

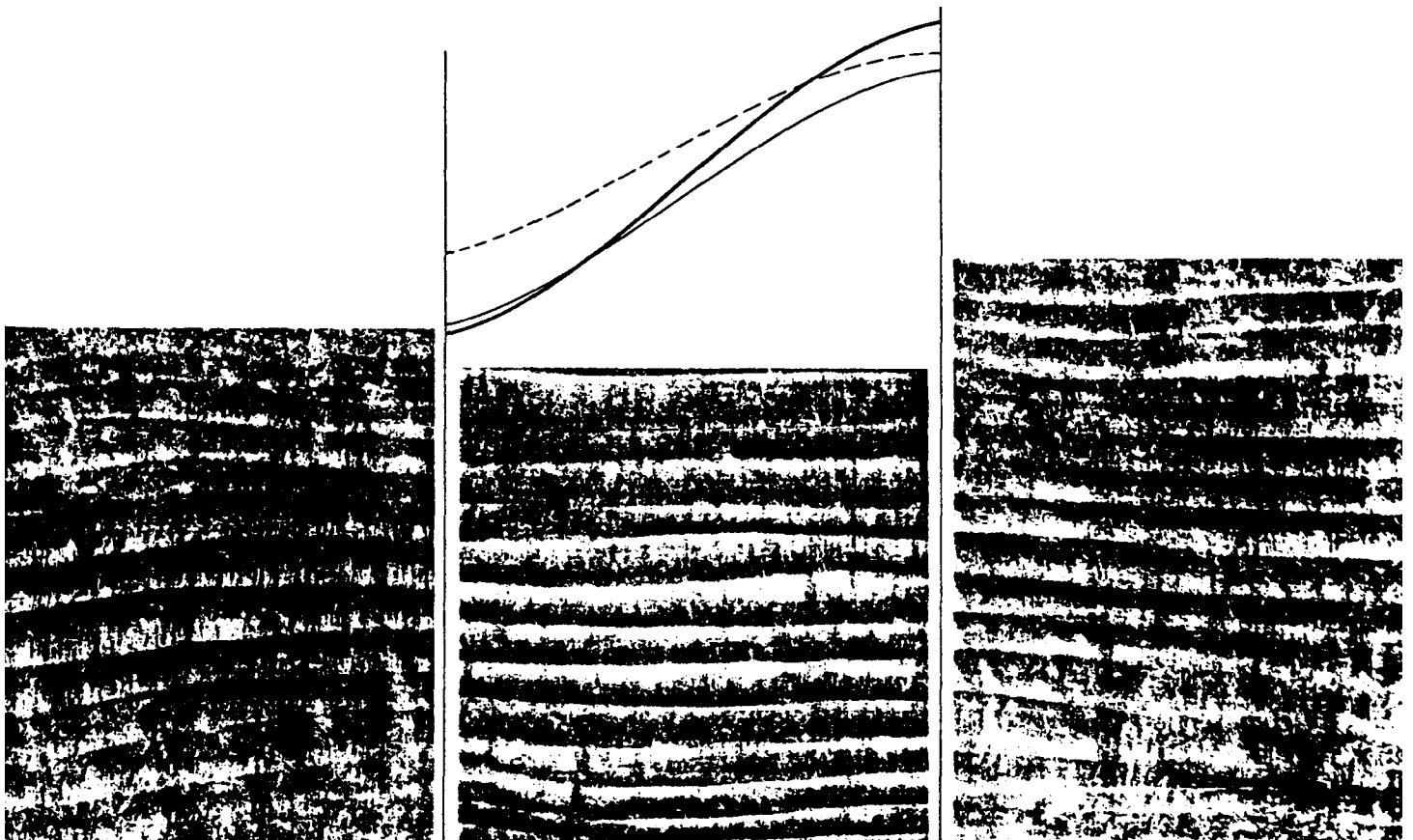
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# SORPTION and SWELLING CHARACTERISTICS of SALT-TREATED WOOD



## ABSTRACT

Seven inorganic salts, commonly used in the impregnation of wood, were investigated in terms of their effect on the sorption and swelling characteristics of ponderosa pine and red oak in a range of relative humidities normally encountered in service.

Swelling was, without exception, greater in chemically treated wood than in matching specimens of untreated wood. Only sodium chloride showed an appreciable effect on the dimensional stability of the two species as measured by volumetric shrinkage and swelling. However, treatment with the various chemicals increased the anisotropic swelling characteristics of both species. Equilibrium moisture content values were substantially increased by treatments with ammonium sulfate, sodium chloride, and zinc chloride. For these salts, equilibrium moisture content was a consistent linear function of the salt-wood weight ratio. Treatment with two phosphate salts had no apparent effect on equilibrium moisture content, while treatment with borax and boric acid caused increases in moisture content that are not considered permanent.

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# SORPTION and SWELLING CHARACTERISTICS of SALT-TREATED WOOD<sup>1</sup>

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## INTRODUCTION

In recent years the demand for chemically impregnated wood has increased significantly as building code requirements, building specifications, promotion by the manufacturers of chemicals, and better premium rates offered by insurance companies have encouraged wider use of such treatment. These treatments are commonly formulated from inorganic salts. There is some concern about the use of these treatments, since it is known that certain inorganic salts or combinations of salts may affect the strength and related properties of wood. Some of the salts themselves are hygroscopic and in the presence of wood may increase its apparent moisture content. An abnormal amount of swelling may also accompany these treatments because of increased moisture content. Furthermore, increases in the dry dimensions may be expected due to chemical bulking or restraint of shrinkage upon drying (2, 3, 4, 8).<sup>3</sup>

Wood moisture-swelling relationships frequently assume great importance, especially in structural uses of wood. All strength properties, with the possible exception of toughness, decrease as wood adsorbs moisture in the hygroscopic

range. Important properties such as modulus of rupture and compressive strength parallel to grain may decrease up to 4 and 6 percent, respectively, for each 1 percent increase in moisture content (9). In addition to this intimate moisture-strength relationship, the integrity of a structural assembly such as a truss may be affected by the dimensional stability of its components. The ability to "stay in place," a term frequently applied to wood having good dimensional stability, is also important in both interior and exterior wall coverings made of wood, in millwork, and for all other decorative purposes. Increased hygroscopicity may also influence the gluability, paintability, and the permanence of the preservatives themselves.

This research evaluates the effects of several inorganic salts, commonly used in formulating proprietary treatments, on certain physical properties of wood, particularly upon the sorption and swelling characteristics. It must be emphasized that the research deals with individual chemical effects only. The interaction effects of several chemicals in a single formulation were not studied. Therefore, the results of the study are not meant to imply that treatment with proprietary formulations will have similar effects or that the effects of a formulation can be easily

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<sup>2</sup>Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

<sup>3</sup>Underlined numbers in parentheses refer to Literature Cited at the end of this report.

predicted based upon a knowledge of its components. However, it is hoped that further research will substantiate how such predictions can be made.

Specifically, the study encompasses the sorption and swelling characteristics of ponderosa pine and red oak when treated with seven inorganic salts--diammonium phosphate, monoammonium phosphate, borax, boric acid, ammonium sulfate, sodium chloride, and zinc chloride. A typical hardwood and a typical softwood were selected for their treatability and because they differed substantially in specific gravity. Chemical treatments were made to three levels of retention, 0.5, 1.5, and 4.5 pounds per cubic foot. Water-treated controls were also prepared; these had no salt content. Observations of weight and dimension changes were limited to the 30 to 80 percent relative humidity range, since it is this part of the overall hygroscopic range that is commonly encountered by wood in service.

## PROCEDURE

Wafers, 1/4 inch along the grain, were cut from a ponderosa pine and a red oak stick approximately 2 by 2 inches in cross section and 10 feet long. In order that true tangential and radial characteristics might be measured, the sticks were machined so that one face was tangent to the annual rings. The oak specimens were approximately 2 by 2 inches in cross section, while the pine specimens were approximately 1-1/2 by 1-1/2 inches. Ten replicate specimens were provided for each combination of the seven chemicals, the three nominal levels of salt retention, and the water-treated controls for a total of 280 specimens of each species. They were arranged and identified in an end-matching scheme that permits principal comparison between chemicals and secondary comparison between retention levels. All matching was good, however, as one complement of all chemicals and retention levels required only about 9 inches along the grain. A test for growth stresses was conducted by measuring the transverse dimensions of several extra specimens before and after heating in water. No change in the relative radial and tangential dimensions during heating indicated a freedom from such stresses.

Before treatment, the specimens were carefully air dried to approximately 6 percent mois-

ture content and then further dried under vacuum and slightly elevated temperatures to essentially oven-dry condition. This technique was selected in preference to oven-drying to minimize the effect of drying on subsequent measurements for determining sorption and swelling characteristics. Measurements of weight and dimensions in the dry condition before treating were used as a base for computing all moisture content, swelling, and specific gravity results.

Treating was also done in such a manner to minimize processing effects on the sorption and swelling characteristics. Salt was impregnated into the wood by initially pulling a vacuum over the specimens, followed by soaking at atmospheric pressure after solution flow-in. Slightly elevated temperatures were required for the borax and boric acid treatments because of their low water solubility. The concentration of treating solutions required to obtain the nominal retention levels was computed from solution pickup data obtained during the processing of the water-treated controls.

After treatment, the specimens were cycled through an initial desorption cycle, an adsorption cycle, and a final desorption cycle. The cycles were limited to the 30 to 80 percent relative humidity range. During each cycle, measurements of weight and dimensions were made on each specimen while at equilibrium moisture condition in atmospheres controlled at 80° F. and 80, 65, 50, and 30 percent relative humidity. Following the initial desorption cycle, the specimens were partially air dried over vacuum, so that equilibrium would be approached during the adsorption cycle at 30 percent relative humidity.

## RESULTS

### Salt Retention

In a study of this nature, it is essential that the amount of salt in a specimen be determined as accurately as possible. If the amount of salt is overestimated, equilibrium moisture content will be too low; if underestimated, the equilibrium moisture content will be too high. Furthermore, any attempt to establish relationships between retention levels and the effects of salts on physical properties of wood will be in error if the salt retentions themselves are inaccurate.

It is common to calculate salt retentions by using solution pickup data and the concentration of the treating solutions. However, selective adsorption of either the chemical or the water can cause an error in this estimate. Another method is the oven-drying technique where the difference between the dry weights before and after treating is interpreted as being the weight of the salt present. Some salts, however, are not stable at temperatures required to drive off all the water and, consequently, retentions determined by this method are too low. In borax, another similar source of error in the drying technique would be that associated with the loss of an indeterminate number of molecules of water of crystallization. Another alternative is chemical analysis. Appendix A shows the results of estimates of salt retention by each of these methods: the method of chemical analysis for each chemical is also given. The results obtained by chemical analysis were selected as being most accurate, and all of the results in this report are based upon retentions obtained by this method.

#### Effect of Salts on Moisture Content

In a study of this type, moisture content is often expressed as a percent of the combined dry weight of the salt and wood. However, in this research, moisture content is based upon the oven-dry weight of the untreated wood. This permits better comparisons between chemical effects and between treated specimens and controls, because the base for computing moisture is consistent in all cases. The equation for computing moisture must, however, consider the salt in the specimen and is:

$$M = 100 \frac{W_T - W_D - W_S}{W_D} \quad (1)$$

where M = moisture content in percent

$W_T$  = weight of specimen (grams) at the equilibrium moisture content under consideration

$W_S$  = weight (grams) of salt in the specimen

$W_D$  = untreated dry weight (grams) of the specimen

Moisture content values computed by this meth-

od for treated oak and pine specimens and for water-treated controls are presented in Appendixes B and C respectively.

Trends such as apparent increases in moisture content due to certain salts, increasing moisture content with increasing salt retention, and the more pronounced effects in pine than in oak are readily seen by examination of the data in Appendixes B and C. However, because the data are voluminous, graphic analysis has been used to elucidate the trends.

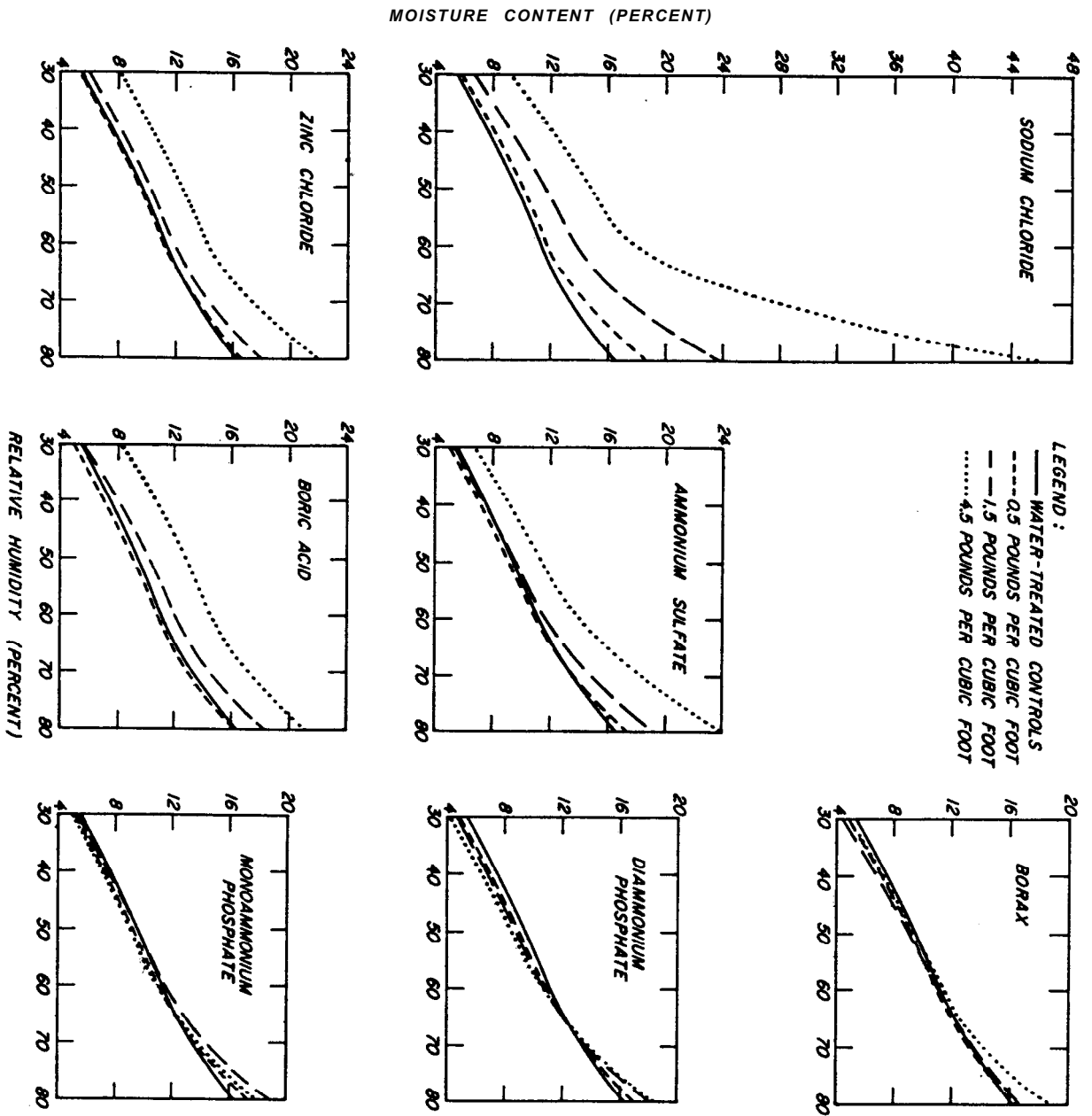
Initial desorption--Figures 1 and 2 show the initial desorption curves for treated oak and pine, respectively, and for the water-treated controls for each chemical. These curves are plots of data obtained upon drying from the saturated condition after treatment.

The effect of the seven chemicals is varied in magnitude and nature, yet all the curves retain the typical sigmoid shape which describes the normal relationship between moisture content and relative humidity. These normal relationships are represented here by the curves for the water-treated controls.

It appears from these curves that the chemicals can be divided into two groups based upon their apparent hygroscopic effect. One group, represented by diammonium phosphate and monoammonium phosphate, is characterized by little overall effect on moisture content but typically shows a slight decrease in moisture content at 30 percent relative humidity, which grades to a slight increase at 80 percent relative humidity. This effect increases with increasing salt retention.

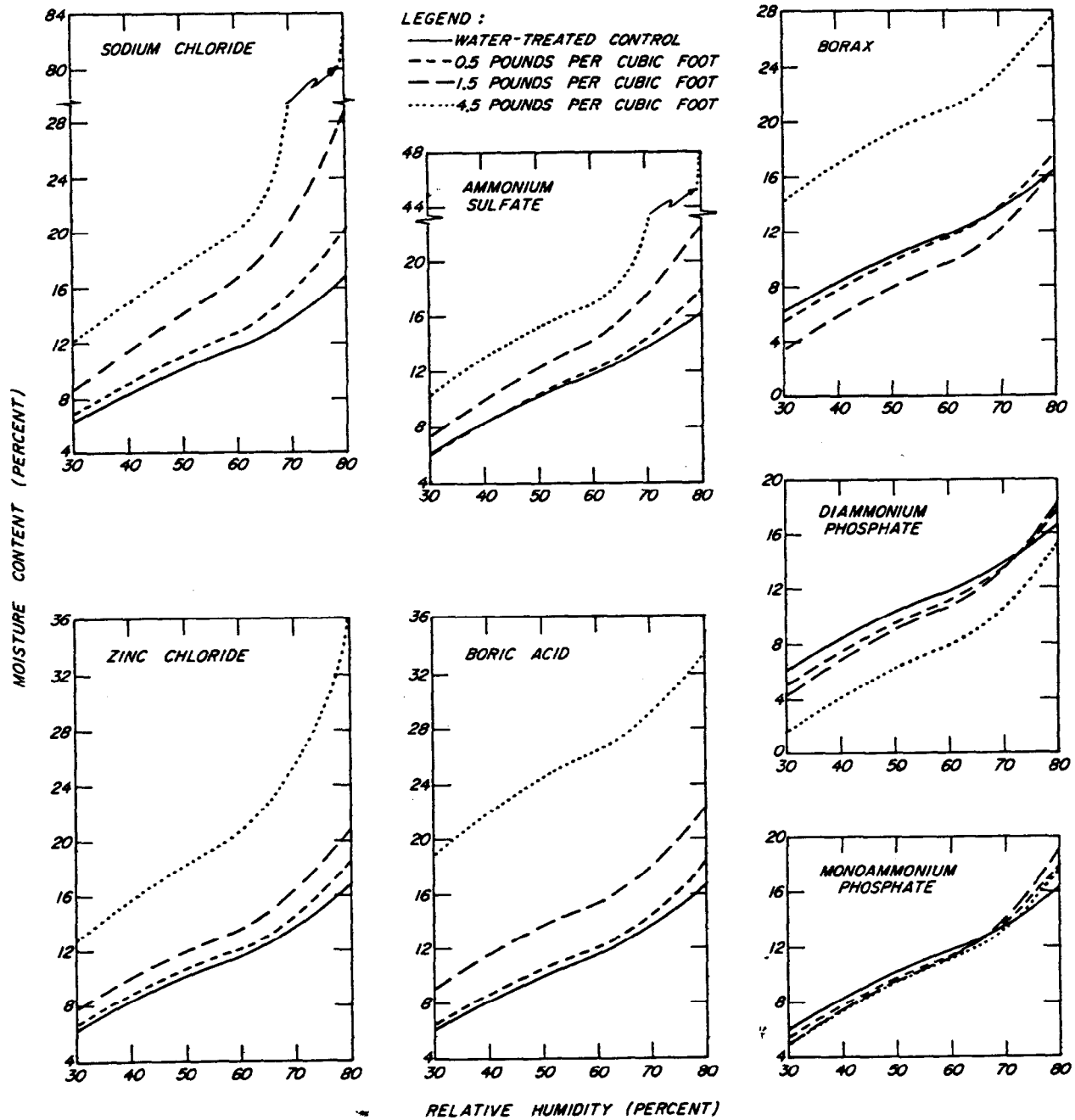
The other group, which includes borax, boric acid, ammonium sulfate, zinc chloride, and sodium chloride, shows a characteristic increase in moisture content throughout the 30 to 80 percent relative humidity range considered: this effect also increases with increasing salt retention.

