HIGH FREQUENCY DRYING OF THICK LUMBER

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1. Introduction

Generation of internal heat with high frequency electromagnetic waves has found many applications over the last fifty years in various industrial operations, and in several occasions has replaced the less efficient and economic convective methods. A distinct example is the drying of materials that contain large quantities of water (separation process) such as, ceramics, textiles, foodstuffs, agricultural grains, paper products and wood (Lyons et al. 1972; Perkin 1980; Wei et al. 1985; Chen and Schmidt 1990; Avramidis and Zwick 1992; Tong and Lund 1993).

Wood, a typical dielectric material, is characterized by the presence of relatively few charge carriers (i.e. ions), so that the application of a voltage gradient, will result in only a very small current (Stamm 1964; Skaar 1988). However, when wood is placed in an electric field, there is a displacement of charge, and if the field is alternating (AC), the displacement attempts to follow the particular changes. The energy absorbed during the charge displacement, is dissipated as heat and if this energy is large, the technique is viable for industrial heating processes.

Because the average loss factor (ϵ'') for water is larger than that of dry cell-wall for the same frequency range (1 to 10 MHz), water will heat at a much more rapid rate than wood (Pound 1966; Skaar 1988; Torgovnikov 1993). Water is therefore selectively heated internally more than the surrounding cell-wall material thus eliminating the slow heat conduction from the surface to the core of lumber that normally occurs in conventional kiln drying processes.

When a high frequency (i.e., radio-frequency) field is combined with low ambient pressures, high temperature and pressure gradients can emerge in both the longitudinal and transverse lumber directions. Since both types of gradients will develop toward the same direction, i.e. from the geometric centre of the board to its ends and surface, moisture will be driven out fast in both liquid and gas phase during the initial stages of drying. As a result, the drying process is accelerated without the quality of the dried lumber being adversely affected (Biryukov 1961; Nelson and Kraszewski 1990). Both gradients can be controlled by the amount of electromagnetic power transmitted to unit volume of wood and the level of the ambient vapour pressure inside the dryer (Biryukov 1961; Perkin 1980).

Wood RF drying was first applied by Pratt and Dean in 1949. Since then a number of attempts were made to dry lumber under atmospheric and reduced ambient pressures (Pound 1966, Miller 1966, 1973, Simpson 1980, Wengert and Lamp 1982, Harris and Taras 1984, Lee and Harris 1984, Kanagawa 1989, Taniguchi and Nishio 1991). The results reported were mixed and from a limited number of specimens. Recently, three west coast softwood species were dried as part of an exploratory study, in a commercial RF/V dryer designed for red oak, with very promising results (Avramidis and Zwick 1992). The thermodynamic and sensitivity analysis performed, showed that above certain energy and kiln loading efficiency levels, RF/V drying should economical and fast. This finding was particularly true with lumber thicknesses over 8-cm.

The purpose of this communication is to present the results from a study whose objectives were to evaluate the drying characteristics of two softwood species lumber of various cross-sections, in a laboratory and a commercial prototype RF/V dryer, and at constant and variable electrode plate voltages.

2. Methodology

Laboratory RF/V dryer description

A laboratory radio-frequency/vacuum dryer was designed and built (Fig.1). The drying chamber consists of a 2.75-m-long and 0.76-m-diameter carbon steel cylinder that has removable bolted caps on both ends. Both caps are fitted with o-rings which are coated with silicon grease for the elimination of possible air leaks. One cap is also fitted with observation windows. The internal surfaces of the cylinder are coated with epoxy paint.

Two 30 by 224 by 1.27-cm in thickness aluminum electrode plates (E) supported by polyethylene bolts (S), are horizontally fixed in the centre of the cylinder. The lower electrode is also used to support the lumber load (W). The vertical space between the plates can be adjusted by raising or lowering the upper electrode plate in order to accommodate lumber loads of different height. The maximum lumber load height and width is 400-mm, approximately. This RF/V dryer configuration has an approximately 0.25 m^3 lumber holding capacity.

The ambient pressure in the cylinder is controlled by a liquid ring vacuum pump (VP) with an air injector attached to the main input line. This way, the pressure can be lowered to an absolute value of 2.7 kPa, approximately. The evaporated water from the drying wood is condensed by passing over cold copper coils in a unit (CD) located between the cylinder and the vacuum pump. Cooling of the coils and sealing of the vacuum pump, is achieved by circulating regular tap water. The condensed vapour is collected in a steel tank under vacuum (CT) where the height and therefore, the volume of the accumulated water is monitored with a pressure differential transducer. At the same time, any condensation accumulating at the bottom of the drying chamber, is transferred to the collection tank by a pump (P) located underneath the main cylinder. This way, the amount of water extracted from the lumber load, can be monitored with time, and therefore, the drying curve of each run can be determined.

The electromagnetic radiation responsible for the thermal energy generated within the lumber load is provided by an air cooled, 10 kW, radio-frequency generator (RFG) which is operating at a fixed frequency of 13.56 MHz and can provide a maximum electrode voltage of 5 kV at 2 amperes. The generator is connected to the electrode plates by a set of copper leads. Adjustments of the electrode plate voltage are done manually.

Commercial RF/V prototype

The commercial RF/V dryer (Fig. 2) was designed with the intention of commercially operating it at a west coast softwood sawmill. Previous RF/V dryer designs were primarily for specialty hardwood sawmills. They had in relative terms a low capacity, and were very cumbersome to load and unload. Therefore, the softwood dryer had to be larger, and with a totally redesigned material handling system.

The new design, resulted in having vertical rather than horizontal electrodes used in previous RF/V dryer designs. This allows for the rapid loading of the dryer carts with existing sawmill forklift equipment. The dryer can also have doorways on both ends thus allowing for back and forth shuttling of the carts to improve loading/unloading. With very short drying times, it is essential for the RF/V dryer to be utilized to its maximum.

The prototype's dimensions are 13.7-m long by 4-m wide by 3.5-m high. It was designed to withstand a total vacuum pressure of negative 101 kPa gauge. The chamber is capable of holding approximately 56.6 m^3 of wood; making it the largest RF/V dryer in the world. The lumber packages do not require any stickering and are loaded just as they would be on a truck. This way, handling time and cost is drastically reduced when compared to the ones for regular dry kilns.

The RF generator is a triode oscillator with a circuit designed to operate at a frequency which "floats" between 5 and 7 MHz; depending upon the moisture content of the wood. The RF voltage varies between 3 kV when the wood is wet, to approximately 25 kV with a dry load. The generator is capable of providing a 350 kW RF output and operates with a conversion efficiency of approximately 65%.

