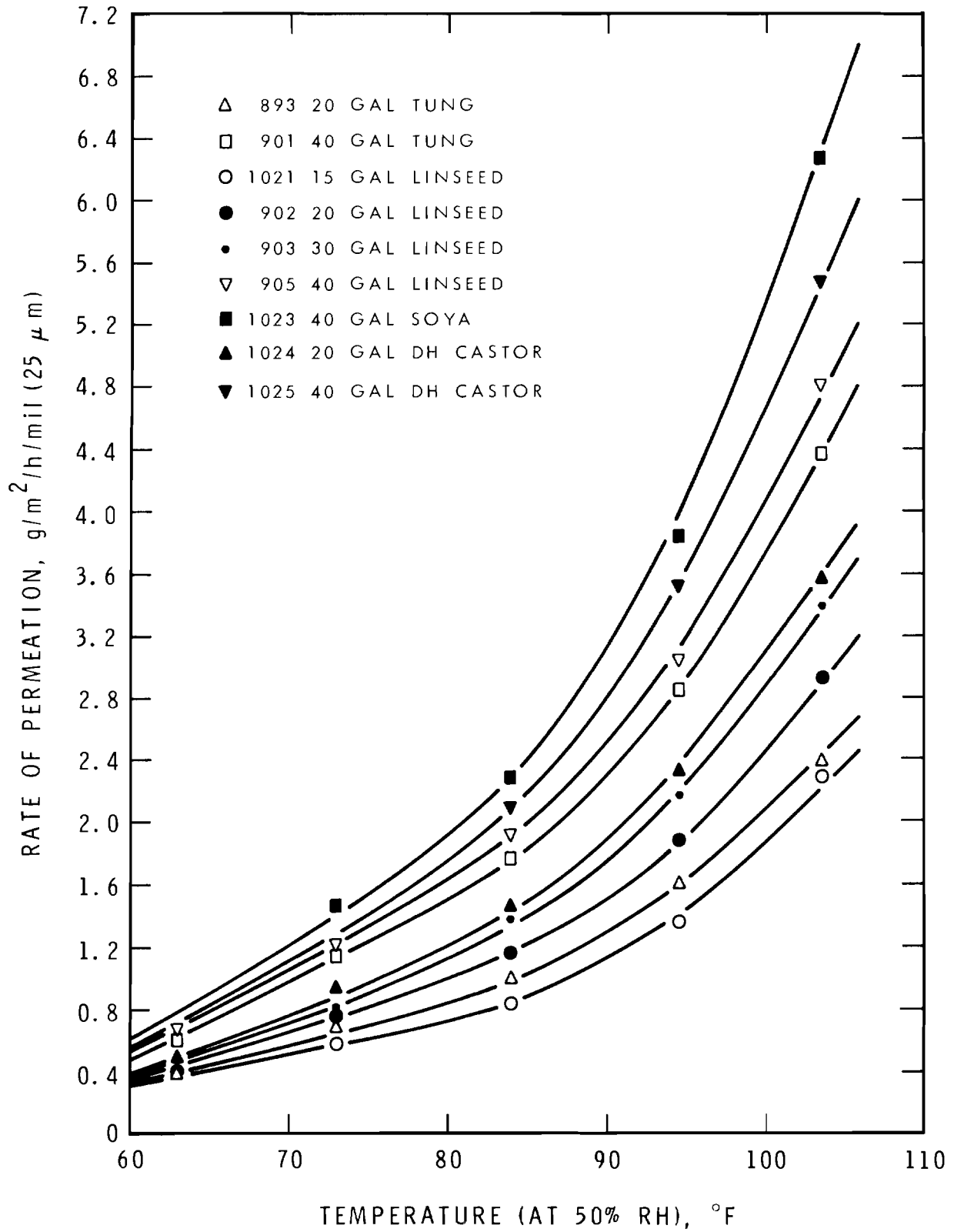


FIGURE 7

EFFECT OF TEMPERATURE ON RATE OF WATER VAPOR PERMEATION THROUGH PHENOLIC VARNISHES

