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Response of Flakeboard Properties to Changes in Steam Injection Pressing Environments

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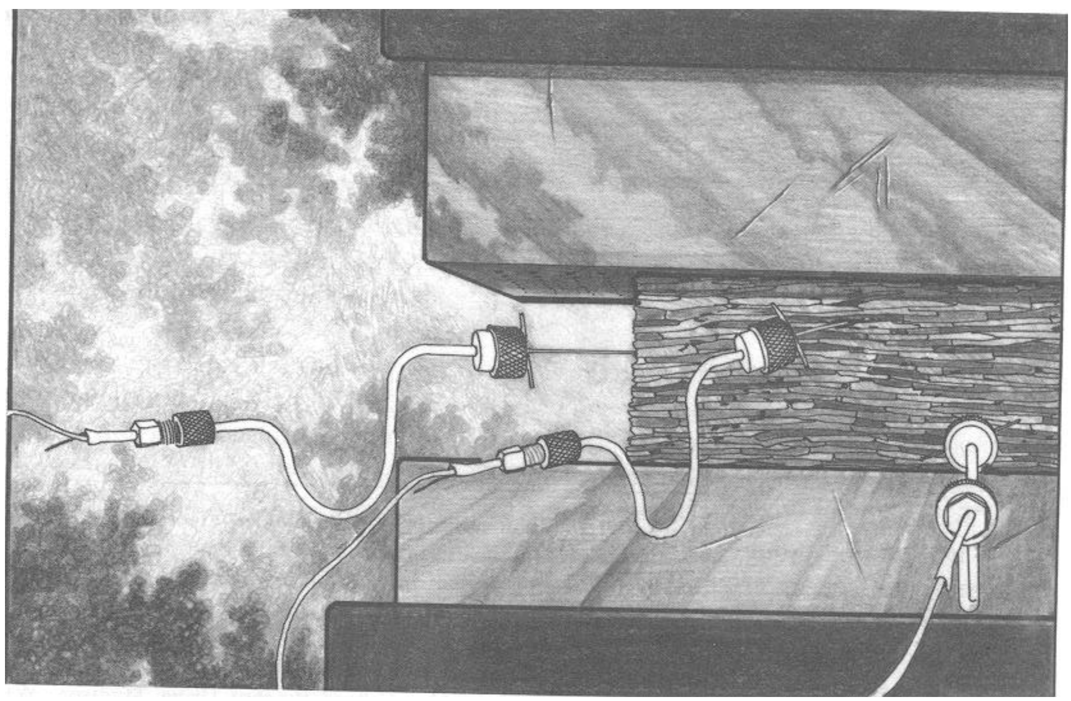

Abstract

Mechanical strength properties and dimensional stability of composite wood products are determined to some extent by the environment within the mat during pressing. The objectives of this study were to define time-related temperature and vapor-pressure parameters occurring in a mat during different steam injection pressing (SIP) schedules and to relate these conditions to board properties.

One-in.- (25.4-mm-) thick aspen flakeboards made with either phenol formaldehyde or isocyanate resin using a 12-min conventional press schedule were compared to boards made with four different SIP schedules of shorter duration. Maximum temperatures in the SIP boards varied from 220°F to 302°F (104°C to 150°C) as compared to a maximum of 270°F (132°C) in the conventional boards. Measured temperatures sometimes deviated from temperatures predicted from saturated steam tables at the measured vapor pressures. Vapor pressure differentials of >30 lb/in^2 (>207 kPa) occurred for short periods at different locations within a board. The vapor pressures at various board locations tended to equalize and simultaneously rose and fell at different rates depending on the dynamics of the system, their relative position, and the permeability of the board.

The maximum temperature of 302°F (150°C) attained in SIP boards made with high steam consumption was sufficient to bond a board with phenolic adhesive in 400 s. With less severe steam treatment, maximum temperatures decreased, and additional press time was needed to achieve adequate internal bond strengths.

Acceptable boards, as measured by internal bond strength, were produced with the isocyanate resin at all steaming schedules. Press times could often be reduced to less than half of that needed to bond boards made with phenolic resins. Shear and thickness swelling properties followed the same trends measured for internal bond strength. However, bending properties of SIP boards were influenced by the reduced density gradient of the boards and were below the bending properties of boards pressed in a conventional manner.

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Response of Flakeboard Properties to Changes in Steam, Injection Pressing Environments

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Introduction

Many empirical studies have been conducted to determine the fabrication parameters and pressing conditions that influence properties of wood particleboards. Investigations of species, particle geometry, adhesives, resin distribution, moisture content, density, press closure rates, press temperature, and a host of other variables that affect ultimate particleboard properties (Kelly 1977) have been extended to characterize fiber and flake composites, Additional variables, such as flake alignment, are being analyzed to facilitate the commercialization of composite products designed specifically for structural end-uses.

Computers have made it possible to investigate, in depth, the interaction of many variables. Progress is being made in modeling the pressing variables that control the properties of composite wood products. Basic relations are being developed for heat and mass transfer (Bolton and others 1989a, 1989b; Humphrey and Bolton 1989) rheology (Wolcott and others 1990), density gradients (Harless and others 1987, Wolcott and others 1990), porosity (Bolton 1988), and resin cure and bonding (Follensbee and others, in preparation, Geimer and others 1990b, Humphrey and Bolton 1979, Humphrey and Ren 1989, Humphrey and Zavala 1989). Studies by Kamke and Casey (1988), Kamke and Wolcott (1991), and Wolcott and others (1990) measured internal vapor pressure in conjunction with temperature to predict the moisture content of the wood and to define conditions affecting the glass transition temperature of lignin. These investigations showed that environmental conditions existing in conventionally pressed boards can modify the density gradient and possibly affect the bonding of adhesives and the ultimate dimensional stability of the product.

We were interested in extending the investigations of Kamke and Casey (1988) to steam injection pressing (SIP), a process whereby saturated steam is injected directly into the mat during pressing (Geimer 1983). Moisture and temperature environments in a SIP board are more severe and change faster than those in a conventionally pressed board (Geimer 1982, Hata and others 1989, 1990). However, with proper equipment, SIP conditions can be closely controlled and manipulated over a much wider range than is obtainable in conventional pressing. Maximum. moisture conditions are dependent on the amount of steam introduced and are higher than those in conventional pressing, retarding the curing of phenolic resins (Geimer and Price 1986). Conversely, isocyanate resins cure at lower temperatures and react quickly in the presence of moisture (Geimer 1985, Palardy and others 1989). Rapid plasticization of the wood reduces the pressure needed to close the press and, in some cases, improves dimensional stability. Because temperature and moisture can be extreme, the range of conditions for successful board manufacture need to be defined.

The objectives of our study were (1) to define the time-related temperature and vapor-pressure parameters occurring in a mat during different SIP schedules and (2) to relate these conditions to board properties.

Procedures

Four SIP schedules (B-E) and a conventional pressing schedule (A) were used to manufacture boards from both phenol formaldehyde and isocyanate (methylene diphenylisocyanate) adhesives. For each condition, three boards were constructed, for a total of 30 boards. Total press times were successively extended when necessary to prevent delaminations and were shortened if the boards appeared well bonded. Temperature and vapor pressure were measured in three locations inside the mat during pressing. Following conditioning at 80°F (27°C), 65 percent relative humidity, the boards were tested for mechanical properties and dimensional stability.

Board Fabrication

All boards were constructed to an ovendry specific gravity (SG) of 0.640 using 0.03-in.- (0.76-mm-) thick by 0.5-in.- (12.7-mm) wide by 2.0-in.- (50.8-mm-) long aspen disk-cut flakes. The furnish was screened to eliminate the "fines" passing through a 1/4-in.- (6.35-mm-) mesh screen. Target board thickness was 1 in. (25.4 mm). The material was sprayed with either 5 percent GP-3195 phenolic resin (Georgia Pacific, Decator, Georgia),[1] or 4 percent MF-184 isocyanate resin (Rubicon, Wilmington, Delaware). These resins were developed for conventional flakeboard production and were 'not modified specifically for steam injection pressing. Mat moisture content averaged 10 and 9 percent, for the phenolic-bonded conventional and SIP boards, respectively, and 7 and 5 percent for the isocyanate-bonded conventional and SIP boards, respectively. Moisture content was higher in the phenolic-bonded boards as a result of the additional moisture used as a solvent in phenolic resin. The boards were hand formed in a 30- by 26-in. (762- by 660-mm) deckle box.

The edge to surface ratio, a major factor in determining steam escape, is much higher in small laboratory-fabricated boards than in large commercially manufactured panels. To approximate the conditions experienced in a large panel, the edges of the laboratory boards were densified by placing a 1/8-in.- (3.175-mm-) thick by 1-in.- (25.4-mm-) wide square steel frame measuring 30 by 26 in. (762 by 660 mm) on the outside edge on top of the mat. The mat was formed on a 0.07-in.- (1.78-mm-) thick screen caul, which had been sealed around the edges to prevent the escape of steam (Geimer and Price 1986). A similar screen was placed on top of the mat prior to pressing. The oil-heated platens were maintained at 375°F (190°C).

