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Title: THE EFFECTS OF THIN KILN STICKS ON THE DRYING OF TWO INCH WESTERN HEMLOCK LUMBER

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Helmuth Resch

New technology allows the production of thinner kiln sticks manufactured of phenolic resin impregnated paper which are both structurally and economically realistic. This project tested the effects of kiln stick thicknesses on dry kiln air circulation and on lumber drying degrade.

Three variables, stick thickness (3/4, 9/16, 7/16 and 1/4 inch), fan speed (250, 480, and 660 RPM), and plenum width (13 and 25 inches) were tested in a laboratory kiln in different combinations to explore their effects on air velocity and power consumption of the fan motors. The results indicated that the 1/4 inch kiln sticks produce very ununiform drying with correspondingly low velocities. However, with 9/16 inch sticks, maximum velocities were obtained followed by a slight drop in velocities with the 3/4 and 7/16 inch sticks. Uniformity of air velocities was maximized when using the wider 25 inch plenum width and any of the three thicker sticks.

Power consumption of the fan motors was not greatly influenced by plenum width or stick thickness. However, fan speed directly affected power consumption.

In a second experiment, evaporation rates were measured using the four different stick thicknesses. The results indicated the same pattern as the magnitude of the air velocities followed. Highest evaporation was with the 9/16 inch stick, lowest with the 1/4 inch stick.

In a commercial dry kiln, the amount of degrade was recorded in lumber dried using both 3/4 inch wood sticks and 1/2 inch phenolic sticks. No significant difference in drying degrade was found. Since air velocities were slightly lower and there was ten percent more lumber using the thinner kiln sticks, a higher moisture content distribution resulted.

The Effects of Thin Kiln Sticks on the Drying of Two Inch Western Hemlock Lumber

by

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This project was made possible through a generous grant from Simpson Timber Company's Chemicals Division at Portland, Oregon.

International Paper Company's Long Bell Division at Vaughn, Oregon was very helpful in performing the mill trial portion of this study.

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And to my wife, Renee, a very special thanks is extended. Her sacrifices and limitless enthusiasm were warmly appreciated.

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THE EFFECTS OF THIN KILN STICKS ON THE DRYING OF TWO INCH WESTERN HEMLOCK LUMBER

I. INTRODUCTION

Simpson Timber Company has developed kiln sticks made of a kraft reinforced thermosetting phenolic laminate. This material has two principal advantages over conventional wood, durability and strength (Rash, J., 1973). Thus, it can be used to produce thinner stick thicknesses with little resultant breakage.

One of the most important benefits resulting from the use of phenolic kiln sticks is the great increase in their life expectancy. Tests conducted by Simpson showed that the average life for the industry's standard 3/4 inch solid wood stick was about 15 kiln cycles. When the phenolic sticks were used, an average life expectancy of 90 cycles was established on a stick which is up to 1/4 inch thinner than the wooden ones (Anon, 1974).

As the stick thickness is decreased, the capacity of the kiln increases as more space is available for additional courses of lumber. By changing from 3/4 inch to 1/2 inch thick kiln sticks, a capacity increase of about ten percent would be obtained when drying two inch lumber. For a mill with ten kilns, a capacity gain of one kiln could be realized.

Another area where the phenolic stick out performs the traditional wood stick is in efficiency of the automatic stacking machines.

The smooth surfaces and the homogeneous high density of the sticks facilitate mechanical handling which reduces machine down-time (Anon, 1974). Hence, there are important advantages gained in using phenolic sticks. However, the purpose of this project was to investigate the influence of thin kiln sticks on air circulation and drying degrade, factors which had not yet been established.

II. OBJECTIVES

The manager of a lumber plant has the obvious goal of maximizing profits within the limits of his resources. He is concerned with the timely delivery of his product at minimum cost and as the demand for dried lumber has increased, the need for optimizing his kiln system has also increased. With the advent of thin stick technology, new options are available to mills wishing to improve their performance. Before the manager can make wise decisions, he must be aware of the facts involved. Regarding thin kiln sticks, all the facts are not yet available, hence providing decision making information is the goal of this project.

The specific objectives of this paper were to evaluate the effects of thin kiln sticks on air circulation and on degrade losses. Three independent experiments were employed:

1. Air velocity between courses of lumber
2. Evaporation rate from a free water surface
3. Lumber drying degrade

The first two parts were designed as laboratory experiments and were performed at the Forest Research Laboratory at Oregon State University. The degrade portion of the project was completed at International Paper Company's sawmill at Vaughn, Oregon.

III. BACKGROUND

General Drying

In a lumber dry kiln, the degree of air circulation exerts a great influence on both the amount of time required and the quality of lumber produced. The air performs two critical functions, first, it carries the heat from the source to the wood. And secondly, the air carries the evaporated moisture away from the wood and allows it to escape at the vents when too high of humidity has been reached. Air circulation is the factor responsible for even distribution of heat and humidity throughout the kiln (Kearns, R., 1931).

The main reason for using heat in drying is found in the physical behavior of wood. The movement of moisture through wood is more rapid at higher temperatures because of the increased energy levels of the water molecules. To produce the same rate of moisture movement at 140° as at 180°, a much lower humidity would be required and thus a steeper moisture gradient would result. Water cannot be evaporated from the surface at any faster rate than it is brought to the surface. Thus, in order to speed the drying process, the water in the wood must be heated to facilitate removal at an adequate rate. However, accelerated drying may adversely affect the quality of lumber produced.

Timber drying cannot be controlled by temperature alone. The relative humidity (which is an expression of how much water is in the air versus how much it can hold at that particular temperature) and the rate at which moisture diffuses from the interior must be considered together. It is economically important that the surface moisture be evaporated as fast as possible but if the surface moisture is evaporated too rapidly, then serious lumber degrade can result. Moisture is required to assist in reducing stress in the outer zones of the wood during drying (Brown, W., 1965).

Air Circulation

In most dry kilns, fans are employed to circulate the air through the courses of lumber which accelerates the heat transfer to the wood and mass transfer of water away from the wood. It is necessary to baffle the kiln to insure that the air goes through the load and not around it. If baffling is not employed, then the air will naturally follow the path of least resistance and will short circuit the courses of lumber (Brown, W., 1965). Baffles must be placed wherever there are lateral voids in the kiln. Most commonly, these are underneath, on top of and at the ends of the lumber loads. Better baffling in the dry kiln can result in greater uniformity in the moisture content distribution of the lumber and permits an improvement in the quality of drying (Behrens, J., 1956).

Good air circulation is also directly related to good stacking. Obviously, there will be more voids for the air to short circuit if lumber is piled in random lengths rather than putting all the pieces of equal lengths in the same load. If the sides of the loads are not aligned, then projecting edges obtained in stacking will funnel more air through the course above and starve the course below (Torgeson, O., 1940). When sides are uneven, the projecting boards act as baffles, and rob the adjacent courses of their share of airflow (Knight, E., 1952). Thus, it is clear that uneven ends and edges contribute to uneven drying.

Air circulation is an important factor in dry kiln efficiency, particularly in the early stages of drying. Research and practical experience have shown that a high and uniform rate of flow of the drying medium is necessary to achieve the highest drying rate (Salamon, M., 1960). The magnitude of the air velocities influences the drying rate while the uniformity of air velocities affects the quality of lumber dried. Uniform air velocities are a more important consideration than extremely high air velocicies (Hermann, A., et al., 1952).

Water cannot be removed from the wood any faster than it can travel to the surface so air velocity exerts its greatest drying effect when the wood is in the initial stages of drying. As lumber is dried below the fiber saturation point (FSP), the cost of power could be reduced by running the fans at lower speeds without any significant loss in drying time. Steinhagen (1974) found that the drying rate of green 4/4 yellow-poplar lumber was not affected by increasing kiln air velocities at moisture contents below 40 percent. However, Salamon (1966) has performed experiments showing that when fan speeds are reduced after FSP has been attained that a greater range of final moisture content distribution may be produced.

Maximum air velocities are recorded at the center of any course opening and diminish closer to the boards. This results in boundary layer conditions in which air velocity at the surfaces of the boards is zero and increases to maximum free stream velocity towards the center. The zone of still air acts as an insulating layer and inhibits heat transfer to the wood and mass transfer away from it.

There are two types of boundary layers: laminar and turbulent. When the air in a dry kiln first passes over the lumber, the boundary layer is laminar. But at a critical distance from the leading edge, the flow becomes turbulent (Lyman, L., 1963). With laminar flow, little mixing of air occurs and an insulating effect results. However, with turbulent flow, the air is scattered both in the horizontal and vertical directions. Hence, turbulent flow promotes heat and mass transfer while laminar flow does not. Greater turbulence can be created by increasing air velocities.

Kiln Stick Dimensions

Kiln sticks are used to separate the courses of lumber so that the air in the dry kiln can circulate between them and effectively dry the lumber. Sticker length is governed by the width of the load of lumber. Kiln sticks must be wide enough to distribute the load above them over a wide enough area to prevent indentation of the lumber. If sticks are too wide, they may slow up the drying of lumber at areas of contact and may leave it at a higher final moisture content than the areas not covered by stickers (Rasmussen, E., 1961).

The stick must be thick enough to survive handling and repeated cycles through the kiln. On the other hand, the economics demand that the stick be made as thin as structurally possible so that the maximum amount of lumber can be put in the kiln. As the thickness is reduced, air velocities may tend to increase due to the higher static pressures resulting from a smaller volume available for air flow. With the conventional solid wood stick, the structural limit to thickness has been limited to about 3/4 of one inch. One-half inch sticks made of laminated veneer plys have been successfully used by Weyerhaeuser (Dineen, N., 1965). Using composition materials such as fiberglass, or aluminum, or the new phenolic based stick, it is possible to make the sticks even thinner and still have realistic strength properties. Of these last three materials, only the phenolic sticks appear to be economically feasible. Thus, kiln sticks can be made as thin as one quarter of an inch, but their performance criteria have not yet been established.

As the stick thickness is reduced, air velocity will tend to increase (Knight, E., 1970). However, the total volume of air circulating through the lumber may decrease. This factor may become critical where large amounts of water need to be removed in a very short time as in ponderosa pine schedules.

As thinner sticks are used in double track kilns, it becomes more difficult to match the loads on both sides (DeWeese, A., 1955). Thus, air circulation may become blocked unless a chamber is left between the loads to redistribute the air as it passes into the second load.

Drying Stresses

As the drying of lumber progresses, the amount of free water in the cells gradually diminishes, beginning at the lumber's surface and ending in the interior. When the cells are dried below fiber saturation, the wood starts to shrink and will continue to shrink as long as it loses moisture. The amount of shrinkage is very nearly proportional to the degree of drying below the fiber saturation point (Rasmussen, E., 1961). Although the surface moisture content may be dried to below FSP, the interior may still remain well above FSP. Hence, the average moisture content for the lumber may be above FSP but shrinkage can still take place due to the dry surface condition.

Wood is a cellular material with different properties along different axes due principally to variation in cell wall thickness. Deformation of lumber in drying is due to these differences. Wood shrinks about 1 1/2 or 2 times as much parallel to the annual growth rings (tangentially) as it does across the rings (radially). The shrinkage along the grain (longitudinally) is very little in normal wood (Panshin, A., et al., 1964). The amount of shrinkage and the difference between radial and tangential shrinkage have a direct bearing on the seasoning defects that occur during drying.

The greatest deformation of drying lumber usually takes place at the top courses of the load. The lower courses have the weight of the lumber abobe them to constrict deformation. However, the top courses have no such weight and suffer more degrade as a result. Some mills minimize this problem by placing heavy weight on the loads. In a study by Peter Koch (1974), degrade was reduced using sharply serrated aluminum kiln sticks pressed into the lumber and thus restraining it during the drying process.

IV. AIR VELOCITY BETWEEN COURSES

The Variables

The purpose of this phase of the project was to investigate the effects of four kiln stick thicknesses, 1/4 inch, 7/16 inch, 9/16 inch and 3/4 inch and their relationships with the plenum width and fan performance on air velocity between courses of lumber. A sufficient quantity of the various sticks was obtained through a grant from Simpson Timber Company and were checked to insure uniformity of thickness. Approximately 15 percent of the 3/4 inch sticks were rejected for being too thick. All the other sizes fell within the limits of $\pm$ 1/16 of an inch.

The second variable, plenum width, presented more of a problem. Since our kiln did not have movable walls, the only possible solution was to move the load closer to the air entering side of the kiln (Figure 1). Thus, as the plenum decreased on the critical air entering side, it increased on the air leaving side. A roller assembly was constructed which allowed the kiln charge to be easily moved laterally in the kiln. When the kiln charge was centered in the kiln, a plenum width of 25 inches resulted and when moved to its extremity, a plenum of 13 inches resulted. Hence, these two settings were established as the plenum width variables. Three fan speeds were selected, 660 RPM, 480 RPM, and 250 RPM, which represented the

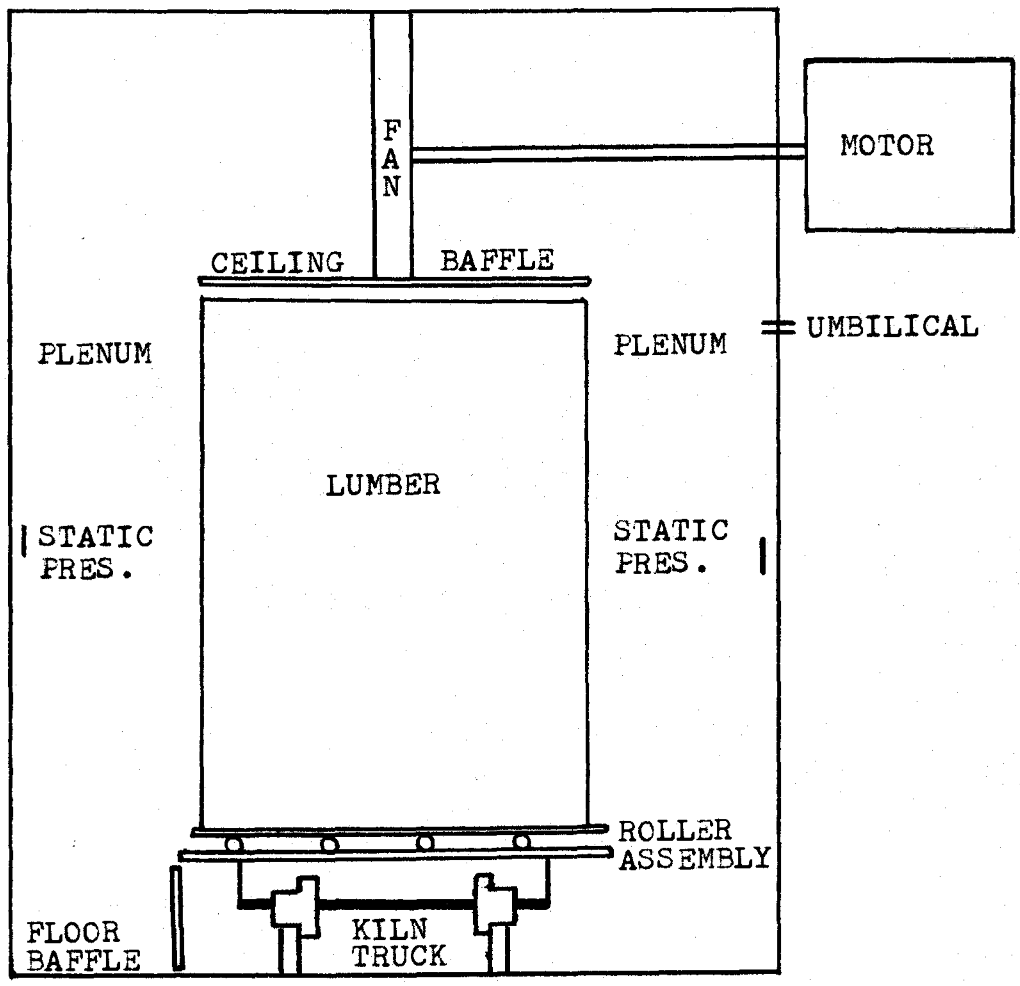


Figure 1. Cross section of experimental kiln showing components.

upper, mid, and low ranges respectively of the fan system. It was noted that with a tachometer, these RPM settings could easily be duplicated.

The test kiln used in this experiment had a capacity for loads measuring four feet wide, five feet high and eight feet long. Two, four-bladed fans, 36 inches in diameter were propelled by a single five horsepower variable speed drive unit.

Thus, with the four different stick thicknesses, the three different fan speeds, and the two plenum widths, a total of 24 different variable combinations was necessary to examine.

In an attempt to remove as many extraneous variables as possible, all the air velocities were taken on dry lumber (2 x 8 western hemlock, mill run) (drying schedule given in Appendix A). The lumber had not been planed and was cut using double arbor sawing. The only feasible method of changing stick thickness involved a complete restacking procedure. In order to remove stacking from being a possible source of bias, each piece of lumber was numbered. Random numbers were generated for each restacking on the Hewlett-Packard model 9830-A programmable calculator and the lumber was restacked according to the positions given in randomized numbers.

Proper baffling was another source of concern. If air flow was to be maximized, the kiln baffling also had to be optimum. The lumber charge filled the entire distance between the kiln truck and the ceiling baffle. Both ends and the bottom were also baffled with sheet metal or plywood.

In order to be assured of a statistically sound experiment, Dr. Kenneth Rowe of Oregon State University's Department of Statistics recommended the proper method of setting up the experiment. His advice was to perform the experiment randomly and with at least three complete replications of all variable combinations. Therefore, it was necessary to plan on 3 replications x 4 stick thicknesses x 3 fan speeds x 2 plenum widths = 72 different data runs.

Air Velocity Measurement Procedure

In order to meet the requirements of numerous accurate air velocity measurements, a data gathering system was specially designed. This system was composed of four major units: (1) the Hastings Model LAM5K Airmeter, (2) the digital voltmeter, (3) the HP 9830-A programmable calculator and (4) the teletype printer. The use of the airmeter alone made detailed air velocity analysis difficult since a human judgement factor would need to be employed to read the output signal of the fluctuating indicating needle. However, with the air meter coupled to electronic recording devices, the human error factor was eliminated and consistent results were possible.

A remote control unit was built so that the air velocity measurements on the leaving air side could be recorded while I was in the kiln manipulating the probe on the air meter. With this method, I could position the probe until a maximum reading was indicated on the meter's dial and then signal the recording system to take a series of ten readings over a time period of about three seconds. The programmable calculator could analyze these ten readings and record them on its magnetic tape cassette.

In all cases the kiln door was tightly closed, and the necessary electronic connections were made through a small umbilical tube through the kiln wall.

The program that was used in conjunction with the HP 9830-A is given in Appendix B.

After the recording system had been developed, the air velocity measuring procedure was established. The goal of the project was a careful analysis of air movement in the kiln, thus it was decided that velocity measurements would be taken at every opening at distances two feet apart. Since the kiln load was eight feet long, the measured scans were 1 foot, 3 feet, 5 feet, and 7 feet from the door end of the load.

As the thickness of the stick decreases, the lumber capacity of the kiln increases as room for more courses of lumber becomes available. Hence, with the 3/4 inch stick, 24 openings resulted, 9/16 - 25, 7/16 - 27, and 1/4 - 29. The lowest course was established as the base line and the scans were numbered from bottom to top.

Air Velocity Data Collection

Careful stacking of the lumber was necessary to prevent uneven flow of air due to the overhang and indentations on the sides of the loads. On the average, one day was spent restacking and another full day to take the measurements for one particular stick thickness.

In order to be assured of instrument stability, the air meter and the digital voltmeter were warmed up for at least one hour before measurements were started. The air meter was then adjusted through the potentiometers until a zero meter indication was obtained. The other components of the data gathering system were connected and air velocity data could then be taken (Figure 2).

Within each stick thickness set, six variable combinations existed; three fan speeds and two plenums. The order in which the combinations were run was randomized. Each combination of variables required about one hour of time to gather the data. This time was spent inside the kiln moving the air meter probe up the four different scans. From 24 to 29 readings were required for each scan, and each reading required the operator to turn the probe until the meter read a maximum. Then the remote button was depressed and the readings could be recorded as described before. All readings were taken at a temperature of 72° F. $\pm 5^{\circ}$ F.