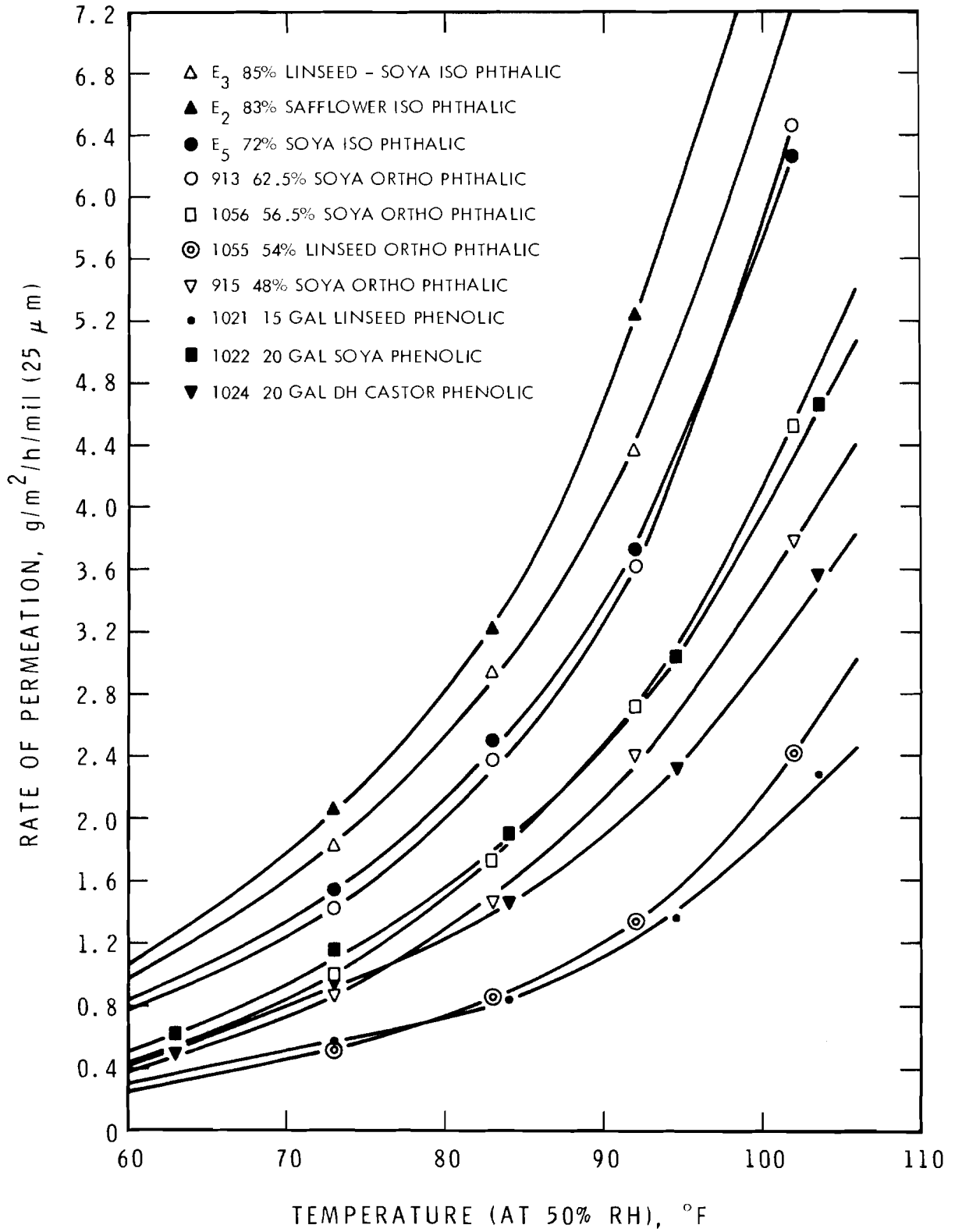


FIGURE 8
 EFFECT OF TEMPERATURE ON RATE OF WATER VAPOR
 PERMEATION THROUGH ALKYDS

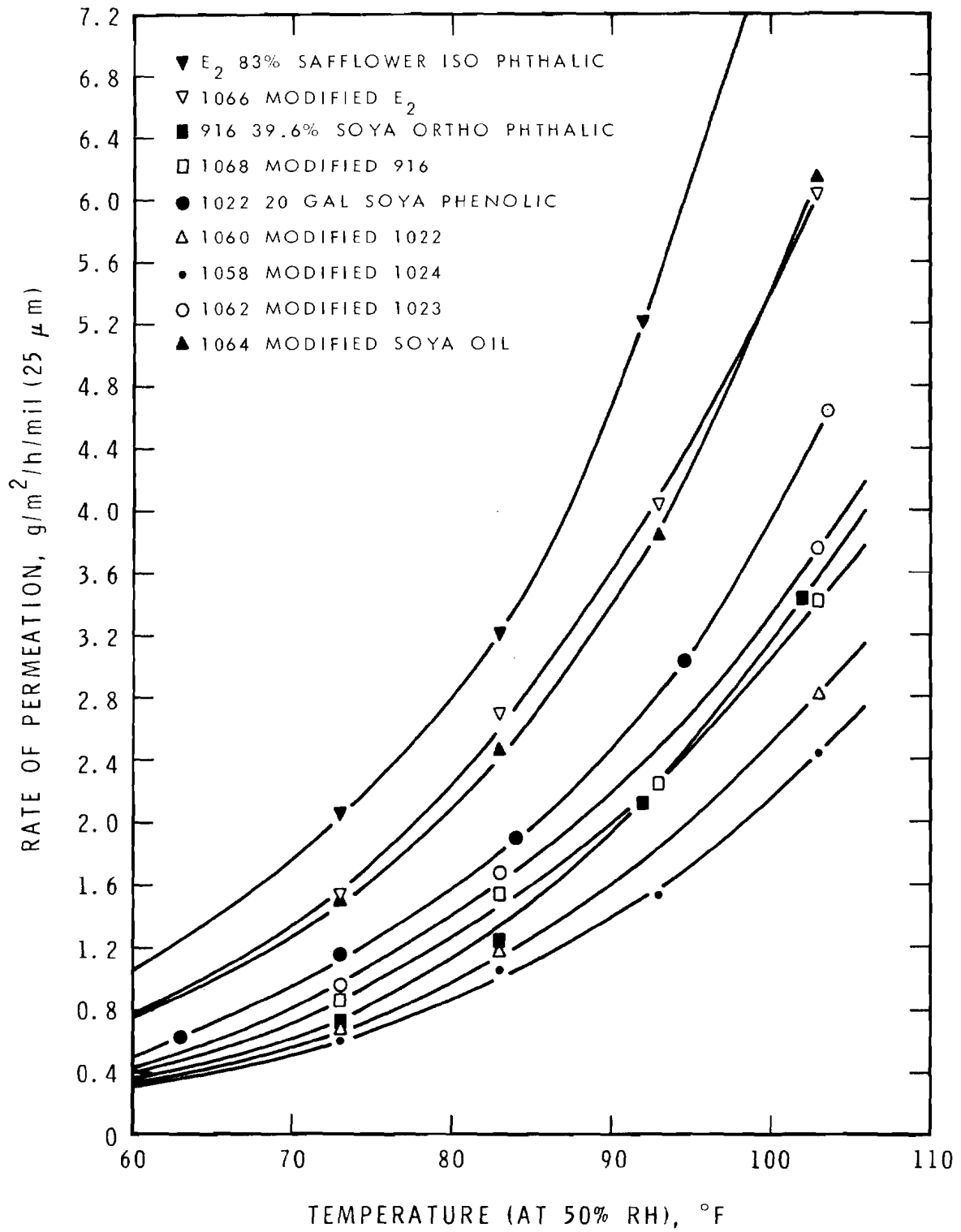