Press Schedules

The computer system used to control the pressing and steaming operation was described previously (Geimer and others 1982, 1990). The first seven segments of the press schedule prescribed a press positioning sequence identical for all SIP boards (Table 1). Controlling the steam flow in segments 4 through 7 allowed us to use four different steaming schedules, B through E, in which the total steam-supplied heat varied from 65 to 280 Btu/lb (151 to 651 kJ/kg) of wood. Following closure, the press was normally held at target board thickness for 90 s, while the steam trapped in the

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1—Press and steam schedules

Segment	Segment end-time (s)	Position (in.) (pressure (lb/in^2))[a]	Steam flow per schedule (lb/h)[b] B	C	D	E
1	0	10	0	0	0	0
2	23	3	0	0	0	0
3	33	2.4	0	0	0	0
4	37	2.4	800	800	0	800
5	45	1.6	600	400	400	0
6	53	1.0	600	0	0	0
7	55	1.0	600	600	600	0
8	145	1.0	0	0	0	0
9	325	1.0	Vent			
10	330[c]	(20)	Vent			
11	360	(20)	Vent			
12	365	1.25	Vent			
13	400	10.0	Vent			

[a] 1 in. = 25.4 mm. 1 lb/in^2 = 6.89 kPa.
[b] 1 lb = 0.45 kg.
[c] The time varied between 1 and 35 s depending on the compaction pressure prior to decompression. Press was scheduled to decompress at a rate of 4 lb/in^2/s (27.6 kPa/s).

manifold and platens was allowed to dissipate into the board (Table 1, segment 8). During segment 9, normally 180 s long; press position was maintained while the manifolds were exhausted to atmosphere and the board was allowed to vent through the platens. Segment 9 was lengthened in the case of the phenolic-bonded schedule E boards to produce an acceptable board. Segments 8 and 9 were shortened for several isocyanate-bonded boards when it appeared that acceptable boards could be made in less time. Schedule variations and board replications are listed in Table 2. Following segment 9, the press was slowly decompressed to 20 lb/in^2 (137.9 kPa), held at this pressure for 30 s, and then opened to permit removal of the board. The decompression and opening portions of the press schedule were the same for all boards. Conventional boards were pressed with schedule A. The 60-s closing approximated the SIP closing schedule with the omission of the 4-s hold in segment 4. In addition, segment 9 was lengthened to 555 s.

Steam Injection

The system was supplied with 200 lb/in^2 (1.379 MPa) steam from the laboratory's central heating boiler. Energy provided to the mats was varied by specifying both the steam flow rate and the duration of steaming (Table 1). Steam flow was monitored and provided the feedback signal for modulating the control valve. Target steam flow varied from 400 to 800 lb/h (180 to 360 kg/h) depending on the schedule and the segment within the schedule.

Table 2—Schedule conditions and properties for phenolic- and isocyanate-bonded boards[a]

Schedule (Btu/lb)	Steam flow[b] (Btu/lb)	Press time (s)	Number of boards	Board thickness (in.)	Board pressure[c] (lb/in^2)	IB (lb/in^2)	Shear strength (lb/in^2)	MOE ($\times 10^3$ lb/in^2)	MOR (lb/in^2)	Thickness swelling (pereent)	Furnish MC (percent)	Board MC (percent)
					Phenolic							
A	0	775	3	0.999	46 (108)	66	381	654	5.020	24	8.9	2.8
B	280	400	3	1.015	28	69	384	697	4,220	13	8.6	7.2
C	150	400	3	1.047	56	57	333	711	4,410	20	8.5	6.3
D	90	400	3	1.070	57	41	279	696	3,920	19	8.2	7.5
E	65	400	1	1.167	111	—	—	—	—	—	9.3	7.4
		680	1	1.090	78 (102)	45	297	578	3,310	24	9.3	4.9
		1,000	1	1.027	47 (96)	75	445	646	4,360	27	9.3	3.3
					Isocyanate							
A	0	775	2	0.995	44 (108)	121	482	897	6,360	11	7.1	2.7
		485	1	1.033	86 (108)	60	364	820	5,500	13	6.2	5.0
B	280	400	1	1.005	23	110	578	742	5,420	7	4.6	7.7
		310	2	1.005	28	131	612	770	4,700	7	4.6	5.6
C	150	400	1	1.014	51	141	701	774	5,840	9	4.6	5.0
		230	1	1.032	81	138	607	741	4,880	7	5.1	5.9
		200	1	1.039	102	140	609	733	4,970	6	5.1	6.8
D	90	400	1	1.007	37	149	637	773	5,720	7	5.1	4.3
		230	1	1.018	75	151	667	701	5,330	8	3.6	6.2
		210	1	1.036	133	150	627	666	5,130	7	3.6	5.4
E	65	400	1	1.047	131	136	655	668	4,320	11	3.6	4.3
		270	1	1.079	186	142	576	653	5,030	11	5.8	7.0
		250	1	1.080	228	147	610	642	4,880	9	5.0	7.0

[a] 1 Btu/lb = 2.324 kJ/kg; 1 in. = 25.4 mm; 1 lb/in^2 = 6.89 kPa.
IB is internal bond, MOE modules of elasticity, MOR modulus of rupture, and MC moisture content.
[b] Steam flow per unit of wood.
[c] Board compaction pressure at end of segment 9, immediately prior to decompression.
Value in parenthesis is board pressure after 325 s, the time of decompression for control (400-s) SIP boards.

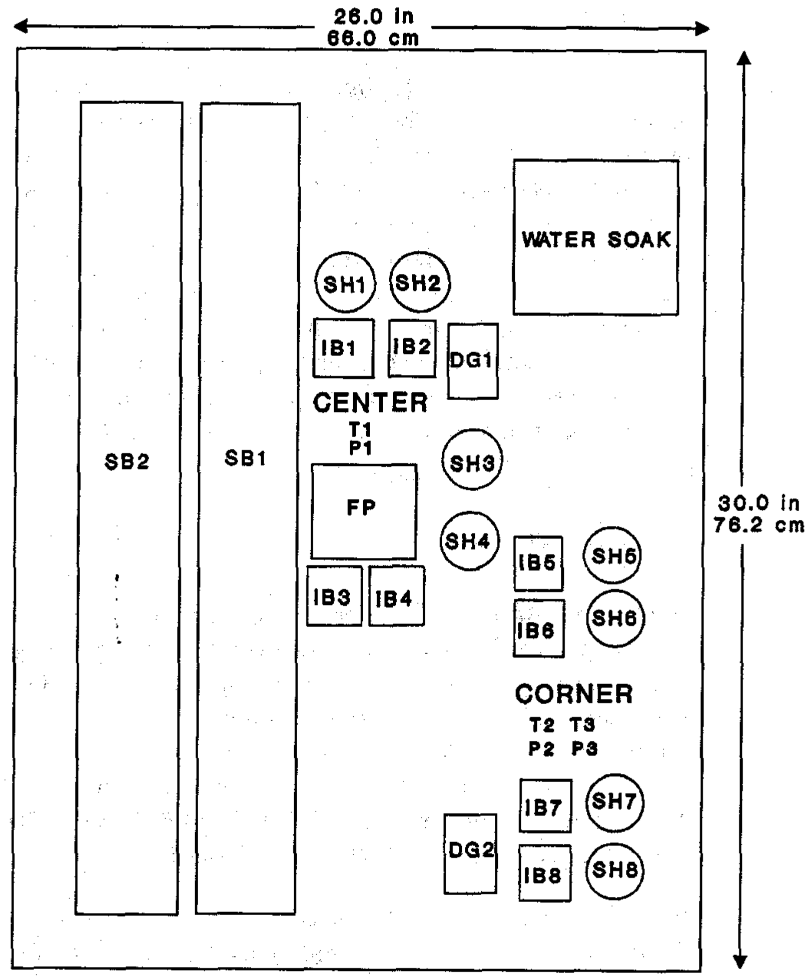

Figure 1—Location of pressure transducers (P), thermocouples (T), and test specimens. IB, 2- by 2-in. (51- by 51-mm) internal bond specimen; SH, 2-in.- (51-mm-) diameter shear specimen; SB, 3- by 24-in. (7.6- by 60.9-cm) static bending specimen; FP, 4- by 4-in. (102- by 102-mm) recoverable Bakes; and DG, 2- by 3-in. (51- by 76-mm) density gradient.

Data Collection

Internal vapor pressures were measured at three locations with Omega PX302, 150-lb/in^2 (1,034-kPa) pressure transducers connected to microbore tubing with an inside diameter of 0.042 in. (1.067 mm). The tubing was placed to monitor vapor pressure at the center-core, corner-core, and corner-quarter point (thickness) positions (Fig. 1). One type-T, 30-gauge thermocouple accompanied each vapor-pressure transducer, and an additional thermocouple acted as a “floater” to monitor the temperature at various other board locations. Board thickness, compaction pressure; steam flow, steam manifold pressure, and steam manifold temperature were also monitored. Data were recorded every 0.5 s for the first 60 s of the press cycle and every 5 s thereafter. The boards were weighed and measured for average thickness immediately following pressing.