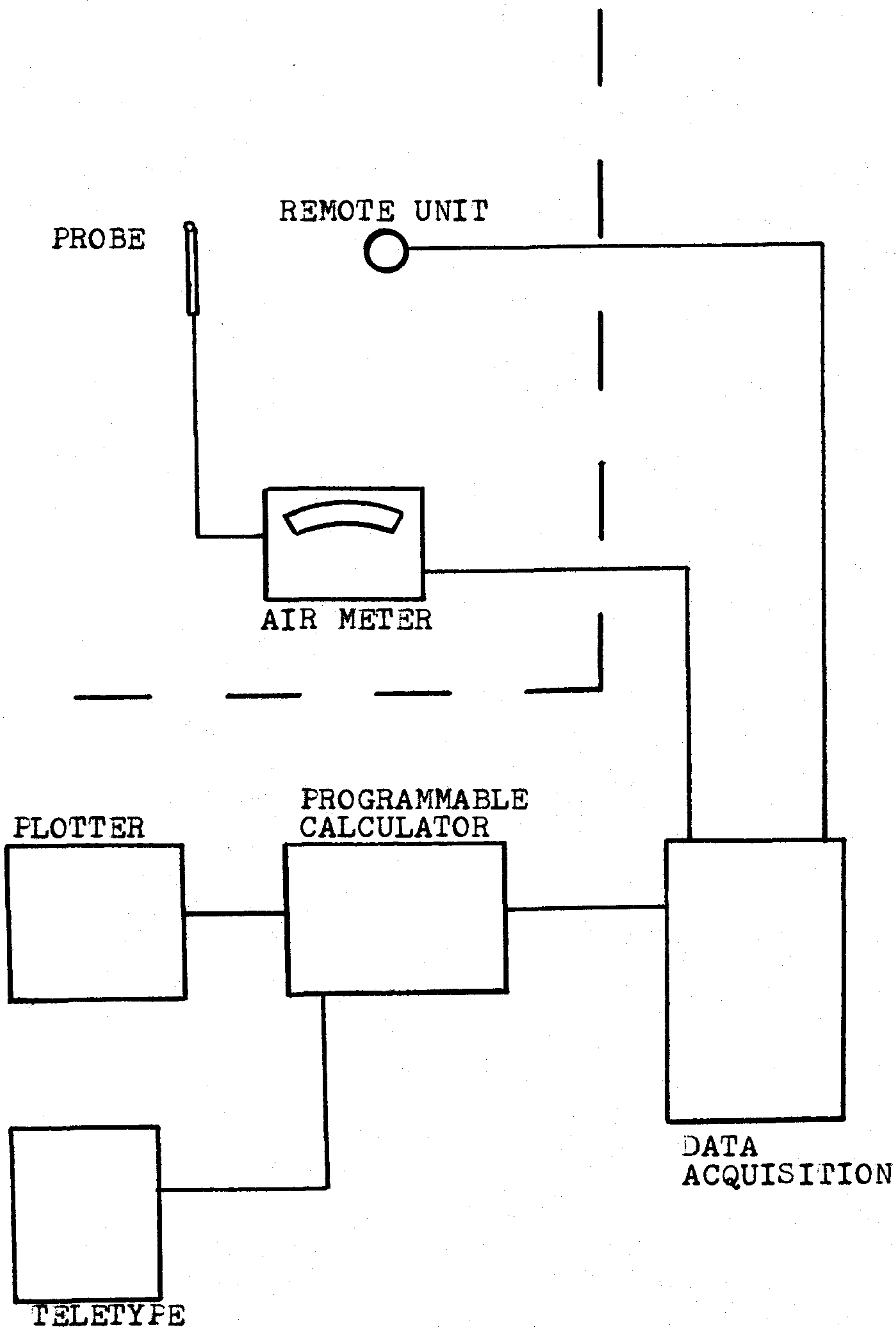


Figure 2. Schematic diagram of electronic components used in gathering air velocity data.

After the four scans had been measured, I would come out of the kiln and call for a print out of the data on the teletype where it could be checked for errors. The most common error was a missed reading. A correction routine saved a significant amount of time by allowing individual scans to be remeasured instead of all four scans.

When a printout of the data revealed that all positions had been measured, the next set of variables was established and the process repeated.

If visual comparison of the data was desired, use of the automatic plotter would produce an overlapping graph of the data in about three minutes.

Power Consumption Data Collection

Power consumption was another aspect of kiln operation that needed exploration. A newly calibrated kilowatt-hour (KWH) meter was installed on the electrical lines to the fan motor. This installation made it easier to record the data than measuring both amperage and voltage. For each of the 72 runs, power consumption was monitored by recording the beginning and ending time with the corresponding kilowatt hour readings from the meter. A final reading of at least one KWH was desired to overcome the difficulty in exactly expressing the beginning and ending KWH. Thus, with a low fan speed, more time was required to reach this point than with a high fan speed. However, none of the time periods fell below a 40 minute minimum.

Static Pressure Data Collection

Another important factor in kiln air flow is the static pressure difference through the load. Two static pressure probes were made and placed in both the entering and leaving plenums. Both probes were located on the kiln wall, halfway into the kiln and at the midpoint between the ceiling and floor. These probes were connected to a manometer which measured static pressure in inches of water and readings were always made after equalization had been attained in the kiln. For every combination of sticker thickness, plenum width and fan speed for all three replications, static pressure measurements were recorded.

Statistical Evaluation

Since all of my air velocity, power consumption and static pressure information was stored on magnetic tape cassettes, the obvious solution for me to statistically analyze the data was to again utilize the Hewlett Packard model 9830-A programmable calculator. Unfortunately, the memory capacity of the calculator was not adequate nor were suitable statistical programs commercially available. Dr. Kenneth Rowe of the OSU Department of Statistics recommended utilization of the OSU computer system. This required that the data be transferred from the tape cassettes to files available on the larger campus computer. The information was fed into the HP 9830-A which was programmed to print out a paper tape of the data for transmittal to the new computer file on the Control Data Corporation's model 3300. This computer was programmed to change the data format from a linear listing to a matrix listing.

Dr. Rowe performed the analysis utilizing the Statistical Interactive Programming System (Gutherie, D., et al., 1973). A randomized block design was employed followed by factorial treatment. The resulting F values could be used to determine which variables were exerting an effect independently as well as indicating interactions between variables. The program also listed the mean values for each variable or set of variables which could be further evaluated by the least significant difference method (Li, J., 1964). Confidence levels of 0.05 were used to determine the least significant differences (L. S. D.).

Results and Discussion

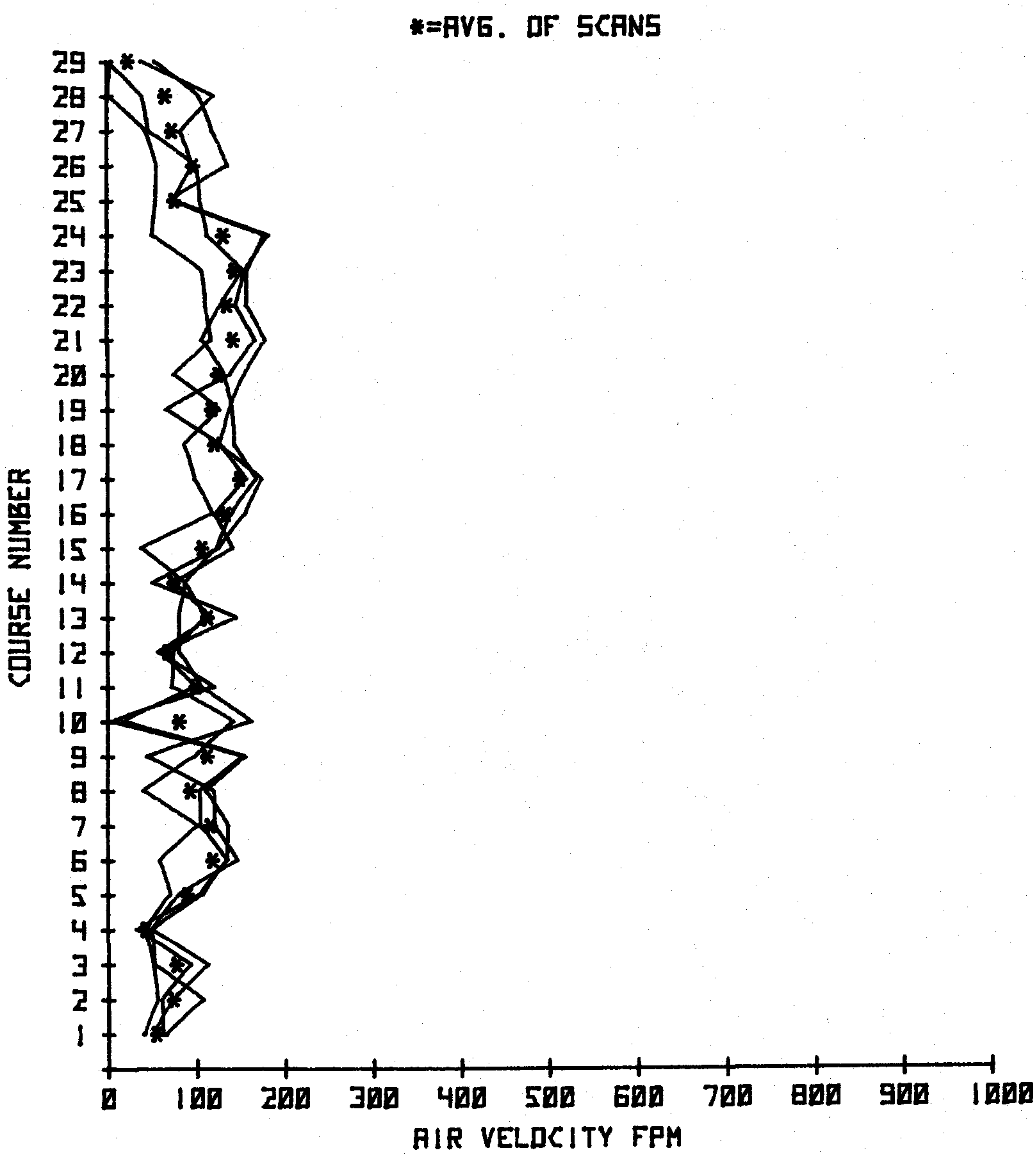
Magnitude of Air Velocity

After the 24 combinations of variables were each repeated three times, the analysis of air velocities was begun. The HP 9830-A and its automatic plotter produced graphs depicting position in load of lumber versus air velocity. These air velocity profiles made visual evaluation quite easy and some of the more obvious conclusions of the project can be made from them.

The air velocity profiles as shown in Figures 3 to 4 and 10 to 19 have four lines, each representing the air flow along one of the vertical scans. Thus, looking at all four lines, gives a picture of the total air circulation pattern. The asterisk occurring at each course opening represents the average of the four scans.

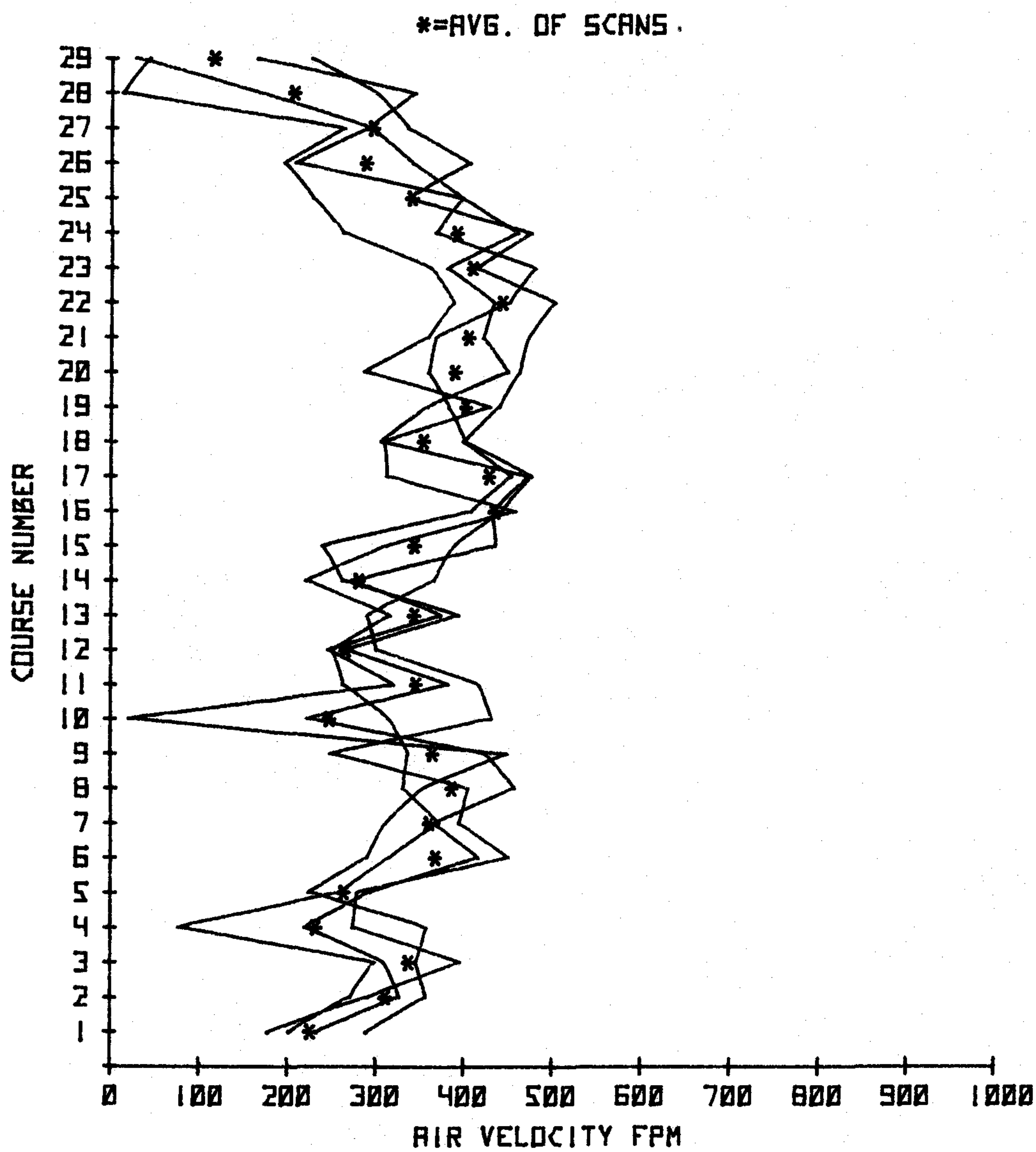
Utilization of the 1/4 inch sticks and slight deformation of the lumber often blocked the openings resulting in little if any air movement. Sticks were placed on four foot centers throughout this experiment, hence moving the kiln sticks closer together would solve part of the problem. However, some of the blockages were so complete that increasing the fan speed to its maximum still resulted in near zero air velocities (Figures 3 and 4). The three thicker stick sizes did not suffer from this problem.

The effect of surface resistance on the volume available to air flow is so great with the 1/4 inch stick that air velocity is lowered significantly. Regardless of the combinations of plenum width or fan speed, 1/4 inch sticks always decreased the air velocity by at least 90 feet per minute (FPM).



1/4 IN. EKS STICKERS, 25 IN. PLENUM WIDTH, 250 R.P.M., #2.

Figure 3. Air velocity profile showing the blockages of air flow at courses number 10 and 28. (Compare to Figure 4).



1/4 IN. EKS STICKERS, 25 IN. PLENUM WIDTH, 660 R.P.M., #2.

Figure 4. Air velocity profile showing that although the fan speed is much higher, air flow is still blocked at courses number 10 and 28.

The statistical analysis showed for the 13 and 25 inch settings tested, that the plenum width had little effect on the average magnitude of air velocity. Both plenum widths resulted in the same average air velocities of 310 feet per minute.

Each set of variable combinations was evaluated three times. However, analysis showed that replication did not alter results very much (Figure 5).

Fan speed directly affects air velocity. Figure 6 shows the general trend, while Figure 7 breaks the data down by stick thickness. Throughout the range of fan speeds, maximum velocities occurred with the 9/16 inch stick. Velocities with the 3/4 and 7/16 inch sticks followed closely, while the 1/4 inch sticks decreased air flow well below the other three. The differences in all cases are significant at the 0.05 level of confidence with a L. S. D. of 12 FPM (Figure 8).

Consideration of air velocity alone in drying is not sufficient. With fast drying species such as ponderosa pine, the volume of air circulated is a far more important factor than velocity alone since large amounts of water need to be removed in a relatively short period. Although the 9/16 inch sticks resulted in highest velocities, the 3/4 inch sticks always gave the highest volume of air circulation (Figure 9). Increases in air velocity due to changing kiln stick thickness were not sufficient to yield the higher volumes obtained with the 3/4 inch sticks. Thus, my data shows that increasing both stick

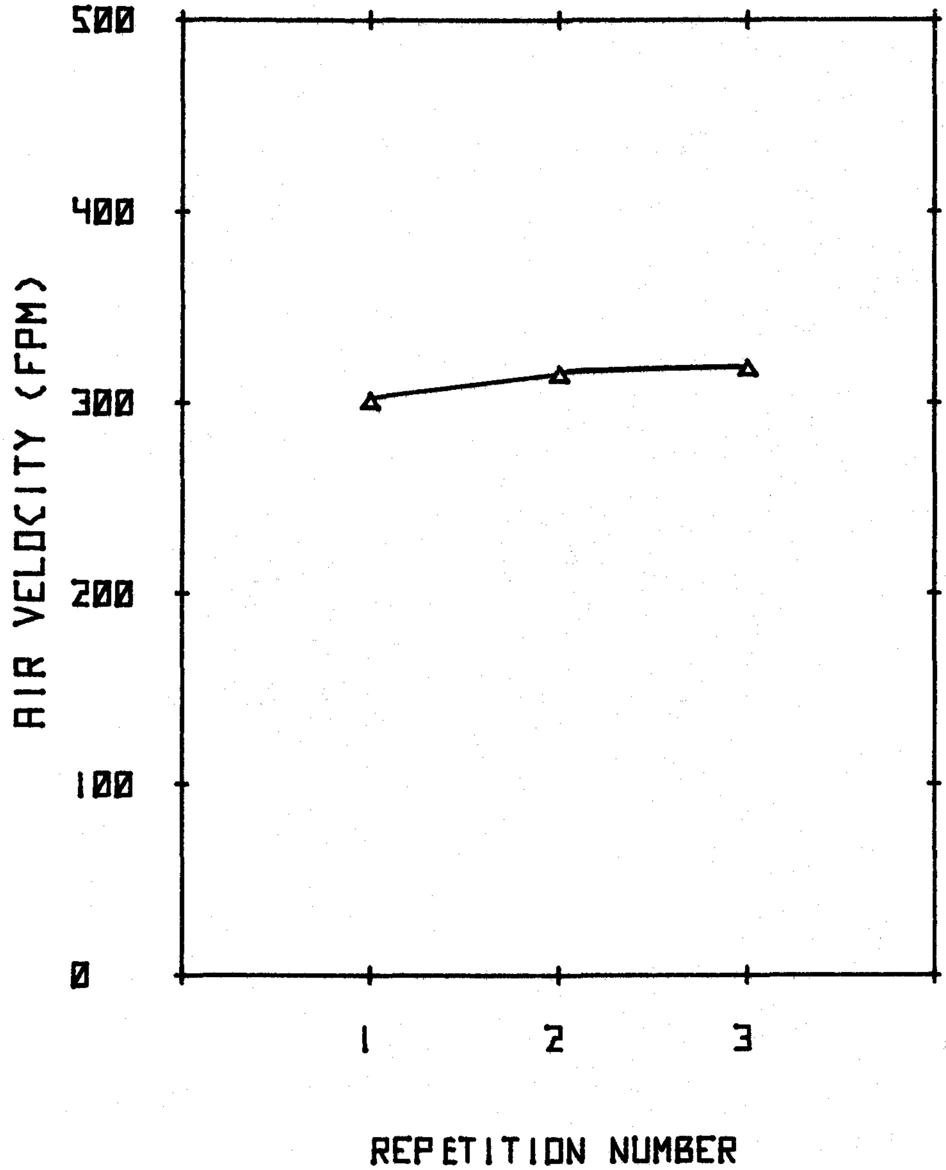


Figure 5. Replication had little effect on air velocity between courses.

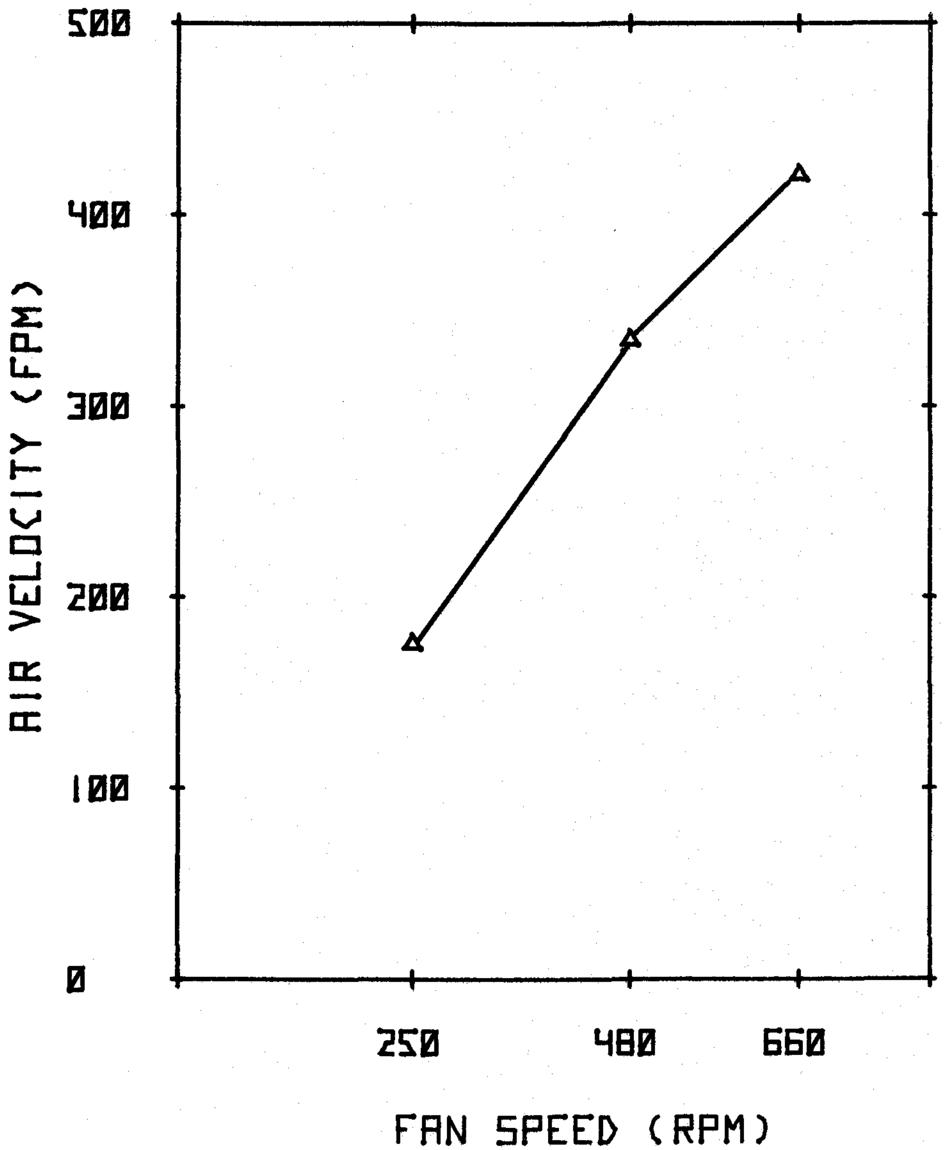


Figure 6. Average air velocity between courses increased with fan speed.

