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Evaluation and Performance Assessment of Innovative Low-VQC Contact Adhesives in Wood Laminating Operations

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FOREWORD

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Executive Summary

The purpose of this research project was to evaluate and assess the performance, economics, and emission reduction potential upon application of low-volatile organic compound (VOC) waterborne contact adhesive formulations specifically in a manual laminating operation for assembling store fixtures.

The primary objective of this project was to determine whether three waterborne contact adhesives could achieve adhesion performance levels equivalent to, or exceeding that of, a currently used solvent-borne contact adhesive while emitting lower VOCs and/or hazardous air pollutants (HAPs) upon application. Two secondary objectives were to determine the relative cost of using each alternative contact adhesive as compared to the currently used product (hereinafter called the "Control"), and to estimate the emission reduction potential from the use of each alternative adhesive.

The evaluation facility hosting this research wants to meet a long-term VOC regulation required by its state's Industrial Adhesives Reasonably Available Control Technology regulation. The regulation states that, as of July 1, 1996, facilities using adhesives or adhesive primers in the production of wood furniture, wood office partitions, or wood entry or passage doors must comply with a short-term VOC emissions limit. This limitation states that the adhesive/adhesive primer must have a solids content greater than or equal to 23 percent by weight, as applied. By May 1, 1999, however, facilities must meet a long-term emissions limit by using an adhesive/adhesive primer that does not emit VOCs in excess of 540 g/L (4.5 lb/gal), excluding water.

Since the facility wants to comply with the long-term emissions limit of 540 g/L (4.5 lb/gal) VOC content, they must find an alternative adhesive that they can use in their operation that will meet not only this limit but also several other criteria, including cost-effectiveness, nonflammability, and ability to achieve performance requirements demanded by customers. Thus, in cooperation with EPA, this research project assisted this small business in evaluating several alternative contact adhesives using the above criteria.

Results from the evaluation show that the actual and theoretical VOC emissions resulting from the use of the waterborne adhesives were significantly lower than the emissions resulting from the use of the Control. Actual applied VOC emissions per side measured in this evaluation averaged about 30.3 g/m^2 (2.8 g/ft^2) for the waterborne products compared to 143 g/m^2 (13 g/ft^2) for the solvent-borne Control.

Furthermore, the waterborne adhesives were applied at application rates higher than recommended by the manufacturer's rates, and the Control was applied at a lower rate than recommended by the manufacturer. If the adhesives were applied at the generic application rates recommended by the manufacturers then, theoretically, the VOC emissions from the application of the waterborne products would have averaged approximately 13 g/m^2 (1.2 g/ft^2) as compared to the Control at 207 g/m^2 (19.2 g/ft^2). However, discussions with adhesive vendors indicated that wide variations in the amount of dry solids applied would not have an appreciable effect on performance.

Based on the quantity of adhesive used during the evaluation, all waterborne products ranged from approximately 4 to 10 times more costly per m^2 to use than the Control. Note that these costs were calculated on the basis of the cost for the adhesives and did not include costs for labor, application equipment, environmental compliance, etc. Again, if the adhesives were applied at the generic application rates recommended by the manufacturers, then the cost of using the waterborne products would have ranged from approximately $0.22/m^2 to 0.55/m^2 ($0.02/ft^2 to 0.05/ft^2) versus the Control at $0.31/m^2 ($0.03/ft^2) based on adhesive cost only.

The operator who applied the adhesives in this evaluation was unfamiliar with the use of waterborne adhesives and the use of high-volume, low-pressure (HVLP) spray technology. Although attempts were made to follow the spray equipment manufacturers' recommendations, this research suggests that the operator's familiarity with the waterborne adhesive products and application equipment can substantially affect the cost and VOC emissions associated with the adoption of a new product.

This report was submitted in partial fulfillment of EPA Cooperative Agreement No. CR-824 152 by Research Triangle Institute under the sponsorship of the U.S. EPA. This report covers a period from October 1995 to October 1997, and work was completed October 1997.

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Project Description

1.1 Overview

The purpose of this research project was to evaluate and assess the performance, economics, and emission reduction potential upon application of low-volatile organic compound (VOC) waterborne contact adhesive formulations specifically in a manual laminating operation for assembling store fixtures.

The primary objective of this project was to determine if three waterborne contact adhesives could achieve adhesion performance levels equivalent to, or exceeding that of, a currently used solvent-borne contact adhesive while emitting lower VOCs and/or hazardous air pollutants (HAPs) upon application. Two secondary objectives were to determine the relative cost of using each alternative contact adhesive as compared to the currently used control, and to estimate the emission reduction potential from the use of each alternative contact adhesive.

Research Triangle Institute (RTI) worked in cooperation with the U.S. Environmental Protection Agency's (EPA's) Air Pollution Prevention and Control Division to coordinate this evaluation study with (1) a store fixture manufacturing facility, (2) four contact adhesive suppliers, and (3) an independent testing laboratory.

Results obtained from this study are intended to be used by facilities in the store fixture laminating industry in their examination of low-VOC contact adhesives for their operations. Test results from this evaluation will facilitate technology transfer of nonproprietary information to other businesses facing similar emissions issues. The use of low-VOC contact adhesive formulations by manufacturers of various laminated products to replace solvent-based contact adhesive formulations could ultimately reduce the national VOC emissions from this industry.

1.2 Background

Over the past several years, manufacturers have been increasing the use of adhesives to replace mechanical fasteners for industrial bonding. Manufacturers prefer adhesives for sensitive substrates such as plastics where material stress must be distributed evenly to prevent failure. By the year 1998, U.S. sales of adhesives and sealants are expected to reach $26.5 billion, with an average annual growth in sales of 10.6 percent between 1988 and 1998.

In wood furniture manufacturing, manufacturers with lamination operations are realizing that the most common cause of solvent emissions to the atmosphere are from the use of, specifically, contact adhesives in these operations. In general, contact adhesives are defined as adhesives that are dry to the touch in a relatively short period of time and that instantaneously adhere to themselves upon contact (McIlrath, 1993). These adhesives are used for laminating high-pressure laminate and low-pressure laminates to various substrates. They are fast-bonding adhesives used to manufacture kitchen cabinets, household and office furniture, and store fixtures.

Many contact adhesives are formulated with solvents that are classified as VOCs or HAPs, and these solvents can represent more than 80 weight percent of the adhesive. Some solvents commonly used in formulating contact adhesives are hexane, methyl ethyl ketone, toluene, and methylene chloride, all of which are VOCs and/or HAPs (Crumpler, 1996). Depending upon the application method employed, cleanup activities generate hazardous waste materials that require special disposal.

From an emissions standpoint, in 1995, the national solvent utilization emissions of industrial and non-industrial adhesives were 370,000 and 346,000 metric tons (407,000 and 380,000 short tons), respectively.[1] These emissions combined represent 12.4 percent of the total emissions from solvent utilization, which were 5,819,000 metric tons (6,394,000 short tons) in 1995.

To control emissions from the use of adhesives, manufacturers employ conventional end-of-the-pipe control and treatment methods and systems, which can potentially be difficult to operate and expensive to install. As an alternative approach, manufacturers have the option of converting to currently available low- and no-VOC/HAP adhesive formulations. However, manufacturers are reluctant to make this kind of change because of concerns related to the alternative materials meeting or exceeding cost and performance requirements of their current products.

The focus of this project, then, was to evaluate low-emitting alternative adhesives that will aid in the reduction of national VOC and HAP emissions from the use of contact adhesives in laminating operations. Specifically, this project focuses on evaluating alternative waterborne contact adhesives in the manufacture of retail store fixtures.

1.3 Store Fixtures Manufacturing

Manufacture of retail store fixtures involves forming and attaching several types of laminates to particleboard or medium-density fiberboard substrates using contact adhesives. Examples of laminate materials used to make store fixtures include melamine-impregnated papers, vinyl, top-coated papers, and high-pressure laminates. Examples of retail store fixtures include refund counters, layaway department counters, and sunglass stands. During assembly, both the laminate and substrate surfaces are coated with a contact adhesive and allowed to dry, or cure, by air-drying, force-drying, or applying heat through an external source. The laminate and substrate are then pressed together manually or mechanically using a rotary press or nip roller to form a final bond (Choosing the Right Laminating Adhesives, 1988).

Many facilities that laminate wood products together with contact adhesives are looking for alternatives to their current solvent-based contact adhesives in order to meet local, state, and Federal regulations. These facilities are interested in alternatives that not only meet regulations but also perform as well as, or better than, what they are currently using. Performance requirements include strength of adhesion to both substrates, dry time, application time, low VOC content, and comparable costs to currently used contact adhesives.

[1] English units are prevalent in this industry. However, metric units are used throughout this report. For the reader's convenience, a table is provided in Appendix A for converting Metric units to English units.

1.4 Evaluation Facility

The evaluation facility hosting this research was a store fixtures manufacturer located in Manitowoc, Wisconsin. This facility has been operating as a custom manufacturer of retail store fixtures since October 1992. Their manufacturing space is approximately 2,044 m^2 (22,000 ft^2). The facility operates 8 hours per day, 5 days per week, 260 days per year with a work force of 27 employees. With respect to laminating activities, approximately 98 percent is performed in-house.

Before products can be laminated, the substrate and laminate must be cut to predetermined dimensions. Substrate and laminate cutting and laminating operations are described below.

1.4.1 Substrate and Laminate Cutting

Substrate (herein referred to as board and/or substrate) is typically received at the facility in bulk in what are called units. Each unit contains 35 sheets of boards each 1.22 m wide, 3.05 m long, and 0.02 m thick (4 ft by 10 ft by ¾ in). These units are placed in temporary storage until they can be cut into desired sections on a front loading beam saw. At the beam saw, operators manually feed three sheets of boards at a time stacked on top of each other to the saw which cuts the boards to predetermined dimensions. Since the machine is manually operated, only six units, or 210 sheets, can be cut per 8-h shift.

The front loading beam saw is controlled by a computer which receives programming instructions for cutting dimensions from a computer in the engineering department located in the main office area of the facility. In addition, an operator manually enters additional information into the computer pertaining to substrate type, cut size, etc., for printing identification labels for each set of cut boards. The labels are then applied to the cut boards, indicating where the stack should be sent next for processing.

Laminate is shipped to the facility in a similar fashion as the substrate. However, laminates are supplied in many different shapes, colors, and varieties. They are made from Formica, melamine, vinyl, or paper.

1.4.2 Laminating

Laminating activities primarily consist of Formica topping. Formica topping is performed manually by two operators who apply adhesive and attach Formica laminates to particleboard or medium-density fiberboard substrates. Figures l-l and l-2 illustrate the laminating operation.

This process typically requires two operators. One operator cleans the surfaces of the board and laminate and applies adhesive to one side of the board and to the opposing side of the laminate. Adhesive application is performed by using a conventional air spray gun to apply a solvent-borne contact adhesive. The adhesive is typically nearby and is supplied fed to the spray gun from a 208-L (55-gal) drum. After adhesive is applied to the board and laminate, both substrates are set aside and the adhesive is allowed to air-dry for approximately 30 min. Then, the second operator attaches the laminate to its corresponding board by pressing the two surfaces firmly together. This operator uses a hand-held, 5-cm (2-in)-diameter roller as a final press. The formed piece is typically allowed to air-dry for approximately

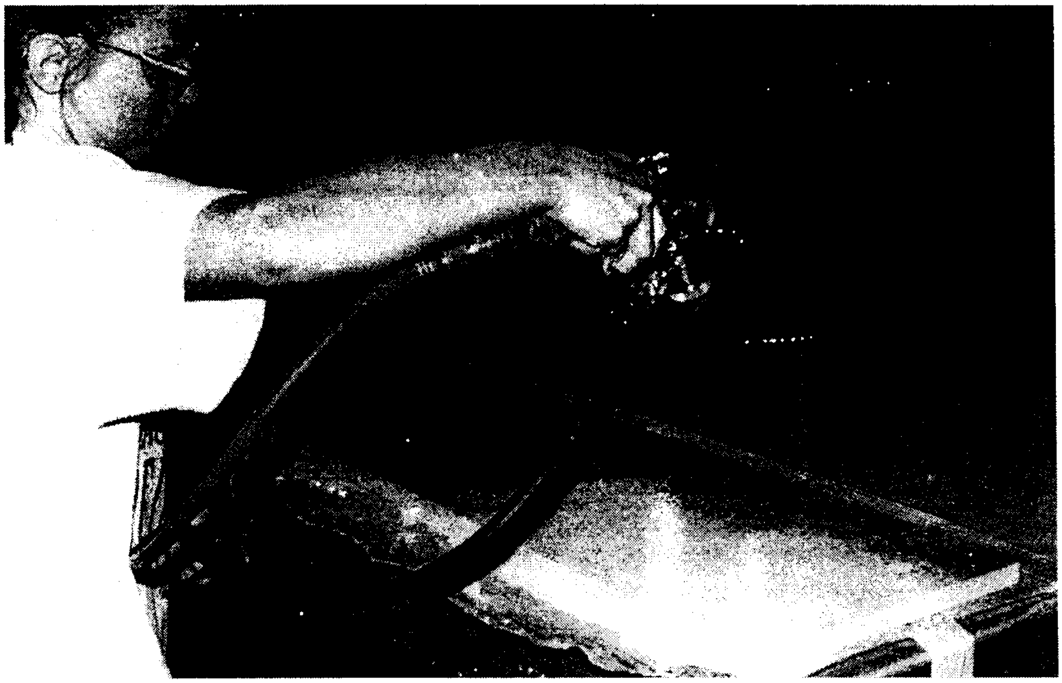

Figure 1-1. Operator spraying adhesive onto board.