Testing

The boards were tested for internal bond (IB), interlaminar shear, bending modulus of rupture (MOR), and bending modulus of elasticity (MOE). Thickness swelling measurements were obtained after a 2-h and 24-h soak. These tests were performed according to ASTM-D1037 (ASTM 1987). Shear strength was obtained using a special jig built at the Forest Products Laboratory to test the 2-in.- (50-mm-) diameter specimen in a manner similar to that described by Passialis and Tsaumis (1982). Density gradients were measured using a nuclear densitometer (Laufenberg 1986). Four IB and four shear specimens were clustered around the center position and also the corner position (total of eight IB and eight shear specimens), as shown in Figure 1. Their locations were determined in part by the presence of retrievable resin and flake samples (not discussed in this report) and the location of the thermocouple and vapor-pressure probes.

Results and Discussion

Press Schedules

Contrasting SIP schedules were developed to meet the objectives of this study. Experience has shown that for steam to be effective in shortening press times, the steam must be introduced prior to compressing the mat to SG > 0.432 and that mat temperature must reach 212°F (100°C) prior to compressing to SG > 0.560 (Geimer 1983). These parameters were verified in exploratory trials and served as the basis for developing the press schedules given in Table 1 and shown in Figures 2 through 6. The average total steam energy supplied was 280, 150, 90, and 65 Btu/lb (650, 349, 209, and 151 kJ/kg) of wood for schedules B, C, D, and E, respectively.

Steam was first introduced to boards made with schedules B, C, and E while the boards were held at a SG of 0.266. This 4-s burst of steam at 800 lb/h (360 kg/h) provided approximately 65 Btu/lb (151 kJ/kg) of wood and accounted for all the additional heat and moisture supplied to the schedule E boards. Following the initial 4-s burst, steam flow in the schedule B boards was reduced to and held at 600 lb/h (272 kg/h) for an additional 18 s; steam flow was terminated 2 s after the press was closed. In schedule C, the steam flow was reduced to 400 lb/h (181 kg/h) after the initial 4-s burst. Flow was maintained at this rate for approximately 8 s until the board was reduced to a thickness of 1.6 in. (40.6 mm). Steam flow was then interrupted and the press closed to the target thickness of 1 in. (2.54 mm). Following closure, steam was again injected for 2 s at a flow rate of 600 lb/h (272 kg/h). Except for the omission of the initial 4-s period of steaming, schedule D was the same as schedule C.

Board permeability was reduced rapidly as the press closed to target thickness, and board SG climbed from 0.4 to 0.64 during segment 6. A maximum manifold gas pressure of 120 lb/in^2 (827 kPa) was attained in schedule B boards. The short 2-s post-closure burst of steam used in schedule C and schedule D boards raised manifold pressure to 70 lb/in^2 (482 kPa). As a result of the low permeability of the mat, relatively little extra steam was consumed during this period. In a normal steam pressing operation, this post-closure steam period would be extended until all areas in the board were similar in temperature and/or the resin had cured. In our study, the post-closure steam period was minimized to avoid masking the effect of variations in other portions of the press cycle.

Initial plans called for all schedules to incorporate a 90-s period in which steam flow was stopped and the steam in the manifold and platen was allowed to dissipate into

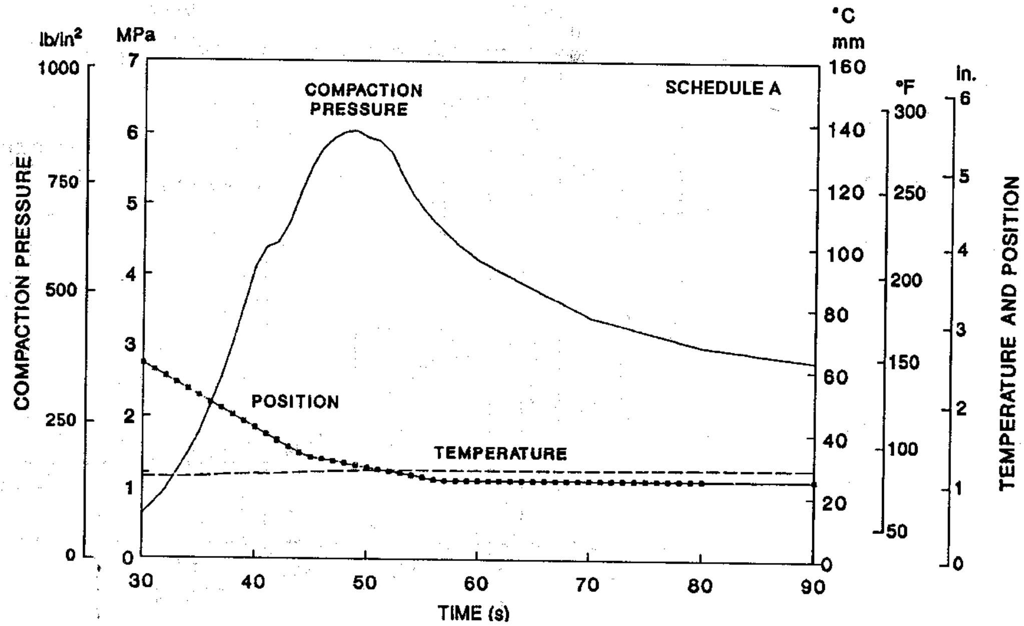

Figure 2—Board temperature, and compaction pressures for conventional schedule A.

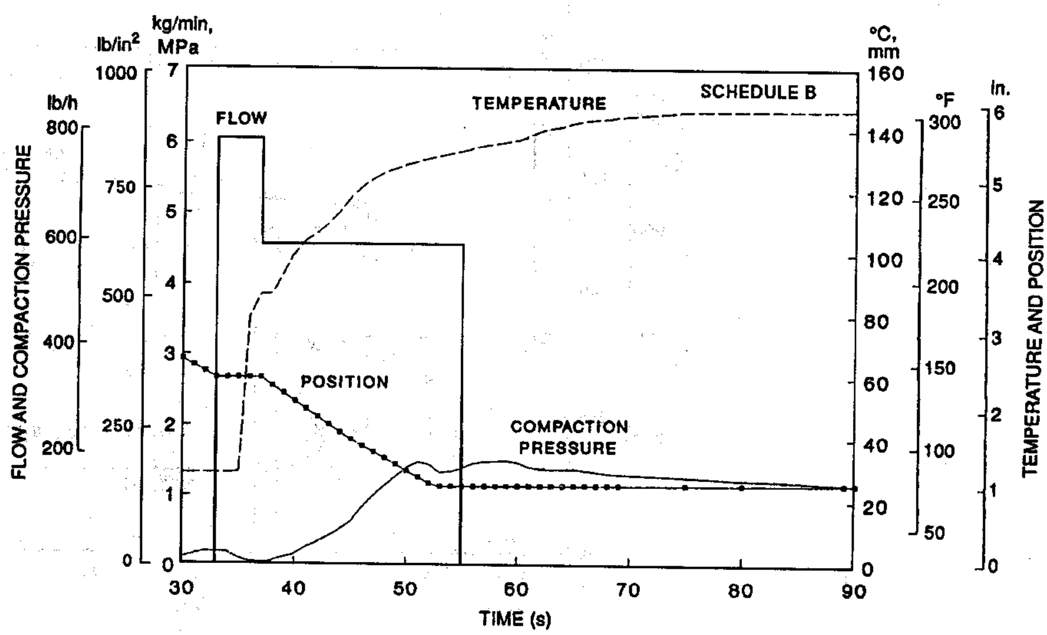

Figure 3—Board temperature and compaction pressures for SIP schedule B.

the mat (Table 1, segment 8). The manifold was then exhausted to atmosphere and the press held at target thickness for a 180-s venting period prior to decompression. The total time from the start of press closure to the beginning of the decompression period was normally 325 s. Out-of-press thickness measurements indicated that excellent boards were being made with the isocyanate resins. Consequently, the scheduled hold and vent periods, segments 8 and 9, were selectively changed to successively reduce total press time for isocyanate-bonded boards to as short as 200 s (Table 2). Phenolic-bonded boards, on the other hand, often showed signs of excessive springback,

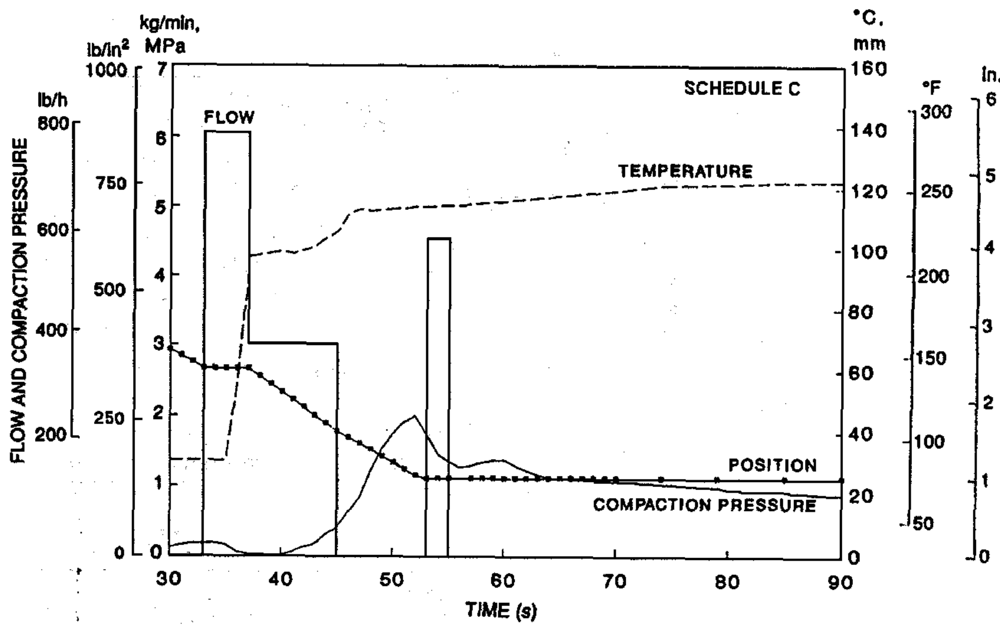

Figure 4—Board temperature and compaction pressures for SIP schedule C.