There are several exceptions to the above grouping. The borax treatments of oak show effects similar to those chemicals in the first group, while the 4.5-pound diammonium phosphate treatment of pine shows a considerable decrease in moisture content throughout the humidity range. This apparent decrease in moisture content may reflect a loss of ammonium from the chemical rather than an actual decrease in moisture content, as there is a tendency for this chemical to decompose into monoammonium phosphate, particularly at high relative humidity. Also, the 0.5-pound treatments of boric acid, ammonium sulfate, and



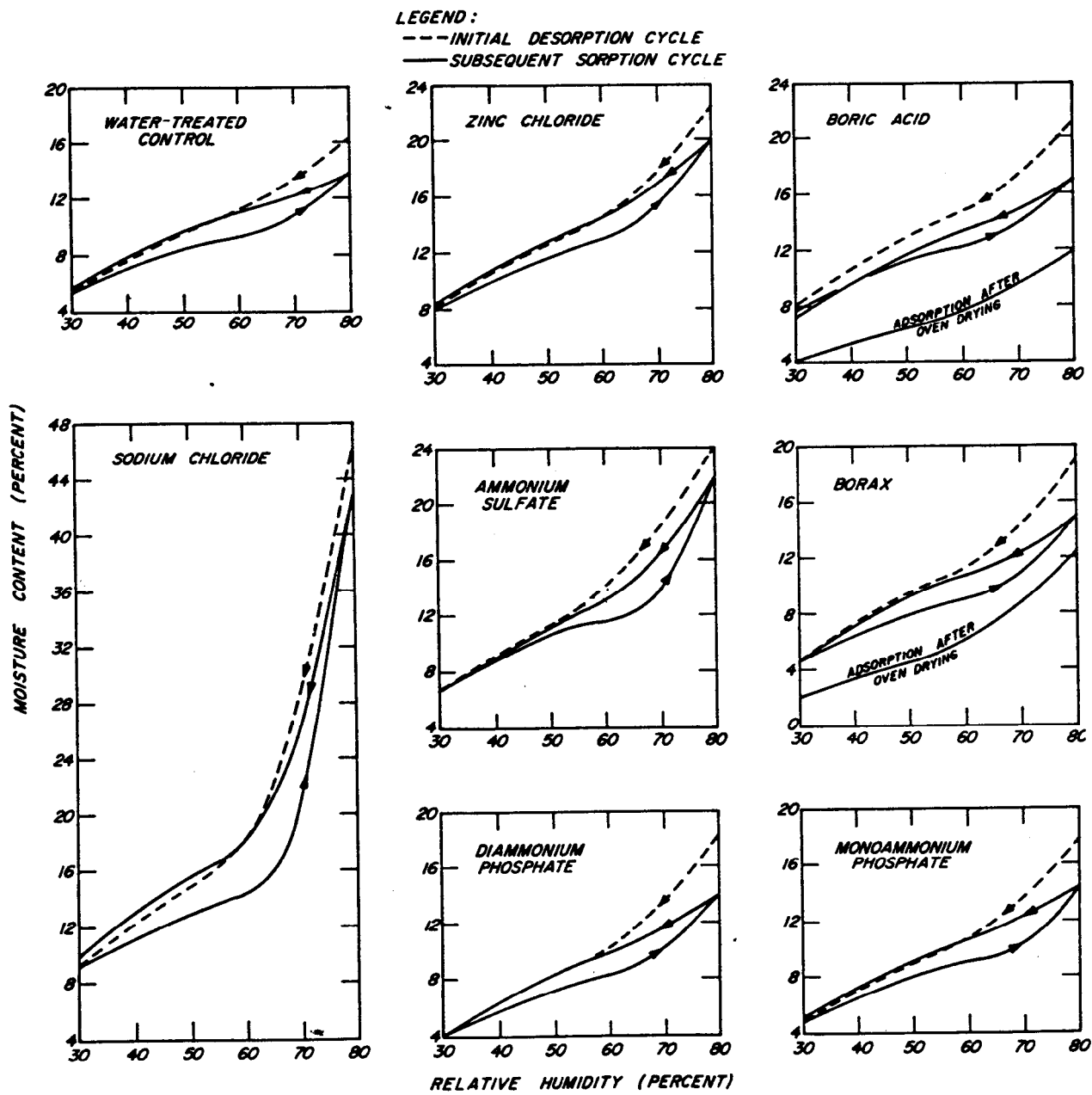
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Figure 1.--Oak: Initial desorption curves for salt-treated wood and for the water-treated controls.



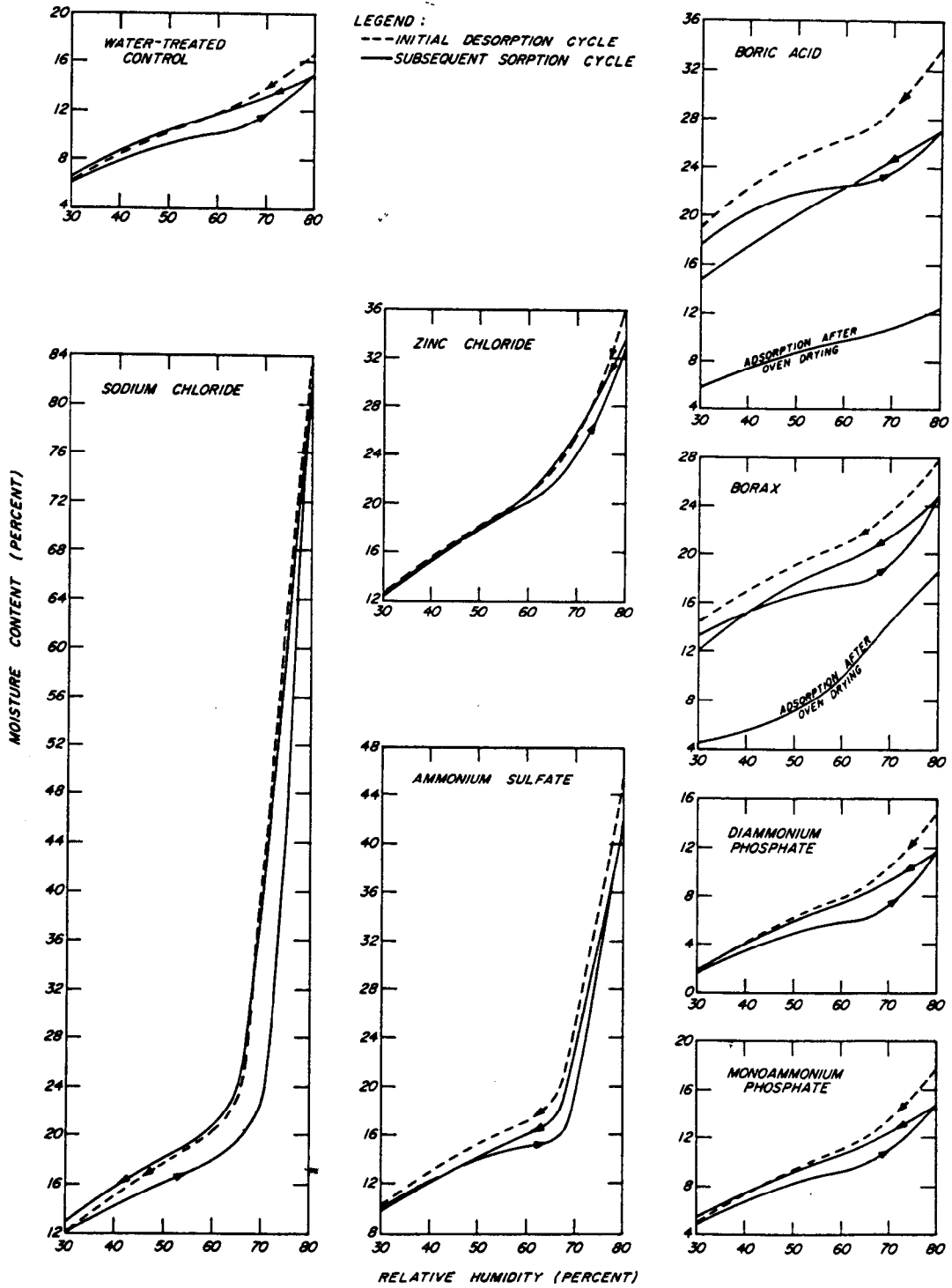
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Figure 2.--Pine: Initial desorption curves for salt-treated wood and for the water-treated controls.



N 130 653

Figure 3. --Oak: Sorption curves for untreated wood and wood treated to a nominal salt retention of 4.5 pounds per cubic foot.



M 130 656

Figure 4. --Pine: Sorption curves for untreated wood and wood treated to a nominal salt retention of 4.5 pounds per cubic foot.

zinc chloride in oak showed little or no effect; in fact, at certain humidities the moisture content actually decreased at this level of salt retention.

The effects observed on moisture content at all levels of treatment are generally greater in pine than in the corresponding treatments in oak. One would expect these effects to be more prominent in pine because there is approximately twice as much salt in the pine as in the oak on a weight basis (weight of salt per unit weight of wood). This effect will be discussed later in this paper where it is shown that the difference in moisture content between the two species is proportional to the difference in specific gravity.

It is interesting to note that in both groups, regardless of whether the chemical effect results in an increase or decrease in the moisture content, the change of moisture content from 30 to 80 percent relative humidity was greater in all chemically treated specimens than in the water-treated controls. This, in effect, means that the slope of the curves of treated material is probably everywhere greater than that of untreated material. This is important from the standpoint of strength properties, because it means that strength properties of treated material will decrease more rapidly than those of untreated material as relative humidity increases: the strength-moisture relationship for treated wood is assumed to be similar to that for untreated wood. Dimensional stability may also be affected.

Adsorption-desorption cycle.--When wood is dried in successive steps from an initial green or saturated condition, the equilibrium moisture content measured will be higher than during any subsequent desorption or adsorption cycle at the same atmospheric conditions. Repeated desorption-adsorption cycling results in sorption curves forming closed hysteresis loops which essentially coincide except for the first desorption curve (1).

In service, when seasonal atmospheric changes occur, small hysteresis loops will be formed if the moisture content of the wood is plotted as a function of the relative humidity of the atmosphere. The location of the small loops relative to the main hysteresis loop will depend upon the previous exposure of the particular piece involved. If the piece was placed in service at a moisture content above or near that of the equilibrium moisture conditions of the atmosphere, the small loops would be formed near the desorption side

of the main hysteresis loop. If placed in service at a moisture content substantially below the equilibrium moisture content of the atmosphere, they will be formed near the adsorption side of the main hysteresis loop (5). For these reasons, it is important that subsequent adsorption and desorption cycles be considered in addition to the initial desorption cycle already discussed.

Figures 3 and 4 show sorption curves, which include the initial desorption cycle, a subsequent adsorption cycle, and a final desorption cycle, for oak and pine treated to the nominal 4.5-pound retention level with the various chemicals considered. Similar curves for water-treated controls are shown in the upper left-hand corner of each figure.

Except for the borax and boric acid treatments, the curves for treated material, in general, resemble those of the water-treated controls. However, a displacement of the curves on the moisture content axis, which reflects the hygroscopicity or the nonhygroscopicity of the chemical, and an increase in the slope of the curves are still evident. Essentially no difference is apparent in either the oak or pine curves representing treatments with the phosphate compounds. The ammonium sulfate and sodium chloride curves resemble the shape of the control curves in the 30 to 65 percent relative humidity range but thereafter deviate upward quite abruptly. The zinc chloride curves for oak are similar to the controls, but in pine the hysteresis effect was somewhat reduced, particularly at low levels of humidity.

Perhaps of most significance in the sorption curves is that they indicate whether the effects noted are of a permanent nature. It is reasonably certain that additional desorption-adsorption cycling with diammonium phosphate, monoammonium phosphate, zinc chloride, ammonium sulfate, and sodium chloride would result in curves coincidental with the adsorption and final desorption curves already obtained. This premise is based on the observation that the second desorption to 30 percent relative humidity yields essentially the same equilibrium moisture content as the first desorption.

The sorption curves for boric acid and borax-treated pine, however, differ considerably from those of the other chemicals and from the controls. A much larger hysteresis effect occurred between the initial desorption and the adsorption curve and, in addition, the moisture content

obtained in the final desorption cycle at low relative humidity was lower than that previously obtained under adsorbing conditions. It appears that the moisture data were obtained before the specimens reached true equilibrium; however, check weights before actual measurement at each condition indicated that the specimens were oscillating in weight with fluctuating control conditions. This does not necessarily establish that equilibrium was reached, as it is possible that the gross weight of the wood and chemical could oscillate with the control conditions due to the hygroscopicity of the wood, masking a much slower loss of water from the chemical itself. This is unlikely, however, since aqueous solutions of boric acid quickly became anhydrous when placed in atmospheres in the 30 to 80 percent relative humidity range. Therefore, repeated cycling would probably show a continued trend toward a lower moisture content which would eventually result in coincidental sorption curves, and the equilibrium moisture content would be comparable, or nearly so, to that of untreated wood or to wood treated with chemicals of the nonhygroscopic group.

After the completion of the final desorption cycle, the borax- and boric acid-treated pine specimens were oven-dried and again exposed successively to atmospheres of 80° F. and 30, 50, 65, and 80 percent relative humidity. The data obtained offer further evidence that the increased moisture content shown previously for borax and boric acid is not a permanent effect, because the equilibrium moisture content was approximately equal to or less than that for untreated wood. These data are included in the graphs for borax and boric acid in figures 3 and 4. The loss of the typical sigmoid shape of the curves for the borax treatments perhaps reflects a regaining of the water of hydration to the borax molecule lost during oven-drying.

It is also recognized that exposing wood to elevated temperatures may reduce its hygroscopicity by converting the hygroscopic hemicellulose to polymers that are much less hygroscopic (7). The rate at which these reactions occur is greatly accelerated by certain inorganic salts. The time required to oven-dry these specimens was sufficient for a reaction of this nature to occur, and undoubtedly accounts for a part of the reduced equilibrium moisture content obtained after oven-drying.

Because of these considerations, boric acid will not be considered in further discussion regarding hygroscopic effects. The same reasoning can be applied to the 4.5-pound borax treatment of pine. Regarding permanent effects on moisture content, boric acid and borax should therefore be grouped along with diammonium phosphate and monoammonium phosphate.

Relative chemical hygroscopicity.--A comparison of the relative hygroscopicity of wood treated to the same nominal retention level with ammonium sulfate, zinc chloride, or sodium chloride, is not realistic because in certain cases the actual retention level varies considerably from that of the nominal level. However, comparisons can be made by using figure 5, which shows the relationship between salt retention and the moisture content of pine and oak when treated with the hygroscopic chemicals. Selecting a common salt retention from these plots for any species-chemical-humidity combination and reading the corresponding moisture content permits direct comparisons of the relative hygroscopicity of the three chemicals.

It is readily apparent that wood treated with sodium chloride is considerably more hygroscopic at any level of humidity and salt retention than wood treated with either zinc chloride or ammonium sulfate. For instance, sodium chloride-treated pine has a moisture content of 42 percent and similarly treated oak has a moisture content of 26 percent at the same retention level of 2.5 pounds per cubic foot and 80 percent relative humidity. For the same conditions the moisture content of zinc chloride-treated pine is 23 percent and of oak is 17 percent. The ammonium sulfate treatment results in a 31 and 20 percent moisture content for pine and oak respectively. However, at other levels of humidity, zinc chloride and ammonium sulfate produce nearly the same moisture content conditions.

Probably most obvious in figure 5 is the much greater effect of the three chemicals on the moisture content of pine than on oak. However, this does not necessarily indicate a greater chemical effect, since absolute increases in water would reflect a larger increase in pine than in oak by an amount in proportion to the difference in their specific gravity. By definition, the water in salt-treated wood may be considered in two parts--that representing the normal equilibrium moisture content of untreated wood, and the additional

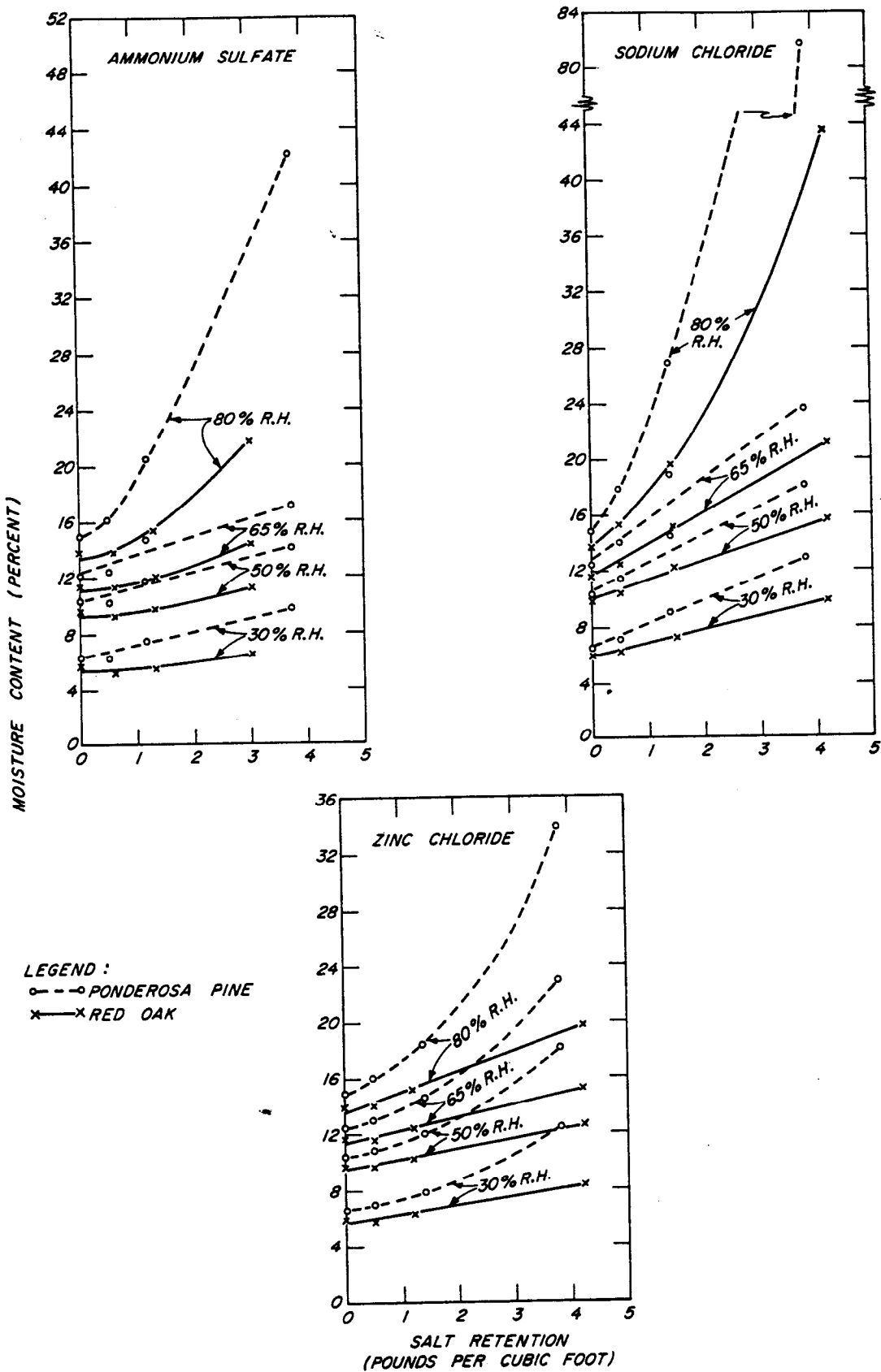


Figure 5.-- Relationship between salt retention and moisture content of pine and oak at several levels of relative humidity when treated with three hygroscopic chemicals.

moisture due to the influence of the salt. Symbolically,

$$M = 100 \frac{W_{w,u} + W_{w,s}}{W_D} \quad (2)$$

where  $W_{w,u}$  = weight of water at equilibrium for untreated wood,

$W_{w,s}$  = weight of water associated with the salt.

Other symbols are as previously defined.

It is recognized that, at a given temperature and relative humidity, the equilibrium moisture content is essentially constant if the wood is relatively free of extractives (9). That is, the weight of adsorbed water is proportional to the weight of the wood or

$$W_{w,u} = AW_D \quad (3)$$

where  $A$  is the proportionality constant. If equation (3) is true for wood (a complex hygroscopic material), it is reasonable to suppose that an analogous relationship exists for any of the salts (relatively simple hygroscopic chemicals) considered in this study when they are in the presence of wood. Then

$$W_{w,s} = BW_S \quad (4)$$

where  $B$  is the proportionality constant. Equations (3) and (4) may be substituted into (2) to eliminate  $W_{w,u}$  and  $W_{w,s}$  and the equation becomes

$$M = 100(A + Bx) \quad (5)$$

where  $x = \frac{W_S}{W_D}$  or the ratio of the weight of salt to the weight of dry wood.

For those concerned with the use of these chemicals in treating solutions, equation (5) can be used for predicting an increase in moisture content due to treatment to any level of retention, regardless of the species treated. To test the validity of equation (5),  $M$  was plotted as a function of  $x$  for ammonium sulfate, zinc chloride, and sodium chloride (figures 6, 7, and 8). The plots are practically independent of the two species evaluated, and appear to be essentially straight

lines for salt-wood weight ratios up to 0.10. Since proprietary solutions are always made of combinations of salts, it is doubtful if individual salt retentions would ever exceed this value, as a salt-wood weight ratio of 0.10 is approximately equivalent to a retention of 4.0 and 2.0 pounds per cubic foot in the oak and pine, respectively, used in this study.