The control system on the RF generator is designed to produce a requested RF power output at any set value. Power densities within the lumber load can reach 7 kW/m^3, approximately.

The vacuum system is a conventional helical screw pump. The evaporating water is brought through a heat exchanger and the steam is condensed out. The air stream then is sent through a cyclone or knockout tank, in order to remove any remaining slugs of water. All water is collected into a holding tank and after quick treatment for pH and phenols content, is discharged into the municipal sewer. The vacuum system requires no sealing water and it is energy efficient.

Water that is condensed on the chamber walls is collected at one end of the dryer and drained into a collection tank. The amount of wall condensed water depends on the ambient air temperature, but typically varies between 20 and 50% of the kiln discharge.

Wood specimens for the laboratory runs

Specimens of green western red cedar (*Thuja plicata* Donn), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), 224-cm long were dried in a series of experimental runs. All specimens were of the same quality grade, had smooth surfaces (planed), and with no specific annual growth ring orientation. Cedar specimens had either a 91 by 91-mm (4x4) or a 254-mm by 254-mm (10x10) cross-section. Hemlock specimens had a 91 by 91-mm (4x4), or a 254 by 254-mm (10x10) cross-section.

Since each specimen was freshly cut from a group 3.6-m long green pieces of lumber of the same cross-section, initial moisture contents could be obtained from oven-drying at 103±2°C, 30-mm thick slabs cut from both ends as seen in Figure 3. The average moisture value from each pair of slabs was the one assigned to the particular specimen as its initial moisture content (M_i). Based on the M_i and the weight of each specimen before RF/V drying, the amount of moisture (free and bound) to be removed could be estimated in advance. Nine specimens of the same cross-sectional dimensions were dried in each run. The specimens rested on the lower electrode plate, in a three row and three column cross-sectional configuration, and were solid packed without stickers (Fig. 4).

The temperature rise inside the heated specimens and in the surrounding partial pressure environment were monitored by four fibre optic temperature sensors, each 1.4-mm in diameter. Vapour pressures were measured by teflon fittings tightly attached to the specimens, and connected with teflon tubes to pressure transducers located outside the cylinder. Three locations were chosen for temperature and pressure monitoring along the centre line of specimen No. 5 which was located in the middle of the pile (Fig. 4). All process data were collected and saved in a personal computer through a data acquisition system. The system could also be programmed so that the RF generator could automatically be shut down, the target, oven-dry based, average moisture content of 15 percent was reached.

At the end of each drying run, five blocks, each one comprised of three 3-cm long slabs (A_i, B_i, C_i, where i = 1,...,5), were cut from each specimen as shown in Figure 3. Each first slab of each block (A_i), was oven-dried for the evaluation of the final moisture content (M_f) and its lengthwise distribution. Each second slab (B_i), was cut into a core and two shell sections for the calculation of their moisture content differences. Each third slab (C_i), was used for the evaluation of the level of internal stresses by the prong test (Simpson 1991). All boards were visually evaluated for external shake, collapse and surface discolouration, and all surface checks were clearly marked before and after drying. The size and number of internal checks was also noted after drying. Two out of four 56-cm long sections from each specimen marked as LC in Figure 3, were cut in half lengthwise for the evaluation of the longitudinal internal stresses.

Lumber specimens for commercial runs

The sizes dried in the commercial RF/V prototype were: 50-mm by random width and 100-mm by random width western red cedar; 100-mm by 100-mm and 150-mm by random width western hemlock; and 100-mm by random width and 150-mm by random width Douglas-fir. The green and dry lumber evaluation protocol was similar to that followed in the laboratory studies with the only exception being the fact that due to the large lumber population, only 10% of them were evaluated in each run. However, due to the large sample size, initial and final moisture content distribution within each drying charge, as well as total degrade could be evaluated in the prototype runs.

The objectives for the experimental program with the large RF/V dryer is focused primarily on investigating the commercial feasibility of the drying process. Therefore, the dryer has the appropriate instrumentation to determine its electric energy and water consumption.

3. Results and Discussion

Laboratory RF/V dryer

A series of fifteen runs were carried out with western red cedar and twenty-seven runs with western hemlock specimens. Only the results from seven runs out of forty-two in total which are considered to be characteristic representatives of the two RF/V drying methods are reported in this paper.

Fig. 5 shows the ambient temperature (T_e) variation with time, as well as the temperature at the middle (T_c) and end (T_s) of specimen No. 5 located at the centre of the load, for two cedar runs which were carried out with constant electrode plate voltage (0.6 and 1.0 kV). Similar plots for the two hemlock runs at 0.8 and 1.0 kV are shown in Fig. 6. In cedar, Fig. 5, the specimen middle temperature (T_c) increased from ambient to about 55°C and 105°C in 7-hours at 0.6 and 1.0 kV electrode voltage, respectively. After the initial rise, the T_c at 1.0 kV remained constant until the end of the drying run, whereas the T_c at 0.6 kV after a short plateau, slowly increased to approximately 105°C in about 12 hours. The ambient and specimen end (T_s) temperatures increased quickly in the initial stages of the run, but after two hours, they reached a plateau and remained constant thereafter. The same trend was also observed with hemlock (Fig. 6), the only exception being the slow temperature drop until the end of the drying cycle. In both species, higher electrode voltages resulted in higher temperature levels inside the specimens.

The variation of the partial vapour pressure for cedar and hemlock, and in the same locations as described above are shown in Figs. 7 and 8, respectively. In both species, the middle pressure (P_c) increased with the electrode voltage. Only the P_c in the 0.6 kV cedar run (Fig. 7), became greater compared to the 1.0kV one after nine hours of drying. End pressures (P_s) remained constant during drying in all runs.

The drying curves for cedar(C) and hemlock(H) are show in Figs. 9 and 10, respectively. The total drying time for C1 where the specimens had a 91 by 91-mm cross-section and was carried out at 0.6 kV, was 24 hours from an initial moisture content (M_i) of 38% to a final moisture content (M_f) of 15%. In C2, where the electrode voltage was raised to 1.0 kV, the total drying time was reduced to 14 hours from an M_i of 35% to an M_f of 15%.

Western red cedar of 50-mm thickness will normally require more than 20 days of drying time in a conventional "heat-and-vent" kiln for the same initial and final moisture content levels. This dramatic reduction in drying time observed in Fig. 9, is because the heat and mass transfer mechanisms in RF/V are very different compared to the ones in conventional drying. With internal heat generation in the former, mass transfer is primarily due to the longitudinal pressure gradients established because of the rapid vapour generation within wood. Flow of water vapour takes place primarily in the longitudinal direction which for softwoods can be 500 to 80,000 times greater compared to tangential, and 15 to 50,000 times greater compared to radial permeability (Siau 1984).