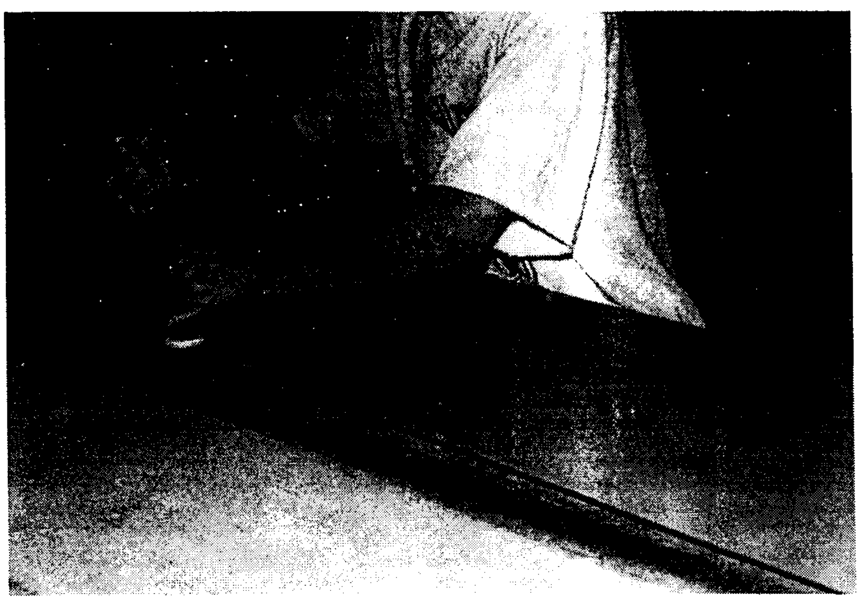

Figure 1-2. Operator laminating Formica to substrate using a 5-cm diameter roller.

24 h before being sent to another station for assembly.

1.4.3 Facility Experience with Alternative Adhesives

The facility has experimented with several water-based contact adhesives over the past year and a half, but none of these products dried quickly enough nor did they retain their adhesion to the substrate. One product they evaluated in-house was a solvent-based adhesive having a VOC content of 610 g/L (5.1 lb/gal). However, this facility wants to meet the long-term VOC regulation required by their state's Industrial Adhesives Reasonably Available Control Technology (RACT) regulation. The regulation states that, as of July 1, 1996, facilities using adhesives or adhesive primers in the production of wood furniture, wood office partitions, or wood entry or passage doors must comply with a short-term VOC emissions limit. This rule also states that the adhesive/adhesive primer must have a solids content greater than or equal to 23 percent by weight, as applied. By May 1, 1999, however, facilities must meet a long-term emissions limit by using an adhesive/adhesive primer that does not emit VOCs in excess of 540 g/L (4.5 lb/gal), excluding water.

Since the facility wants to comply with the long-term emissions limit of 540 g/L (4.5 lb/gal) VOC content, they have been looking for an alternative adhesive that they can use in their operation that will meet not only this limit, but also meet several other criteria, including cost-effectiveness, nonflammability, and the ability to achieve performance requirements demanded by their customers.

Thus, in cooperation with EPA, this research project assisted this small business in evaluating several alternative contact adhesives using the above criteria.

Section 2.0
Materials and Methods

This section describes the materials and methods used to evaluate the three alternative waterborne contact adhesives as compared to the currently used solvent-borne adhesive, or Control. A discussion of materials, measurements, and evaluations is included. Each is described below.

2.1 Materials

Three types of raw materials were used in this evaluation: adhesives, boards, and laminates.

2.1.1 Adhesives

The adhesives evaluated consisted of three waterborne contact adhesives and the Control. Selection of the alternatives was based on the ability of each to meet the following criteria:

- Contain less than 540 g/L (4.5 lb/gal) of VOC;
- Applicable to Formica topping or laminating;
- Commercially available; and
- Willingness of vendors to provide samples of, and technical information on, each adhesive.

Two of the three contact adhesives were single-component waterborne, and one was a two-component waterborne. The Control was a single-component solvent-borne contact adhesive. A summary of each adhesive is shown in Table 2- 1. A 19-L (5-gal) container of each adhesive was requested from each vendor for the evaluation.

2.1.2 Boards

Boards most commonly used at this facility consist of industrial-grade particleboard and medium-density fiberboard. The most common type of board is 20-kg (45-lb) density particleboard, which makes up 95 percent of incoming stock. 20-kg (45-lb)-density particleboard was used as the substrate in this evaluation. Four sheets of 3.05 m wide, 3.05 m long, and 1.91 cm thick (10 ft by 10 ft by ¾ in) were cut into 10, 1.22 m wide, 3.05 m long, and 1.91 cm thick sheets (4 ft by 10 ft by ¾ in) to provided a total of 40 boards for the evaluation. See Table B-2 in Appendix B to see how these 40 test boards were distributed for the evaluation.

2.1.3 Laminates

The laminate evaluated consisted of Formica. Formica laminates were taken from a common lot, pre-cut to dimensions slightly larger than the boards to which they were to be laminated.[2]

[2] Laminate is always cut larger than the substrate to which it is applied so that an even edge can be achieved on all sides after cutting away and sanding of excess laminate.

Table 2-1. Contact Adhesives Evaluated [a]

	Adhesive 1		Adhesive 2	Adhesive 3	Control
Generic description	Waterborne, two-component		Waterborne, single-component	Waterborne, single-component	Solvent-borne, single-component
Resin base	Polychloroprene		Neoprene	Rosin/terpene-phenolic	Polychloroprene and phenol
	Part A [b]	Part B [c]			
Density, g/L	1,126 - 1,174	1,066 - 1,114	1,102	1,076	755
Solids, weight percent	47-51	15 - 19	53.5	45	17.5
Volatile types	Water	Water, toluene, methanol	Toluene, water	Toluene, water	Acetone, n-hexane, hexane isomers, and toluene
Manufacturer's reported volatile content, g/L [d]	- 0	< 60	70 - 75	43	623
Dry time, min	0.25 - 60		30	15 -30	15

[a] Properties shown were taken from material safety data sheets and/or technical data sheets for each adhesive. Each adhesive was supplied by a different adhesive manufacturer.
[b] Part A of Adhesive 1 is the activator for the adhesive of Adhesive 1. It is a zinc solution.
[c] Part B is the adhesive.
[d] Volatile content includes water and any exempt compounds.
1 lb/gal = 119.8 g/L.

2.2 Measurements

During application of each adhesive, the following measurements were taken:

- Initial and final weights of each board, laminate, and board/laminate assembly;
- Initial and final weights of adhesive used during application to both boards and laminates;
- Application time, including adhesive application and assembly;
- Temperature and percent relative humidity during application and curing; and
- Dry time of the assembled boards/laminates.

Weights of the boards, laminates, and the amount of adhesive used for each adhesive applied were measured using a Sartorius 16000S floor scale, with a capacity of 16 kg (35 lb) and a readability of 0.1 g (0.022 lb). Application and dry times were recorded with a wrist watch to the nearest minute. Temperature and percent relative humidity were measured at periodic intervals during each adhesive application with a TSI VelociCalc, Model 8360 velocity meter rented from Response Rentals, Inc. (temperature range -10 to 60°C [14 to 140°F] with a resolution of 0.1°C [0.2°F] and an accuracy of ±0.28°C [0.50°F]; relative humidity ranges from 20 to 95 percent with an accuracy of ±4 percent).

No adjustments to these environmental conditions were made during the evaluation; however, environmental conditions were monitored to determine if application conditions fell within each adhesive vendor's recommendations. If conditions fell outside the recommended environmental conditions and specifications, the dry times for each adhesive could have been negatively affected and could have taken longer to dry than claimed by the vendors.

Contact adhesives used by the facility are spray applied using conventional air spray techniques. Since the facility's long-term business goals are to convert to high-volume, low-pressure (HVLP) spray technology, their current spray equipment, conventional air spray, was not used in this evaluation. Instead, a local BINKS vendor supplied a new BINKS Mach 1 HVLP spray gun with appropriate fittings, new 1 S-m long, 2-cm-diameter (5-ft, %-in) hoses, and a BINKS Model 80228 1.9-L (2-qt) pressure pot. A separate hose was used for each adhesive to eliminate contamination between contact adhesives. The spray gun and pressure pot were cleaned between adhesive applications with a cleaning solvent recommended by each adhesive manufacturer and allowed to air-dry. Figures 2-1, 2-2, and 2-3 show the facility's conventional air spray gun, and the HVLP spray gun and pressure pot used in the evaluation, respectively.

For application of each adhesive, the facility selected an operator with 5 years of experience spraying solvent-borne adhesives using conventional air spray technology. The operator had no experience using HVLP spray technology. Thus, efforts were made to meet manufacturer recommendations for the HVLP spray equipment settings and handling for each adhesive. To facilitate this transition, the adhesive manufacturers furnished numerical values and other specific information on each of their adhesives for each of the following variables:

- Complete procedures for adhesive set up and use instructions;
- Parameters during adhesive application (e.g., rate of spread of film, number of coats applied, environmental conditions); and
- Recommended curing times and conditions.

2.3 Evaluations

Each adhesive evaluated was applied to several pairs of test boards and laminates. Then they were laminated together and allowed to air-dry for approximately 24 h. Performance of each adhesive was then evaluated on samples from the laminated assemblies using the following observations/evaluations:

- Onsite subjective peel test;
- Offsite cyclic temperature-exposure test;
- Offsite peel strength evaluation; and
- Offsite determination of each adhesive's physical properties.

Appendix B provides detailed descriptions of test preparations and measurement procedures used to obtain gravimetric and environmental data at the facility.

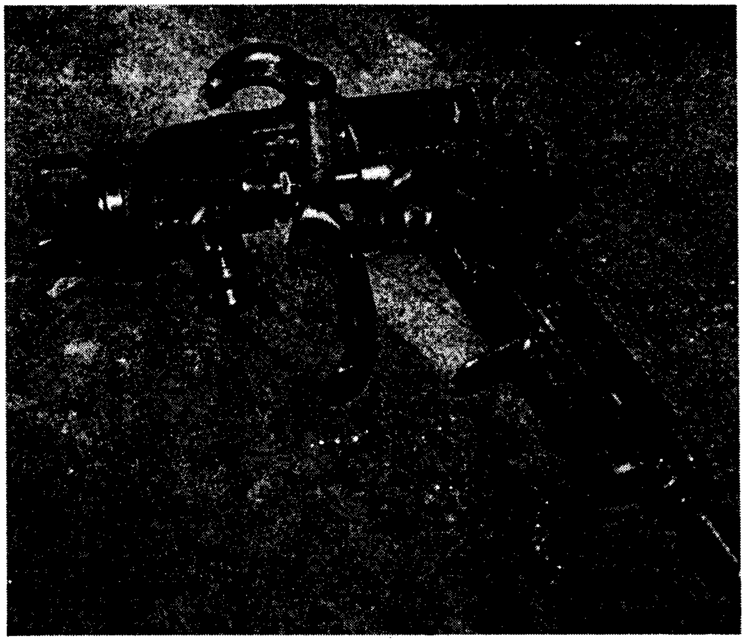

Figure 2-l. Picture illustrating the facility's conventional air spray gun.