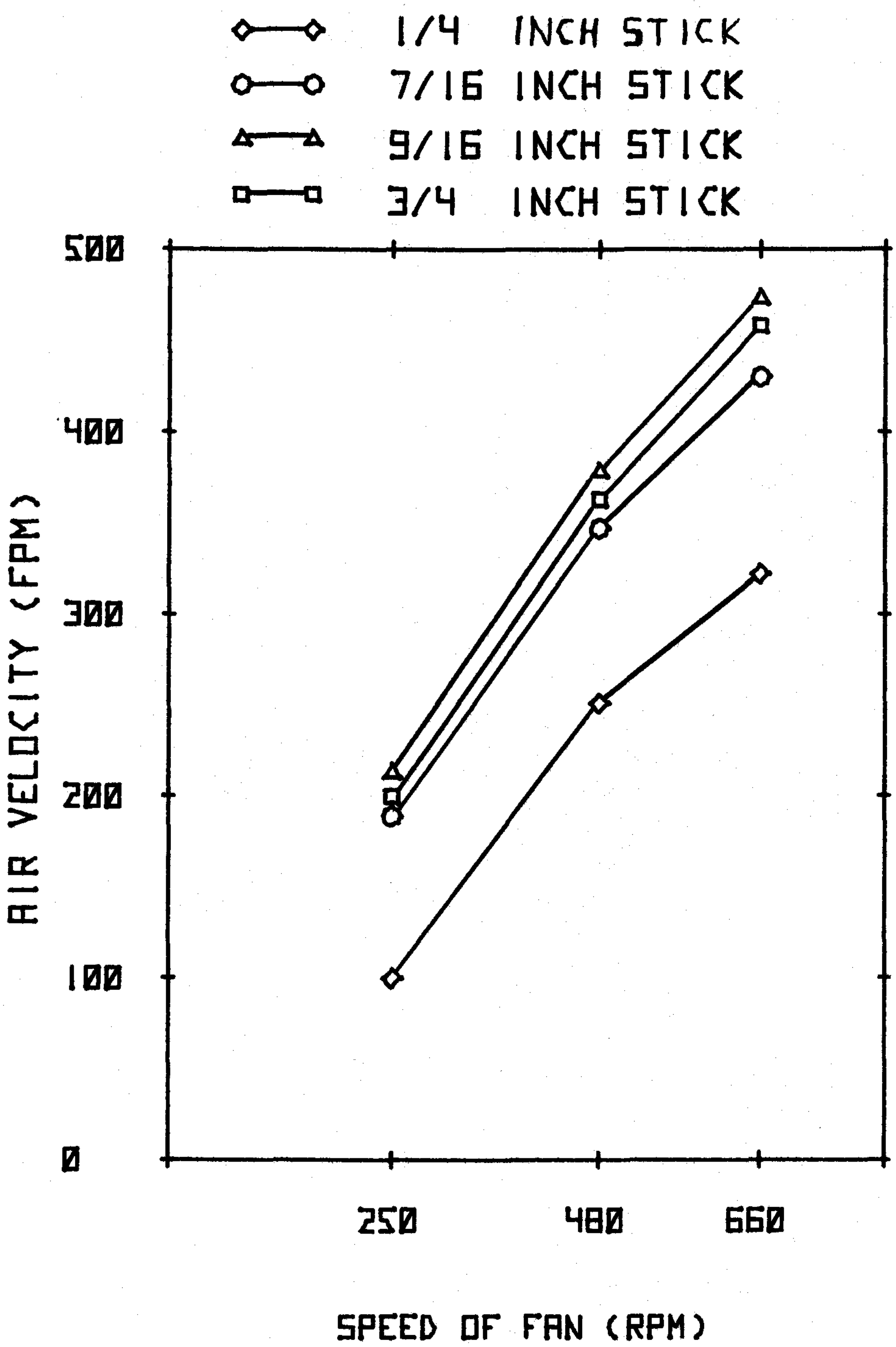


Figure 7. Air velocity between courses versus fan speed for all four stick thicknesses.

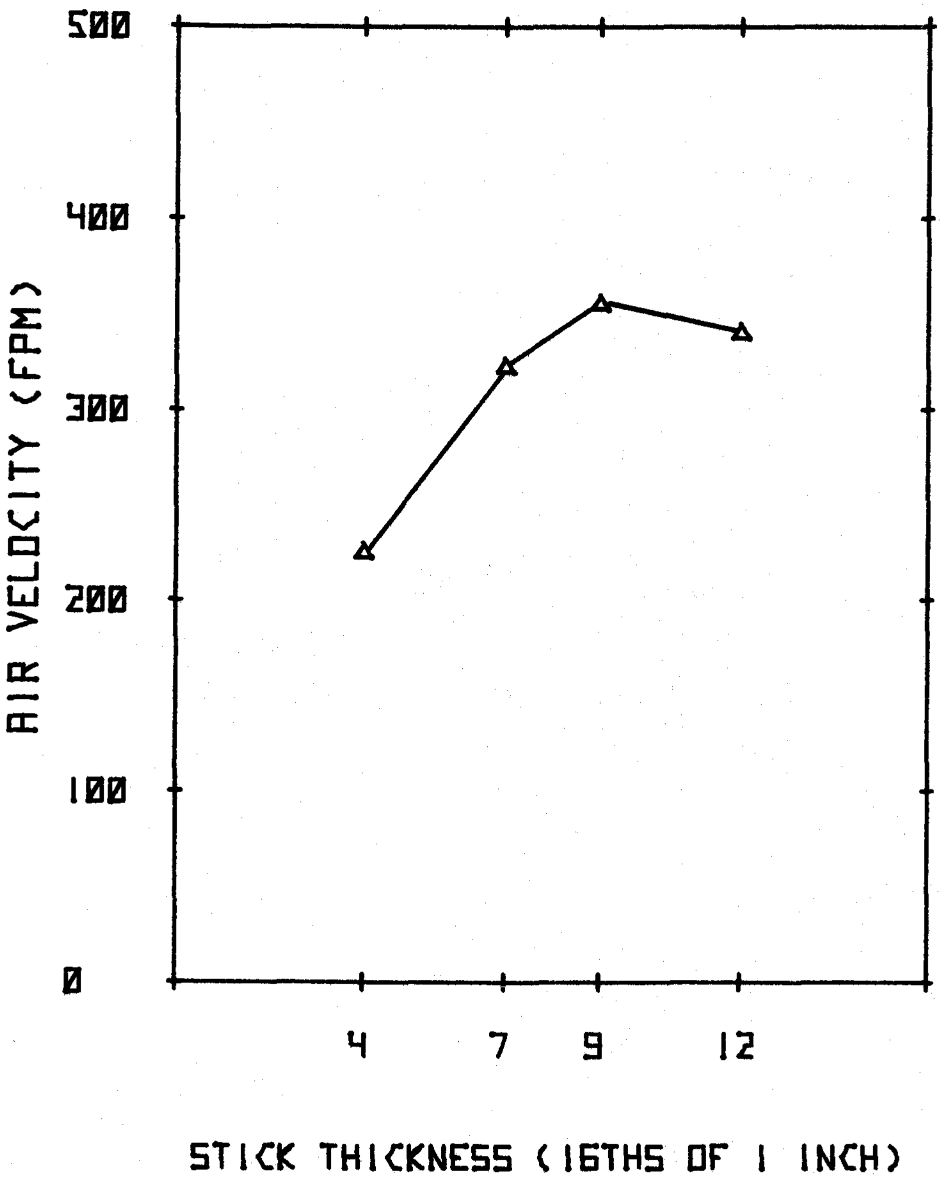


Figure 8. Air velocity between courses versus stick thickness showing maximum velocities with the 9/16 inch kiln sticks.

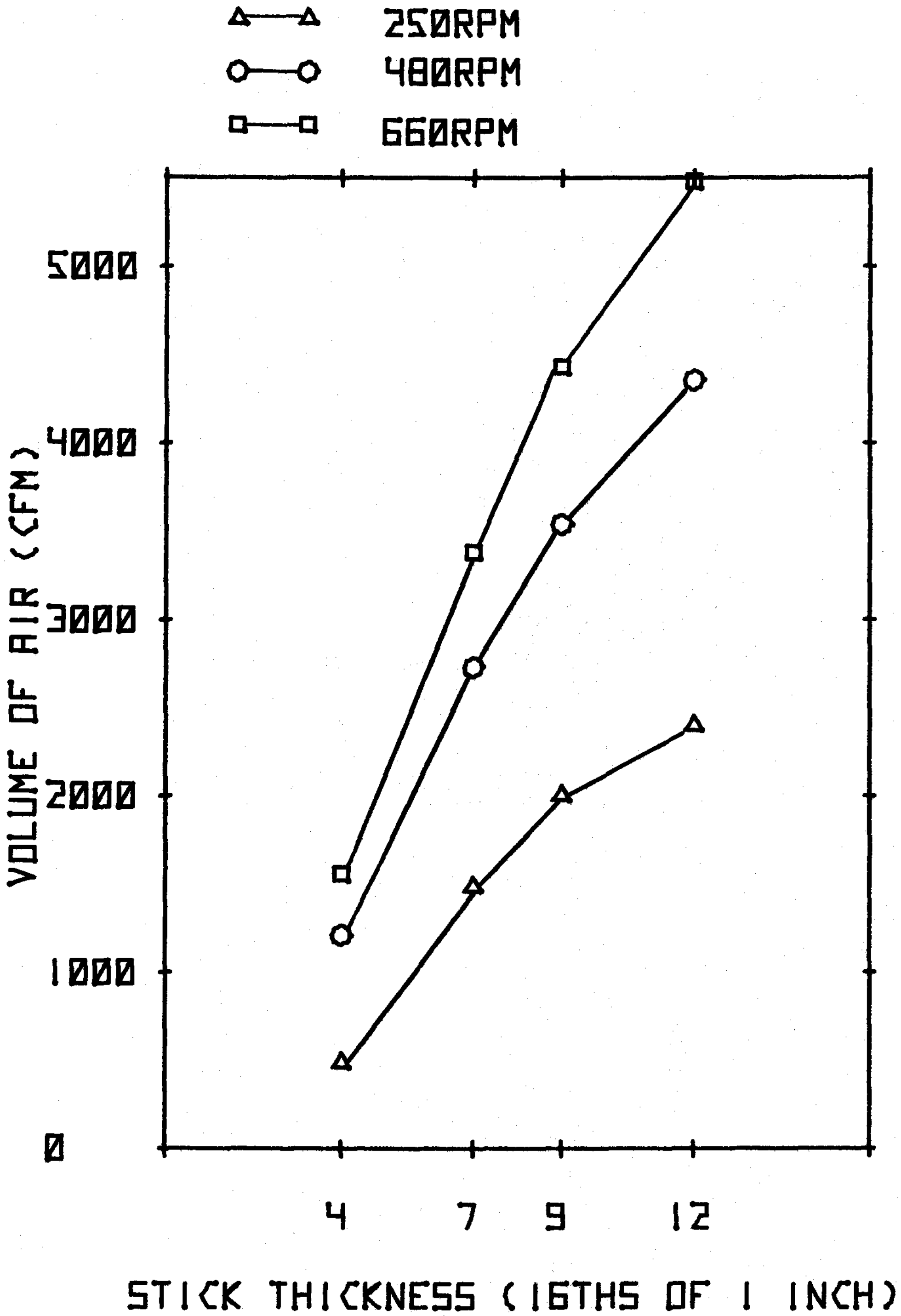


Figure 9. The volume of air circulating through the lumber increased with stick thickness at all three fan speeds.

thickness and fan RPM resulted in higher volumes of air.

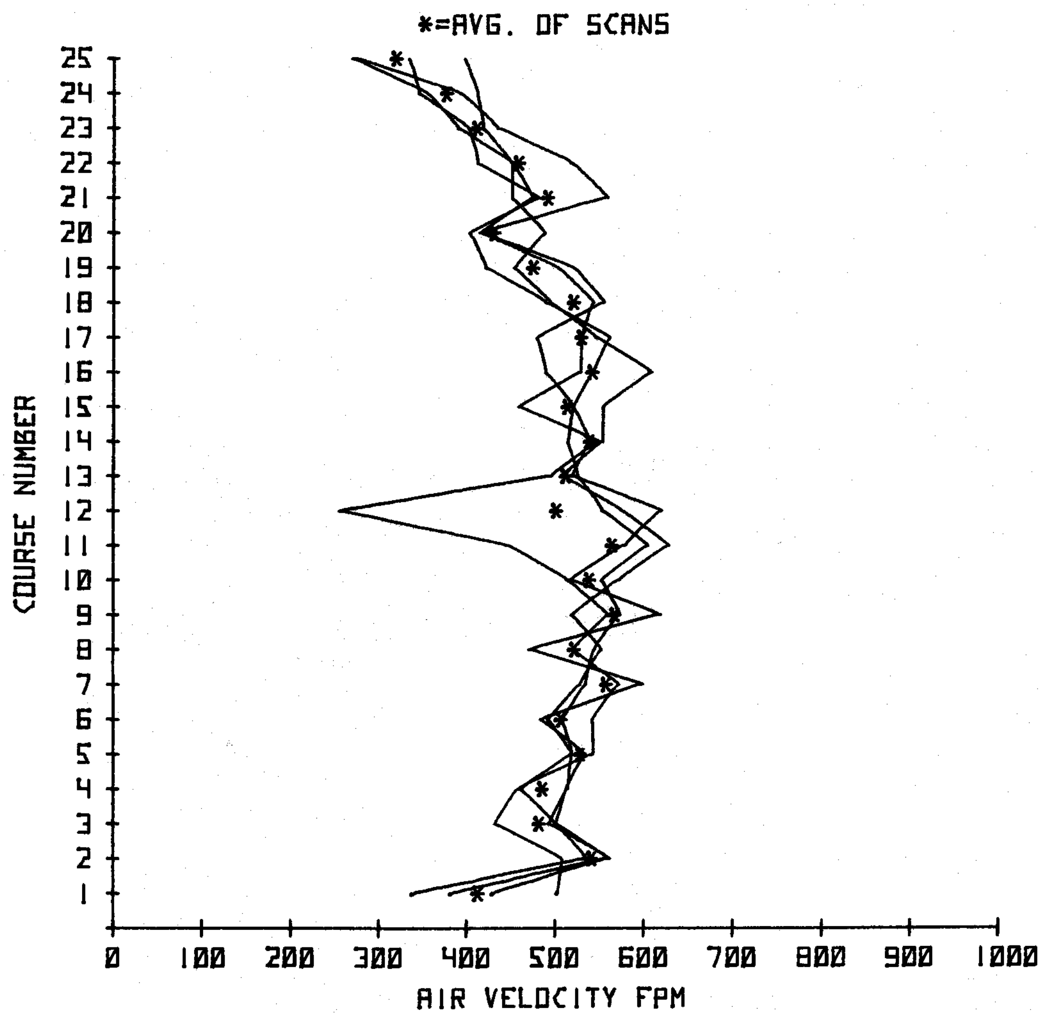
Uniformity of Air Velocity

The air velocity profiles show the effect of plenum width on air distribution in the kiln (Figures 10 to 13). Using 3/4 inch sticks and the narrower plenum, lower velocities were always observed at the top of the load. When the width of the plenum was increased, the uniformity also increased. The 9/16 and 7/16 inch sticks both reflected this same trend, however, it was most noticeable with the thickest sticks.

The profiles illustrate the effect of increasing air velocities on the uniformity of air circulation. As the fan speed (velocity) was increased, the dispersion of the scan lines increased (Figures 14 to 19). Decreasing the stick thickness over the range of 3/4 to 1/4 inch also resulted in less uniform air flow.

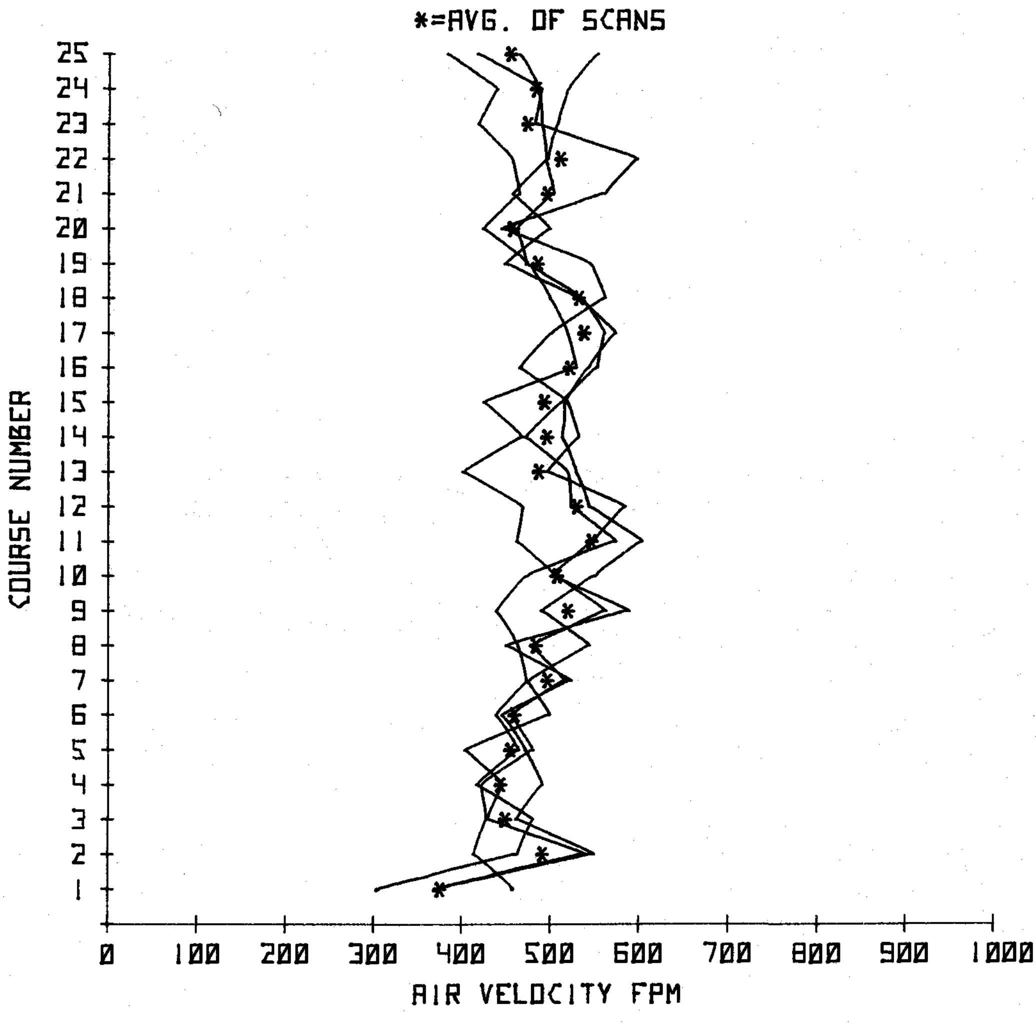
It is generally believed that the uniformity of air circulation increases with increased velocity. Under the conditions of my experiment, the reverse was true, that is, air flow uniformity decreased as velocity increased with all four kiln sticker thicknesses (Figure 20).

Although the change in plenum chamber width had little effect on the average magnitude of air velocities, it greatly affected the uniformity. With the 13 inch plenum, the highest rates of air flow occurred near the bottom of the charge with lower velocities at the top.



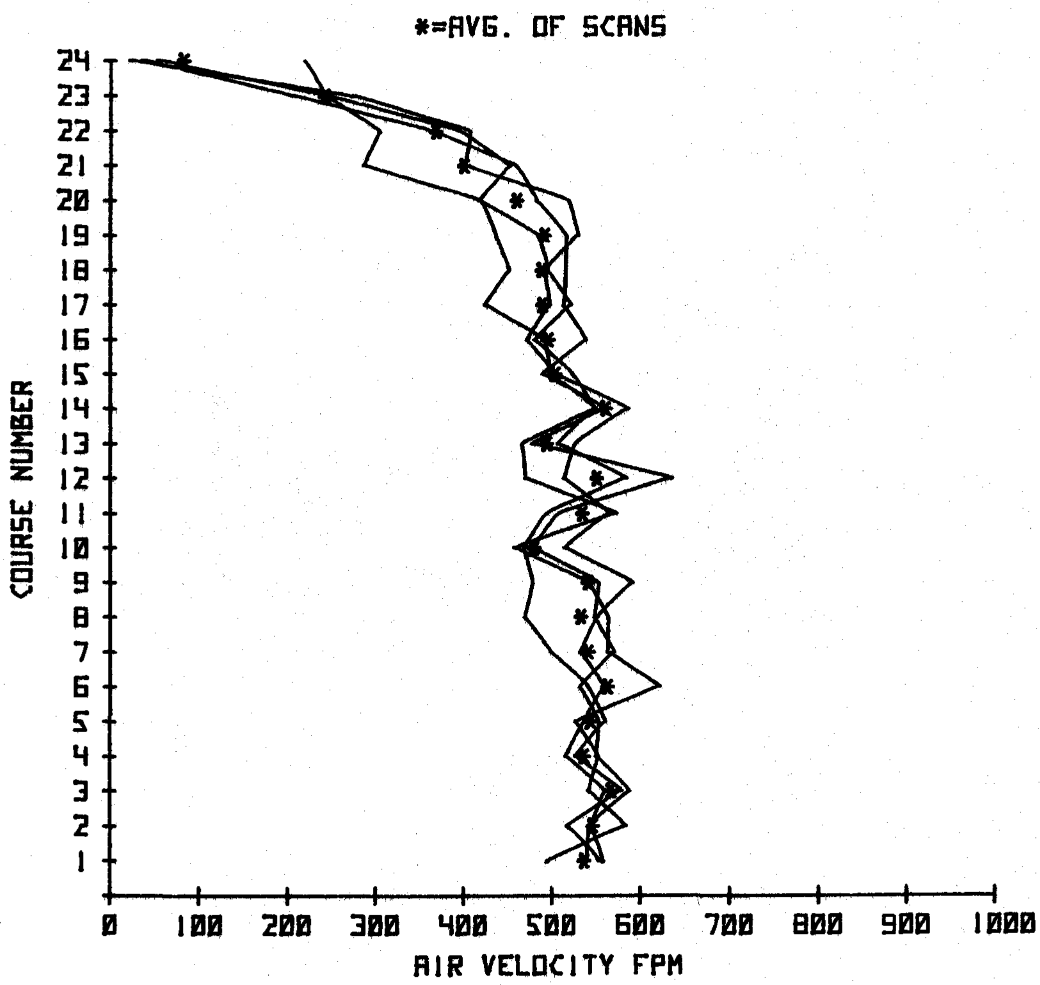
9/16 IN. EKS STICKERS, 13 IN. PLENUM WIDTH, 660 R.P.M., #2.