It is also interesting to note from Figs. 9 and 10, that the thickness of the specimens did not affect the total drying times as in conventional drying. Both 254-mm thick cedar and hemlock specimens, required nearly the same amount of drying time from the same M_i down to an M_f of 15%, when compared to the 91-mm thick specimens. This is because the bulk of moisture flow from the middle parts of lumber takes place in the longitudinal direction, ultimately evaporating into the low pressure ambient environment from the end surfaces. Furthermore in RF/V, heat is instantaneously generated within the lumber body and immediately utilized in the conversion of liquid water to vapour whereas in conventional drying, heat has to be transferred by conduction from the surfaces to the geometric centre. The same effect of the electrode voltage level on drying times, was also observed in hemlock (H1 and H2) as seen in Fig. 10.

The calculated drying rates for cedar and hemlock specimens expressed as a percent of moisture loss per hour, are shown in Figs. 11 and 12, respectively. For both species, the drying rates dropped as the drying process progressed when the electrode voltages were kept constant. Hemlock exhibited a faster rate of drying rate reduction. The increase of drying rates due to higher electrode voltage levels, C1 vs. C2 and H1 vs. H2, is also evident. Drying rates ranged from a maximum of 2.5%/hr in the beginning, to a minimum of 0.5%/hr at the end of the drying run.

The decrease in drying rate as the specimen's average moisture content drops is presumably the result of diffusion becoming the predominant mechanism for moisture transfer at Ms close or below the fibre saturation point. However, the fact that the loss factor ϵ'' changes with moisture content and temperature, could also explain the drying rate decline (Avramidis and

Dubois 1992; Biryukov 1961).

The reduction in total drying times as the electrode voltage increased was also anticipated since the intensity of dielectric heating which depends on the power absorbed by unit volume of the material, is directly proportional to the square of the strength of the electromagnetic field between the two electrodes. In order to achieve a given amount of energy transfer to wood, and maintain a constant drying rate, the lower the loss factor, the higher the electric field is required to be a fixed frequency. In green wood, the water molecules are the major contributors to its heating mechanism since they have a permanent dipole. Therefore, at a constant voltage there is a direct relationship between M and ϵ'' (Avramidis and Dubois 1992; Torgovnikov 1993). At the beginning of the drying process, M and ϵ'', are both high resulting therefore, in high power densities within the drying lumber load. As drying progresses, the value of ϵ'' decreases due to the loss of moisture and with the constant electrode voltage, the power density decreases. The power density decline will result in reduced drying rates and longer drying times as was seen in Figs. 9 to 12. To maintain a constant drying rate, the electrode voltage has to be adjusted during drying: that is, the voltage should be raised as the average M of the drying lumber load decreases.

Voltage adjustments were performed in several hemlock runs. One such example is H4 (Fig. 12), where the electrode voltage was initially set at 0.8 kV but it was raised in steps reaching a maximum of 3.0 kV at the end of the run. By using a variable voltage, a constant drying rate of 1.75 1.8%/hr was maintained during the drying cycle resulting in a much shorter total drying time (Fig. 10).

Fig. 13 shows the temperature variations with time in the middle, and end of the specimen located at the centre of the load and in runs H4 and H5, where the electrode voltage varied with time. It is apparent that both T_c and T_s levels were higher in H5 compared to H4 since the voltages in the former were much higher. Furthermore, both T_c and T_s increased with time as opposed to the ones shown in Fig. 6, where they dropped with time due to constant electrode voltages. The vapour pressure levels (P_c and P_s) as a function of time, location and voltage are shown in Fig. 14. Calculated maximum pressure differences (ΔP) between the middle and the end parts of the hemlock specimens were 490 mm Hg in H5 and 50 mm Hg in H4. Again, the effect of the level of variable voltage on P is very pronounced.

The difference between shell and core moisture contents in C2 and H4 are shown in Fig. 14. The average values were very close to zero, whereas in the majority of the specimen length, they ranged between 0.6 and -0.7 percentage points. Shell and core M differences in conventionally dried 91 by 91-mm hemlock, normally range between 8 and 12 percentage points (Avramidis et al. 1993). Furthermore, the moisture content variation along the length of each cedar and hemlock specimen in all forty-two runs did not vary from the average value for more than $\pm$ 3 percentage points.

Evaluation of the casehardening prongs, revealed that there were no detectable internal stresses both in the longitudinal and transverse directions. The average total shrinkage for cedar and hemlock, ranged between 1.6 and 2.2%, about half of what is found after conventional kiln drying. Complete specimen slicing revealed no internal checking in both species for the voltage levels tested with the only exception of C2 where massive internal checking was observed, indicating a lower limit of about 20 hours of drying time for cedar. For hemlock, the same limit was about 30 hours. Typical brown stain discoloration found after conventional kiln drying of hemlock, was totally absent.

Commercial RF/V dryer

Evaluation of the commercial runs showed similar lumber quality to the laboratory ones. The power densities were variable and the commercial dryer experimental program used similar ones to those established by the lab dryer. Obviously the sample size for each drying run was much larger, and therefore the variability of wood was reflected in the results of the drying runs. This included variability in initial moisture content, permeability, dielectric properties, and mechanical properties such as tension perpendicular to grain. The type of wood species, or its natural wood defects such as compression wood or spiral grain also plays a role in the final dried product quality as well as its drying times. In addition, equipment issues such as the location of the lumber pieces within the kiln chamber (there could be variable power densities inside the kiln chamber) or vacuum pressure (which was varied in some runs) have an impact on the final results. All the above parameters influence the final moisture content and quality of the dried product.

The principle drying defect of concern was internal honeycombing which depending on its severity, could render the value of the wood piece worthless. The commercial dryer experimental program attempted to have an occurrence of this defect to be less than 2% of the total kiln charge volume. As stated previously, the laboratory program established that the occurrence of internal honeycombing was directly related to power density. The commercial dryer investigations showed conclusively that lumber cross-sectional area also has a direct relationship to the occurrence of internal honeycombing. Preliminary results indicate that this relationship is likely linear; which translates to a linear reduction in drying times related to an increase in the cross-sectional area of the piece of lumber. It should be noted that in conventional drying, the relationship of drying times to lumber thickness is exponential.

Drying times ranged from 24 to 80 hours; depending on the species, initial moisture content and cross-sectional area of the lumber. In particular, 26-70 hours for hemlock, 30-80 hours for western red cedar, and 24-60 hours for Douglas-fir. Species with a low initial moisture content such as D-fir would have substantially reduced drying times.