The dashed lines in figures 6, 7, and 8 are freehand curves fitted to these data. Curvilinear relationships are indicated by these curves for all chemicals at the 80 percent relative humidity level with the slope of the curve increasing with increasing salt-wood weight ratio. At lower humidities, a similar effect was noted for zinc chloride, although the rate of increase appears to decrease as relative humidity increases. At lower humidities in sodium chloride-treated material the relationships were also curvilinear but the rate of increase in moisture decreased with an increasing salt-wood weight ratio. The data for ammonium sulfate at lower humidities, however, appear to fit a straight line.

The solid lines are linear regressions of moisture content on the salt-wood weight ratio in the 0 to 0.10 range. Individual data were used in the regression analysis, while the plotted points represent the averages of 10 values.

Table 1 gives the regression coefficients ( $A$  and  $B$ ), coefficients of correlation, and the number of specimens for each of the regression analyses. Correlations are extremely good, ranging from 0.88 for material treated with zinc chloride and exposed to 30 percent relative humidity conditions to 0.99 for sodium chloride at both the 30 and 80 percent relative humidity exposures. These correlations indicate the validity of equation (5).

The use of the regression results to predict increases in moisture due to treatment might be more accurate if the equilibrium moisture content of the species or preferably of the untreated material involved were substituted in place of the regression coefficient  $A$  in the equation. This would be particularly true in species such as redwood, in which the equilibrium moisture content values differ substantially from those of a wood containing a more normal amount of extractives or from those of the species involved in these regression analyses (6, pp. 155-158). In figures 6, 7, and 8 the equilibrium moisture content of oak is almost consistently lower than

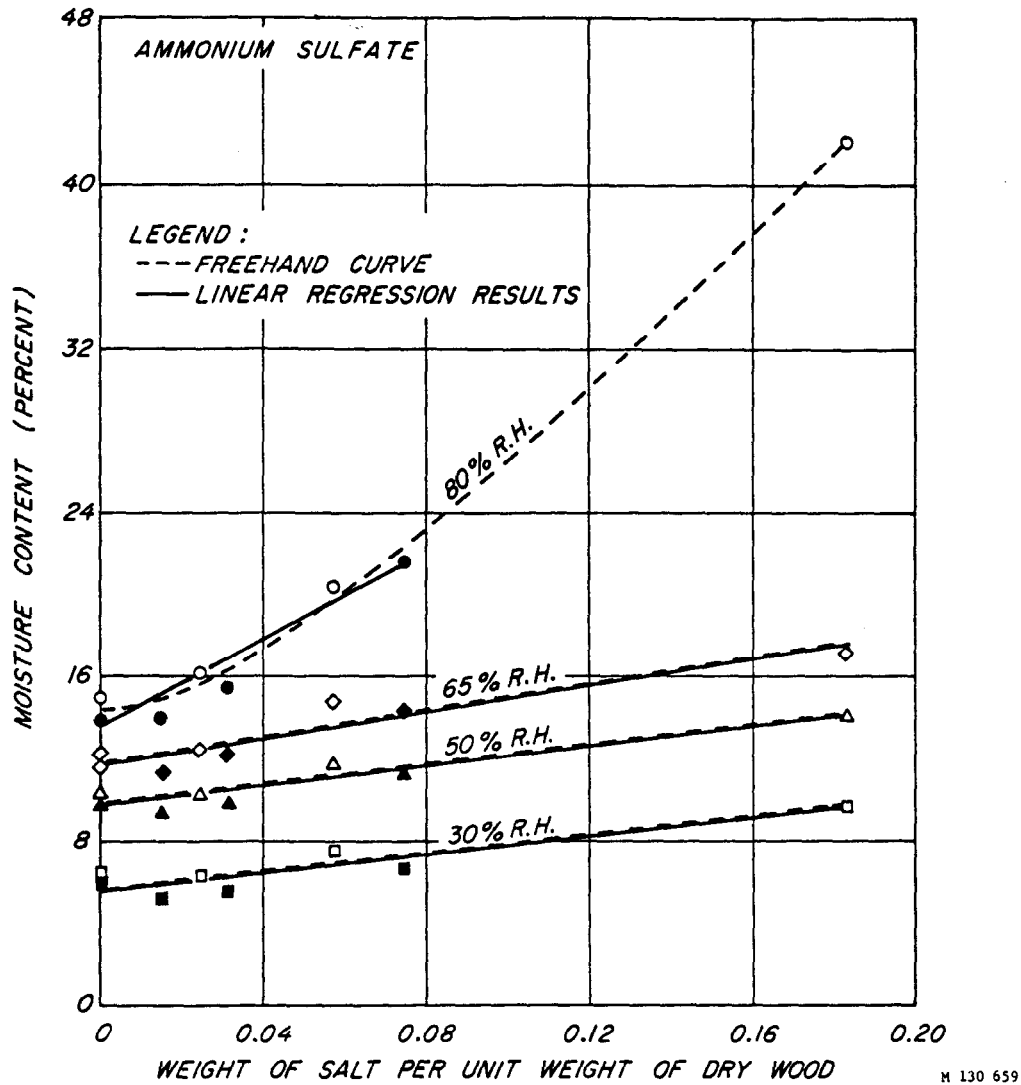


Figure 6.--Relationship between moisture content and the salt-wood weight ratio for ammonium sulfate. Solid symbols represent oak and the open symbols represent pine.

that of pine at comparable levels of the salt-wood weight ratio. This difference is probably characteristic of the particular material involved in the study rather than a species characteristic.

As indicated by the regression coefficient  $\underline{B}$ , the slope of the regression line, the hygroscopicity of sodium chloride-treated material is considerably greater at all levels of humidity than that treated with either ammonium sulfate or zinc chloride. At the 80 percent level of humidity, ammonium sulfate-treated material was approximately twice as hygroscopic as that treated with zinc chloride, whereas at lower humidities there is little difference between the two. Without exception, the hygroscopicity of the treated mate-

rial increased with each increase in relative humidity.

Interaction of wood-chemical hygroscopicity.-- From equation (4),  $\underline{B}$  is the hygroscopicity of the salt considered by itself, when in the presence of wood. It is of interest to know if this is any different from the hygroscopicity of the free salt (not in wood); i.e., can the superposition of effects implied by equation (2) be treated as independent effects of wood and salt, or does each mutually affect the hygroscopicity of the other? To answer this question, increases in weight by the addition of water were observed when anhydrous ammonium sulfate, zinc chloride, and sodium chloride were exposed to an atmosphere controlled at

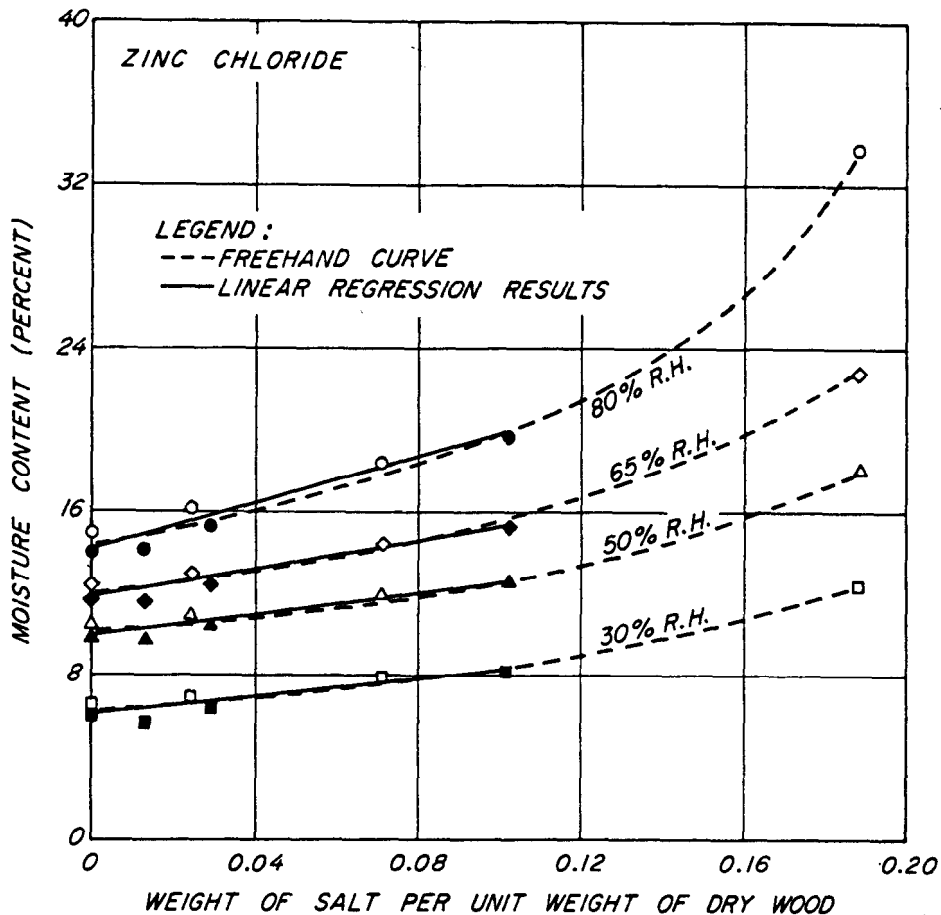


Figure 7.-- Relationship between moisture content and the salt-wood weight ratio for zinc chloride. Solid symbols represent oak and the open symbols represent pine.

80° F. and 80 percent relative humidity. The hygroscopicities of the three chemicals defined by equation (4), but now not in wood, were determined to be 1.350 for ammonium sulfate, 1.700 for zinc chloride, and 3.454 for sodium chloride. Note that ammonium sulfate and zinc chloride are reversed from the ranking found in material treated with the three chemicals as indicated by the regression coefficient  $B$  for 80 percent relative humidity in table 1. These hygroscopicities for the salts, and the hygroscopicities for untreated wood from Appendixes B and C were substituted into equation (5) to give predicted moisture content values for specimens exposed under adsorbing conditions at the high relative humidity. The predicted moisture content is compared with measured moisture content in table 2.

The amount by which the estimated moisture content differs from the measured moisture content is indicated in column (12) of table 2. A

negative value indicates that the estimated moisture content is greater than the measured, while positive values indicate that the actual moisture content is higher.

The results for the two species parallel each other reasonably well. Where differences do exist, they can probably be attributed to the difference in specific gravity, and to the inability to exactly determine salt content in the wood. A third possibility for a difference is the tacit assumption that the hygroscopic properties of a salt in wood are the same as those of the pure, separate crystal. Actually, the salt in the cell wall is extremely subdivided and one would expect a somewhat different hygroscopic property. The differences between comparable values for pine and oak in column (8) of table 2 is, in part, an index of the magnitude of the specific gravity effect. With two exceptions, the nominal 4.5-pound retention of ammonium sulfate- and sodium

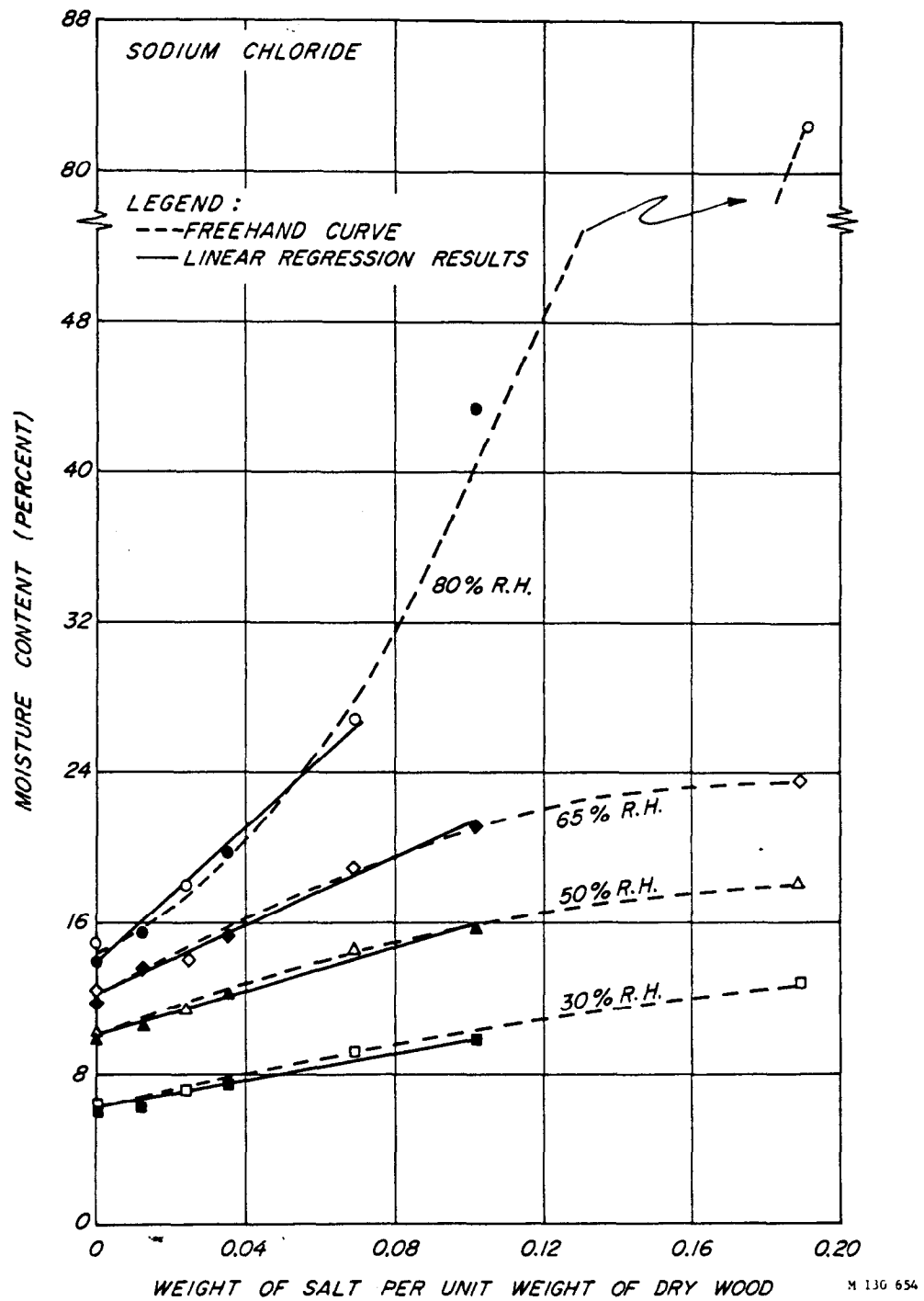


Figure 8.--Relationship between moisture content and the salt-wood weight ratio for sodium chloride. Solid symbols represent oak and the open symbols represent pine.

Table 1.--Regression results for moisture content versus the salt/wood weight ratio

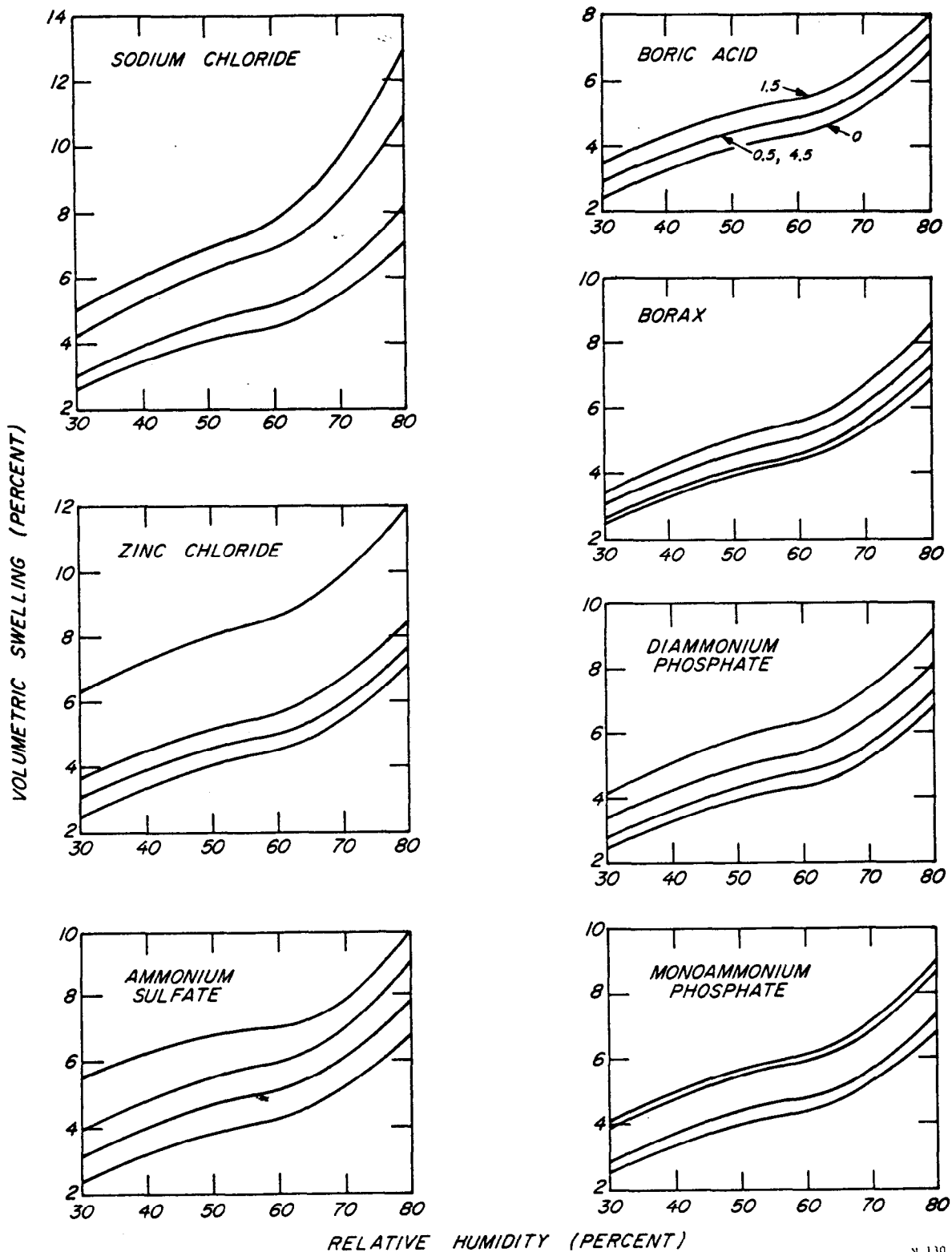
Chemical	Relative humidity	A <sup>1</sup>	B <sup>1</sup>	Coefficient of correlation	Number of specimens
	<u>Percent</u>				
Ammonium sulfate	80	0.1358	1.067	0.94	70
	65	.1173	.3176	.94	80
	50	.0963	.2474	.93	80
	30	.0558	.2205	.91	80
Sodium chloride	80	.1391	1.804	.99	60
	65	.1218	.9099	.93	70
	50	.1013	.5770	.98	70
	30	.0626	.3578	.99	80
Zinc chloride	80	.1414	.5636	.96	70
	65	.1186	.3449	.93	70
	50	.0992	.2705	.91	70
	30	.0607	.2227	.88	70

<sup>1</sup>Coefficients in the relation  $M = 100(A + Bx)$  where  $M$  is the moisture content (percent of untreated dry weight) and  $x$  is the weight of salt per unit weight of dry wood.