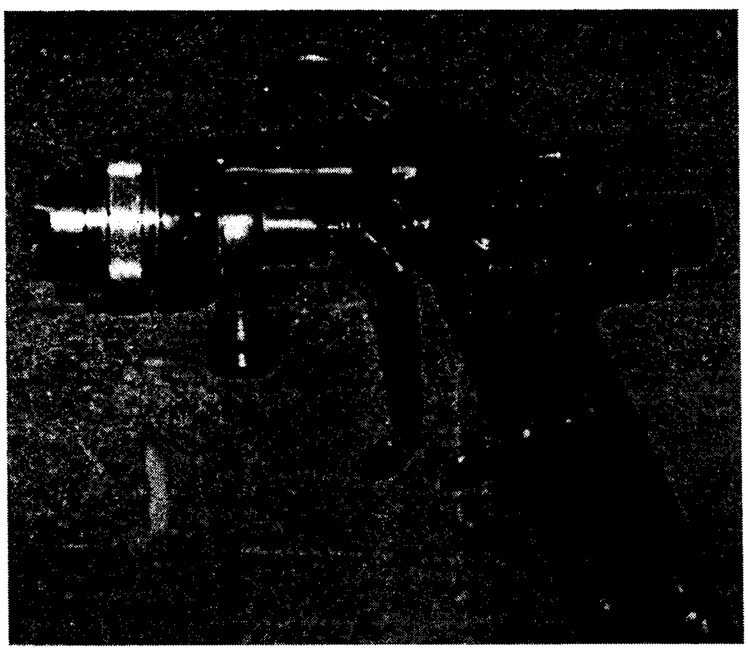

Figure 2-2. Picture illustrates the BINKS Mach 1 HVLP gun used in the evaluation.

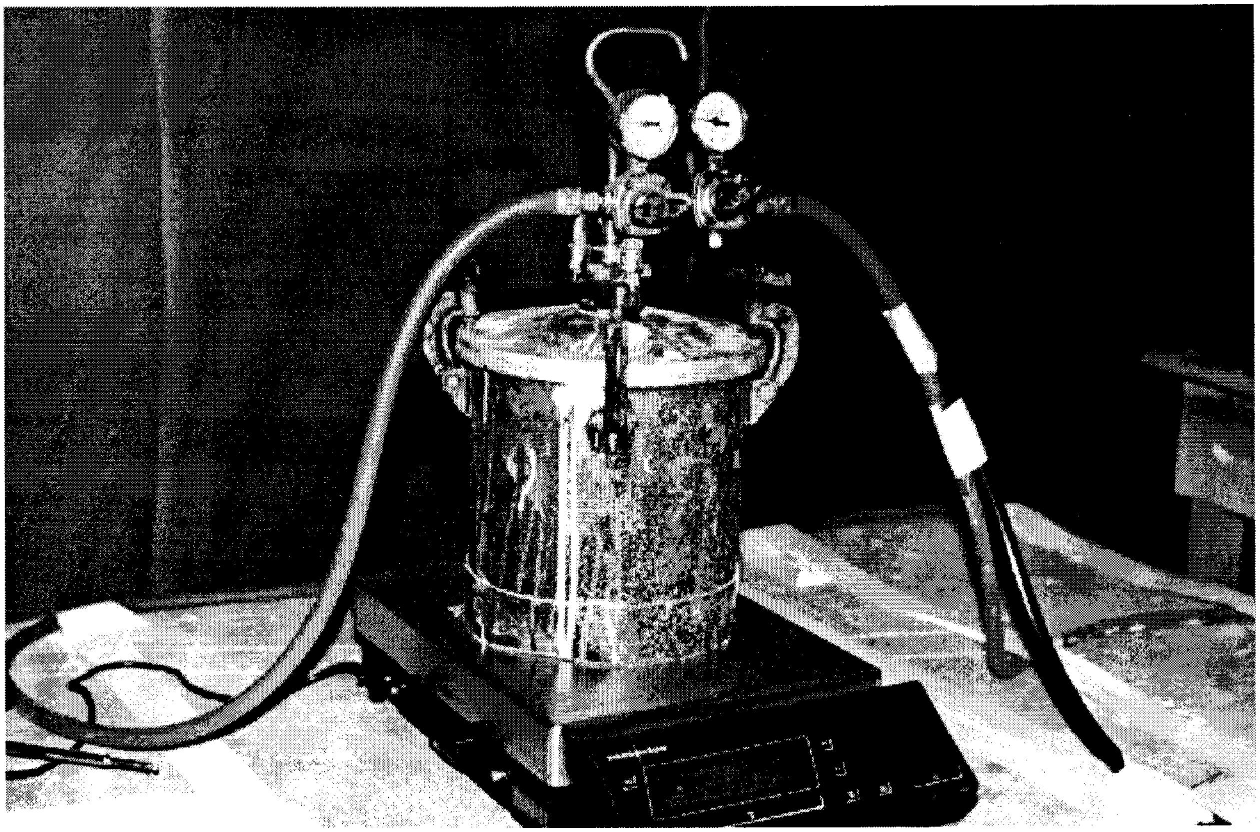

Figure 2-3. Weighing of pressure pot used in the evaluation.

2.3.1 Onsite Subjective Peel Test

The subjective evaluation of test samples was conducted at the facility approximately 24 h after adhesive application. This test is normally conducted at the facility as part of their routine quality assurance check of assembled products. It consists of manually peeling back the laminate from the board to observe how easily it can be pulled back and to count the number of strands remaining on the pulled laminate. A strand is a piece of particleboard that is removed from the substrate and remains on the laminate due to the adhesion strength of the adhesive. Figure 2-4 illustrates this concept. Figure 2-5 is a piece of pulled laminate from one of the Control samples showing what the plant manager looks for in terms of number of strands.

Figure 2-4. Example of how one manually checks for strands between laminate and substrate.

Figure 2-5. A piece of pulled laminate from one of the Control samples illustrating what the plant manager looks for in terms of number of strands.

2.3.2 Offsite Cyclic Temperature-exposure Test

Four sample boards from each adhesive set (A#S(l-4)A and B) for temperature exposure testing were packaged at the facility and shipped to RTI's Analytical and Chemical Sciences (ACS) research laboratory, where they were immediately unwrapped and placed in stainless steel cans and sealed. These cans contained both the control samples (A#S(1-4)A) and exposure samples (A#S(l-4)B) in separate cans, respectively. The test samples were preconditioned for 7 days at 50 ±2 percent relative humidity and 23 ±1°C (73 ±1.8°F) before being placed in an incubator for cyclic, temperature-exposure testing. The control samples remained in the control environment throughout the test.

The preconditioned samples were subjected to two 24-h exposure cycles, cold then hot, at conditions specified in Table 2-2.

Table 2-2. Exposure Test Conditions

Exposure cycle	Temperature, °C	Moisture conditions
Cold	0	Freezer, uncontrolled humidity
Hot	49	Open, uncontrolled humidity

1 °F = 0.6°C.

2.3.3 Offsite Peel Strength Evaluation

The remaining test samples were packaged and shipped to SGS US Test Corporation, in Fairfield, New Jersey, for peel strength evaluation of adhesive bonds using the American Society for Testing of Materials (ASTM) Test Method D 903-93. An Instron Universal testing machine, Model TTC, S/N 4384 was used with a 454 kg (1,000 lb) load cell on a 9 kg (20 lb) range, S/N 315 (load cell accuracy is ±1 percent). See Appendix C for a summary of this test method.

2.3.4 Offsite Determination of Each Adhesive's Physical Properties

To determine each adhesive's physical properties, triplicate samples of each adhesive were obtained. Before adhesive application, an operator thoroughly mixed each 19-L (5-gal) container of adhesive. After opening each adhesives container, the operator took three grab samples from the center of each container using 500-mL (17-fl-oz.) amber sample jars with sealing lids. These jars were supplied by VWR Scientific. These samples were packaged and shipped to RTI's analytical laboratory and were analyzed in triplicate for total volatiles, non-volatile content, water content, and density of each adhesive. The analyses were conducted according to the standard test methods shown in Table 2-3. See Appendix C for summaries of these test methods.

Physical property data were used to determine the secondary objectives of this evaluation, determining VOC emissions as applied and relative costs of each adhesive as applied. These estimates were calculated using each adhesive's percent solids by weight, and total weight loss of each adhesive during application. Weight loss per adhesive was determined by recording the weight of the adhesive

Table 2-3. Physical Analysis of Adhesive Samples

Physical Property	Analysis Method	Method description
VOC content	EPA Method 24	Determination of volatile matter content, water content, density, volume solids, and weight solids of surface coatings
Nonvolatile content	ASTM D 1489-93	Standard test method for nonvolatile content of aqueous adhesives
Water content	ASTM D 3792-79	Standard test method for water content of water-reducible paints by direct injection into a gas chromatograph
Density	ASTM D 187.590	Standard test method for density of adhesives in fluid form

in the pressure pot before and after each adhesive was applied to each board and laminate. The sum of the adhesive usage for each board and laminate assembly was used in calculating VOC emissions.

See Appendix D for all weight test data, and VOC equations and examples. See Appendix E for test results of physical property testing.

Section 3.0
Results

This evaluation of three low-VOC waterborne contact adhesives and a solvent-borne Control took place over a test period of 3 days at a store fixtures manufacturing facility in Manitowoc, Wisconsin The ambient air temperature and percent relative humidity in the test area were monitored at periodic intervals during adhesive application. The average temperature was 24°C (75 “F) and the average percent relative humidity was 47 percent. These application conditions fell within the range of each adhesive manufacturer’s specifications.

This Section includes results from the on-site peel observation, off-site peel test, and the temperature exposure test; adhesive dry times and total application times, and adhesive usage; and a discussion of emission estimates, estimated costs of alternative adhesives, and data quality. Results from each test are described below.

3.1 On-Site Peel Observation

The on-site peel observation was conducted by the plant manager on assemblies labeled A#S5O through A#S9 approximately 18 to 22 h after adhesive application and lamination. To determine the results of the peel test, each assembly was given a pass/fail rating by the plant manager. Table 3-l shows which adhesives passed and which failed for each set of tested assemblies.

Table 3-1. Subjective Peel Test Results

Assembly Number	Adhesive 1	Adhesive 2	Adhesive 3	Control
A#S5O	Pass	Pass	Fail	Pass
A#S6O	Pass	Pass	Fail	Pass
A#S7O	Pass	Pass	Fail	Pass
A#S8O	Pass	Pass	Fail	Pass
A#S9O	Pass	Pass	Fail	Pass

The alternative waterborne adhesives, Adhesives 1 and 2, and the Control adhesive passed the subjective peel test at the facility. Every laminate fully delaminated from each test assembly for Adhesive 3. However, with longer cure times, this adhesive did achieve adequate peel strength (See Section 3.2 discussion).

3.2 Peel Strength Test

Peel strength testing was conducted at SGS US Test Corporation in Fairfield, New Jersey. This laboratory conducted a peel strength test using ASTM Method D 903-93 on each of the five test samples from test board 10 of each adhesive set. Test method D 903-93 is designed for a flexible laminate that can be pulled back at a 180” angle. Because the Formica laminate used in this test was somewhat inflexible, the testing laboratory had to modify this test. The testing facility found that the samples were too stiff to be pulled back at a 90” angle as specified by the ASTM test method. Thus, the samples were adjusted to a 22” angle to the horizontal to keep the laminates from cracking across their widths. The rate at which the testing apparatus pulled each laminate back was 30 cm/min (12 in/min). Ambient conditions were 23 °C (73°F) and 50 percent relative humidity. The results from the peel strength test are shown in Table 3-2.