FIGURE 9

EFFECT OF TEMPERATURE ON RATE OF WATER VAPOR PERMEATION THROUGH MODIFIED COATINGS

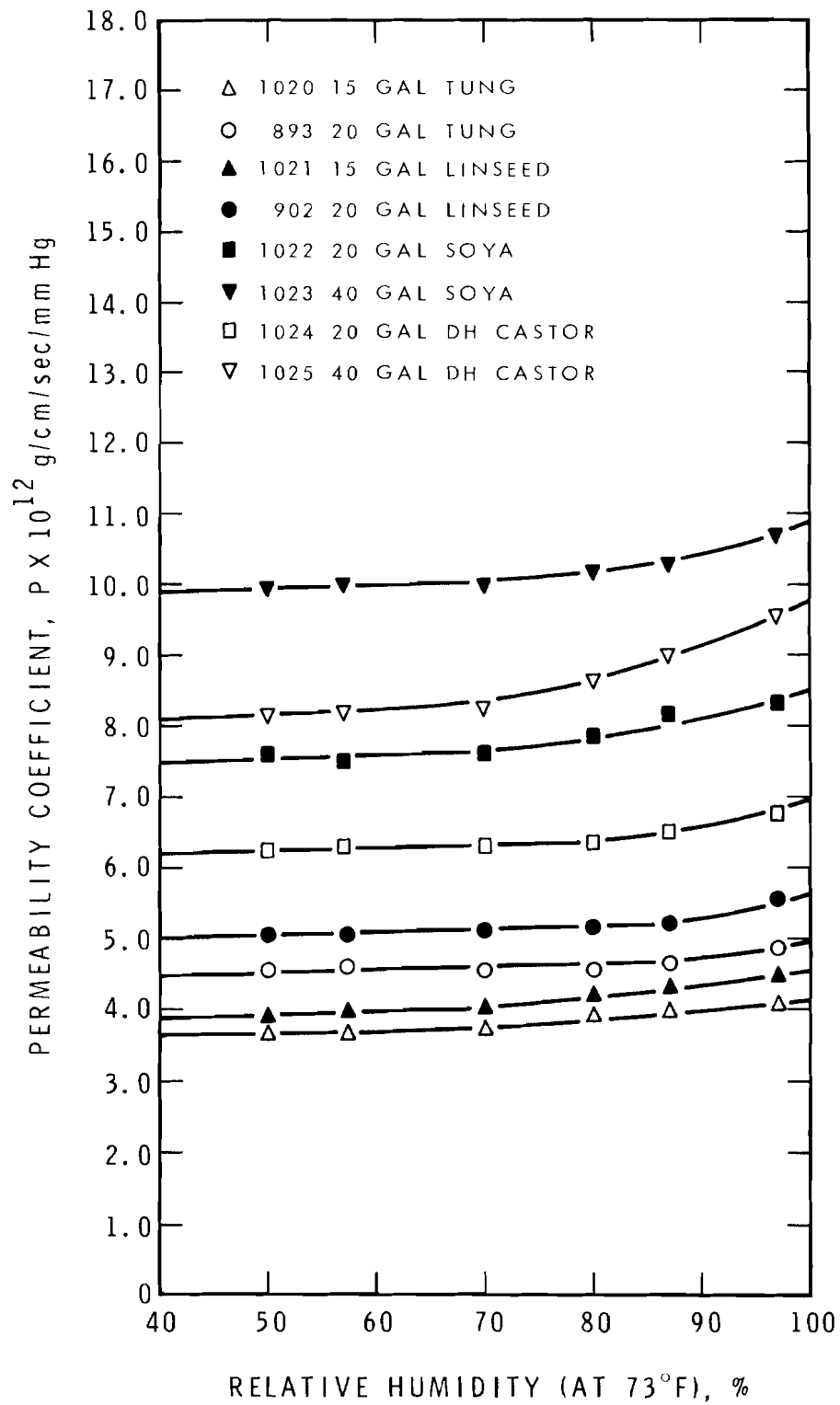