Table 2.--Estimated moisture content of treated wood compared to the measured moisture content at 80 percent relative humidity<sup>1</sup>

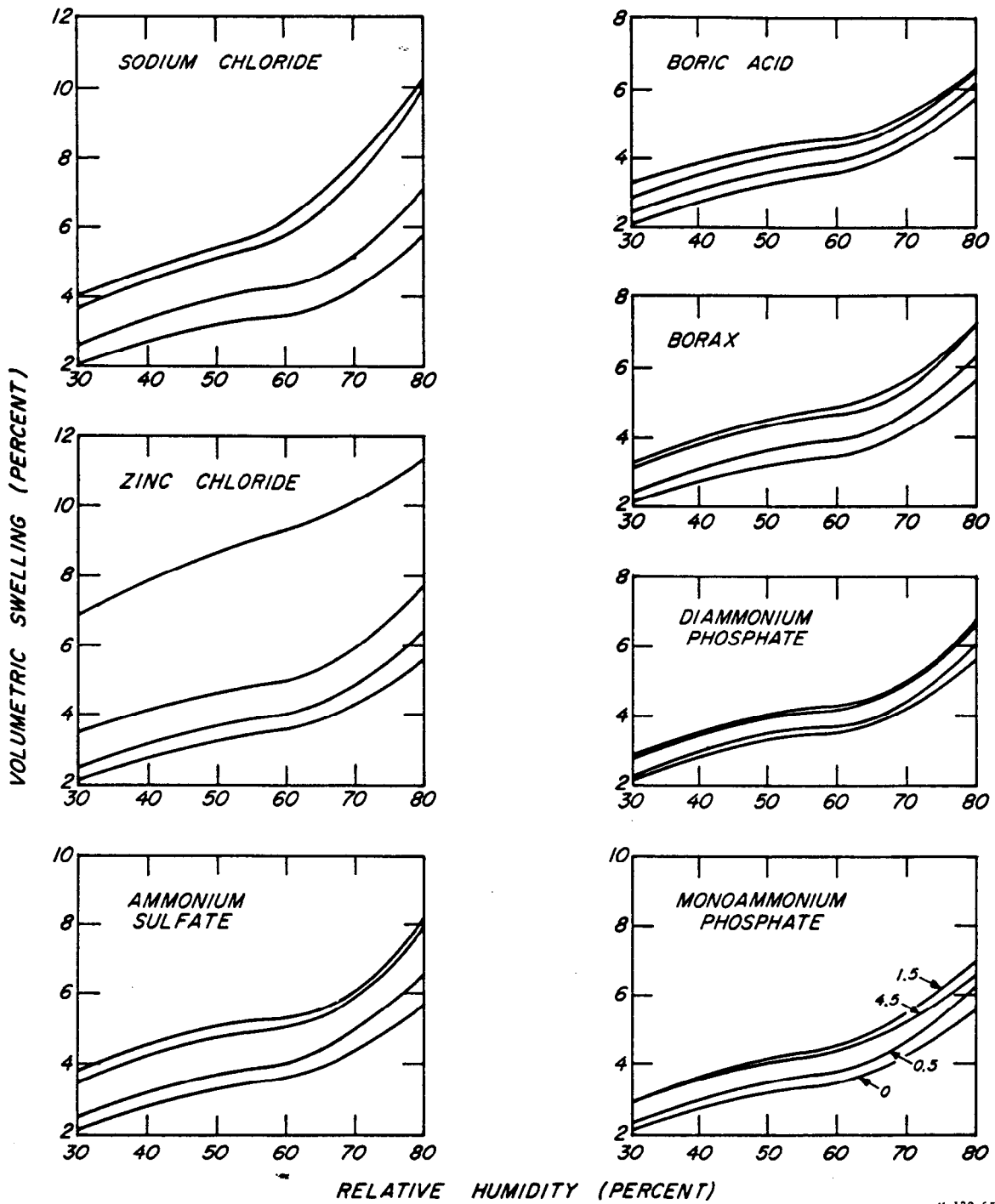
Species	Chemical	Nominal retention level	Oven-dry wt. of wood	Weight of salt	Salt hygroscopicity factor	Wt. water due to salt	M.C. expected by salt	M.C. expected by wood	Total M.C. expected	Actual M.C. measured	Interaction effect
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
		<u>Lb. per cu. ft.</u>	<u>G.</u>	<u>G.</u>		<u>G.</u>	<u>Pct.</u>	<u>Pct.</u>	<u>Pct.</u>	<u>Pct.</u>	<u>Pct.</u>
Oak	Ammonium sulfate	0.5	9.924	0.147	1.350	0.198	2.00	13.83	15.83	13.92	- 1.9
		1.5	9.893	.309	1.350	.417	4.22	13.83	18.05	15.49	- 2.5
		4.5	9.928	.732	1.350	.988	9.95	13.83	23.78	21.66	- 2.1
	Sodium chloride	0.5	9.941	.117	3.454	.404	4.06	13.88	17.94	15.39	- 2.5
		1.5	9.959	.348	3.454	1.202	12.08	13.88	25.96	19.67	- 6.3
		4.5	9.960	1.011	3.454	3.493	35.07	13.88	48.95	43.41	- 5.6
	Zinc chloride	0.5	9.920	.127	1.700	.216	2.18	13.90	16.08	14.04	- 2.0
		1.5	9.978	.288	1.700	.490	4.91	13.90	18.81	15.21	- 3.6
		4.5	9.961	1.012	1.700	1.720	17.28	13.90	31.18	19.72	-11.5
Pine	Ammonium sulfate	0.5	2.886	.070	1.350	.094	3.26	14.97	18.23	16.18	- 2.0
		1.5	2.891	.165	1.350	.223	7.71	14.97	22.68	20.51	- 2.2
		4.5	2.902	.531	1.350	.716	24.68	14.97	39.65	42.25	+ 2.6
	Sodium chloride	0.5	2.881	.070	3.454	.242	8.40	14.94	23.34	17.98	- 5.3
		1.5	2.892	.200	3.454	.691	23.90	14.94	38.84	26.83	-12.0
		4.5	2.866	.542	3.454	1.872	65.32	14.94	80.26	81.58	+ 1.3
	Zinc chloride	0.5	2.873	.070	1.700	.119	4.14	14.93	19.07	16.12	- 3.0
		1.5	2.893	.205	1.700	.348	12.03	14.93	26.96	18.53	- 8.5
		4.5	2.874	.659	1.700	1.120	38.97	14.93	53.90	33.86	-20.0

<sup>1</sup>All values in table are the averages of ten specimens except column (6) which is the average of two.  
 Column (7) = (5) x (6).  
 Column (8) = (7)/(4).  
 Column (9) = E.M.C. of untreated wood at 80% R.H. from Appendixes B and C (Adsorption cycle).  
 Column (10) = (8) + (9).  
 Column (11) = E.M.C. of treated wood at 80% R.H. from Appendixes B and C (Adsorption cycle).  
 Column (12) = (11) - (10).



N 130 643

Figure 9.--Oak: Volumetric swelling-relative humidity relationships for salt-treated wood and for untreated controls. Swelling is based on untreated dry volume. Except where indicated the four curves in each group represent, from top to bottom, nominal salt retentions of 4.5, 1.5, and 0.5 pounds per cubic foot, and the water-treated controls.



M 130 655

Figure 10.--Pine: Volumetric swelling-relative humidity relationships for salt-treated wood and for untreated controls. Swelling is based on untreated dry volume. Except where indicated the four curves in each group represent, from top to bottom, nominal salt retentions of 4.5, 1.5, and 0.5 pounds per cubic foot, and the water-treated controls.

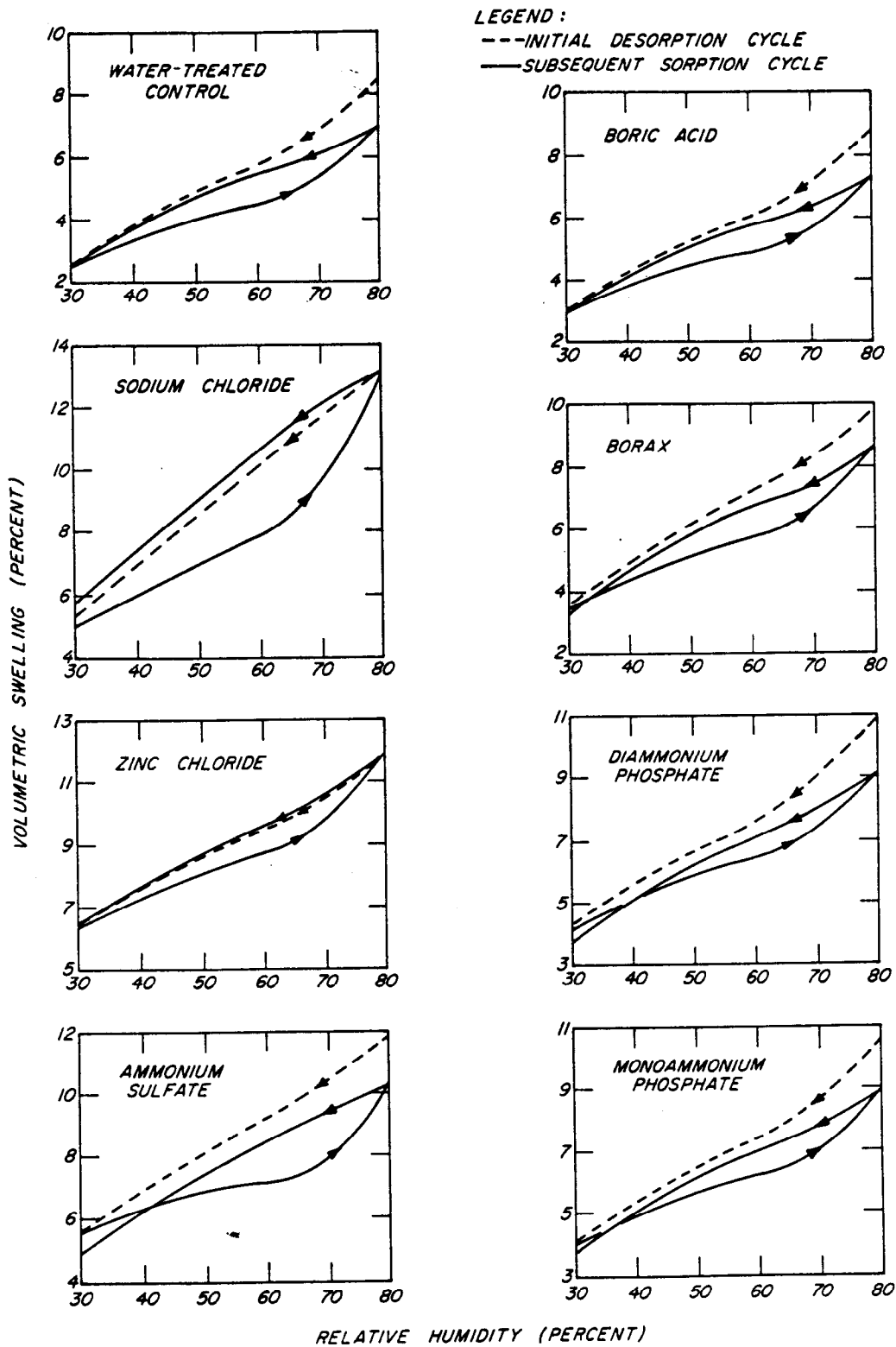


Figure 11.--Oak: Volumetric swelling-relative humidity relationships for wood treated to a nominal retention of 4.5 pounds per cubic foot. Swelling is based on untreated dry volume.

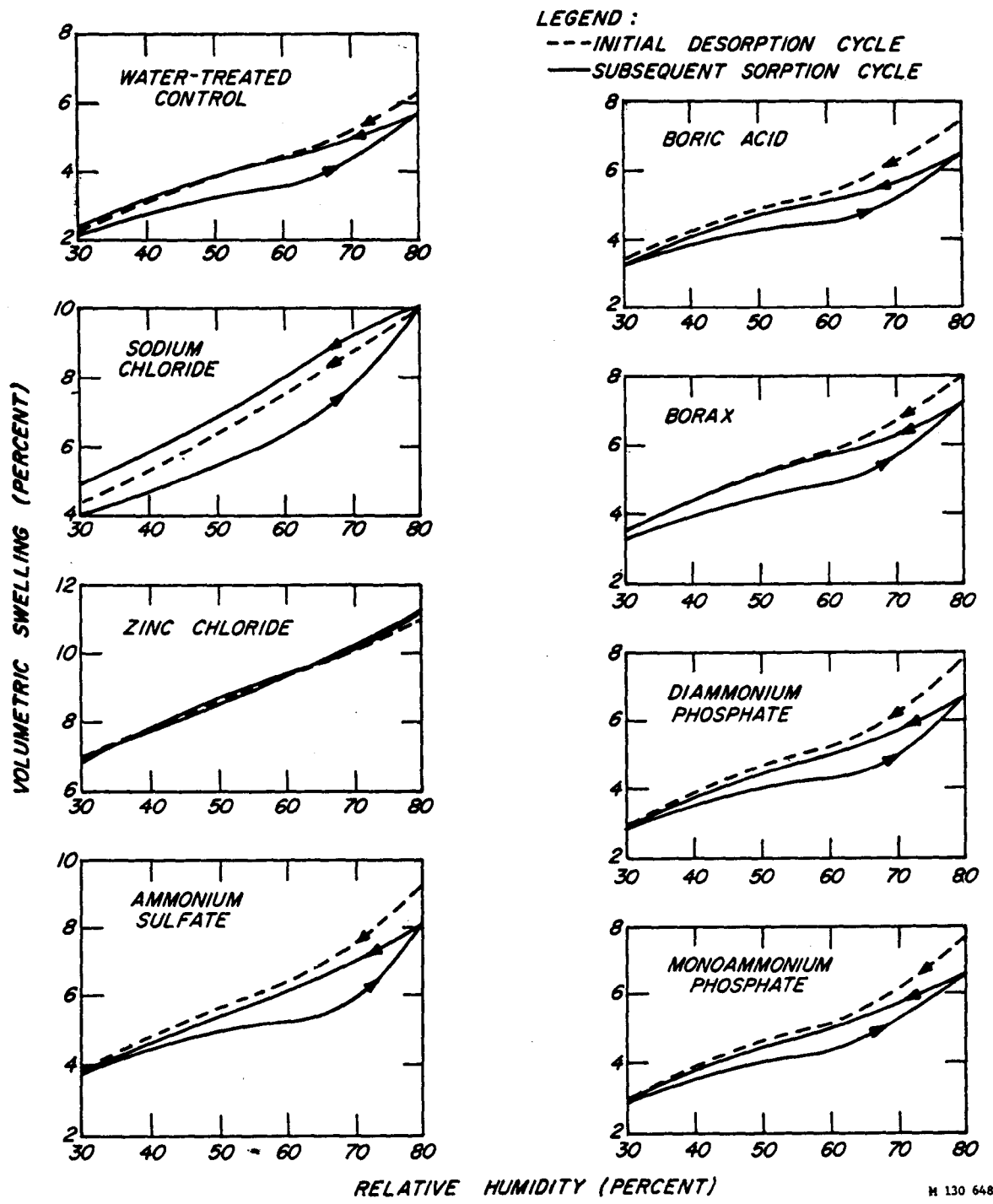


Figure 12.--Pine: Volumetric swelling-relative humidity relationships for wood treated to a nominal retention of 4.5 pounds per cubic foot. Swelling is based on untreated dry volume.

chloride-treated pine, the estimated moisture content is greater than the measured moisture content. These negative interactions perhaps suggest a mutual sharing of water by the wood and chemical or that the chemical reacts with cellulose to satisfy a portion of the adsorption sites. This mutual sharing or chemical reaction effect was much greater in zinc chloride at the 4.5-pound retention than either sodium chloride or ammonium sulfate. In the 4.5-pound zinc chloride treatment of pine it appears that there was mutual sharing of water or chemical satisfaction of all the wood sorption sites since the interaction effect was greater than the normal equilibrium moisture content of untreated wood. In sodium chloride and ammonium sulfate the effect appeared to maximize at or near the 1.5-pound retention. Thereafter it remained relatively the same in ammonium sulfate but decreased sharply in sodium chloride to the 4.5-pound retention.

Based upon the individual hygroscopicity of the chemical and the wood, certain generalizations can be made about the predicted equilibrium moisture of wood treated with the hygroscopic chemicals. In an atmosphere controlled at 80 percent relative humidity, ammonium sulfate-treated material will equilibrate at approximately the moisture content expected; zinc chloride-treated material will be somewhat lower than expected; and at high levels of retention sodium chloride-treated material will be approximately that estimated but perhaps somewhat less than expected at low retention levels.

#### Effect of Salts on Volumetric Swelling

Volumetric swelling data are presented in Appendixes D and E for oak and pine, respectively. Included are data collected during an initial desorption cycle and subsequent adsorption and desorption cycles for material treated with seven chemicals to three levels of retention, and the water-treated controls. Swelling in all cases has been based upon the untreated dry dimensions and includes swelling due to moisture and due to chemical bulking or the restraint of shrinkage upon drying.

##### Volumetric swelling versus relative humidity.--

Figures 9 and 10 show the relationship between volumetric swelling and relative humidity over the 30 to 80 percent relative humidity range evaluated for treated oak and pine and the water-treated

controls. These curves represent data obtained under adsorbing conditions.

Increased swelling occurred in all treated specimens, and this effect generally increased with increasing salt retention. The swelling is considerably greater in specimens treated with the three chemicals considered as having a permanent hygroscopic effect--ammonium sulfate, sodium chloride and zinc chloride--than in those treated with the nonhygroscopic chemicals. This reflects the fact that the swelling by the hygroscopic group is due to the combined effect of increased moisture content and to chemical bulking. Swelling by the nonhygroscopic group is largely a bulking effect only, with perhaps a slight effect due to increased moisture. In sodium chloride the increase in swelling due to treatment is minimum at the 30 percent humidity level and increases uniformly to a maximum at the 80 percent level. In all other treatments the increased swelling appears to be constant throughout the humidity range considered. In some instances, swelling reaches a maximum at or near the 1.5-pound retention level, with little additional swelling at the 4.5-pound level. In the 4.5-pound monoammonium phosphate treatment of pine and the boric acid treatment of oak the swelling was not as great as in the 1.5-pound treatments.

Figures 11 and 12 show volumetric swelling--relative humidity relationships for salt-treated and water-treated controls for the initial desorption cycle and subsequent adsorption and desorption cycles. With a few exceptions, the curves for treated material closely resemble those of the controls. The most obvious differences occur with the hygroscopic chemicals. In the sodium chloride-treated oak and pine, swelling was greater during the second desorption cycle than in the first, which is contrary to that of all other treated material, including the water-treated controls. Furthermore, some of the curves for the hygroscopic chemicals do not have the characteristic sigmoid shape. However, this is probably because at some point below 80 percent relative humidity the specimens reached the fiber saturation point because of the hygroscopicity of the chemical, and thereafter the swelling did not increase as the relative humidity increased to 80 percent. Although additional data points would be required between 65 and 80 percent relative humidity to show whether or not this is true, it seems very probable because the saturation vapor pressure of sodium chloride is about 75 per-

cent relative humidity.

It is interesting to note that essentially no hysteresis effect occurred in zinc chloride-treated pine: practically the same swelling values were obtained during both desorption cycles and the adsorption cycle.

These figures are particularly interesting when considered in retrospect with corresponding figures 3 and 4 that show the relationship between moisture content and relative humidity. High equilibrium moisture content values were obtained for boric acid-treated pine and oak and borax-treated pine during the initial desorption cycle, but the effect was not considered permanent because equilibrium moisture content values obtained during a later adsorption-desorption cycle were considerably lower. Generally, it seems the swelling curves would show an effect comparable to that of the moisture content-relative humidity curves. However, the swelling curves for borax and boric acid generally show an effect similar to that of other treated material and to the water-treated controls. Only the borax treatment of oak shows an effect comparable to the moisture content curves. This inconsistency indicates that swelling was probably internal and progressed into the cell cavity.

Chemical bulking.--Figures 13 and 14 show the moisture-swelling relationships for treated oak and pine obtained under adsorbing conditions. The swelling of treated material is greater than that of untreated material at any selected moisture content because of chemical bulking of the fibers. However, in those chemicals which are hygroscopic, this does not necessarily reflect all the bulking that occurred. It is possible with these chemicals that water normally in the cell wall for untreated wood is associated with salt in the cell cavities. If the water is held by the salt it will not cause the increase in volume of the wood normally associated with such a moisture content. If this is true, the bulking effect is greater than that shown by these curves.