Figure 10. Using the 13 inch plenum, note the lower average velocities at the top of the load and compare to Figure 11.



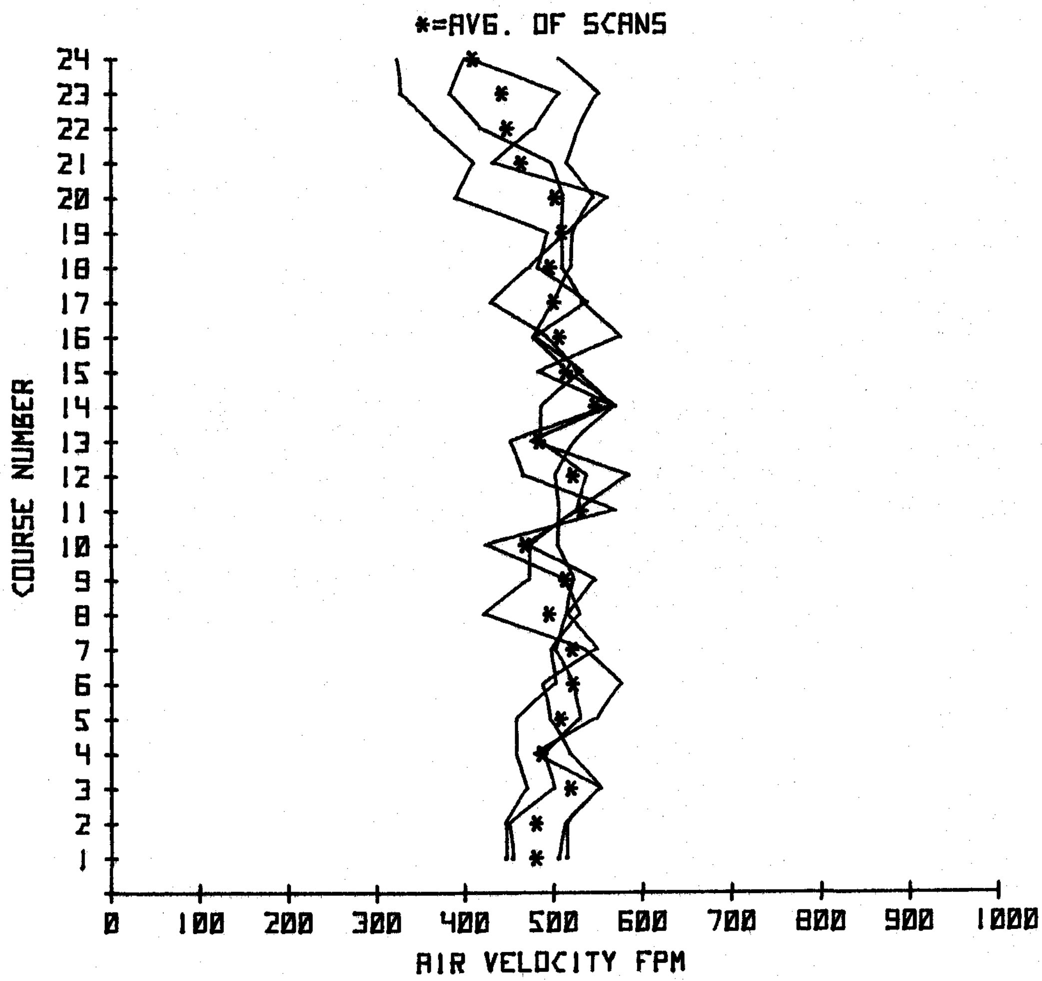
9/16 IN. EKS STICKERS, 25 IN. PLENUM WIDTH, 660 R.P.M., #2.

Figure 11. When the plenum width was changed to 25 inches, better uniformity of air circulation resulted. This trend was most noticeable with the 9/16 and 3/4 inch sticks.



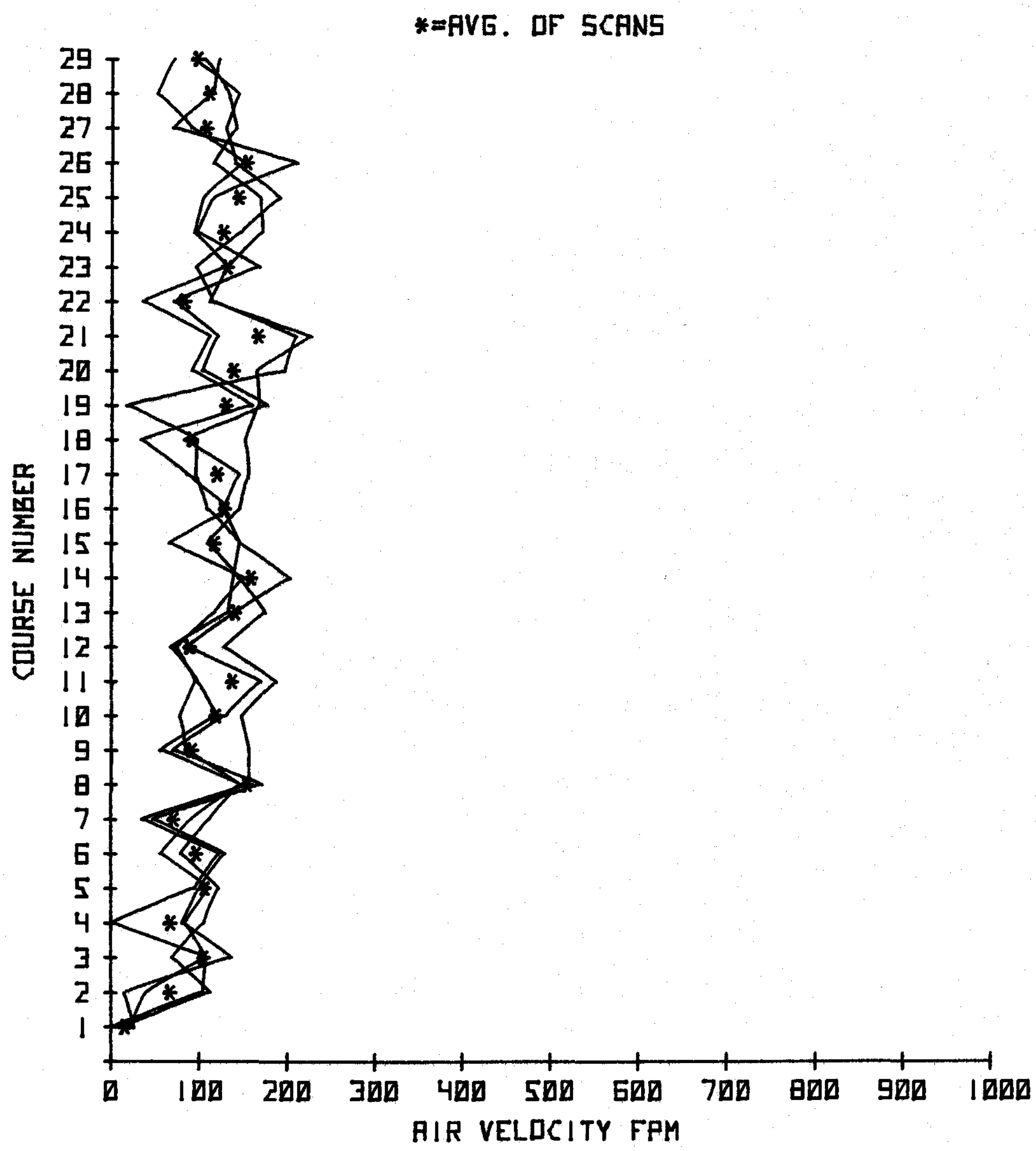
3/4 IN. EKS STICKERS, 13 IN. PLENUM WIDTH, 660 R.P.M., #3.

Figure 12. Note the far lower average velocities at the top of the load and compare to Figure 13.



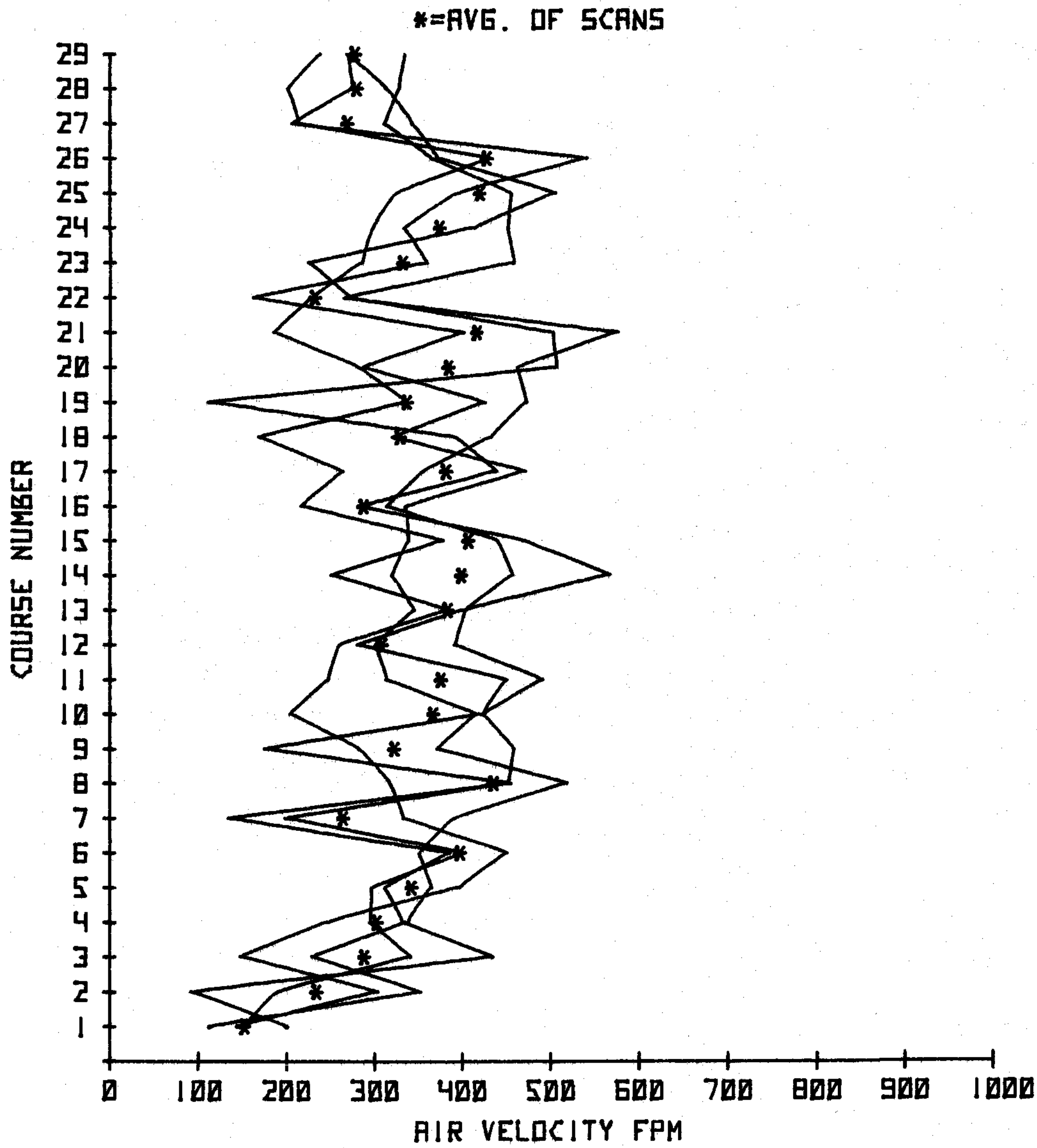
3/4 IN. EKS STICKERS, 25 IN. PLENUM WIDTH, 660 R.P.M., #3.

Figure 13. A wider plenum chamber resulted in better uniformity of air circulation.



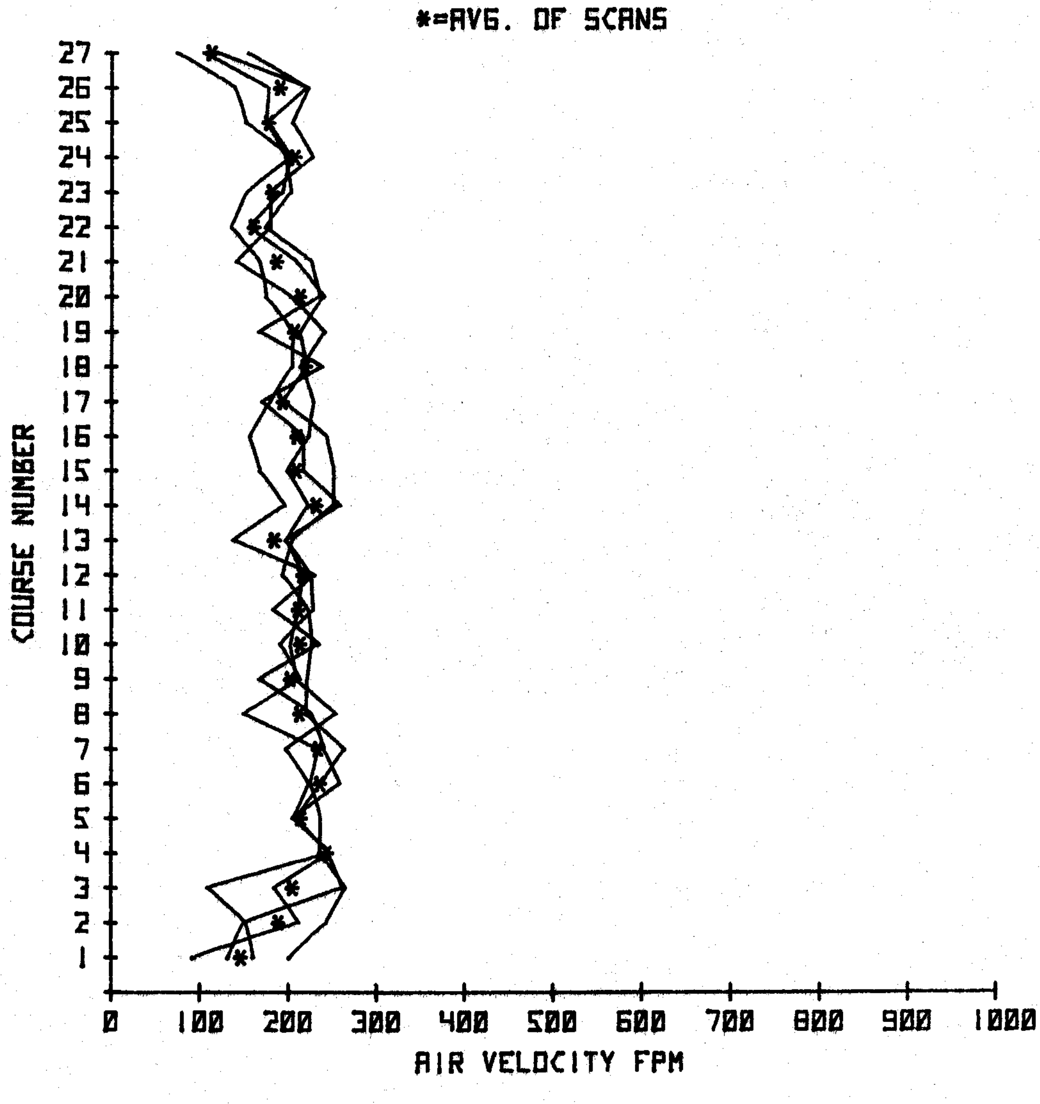
1/4 IN. EKS STICKERS/ 13 IN. PLENUM WIDTH/ 250 R.P.M./ #3.

Figure 14. Note the uniformity of air circulation and compare to Figure 15.



1/4 IN. EKS STICKERS, 13 IN. PLENUM WIDTH, 660 R.P.M., #3.

Figure 15. Increased fan speed resulted in poor air circulation uniformity.



7/16 IN. EKS STICKERS, 13 IN. PLENUM WIDTH, 250 R.P.M., #2.

Figure 16. Note the uniformity of air circulation and compare to Figure 17.