Table 3-2. Peel Strength Test Results

	Adhesive 1	Adhesive 2	Adhesive 3	Control
Average Peel Strength, kg/30 cm/min	6.4 [a]	3.6	6.9	3.4 [b]

[a] The laminate for test sample 1 cracked before the true peel strength could be measured. The result was not included in the average shown.
[b] The laminates for test samples **2, 3,** and **4** cracked before the true peel strength could be measured. The results were not included in the average shown.
1 lb = **0.454** kg.

In comparison to the Control, all of the adhesives had equal or better peel strengths. Adhesives 1 and 3 had peel strengths of about twice the control, indicating a stronger bond than the Control adhesive. As discussed above, Adhesive 3 had failed with the subjective peel strength tests conducted at the facility after a 24-hour cure. In that test, each test sample for Adhesive 3 failed, delaminating completely from each board. The reason for this difference could be attributed to the length of cure time of more than four weeks between the sample leaving the facility and testing. It was beyond the scope of this study to determine how long a cure period at ambient or higher temperatures would be required for Adhesive 3 to reach adequate peel strength.

3.3 Temperature Exposure Test

At the end of the temperature exposure testing period (See Section 2.3.2), the exposed test samples were allowed to reach room temperature. After reaching room temperature, the evaluation facility’s plant manager performed a subjective peel test on the exposed test samples and compared their performance with the performance of their corresponding conditioned samples. Table 3-3 shows the results of the plant manager’s observations.

Overall, the plant manager determined that the Control matched normal peel tests conducted at the facility. However, one control test board, ASS3B, delaminated completely after prying of the edges indicating a weak adhesive bond between the board and laminate. For Adhesive 1, the plant manager did not find a difference between the conditioned and test samples. The bond was determined to be sufficient for a passing rating and comparable to the Control. All of Adhesive 2’s conditioned and exposed test samples fully delaminated and were determined to have no difference in manual peel strength. Adhesive 3 was determined to have no difference in manual peel strength between the conditioned and exposed samples, except that it had a weaker bond than Adhesive 1, but a stronger bond than Adhesive 2.

Table 3-3. Observation Results of Temperature Exposure Tests

Sample #	Adhesive	Result
A1S(1-4)B	1	Pass
A2S(1-4)B	2	Fail
A3S(1-4)B	3	Pass
ASS(1-4)B [a]	Control	Pass

[a] ASS3B delaminated.

3.4 Adhesive Dry Times and Total Application Times

The amount of time it takes for an applied adhesive to dry affects not only the performance of any laminated assembly but also the amount of time it takes an operator to put together that assembly. In evaluating the performance of the alternative waterborne contact adhesives, the actual, or measured, dry time of each adhesive and the total application time, or process time, for adhesive application to each assembly were measured. Table 3-4 illustrates the measured dry times and total application times and the manufacturer's recommended dry times for each adhesive. See Appendix D for equations and sample calculations for dry times.

Table 3-4. Average Application, Dry, and Total Application Times

	Adhesive 1	Adhesive 2	Adhesive 3	Control
Application time, min [a]	1	2	1	2
Measured dry time, min	5	28	47	24
Recommended dry time, min [b]	0.083 to 0.25	15	30	15
Total application time, min [c]	6	31	48	26

[a] Application time is the time it takes to apply adhesive to both the board and laminate.
[b] Assumes acceptable temperature and percent relative humidity as recommended by each manufacturer's technical data sheet during application.
[c] Total application time includes the time it takes to apply adhesive to both the board and laminate, drying time before lamination, and the time it takes to laminate the board and laminate together.

In comparison to the Control, Adhesive 1 had the quickest measured dry time of 5 min, whereas Adhesive 3 had the longest of 47 min The measured dry time for Adhesive 2 was within four min of the dry time for the Control. Adhesive 3 did not meet the dry time of the Control, although the dry time for Adhesive 2 was comparable to the Control. With respect to the manufacturer's recommended dry times, all of the adhesives dried more slowly than specified by the manufacturer's recommendations, but the dry time for Adhesive 1 was very fast (21% of the control's dry time).

Total application time, as defined by the facility, is the amount of time it takes an operator to apply adhesive to both boards, allow each board to dry, and laminate them together for further processing. As shown in Table 3-4, the total application time for Adhesive 1 was approximately four times quicker than the Control. Total application times for Adhesives 2 and 3 were greater than the Control.

Thus, overall, Adhesive 1 had the highest peel strength and the quickest dry and application times as compared to the other waterborne adhesives and the Control.

3.5 Adhesive Usage

Another objective of this evaluation was to determine the average amount of adhesive used per board/laminate assembly per adhesive tested and to use this information to calculate VOC emissions as applied per assembly and the relative costs of using each adhesive. Table 3-5 shows the average adhesive used and the dry solids applied per assembly and a comparison of measured versus the manufacturer's recommended applied solids per square meter of area per side coated. See Appendix D for equations and sample calculations for adhesive usage.

Table 3-5. Average Adhesive Used per Board/Laminate Assembly

	Adhesive 1	Adhesive 2	Adhesive 3	Control
Adhesive used, g	105	83	168	64
Dry solids applied, g	48	44	74	6
Dry solids applied, g/m^2 per side	6.5	59	100	8
Manufacturer's recommended dry solids applied, g/m^2 per side	32 [a]	32 [a]	32	22

[a] Average value.
1 lb = 454 g.
1 g/ft^2 = 10.765 g/m*.

In Table 3-5, the resulting dry grams of each adhesive applied was about two to three times the manufacturer's recommended amount. The Control, however, was applied at almost a third of the recommended amount. The reasons for these results are: 1) the unfamiliarity of the operator with the HVLP gun used, with different pressure settings, tip sizes, etc., and 2) a slightly larger, or excess, surface area of laminate sprayed than the board (1.22 m by 0.30 m [4 ft by 1 ft]). This excess surface area[3] had adhesive on it and was included in the final board/laminate assembly weights used to calculate the dry solids applied.

More experimentation is needed to optimize processes for use of waterborne adhesives to reduce cost, and to maintain adequate peel strength. For example, more experimentation is needed to determine

[3] Excess surface areas were not measured for each laminate. However, the approximate overhang was in the range of 1 to 4 cm (0.5 to 1.5 in) per side per test assembly. Also, there was no consistency in excess surface area between assemblies.

if Adhesive 1 can maintain adequate peel strength with less adhesive applied. Similarly, more experimentation with Adhesive 3 with less adhesive applied is needed to determine if its cure time could be shortened with a concurrent development of adequate peel strength.

3.6 Emission Estimates

3.6.1 Physical Properties

A secondary objective of this evaluation was to compare estimates of VOC emissions of each adhesive, as applied. To calculate estimates of applied VOC emissions from each adhesive, physical properties including VOC content minus water, adhesive density, and weight percent solids were determined. Water content, in weight percent, was determined to identify the amount of water in each water based adhesive. Table 3-6 summarizes the analytical results for each adhesive's physical properties.

Table 3-6. Analytical Results for Each Adhesive [a]

	Adhesive I				
	Part A [b]	Part B [c]	Adhesive 2	Adhesive 3	Control
VOC content [d,e], g/L	44 [f]	145	86	88	653
Manufacturer's reported VOC content, g/L [g]	0	< 60	70-75	43	623
Density, g/L	1,163	1,101	1,085	1,107	791
Solids content, wt. %	13.81	45.96	51.46	51.53	17.14
Water content, wt. %	82.4 [h]	40.84	40.61	40.55	0.0038

[a] Values shown are the mean of three samples per adhesive.
[b] Part A is a zinc solution used to activate the adhesive, Part B.
[c] Part B is the adhesive.
[d] Adhesive VOC content is g of VOC per L of adhesive.
[e] No bias determined for VOC content measurements.
[f] By analysis method, zinc sulfate did not precipitate out completely prior to water analysis thus contributing to total volatiles.
[g] Manufacturer's reported VOC content is g of VOC per L of adhesive, including water and exempt solvents.
[h] Water content of Part A for Adhesive 1 analyzed by Karl Fischer titration method. Average shown is the mean of three samples.
1 lb/gal = 119.8 g/L.

As shown in Table 3-6, the analyzed VOC content of all of the alternative adhesives evaluated met the facility's RACT limit on VOC content of 540 g/L (4.5 lb/gal) for the year 1999. The differences between the measured VOC contents and the manufacturer's VOC content can be explained by several reasons. One, at relatively high temperatures, at testing conditions of 110°C (230 "F) in this case, it is possible for some of the adhesive resin and other ingredients, such as unreacted resin monomers, to evaporate. In addition, the samples may not have been well mixed. However, VOC content measured by Method 24 includes solvents and any unreacted resin monomers that evaporate during the test. Also, historically, VOC contents of water based and exempt solvent materials measured by Method 24 have been contested and differ from manufacturer claims because it is a directly measured value and not calculated, as provided in most material safety data sheets.

3.6.2 Emissions

VOC emissions per unit of area for each adhesive were estimated using physical property data from analytical testing, including VOC content and liquid density, the average quantity of wet adhesive used per board/laminate assembly, and the surface area of the assembly. Table 3-7 shows the actual, or measured, applied VOC emissions for each adhesive as compared to the theoretical VOC emissions as applied based on the manufacturer's recommended application rates. See Appendix F for equations and examples for calculating applied VOC emissions per unit area.

Table 3-7. Applied VOC Emissions for Each Adhesive [a]

	Adhesive 1 [b]	Adhesive 2	Adhesive 3	Control
VOC content, minus water, g/L	145	86	88	653
Density, g/L	1,101	1,085	1,107	791
Weight fraction solids, g/g	0.4596	0.5146	0.5153	0.1714
Wet adhesive used, g [c]	105	83	168	64
Wet adhesive used, L	0.0954	0.0765	0.1518	0.0809
Calculated VOC emissions g/m^2, of assembly based on weight of adhesive used	37	18	36	143
Theoretical coverage rate, g/m^2 per side [d]	32	32	32	22
Theoretical VOC emissions g/m^2, per assembly	19	10	10	207

[a] Emissions are expressed as grams per square meter for a constant assembly area of 0.37 m^2 (4 ft^2).
[b] Assumes properties of Part B, the adhesive, of Adhesive 1 since the applied mix ratio of adhesive to activator is 15 parts of adhesive, Part B, to 1 part of activator, Part A.
[c] Wet adhesive used is the average amount of adhesive used per board/laminate assembly and includes overspray.
[d] Theoretical coverage rates taken from each adhesive manufacturer's technical data sheets, which assumes 100 percent of the adhesive applied solids ends up on the substrate.
1 lb/gal = 119.8 g/L.
1 lb = 454 g.
1 gal = 3.7854 L.
1 g/ft^2 = 10.765 g/m^2.

Table 3-7 shows that the average measured VOC emissions of the waterborne adhesives were lower than the Control; this coincides with theoretical emission estimates based on manufacturer recommendations. The VOC emissions are calculated from the solids content of each adhesive, VOC content of each adhesive, and the quantity of adhesive applied to each assembly. Theoretical VOC emission rates based on vendor recommendations for adhesive quantity per unit area were substantially lower. Factors for deviations between measured and theoretical VOC emission estimates are adhesive overspray and the use of more adhesive on the substrate than recommended by adhesive manufacturers (see Table 3-7). However, it is obvious from the data in Table 3-7 that, even when waterborne adhesives are used in excess of their manufacturers specifications, over 90% reduction in VOC emissions can be attained in comparison to the control adhesive.

3.7 Estimated Costs of Alternative Adhesives

Product density, weight percent solids, quantity applied (coverage), and cost data were used to calculate cost estimates for each waterborne contact adhesive. The cost per L, the theoretical coverage and cost, and the measured coverage and cost are shown in Table 3-8 for each adhesive. See Appendix G for equations and examples for calculating adhesive coverage and cost information.

Based on the use rates of adhesive applied in this evaluation, the cost estimates in Table 3-8 show that the waterborne products are more costly to use than the Control for the same coverage area. However, on a theoretical basis, only Adhesives 2 and 3 are less costly than the Control at approximately three times the coverage area. The cost estimate for each alternative waterborne contact adhesive was based solely on the cost of the adhesive and does not include equipment costs or the costs of environmental compliance.