The bulking effect characteristically increased with increasing retention to the 1.5-pound level in all but the boric acid treatment of pine. When increasing the retentions to the 4.5-pound level, however, several species-chemical combinations showed no further increase. In fact, in some instances a negative bulking is apparent at the 4.5-pound level. This negative bulking probably reflects the effect discussed in the preceding

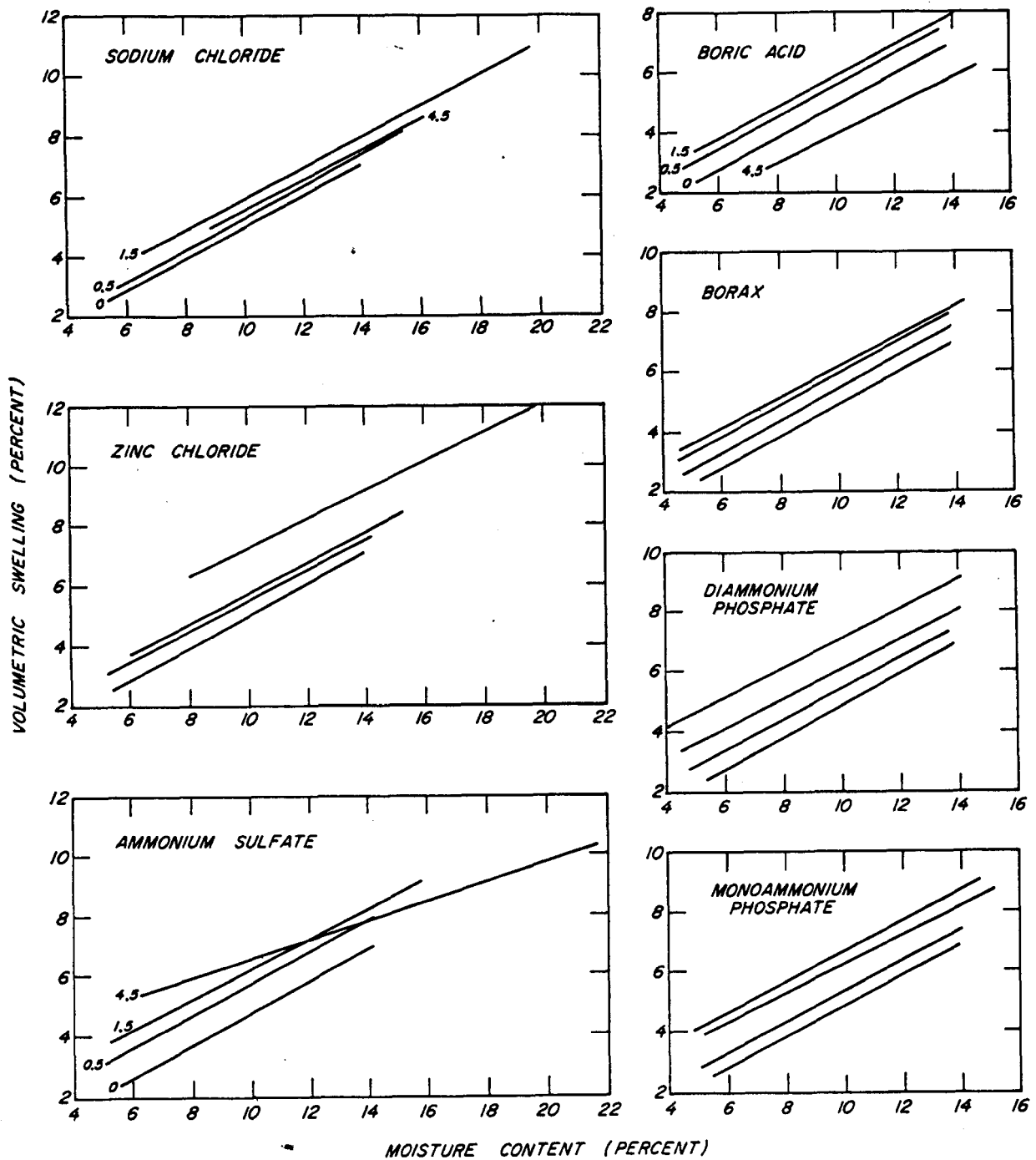
paragraph regarding the location of salt in the cell cavities. It is also possible that the cell is in a fully distended condition and additional swelling may progress internally into the cell cavity.

The hygroscopic character of some of the salts makes them a poor means of dimensionally stabilizing wood; additional swelling is caused by additional moisture adsorbed by the salt. However, even if the salts were not hygroscopic, at these levels of treatment, one would not expect much stabilization because of the relatively high density of the salts. Consider, for instance, a 20 percent treatment, that is, 20 grams of salt per 100 grams of wood. If the treatment is with material with a density of unity, bulking amounts to 20 cubic centimeters. If the treatment is with a material of a density of 2.0 or 3.0, only 10 or 7 cubic centimeters of bulking results.

The uniformity of the slopes of the moisture-swelling curves for treated material and for those of the controls shown in figures 13 and 14 indicates that bulking in general (except the 115-pound treatment of ammonium sulfate) is not an indication of improved dimensional stability with respect to changing moisture content. In fact, since all treated material showed a slightly increased rate of change in moisture content with respect to relative humidity, the dimensional stability can be expected to decrease by a corresponding amount. From the swelling-relative humidity curves in figures 9 and 10 it can be seen, however, that only in the case of sodium chloride is this effect of any significance. In specimens treated with this chemical to the 4.5-pound level, the total swelling or shrinkage over the 30 to 80 percent relative humidity range was approximately double that of the controls in both pine and oak.

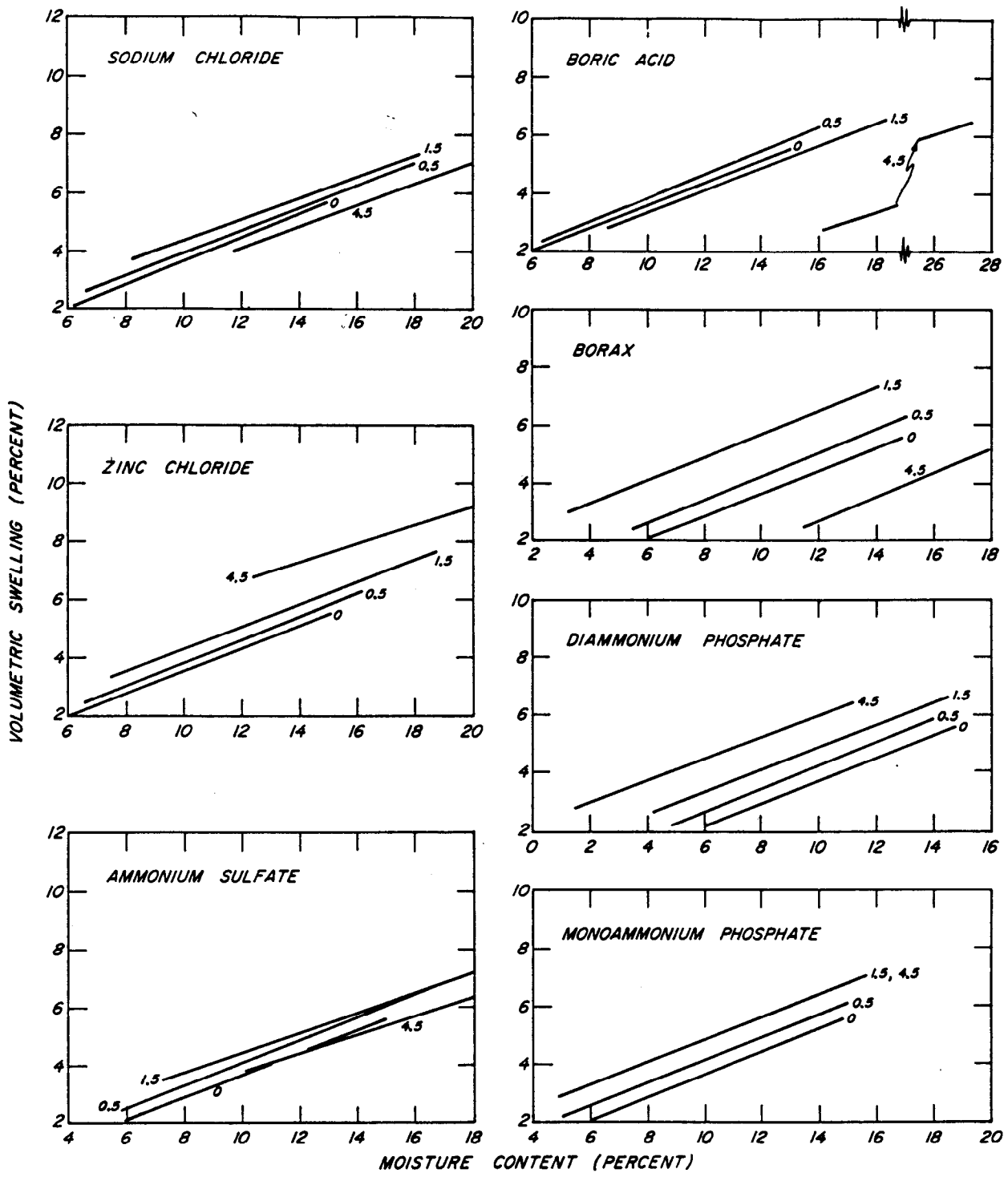
The lower slope of the moisture content-swelling curves of the 4.5-pound ammonium sulfate treatment (figure 13) indicates considerable dimensional stabilization with respect to moisture content changes. However, with respect to changing relative humidity, this is at least partially offset by the increased rate of change of moisture content with respect to relative humidity changes. Figures 9 and 10 show that the net effect results essentially in no change in the dimensional stability of oak and only a slight decrease in pine.

Excess swelling.--Excess swelling, or the dif-



M 130 647

Figure 13.--Oak: Moisture-swelling relationships for treated wood under adsorbing conditions. Swelling is based on untreated dry volume. Except where indicated the four curves in each group represent, from top to bottom, nominal salt retentions of 4.5, 1.5, and 0.5 pounds per cubic foot, and the water-treated controls.



H 130 646

Figure 14.--Pine: Moisture-swelling relationships for treated wood under adsorbing conditions. Swelling is based on untreated dry volume. Numbers on lines indicate nominal salt retention in pounds per cubic foot.

ference in swelling between treated and untreated specimens, is plotted as a function of salt retention in figure 15; data were obtained under adsorbing conditions. Although these curves represent swelling measurements obtained at 65 percent relative humidity, they should apply reasonably well at other levels of humidity in the 30 to 80 percent range, since in figures 9 and 10 it was shown that the increase in swelling due to treatment was generally constant in the range of humidities investigated. Sodium chloride-treated material is an exception, and the use of the curves in figure 15 must be limited to 65 percent relative humidity, as in this instance the excess swelling due to treatment increased with increasing relative humidity.

For a given chemical, the swelling-salt retention relationship for the two species is quite similar and generally appears to be linear in the 0- to 1.5-pound nominal retention range. The rate of swelling decreases quite sharply when the salt retention increases from the 1.5-pound to the nominal 4.5-pound level and in some instances is maximum at the 1.5-pound level. In zinc chloride, the relationship is linear throughout the retention range considered for oak, whereas in pine the rate of swelling increases throughout the range.

In terms of the relative excess swelling caused by the various chemicals, it is apparent from the curves in figure 15 that the swelling caused by the hygroscopic chemicals ammonium sulfate, sodium chloride, and zinc chloride is considerably greater than that of the nonhygroscopic group. In the hygroscopic group, the excess swelling is greatest in the zinc chloride treatments, least in ammonium sulfate, and intermediate in sodium chloride. Excess swelling of approximately 6 percent for pine and 4 percent for oak was noted for the nominal 4.5-pound zinc chloride treatments, while at the same nominal retention level the excess swelling was approximately 3 and 3-1/2 percent for the sodium chloride treatments of pine and oak and approximately 1-1/2 and 2-1/2 percent in the ammonium sulfate treatments.

#### Effect of Salts on the Anisotropic Swelling-Shrinkage Properties

It is well known that wood shrinks more in the tangential direction than in the radial direction

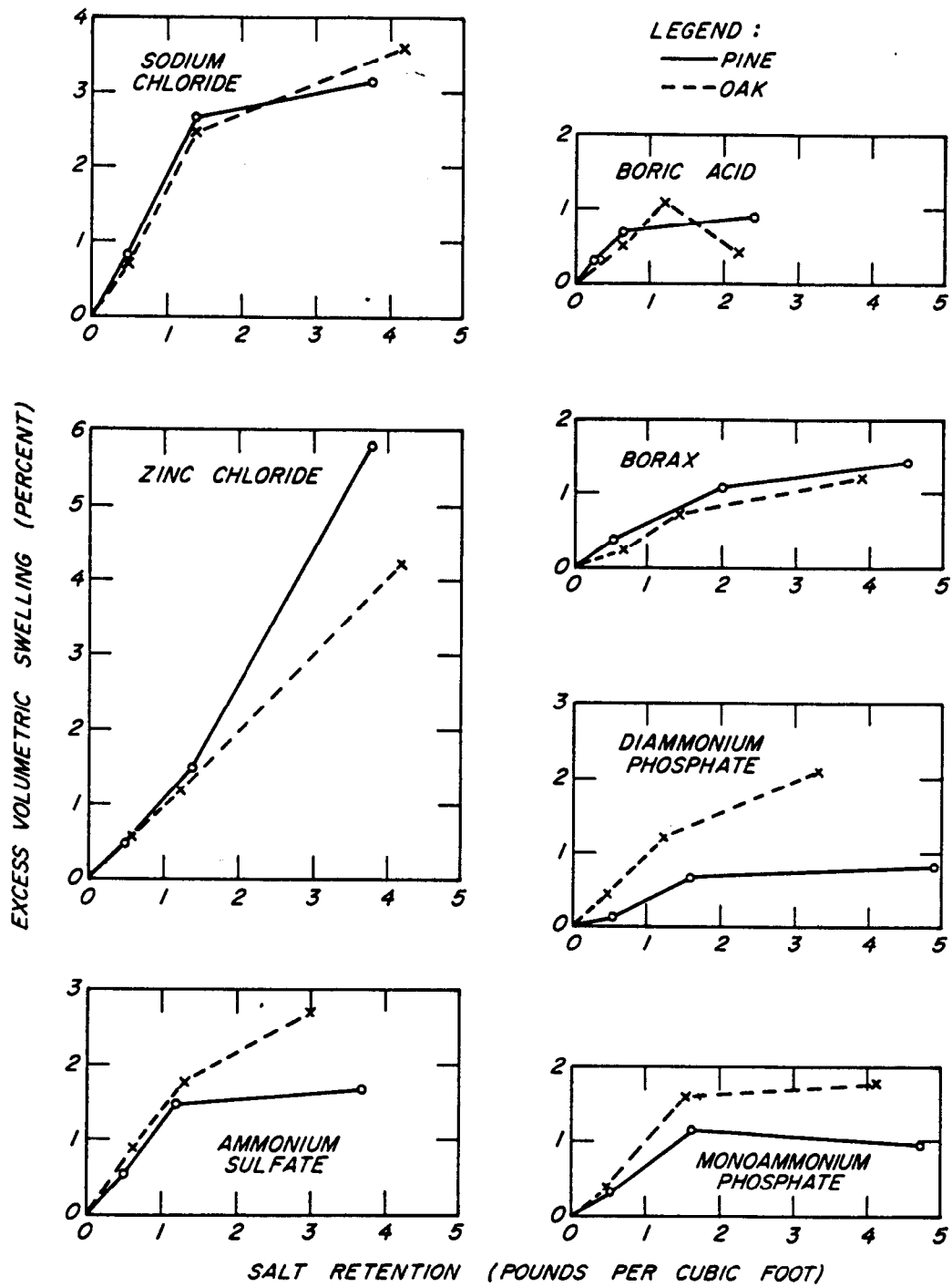
This differential transverse shrinkage or anisotropy of wood is responsible for the distortion that occurs in a piece of wood as it dries. As the degree of anisotropy increases, so does the distortion. Also, for a given amount of volumetric swelling, it is likely that the perpendicular-to-grain stresses developed during drying will increase with increasing anisotropy, making it more difficult to dry wood without degrade. It is important, therefore, that the transverse swelling and shrinkage also be considered.

Tangential and radial swelling data for treated oak and water-treated controls are presented in Appendixes F and G, respectively. Comparable data for pine are presented in Appendixes H and I.

In figures 16 and 17 for oak and pine, respectively, the transverse swelling-relative humidity relationships are shown for the water-treated controls and for specimens treated with the various chemicals to the three nominal retention levels. These curves are quite similar to those shown in figures 9 and 10 for the volumetric swelling. As in figures 9 and 10, these curves reflect total swelling due to increased moisture content, where this is an effect, and to chemical bulking. It is apparent that the increase in swelling due to treatment, as measured by the vertical distance between the curves representing treated material and those of the appropriate controls, is greater in the tangential direction than in the radial. As would be expected from previous discussion of volumetric swelling, the increase in transverse swelling was greatest in specimens treated with the hygroscopic chemicals ammonium sulfate, sodium chloride, and zinc chloride.

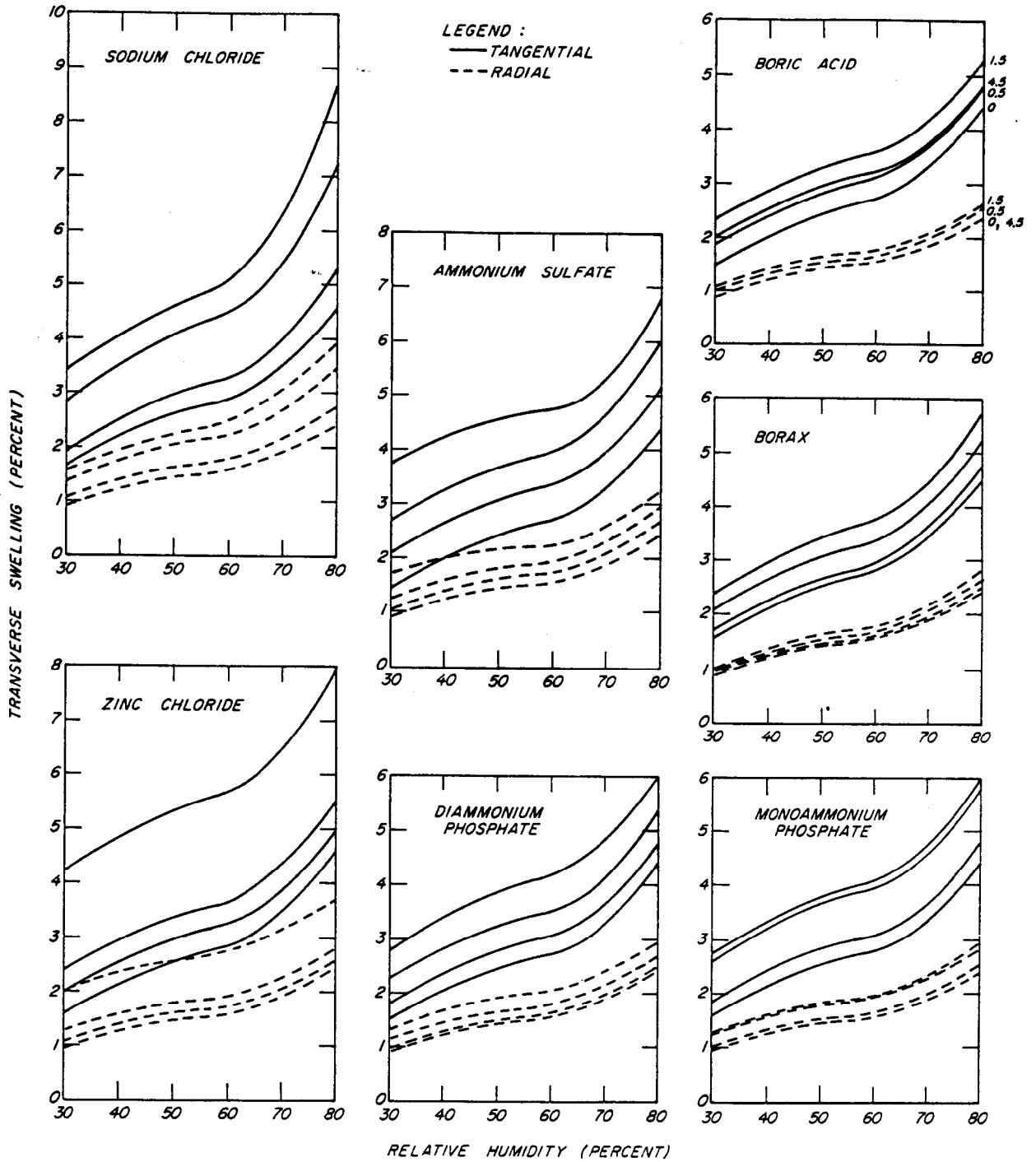
The greater overall tangential swelling and the greater slope of the tangential swelling curves characterizes the anisotropic properties of the treated and untreated material, but it is difficult to analyze this effect from these curves. This will be discussed later in conjunction with other figures.

In figures 18 and 19, for oak and pine, respectively, the excess transverse swelling due to treatment (in excess of the water-treated controls) is plotted as a function of salt retention. For all combinations of chemicals and species, it is apparent that the excess tangential swelling exceeds that of the radial at all levels of retention. This was expected in specimens treated with the hygroscopic chemicals, since at least part of the excess swelling was due to increased



M 130 652

Figure 15.--Excess swelling due to treatment at 65 percent relative humidity (adsorbing conditions). Swelling is based on untreated dry volume.



M 130 650

Figure 16.--Oak: Transverse swelling-relative humidity relationships for treated wood and for untreated controls (adsorbing conditions). Swelling is based on untreated dry volume. Except where indicated the four curves in each group represent, from top to bottom, nominal salt retentions of 4.5, 1.5, and 0.5 pounds per cubic foot, and the water-treated controls.