The dried lumber quality varied widely, depending on the type of kiln schedule used. With proper power densities, there was a minimum internal and external checking and no surface discoloration (brown stain in hemlock). Transverse and longitudinal casehardening were absent. Average linear shrinkage ranged between 1.5% and 3.5% (in conventional drying 2.5-4.5%) for all species and sizes. Lumber value reduction due to degrade ranged between 3 and 7% for all grades. For the same species in conventional drying, degrade ranges between 5 and

15%.

Conventional kiln drying requires a thermal energy input between 0.75 and 6.75 Gj/m^3. depending on the size of lumber, grade, species, and initial moisture content. The electrical energy consumption is estimated to be between 70 and 1000 kWh/m^3, primarily depending on the size of lumber (the extreme case being for lumber 150-mm thick). The thermal energy is normally derived from natural gas or wood waste. The total energy consumption is thus in the range of 250 to 2300 kWh/m^3. It should be cautioned that thermal energy requirements for conventional kiln drying has not been properly researched, and these numbers are only estimates. Better information is presently being analyzed in the RF/V kiln project.

In the RF/V process the energy is all electric, with a total energy consumption of between 230 and 500 kWh/m^3. These are values that have been developed from the present RF/V kiln project. In comparison with conventional drying, the total process energy is reduced by a factor of 2 to 5 times although smaller sizes and lower grades of conventionally dried lumber have similar energy consumption values. The total average energy efficiency in the commercial RF/V prototype varied between 65-70%. Drying costs were about \$5.5/m^3 for cedar and Douglas-fir, and about \$8.5-\$9.3/m^3 for hemlock (B.C. electricity rates are about \$0.028/kW-hr).

4. Future Research Prospects

The very promising results of this study open up a great number of potential applications in the primary and secondary sector of the forest products industry. Some examples are

a) the rapid conditioning, pasteurization and fixation of wood (timbers, poles) treated with waterborne preservatives,

b) drying of hardwood species (eastern, western), of various thicknesses with minimum degrade due to low internal stresses and discoloration,

c) redry of veneer with high final moisture content variation and drying of high quality veneers,

d) easy and rapid drying of short pieces of lumber due to no stickering (solid pile) requirements,

e) drying of difficult to dry species.

This way, the RF/V technology will improve the quality, performance, and profitability of existing and new solid, sawn, composite and treated wood products; increase fibre recovery from existing processing operations; increase fibre recovery from under-utilized species; and support the creation of an equipment and process control manufacturing base.

5. Literature

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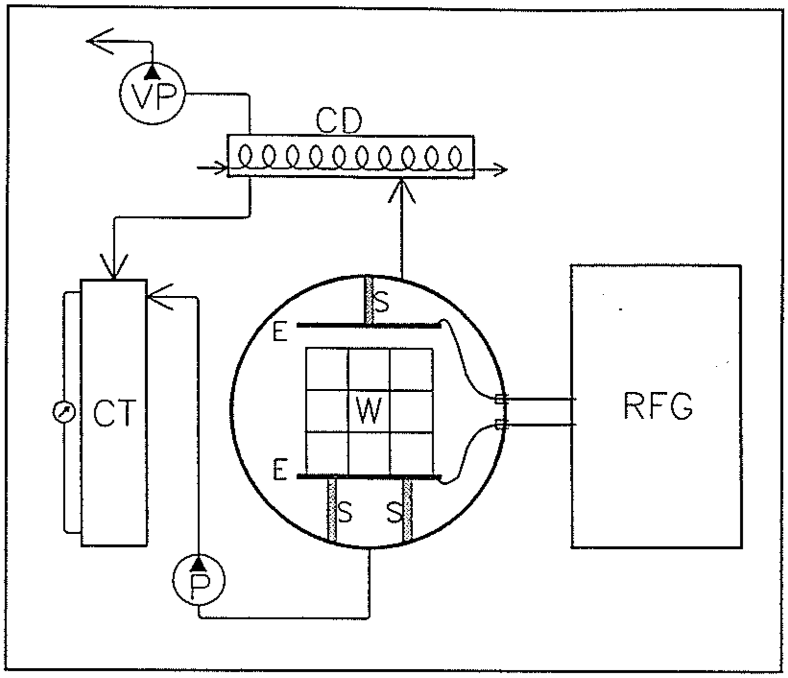

Fig. 1. Cross-section of laboratory RF/V unit.

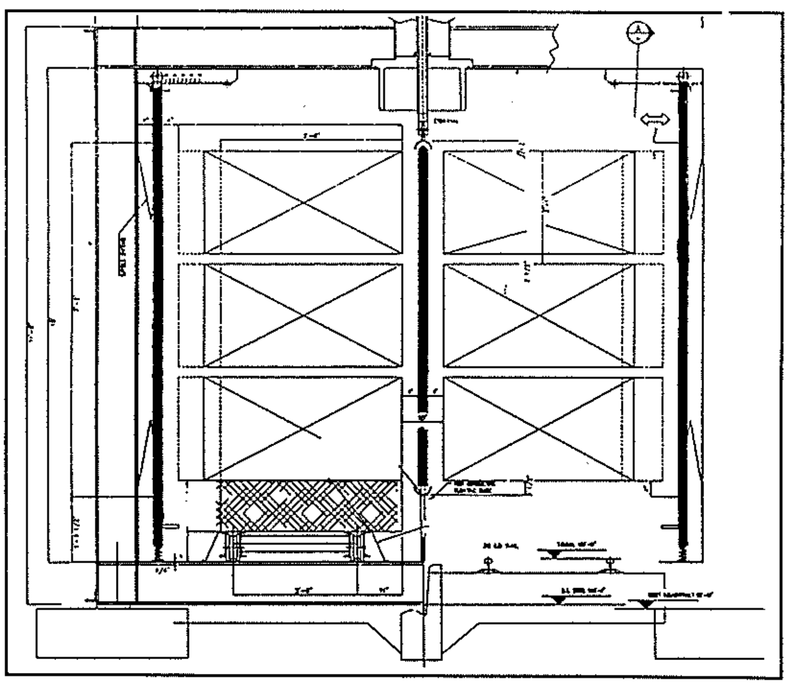
Fig. 2. Cross-section of commercial RF/V prototype