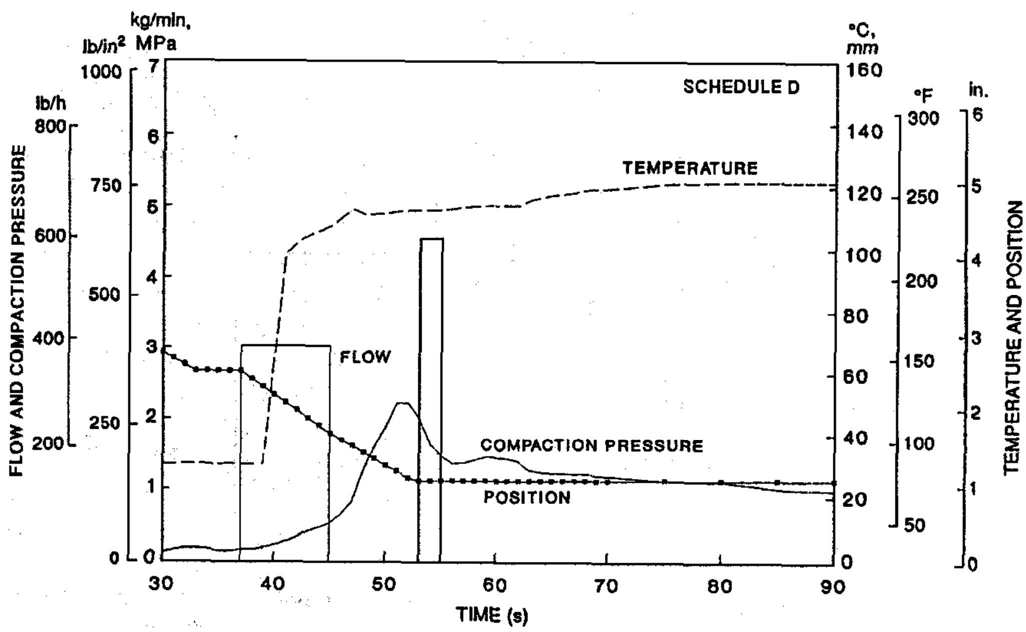

Figure 5—Board temperature and compaction pressures for SIP schedule D.

culminating in a blow for the schedule E board. Press time for these boards was lengthened to as long as 1,000 s by extending segment 9.

Energy consumption was relatively high in schedule B, and much steam was lost during the early portions of the cycle while the press was still closing. An ideal schedule for the isocyanate resins would be similar to schedule C or D during the initial closing, using just enough steam to completely heat the mat to near the desired temperature. After press closing, manifold pressure would be brought up to and maintained at 100 to 120 lb/in^2 (689 to 827 kPa) for the time necessary to obtain full board strength.

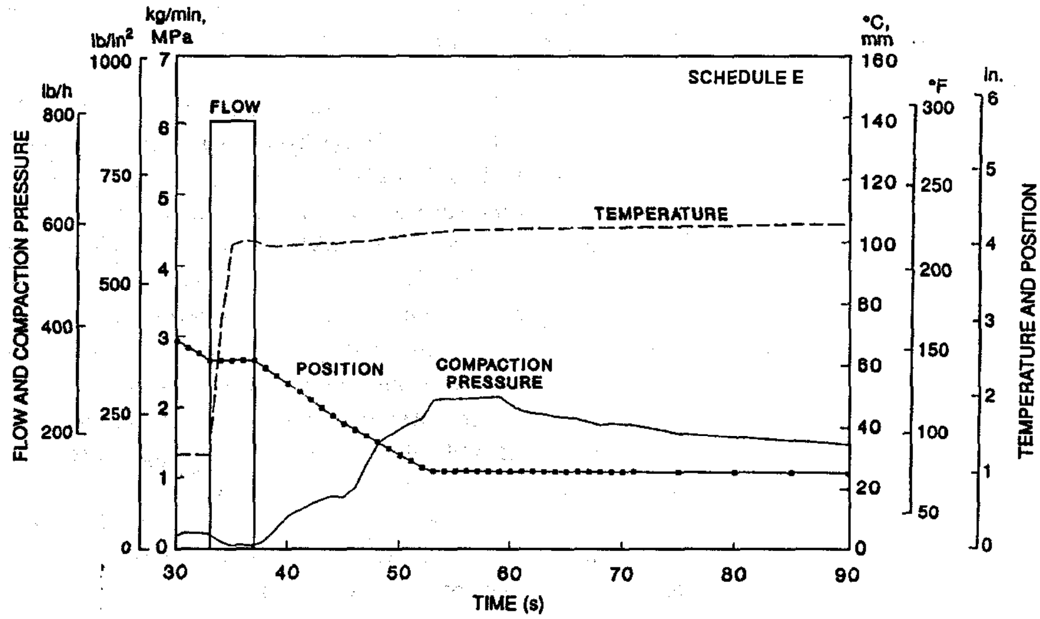

Figure 6—Board temperature and compaction pressures for SIP schedule E.

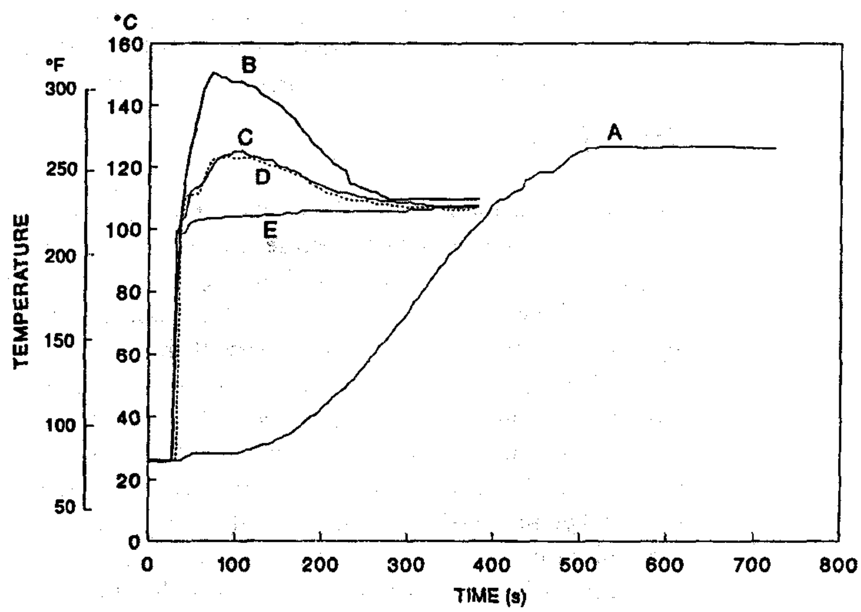

Figure 7—Comparison of center-core temperatures for all press schedules for phenolic-bonded boards.

Temperature

Temperatures in the geometric center of the board (the center-core position) are depicted for the duration of the pressing time for schedules A through E in Figure 7. Temperatures in all SIP boards rose to 220°F (104°C) within seconds of steam injection. The center-core temperature of the schedule B boards was subsequently elevated to 302°F (150°C) by the continued supply of steam. Maximum center-core temperatures measured in the schedule C and D boards were between 250°F and 280°F (121°C and 138°C).

The energy needed to raise ovendry wood from 70°F to 220°F (21°C to 104°C) is 90 Btu/lb (209 kJ/kg) (Forest Products Laboratory 1987). The energy requirement increases to 115 Btu/lb (267 kJ/kg) if the moisture content is 8 percent. These theoretical values increase to 165 and 190 Btu/lb (383 and 441 kJ/kg) as the maximum temperature rises to 320°F (158°C). The 65-Btu/lb (151-kJ/kg) heat supplied by the steam in schedule E was below that necessary to raise the entire mat to 212°F (100°C). However, the center-core temperature and all other monitored temperatures of schedule E boards rose immediately and remained at 219°F (104°C). This indicates that heat transfer into the center of a flake is not instantaneous, and the measured temperature is dominated by the steam in the voids between the flakes. On the other hand, the 280 Btu/lb (651 kJ/kg) of heat supplied to the schedule B boards was well above that needed to obtain the maximum mat temperature of 302°F (150°C). Center-core mat temperatures did rise to 302°F (150°C), but they then fell to 250°F (121°C) when the steam was allowed to dissipate, indicating again that the steam and wood temperatures are not necessarily equal and that evaporation of condensed moisture can play: a critical role in the change of temperature.