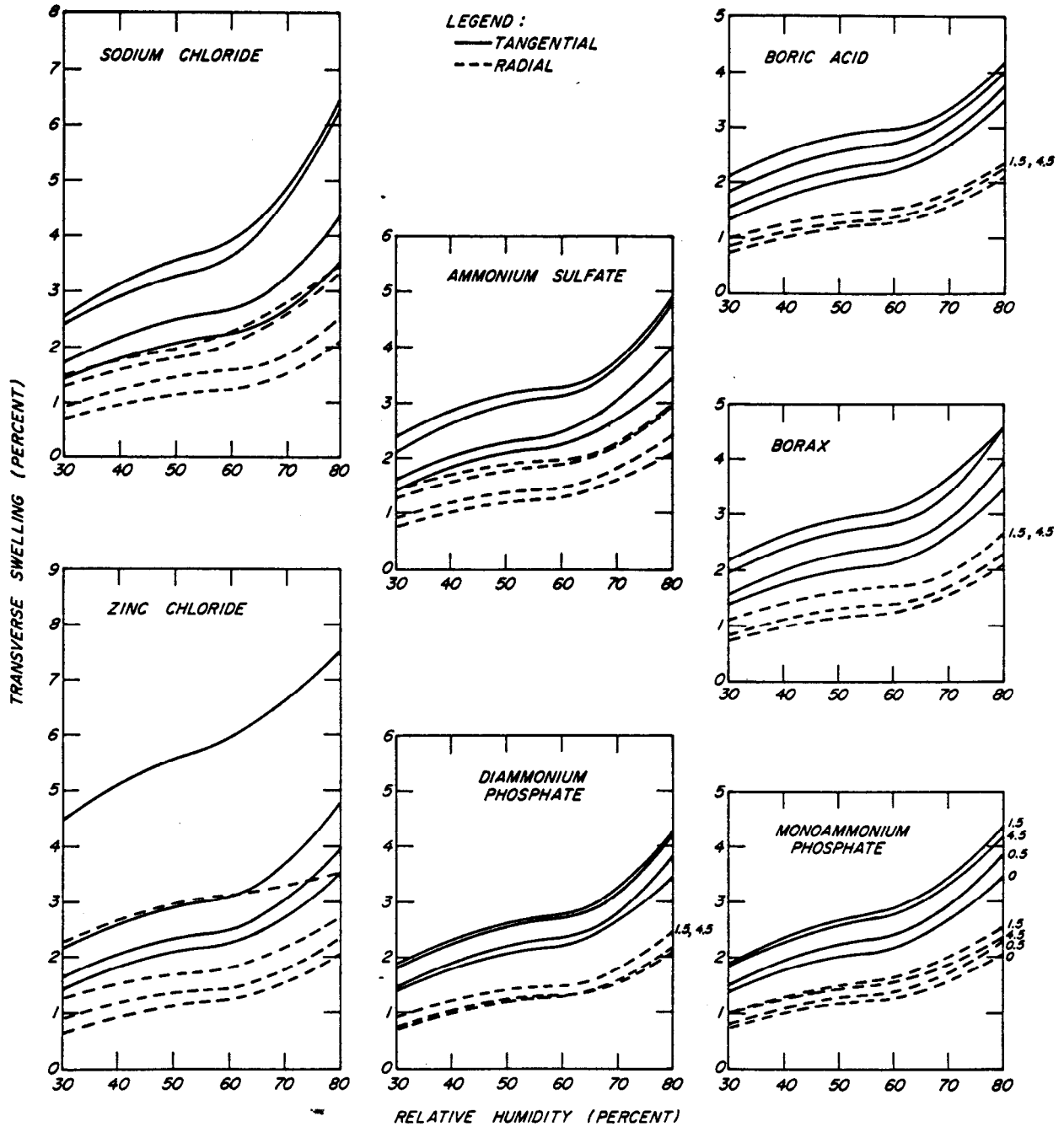
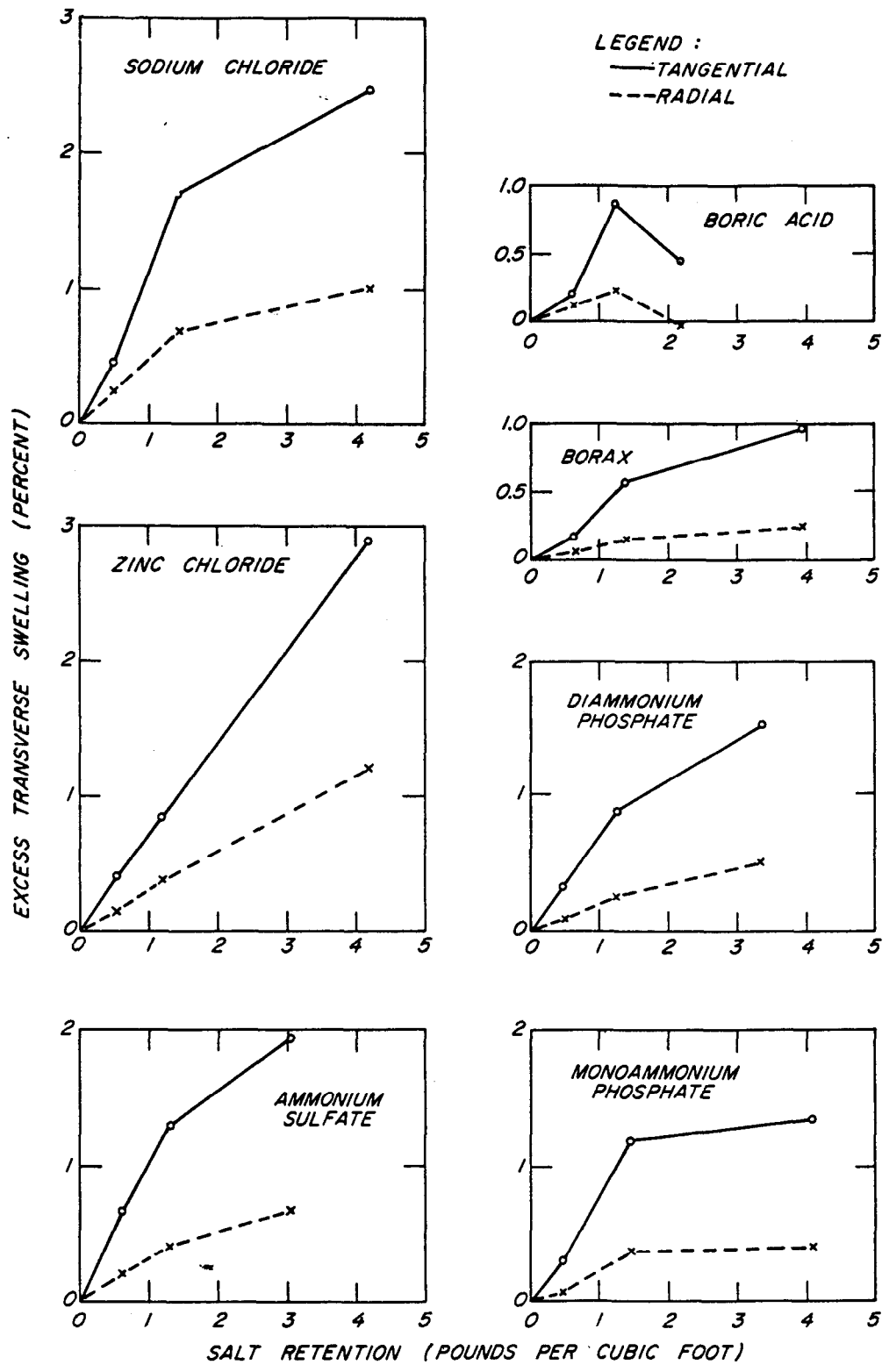
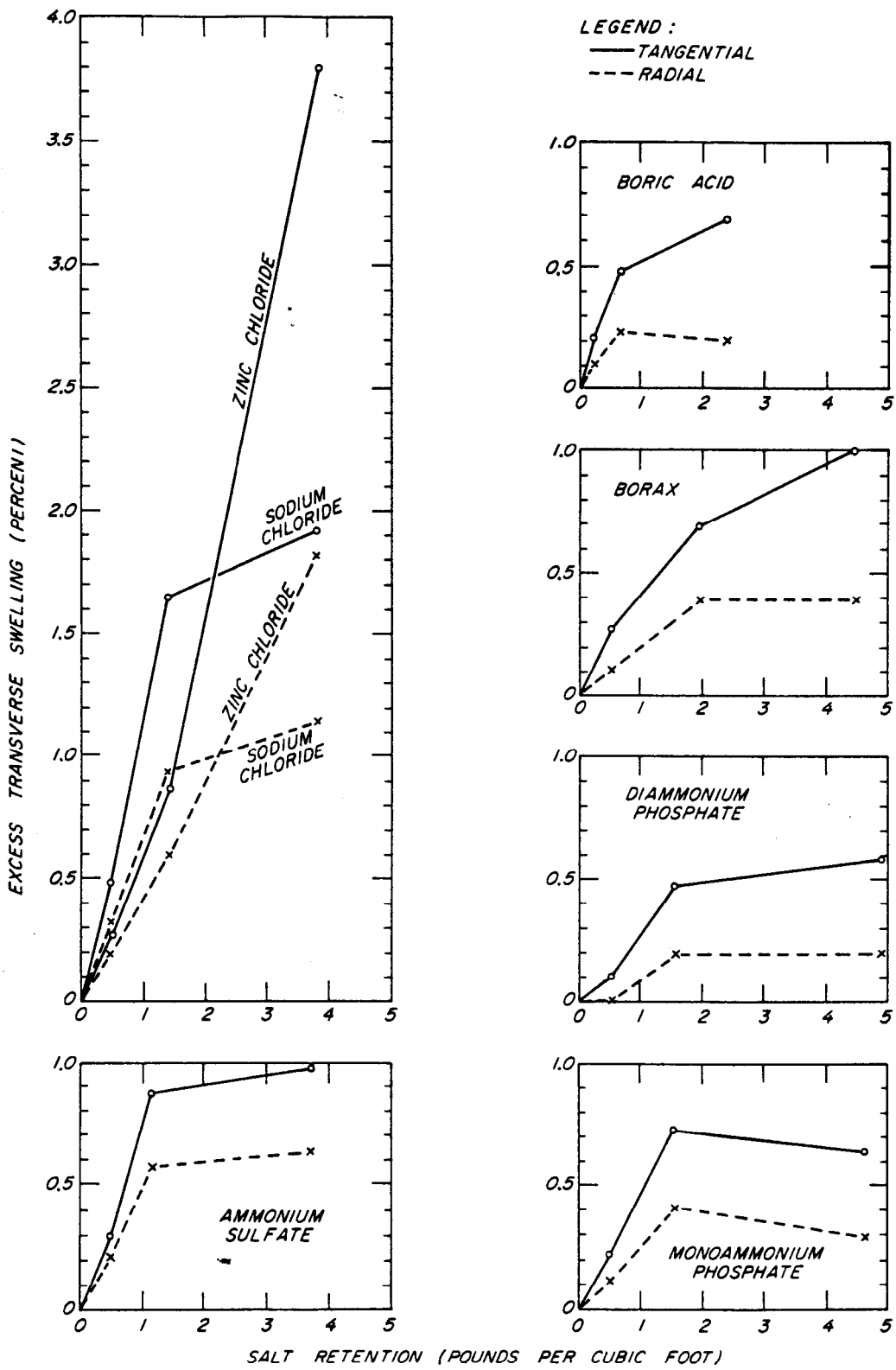


Figure 17. --Pine: Transverse swelling-relative humidity relationships for treated wood and for untreated controls (adsorbing conditions). Swelling is based on untreated dry volume. Except where indicated the four curves in each group represent, from top to bottom, nominal salt retentions of 4.5, 1.5, and 0.5 pounds per cubic foot, and the water-treated controls.



H 130 641

Figure 18.--Oak: Excess transverse swelling in wood at 65 percent relative humidity due to treatment (adsorbing conditions). Swelling is based on untreated dry volume.



M 130 645

Figure 19.--Pine: Excess transverse swelling in wood at 65 percent relative humidity due to treatment (adsorbing conditions). Swelling is based on untreated dry volume.

moisture content. It is interesting to note that the excess swelling due to bulking, as indicated by those specimens treated with nonhygroscopic chemicals, is greater in the tangential direction than in the radial. It appears that this anisotropic phenomenon always occurs with respect to dimensional changes whether it is because of swelling by water, thermal expansion strain caused by external loading, or other factors.

The degree of anisotropy in wood is commonly expressed as the T/R ratio or the ratio of the tangential shrinkage to the radial shrinkage. It is usually determined on the total shrinkage from the green to the dry condition and is generally assumed to be constant at all intermediate moisture conditions. Ratios of T/R calculated at various equilibrium moisture conditions in the 30 to 80 percent relative humidity range for treated and untreated material are shown in figures 20 and 21 for oak and pine, respectively. These ratios are computed from swelling measurements that are based upon dry dimensions; however, the only effect resulting from this technique is a slight increase in the T/R value because of the difference in bases involved in computing swelling or shrinkage. Relative differences between humidity levels are not affected.

It is interesting to note that the T/R ratios are not constant at different moisture levels. Pine control groups generally show an overall decrease in the ratio going from 30 to 80 percent relative humidity and appear to resemble quite closely the mirror image of the sigmoid-shaped sorption curves. In oak the various control groups generally show an increased T/R ratio going from 30 to 80 percent relative humidity.

In treated oak specimens the ratio increased with increasing chemical retention for all treatments. The effect of treatment was especially pronounced at 30 percent relative humidity, where the average change for the seven chemicals was from approximately 1.7 for the controls to 2.2 for the 4.5-pound nominal retention level. This increase in anisotropy of oak due to treatment makes drying without checking more difficult.

The T/R curves for treated pine are not as consistent between chemicals and between treatment levels as those for oak. Similar to the controls, however, there is an overall tendency for the ratio to increase with decreasing relative humidity. The T/R ratio of pine when treated with the nonhygroscopic chemicals generally in-

creased with increasing retention, which is similar to, but not as great as that noted for oak. In treatments by the hygroscopic chemicals, however, the tendency is toward a decreasing T/R ratio at higher retentions, particularly as drying progressed to the 30 percent relative humidity level.

#### Distribution of Salt in the Wood

The distribution of salt between the cell walls and the cell cavities may be important in understanding the nature of the effect of chemicals on the strength and related properties of treated wood. The data obtained make it possible to estimate the relative amounts of the total impregnated salt located in the cell walls and in the cell cavities at the various equilibrium conditions studied. Required in the calculations are: the untreated dry weight and volume of the specimen, the moisture content and volume of the specimen at the equilibrium moisture condition under consideration, the weight of the impregnated salt, and the density of the salt involved. The equation for computing the salt distribution is:

$$S = \frac{100D \left[ (V_T - V_D) - \left( \frac{MW_D}{100} \right) \right]}{W_S} \quad (6)$$

where S = amount of salt located in the cell wall (percent of impregnated salt by weight)

$V_T$  = volume of specimen at equilibrium moisture content considered (cubic centimeter)

$V_D$  = untreated dry volume (cubic centimeter)

M = moisture content at same equilibrium moisture content as  $V_T$  (percent untreated dry weight)

$W_D$  = untreated dry weight of the specimen (gram)

D = density of the salt

$W_S$  = total weight of salt in the specimen (gram).

In this equation,  $V_T - V_D$  represents the total change in volume because of chemical bulking and swelling with water from the untreated dry condition to the equilibrium moisture condition

being considered, and  $\frac{MW_D}{100}$  represents the increase in volume because of swelling with water alone (cgs system only). The difference between the total increase in volume and the increase due to water,  $(V_T - V_D) - \frac{MW_D}{100}$ , represents the increase in volume because of chemical bulking. Multiplying the calculated volume increase due to bulking by the density of the salt gives the weight of the salt required to do the bulking. This also represents the weight of salt in the cell walls.

In equation (6) it is assumed that, (a) 1 gram of water swells wood by 1 cubic centimeter, (b) the salt exists in the same state or at least at the same density in the specimen as when the density measurement was made, and (c) lumen diameter is not changed by treatment. It is known that the first assumption is not true because a part of the adsorbed water is compressed by adsorption forces. This results in slightly less than a cubic centimeter of swelling for an increase of 1 gram of water. This effect is most pronounced at lower equilibrium conditions because the first water adsorbed is compressed to the greatest extent. By including a factor,  $K$ , this effect can be corrected for and equation (6) becomes

$$S = \frac{100D \left[ (V_T - V_D) - \left( \frac{KMW_D}{100} \right) \right]}{W_S} \quad (7)$$

$$\text{where } K = 100 \left( \frac{V_T - V_D}{MW_D} \right)_c \quad (8)$$

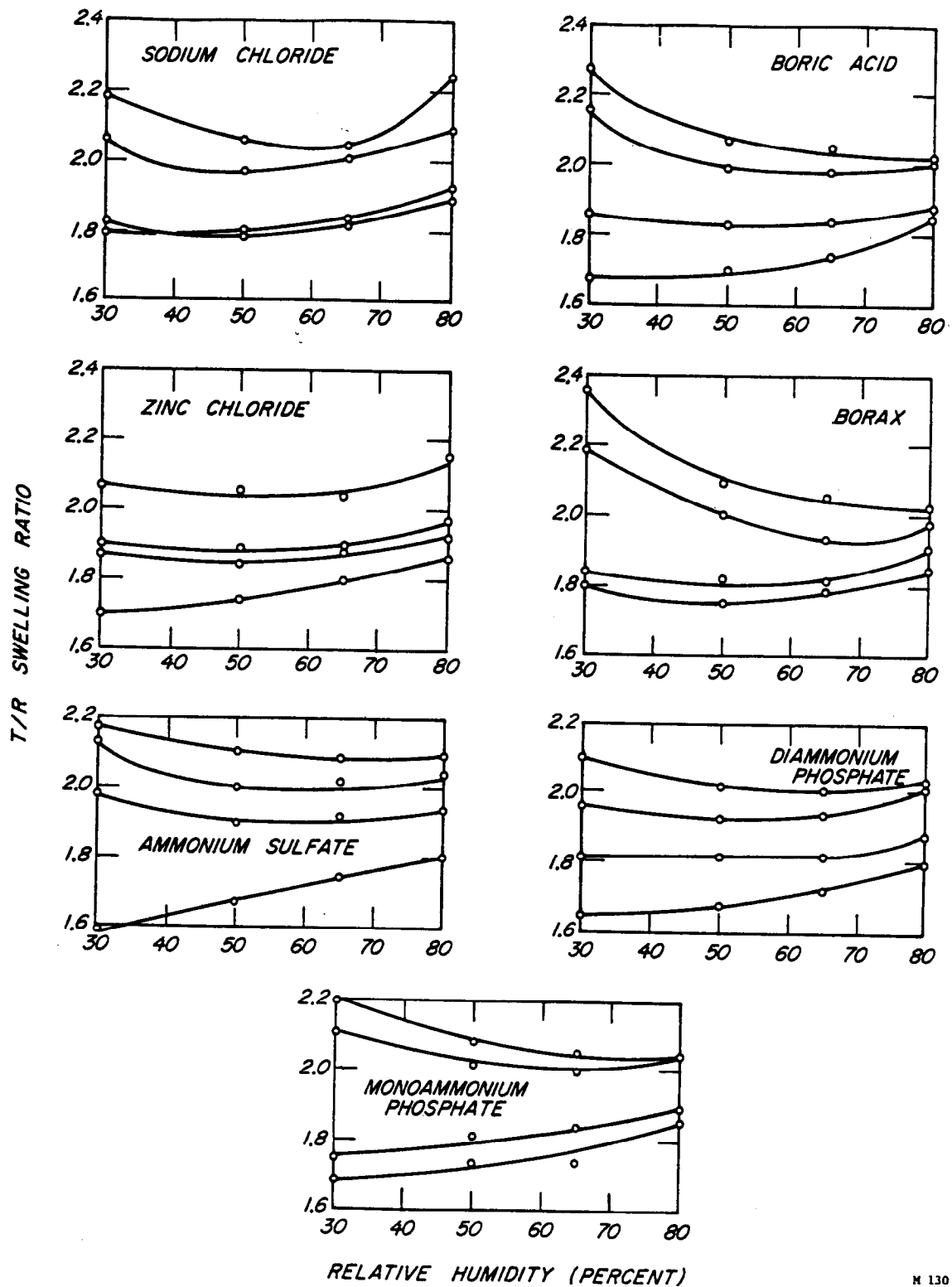
The symbols for equation (8) are the same as for (6) except they represent values for the appropriate untreated controls, as indicated by the subscript  $c$ . Since  $K$  varies with temperature and relative humidity, it was necessary to determine  $K$  for each atmospheric condition considered.

Table 3 shows the percent by weight of the total impregnated salt that is located in the cell wall when calculated by equation (7). The data were obtained under adsorbing conditions and represent measurements for three levels of salt retention for each combination of two species and seven chemicals.