FIGURE 10

EFFECT OF RELATIVE HUMIDITY ON
PERMEABILITY COEFFICIENT OF PHENOLIC
VARNISHES

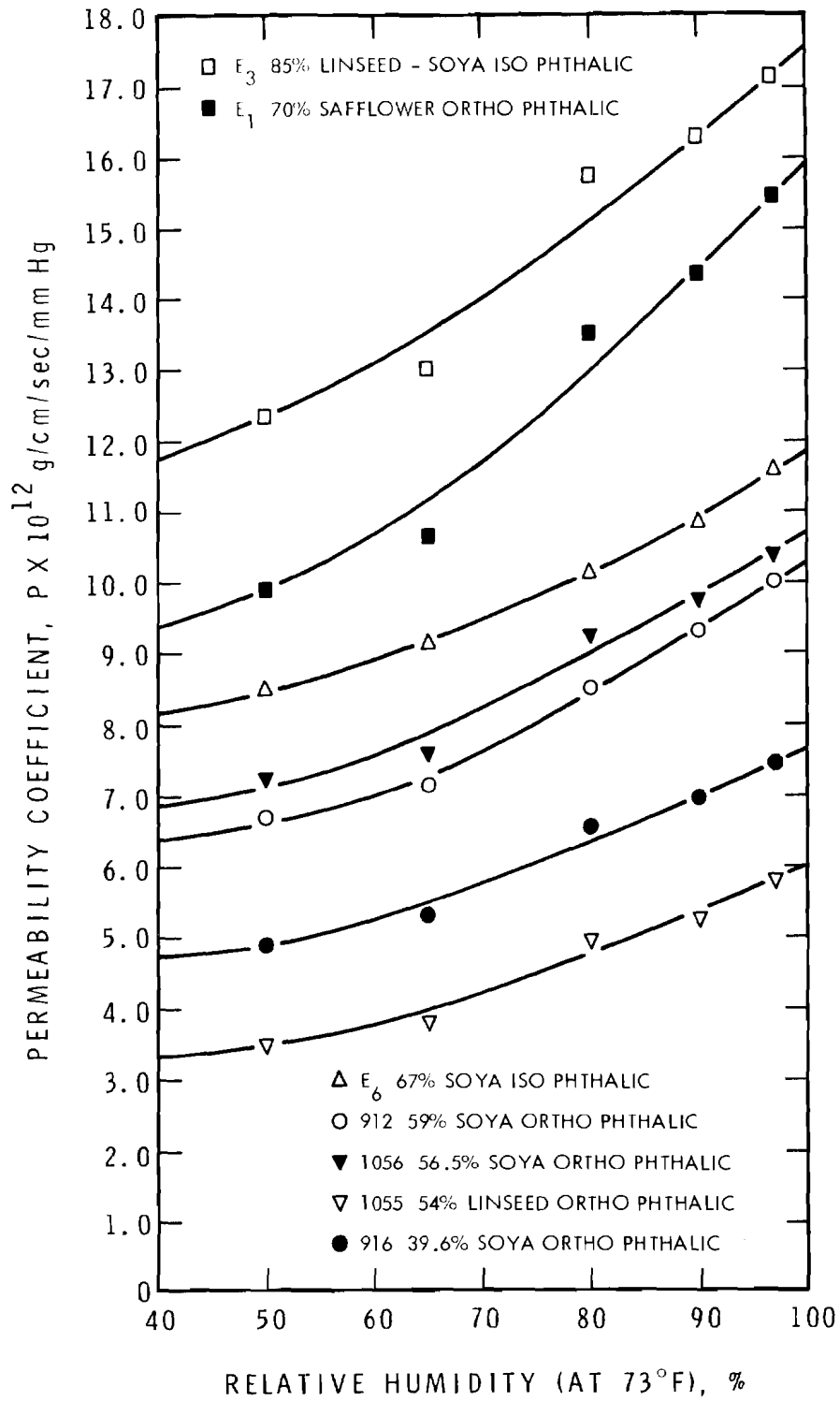


FIGURE 11