Within-board temperature variations are shown for schedules B and E in Figures 8 and 9, respectively. Temperature differences between the monitored locations recorded early in press schedule E were small compared to differences noted in schedule B during the same period. However, temperatures in schedule B boards tended to equalize with time, whereas temperature differences between the quarter-point and the core positions in the schedule E boards increased with time.

Vapor Pressure

As with conventional boards, heat transfer throughout a SIP board depends on steam convection. However, vapor pressure gradients are more severe in SIP boards. In laboratory-size boards, this condition is aggravated by large edge-to-surface-area ratios. To mimic the conditions found in large boards, we inserted a 0.125-in.- (3.175-mm-) thick spacer around the periphery of the board to increase the edge density and retard steam escape. We measured vapor pressure differences of 40 lb/in^2 (275 kPa) between the center-core and corner-core locations, and, for short periods, differences of up to 20 lb/in^2 (137 kPa) between the corner-core and corner-quarter locations of boards made with schedule B. Vapor pressures at various locations in a phenol-formaldehyde-bonded schedule B board are compared in Figure 10. Note that pressure in all board locations increased until the center-core reached the same pressure as that of the manifold. The vapor pressures at any location then rose or fell depending on the relative distance, permeability, and pressure differential from a source of higher pressure and a vent of lower pressure. It is not uncommon to measure falling and rising vapor pressures simultaneously at different board positions. The direction of vapor flow changes throughout the press cycle. During steam injection, the direction of flow is into the core and out the edges of the mat. When the injection stops and the manifold pressure is reduced to that in the mat, the flow is directed towards the edges only. When venting is allowed through the manifold, flow is directed toward both the platen and the edges. This reversal of steam flow causes vapor pressure maximums at specific locations within the mat to occur at different times and at different magnitudes.

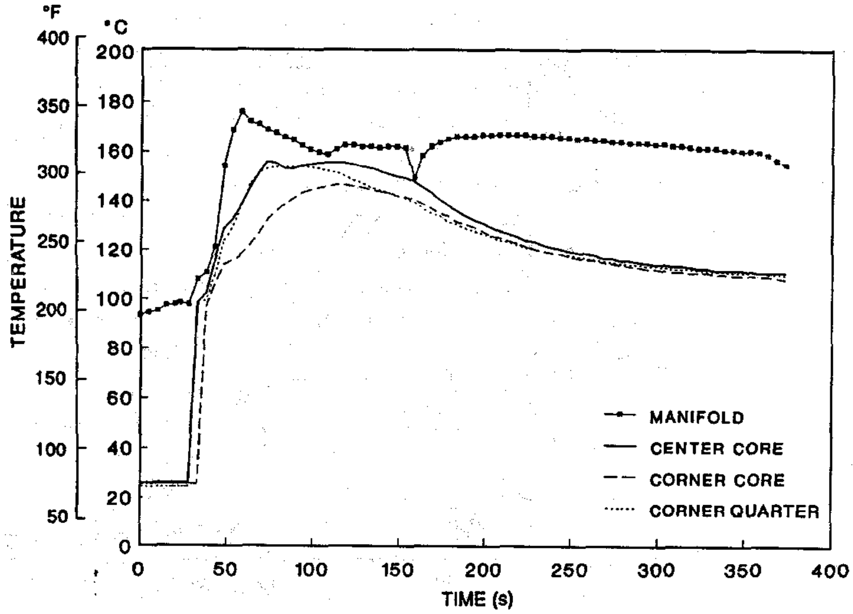

Figure 8—Temperatures at three locations in phenolic-bonded board, schedule B.

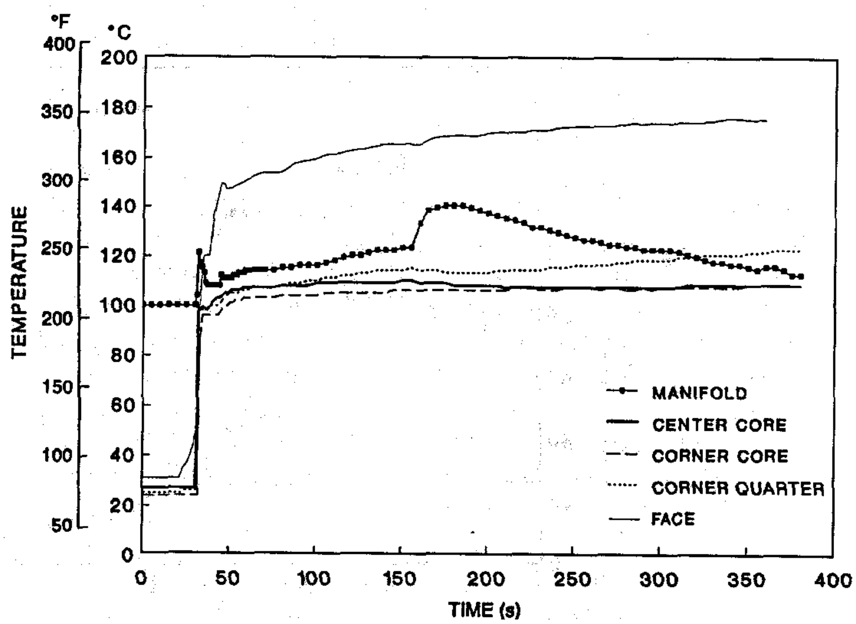

Figure 9—Temperatures at three locations in isocyanate-bonded board, schedule E.

The gas pressure in the isocyanate-bonded panels was significantly higher than that in the phenol-formaldehyde-bonded panels. This was caused by the generation of carbon dioxide during the polymerization of isocyanate in the presence of water. Material stoichiometric calculations indicate that the difference in measured gas pressure between the two adhesives can easily be accounted for by the carbon dioxide (Johnson 1990).

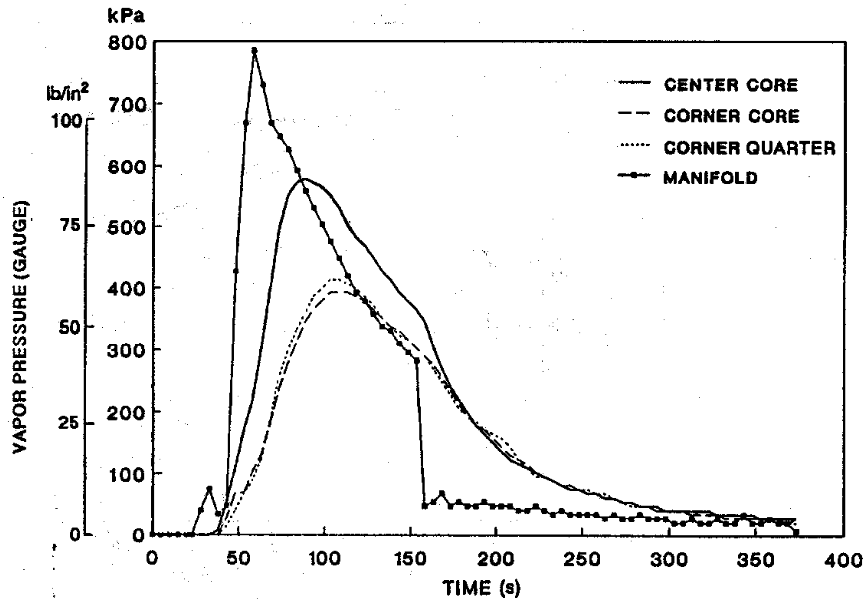

Figure 10—Vapor pressures at three locations in phenolic-bonded board, schedule B.

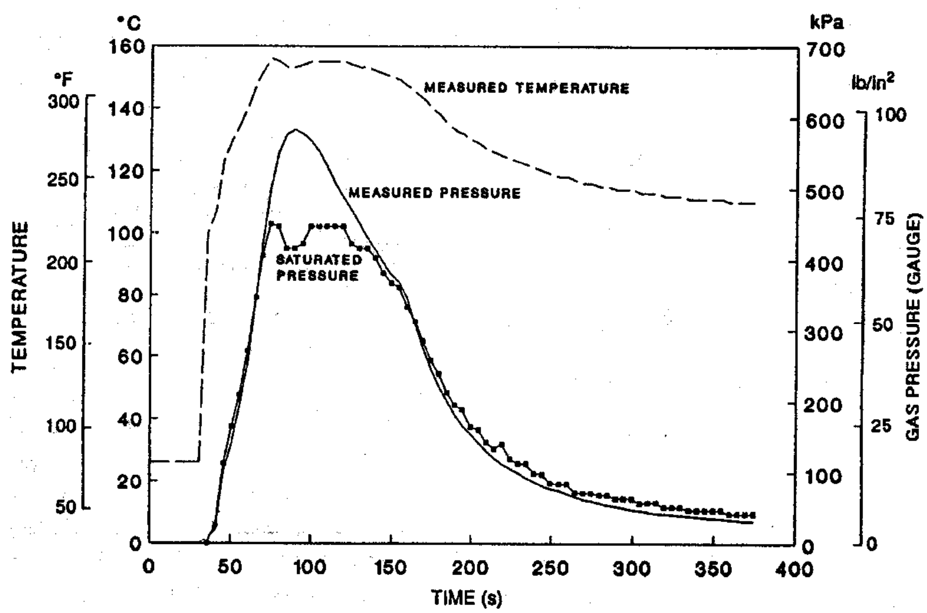

Figure 11—Temperature-vapor-pressure relations in phenolic-bonded board, schedule B.