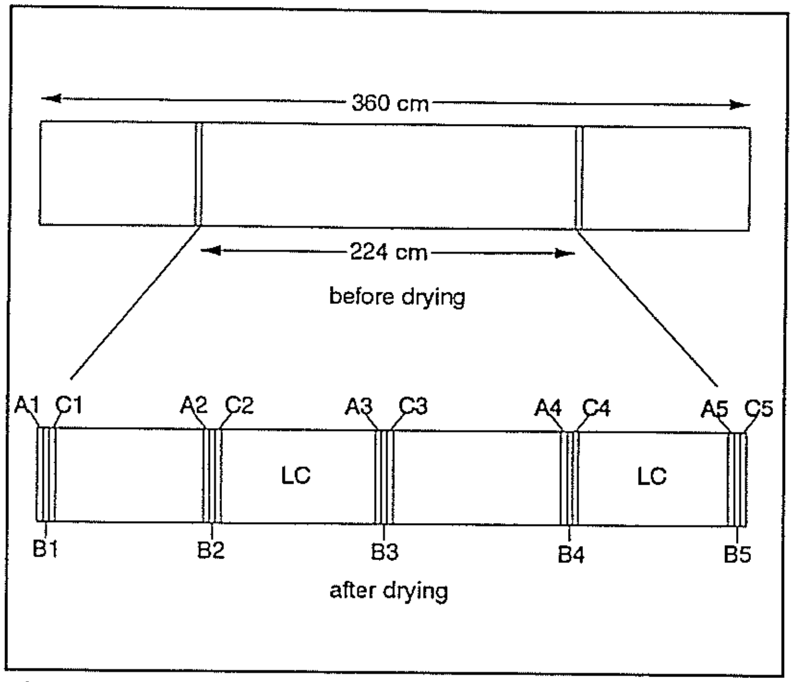

Fig. 3. Cutting pattern of green lumber

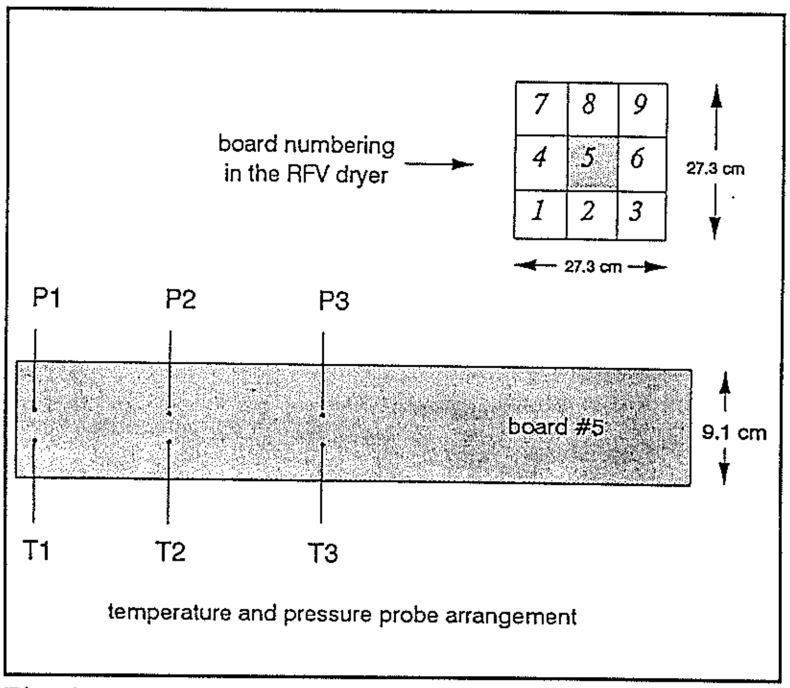

Fig. 4. Arrangement of T and P rpobes in central specimen.

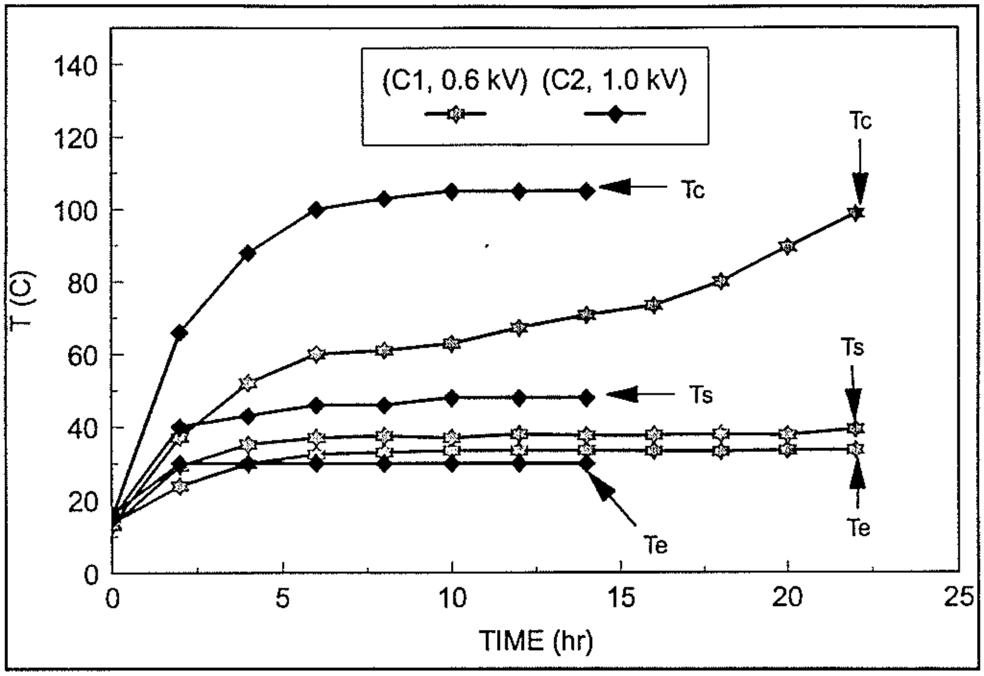

Fig. 5. Temperature variation in cedar specimens.