3.8 Data Quality

The primary objective of this project was to determine whether the application of low-VOC contact adhesives can achieve performance levels equivalent to, or exceeding that of, solvent- based contact adhesives while producing lower VOC and HAP emissions. To achieve this objective, weight data were gathered on boards, laminates, and applied adhesive for each adhesive evaluated and used with weight percent solids data on each adhesive.

Results from gravimetric measurements and ASTM test method measurements were within the data quality objectives specified for this evaluation project, except for the application rates for applying each adhesive. The rate at which each adhesive was applied in the test was higher than the manufacturer's recommended application rate. The higher application rates caused the calculated VOC emissions and estimated usage costs for each waterborne adhesive to be two to three times higher than the theoretical values. However, this should not have effected adhesion performance of each adhesive since discussions with adhesive vendors indicated that wide variations in the amount of dry solids applied would not have an appreciable effect on adhesion performance between Formica laminates and 20-kg (45-lb) density particleboard. In fact, the average range of adhesive applied per square meter per side as quoted by the vendors was between 22 and 215 g/m^2 (2 and 20 g/ft^2). In addition, all of the manufacturer's technical data sheets include standard disclaimers that, although an optimum rate of adhesive applied is given to achieve optimum adhesion performance, the optimum rate is left to the user to decide based on their own product quality requirements.

Table 3-8. Adhesive Coverage and Cost Information [a]

	Adhesive 1	Adhesive 2	Adhesive 3	Control
Density, g/L	1,101	1,085	1,107	791
Weight fraction solids, g/g	0.4596	0.5146	0.5153	0.1714
Dry solids applied, g [b]	48	44	74	6
Dry solids applied per side, g/m^2	65	59	100	8
Theoretical dry solids applied, g/m^2	32	32	32	22
COVERAGE				
Theoretical coverage, m^2/L	16	17	18	6.3
Measured coverage, m^2/L	8	9	6	18
COSTS				
Cost, US dollars/L on a 208-L basis [c]	8.6	3.9	4.9	2.0
Theoretical cost, US dollars/m*	0.55	0.22	0.28	0.31
Measured cost US. dollars/m*	1.10	0.41	0.86	0.11

[a] Cost estimates shown do not include costs for labor, equipment, or other costs like environmental compliance.
[b] Control applied at 22 g/m^2 dry adhesive solids per side. Theoretical coverage for the alternatives is calculated to be 32 g/m^2 dry adhesive solids applied per side.
[c] As of October 1996.
1 g/ft^2 = 10.765 g/m^2.
1 ft^2/gal = 0.025 m^2/L.
1 gal = 3.7854 L.
1 ft^2 = 0.093 m^2.

Section 4.0
Conclusions

This evaluation suggests that selected waterborne contact adhesives on an overall basis can perform as well as or better than a solvent-borne contact adhesive that is currently being used in the store fixture assembly industry. In fact, one of the better performing waterborne adhesives evaluated, Adhesive 1, had actual dry times that were approximately five times lower than the Control. Although this adhesive seemed to perform the best, it was the most expensive alternative tested. However, if more rapid drying allows the throughput of product in these specific lamination activities to be increased, then there could be cost savings from reduced inventory and increased production. Adhesive 2 had comparable application and dry times to the Control, and passed the onsite peel strength test, but failed in the temperature exposure test. Adhesive 3 appeared to have the lowest overall performance, failing in the manual peel test at the facility and having total application and dry times of almost twice the Control.

The actual and theoretical VOC emissions resulting from the use of the waterborne adhesives were significantly lower than the emissions resulting from the use of the Control. Actual applied VOC emissions per side measured in this evaluation averaged about 30.3 g/m^2 (2.8 g/ft^2) for the waterborne products and were 143 g/m^2 (13 g/ft^2) for the solvent-borne Control. If the adhesives were applied at the generic application rates recommended by the manufacturers, then, on a theoretical basis, the theoretical VOC emissions from the application of the waterborne products would have averaged approximately 13 g/m^2 (1.2 g/ft^2) as compared to the Control at 207 g/m^2 (19.2 g/ft^2).

The recommended application values were taken directly from the manufacturer's technical data sheets for each adhesive. These values are generic and cover a range of laminating applications for various industries, but they do not apply specifically to laminating applications for the store fixture industry, nor specifically to this facility. Discussions with adhesive vendors indicated that wide variations in the amount of dry solids applied would not have an appreciable effect on performance; for example, for Adhesive 3, the vendor stated that no appreciable performance effects would be noticed up to 161 g/m^2 (15 g/ft^2) of dry solids applied per side.

Based on the quantity of adhesive used during the evaluation, all waterborne products ranged from approximately 4 to 10 times more costly per m^2 to use than the Control. These costs were calculated on the basis of the cost for the adhesives and did not include costs for labor, application equipment, environmental compliance, etc. Again, if the adhesives were applied at the generic application rates recommended by the manufacturers, then the cost of using the waterborne products would have ranged from approximately \$0.22/m^2 to 0.55/m^2 (\$0.02/ft^2 to 0.05/ft^2) versus the Control at \$0.31/m^2 (\$0.03/ft^2) based on adhesive cost only.

The quantity of applied dry solids had a direct impact on the cost and VOC emissions resulting from the use of each adhesive. During the evaluation, due to the operator's lack of experience using HVLP equipment, as shown in Table 3-5, the dry solids application rate for the waterborne adhesives exceeded the manufacturers' recommended quantities while the application rate for the Control was approximately three times less than recommended by the manufacturer. The VOC emissions and cost of adhesive used would be substantially lower if the waterborne adhesives were applied as recommended by the manufacturers.

The reason why Adhesive 3 failed the subjective peel test and passed the temperature exposure peel strength test is not certain. However, an extensive dry time between the adhesive samples leaving the plant and the time at which they were tested at SGS US Test Corporation could explain why this occurred. The adhesive could have continued to dry beyond the initial 24 h and could have become stronger in bond strength. The results are summarized in Table 4.1 below.

The reader should note that the operator who applied the adhesive was unfamiliar with the use of waterborne adhesives and the HVLP spray system used to apply the waterborne adhesives. Table 3-5 illustrates that, although the operator was quite familiar with the application of the Control adhesive, their inexperience with HVLP spray technology made a difference (8 vs. 22 g/m^2; 0.7 vs. 2.0 g/ft^2) in application rates. Although attempts were made to follow the spray equipment manufacturers' recommendations, this research suggests that the operator's familiarity with the adhesive products and application equipment can substantially affect the cost and VOC emissions associated with the adoption of a new product. Appropriate operator training is essential to a successful switch to HVLP spray technology.

In addition, the analyzed VOC content of each alternative adhesive evaluated ranged from 86 to 145 g/L (0.72 to 1.2 lb/gal). These values met the facility's RACT limit on VOC content of 540 g/L (4.5 lb/gal) for the year 1999.

Table 4.1. Summary of Results

	Control	Adhesive 1	Adhesive 2	Adhesive 3
Dry Time (min)	24	5	28	47
Peel Strength (18 hr)	Pass	Pass	Pass	Fail
Peel Strength (kg/30 cm/min)	3.4	6.4	3.6	6.9
Peel Strength After Conditioning*	Pass	Pass	Fail	Pass
Cost of Adhesive ($/L)	2.0	8.6	3.9	4.9

* Samples conditioned 24 hours at 0° C and then 24 hours at 49°C both with uncontrolled humidity

Section 5.0
Recommendations

This evaluation was conducted as a proof-of-concept research project. The concept was to evaluate adhesive performance of three alternative contact adhesives that contained less than 540 g/L VOC (5.2 lb/gal) and to evaluate their VOC emissions upon application versus a currently used solvent-borne Control as each was applied to a representative surface area of substrate and laminate in a store fixtures laminating facility. Each alternative adhesive and the Control was applied using HVLP spray technology. As a result of the observations discussed in this evaluation, the following recommendations are suggested for consideration as objectives for future research work in the adhesives industry.

Future testing of adhesive performance and VOC emissions, as applied, regardless of low-VOC adhesive type, should be conducted further to investigate four critical factors in the wood laminating industry:

- determine to monitor the effect of using alternative low-emitting adhesives on the throughput rate of a lamination facility,
- to evaluate the effects of different spray technologies on these adhesives,
- to perform a total cost accounting of this evaluation, and
- to observe applications of alternative adhesives in other laminating operations where solvent-borne contact adhesives still predominate.

Section 6.0
References

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Appendix A
Conversion Factors

To Convert from Metic	Units	To English	Units	Multiply by
LENGTH				
meter	m	feet	ft	3.281
meter	m	inch	in	39.37
centimeter	cm	inch	in	*2.54*
AREA				
square meter	m^2	square feet	ft^2	10.765
MASS OR WEIGHT				
gram	g	pound	lb	*0.0022*
kilogram	kg	pound	lb	*2.205*
metric ton	m ton	short ton	s ton	*0.907*
VOLUME				
liter	L	gallon	gal	0.264
milliliter	mL	fluid ounce	fl. oz.	*0.034*
DENSITY				
grams per liter	g/L	pounds per gallon	lb/gal	119.8
TEMPERATURE				
Celsius	°C	Fahrenheit	°F	multiply by 1.8, then add 32

Appendix B
Test Preparation and Testing Procedures

B.l Test Preparation Procedures

Test preparation procedures for this evaluation consisted of adhesive application, adhesive application to boards dedicated for off-site cyclic temperature exposure testing, adhesive application to boards dedicated for onsite subjective peel test, and adhesive application to boards dedicated for off-site peel testing. Each is described below.

B.1.1 Adhesive Application

The Test Matrix in Table B- 1 identifies the experimental design for adhesive application to test boards and laminates and identification of dedicated samples for conducting performance tests.

The adhesive used per board and laminate were recorded for the first nine test boards per adhesive. Weights for test board 10 were not taken because the samples required for peel testing do not allow for complete coverage of the board and laminate. Thus, the weights obtained would not be consistent with the other nine boards per adhesive set. However, weights, temperatures, relative humidities, etc., were monitored during adhesive application to ensure that the same procedure was used for board 10 as that for boards 1 through 9.

Table B-l. Testing Matrix

		Test board/laminate assembly samples			
Performance test	Sample	Adhesive 1	Adhesive 2	Adhesive 3	Control
Paired samples for temperature exposure test	1	A1S1A [a] A1S1B	A2S1A A2S1B	A3S1A A3S1B	ASS1A ASS1B
	2	A1S2A A1S2B	A2S2A A2S2B	A3S2A A3S2B	ASS2A ASS2B
	3	A1S3A A1S3B	A2S3A A2S3B	A3S3A A3S3B	ASS3A ASS3B
	4	A1S4A A1S4B	A2S4A A2S4B	A3S4A A3S4B	ASS4A ASS4B
On-site subjective peel test	5	A1S5O [b]	A2S5O	A3S5O	ASS50
	6	A1S6O	A2S6O	A3S6O	ASS60
	7	A1S7O	A2S7O	A3S7O	ASS70
	8	A1S8O	A2S8O	A3S8O	ASS80
	9	A1S9O	A2S9O	A3S9O	ASS90

(continued)

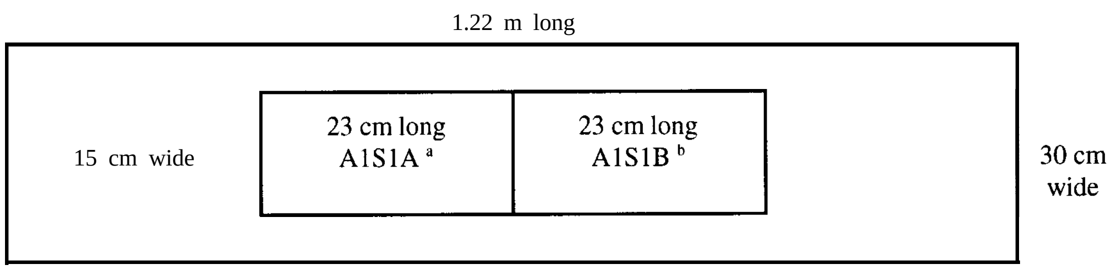
Table B-l. (Continued)

Performance test	Samvle	Adhesive 1	Adhesive 2	Adhesive 3	Control
		Test board/laminate assembly samples			
Off-site peel test	10	A1S10P1 [c]	A2S10P1	A3S10P1	ASS10P1
		A1S10P2	A2S10P2	A3S10P2	ASS 10P2
		A1S10P3	A2S10P3	A3S10P3	ASS10P3
		A1S10P4	A2S10P4	A3S10P4	ASS10P4
		A1S10P5	A2S10P5	A3S10P5	ASS10P5

[a] Al S1A (Adhesive #1, Sample # 1, A control sample for cyclic temperature exposure testing). Al S 1 B adhesive #1, Sample # 1, B exposed sample for cyclic temperature exposure testing).
[b] A1S5O (Adhesive #1, Sample 5, A subjective operator evaluation).
[c] A1S10P# (Adhesive #1, Sample#10, Peel observation #1).