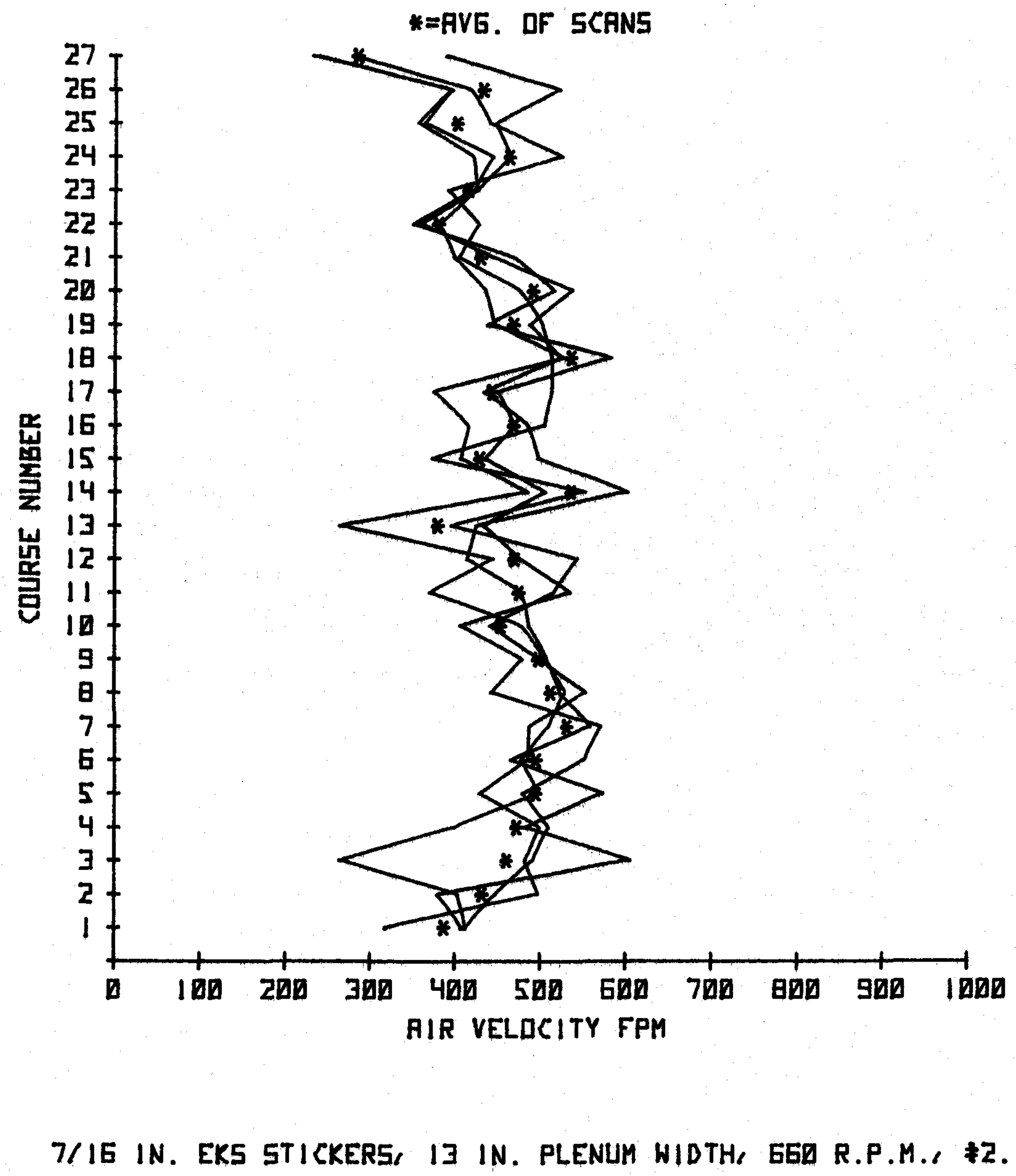
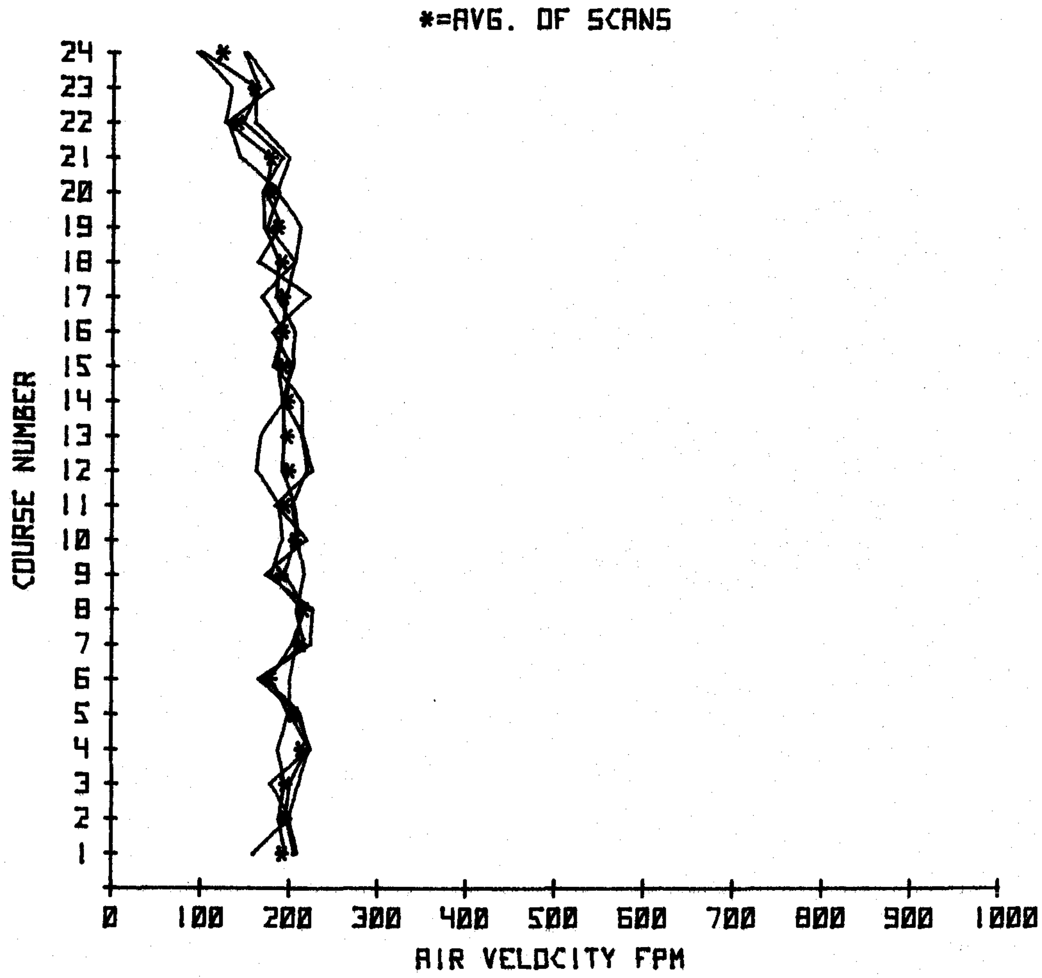
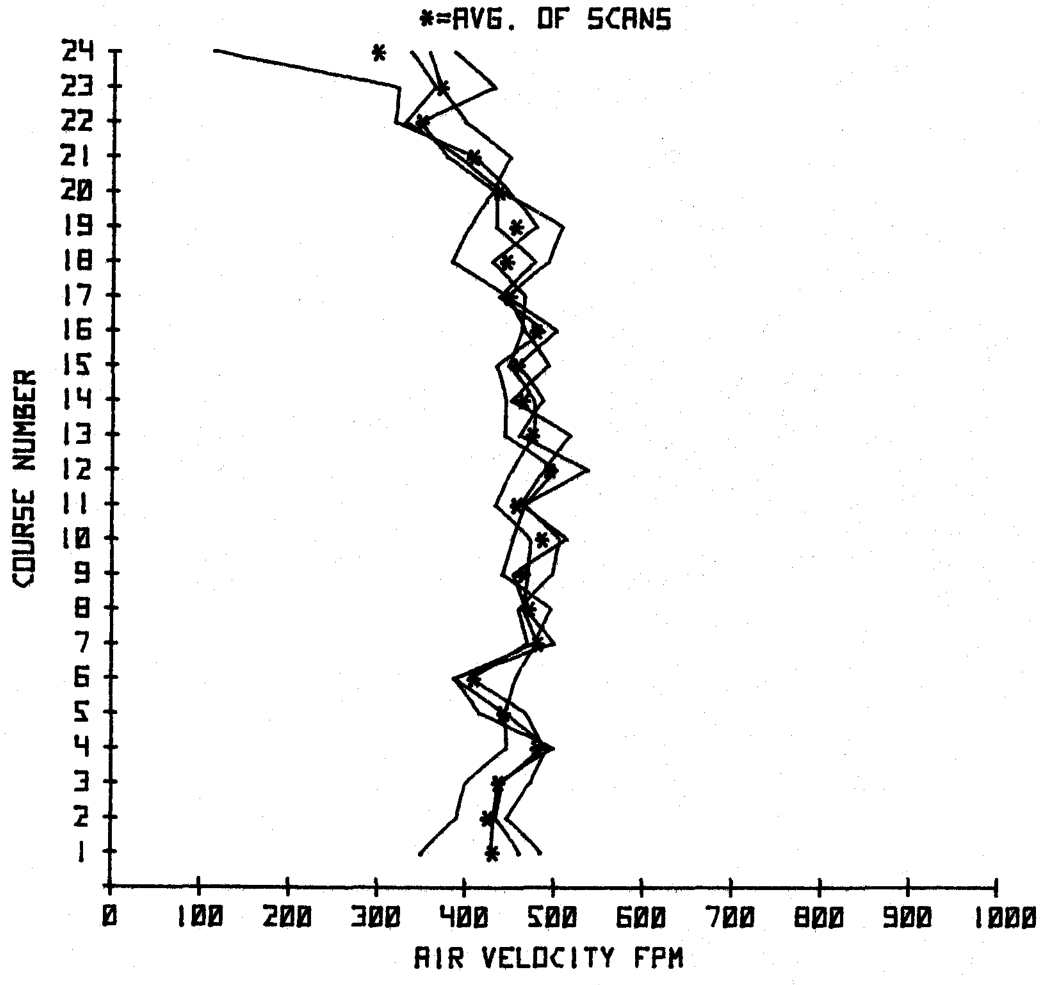


Figure 17. Increased fan speed resulted in poor air circulation uniformity.



3/4 IN. EKS STICKERS, 25 IN. PLENUM WIDTH, 250 R.P.M., #1.

Figure 18. Note the excellent uniformity of air flow at the low fan speed and compare to Figure 19.



3/4 IN. EKS STICKERS, 25 IN. PLENUM WIDTH, 660 R.P.M., #1.

Figure 19. Increased fan speed resulted in poor air circulation uniformity.

Use of the 25 inch plenum always improved the uniformity of air flow through the courses. It appeared that using a narrow plenum did not affect the average velocity since the low velocities at the top were compensated with higher ones at the bottom.

The uniformity of air velocities improved as stick thickness increased, but not linearly. Uniformity was very poor when the 1/4 inch stick was used (Figure 20). Use of the wider plenum and the 7/16, 9/16 and 3/4 inch sticks all resulted in far better uniformity, and differences between them were not too significant.

To optimize air velocity uniformity in the laboratory kiln, my study indicates that the wider plenum, the 9/16 or 3/4 inch sticks, and the lowest fan speed, 250 RPM, would be required. Deviation from these conditions would result in loss in uniformity which would probably be more than offset by other advantages such as faster drying time and increased kiln capacity.

It should not be inferred that a wider plenum will always improve uniformity of air circulation. As has been verified in this study and elsewhere, too narrow of plenum will result in low velocities on the top and higher ones at the bottom. For the experimental kiln in which I gathered all of my data, the 25 inch plenum resulted in good uniformity. However, a study by O. Torgeson (1940) showed that if too wide of plenum is used, then air velocities will be highest at the top of the load and lowest at the bottom. The plenum chamber

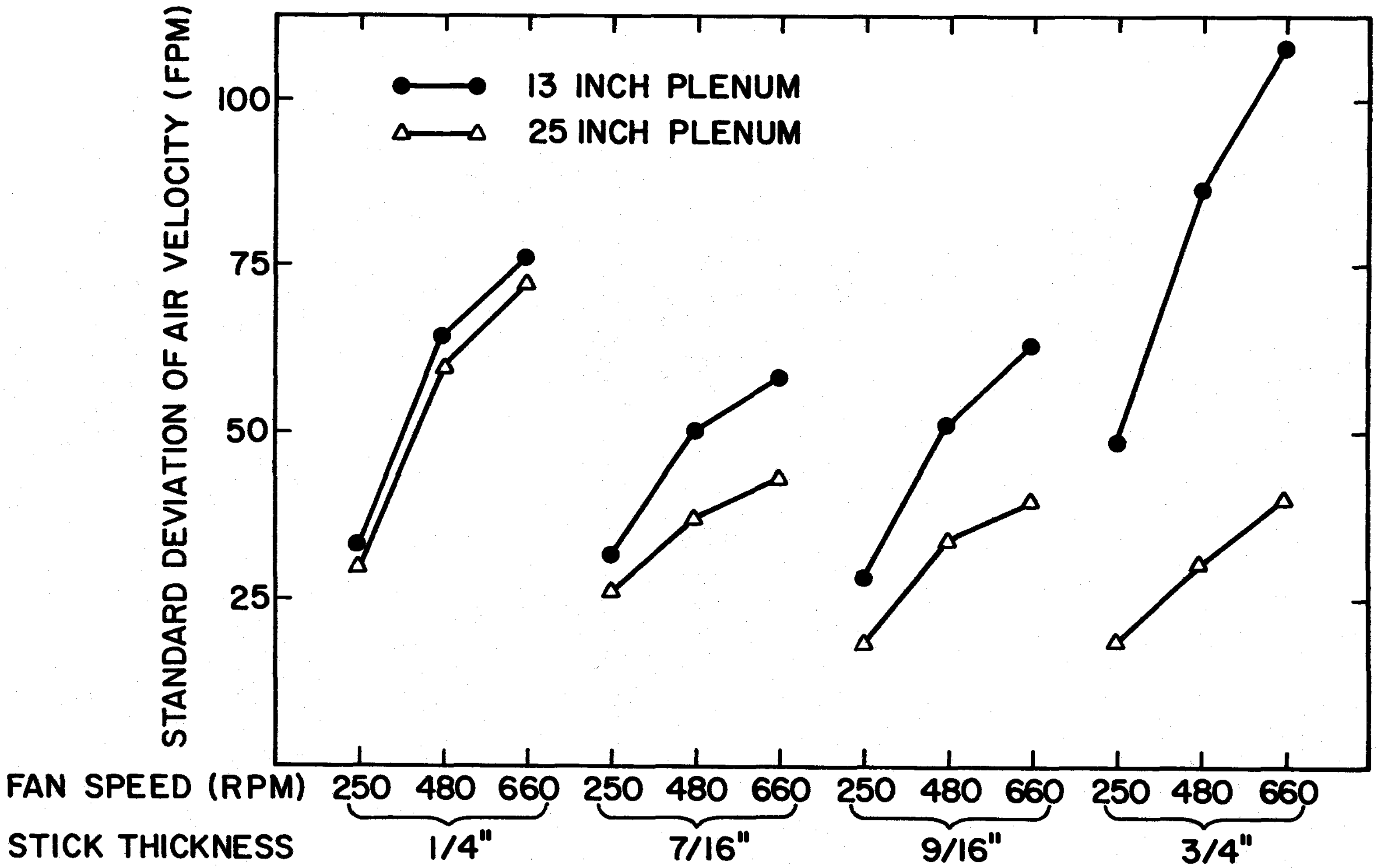


Figure 20. The standard deviation of air velocity flowing through the courses of lumber at the various combinations of stick thickness and fan speed. Note the differences resulting from changes in plenum chamber width.

must be of the right size so that the static pressure buildup is uniform thus resulting in uniform air flow.

An often quoted rule of thumb for establishing the width of the plenum chamber is that the chamber should be as wide as the total amount of openings from the top to the bottom of the load. If a kiln has 40, 1/2 inch sticker openings plus two, four inch openings between the packages, the plenum width should be at least 28 inches (40 x 1/2 + 2 x 4). Due to the capital costs of building kilns, it is far more common to see too narrow of plenums rather than too wide of ones.

Static Pressure

Static pressures were measured through manometers which gave readings in inches of water on both sides of the load and the drop in pressure across the load was determined from the difference between the two readings. Analysis of static pressure drop may provide more insight into the effects of thin kiln sticks on air circulation. Maximum readings on the air entering side approached 0.1 inch of water while minimum readings on the air leaving side were about zero although some were slightly negative. The negative static pressures result when the fans are sucking the air away faster than the incoming air can equalize the pressure.

The static pressure distribution followed the same pattern as that of the air velocity. Neither plenum width nor replication of the experiment had any statistically significant effect on the magnitude of static pressure drop. Referring to Figure 21, the direct effect of increasing fan speed on increasing the pressure difference is seen.

Static pressure differences decreased as the stick thickness increased (Figure 22). Maximum pressure drops were recorded with the 1/4 inch sticks because they resulted in the highest air resistance. For any given stick thickness, increasing the pressure drop would also increase the air velocities. However, the 1/4 inch stick had the lowest air velocities of the four thicknesses tested even though they did have the highest pressure drops. The 9/16 inch sticks had the highest air velocities but as the Figure 22 shows, they had one of the lowest pressure drops. The explanation for this relationship is that there is a stick thickness whose proportion of surface resistance to volume available is optimal for air velocity. In my project, this was measured at 9/16 inch.

When the graph is further broken down by fan speed (Figure 23), the effects of increasing fan RPM can be observed. At 250 RPM, the thickness of the kiln stick had no statistically significant effect on static pressure at the 0.05 level of confidence. However, as fan speed was increased to 480 and 660 RPM, the slope of the curve

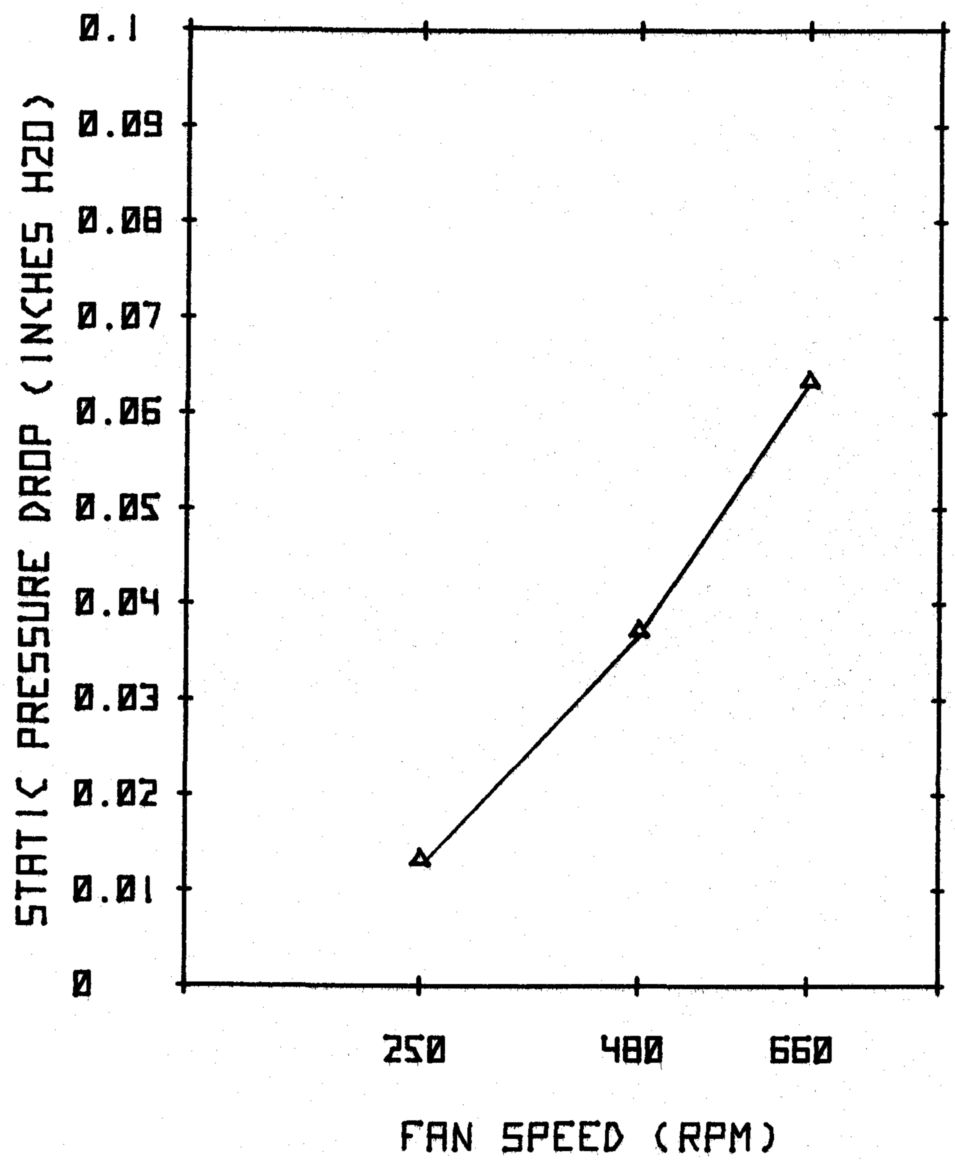


Figure 21. The static pressure drop across the load of lumber increased with fan speed.

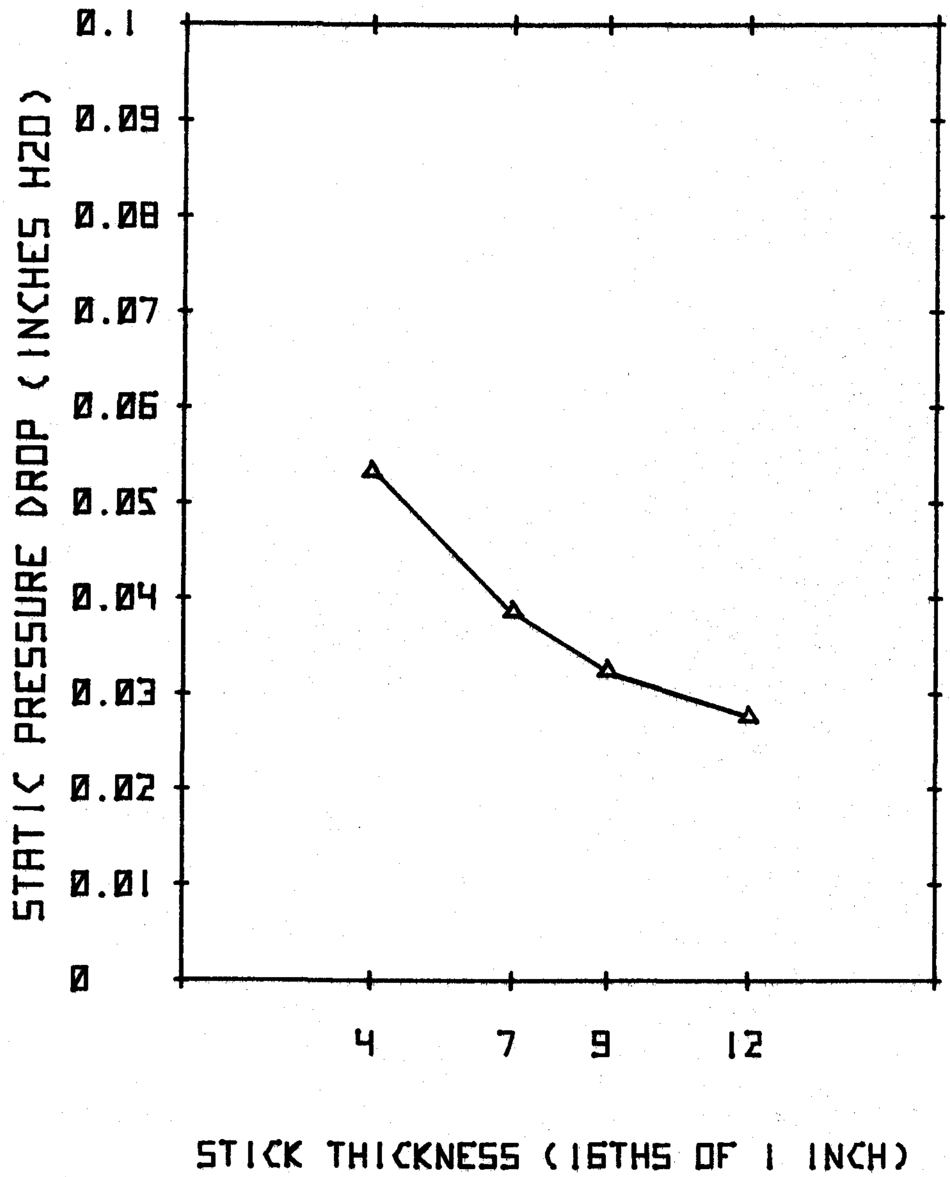


Figure 22. The general trend was for static pressure to decrease as stick thickness increased.