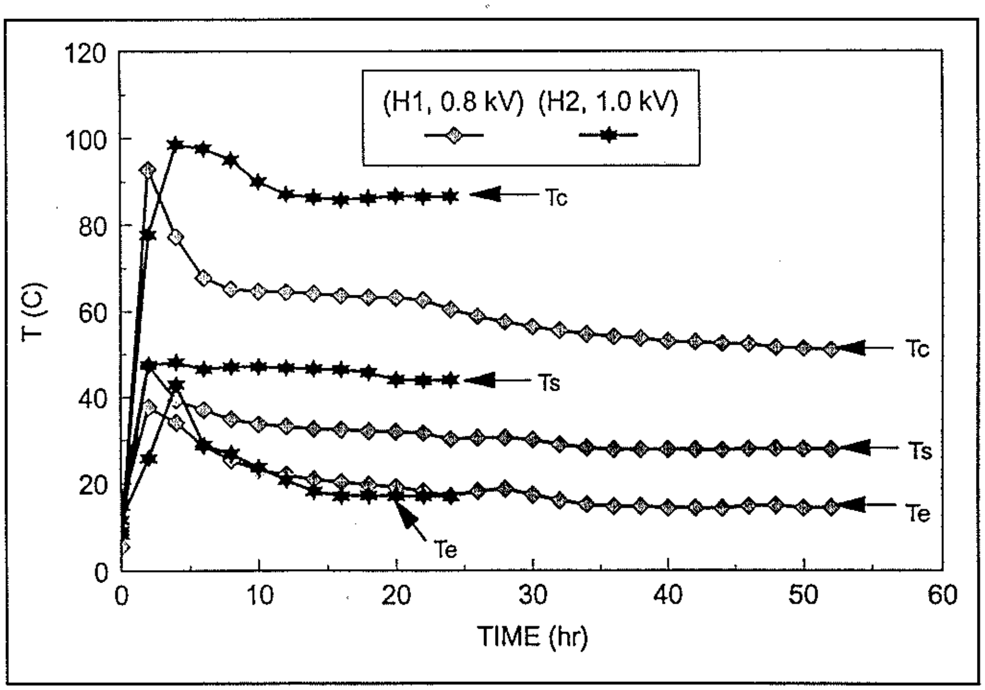

Fig. 6. Temperature variation in hemlock specimens.

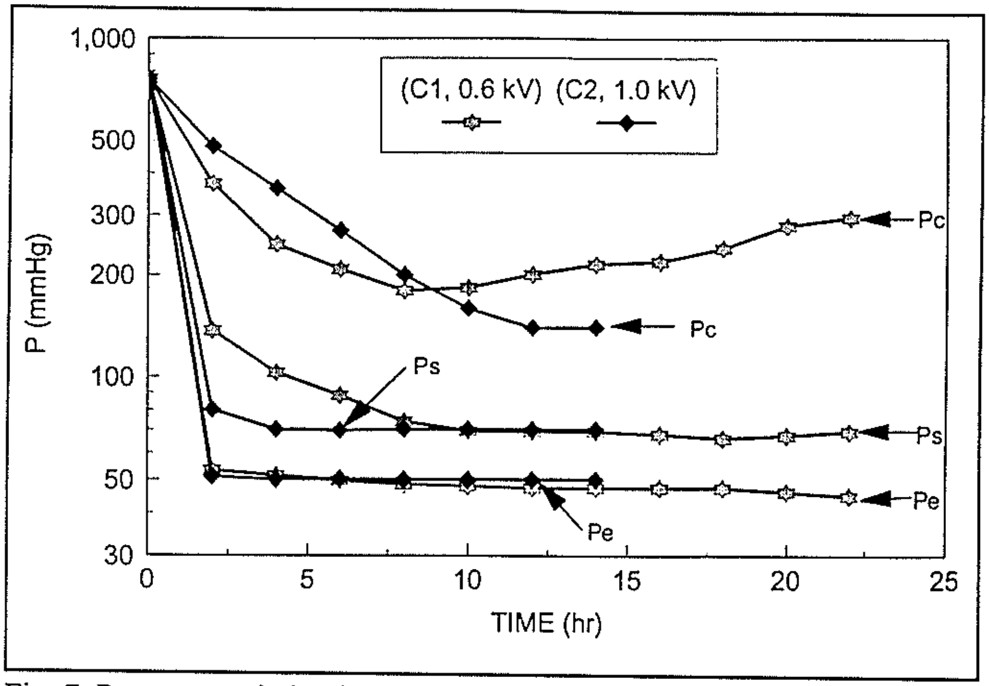

Fig. 7. Pressure variation in cedar specimens.