EFFECT OF RELATIVE HUMIDITY ON PERMEABILITY COEFFICIENT OF ALKYDS

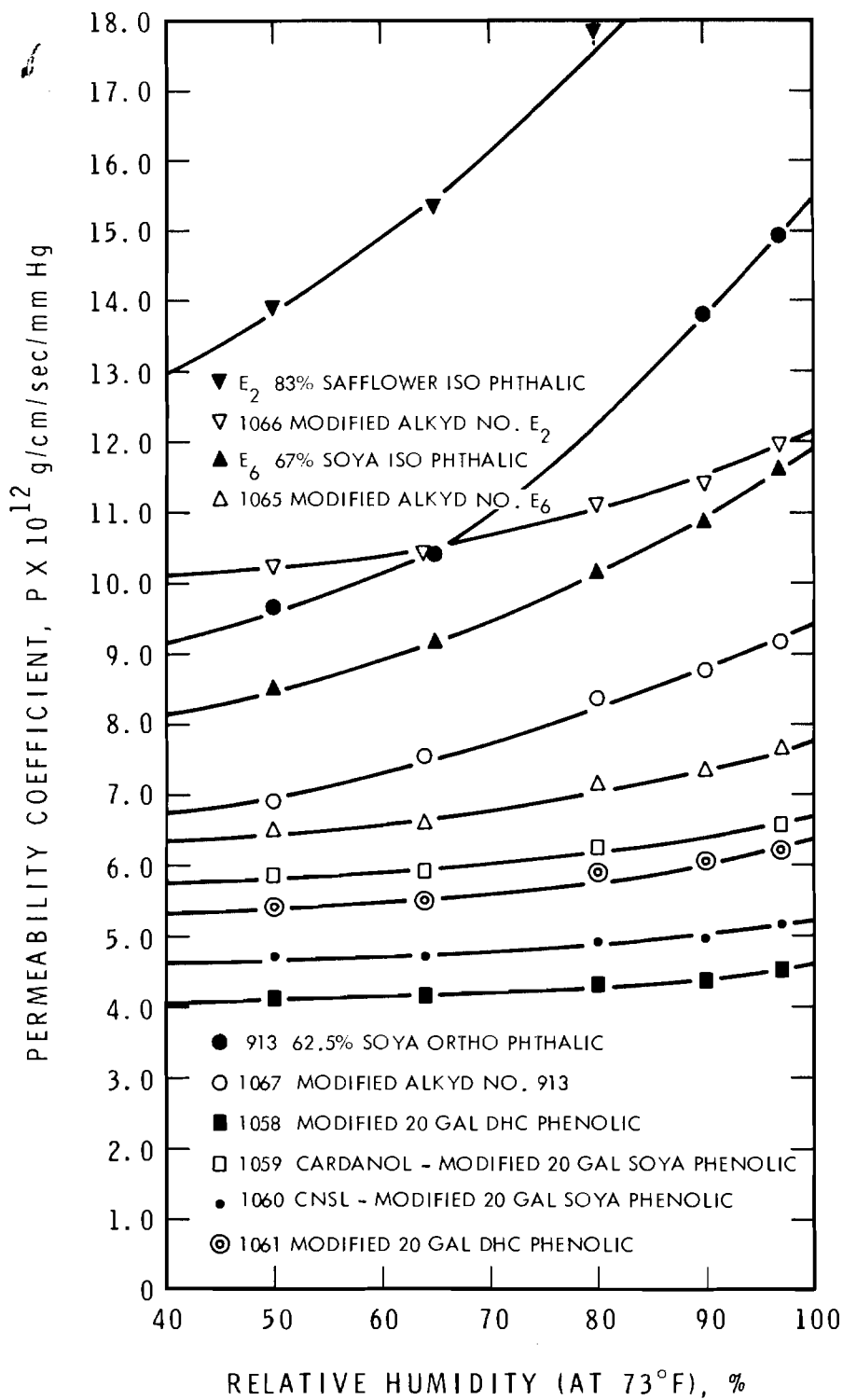


FIGURE 12

EFFECT OF HUMIDITY ON