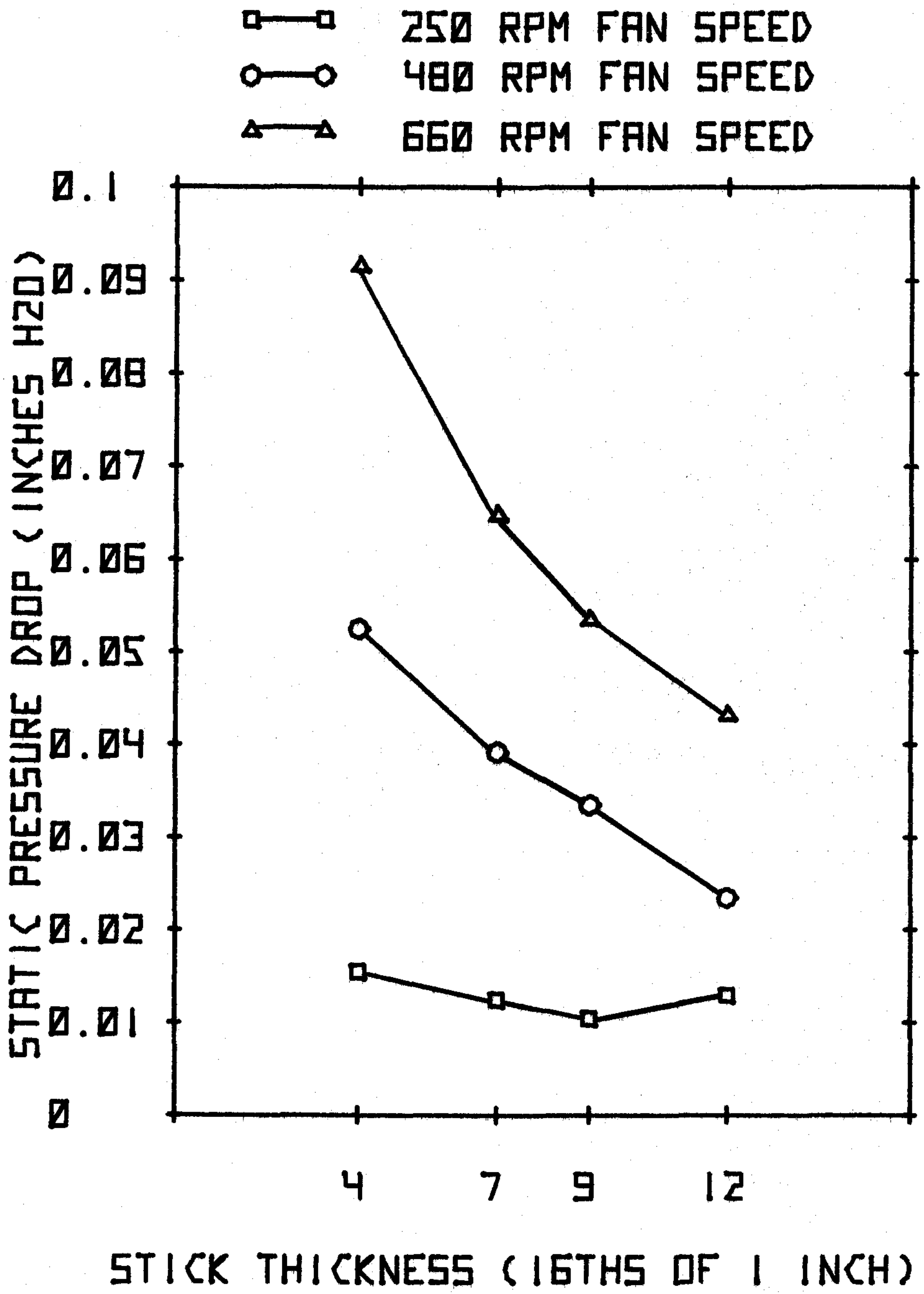


Figure 23. At low fan speeds, the thickness of the kiln sticks had little effect on static pressure. However as the fan speed increased, static pressure was highly influenced by stick thickness.

steepens indicating a greater effect of stick thickness on static pressure at higher fan speeds.

Power Consumption

The power useages at the various combinations of stick thickness, plenum width and fan speed were recorded together with air velocities. Using the OSU computer, an analysis of variance showed that both replication and plenum width had no statistically significant effect at the 0.05 level on power consumption. However, fan speed has a very direct effect on power use (Figure 24).

Stick thickness, when the plenums and fan speeds had been averaged, did not seem to affect power consumption (Figure 25). However, when the stick thickness effect was analyzed at different speeds (Figure 26), the results were more complicated to interpret. Although at both 250 and 480 RPM, the lines were not straight, statistical analysis showed that differences were not significant at the 0.05 confidence level. But at 660 RPM, the differences between the 1/4 inch stick and the 3/4 inch stick were significant. Thus, at the highest fan speed, increasing stick thickness appeared to decrease the power consumption. This may be explained by the effect of lower air resistance with thicker kiln sticks. With thin sticks, the relatively larger effect of surface resistance required that more power be applied to maintain the 660 RPM.

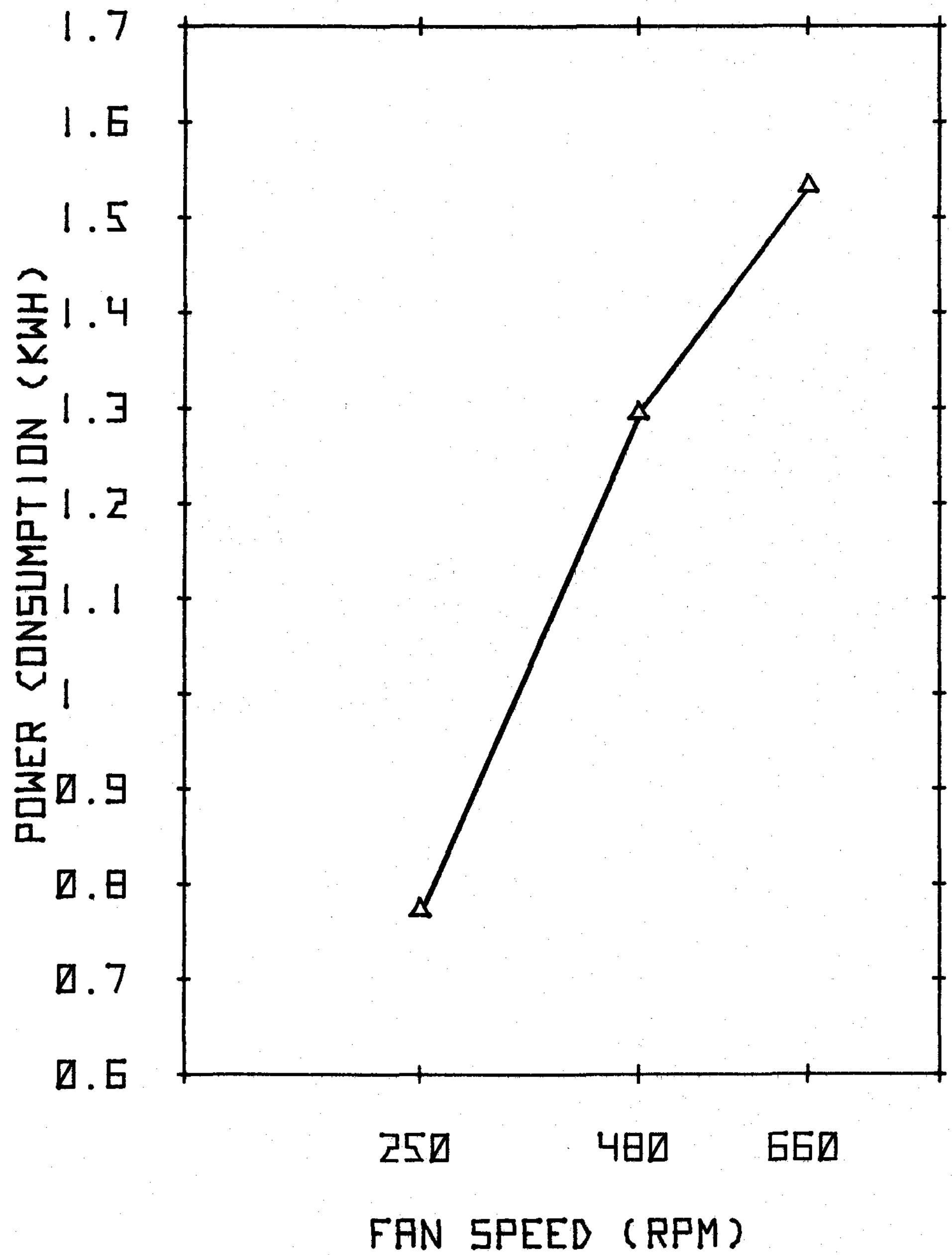


Figure 24. Power consumption increased with fan speed.

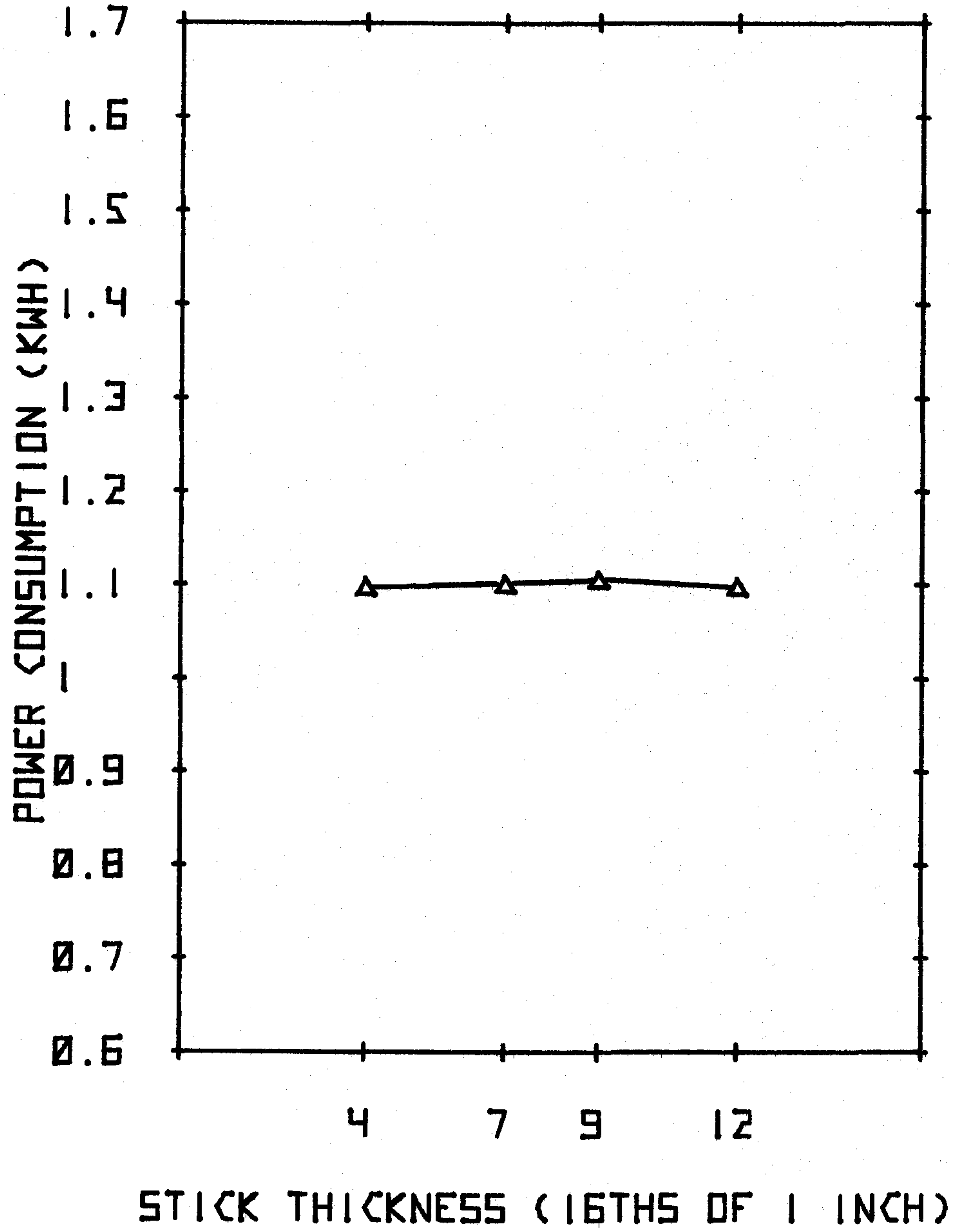


Figure 25. In general, power consumption was not greatly affected by stick thickness.

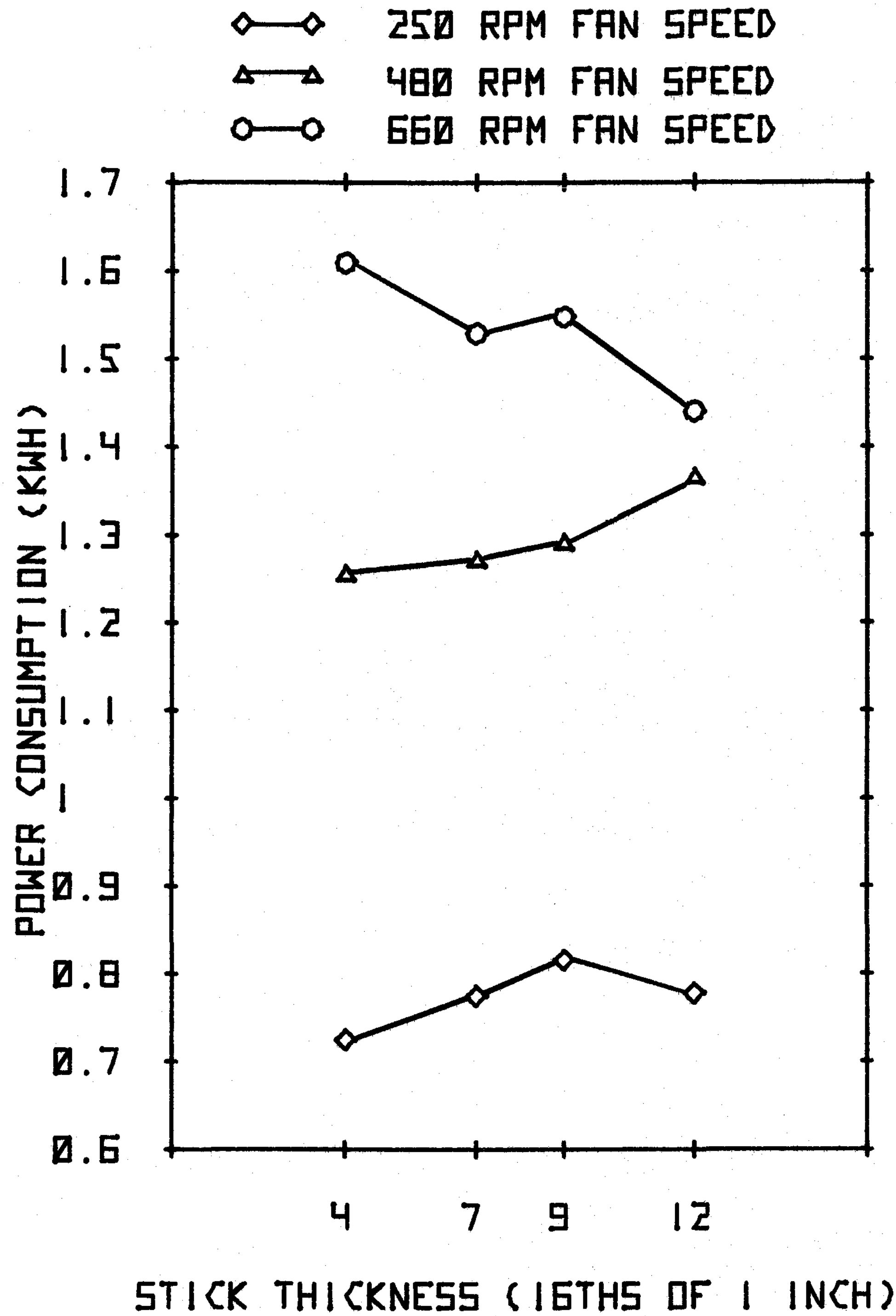


Figure 26. Fan speed influenced the effect of stick thickness on power consumption.

The power consumption as shown on the graphs does not obey the fan law which states that horsepower is proportional to the $(RPM)^3$ (Tutt, R., 1955). The two fans in the experimental kiln were driven with a five HP Reeves Motodrive unit. The fans reached optimum efficiency at 1150 RPM while the experiment was performed at 250 to 660 RPM, well below the optimum conditions. Another factor influencing the low performance was the Reeves drive unit. With the use of belts and gears to transfer the power, efficiency was lost.

Energy consumption was measured at the electric motor before the losses through the belts and pulleys had been absorbed. Therefore, the readings are much higher than they would be if horsepower could have been monitored at the fan shafts. Calculation of air horsepower resulted in good agreement with the fan laws and also verified that the experiment was performed at fan speeds well below the optimal level since efficiency increased with fan speed.

Air horsepower was calculated from the following formula:

(1) $\text{Air HP} = 0.0001575\ pQ$ (Marks, 1951)

where p = total pressure (static pressure + velocity pressure) and

Q = volume of air circulated.

Before Air HP can be computed, the total pressure must be known. Static pressures had been measured and recorded, however, velocity pressure was calculated from:

(2) $P_v = \left[\frac{V}{1096}\right]^2 d$ (Marks, L., 1951)

where P_v = velocity pressure (inches of water),

V = velocity of air through fan shroud in FPM, and

d = density of air in lb/ft^3.

Once the total pressure had been found, the air horsepower could be computed using the first equation. An example using the 7/16 inch sticks follows:

250 RPM resulted in 0.00177 AHP

480 RPM resulted in 0.01050 AHP

660 RPM resulted in 0.02149 AHP

These figures can then be applied to the fan law which states that $HP \sim (RPM)^3$. Hence, $HP_{new} = HP_{old} \left[\frac{RPM_{new}}{RPM_{old}}\right]^3$.

Changing from 250 to 480 RPM, $HP_n = 0.00177 \left[\frac{480}{250}\right]^3 = 0.0125$ AHP.

Changing from 250 to 660 RPM, $HP_n = 0.00177 \left[\frac{660}{250}\right]^3 = 0.0326$ AHP.

Changing from 480 to 660 RPM, $HP_n = 0.01050 \left[\frac{660}{480}\right]^3 = 0.0272$ AHP.

When fan law predicted air horsepowers were compared with the calculated values, a fairly close agreement resulted (Table 1). Thus, as the ratios of calculated versus predicted air horsepower indicate, the fan laws were generally followed.

Table 1. Fan law predicted versus calculated Air Horsepower.

RPM Change	Fan Law Predicted AHP	Calculated AHP	Calculated AHP / Predicted AHP
250 to 480	0.0125	0.0105	0.84
250 to 660	0.0326	0.0215	0.66
480 to 660	0.0272	0.0215	0.79

However, when the power consumption of the motor is applied to the fan laws, far greater dispersion resulted. First, the electrical measurement was converted to horsepower using the equivalent: 1 HP = 0.7457 Kilowatts. Again using the 7/16 inch sticks as an example:

250 RPM corresponded to 1.04 HP

480 RPM corresponded to 1.70 HP

660 RPM corresponded to 2.05 HP

Applying these actual power values to the fan law relating horsepower to RPM, a poor correlation resulted (Table 2).

Table 2. Fan law predicted versus measured beginning horsepower.

RPM Change	Fan Law Predicted HP	Measured HP	Measured HP / Predicted HP
250 to 480	3.68	1.70	0.46
250 to 660	9.56	2.05	0.21
480 to 660	2.21	2.05	0.92

The ratios of measured versus predicted horsepowers on the motor confirm the inefficiency of the motor at lower speeds. At 250 RPM efficiency is very low and low ratios resulted. However the change from 480 to 660 RPM was closer to the optimal operating level of the motor and a high ratio of 0.92 resulted.

V. FREE WATER EVAPORATION RATE

Procedure

The second part of the project was designed to test the effects of kiln stick thickness on the evaporation rate from a free water surface. Air circulation is a more critical factor during the initial stages of drying because the surface of the lumber is kept wet from the capillary flow of water. In this stage, the mass transfer of water from the wood to the kiln atmosphere can be easily compared to water evaporation from a free water surface. This analogy only holds true until moisture movement through the wood becomes controlled by diffusion. The high moisture content of green hemlock and its anatomical structure are such that the free water surface analogy would be valid for up to the first day or so of a normal hemlock drying cycle. Thus, we believed that we could measure the effect of stick thickness on the free evaporation rate using trays of water instead of using the highly variable hemlock lumber.

Three stainless steel trays were constructed which measured 7 1/2 x 12 x 1 1/2 inches. To insure safety against spilling the trays when full of water, drain lines were soldered in place. With 1800 cc of water in a tray, a beginning boundary layer of 0.65 cm was noted.

To remove lumber stacking as a variable, each piece of lumber was placed in the same position for each restacking. Also, the lumber was conditioned at the testing temperature and humidity for five days to insure as little interference from moisture movement to or from the wood as possible.

Pockets for the trays were cut in the third course from the top, the middle course, and the third course from the bottom. The trays were then placed on the appropriate sized sticker on the air leaving side and occupied the same position as the pieces of lumber.

Kiln conditions of 170^{o} F. dry bulb and 150^{o} F. wet bulb with an EMC of 7.8 percent were used throughout the test. All loads were baffled as completely as possible and an air entering plenum width of 13 inches was used. The mid range fan speed of 480 RPM was chosen which resulted in average air velocities of 250 to 375 feet per minute, depending on kiln stick thickness. Using each of the four thicknesses of sticks with three replications for each stick was the design of the experiment. Each replication was taken over a three hour and 50 minute time period. The kiln was brought to equilibrium before any testing was initiated. At the beginning of each test, the trays were filled with 1800 cc of water which was preheated to the equilibrium temperature of the water in the conditioned kiln, 150^{o} F. The door was then tightly sealed and extra steam lines were turned on to bring kiln conditions to the standard setting as quickly as possible. As soon as the proper temperatures were reached, the extra steam lines were turned off and only the normal steam lines were necessary to maintain the proper conditions.

After three hours and 50 minutes, the operations were shut down and measurement of the amount of evaporation was undertaken. Utilizing the built-in drain lines, the three trays were emptied and the contents measured in the 2000 cc graduated cylinder. The difference between the starting 1800 cc of water and the amount of water remaining was the amount lost through evaporation. These steps were repeated three times for each different stick thickness.