B.1.2 Adhesive Application to Boards Dedicated for Off-site Cyclic Temperature Exposure Testing

After allowing the board/laminate assembly to air-dry for approximately 24 h, two identical test samples were cut from the first four test boards; Figure B-l illustrates that sample, A, the Control sample, would be used for conditioning at ambient conditions and sample B, would be used for cyclic temperature exposure testing.



[a] Al S 1 A adhesive #1, Sample # 1, A control sample).
[b] Al S1B (Adhesive #1, Sample # 1, B exposed sample).
Thickness = 1.9 1 cm (¾ in)
1 ft = 0.3048 m.
1 in = 2.54 cm.

Figure B-l. Dimensions and sample locations/designations for each board/laminate assembly labeled A#S(l-4).

Samples A and B were cut from the center of the board and were each 23 cm long by 15 cm wide (9 in by 6 in). Then, cut samples, 1A through 4A and 1B through 4B, of each assembly were placed inside a 20 cm wide by 30 cm tall (8 in x 12 in) (volume = 0.01-m”, 0.349-ft^3) friction-sealed steel cans, respectively. The cans were shipped by overnight delivery to RTI. Figure B-2 shows how each set of samples were packaged.

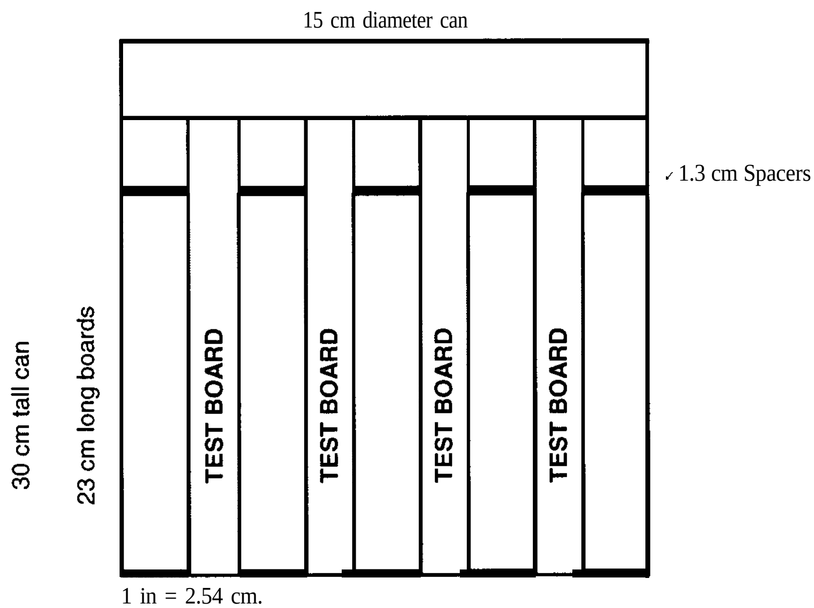
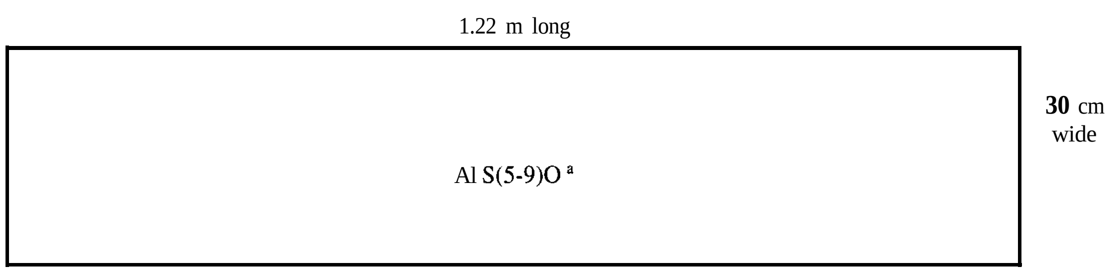


Figure B-2. Side view of a steel can containing four board samples A#S(1-4)A or A#S(1-4)B for cyclic temperature exposure testing.

B.1.3 Adhesive Application to Boards Dedicated for Onsite Subjective Peel Test

After adhesive application, dry, and assembly, each of the test boards for each adhesive A#S(5-9)0 were set aside and allowed to air cure overnight. These boards underwent subjective evaluation on the next test day. Figure B-3 illustrates the subjective evaluation test boards.



[a] A1S(5-9)O adhesive #1, Sample # (5-9), subjective aerator evaluation).
Thickness = 1.9 cm (¾ in).
1 ft = 0.3048 m.
1 in = 2.54 cm.

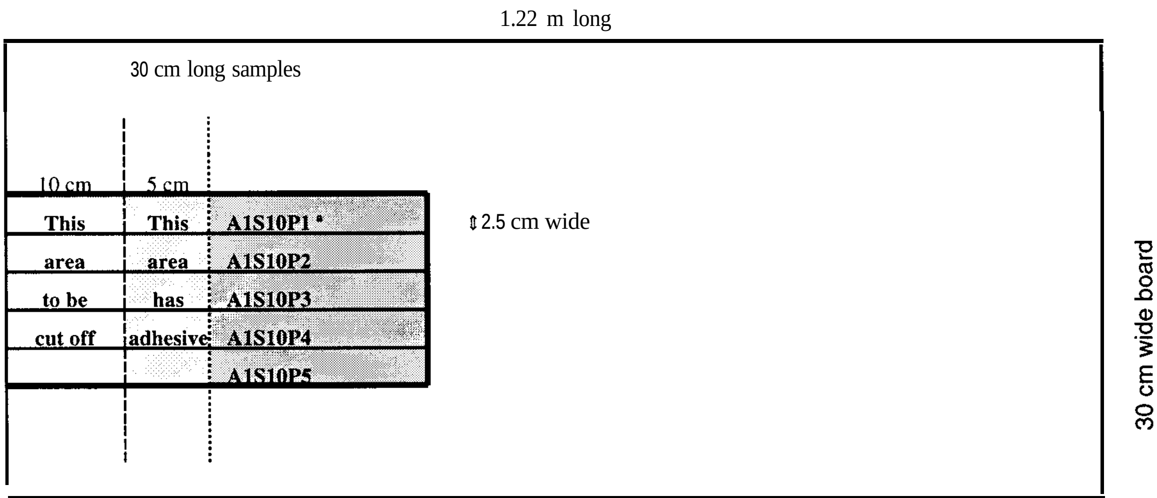
Figure B-3. Dimensions for each board/laminate assembly labeled A#S(5-9)O for onsite peel test.

B.1.4 Adhesive Application to Boards Dedicated for Off-site Peel Testing

Test board #10 of each adhesive set was prepared and handled differently than the other nine boards in each set for conducting the off-site peel strength test. This test was conducted using the

American Society for Testing and Materials (ASTM) Standard Test Method D 903-93. Method D-903-93 requires that no adhesive be applied between the laminate and board up to 15 cm (6 in) from the edge of a 30-cm long (12 in) test sample. See Appendix C for a more detailed explanation of this test method. A piece of masking tape was applied to both board and laminate surfaces up to 15 cm (6 in) from the edge of test board 10 before applying adhesive to the board and laminate. Figure B-4 illustrates where masking tape was applied, where the adhesive was applied, and how the samples were taken from test board 10. Figures B-5 and B-6 illustrate both board and laminate setup.

After masking tape was applied to a board and its respective laminate, adhesive was applied to both surfaces. An incision was made 10 cm (4 in) from the edge of the test board and the adhesive was pulled away with the masking tape. Both surfaces were laminated together and allowed to air dry. After curing for approximately 24 h, the assembly was taken to a saw and 10 cm (4 in) of the board was cut off. Then the required individual samples were cut. Figure B-7 illustrates the resulting cut samples.



[a] A1S10P1 adhesive #1, Sample # 10, Peel test sample 1).
Thickness = 1.9 cm (¾ in).
1 ft = 0.3048 m.
1 in = 2.54 cm.

Figure B-4. Dimensions and sample locations/designations for adhesive application to each board number 10 for peel testing.

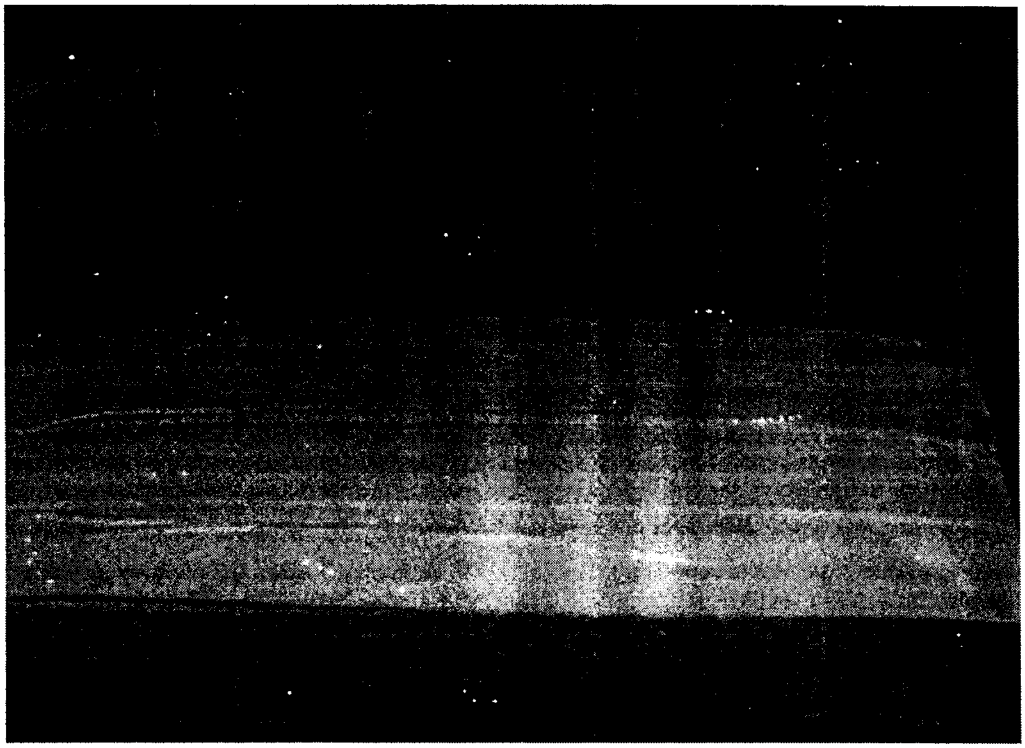


Figure B-5. Picture illustrates how tape was wrapped onto each laminate.