PERMEABILITY COEFFICIENT OF MODIFIED PHENOLICS AND ALKYDS

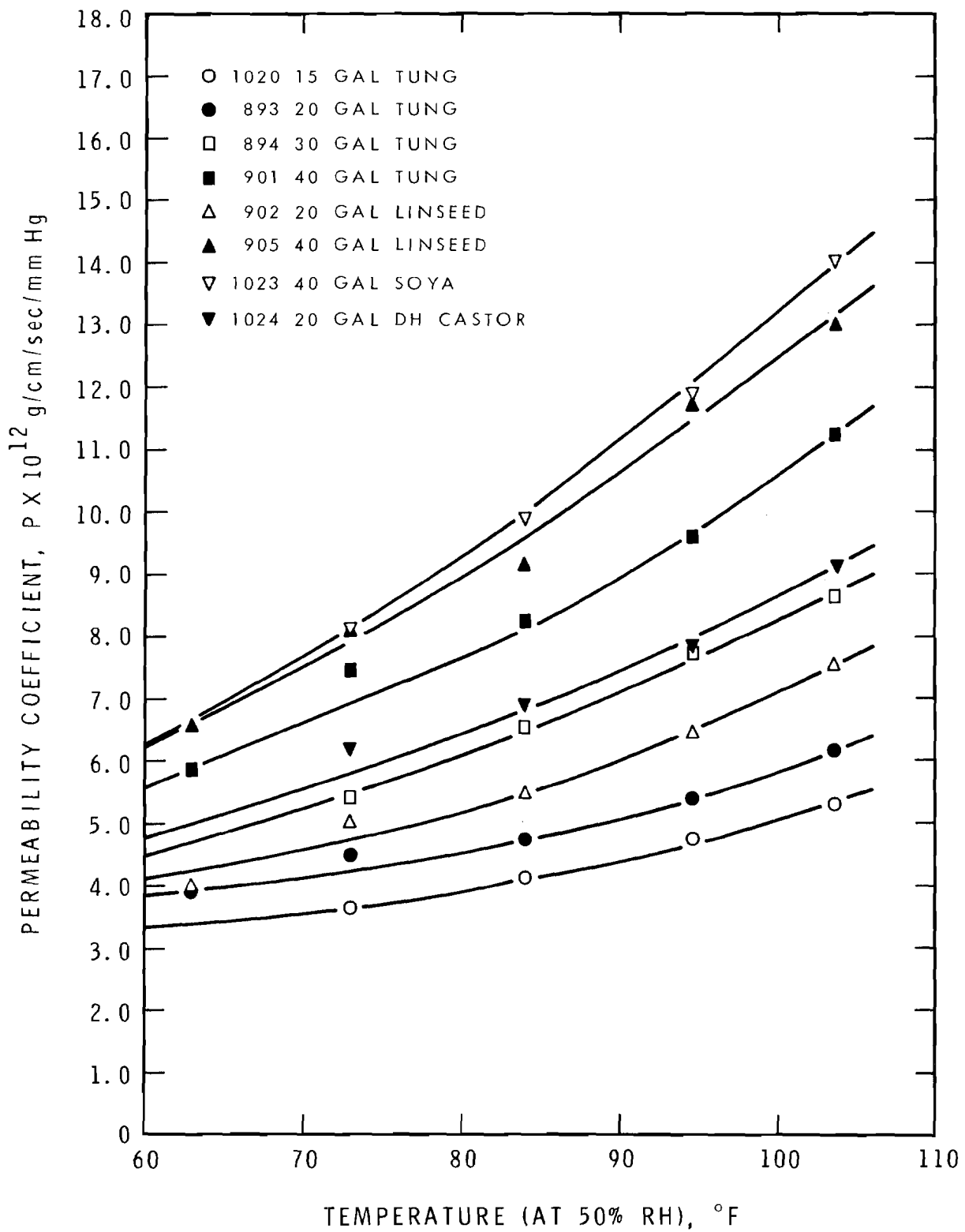


FIGURE 13

EFFECT OF TEMPERATURE ON PERMEABILITY