All values in the table would be expected to range between 0 and 100 percent: however, there are numerous exceptions at each extreme of this range. This can be attributed, at least partially, to experimental error, as the measurements are, admittedly, somewhat crude for this type of calculation. Nevertheless they are sufficiently accurate to indicate differences between species, chemicals, and retention levels. A possible source of error in these data may be the water that is adsorbed to salt present in the cell cavities, thus not affecting swelling. The negative values in the table can be attributed to this effect as these values are limited to those chemicals which were previously shown to be either temporarily or permanently hygroscopic. The values greater than 100 percent suggest an interaction effect and this is entirely realistic as certain inorganic salts are known to be cellulose solvents which disperse the wood fibers or cause the diameter of the lumen to increase (6 pp. 73-74). The data for the nonhygroscopic phosphate compounds are probably the most accurate. There are no negative values which is consistent with the previous discussion in that there should be no water adsorbed to the salt in the cell cavities. The values for these chemicals greater than 100 percent are probably indicative of the magnitude of the error involved in the methods used.

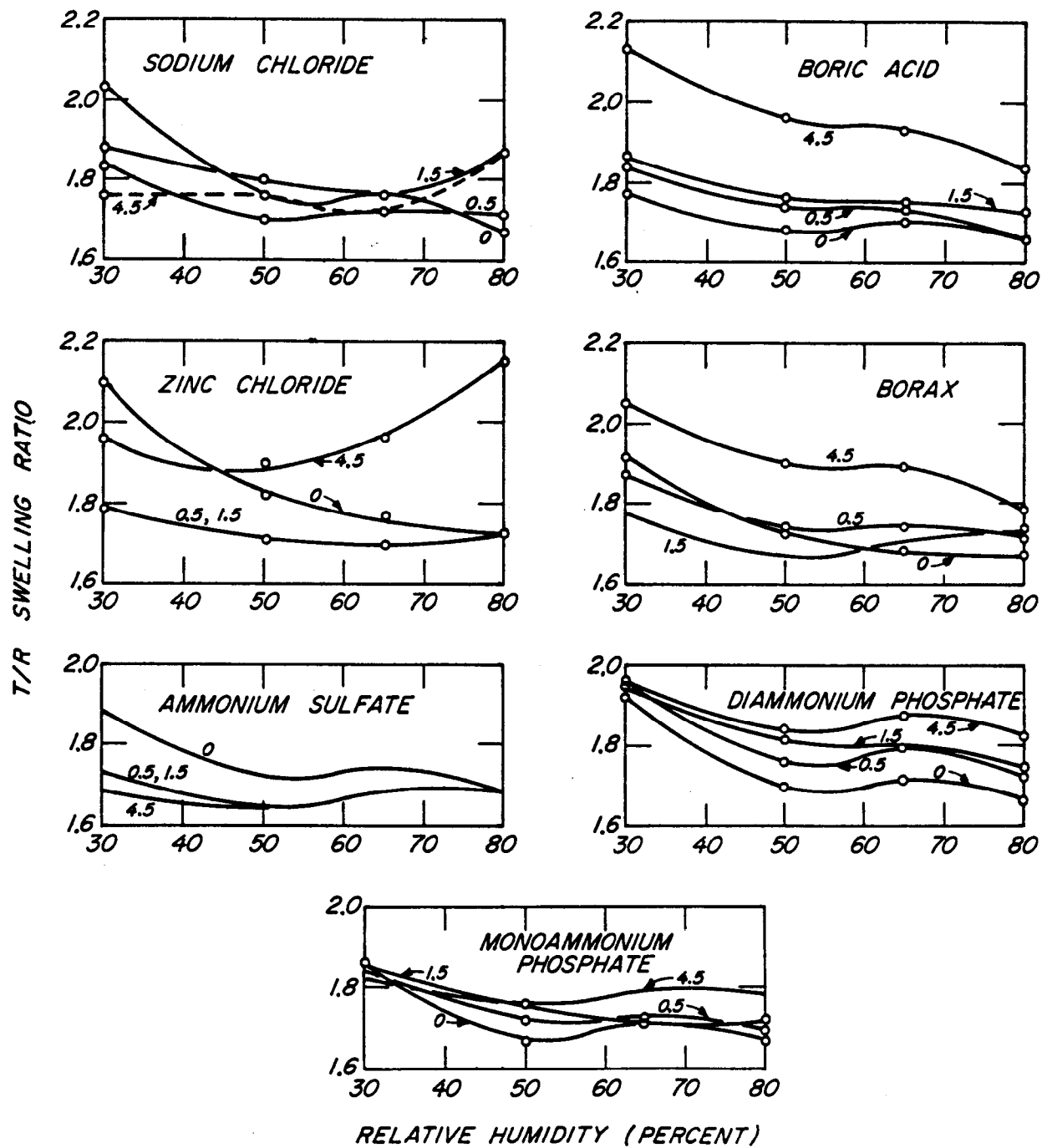
Generally speaking, there is a larger percentage of salt located in the cell walls in oak than in pine, and in both species this percentage decreases with increasing retention level. The greater percentage in oak reflects the difference in specific gravity, because there is more cell wall substance per unit of gross wood volume. The decrease in percentage with increasing retention does not necessarily indicate a decrease in the absolute amount of salt in the cell wall but that the cell walls are approaching a saturated condition. The addition of more salt results in practically all of it being situated in the cell cavities.

Of all the chemicals, zinc chloride provided the largest percentage of salt in the cell walls. Even at the 4.5-pound retention level, particularly at the lower humidity levels, the data show that all or nearly all of the salt is located in the cell walls. This reflects, as was previously shown, that the excess swelling due to treatment is greatest with zinc chloride. It is likely that treatments to higher levels of retention with



M 130 658

Figure 20.--Oak: Relationship between the tangential/radial swelling ratio and relative humidity for treated wood and for untreated controls (adsorbing conditions). The four curves in each group represent, from top to bottom, nominal salt retentions of 4.5, 1.5, and 0.5 pounds per cubic foot, and the water-treated controls.



N 130 657

Figure 21.--Pine: Relationship between the tangential/radial swelling ratio and relative humidity for treated wood and for untreated controls (adsorbing conditions). Numbers associated with lines indicate nominal salt retention level in pounds per cubic foot.

Table 3.--Estimated distribution of impregnated salt between the cell walls and cell cavities<sup>1</sup>

Chemical	Nominal retention level	Percent of total salt that is located in the cell wall							
		Oak				Pine			
		30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	80 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.
	$\frac{\text{lb. salt}}{\text{cu. ft.}}$								
ammonium phosphate	0.5	128	145	24	108	59	85	86	80
	1.5	111	104	63	84	72	78	76	71
	4.5	72	71	54	59	46	44	47	41
monoammonium phosphate	0.5	100	144	111	127	54	84	75	140
	1.5	110	118	107	98	80	86	92	86
	4.5	50	53	52	53	27	25	29	26
borax	0.5	79	74	89	91	82	115	113	150
	1.5	76	74	79	78	103	118	117	120
	4.5	39	38	39	31	-32	-25	-24	-46
boric acid	0.5	104	99	97	105	32	91	117	101
	1.5	73	72	72	66	-19	-30	-21	-39
	4.5	-29	-40	-49	-52	-109	-125	-130	-124
sodium chloride	0.5	198	192	184	173	41	72	78	53
	1.5	146	144	132	120	51	50	47	-14
	4.5	97	72	61	-22	-6	-6	-12	-56
zinc chloride	0.5	97	94	120	97	96	105	118	98
	1.5	108	110	113	95	69	74	85	-3
	4.5	28	28	29	-7	-3	-3	13	15
ammonium sulfate	0.5	207	194	184	126	162	148	63	119
	1.5	118	105	112	91	127	112	91	89
	4.5	106	99	96	77	113	110	82	71

<sup>1</sup>Each value in table is the average of ten specimens.

this chemical would result in even larger amounts of salt located in the cell walls because of the high water solubility of this chemical. Of the seven chemicals, it appears that the relative amount of salt located in the cell walls is minimum in the borax and boric acid treatments which is commensurate with their low solubility.

## SUMMARY and CONCLUSIONS

This research considers the effect of several inorganic salts, commonly used in commercially formulated treating solutions, on the sorption and swelling properties of ponderosa pine and red oak. Salts evaluated were diammonium and monoammonium phosphate, borax, boric acid, sodium chloride, zinc chloride, and ammonium sulfate. Treatments were conducted to three nominal levels of retention--4.5, 1.5, and 0.5 pounds of salt per cubic foot of wood, and the water-treated controls. Observations necessary to determine equilibrium moisture content and

shrinkage and swelling data were made during drying from a saturated condition following treatment (initial desorption cycle), during a subsequent adsorption cycle, and during a final desorption cycle, all at a constant temperature of 80° F. These cycles were limited to the 30 to 80 percent relative humidity range, humidities which are comparable to conditions normally encountered in service,

In terms of their effect on the apparent moisture content of wood, the seven chemicals considered can be separated into three groups. One group, which includes the phosphate treatments only, showed no significant change in equilibrium moisture content values. A second group, represented by borax and boric acid, was characterized by a substantial increase in moisture content throughout the 30 to 80 percent relative humidity range during the initial desorption cycle. However, this effect was not as pronounced during subsequent adsorption and desorption cycling. Also, after the specimens of this group were oven-dried, they were again subjected to an additional adsorption cycle and the equilibrium

moisture content values obtained were nearly comparable to those of the controls. In view of these considerations and the fact that these chemicals themselves are not hygroscopic, it is believed that the increased moisture content noted for borax and boric acid treatments is not a permanent effect. Kiln drying to a desired moisture content or sufficient air-drying time after treatment will probably reduce the increased moisture observed during the initial desorption cycle to a moisture content more nearly normal.

A third group included sodium chloride, zinc chloride, and ammonium sulfate. This group was characterized by a substantially increased moisture content throughout the relative humidity range considered. However, the increases in moisture content due to treatment with these three chemicals were generally not as great as would be expected based upon the individual hygroscopicity of the chemical and the wood. This effect was particularly pronounced in the zinc chloride treatments. Also, the relative increases in moisture content due to treatment with the three chemicals were not as would be expected. The treated wood, ranked in order of decreasing moisture content, contained sodium chloride, ammonium sulfate, and zinc chloride; the chemicals when ranked in order of decreasing hygroscopicity are sodium chloride, zinc chloride, and ammonium sulfate.

The increases in moisture content as a result of treatment with chemicals in the third group were considerably greater in pine than in oak when expressed as a percent of the oven-dry weight of the specimen. However, it was also observed that this moisture difference was inversely proportional to the difference in specific gravity of the two species. When moisture content values at various levels of relative humidity were plotted as a function of salt retention with retentions expressed in terms of a salt-wood weight ratio (grams of salt per 100 grams of dry wood), it was found that the data for one chemical treatment of both species could be combined. Although in some instances these relationships were curvilinear, it was observed that in all instances a straight line could be used to describe the relationships at levels of retentions commonly encountered in practice. Straight-line regression analyses were made on the data at each of four levels of relative humidity for each chemical. Excellent correlations, ranging from 0.88 to 0.99,

were found between moisture content and the salt-wood weight ratio for the various combinations of chemicals and humidity levels. The slopes of the regression lines indicate that the sodium chloride treatment caused a considerably greater increase in the apparent equilibrium moisture content than the other two chemicals and that, without exception, the effects of the treatment increased at increasing levels of humidity.

It is felt that the equilibrium moisture content of a specimen of any species of wood when treated with one of these three chemicals can be predicted by the straight-line regression equation

$$M = 100(A + Bx)$$

where A = the equilibrium moisture content of untreated wood of the species involved at the atmospheric condition being considered,

B = the slope of the regression curves (table 1), and

x = the salt-wood weight ratio (weight of salt per unit weight of dry wood).

Increased volumetric swelling was found in both species with all treatments when swelling was based upon the untreated dry volume of the specimen. This effect was considerably greater in treatments with chemicals that are themselves hygroscopic. In treatments with nonhygroscopic chemicals, the swelling is attributed to chemical bulking of the fibers, while in the hygroscopic group the swelling is due to the combined effect of chemical bulking and swelling as moisture content increases.

The largest increase in swelling occurred in zinc chloride treatments where excess swelling as a result of treatment at the 4.5-pound level was measured at approximately 6 percent in pine and 4 percent in oak. This is important from a standpoint of other properties: for example, a corresponding 6 and 4 percent reduction can be expected in specific gravity.

Generally speaking, there was no significant change in the dimensional stability because of treatment as measured by volumetric changes with respect to humidity changes. There were instances of increased dimensional stability with respect to changes in moisture content. However, with respect to changes in relative humidity this was offset by the increased rate of change in the moisture content with respect to relative humidity changes.

In addition to the increase in volume due to treatment, the anisotropic swelling characteristics of both species were also increased. This property is commonly measured as the ratio of tangential shrinkage to radial shrinkage. At the 30 percent relative humidity level the T/R ratio of oak was increased on an average from 1.7 in

the controls to 2.2 in the 4.5-pound treatments. This effect was somewhat less pronounced at higher humidities and also in the ponderosa pine treatments. It is expected that, with this increased anisotropy, somewhat more caution needs to be exercised in drying treated material, particularly in oak.

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Appendix A.--Comparison of salt retentions obtained by three different methods

Chemical	Salt retention in pounds per cubic foot									Method of chemical analysis
	Nominal 4.5 pound retention level			Nominal 1.5 pound retention level			Nominal 0.5 pound retention level			
	From treating data <sup>1</sup>	Oven-drying method <sup>1</sup>	By chemical analysis <sup>2</sup>	From treating data <sup>1</sup>	Oven-drying method <sup>1</sup>	By chemical analysis <sup>2</sup>	From treating data <sup>1</sup>	Oven-drying method <sup>1</sup>	By chemical analysis <sup>2</sup>	
<u>OAK</u>										
Diammonium phosphate	3.72	2.36	3.33	1.30	0.57	1.23	0.46	0.01	0.47	Gravimetric method
Monoammonium phosphate	4.21	3.54	4.08	1.57	1.04	1.46	.48	.09	.45	
Borax	3.88	1.87	3.93	1.24	.35	1.39	.46	.04	.66	Volumetric determination for borax
Boric acid	3.17	1.18	2.17	1.61	.29	1.25	.51	.05	.64	
Ammonium sulfate	3.79	2.94	3.05	1.36	.93	1.29	.47	.19	.61	Standard Kjeldahl method
Sodium chloride	4.84	4.94	4.19	1.60	1.43	1.44	.52	.40	.49	Silver thiocyanate-ferric alum method
Zinc chloride	4.21	3.95	4.21	1.40	1.06	1.20	.46	.32	.53	Standard potassium ferrocyanide titration method
<u>PINE</u>										
Diammonium phosphate	4.65	4.01	4.91	1.51	1.23	1.58	.51	.36	.56	Gravimetric method
Monoammonium phosphate	4.59	4.54	4.67	1.50	1.38	1.55	.50	.53	.53	
Borax	5.05	3.69	4.48	1.60	.95	1.95	.53	.20	.53	Volumetric determination for borax
Boric acid	4.65	2.15	2.39	1.50	.52	.67	.50	.14	.25	
Ammonium sulfate	4.67	4.32	3.74	1.45	1.26	1.16	.50	.46	.49	Standard Kjeldahl method
Sodium chloride	4.48	4.88	3.82	1.50	1.62	1.41	.50	.56	.49	Silver thiocyanate-ferric alum method
Zinc chloride	4.79	4.81	4.63	1.52	1.61	1.45	.51	.56	.49	Standard potassium ferrocyanide titration method

<sup>1</sup>Average of ten specimens.

<sup>2</sup>Computed average of ten specimens based upon the analysis of two specimens.

Appendix B.--Equilibrium moisture content values for treated and untreated red oak--

Chemical	Nominal retention level	Initial desorption cycle				Adsorption cycle				Final		
		80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.
	<u>Lb. per cu. ft.</u>											
Diammonium phosphate	0	16.25	12.08	9.39	5.37	5.35	8.36	9.78	13.69	11.55	9.66	5.76
	0.5	17.16	11.88	8.94	4.81	4.77	7.88	9.39	13.58	11.17	9.12	5.06
	1.5	18.04	12.06	8.78	4.58	4.54	7.77	9.38	14.07	11.21	8.94	4.71
	4.5	18.33	11.93	8.40	4.06	3.98	7.34	9.08	14.11	10.83	8.42	4.10
Monoammonium phosphate	0	16.36	12.19	9.49	5.47	5.43	8.46	9.73	13.85	11.61	9.78	5.88
	0.5	17.38	12.08	9.18	5.07	5.02	8.14	9.47	13.90	11.42	9.38	5.36
	1.5	18.90	12.78	9.46	5.20	5.16	8.46	10.01	15.03	11.93	9.58	5.37
	4.5	18.05	12.23	9.05	4.84	4.81	8.05	9.58	14.49	11.46	9.24	5.06
Borax	0	16.26	12.18	9.56	5.39	5.32	8.40	9.88	13.76	11.57	9.79	5.93
	0.5	16.68	12.02	9.23	4.80	4.75	7.91	9.46	13.55	11.22	9.35	5.31
	1.5	16.94	11.96	9.12	4.52	4.53	7.78	9.36	13.73	11.14	9.16	4.94
	4.5	18.87	12.69	9.58	4.80	4.61	7.96	9.65	14.92	11.57	9.29	4.54
Boric acid	0	16.39	12.01	9.45	5.27	5.29	8.32	9.74	13.67	11.48	9.79	5.90
	0.5	16.28	11.67	9.07	4.81	4.84	7.94	9.38	13.40	11.04	9.25	5.30
	1.5	18.20	13.01	10.20	5.58	5.21	8.47	9.88	14.17	11.29	9.24	5.07
	4.5	21.19	15.77	12.85	8.16	7.73	1.22	12.76	16.93	13.93	1.72	7.27
Ammonium sulfate	0	16.54	12.13	9.43	5.41	5.50	8.46	9.93	13.83	11.56	9.72	5.78
	0.5	17.30	11.97	9.03	4.93	4.98	8.06	9.63	13.92	11.30	9.27	5.21
	1.5	19.25	13.00	9.61	5.32	5.39	8.68	10.44	15.49	12.29	9.85	5.54
	4.5	23.96	16.00	11.46	6.71	6.72	0.62	12.24	21.66	14.42	1.27	6.61
Sodium chloride	0	16.48	12.25	9.68	5.53	5.47	8.51	9.99	13.88	11.69	9.94	6.05
	0.5	18.69	12.94	10.09	5.91	5.67	8.95	10.67	15.39	12.59	0.44	6.32
	1.5	23.83	15.35	11.66	6.77	6.75	0.62	12.88	19.67	15.25	2.32	7.46
	4.5	45.75	21.92	14.86	9.25	9.02	2.89	15.77	43.41	21.10	5.65	9.90
Zinc chloride	0	16.32	12.17	9.61	5.44	5.37	8.41	9.90	13.90	11.68	9.83	5.93
	0.5	16.77	12.08	9.47	5.31	5.24	8.33	9.88	14.04	11.64	9.67	5.73
	1.5	17.99	12.92	10.19	6.02	5.98	9.14	10.74	15.21	12.46	0.35	6.34
	4.5	22.06	15.54	12.45	8.07	8.03	1.69	13.75	19.72	15.28	2.65	8.24

Each value in table is the average of ten specimens.