Temperature-Vapor-Pressure Relations

Temperature and vapor pressure in the center-core position of schedule B boards bonded with phenol-formaldehyde are shown in Figure 11. The figure also shows theoretical saturated vapor pressure as predicted from steam tables using the measured temperature. Prior to the injection of steam, the void spaces inside the mat contained a mixture of air and water vapor. The steam was injected when the mat was held at a SG of 0.27. The interparticle environment is likely to closely resemble that of pure steam, whereas the environment within the flakes is similar to its original condition. Steam condenses in the core of the mat during this early stage. During the period of actual steam injection and for a few seconds thereafter, the measured gas pressure is very close to the saturated vapor pressure.

After 70 s elapsed press time, the measured gas pressure exceeds the saturated vapor pressure. Two factors could cause this condition. Air trapped in the cell lumens will exert a partial pressure that increases with temperature. If none of the air is lost, the temperature increase could cause an approximate 20-lb/in^2 (138-kPa) partial pressure of air. Another source of pressure could be liquid hydraulic pressure as a result of condensed water. The measured compaction pressure showed that nearly 200 lb/in^2 (1,379 kPa) was required to hold thickness at 70 s into the press cycle. It is not likely that the entire 200 lb/in^2 (1,379 kPa) could be transferred into hydraulic pressure because the void network would allow for pressure relief. The evidence suggests that hydraulic pressure is the predominant cause of the high measured gas pressure because the excess gas pressure was not detected until after the press closing time; a tempgrature-induced increase of air partial pressure should have been evident during the first 40 s when temperature had already drastically increased.

Shortly after venting began, at 145 s, the data indicates that a slightly superheated condition occurred. This may have been due to the presence of the hygroscopic wood acting to reduce the vapor pressure of water. In addition, some measurement error may have been present, particularly if the response time of the thermocouple and the gas pressure probe were different.

Moisture Content

Because the isocyanate resin we used does not contain water, boards made with this resin entered the press at an average moisture content of 5.0 percent as compared to 8.7 percent for the boards made with phenolic resin, which contains 45 percent water. Assuming 1 lb (0.454 kg) of steam at 200 lb/in^2 (1,379 kPa) contains 1,182 Btu (1,247 kJ) of heat, the 65 Btu/lb (151 kJ/kg) of steam supplied to the schedule E boards would increase the mat moisture content by 5.5 percent if no steam escaped. However, moisture content of the schedule E isocyanate-bonded boards pressed for the shortest period (250 s) was 7.0 percent, a gain of only 2.0 percent over the moisture content of the boards when they entered the press. As the total press time increased to 400 s, for the schedule E isocyanate-bonded board, out-of-press moisture content fell to 4.3 percent.

The 280 Btu/lb (651 kJ/kg) of steam supplied in schedule B should have raised the moisture content by 24 percent. Much steam escaped through the edges of the mat or was vented through the cauls, however, and the actual mat moisture content of the isocyanate-bonded board showed a gain of only 3.1 percent at the end of the normal 400-s press schedule. The phenolic-bonded boards pressed under the same conditions actually lost an average of 1.3 percent moisture content. In all cases, the phenolic-bonded panels showed a weight loss whereas, with one exception, the isocyanate-bonded panels gained weight during steam-injection pressing.

A technique described by Kamke and Wolcott (1991) was used to estimate the relative humidity and average flake moisture content at the probe locations in the mat during pressing. Initial conditions, along with measured temperature and gas pressure data, were related through a material balance equation. A heat and mass transfer model was then used to predict the flake moisture content (Schajer 1984). Predictions for relative humidity for schedules A, B, and E phenolic-bonded boards are shown in Figure 12. The initial injection of steam in schedules B and E caused saturation of the environment. Some steam condensed when it reached the core of the mat. The predicted relative humidity in schedule B temporarily dropped below 100 percent, indicating some superheated steam had reached the core. The steam injection was stopped at 55 s. Evaporation of condensed moisture in schedule B again caused saturation at 75 s.

Relative humidity declined in the core of schedule A boards during the first 6 min as a result of increasing temperature, with no significant increase in gas pressure. After 6 min, water vapor migrated to the core, increasing both gas pressure and relative humidity. The low temperatures during the beginning of the press cycle allowed small fluctuations in measured gas pressure to cause large changes in relative humidity.

The predicted average flake moisture content in the mat core for schedules A, B, and E are shown in Figure 13. Declining moisture content was predicted for boards made with the conventional press schedule A. Moisture content in the steam-injected mats was predicted to rise sharply during the initial steaming period. The average predicted moisture content of the core flakes in schedule B reached the fiber saturation point at a press time of about 50 s. (At 284°F (140°C), the fiber saturation point of wood is approximately 16 percent.) The surface of the core flakes probably attained the fiber saturation point immediately after the steam was injected. Approximately 4 to 5 percent of free water content was predicted for the core flakes pressed in schedule B. The average flake moisture content in the core of schedule E did not reach fiber saturation. It is interesting to note that the phenolic-bonded boards of both schedules B and E had nearly identical predicted ending moisture contents. This occurred because both environments had nearly identical ending gas pressures and equilibrium moisture content conditions. This demonstrates the importance of gas pressure in relation to changing mat moisture content. The reader is cautioned that these moisture content predictions are for the center-core location only. Overall mat moisture content would be lower because the outer regions of the mat would be drier.

Physical and Mechanical Properties

Physical and mechanical properties for all board types and schedules are given in Table 2. Several factors influenced the results and may have precluded any statistically significant differences between the strength of samples cut from center or corner locations in the boards. These factors were as follows: (1) the screen and frame reduced temperature variation, (2) the press times were relatively long for SIP, and (3) the specimen cluster was large (reducing sharp distinction between defined locations) as a result of the presence of retrievable resin specimens, thermocouples, and pressure transducers.

Phenolic-Bonded Boards

Average internal bond (IB) for the phenolic-bonded schedule B boards exceeded that of the control. Although the difference is not statistically significant, it does indicate that the high temperatures obtained in schedule B overcame any adverse effects of moisture. The IB declined in the other 400-s steam schedule boards as maximum temperatures diminished. The heat added during the short 4-s steam period in schedule E was insufficient for bonding the phenolic board in the scheduled time of 400 s. Press time extensions of 30 percent were necessary to obtain good board properties,

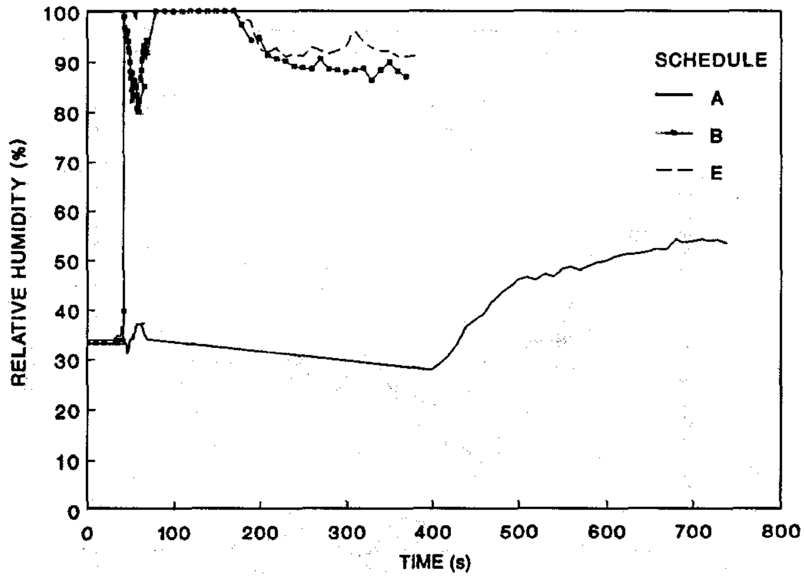

Figure 12—Relative humidity of core location in phenolic-bonded board, schedules A, B, and E.

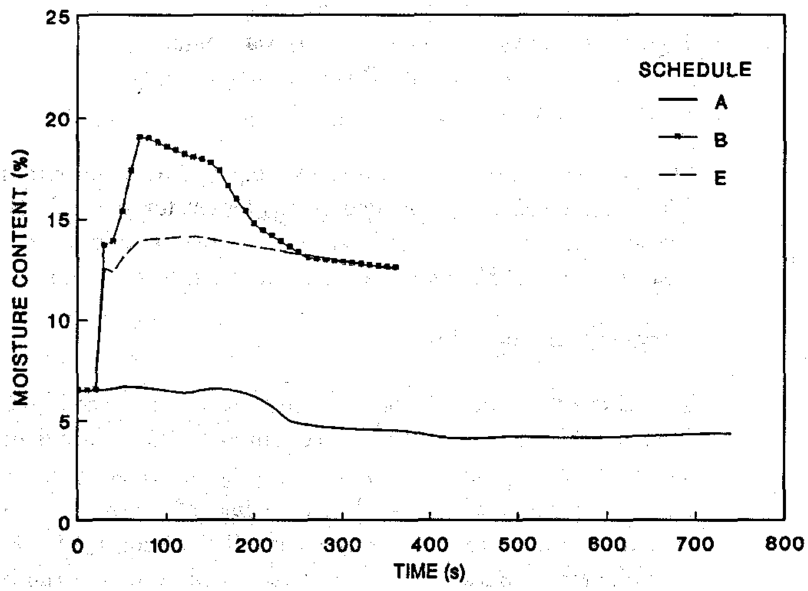

Figure 13—Predicted core flake moisture in phenolic-bonded board, schedules A, B, and E.

indicating that the adhesive properties of the resin had not been destroyed but only retarded by the moisture or low maximum temperatures.