COEFFICIENT OF PHENOLIC VARNISHES

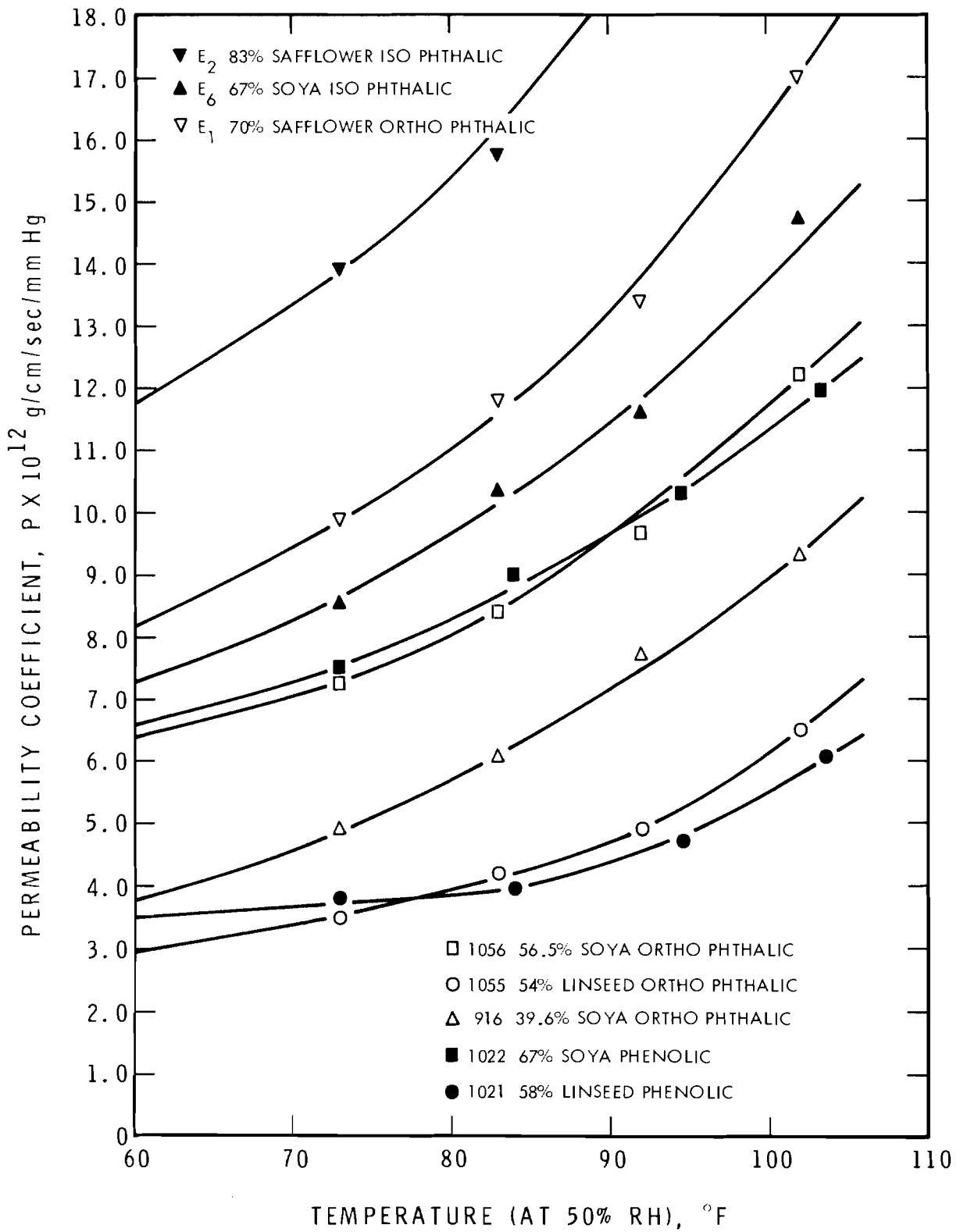


FIGURE 14
EFFECT OF TEMPERATURE ON PERMEABILITY COEFFICIENT
OF ALKYDS