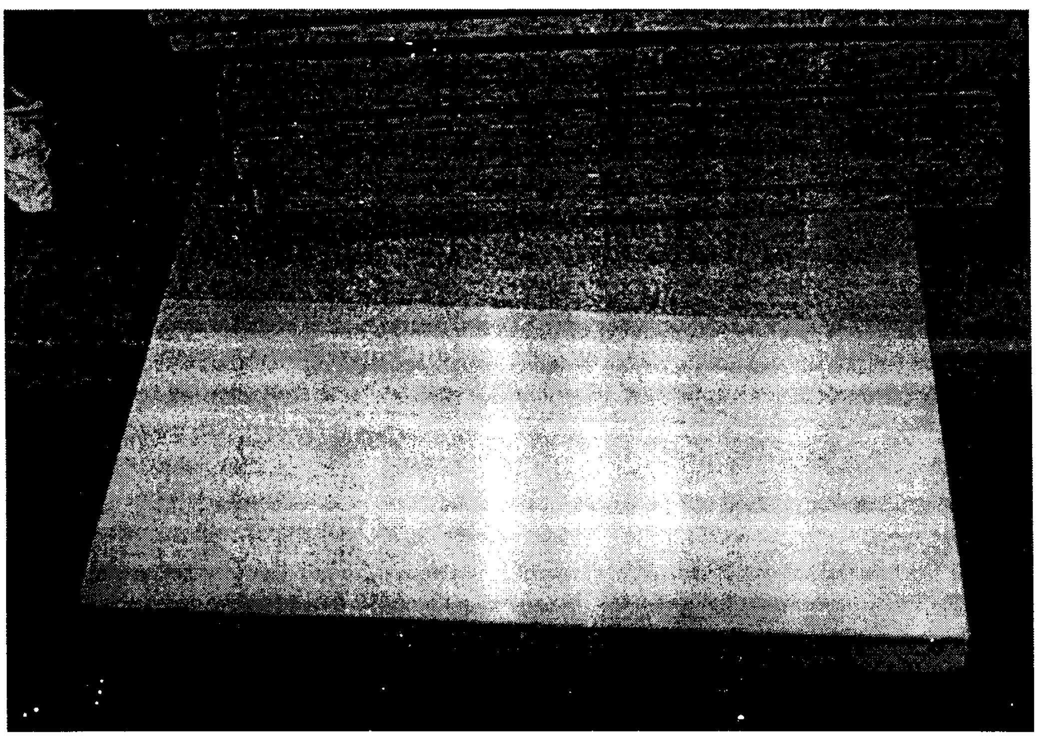


Figure B-6. Picture illustrates how tape was wrapped onto each substrate.

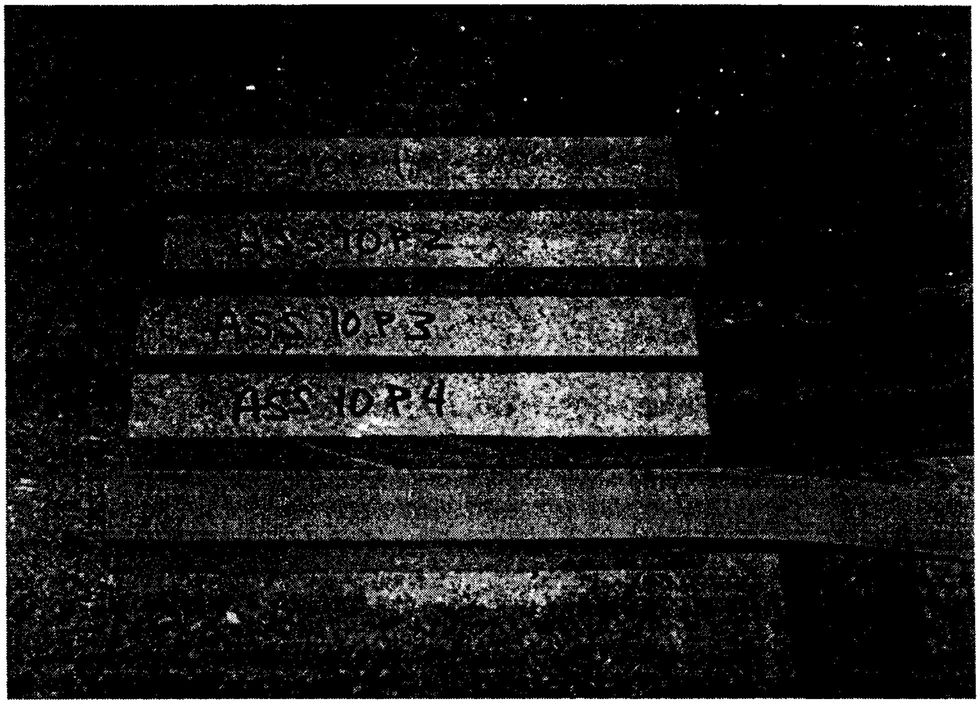


Figure B-7. Resulting cut samples sent to SGS US Test Corporation for mechanical peel strength testing.

B.2 Testing Procedures

The following testing procedures were used in the evaluation of three alternative low-VOC contact adhesives as compared to a Control at a manufacturing facility in Manitowoc, Wisconsin. A Sartorius precision floor scale was used to measure the amount of each adhesive used per test board/laminate assembly per adhesive. A hand-held monitor was used to periodically measure ambient air temperature and percent relative humidity during the test. Step 1 was performed prior to the start of the test and at the conclusion of the test. Steps 2 and 6 were repeated for each adhesive. Steps 3 and 4 were repeated for each adhesive application.

B.2.1 Step 1 Calibration of Sartorius F16000S Floor Scale (The scale was turned on at the start of each test day and turned off at the completion of each test day.)

1.1 Turn on the scale. Wait 30 minutes for equilibration.
1.2 Tare the scale to zero.
1.3 Place a 10-kg (22 lb) calibration weight onto the center of the scale and record the weight.
1.4 If the net value of the weight added in Step 1.3 is 10 kg (22 lb) ± 0.1 g (0.0035 oz), continue. If not, perform an internal calibration (option included in scale model) and repeat steps 1.2 to 1.4.
1.5 Remove the IO-kg (22 lb) calibration weight.
1.6 Tare the scale to zero.

B.2.2 Step 2 Procedure for Preparing Each Test Piece Before Testing (A permanent marker was used for labeling purposes.)

<u>BOARDS</u>

2.1 Remove a 1.22 m wide by 3.1 m long by 1.9 cm thick (4 ft x 10 ft x ¾ in) particleboard sheet from one common unit. One common unit consists of 35 particleboard sheets.
2.2 On the back of the sheet, measure and mark off ten, 1.22 m long by 30 cm wide (4 ft by 1 ft) sections.
2.3 Label each section as follows
On the back of sections #1, 2, 3, and 4:
- 2.3.1 Label as A1S1 (Adhesive, #, Section, #).
- 2.3.2 Measure and mark off two, 15 cm wide by 23 cm long (6 in x 9 in) sections equidistant from each side of the 1.22 m long by 30 cm wide (4 ft x 1 ft) section.
- 2.3.3 Label these two sections A1S1A and A1S1B. (A is the control sample and B is the exposure sample for cyclic temperature exposure testing.)
On the back of sections # 5, 6, 7, 8, and 9:
- 2.3.4 Label as A1S5O (Adhesive, #, Section, #, Operator peel test).
On the back of section # 10:
- 2.3.5 Label as A1S10P (Adhesive, #, Section, #, Peel test).
- 2.3.6 Measure and mark off five, 2.5 cm wide by 30 cm long (1 in x 12 in) sections from a 30 cm (1 ft) wide side.
- 2.3.7 Label as A1S10P1 (Adhesive, #, Section, #, Peel test, #).
- 2.3.8 Measure and mark off 10 cm (4 in) and 15 cm (6 in) inward from the edge of the board into 2.5 cm by 30 cm (1 in x 12 in) sections.
- 2.3.9 Apply masking tape over the entire 6-in area from the edge of the 30 cm (1 ft) side into 2.5 cm by 30 cm (1 in x 12 in) sections.

2.4 Cut the 1.22 m wide by 3.1 m long by 1.9 cm thick (4 ft x 10 ft x ¾ in) sheet into its 10 equivalent 1.22 m long by 30 cm wide (4 ft x 1 ft) sections.
2.5 Clean the surface of the board by applying compressed air to its surface.
2.6 Place the 1.22 m long by 30 cm wide (4 ft x 1 ft) section on the floor scale. Record the weight. This is the weight of each board for each 1.22 m long by 30 cm wide (4 ft x 1 ft) section.

LAMINATES

2.7 Remove Formica laminate from one common lot to cover no less than 0.37 m^2 (4 ft^2).
2.8 On the back of each Formica laminate, label each to match the labeling for the board as prescribed in Step 2.3.
2.9 Clean the surface of the laminate by applying compressed air to its surface.
2.10 Place each cut section on the floor scale. Record the weight. This is the weight of each laminate paired with a corresponding board.

B.2.3 Step 3 Procedure for Applying Contact Adhesive to Test Board/Laminate Assemblies Labeled A#S(1-9)

3.1 Clean the surface of each test board and laminate by applying compressed air to the surfaces.
3.2 Connect one end of a 1.5-m long, 1.9-cm-diameter (5-ft, %-in) hose to the BINKS 1.9 L (2-qt) pressure pot of and the other end to the HVLP spray gun. Connect the air supply hose to the HVLP gun. Tie down the air supply and adhesive feed hoses.
3.3 Connect the manufacturer's suggested spray gun tip to the spray gun.
3.4 Place the empty 1.9 L (2-qt) pressure pot and assembly on the center of the floor scale.
3.5 After allowing the scale to equilibrate, tare the scale to zero (tare out the weight of the pressure pot).
3.6 Place the test board and test laminate side-by-side on a table in the testing area.
3.7 Thoroughly mix a 19-L (5-gal) container of adhesive to be applied by using a stirring rod.
3.8 Open adhesive container and take three, 500-mL (17-fl-oz) samples from the middle of the container.
3.9 Pour adhesive into the clean and empty 1.9-L (2-qt) pressure pot.
3.10 Start the HVLP spray system. Make sure the 1.9-L (2-qt) pressure pot and scale are not touching anything.
3.11 Make necessary adjustments to spray gun fan width, air pressure, etc., while spray applying adhesive to a piece of cardboard. Make sure flow rate of adhesive is per the manufacturer's recommended flow rate.
3.12 Once adjustments have been made, then record the scale weight. This is the starting weight for the adhesive to be applied to one test board and laminate.
3.13 Apply adhesive to a test board and laminate while recording ambient air temperature and percent relative humidity.
3.14 At the completion of the operator's application of adhesive to both test board and laminate, record the scale's displayed weight. This weight is the final weight for adhesive application to a test board and laminate and the starting weight for adhesive to be applied to the next test board and laminate.
3.15 Set aside both the test board and laminate and allow them to air dry per the adhesive manufacturer's recommendation. Record this length of time.
3.16 After drying, apply the laminate to the test board and secure them together using the

facility's standard procedure. Place the assembly in a secured area of the testing facility.

3.17 Record the elapsed time between Steps 3.10 and 3.16. This the total application time.

B.2.4 Step 4 Procedure for Applying Adhesive to Test Board/Laminate Assemblies Labeled A#S1OP#

4.1 Repeat Steps 3.1 to 3.15.

4.2 After applying adhesive, remove the masking tape from both the board and the laminate, being careful not to remove adhesive from the other portion of the board or the laminate.

4.3 Repeat Steps 3.16 and 3.17.

B.2.5 Step 5 Testing Procedure Between Applying Adhesive Types

5.1 Clean the 2-qt pot and spray gun after an adhesive has been applied with the manufacturer's recommended cleaning solvent by circulating the solvent through the system for a minimum of 5 min

5.2 Disassemble the application system, discard solution material per adhesive manufacturer's written specifications, and allow separate assembly parts to thoroughly dry.

5.3 Replace the adhesive feed hose to the HVLP spray gun with a new 1.5-m long, 1.9-cm-diameter (5-ft, %-in) hose.

5.4 Change spray gun tip for next adhesive, if necessary.

5.5 Reposition the 1.9-L (2-qt) pressure pot on the floor scale.

5.6 Tare the scale to zero.

5.7 Repeat instructions given in Step 3 of the procedure.

B.2.6 Step 6 Procedure for Final Weight Measurement of Each Test Board/Laminate Assembly

6.1 Allow each test board/laminate assembly labeled A#S(l-9) to air dry at the facility for a minimum of 24 h.

6.2 Clean the surface of each test board/laminate assembly by applying compressed air to their surfaces.

6.3 Place each 1.22 m long by 30 cm wide (4 ft x 1 ft) test board/laminate assembly on the floor scale. Record the weight. This is the combined weight of board, laminate, and adhesive solids applied for each assembly.

Appendix C
Descriptions of Test Methods

1. Peel Strength Test ASTM D 903-93

ASTM D 903-93, Peel or Stripping Strength of Adhesive Bonds, is used to determine the comparative peel or stripping characteristics of adhesive bonds when tested on standard-sized specimens and under defined conditions of pretreatment, temperature, and testing machine speed. Peel or stripping strength is expressed as the average load per unit width (kg/mm or lb/in) of bond line required to separate a flexible member from a rigid member or another flexible member in the adhered area at a separation angle of 180" and at a separation rate of 152 mm (6 in)/min.