Appendix C.--Equilibrium moisture content values for treated and untreated ponderosa pine<sup>1</sup>

Chemical	Nominal retention level	Initial desorption cycle				Adsorption cycle				Final		
		80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.
	<u>Lb. per cu. ft.</u>											
Diammonium phosphate	0	16.42	12.66	10.30	6.02	5.88	9.08	10.26	14.75	12.17	0.37	6.47
	0.5	17.42	12.05	9.53	5.02	4.88	8.21	9.35	14.48	11.26	9.25	5.30
	1.5	18.02	11.66	8.99	4.29	4.19	7.64	8.89	14.67	10.86	8.54	4.50
	4.5	15.16	8.86	6.31	1.65	1.52	5.00	6.17	11.75	8.17	5.89	1.83
Monoammonium phosphate	0	16.37	12.58	10.18	6.01	5.94	9.21	10.63	14.77	12.37	0.39	6.57
	0.5	18.00	12.27	9.76	5.39	5.21	8.62	10.15	14.98	11.88	9.66	5.80
	1.5	18.99	12.35	9.58	5.05	4.88	8.44	10.13	15.50	11.83	9.30	5.36
	4.5	17.83	11.95	9.45	4.99	4.88	8.28	9.80	14.75	11.50	9.14	5.37
Borax	0	16.32	12.58	10.19	6.17	6.03	9.29	10.43	14.83	12.40	0.46	6.55
	0.5	17.66	12.41	9.94	5.46	5.42	8.72	9.87	14.88	11.82	9.63	5.42
	1.5	16.61	10.60	8.01	3.39	3.28	6.70	7.98	13.92	10.02	7.53	3.11
	4.5	27.91	21.86	19.22	14.29	13.28	16.61	17.80	24.75	20.21	7.62	12.06
Boric acid	0	16.71	12.56	10.13	6.16	6.05	9.24	10.58	14.91	12.35	0.45	6.64
	0.5	18.39	13.13	10.69	6.48	6.37	9.61	10.80	15.26	12.16	0.24	6.37
	1.5	22.44	16.50	13.84	9.15	8.63	11.98	13.12	17.64	14.08	1.36	6.97
	4.5	33.76	27.60	24.64	18.90	17.51	21.75	22.73	27.15	23.32	10.12	14.69
Ammonium sulfate	0	16.19	12.71	10.24	6.02	5.85	9.12	10.65	14.97	12.15	0.24	6.41
	0.5	17.98	13.13	10.43	5.96	5.79	9.22	10.64	16.18	12.40	0.26	6.27
	1.5	22.73	15.74	12.45	7.47	7.26	11.17	12.73	20.51	14.77	1.80	7.51
	4.5	45.35	18.75	15.30	10.37	10.13	14.06	15.64	42.25	17.20	4.16	9.82
Sodium chloride	0	16.85	12.48	10.09	6.17	6.20	9.22	10.47	14.94	12.41	0.36	6.52
	0.5	20.31	13.95	11.14	6.84	6.63	10.27	11.94	17.98	14.09	1.49	7.15
	1.5	29.08	18.40	14.21	8.61	8.26	12.34	15.49	26.83	19.02	4.56	9.13
	4.5	83.18	22.47	17.62	12.14	11.79	16.05	19.36	81.58	23.62	8.21	12.91
Zinc chloride	0	16.66	12.50	10.08	6.20	6.06	9.28	10.81	14.93	12.50	0.50	6.65
	0.5	18.41	13.05	10.69	6.65	6.47	9.82	11.45	16.12	13.09	0.89	7.00
	1.5	20.74	14.76	11.99	7.74	7.60	11.13	13.00	18.53	14.59	2.03	7.92
	4.5	36.46	22.72	18.27	12.73	12.39	17.99	21.57	33.86	23.07	8.13	12.46

<sup>1</sup>Each value in table is the average of ten specimens.

Appendix D.--Volumetric swelling of treated and untreated red,  
oak at various equilibrium moisture conditions--

Chemical	Nominal retention level	Initial desorption				Adsorption cycle				Final desorption cycle		
		80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.
	<u>Lb. per cu. ft.</u>											
Diammonium phosphate	0	8.36	6.13	4.90	2.51	2.46	3.96	4.67	6.91	5.63	4.58	2.38
	0.5	9.10	6.69	5.18	2.87	2.78	4.35	5.10	7.35	6.08	4.96	2.71
	1.5	9.63	7.36	5.81	3.49	3.42	4.96	5.84	8.15	6.79	5.60	3.20
	4.5	10.88	8.21	6.63	4.28	4.15	5.87	6.75	9.10	7.48	6.21	3.75
Monoammonium phosphate	0	8.47	6.26	4.88	2.61	2.54	4.04	4.74	6.86	5.70	4.72	2.47
	0.5	9.17	6.73	5.27	2.95	2.84	4.44	5.11	7.41	6.13	5.05	2.72
	1.5	10.21	7.84	6.34	3.98	3.87	5.54	6.33	8.72	7.24	6.03	3.63
	4.5	10.62	8.00	6.48	4.17	4.06	5.68	6.52	9.04	7.36	6.23	3.77
Borax	0	8.46	6.26	4.93	2.64	2.48	4.03	4.83	6.99	5.77	4.78	2.57
	0.5	9.01	6.61	5.20	2.75	2.68	4.22	5.07	7.37	6.03	5.01	2.65
	1.5	9.58	7.16	5.73	3.18	3.10	4.70	5.58	7.96	6.52	5.48	2.98
	4.5	9.89	7.75	6.17	3.59	3.46	5.16	6.06	8.69	7.03	5.86	3.28
Boric acid	0	8.39	6.13	4.81	2.49	2.41	3.96	4.69	6.86	5.67	4.63	2.45
	0.5	8.98	6.65	5.29	2.95	2.91	4.44	5.20	7.42	6.14	5.11	2.85
	1.5	9.42	7.12	5.84	3.52	3.48	5.03	5.81	8.02	6.65	5.66	3.41
	4.5	8.85	6.47	5.21	2.98	2.91	4.43	5.10	7.27	5.98	5.03	2.87
Ammonium sulfate	0	8.37	6.10	4.61	2.50	2.41	3.94	4.69	6.93	5.57	4.52	2.34
	0.5	9.43	7.03	5.46	3.24	3.22	4.77	5.58	7.94	6.47	5.31	3.11
	1.5	10.32	7.90	6.45	4.01	4.02	5.61	6.45	9.11	7.50	6.25	3.86
	4.5	11.83	9.83	8.13	5.62	5.56	6.88	7.38	10.28	8.95	7.45	4.89
Sodium chloride	0	8.63	6.32	5.10	2.72	2.61	4.13	4.92	7.09	5.89	4.90	2.65
	0.5	9.50	7.01	5.58	3.13	3.01	4.67	5.62	8.21	6.67	5.45	3.06
	1.5	11.25	8.71	7.03	4.34	4.23	6.24	7.37	10.95	8.81	7.28	4.51
	4.5	13.15	10.90	8.52	5.34	5.05	6.97	8.51	12.97	11.42	9.07	5.76
Zinc chloride	0	8.55	6.31	4.96	2.63	2.53	4.07	4.85	7.10	5.84	4.75	2.56
	0.5	9.22	6.79	5.48	3.21	3.09	4.62	5.39	7.64	6.33	5.28	3.07
	1.5	9.77	7.36	5.99	3.83	3.69	5.22	6.10	8.44	6.93	5.85	3.63
	4.5	11.94	9.91	8.59	6.43	6.33	8.04	9.07	11.95	10.04	8.69	6.44

Each value in table is the average of ten specimens.

Appendix E.--Volumetric swelling of treated and untreated pine  
at various equilibrium moisture conditions<sup>1</sup>

Chemical	Nominal retention level	Initial desorption cycle				Adsorption cycle				Final desorption cycle		
		80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.
	<u>Lb. per cu. ft.</u>											
Diammonium phosphate	0	6.28	4.73	3.85	2.24	2.14	3.33	3.74	5.59	4.58	3.87	2.33
	0.5	6.94	4.99	4.04	2.32	2.23	3.49	3.86	6.10	4.81	4.02	2.49
	1.5	7.78	5.62	4.62	2.84	2.74	4.00	4.42	6.77	5.32	4.41	2.83
	4.5	7.83	5.64	4.69	2.97	2.86	4.07	4.53	6.70	5.32	4.48	2.95
Monoammonium phosphate	0	6.23	4.70	3.85	2.23	2.13	3.26	3.83	5.60	4.62	3.96	2.33
	0.5	7.09	5.06	4.13	2.47	2.35	3.57	4.17	6.28	4.99	4.21	2.61
	1.5	8.06	5.80	4.76	3.06	2.94	4.25	5.00	7.01	5.49	4.56	3.01
	4.5	7.70	5.61	4.69	3.00	2.88	4.09	4.78	6.64	5.37	4.53	3.00
Borax	0	6.16	4.68	3.79	2.21	2.11	3.18	3.70	5.59	4.55	3.87	2.33
	0.5	7.09	5.20	4.30	2.54	2.40	3.62	4.09	6.30	5.07	4.26	2.64
	1.5	7.89	5.92	5.00	3.23	3.08	4.35	4.81	7.29	5.81	5.01	3.38
	4.5	7.99	6.19	5.22	3.49	3.27	4.53	5.14	7.23	5.89	5.16	3.49
Boric acid	0	6.20	4.67	3.83	2.11	2.09	3.24	3.82	5.62	4.57	3.92	2.38
	0.5	6.91	5.01	4.18	2.56	2.42	3.59	4.13	6.07	4.85	4.18	2.59
	1.5	7.26	5.44	4.61	2.99	2.86	4.05	4.54	6.42	5.26	4.64	3.01
	4.5	7.52	5.74	4.93	3.41	3.29	4.34	4.72	6.53	5.35	4.75	3.28
Ammonium sulfate	0	6.24	4.76	3.85	2.24	2.15	3.32	3.87	5.62	4.57	3.68	2.36
	0.5	7.14	5.37	4.29	2.65	2.53	3.70	4.40	6.55	5.11	4.14	2.72
	1.5	8.64	6.64	5.43	3.63	3.51	4.80	5.36	7.95	6.30	5.17	3.62
	4.5	9.32	6.99	5.72	3.98	3.81	5.11	5.53	8.16	6.65	5.51	3.93
Sodium chloride	0	6.33	4.68	3.84	2.19	2.11	3.23	3.74	5.68	4.60	3.91	2.40
	0.5	7.73	5.53	4.52	2.75	2.63	3.98	4.55	7.01	5.57	4.73	3.03
	1.5	9.93	7.71	6.21	3.99	3.70	5.12	6.39	9.83	7.88	6.39	4.32
	4.5	9.97	8.15	6.34	4.32	4.02	5.44	6.89	10.14	8.66	6.81	4.87
Zinc chloride	0	6.20	4.66	3.78	2.23	2.09	3.25	3.85	5.57	4.59	3.76	2.47
	0.5	7.03	5.13	4.25	2.61	2.53	3.70	4.32	6.36	5.12	4.25	2.89
	1.5	8.08	6.06	5.15	3.54	3.52	4.65	5.33	7.66	6.12	5.16	3.91
	4.5	11.02	9.69	8.64	7.03	6.81	8.66	9.64	11.30	9.77	8.58	6.98

<sup>1</sup>Each value in table is the average of ten specimens.

Appendix F.--Tangential swelling of treated and untreated red oak  
at various equilibrium moisture conditions<sup>1</sup>

Chemical	Nominal retention level	Initial desorption cycle				Adsorption cycle				Final desorption cycle		
		80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.
	<u>Lb. per cu. ft.</u>											
Diammonium phosphate	0	5.39	3.93	3.09	1.55	1.52	2.46	2.92	4.37	3.59	2.90	1.50
	0.5	5.93	4.34	3.34	1.84	1.78	2.78	3.25	4.72	3.92	3.22	1.76
	1.5	6.35	4.86	3.81	2.29	2.24	3.23	3.80	5.35	4.47	3.70	2.16
	4.5	7.25	5.47	4.39	2.87	2.79	3.87	4.44	5.98	4.93	4.11	2.55
Monoammonium phosphate	0	5.46	4.03	3.08	1.63	1.59	2.54	2.97	4.39	3.66	3.02	1.59
	0.5	5.94	4.37	3.38	1.89	1.79	2.83	3.27	4.76	3.96	3.25	1.77
	1.5	6.73	5.19	4.18	2.67	2.60	3.66	4.16	5.75	4.78	4.01	2.44
	4.5	7.07	5.34	4.31	2.82	2.76	3.79	4.32	5.96	4.90	4.17	2.61
Borax	0	5.48	4.05	3.15	1.70	1.58	2.54	3.06	4.46	3.73	3.09	1.68
	0.5	5.83	4.31	3.36	1.79	1.73	2.69	3.23	4.74	3.91	3.26	1.76
	1.5	6.30	4.72	3.78	2.15	2.11	3.10	3.63	5.18	4.30	3.64	2.05
	4.5	6.53	5.17	4.14	2.47	2.41	3.45	4.02	5.70	4.66	3.92	2.31
Boric acid	0	5.40	3.95	3.06	1.56	1.50	2.46	2.94	4.38	3.62	2.97	1.57
	0.5	5.84	4.33	3.40	1.92	1.88	2.84	3.33	4.76	3.96	3.30	1.85
	1.5	6.18	4.70	3.87	2.39	2.36	3.31	3.81	5.26	4.39	3.76	2.31
	4.5	5.87	4.35	3.48	2.07	2.01	2.96	3.39	4.78	3.99	3.36	1.98
Ammonium sulfate	0	5.38	3.91	2.95	1.56	1.47	2.44	2.95	4.38	3.54	2.90	1.47
	0.5	6.20	4.63	3.59	2.15	2.12	3.09	3.62	5.13	4.25	3.52	2.09
	1.5	6.83	5.24	4.28	2.71	2.71	3.69	4.25	5.99	4.97	4.17	2.62
	4.5	7.94	6.59	5.40	3.77	3.76	4.59	4.90	6.80	5.96	4.97	3.31
Sodium chloride	0	5.59	4.11	3.28	1.73	1.67	2.62	3.13	4.56	3.79	3.18	1.74
	0.5	6.16	4.55	3.59	2.01	1.92	2.97	3.58	5.30	4.32	3.51	1.99
	1.5	7.45	5.73	4.58	2.89	2.82	4.08	4.84	7.24	5.79	4.81	3.02
	4.5	8.88	7.25	5.64	3.61	3.42	4.62	5.60	8.73	7.55	6.01	3.89
Zinc chloride	0	5.53	4.10	3.14	1.67	1.58	2.56	3.08	4.54	3.76	3.05	1.65
	0.5	5.98	4.42	3.52	2.07	2.00	2.96	3.48	4.93	4.10	3.43	2.01
	1.5	6.38	4.82	3.89	2.48	2.39	3.37	3.93	5.49	4.52	3.83	2.37
	4.5	7.95	6.56	5.68	4.30	4.21	5.33	5.97	7.95	6.62	5.76	4.29

<sup>1</sup>Each value in table is the average of ten specimens.

Appendix G.--Radial swelling of treated and untreated red oak  
at various equilibrium moisture conditions<sup>1</sup>

Chemical	Nominal retention level	Initial desorption cycle				Adsorption cycle				Final desorption cycle		
		80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.
	<u>Lb. per cu. ft.</u>											
Diammonium phosphate	0	2.81	2.11	1.75	0.94	0.92	1.46	1.70	2.43	1.97	1.63	0.86
	0.5	2.98	2.24	1.77	1.00	.98	1.53	1.78	2.51	2.07	1.69	.93
	1.5	3.09	2.38	1.93	1.16	1.14	1.67	1.96	2.65	2.21	1.83	1.01
	4.5	3.38	2.60	2.15	1.37	1.32	1.92	2.21	2.94	2.43	2.01	1.17
Monoammonium phosphate	0	2.85	2.14	1.74	0.96	0.94	1.46	1.71	2.36	1.97	1.64	0.87
	0.5	3.05	2.26	1.82	1.04	1.02	1.56	1.78	2.52	2.08	1.73	.93
	1.5	3.25	2.52	2.07	1.27	1.23	1.81	2.08	2.80	2.34	1.94	1.15
	4.5	3.31	2.52	2.08	1.31	1.25	1.82	2.11	2.91	2.34	1.97	1.13
Borax	0	2.82	2.12	1.72	0.92	0.88	1.45	1.72	2.42	1.96	1.63	0.87
	0.5	3.00	2.20	1.78	.93	.94	1.48	1.78	2.50	2.03	1.69	.87
	1.5	3.08	2.32	1.88	1.00	.97	1.55	1.88	2.63	2.13	1.77	.90
	4.5	3.15	2.45	1.94	1.09	1.02	1.65	1.96	2.82	2.26	1.86	.94
Boric acid	0	2.83	2.09	1.69	0.91	0.89	1.45	1.69	2.37	1.97	1.61	0.86
	0.5	2.96	2.22	1.83	1.01	1.01	1.55	1.81	2.53	2.10	1.75	.97
	1.5	3.04	2.31	1.89	1.10	1.09	1.66	1.92	2.62	2.16	1.83	1.07
	4.5	2.82	2.03	1.67	.89	.88	1.43	1.65	2.37	1.92	1.61	.86
Ammonium sulfate	0	2.84	2.11	1.60	0.92	0.93	1.46	1.69	2.43	1.95	1.56	0.86
	0.5	3.04	2.28	1.80	1.06	1.07	1.63	1.89	2.66	2.13	1.72	1.00
	1.5	3.26	2.53	2.07	1.27	1.27	1.84	2.10	2.93	2.40	1.98	1.21
	4.5	3.60	3.03	2.58	1.77	1.73	2.18	2.36	3.25	2.82	2.36	1.53
Sodium chloride	0	2.88	2.12	1.76	0.97	0.92	1.47	1.73	2.42	2.02	1.67	0.89
	0.5	3.14	2.34	1.92	1.10	1.07	1.65	1.96	2.76	2.25	1.86	1.05
	1.5	3.53	2.82	2.34	1.41	1.37	2.07	2.41	3.46	2.85	2.35	1.44
	4.5	3.91	3.40	2.73	1.66	1.57	2.24	2.75	3.90	3.59	2.88	1.80
Zinc chloride	0	2.87	2.12	1.76	0.94	0.93	1.47	1.71	2.44	2.01	1.65	0.89
	0.5	3.06	2.26	1.89	1.11	1.07	1.61	1.85	2.57	2.14	1.79	1.03
	1.5	3.18	2.41	2.02	1.31	1.26	1.78	2.08	2.79	2.30	1.95	1.22
	4.5	3.69	3.13	2.74	2.04	2.03	2.58	2.92	3.69	3.20	2.76	2.05

<sup>1</sup>Each value in table is the average of ten specimens.



Appendix I.--Radial swelling of treated and untreated ponderosa  
 pine at various equilibrium moisture conditions<sup>1</sup>

Chemical	Nominal retention level	Initial desorption cycle				Adsorption cycle				Final desorption cycle			
		80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	30 pct. R.H.	50 pct. R.H.	65 pct. R.H.	80 pct. R.H.	65 pct. R.H.	50 pct. R.H.	30 pct. R.H.	
	<u>Lb. per cu. ft.</u>												
Diammonium phosphate	0	2.35	1.77	1.46	0.80	0.73	1.22	1.36	2.07	1.69	1.44	0.81	
	0.5	2.55	1.84	1.50	.80	.75	1.25	1.37	2.21	1.75	1.44	.84	
	1.5	2.80	2.04	1.69	.99	.93	1.41	1.56	2.44	1.94	1.57	.96	
	4.5	2.77	2.03	1.68	1.01	.96	1.42	1.56	2.34	1.86	1.55	.97	
Monoammonium phosphate	0	2.33	1.77	1.47	0.78	0.74	1.21	1.40	2.07	1.70	1.48	0.81	
	0.5	2.62	1.88	1.53	.90	.82	1.30	1.52	2.30	1.82	1.53	.91	
	1.5	2.92	2.14	1.75	1.08	1.02	1.52	1.82	2.54	2.00	1.63	1.05	
	4.5	2.78	2.08	1.76	1.09	1.01	1.47	1.69	2.35	1.93	1.61	1.04	
Borax	0	2.31	1.76	1.44	0.78	0.72	1.16	1.37	2.07	1.67	1.41	0.82	
	0.5	2.62	1.93	1.61	.90	.85	1.31	1.48	2.29	1.86	1.54	.93	
	1.5	2.91	2.20	1.90	1.20	1.10	1.61	1.76	2.63	2.13	1.79	1.18	
	4.5	2.87	2.22	1.88	1.16	1.06	1.54	1.76	2.55	2.10	1.80	1.14	
Boric acid	0	2.35	1.76	1.46	0.76	0.75	1.20	1.40	2.08	1.70	1.45	0.84	
	0.5	2.56	1.86	1.58	.92	.85	1.30	1.50	2.24	1.77	1.52	.91	
	1.5	2.71	2.02	1.73	1.08	.99	1.45	1.63	2.32	1.91	1.67	1.03	
	4.5	2.73	2.06	1.76	1.11	1.04	1.45	1.59	2.27	1.82	1.59	1.01	
Ammonium sulfate	0	2.33	1.76	1.45	0.80	0.74	1.21	1.40	2.07	1.68	1.34	0.82	
	0.5	2.67	2.03	1.63	.96	.92	1.38	1.62	2.41	1.89	1.54	.99	
	1.5	3.16	2.46	2.04	1.33	1.27	1.78	1.98	2.92	2.33	1.93	1.35	
	4.5	3.32	2.56	2.15	1.49	1.41	1.89	2.04	2.99	2.48	2.10	1.57	
Sodium chloride	0	2.35	1.75	1.44	0.76	0.69	1.16	1.34	2.10	1.68	1.42	0.82	
	0.5	2.84	2.07	1.71	1.01	.92	1.46	1.66	2.54	2.05	1.74	1.10	
	1.5	3.39	2.72	2.23	1.42	1.27	1.81	2.28	3.35	2.80	2.30	1.53	
	4.5	3.41	2.95	2.33	1.60	1.44	1.95	2.49	3.45	3.11	2.50	1.81	
Zinc chloride	0	2.28	1.69	1.39	0.76	0.67	1.14	1.37	2.02	1.66	1.33	0.85	
	0.5	2.61	1.92	1.58	.94	.89	1.35	1.56	2.32	1.88	1.54	1.03	
	1.5	2.94	2.25	1.93	1.28	1.25	1.69	1.96	2.73	2.23	1.84	1.37	
	4.5	3.45	3.24	2.92	2.37	2.27	2.93	3.19	3.50	3.17	2.81	2.30	

<sup>1</sup>Each value in table is the average of ten specimens.