Calculated Evaporation Rates

After the actual evaporation rates were obtained, calculations of the theoretical evaporation rates were made using the following procedure:

1. Calculate the Reynolds number:

$$(3) \qquad Re = \frac{LVp}{\mu}$$

where: Re = Reynolds number.

L = length across tray in ft.

V = velocity in ft./sec.

p = density of air in lb./ft.^{3}

μ = viscosity of air in ft. lb./sec.

2. Calculate the Nusselt number:

$$(4) \qquad Nu = 0.036\ Pr^{1/3}\ Re^{.8}$$

where: Nu = Nusselt number.

Pr = Prandtl number.

3. Calculate the convective heat transfer coefficient:

$$(5) \qquad h_c = \frac{Nu\ k}{L}$$

where: h_c = convective heat transfer coefficient in Btu/hr. ft. $^\circ$F.

k = thermal conductivity of air Btu/hr. ft. $^\circ$F.

4. Calculate the rate of heat transfer:

$$(6) \qquad q = h_c A (T_D - T_W)$$

where: q = rate of heat transfer Btu/hr. ft.

A = area of tray ft.^{2}

T_D = dry bulb temperature $^\circ$F.

T_W = wet bulb temperature $^\circ$F.

5. Calculate evaporation rate:

$$(7) \qquad E = \frac{q}{Ht.\ Vp.}$$

where: E = evaporation rate lb./hr.

Ht. Vp. = heat of vaporization Btu/lb.

6. Convert to metric units.

The results indicated a straight line relationship between air velocity and evaporation (Figure 27). Also shown with the triangular

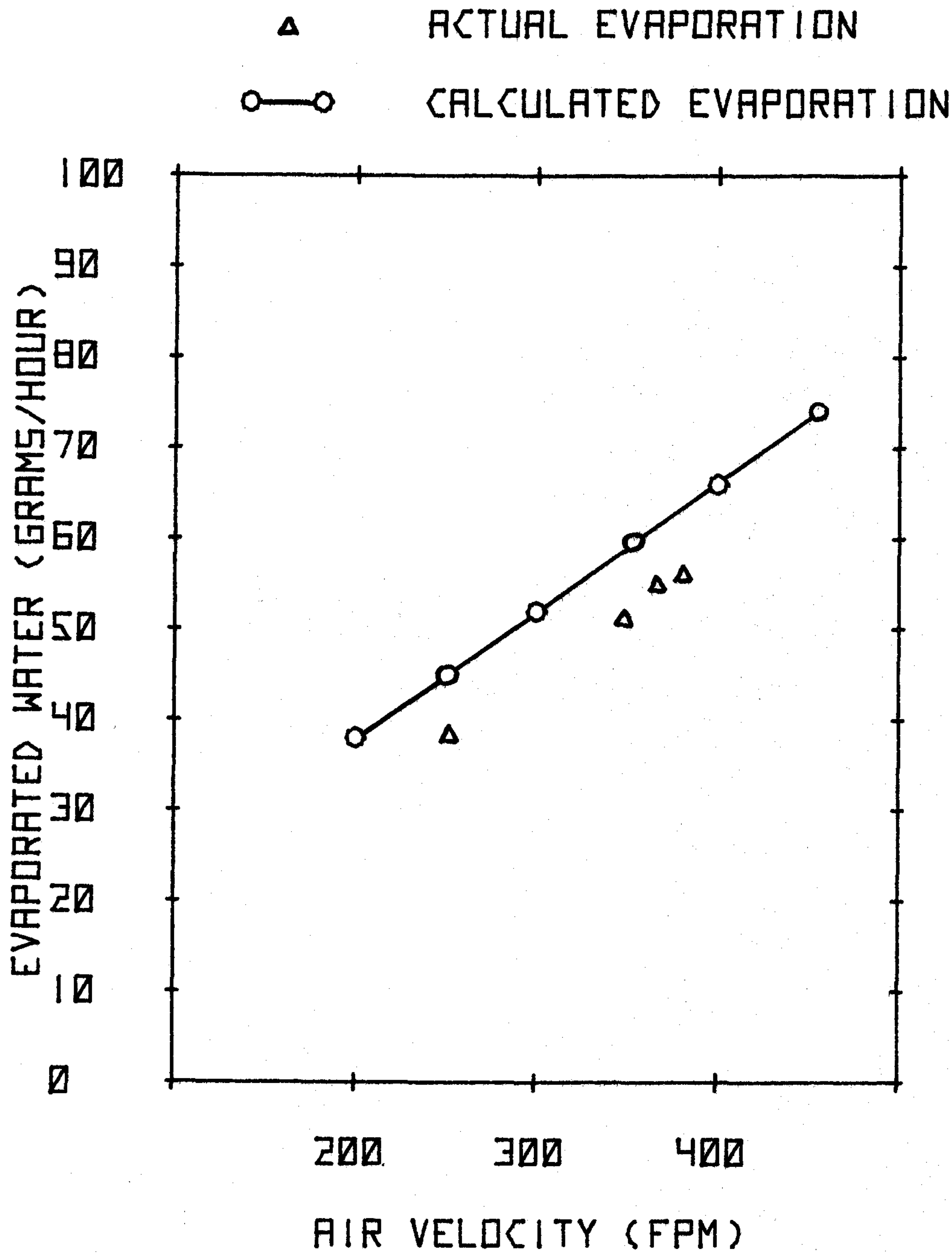


Figure 27. Calculated evaporation rates at different air velocities. The points below the line are actual evaporation rates.

symbols were the actual evaporation rates which corresponded rather closely to calculated results. The differences between the calculated and actual evaporation rates were not large and can be probably attributed to two causes. First, the area of the trays available to turbulent air flow was smaller than the total area of the trays due to the influence of the sides of the tray. The effect of the sides increased as the water was removed and the water level dropped. And secondly, the actual evaporation rates were measured over a three hour, 50 minute period. However, a portion of this time was necessary to reheat the atmosphere in the kiln after the trays were refilled. Thus, a higher rate than was actually obtained would be expected.

Calculation of evaporation rates using formulas developed by Stevens et al. (1957) and Hinchley et al. (1924) resulted in poor correlation with actual evaporation. These empirical formulas showed general trends but the values were always about 50% lower than the actual evaporation rate. Applying these formulas outside the range of conditions through which they were derived illustrated the danger in using empirical equations.

Results and Discussion

The evaporation data was also subjected to an analysis of variance using the OSU computer in the same way that air velocities were analyzed. The results show that replication had no statistically significant effect on evaporation rates.

However, the position of the trays in the load appeared to exert an effect on evaporation (Figure 28). The graph indicates lowest evaporation for the tray in the middle position which was statistically different from the top and bottom positions. But the differences in the top and bottom trays were not statistically different. Since the narrow 13 inch plenum which resulted in low velocities on top and high velocities on the bottom was used, these results were not expected. Instead, a high rate of air flow with correspondingly high evaporation rates was expected from the middle tray. The explanation for this contradiction is found in the stacking procedure for this experiment. Each board was placed in exactly the same place for all four stick thickness trials. Hence, if a board had splinters that hung down and blocked air circulation for one stick thickness it would affect the other thicknesses as well because the board was restacked in the same place. When the effect on evaporation was analyzed in greater detail by both position and stick thickness, the trends were more clearly seen (Figure 29). With the 1/4 inch sticks, the middle tray was nearly blocked of air circulation and evaporation was lowest. As stick thickness increased, the effect of the splinters decreased because what was blockage on the 1/4 inch sticks was merely a minor interruption for the 3/4 inch stick.

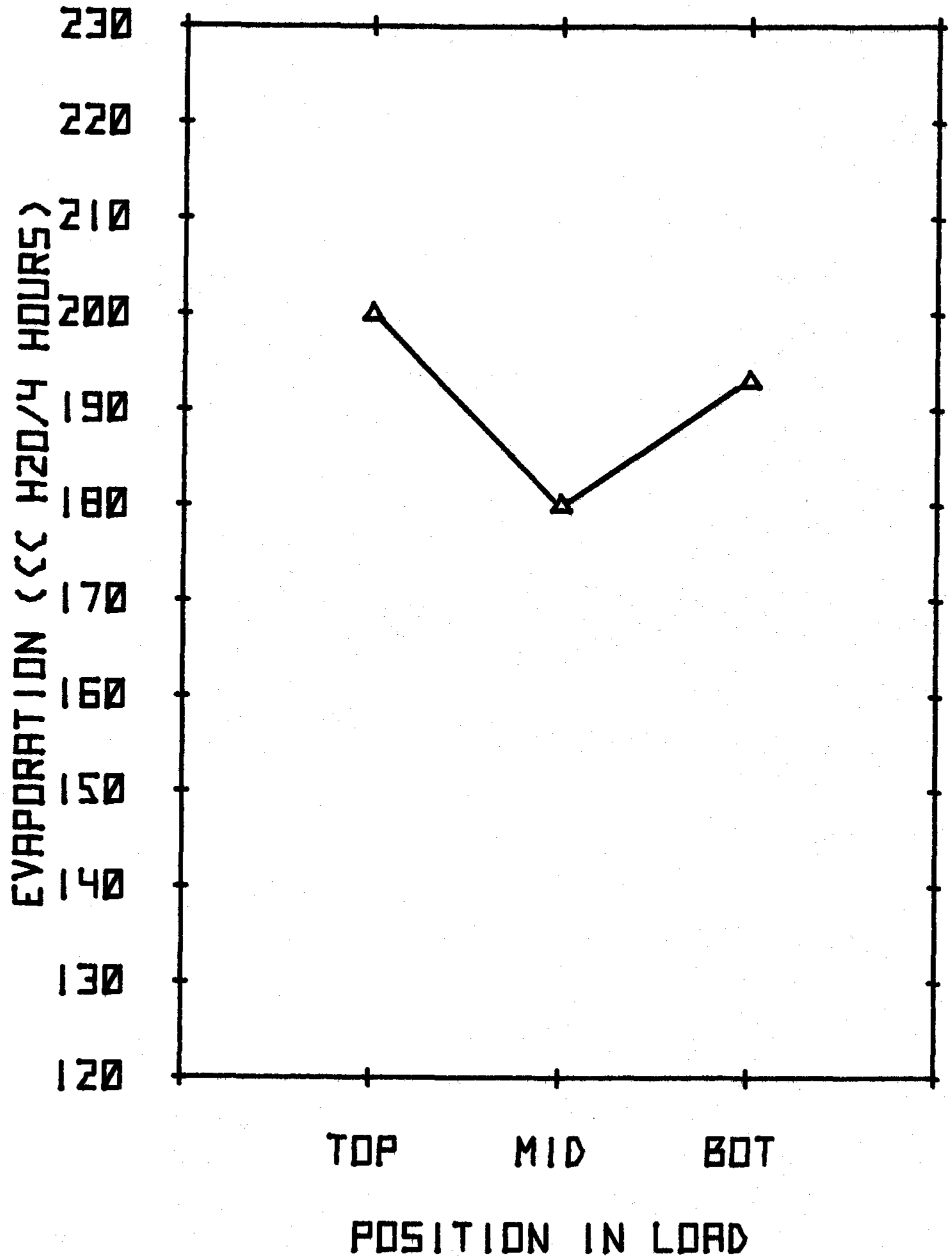


Figure 28. Position of the trays in the load influenced evaporation rates.

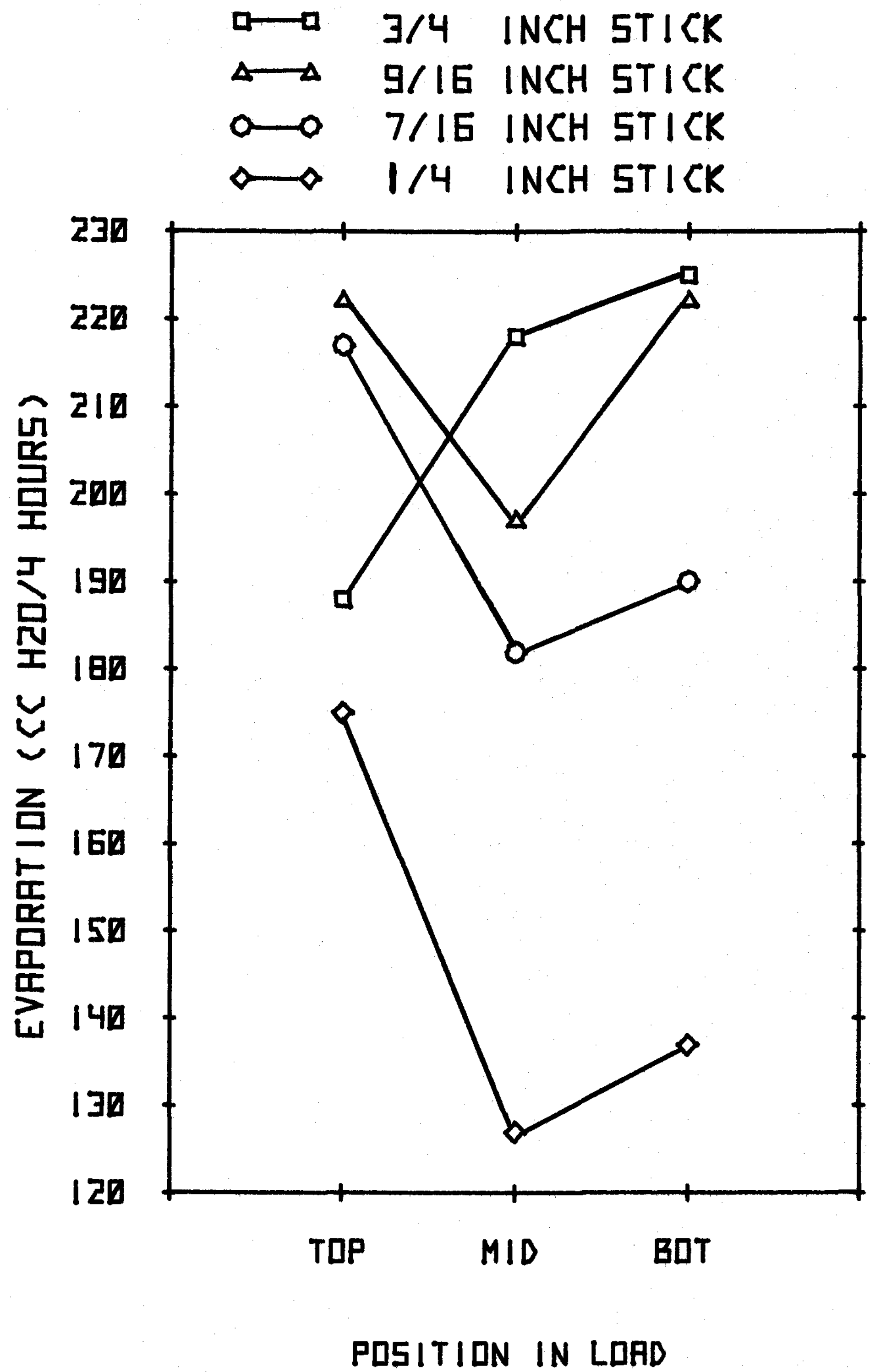


Figure 29. Stick thickness influenced the effect of position in load on evaporation rates.

The narrow 13 inch plenum did not greatly affect evaporation rates with the three thinner sticks, but with the 3/4 inch sticks it lowered air velocities at the top of the load and consequently lowered evaporation rates (Figure 29).

Figure 30 indicates the relationship between evaporation rate and stick thickness. This graph follows the same pattern as air velocity versus stick thickness and portrays the direct relationship between air movement and evaporation from a free water surface. The maximum evaporation was obtained using 9/16 inch sticks followed by the 3/4, 7/16 and 1/4 inch sticks' evaporation rates, respectively. However, there was no statistical difference in the results obtained using the 9/16 and 3/4 inch sticks.

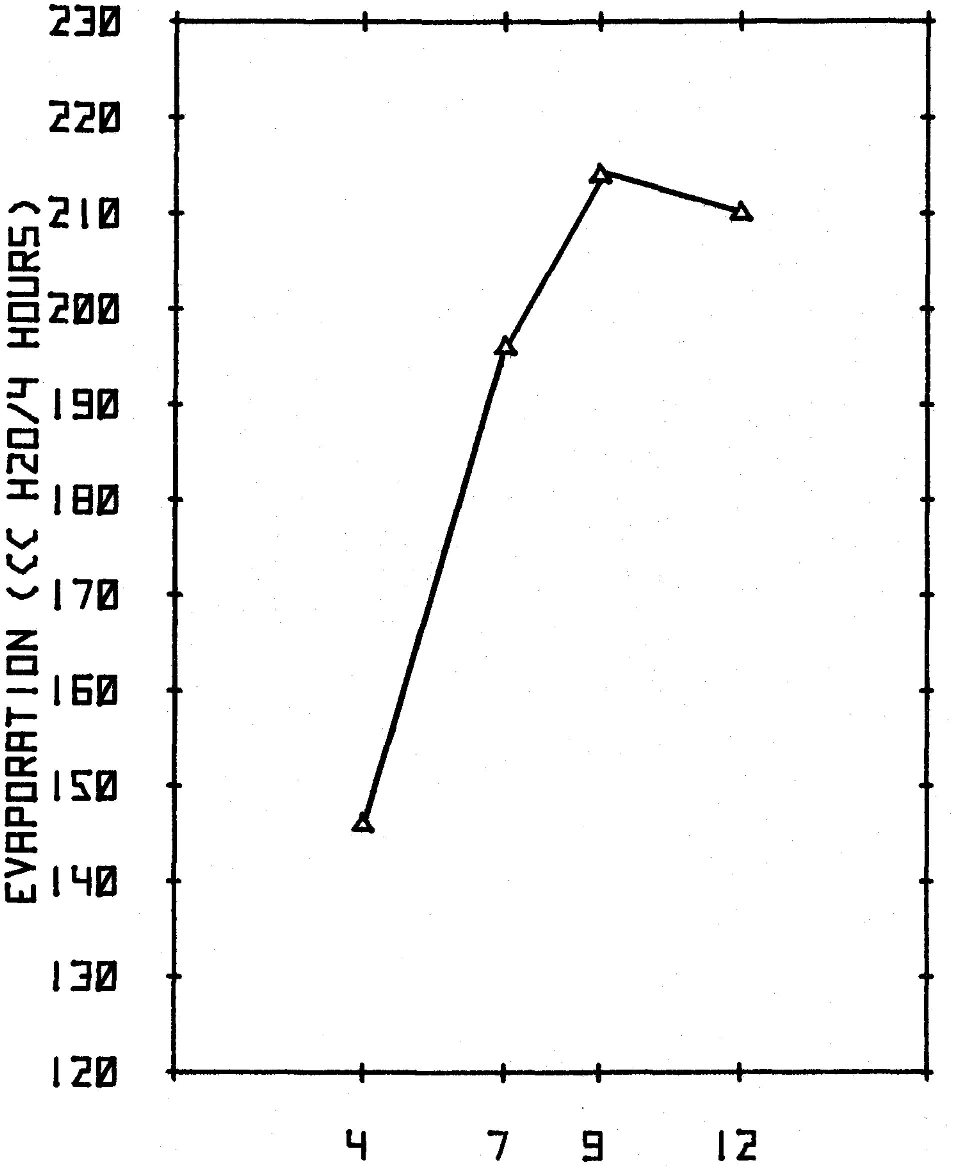


Figure 30. Use of the 9/16 inch kiln stick resulted in the highest evaporation rate.

VI. DRYING DEGRADE AND MOISTURE CONTENT DISTRIBUTION

Procedure

The purpose of this portion of the project was to determine the effect of thin sticks on drying degrade and final moisture content distribution. An experiment of this type could have been performed under laboratory conditions. However, gathering data in a commercial facility was more appealing since results may have a wider scope of practicality.

The requirements for a cooperating mill site were as follows: First, the mill had to be processing two inch western hemlock lumber. Second, the mill had to be drying its lumber using a mixture of thick wooden sticks and thinner phenolic sticks. Preferably, the wood stickers would measure 3/4 of an inch thick and the phenolic sticks at about 1/2 inch. The last major prerequisite was for the plant to have a horseshoe type continuous moisture meter. International Paper Company at Vaughn, Oregon was the only mill within close proximity to OSU that met these requirements and they were most willing to cooperate in the study.

The ideal method to follow in testing the effects of stick thickness would be to subject an entire kiln charge of thick sticked loads and another whole charge of thin sticked loads to the same drying schedule. Unfortunately, it would be very difficult to be assured of duplicating identical kiln conditions, hence, comparative analysis of the two charges would not be valid. Thus, to assure equal kiln conditions, we chose to load one half of the kiln charge with thin sticks and the other half with thick sticks. The total length of the kiln charge was 86 feet. The 3/4 inch wooden stickered portion was in the west end of the kiln and was composed of two 16 foot loads and one 14 foot load. The 1/2 inch phenolic stickered east end of the kiln was made up of a 16 foot, a 14 foot, and a 10 foot load. All pieces were 2 x 6's destined for dimension lumber and therefore their final moisture content should not exceed 19 percent after drying. The timber from which this lumber was cut came from Oregon's Coastal Range. After the lumber was in the sawmill, it was stored not longer than four days in the mill's open yard. After it was stickered, the lumber was placed in the dry kiln and air velocities were measured to check for uniformity and magnitude. Air velocities averaged 25 FPM higher with the 3/4 inch stickered load. The lumber was then dried at the following schedule from 24 Oct., 5 P.M. to 29 Oct., 5 P.M.

Table 3. Commercial Kiln Schedule for 2 x 6 inch hemlock lumber.