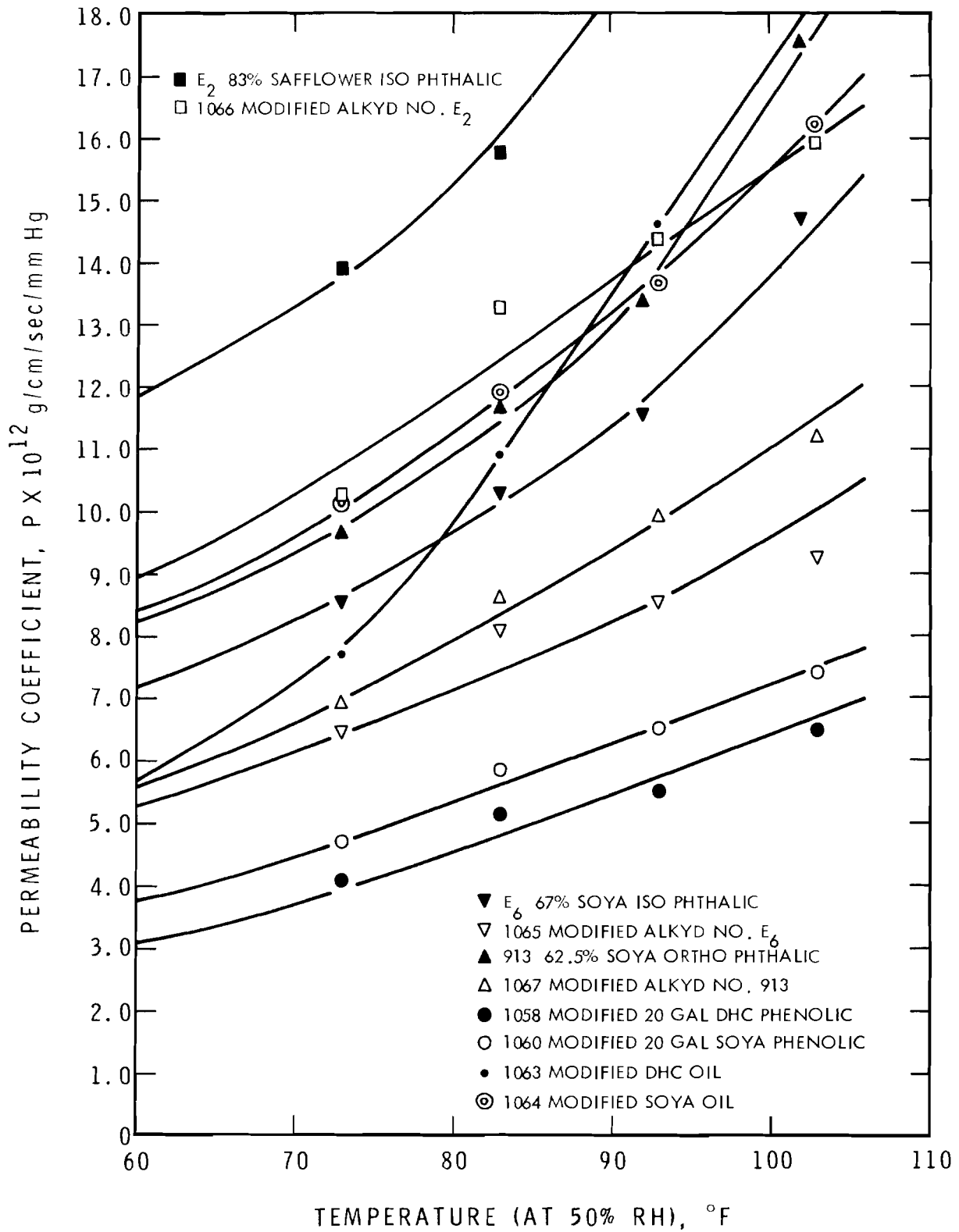


FIGURE 15

EFFECT OF TEMPERATURE ON PERMEABILITY COEFFICIENT OF MODIFIED PHENOLICS, OILS AND ALKYDS