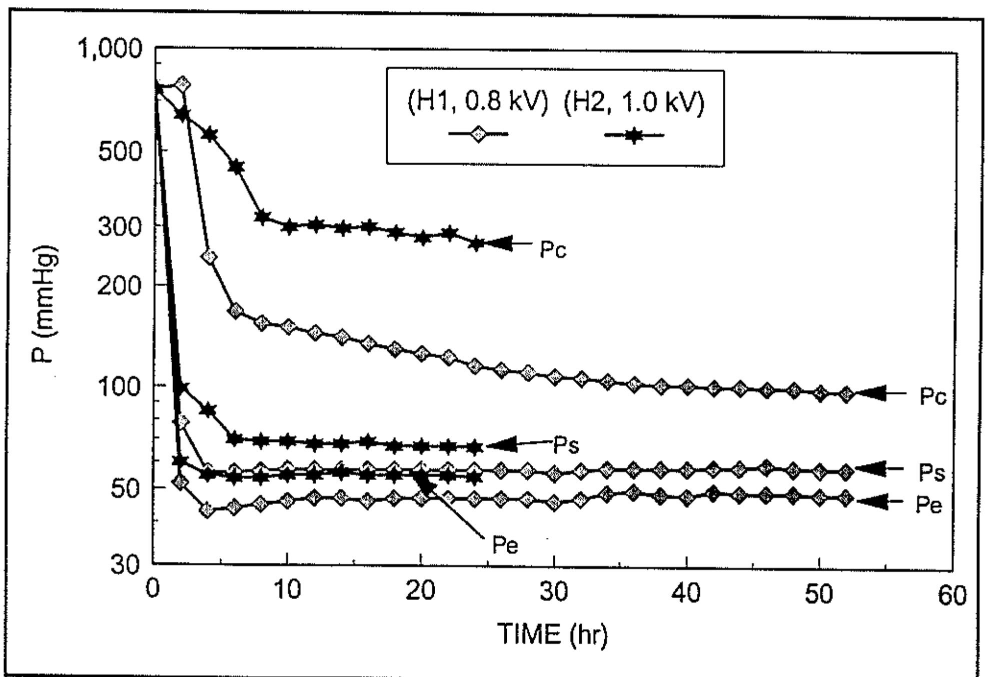

Fig. 8. Pressure variation in hemlock specimens

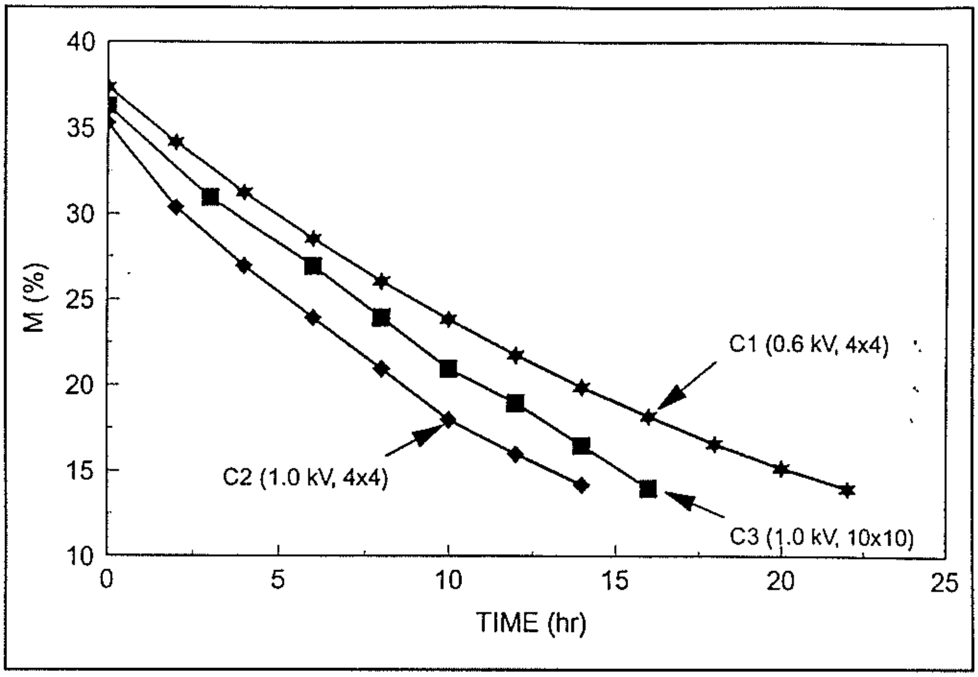

Fig. 9. Drying curves for cedar runs with the lab dryer.

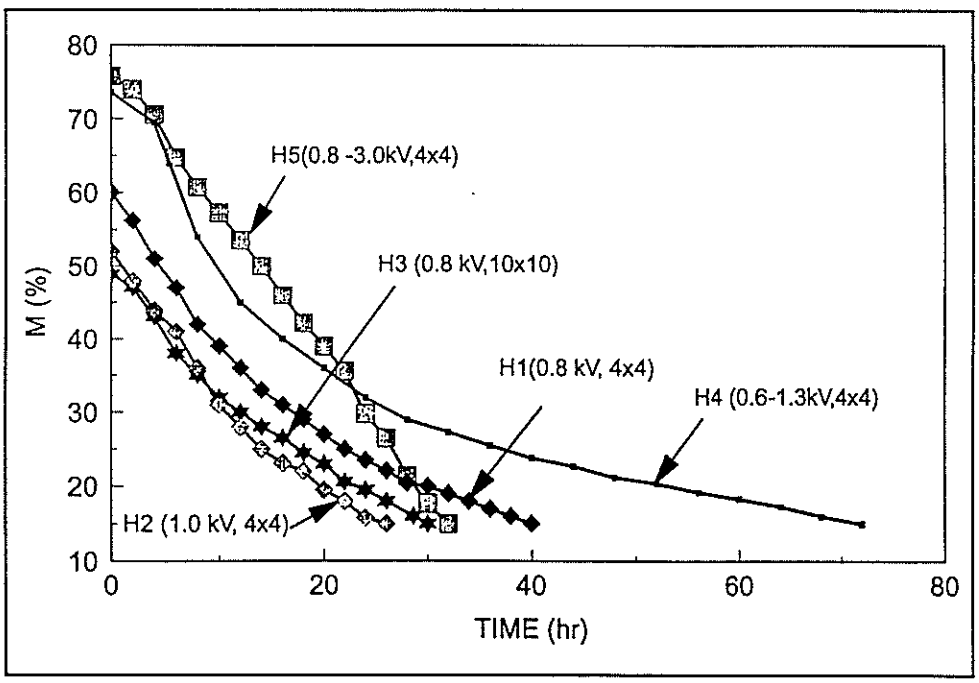

Fig. 10. Drying curves for hemlock runs with the lab dryer.

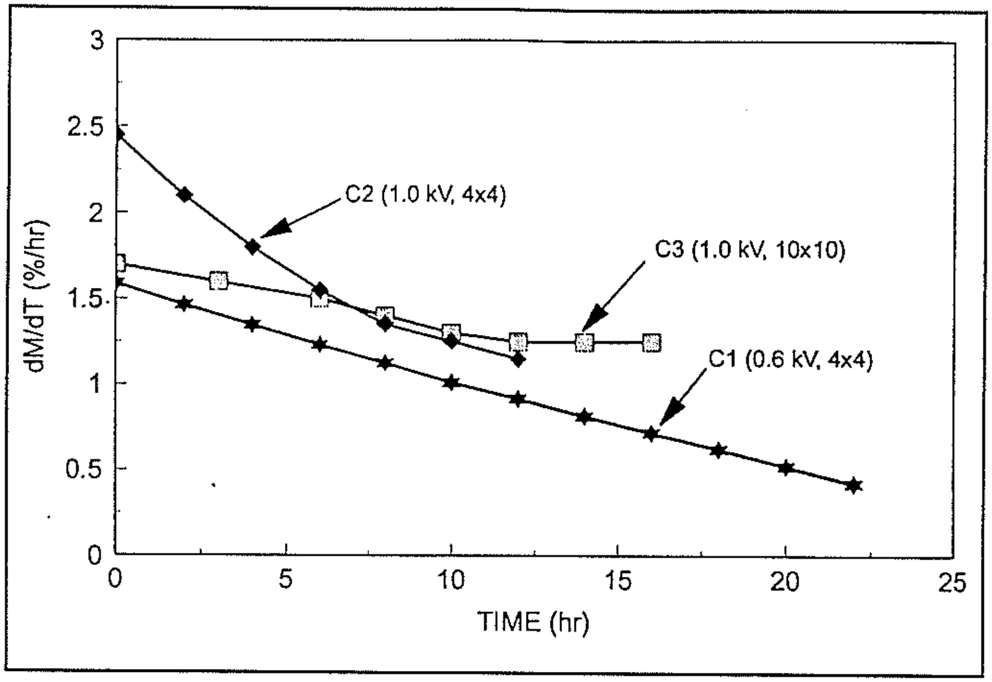

Fig. 11. Drying rates for cedar runs with the lab dryer.