Hour	Dry Bulb (^{o}F.)	Wet Bulb (^{o}F.)
0	160	150
12	165	150
24	170	150
36	175	150
48	180	150
60	185	150
72	190	150
84	195	150
93	195	190
96	OFF	OFF

After the lumber was dried, it remained in the dry storage area for one full day and was then passed through the normal channels to the planer. Two lumber graders from the Western Wood Products Association (WWPA) evaluated drying defects before the lumber was planed. Defects were broken down into the following categories: Cup, Twist, Crook, Split and Sticker Crook. Each grader evaluated every other board so that the entire kiln charge was graded. A defect was not tallied unless it was severe enough to have caused that board to be permanently degraded one or more grades. The two graders wrote a number code for each defect category on any piece that was degraded and the results were then tallied by a helper.

After degrade had been established, the lumber passed through the planer and onto the dry chain. A continuous dielectric moisture meter (Wagner Model 524MK) checked each piece and marked those pieces that exceeded 19 percent moisture content. The Wagner meter had a D.C. output signal that was tapped from the meter's indicating assembly. This signal was filtered of all 60 cycle interference and then amplified before being passed into a strip chart recorder. The recorder had a very fast response time and was adequate for monitoring moisture content as boards passed through the detector at the speed of 500 feet per minute. A chart speed of five mm per second was used with a total chart length of about 400 feet. The recorder was calibrated before , during, and after the data collection. Using the Hewlett Packard model 9864-A digitizer, the data on the chart paper was converted to numerical readings.

Results and Discussion

Drying Degrade

The results of the WWPA lumber graders' analysis of the test kiln charge are shown in Table 4. The results indicated that no significant differences in degrade loss could be attributed to thin sticks.

Table 4. Drying degrade comparison between 3/4 inch wood kiln sticks and 1/2 inch phenolic kiln sticks.

Drying Defect	3/4 Inch Wood Stick	1/2 Inch Phenolic Stick
Cup	40	55
Twist	196	193
Crook	177	182
Split	11	24
Sticker Crook	9	1
Total Number of Pieces Defective	433	455
Total Pieces	2016	2208
Degrade %	21.5	20.6

After the lumber was graded in the rough, it passed through the planer and the lumber was graded again. The developing grades and footage that resulted for the total charge are listed in Table 5.

Table 5. Developed grades of test charge.

Grade	Amount
Number 2 and better	28,446 board feet
Number 3	15,014 board feet
Economy	7,530 board feet
Trim loss	1,750 board feet
Total	52,740 board feet

Moisture Content Distribution

After the maximum moisture contents had been determined, a distribution of them could be formed (Figure 31). The average maximum moisture content for the pieces of lumber stickered with 3/4 inch wood sticks was about seven percent while the 1/2 inch phenolic stickered pieces resulted in eight percent average maximum moisture content. However, as the chart shows, after seven percent moisture content had been attained, the phenolic sticks tended to yield wetter wood. This can probably be accounted for by the differences in air velocity between the two sticks. With the phenolic stick, air velocities averaged about 25 FPM less than with 3/4 inch wooden sticks.

Despite the low average moisture contents, both the 1/2 inch stickered lumber and the 3/4 inch stickered lumber exceeded the allowable limits for dimension lumber. About 14 percent of the phenolic stickered lumber was over 19 percent moisture content compared to about 11 percent of the wooden stickered lumber being over. Again, these differences can probably be explained by the 25 FPM lower average air velocities with the 1/2 inch phenolic sticks.

In a study done at Weyerhauerser (Bassett, K., 1973), results indicated that the rate of degrade for softwood dimension lumber is in the magnitude of one to three dollars per thousand board feet for

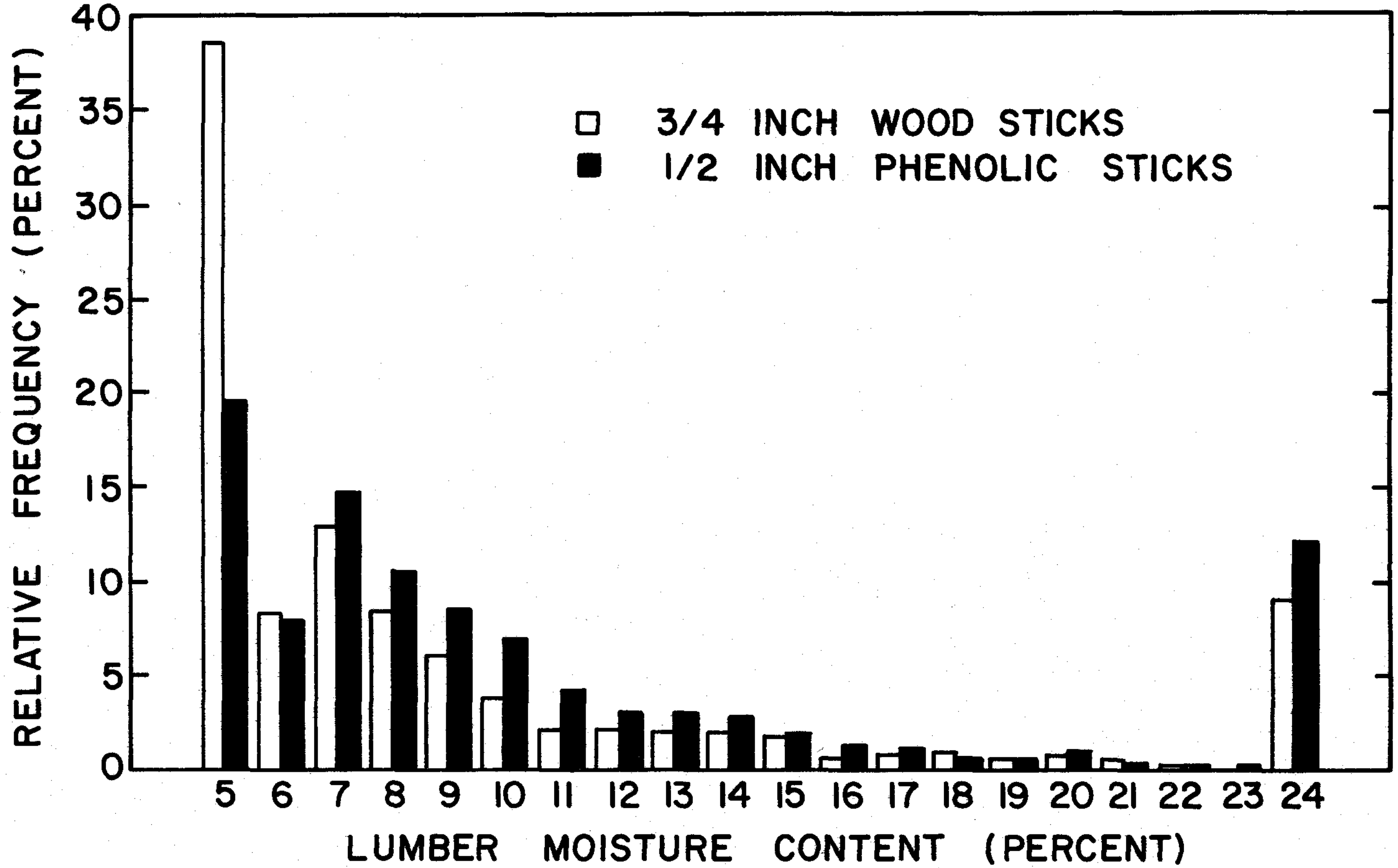


Figure 31. Moisture content distribution of 3/4 inch wood and 1/2 inch phenolic stickered lumber subjected to the same drying schedule.

every one percent of moisture lost in the normal (15 percent) drying range. Using these figures and an average moisture content for the test charge of eight percent, possible degrade costs of $371 [(15 - 8) (1) (53M board feet)] to $1113 [(15 - 8)(3)(53M)] are computed.

As the stick thickness decreases, more courses can be put into the kiln and higher air velocities are required to circulate the same volume of air through the load. Thus, another reason for differing moisture content distributions may be that along with lower air velocities with 1/2 inch sticks, there was also more lumber in the kiln. This relationship may indicate the need for longer drying schedules when thin sticks are employed.

VII. CONCLUSIONS

One: Utilization of 1/4 inch kiln sticks always resulted in low and ununiform air velocities indicating that commercial application would not be wise.

Two: The optimum stick thickness to maximize air velocity probably occurs between 7/16 and 3/4 inches and presumably lies at 9/16 $\pm$ 1/16 inch.

Three: Increasing the fan speed through the range tested always decreased the uniformity of air circulation.

Four: Plenum width exerts a great effect on the uniformity of air circulation. Best results occurred when the plenum chamber was approximately as wide as the total amount of vertical openings in the lumber.

Five: Kiln stick thickness affects the uniformity of air circulation with optimum results occurring when either the 9/16 or 3/4 inch sticks are used with the appropriate plenum width.

Six: A plant manager wanting to increase kiln capacity could change from 3/4 inch sticks to 7/16 inch sticks and any small loss in air velocity uniformity may be compensated for by increased kiln capacity.

Seven: A critical factor involved with fast drying species is not just the air velocity, but also the total volume of air circulated. Over the range of fan speeds tested, reduction in stick thickness always resulted in lower volumes of air circulating through the lumber. Although the 9/16 inch sticks showed the highest air velocities, the 3/4 inch sticks gave the highest volumes. Hence, where there is need for maximum volume of air circulation, reduction in stick thickness should be approached with caution.

Eight: If a kiln operator is faced with nonuniform drying and has measured air velocities in his kiln, he can recommend suitable courses of action. If the velocities are higher at the top of the loads than at the bottom, then using a thicker kiln stick may solve the problem. However, as is more commonly the case, higher velocities occur at the bottom of the kiln and the use of a thinner kiln stick would more evenly distribute the air flow.

Nine: Power consumption of the fan motors was not significantly affected by changes in stick thickness or plenum width.

Ten: Evaporation rates corresponded directly to the magnitude of air velocities. Highest rates were recorded with the 9/16 inch stick, followed closely by the 3/4 and 7/16 inch sticks. However, the 1/4 inch stick's rate was well below the other three.

Eleven: The use of thinner kiln sticks did not appear to affect drying degrade although more work is suggested in this field to validate this finding.

Twelve: Moisture content distribution in the mill study project was shown to be affected by the reduction in stick thickness. Compared to the 3/4 inch stickered lumber, the higher moisture contents using the 1/2 inch sticks were probably due to the 25 FPM lower air velocities or the additional (ten percent) volume of lumber to be dried; or a combination of both of these factors.

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APPENDICES

APPENDIX A

DRYING SCHEDULE FOR 2 X 8 WESTERN HEMLOCK LUMBER

Hour	Dry Bulb Temp. °F.	Wet Bulb Temp. °F.
1-4	180	175
4-24	180	170
24-60	180	165
60-160	180	155

APPENDIX B

COMPUTER PROGRAM FOR GATHERING AIR VELOCITY DATA

```
FILE 0
10 COM A$[70]
20 DIM HS[35,4],AS[35,4],CS[35,2]
1010 LOAD  KEY  1
1020 Z=FNZ(0)
1030 DEF FNA(Z)
1040 GOTO Z OF  1050,1060,1070,1080,1090
1050 Z=FNZ(0)
1060 LOAD 2,1010,1080
1070 LOAD 3,1010,1090
1080 LOAD 4,1010,1010
1090 LOAD 6,10,10

FILE 1
10 Z=1
20 Z=FNA(1)

10 Z=2
20 Z=FNA(2)

10 Z=3
20 Z=FNA(3)

10 Z=4
20 Z=FNA(4)

10 Z=5
20 Z=FNA(5)

10 DEF FNZ(Z)
20 DISP "PUSH DESIRED F(N) KEY"
30 STOP

FILE 2
1010 Z=FNZ(0)
1020 DEF FNA(Z)
1030 GOTO Z OF 1040,1050,1060,1070
1040 Z=FNZ(0)
1050 GOTO 1080
```

```
1060 LINK 3,1010,1160
1070 LINK 4,1010,1010
1080 A$[1,70] =" IN. EKS STICKERS,  IN. PLENUM WIDTH R.P.M.,
1090 DISP A$[14,20] " THICKNESS";
1100 INPUT A$[1,4]
1110 DISP A$[31,42] ;
1120 INPUT A$[24,25]
1130 DISP A$[49,54] ;
1140 INPUT A$[45,47]
1150 DISP "REP. #";
1160 INPUT A$[58,58]
1170 DISP "FILE #";
1180 INPUT F.
1190 STORE DATA F
1200 PRINT A$[1,70]
1210 F1=F+1
1220 F2=F+2
1225 DISP "SET SCANNER"
1226 WAIT 32000
1230 DISP "I. VOLT. G";
1240 INPUT V
1245 S=0.00096249
1250 FOR J=1 TO 4
1260 FOR I=1 TO 35
1270 CMD "?6U","R7F0TIM3"
1280 WRITE (9,*)WBYTE255;
1290 CMD "?6U","E","?5V"
1300 ENTER (13,1310)X
1310 FORMAT 4X, E10.0
1320 IF X<8 THEN 1280
1330 CMD "?6U","E","?5V"
1340 ENTER (13,1310)X
1350 GOTO X-7 OF 1280,1370,1370,1370,1370,1540,1540,1540,1540,
     1540,1540
1355 IF X<7 THEN 1280
1360 GOTO 1590
1370 FOR R=1 TO 10
1380 WRITE (9,*)WBYTE254;
1390 CMD "?6U","E","?5V"
1400 ENTER (13,1310)X[R]
1410 NEXT R
1420 FOR X=1 TO 3
1430 R=1
1440 FOR N=2 TO 10
1450 IF X[R] > = X[N]  THEN 1470
```

```
1460 R=N
1470 NEXT N
1480 D[ X] =X[ R]
1490 X[ R] =-100
1500 NEXT X
1510 H[ I, J] =(D[ 1] -V)/S
1520 A[ I, J] =(((D[ 1] +D[ 2] +D[ 3] )/3)-V)/S
1530 NEXT I
1540 PRINT I-1
1545 WAIT 6000
1550 NEXT J
1560 STORE  DATA F1,H
1570 STORE  DATA F2,A
1580 Z=FNZ(0)
1590 GOTO 1260
```

FILE 3

```
1010 Z=FNZ(0)
1020 DEF FNA(Z)
1030 GOTO Z OF 1040,1050,1060,1070,1075
1040 LOAD 0,10,10
1050 LINK 2,1010,1080
1060 GOTO 1090
1070 LINK 4,1010,1010
1075 LOAD 6,10,10
1080 Z=FNZ(0)
1090 DISP "TITLE FILE NO.";
1100 INPUT F
1110 F1=F+1
1120 F2=F+2
1130 LOAD  DATA F
1140 LOAD  DATA F1,H
1150 LOAD  DATA F2,A
1160 PRINT A$[1,70 ]
1170 DISP "ENTER COURSES/SCAN";
1180 INPUT C
1190 PRINT
1200 PRINT "CRS.NO.  SCAN#1  SCAN#2  SCAN#3  SCAN#4"
1210 FORMAT F5.0,F9.0,3F8.0
1220 FOR B=1 TO 2
1230 FOR I=C TO 1  STEP -1
1240 GOTO B OF 1300,1320
1250 NEXT I
1260 PRINT LIN2
1270 NEXT B
1275 PRINT "DATA STORED IN FILES"F;F1;F2
```

```
1280 PRINT LIN10
1290 Z=FNZ(0)
1300 WRITE (15,1210)I,H[I,1] ,H[I,2] ,H[I,3] ,H[I,4]
1310 GOTO 1250
1320 WRITE (15,1210)I,A[I,1] ,A[I,2] ,A[I,3] ,A[I,4]
1330 GOTO 1250
```

FILE 4

```
1010 DISP "I. VOLT. G";
1020 INPUT V
1025 S=0.00096249
1027 DISP "SET SCANNER";
1028 WAIT 32000
1030 FOR I=1 TO 35
1040 CMD "?6U","R7F0T1M3"
1050 WRITE (9,*)WBYTE255;
1060 CMD "?6U","E","?5V"
1070 ENTER (13,1080)X
1080 FORMAT 4X,E10.0
1090 IF X<8  THEN 1050
1100 CMD "?6U","E","?5V"
1110 ENTER (13,1080)X
1120 GOTO X-7 OF 1050,1140,1140,1140,1140,1310,1310,1310,1310,
     1310,1310
1125 IF X<7  THEN 1050
1130 GOTO 1330
1140 FOR R=1 TO 10
1150 WRITE (9,*)WBYTE254;
1160 CMD "?6U","E","?5V"
1170 ENTER (13,1080)X[R]
1180 NEXT R
1190 FOR X=1 TO 3
1200 R=1
1210 FOR N=2 TO 10
1220 IF X [R]>= X[N]  THEN 1240
1230 R=N
1240 NEXT N
1250 D[X] =X[R]
1260 X[R] =-100
1270 NEXT X
1280 C[I,1] =(D[1] -V)/S
1290 C[I,2] =(((D[1] +D[2] +D[3] )/3)-V)/S
1300 NEXT I
1310 PRINT I-1
1315 WAIT 6000
1320 LINK 5,1010,1010
```

```
1330 GOTO 1030
1340 DEF FNA(Z)
1350 LINK 0,10,1020

FILE 5
1010 DISP "FILE # FOR ORIG. L DATA OR 0";
1020 INPUT D
1030 IF D=0, THEN 1110
1040 F=D
1050 F'=F+1
1060 F2=F+2
1070 LOAD  DATA F1,H
1080 LOAD  DATA F2,A
1090 LOAD  DATA F
1100 PRINT A$[70]
1110 DISP "CRS/SCN";
1120 INPUT C
1130 PRINT "CS.NO.   HIGHS   AVG.S"
1140 FOR I+C TO I `STEP -1
1150 FORMAT F5.0,2F9.0
1160 WRITE (15,1150)I,C[I,1] ,C[I,2]
1170 NEXT I
1180 DISP "SCAN# OR 0 TO RETAIN ORIG. DATA.";
1190 INPUT J
1200 IF  J=0 THEN 1280
1210 IF J>4 THEN 1180
1220 FOR I=C TO 1 STEP -1
1230 H[I,J] =C[I,1]
1240 A[I,J] =C[I,2]
1250 NEXT I
1260 STORE  DATA F1,H
1270 STORE  DATA F2,A
1275 PRINT
1276 PRINT "STORED IN FILE NO.S"F;F1;F2
1280 Z=FNA(0)
1290 DEF FNA(Z)
1300 GOTO Z OF 1310,1320,1330,1340
1310 Z=FNZ(0)
1320 LOAD 2,1010,1080
1330 LINK 3,1010,1160
1340 LINK 4,1010,1010
1350 LOAD 6,10,10

FILE 6
10 COM A$[70]
```

```
20 DIM HS[ 35, 4] , AS[ 35]
1010 DISP "TITLE FILE #";
1020 INPUT F
1030 DISP "D. FILE #";
1040 INPUT F1
1050 LOAD  DATA F1, H
1060 LOAD  DATA F
1070 DISP "NO. OF COURSES/SCAN";
1080 INPUT C
1090 SCALE -200, 1100, -10, 40
1100 LABEL (*, 1, 1. 7, 0, 9/6)
1110 XAXIS 0, 100, 0, 1000
1120 YAXIS 0, 1, 0, C
1130 DEG
1140 FOR I=1 TO C
1150 PLOT 0, I, 1
1160 IF I>9 THEN 1190
1170 CPLOT -3, -0. 3
1180 GOTO 1200
1190 CPLOT -4, -0. 3
1200 LABEL (*)I
1210 NEXT I
1220 PLOT 0, 0, 1
1230 CPLOT -0. 3, -1. 3
1240 LABEL (*)"0"
1250 FOR J=100 TO 1000 STEP 100
1260 PLOT J, 0, 1
1270 CPLOT -2. 3, -1. 3
1280 LABEL (*)J
1290 NEXT J
1300 PLOT 500, -2, 1
1310 CPLOT -8, -0. 3
1320 LABEL (*)"AIR VELOCITY FPM"
1330 LABEL (*, 1, 1. 7, 90, 9/6)
1340 PLOT -100, C/2, 1
1350 CPLOT -7, -0, 3
1360 LABEL (*) "COURSE NUMBER"
1370 LABEL (*, 1, 1. 7, 0, 9/6)
1380 PLOT 600, -6, 1
1390 A=LEN(A$)/10
1400 FOR I=1 TO 5
1410 CPLOT -A, 0
1420 NEXT I
1430 LABEL (*)A$
1440 FOR J=1 TO 4
```

```
1450 DISP "CHANGE PEN, PRESS 0";
1460 INPUT R
1470 IF 4=0 THEN 1490
1480 GOTO 1450
1490 FOR I=1 TO C
1500 PLOT H[ I, J] , I
1510 NEXT I
1520 PEN
1530 PLOT 1100, 40, 1
1540 NEXT J
1550 FOR I=1 TO C
1560 A[ I] =(H[ I, 1] +H[ I, 2] +H[ I, 3] +H[ I, 4] )/4
1570 NEXT I
1580 DISP "CHANGE PEN FOR AVG.S PRESS 0";
1590 INPUT R
1600 IF R=0 THEN 1620
1610 GOTO 1590
1620 FOR I=1 TO C
1630 PLOT A[ I] , I, 0
1640 CPLOT -0. 3, -0. 3
1650 LABEL (*)"*"
1660 NEXT I
1662 PLOT 500, C+1, 1
1664 CPLOT -8, -0. 3
1666 LABEL (*)"*=AVG. OF SCANS"
1670 DISP "ENTER FILE # FOR AVG.S";
1680 INPUT D
1690 STORE DATA D, A
1700 PLOT 1100, 40, 1
1710 Z=FNZ(0)
1720 DEF FNA(Z)
1730 GOTO Z OF 1750, 1740, 1740, 1740, 1760
1740 Z=FNZ(0)
1750 LOAD 0, 10, 10
1760 GOTO 1010
```