Shear strengths followed the same general pattern as that observed for IB (Table 2). However, bending MOR values of the SIP boards were below those of the conventionally pressed boards. This is attributed to a reduction in the density gradient (Fig. 14). Average bending MOE values improved in SIP schedules B, C, and D. (A significant difference was noted only for schedule C.) We cannot explain why these two bending properties responded differently.

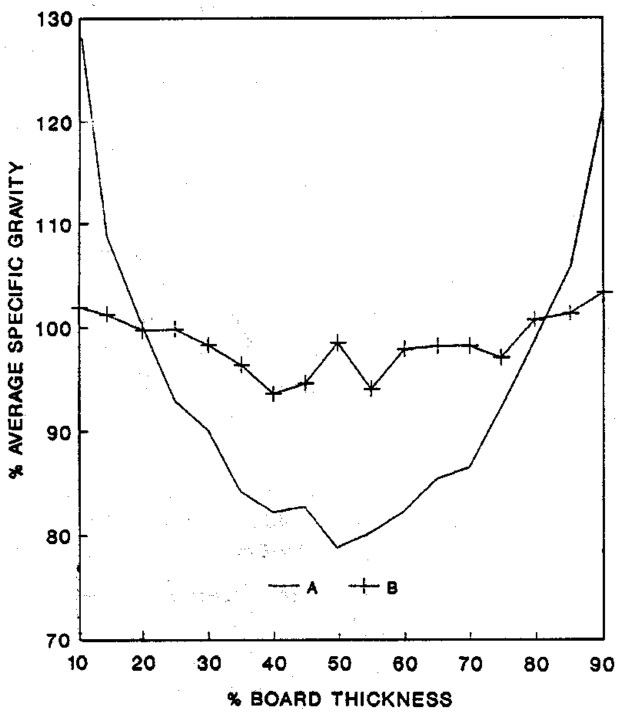

Figure 14—Density gradient for conventional (schedule A) and schedule B isocyanate bonded boards.

Steam injection reduced 24-h thickness swelling in all but the schedule E boards. Thickness swelling of SIP boards was lowest for schedule B boards and increased as the total steam energy diminished. This response is to be expected for steam-treated material (Hsu 1989) and is a function of time and temperature.

Isocyanate-Bonded Boards

The isocyanate-bonded boards were superior to those bonded with phenolic resin. Much of this difference can be attributed to the adhesive qualities of the isocyanates as noted by the difference in IB strengths of the isocyanate- and phenolic-bonded conventionally pressed boards. The IB values of control boards bonded with 4 percent isocyanate were 57 percent stronger than that of control boards bonded with 5 percent phenolic resin. Boards produced with schedule D had the best IB and shear strength properties, possibly as a result of reduced precure. As was the, case for the phenolic-bonded boards, static bending properties were adversely affected by the flatter density gradient common in SIP boards.

Favorable appearance of the isocyanate-bonded boards prompted us to successively reduce press times for all the schedules (Table 2). Reduction of schedule A press time from 775 to 485 s clearly indicated the slow process of heat transfer in a conventionally pressed board and resulted in a 50-percent reduction in IB strength values. Reduction of total press times in the SIP schedules to as short as 200 s, however, did not adversely affect IB or any of the other mechanical properties measured.

Stress Relaxation

The introduction of high temperatures and moisture during press closure plasticizes the wood, reduces the pressure needed to close the press, and alters the vertical density

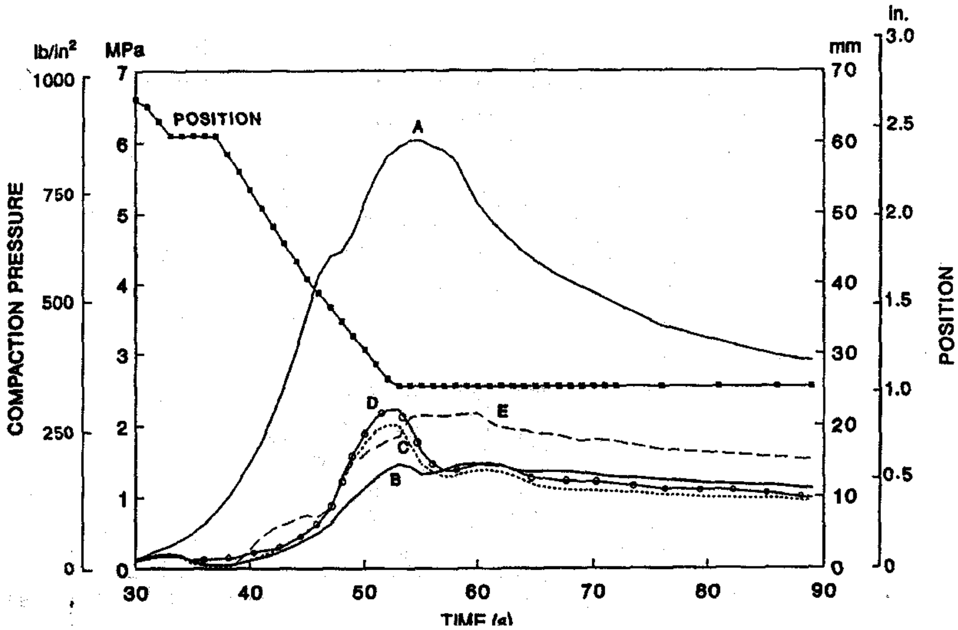

Figure 15—Comparison of compaction pressures for all schedules.

gradient. Compaction (board) pressures for the various steam schedules are compared to those needed in conventional pressing in Figure 15. Maximum compaction pressure in all the SIP boards was considerably less than that needed to press boards in a conventional manner, indicating that the flakes were partially plasticized.

Using procedures described by Wolcott and others (1990), the temperature and vapor pressure data were used to estimate the glass transition temperature of lignin in the core flakes. The difference between the glass transition and measured temperatures indicates that the conditions necessary to plasticize wood (minimum temperatures within ±77°F (±25°C) of the glass transition temperature for lignin) were exceeded for most of the pressing time for all the SIP pressing schedules (Fig. 16). The center-core position in schedule A did not reach the glass transition region until after 4 min, when most closing pressure had dissipated.

The reaction of flakes to rapid environmental changes in the interparticle spaces, such as occurs during SIP, is different from that of particles or fibers under the same circumstances. Core temperatures in 0.5-in.- (12.7-mm-) thick flakeboard are elevated to above 212°F (100°C) in <1 s following steam injection. This same temperature rise in fiberboard of similar thickness is often delayed 4 or 5 s. Closing (board) pressure for fiberboard, however, is reduced to approximately 50 lb/in^2 (344 kPa), considerably less than the 250 lb/in^2 (1,723 kPa) needed to consolidate a flakeboard SIP mat. Considering the short exposure times prior to closing and the time-dependency of moisture and heat movement into the flakes, it is possible that a “plasticization gradient” occurs within individual wood flakes. Softening the outer cells of flakes would significantly reduce their bending stiffness. Besides affecting the dynamics of press closure, these events could significantly affect the bonding characteristics of the adhesive as well as the dimensional stability of the board.

The compaction pressure needed to maintain target thickness during pressing indicates changes in the plaaticization of the constituent particles (Heebink and Hefty 1972). At the end of the venting period, immediately prior to decompression, the board pressure for phenolic-bonded boards made with 400-s schedules B through E was 28, 56,

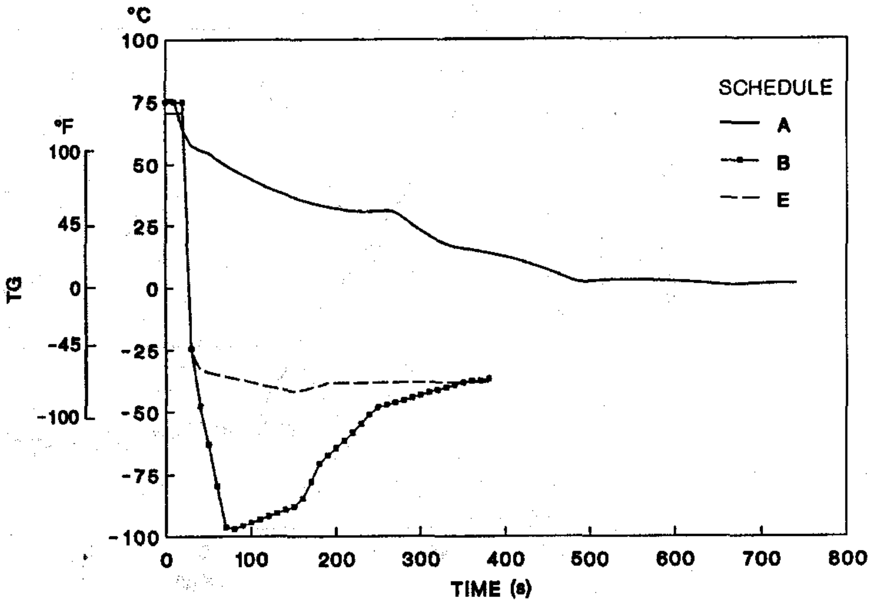

Figure 16—Difference between predicted glass transition temperature (TG) and measured center-core temperature for schedules A, B, and E.