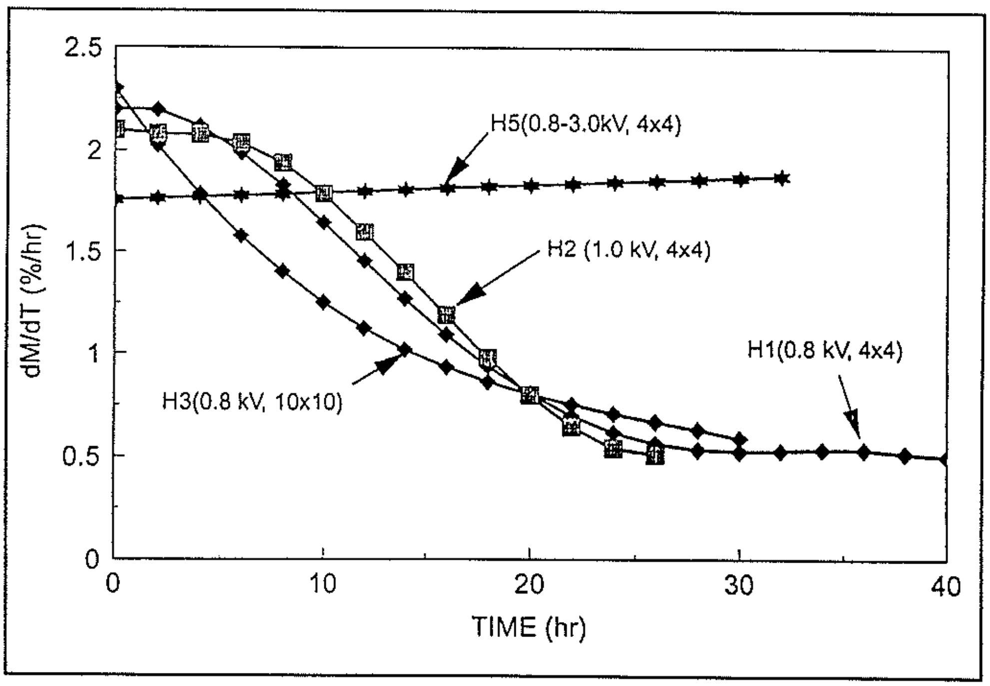

Fig. 12. Drying rates for hemlock runs with the lab dryer.

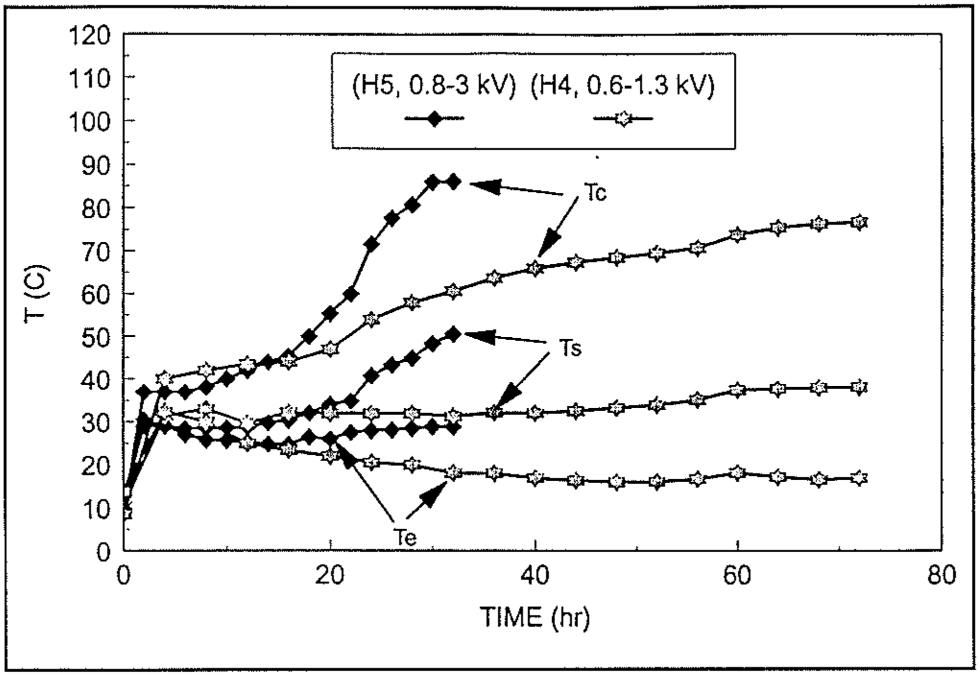

Fig 13. Temperature variation in hemlock specimens under variable electrode plate voltage (0.6 to 1.3 kV).

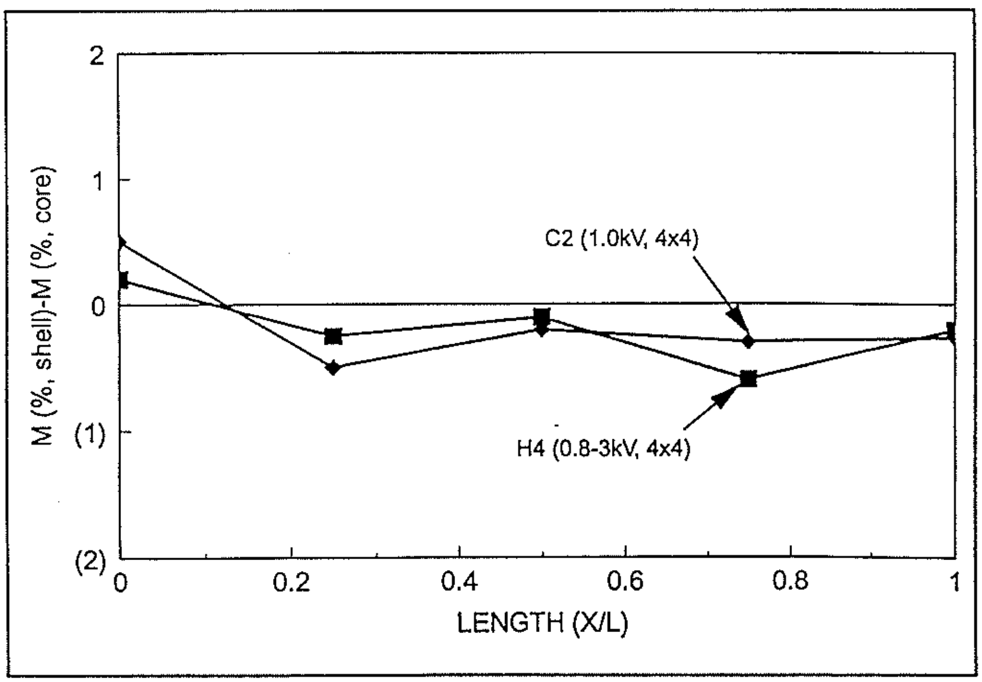

Fig. 14. Average longitudinal final moisture content variation.