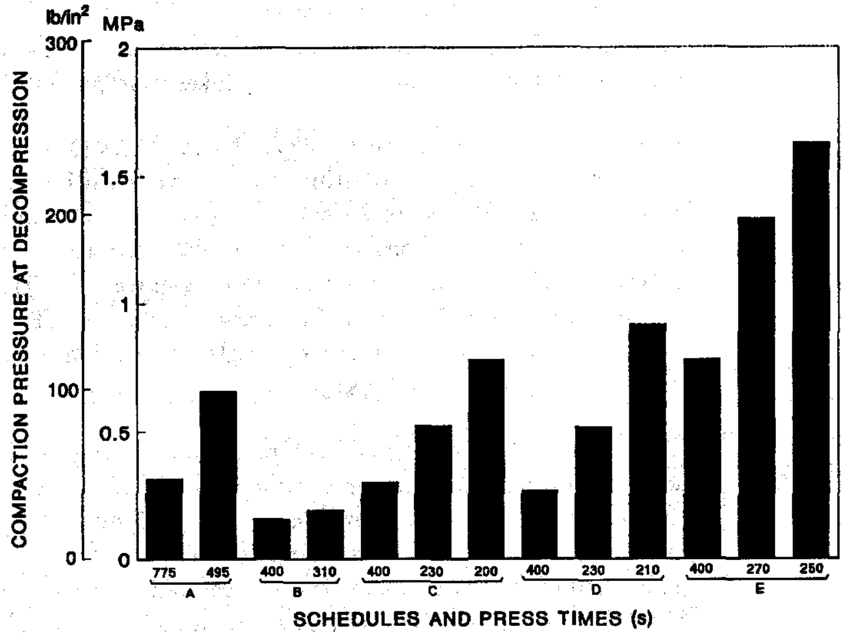

Figure 17—Compaction pressure at decompression time for isocyanate-bonded boards pressed with various schedules. Press times expressed in °F (-32 (0.55)° C).

57, and 111 lb/in^2 (193, 386, 393, and 765 kPa, respectively). At the same time (that is, 325 s into the press schedule), the compaction pressure in the conventional board was 108 lb/in^2 (744 kPa). Compaction pressures at decompression are given for all boards in Table 2 and are shown for the isocyanate-bonded boards in Figure 17. Note the change for those boards subjected to reduced press times. While the residual compaction pressures for the isocyanate-bonded SIP boards increased with a reduction in press times or lower heat input, the IB values remained relatively constant. Assuming that IB is an indicator of adhesive bond strength, bond development had little effect on the magnitude of the residual stresses. This result is also evident in a comparison of phenolic- and isocyanate-bonded boards pressed by schedule E for 400 s. Both of these boards had a similar counterpressure of >100 lb/in^2 (>689 kPa) at the beginning of decompression. The isocyanate board had an IB of 135 lb/in^2 (930 kPa), whereas the phenolic board "blew" or delaminated. Vapor pressure in either board at the start of the decompression cycle was <5 lb/in^2 (<34 kPa), leaving the residual stress as the major source of counterpressure and the prime reason for delamination of the phenolic board. A factor to consider in determining the minimum IB necessary to prevent delamination is the difference between this property, tested at equilibrated conditions, and actual strength at the elevated press temperature and humidity. Of course, this difference could be of different magnitude for phenolic and isocyanate resins.

The interaction of bond strength and counterpressure is very apparent when the press is opened and the compaction pressure is released. Discontinuous adhesive bonds and a random layering of flakes permit the board to spring back (that is, become thicker, in a manner similar to that associated with the unfolding of a honeycomb tissue decoration) until the magnitude of the internal stresses is decreased to that point where they are compensated by resisting forces carried through the adhesive bonds. If the bonds are not strong enough, the board will delaminate. Out-of-press board thickness is given for all boards in Table 2 and is shown for the isocyanate-bonded boards in Figure 18. Note especially the similarity in trends between board thickness (Fig. 18) and compaction pressure at decompression (Fig. 17) for the isocyanate-bonded boards with reduced press times. The significance of this observation is that there is no set level of residual stress at which boards blow. All of these boards had similar IB values. This phenomenon has a direct bearing on the considerable variability often obtained in relating IB strength to density. Of primary importance in considering short press schedules for SIP is the tradeoff among shortened press times, reduction of internal stress, and IB strength. Taylor and others (1985) showed the advantage of applying a vacuum near. the end of the press cycle. The vacuum lowers both the moisture and the temperature of the board, thus reducing stresses and increasing the stiffness of the resin.

Conclusions

Heat and moisture transfer into a steam-injection-pressed (SIP) board is extremely fast as compared to that in conventional boards. Temperatures above 212°F (100°C) were obtained throughout a 1-in.- (25.4-mm-) thick SIP board in less than 4 s following the introduction of steam. Vapor pressure variations of >30 lb/in^2 (>206.8 kPa) were observed in different board locations for short periods during the steaming period. Increasing and decreasing vapor pressures occurred simultaneously in different board locations as the pressures tended to equalize.

Resin curing and bonding in a SIP flakeboard occur for the most part under saturated conditions. An exception is a short but important period after press closure when the measured temperature is less than that predicted by the measured vapor pressure. This difference is thought to be primarily caused by an increase in measured pressure values resulting from the presence of hydraulic pressure of condensed steam. The additional moisture of steam injection retards the development of board properties, either by slowing the bonding rate or limiting core temperature. Evidence presented here indicates that acceptable board properties may be rapidly-obtained if temperatures exceed 302°F (150°C). Acceptable phenolic-bonded boards were obtained at lower temperatures by extending press times. Isocyanates responded very well to the environmental conditions of SIP. In general, the flatter density gradient characteristic of SIP

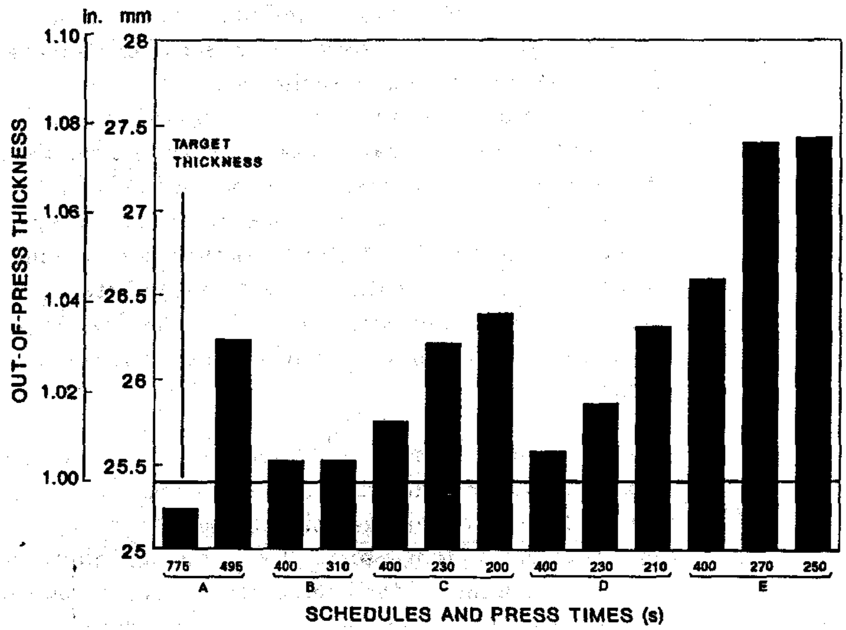

Figure 18—Out-of-press board thickness of isocyanate-bonded boards pressed with various schedules. Press times expressed in °F (-32 (0.55)°C).

improved internal bond and lowered bending strength. Reduction of thickness swelling observed in SIP boards was proportional to the degree of steaming.

All SIP boards required substantially less compaction pressure than did conventionally pressed boards. Because of the short press closure time, it is possible that only the outermost layers of the individual flakes are initially plasticized. Compaction pressure needed to maintain board thickness is primarily dependent on flake plasticization and the resultant stress relaxation, and only slightly affected by adhesive curing and bonding. Out-of-press-thickness springback varies directly with the compaction pressure needed to maintain thickness. The board increases in thickness until the internal flake stresses are reduced and counterbalanced by forces carried through the adhesive bonds. If the bond strength between flakes is low, delamination may occur. The data derived from this study indicate that delaminations may occur at very low vapor pressures.

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