2. Sampling and Analytical Procedures for Obtaining Physical Properties of Each Adhesive

Sampling procedures for this evaluation are limited to the physical property testing conducted on each of the alterative contacts adhesives and the Control. The procedures for taking these samples from each contact adhesive are discussed in Section 2, Methods and Materials.

Samples of liquid adhesives were analyzed according to four ASTM test methods:

- ASTM D 2369-8 1,
- ASTM D 1489-93,
- ASTM D 3792-79, and
- ASTM D 1875-90.

These ASTM Methods are described below in Table C- 1.

Table C-l. Summary Table of Standard Methods and Procedures

	VOC [a]	Non-volatiles	Water Content	Density [b]
Method number	ASTM D 2369-81	ASTM D 1489-93	ASTM D 3792-79	ASTM D 1875-95
Method title	Standard Test Method for Volatile Content of Coatings	Standard Test Method for Nonvolatile Content of Aqueous Adhesives	Standard Test Method for Water Content of Water-Reducible Paints by Direct Injection into a Gas Chromatograph	Standard Test Method for Density of Adhesives in Fluid Form
Method type	See ASTM Method below	Gravimetric	Gas Chromato-graphic	Gravimetric
Reference	CFR 40, Pt. 60, App. A, Meth. 24	ASTM	ASTM	ASTM

[a] VOC content of liquid adhesives was calculated, as is done with coatings by EPA Method 24, as weight fraction total volatiles (or 1 .000 minus non-volatiles) minus weight fraction water.
[b] Density was used to calculate volume fraction of VOC.

a. ***ASTM D 2369-81***

ASTM D 2369-8 1. Standard Test Method for Volatile Content of Coatings, involves evaporation of volatiles from a weighed sample of material at 110°C (230°F) for 1 h. Weight fraction of volatiles is calculated as the weight lost by the sample during heating divided by the weight of the original sample.

b. ***ASTM D 1489-93***

ASTM D 1489-93. Standard Test Method for Nonvolatile Content of Aqueous Adhesives, involves evaporation to constant weight of an aqueous solution of the adhesive at 105°C (221 “F). Percent non-volatiles is calculated as 100 times the weight of the residue following heating divided by the weight of the original sample.

c. ***ASTM D 3792-79***

ASTM D 3792-79. Standard Test Method for Water Content of Water-Reducible Paints by Direct Injection into a Gas Chromatograph, involves measurement of the water present in a material by gas chromatography with thermal conductivity detection (GC-TCD). A known mass of sample is dissolved in a solvent (dimethylformamide or DMF) and spiked with a known mass of an internal standard (2-propanol). The solution is then shaken thoroughly, any solids present are allowed to settle out, and a 0.001-mL (3.4 x 10^{-5} fl. oz.) volume of the supematant liquid is injected directly into a GC-TCD. The TCD response for water relative to the response for the internal standard (determined during calibration) is used to calculate the mass of water in the original sample. The weight fraction of water is calculated as the weight of water in the original sample divided by the weight of the original sample.

d. ***ASTM D 1875-95***

ASTM D 1875-95. Standard Test Method for Density of Adhesives in Fluid Form, involves use of a weight-per-gallon cup of known volume and subsequent measurement of the mass of sample required to exactly fill the cup at 25 °C (77 “F). Density is calculated as the mass of sample required to exactly fill the cup divided by the volume of the cup.

Appendix D
Test Data

TABLE D-l. RAW WEIGHT DATA FOR BOARDS AND LAMINATES

Assembly identification	Board weight, g	Laminate weight, g	Total weight, g
A 1 S 1	5,207.3	423.5	5,630.8
A 1 S 2	5179.1	402.9	5,582.0
A 1 S 3	5,227.0	403.5	5,630.5
A 1 S 4	5,167.5	406.2	5,573.7
A 1 S 5 0	5,193.1	400.1	5,593.2
A 1 S 6 0	5,212.9	401.5	5,614.4
A 1 S 7 0	5,116.0	407.2	5,523.2
A 1 S 8 0	5,126.1	403.1	5,529.2
A 1 S 9 O	5,125.8	402.3	5,528.1
Average	**5,172.8**	405.6	**5,578.3**
A 2 S 1	5,154.3	401.9	5,556.2
A 2 S 2	5,172.2	406.4	5,578.6
A 2 S 3	5,141.1	404.1	5,545.2
A 2 S 4	5,170.6	404.5	5,575.1
A 2 S 5 0	5,207.7	405.3	5,613.0
A 2 S 6 0	5,217.5	405.0	5,622.5
A 2 S 7 0	5,114.0	405.5	5,519.5
A 2 S 8 0	5,086.0	403.9	5,489.9
A 2 S 9 0	5,117.5	407.8	5,525.3
Average	**5,153.4**	**404.9**	**5,558.4**

1 g = 0.0022 lb.

Equation and Example:

Total weight, in g, for test assembly Al S 1 = board weight, g + laminate weight, g
= 5,207.3 g + 423.5 g
= 5,630.8 g

(continued)

TABLE D-l. (Continued)

Assembly identification	Board weight, g	Laminate weight, g	Total weight, g
A 3 S 1	5,161.7	400.5	5,562.2
A 3 S 2	5,171.6	403.0	5,574.6
A 3 S 3	5,179.2	398.3	5,577.5
A 3 S 4	5,202.0	402.3	5,604.3
A 3 S 5 0	5,171.6	400.7	5,572.3
A 3 S 6 0	5,278.7	399.4	5,678.1
A 3 S 7 0	5,049.6	381.2	5,430.8
A 3 S 8 0	5,020.5	405.8	5,426.3
A 3 S 9 0	5,070.3	396.8	5,467.1
Average	**5,145.0**	**398.7**	**5,543.7**
A S S 1	5,249.0	400.6	5,649.6
A S S 2	5,310.1	398.8	5,708.9
A S S 3	5,342.0	397.7	5,739.7
A S S 4	5,329.0	400.0	5,729.0
A S S 5 0	5,300.0	407.5	5,707.5
A S S 6 0	5,354.2	411.2	5,765.4
A S S 7 0	5,243.0	397.3	5,640.3
A S S 8 0	5,178.0	399.2	5,577.2
A S S 9 0	5,239.4	395.6	5,635.0
Average	**5,282.7**	400.9	**5,683.6**

1 g = 0.0022 lb.

Equation and Example:

Total weight, in g, for	=	board weight, g + laminate weight, g
test assembly A3S 1	=	5,161.7 g + 400.5 g
	=	5,562.2 g

TABLE D-2. RAW WEIGHT DATA FOR THE ADHESIVES

Assembly identification	Pot wt. before adhesive application to board and laminate, g	Pot wt. after adhesive application to board and laminate, g	Adhesive used, g
A 1 S 1	6,169.0	6,070.0	99.0
A 1 S 2	6,070.0	5,967.0	103.0
A 1 S 3	5,967.0	5,865.0	102.0
A 1 S 4	5,865.0	5,757.0	108.0
A 1 S 5 0	5,757.0	5,665.0	92.0
A 1 S 6 O	5,665.0	5,560.0	105.0
A 1 S 7 O	5,560.0	5,464.0	96.0
A 1 S 8 O	5,464.0	5,358.0	106.0
A 1 S 9 O	5.358.0	5.227.0	131.0
Average	**5,763.9**	**5,659.2**	104.7
A 2 S 1	10,442.0	10,340.0	102.0
A 2 S 2	10,331.0	10,268.0	63.0
A 2 S 3	10,233.0	10,147.0	86.0
A 2 S 4	10,140.0	10,058.0	82.0
A 2 S 5 O	10,051.0	9,976.0	75.0
A 2 S 6 O	9,972.0	9,887.0	85.0
A 2 S 7 O	9,849.0	9,786.0	63.0
A 2 S 8 O	9,779.0	9,681.0	98.0
A 2 S 9 O	9.657.0	9.564.0	93.0
Average	**10,050.4**	**9,967.4**	83.0

Eauation and Example:

Adhesive used for test assembly Al S 1, in g = pot weight before adhesive application to board and laminate, g +pot weight after adhesive application to board and laminate, g

= 6,169.0 g + **6,070.0** g

= 99.0 g

(continued)

TABLE D-2. (Continued).

Assembly identification	Pot weight before adhesive application to board and laminate, g	Pot weight after adhesive application to board and laminate, g	Adhesive used, g
A 3 S 1	13,691.0	13,492.0	199.0
A 3 S 2	13,492.0	13,304.0	188.0
A 3 S 3	13,304.0	13,127.0	177.0
A 3 S 4	13,127.0	12,908.0	219.0
A 3 S 5 O	12,908.0	12,718.0	190.0
A 3 S 6 O	12,718.0	12,591.0	127.0
A 3 S 7 0	12591.0	12,459.0	132.0
A 3 S 8 O	12,459.0	12,320.0	139.0
A 3 S 9 O	12,320.0	12,180.0	140.0
Average	**12,956.7**	**12,788.8**	**167.9**
A S S 1	11,431.6	11,387.6	44.0
A S S 2	11,378.0	11,313.0	65.0
A S S 3	11,310.0	11,249.0	61.0
A S S 4	11,234.0	11,179.0	55.0
A S S 5 0	11,165.0	11,090.0	75.0
A S S 6 0	11,094.0	11,029.0	65.0
A S S 7 0	11,026.0	10,947.0	79.0
A S S 8 0	10,940.0	10,889.0	51.0
A S S 9 0	10,875.0	10,790.0	85.0
Average	**11,161.5**	**11,097.1**	64.4

1 g = 0.0022 lb.

Eauation and Example:

Adhesive used for test assembly A3S 1, in g = pot weight before adhesive application to board and laminate, g +pot weight after adhesive application to board and laminate, g

= 13,691.0 g + 13,492.0 g

= 199.0 g

TABLE D-3. APPLICATION AND DRY TIMES

Assembly identification	Adhesive application start time	Adhesive application end time	Total application time, min [a]	Time laminated	Dry time, min
A 1 S 1	1515	1516	1	1521	5
A 1 S 2	1519	1520	1	1525	5
A 1 S 3	1522	1523	1	1527	4
A 1 S 4	1545	1546	1	1550	4
A 1 S 5 0	1546	1547	1	1552	5
A 1 S 6 O	1548	1548	1	1555	7
A 1 S 7 O	1551	1551	1	1557	6
A 1 S 8 0	1554	1554	1	1558	4
A 1 S 9 O	1556	1556	1	1600	4
Average			1		5
A 2 S 1	1234	1237	3	1303	26
A 2 S 2	1239	1241	2	1307	26
A 2 S 3	1243	1250	7	1317	27
A 2 S 4	1251	1253	2	1319	26
A 2 S 5 O	1254	1257	3	1324	27
A 2 S 6 O	1300	1302	2	1328	26
A 2 S 7 O	1309	1311	2	1339	28
A 2 S 8 O	1312	1314	2	1347	33
A 2 S 9 0	1315	1317	2	1349	32
Average			3		28

[a] Total application times were rounded up to the nearest minute. For example, since it took less than one minute total to apply adhesive to both board and laminate for assembly Al S6O, the total application time was rounded up to one minute.

Equations and Examples:

Total application time for assembling A 1 S 1, min = Adhesive application end time - adhesive application start time
= 1516 - 1515
= 1 min

Dry time for A1S1, min = Time laminated - adhesive application end time
= 1521 - 1516
= 5 min

(continued)

TABLE D-3. (Continued)

Assembly identification	Adhesive application start time	Adhesive application end time	Total application time, min [a]	Time laminated	Dry time, min
A 3 S 1	1437	1438	1	1525	47
A 3 S 2	1441	1442	1	1529	47
A 3 S 3	1443	1444	1	1531	47
A 3 S 4	1445	1446	1	1536	50
A 3 S 5 O	1446	1447	1	1538	51
A 3 S 6 O	1448	1449	1	1540	51
A 3 S 7 O	1450	1450	1	1532	42
A 3 S 8 O	1451	1452	1	1535	43
A 3 S 9 O	1452	1453	1	1534	41
Average			1		47
A S S 1	1354	1356	2	1413	17
A S S 2	1358	1400	2	1418	18
A S S 3	1401	1403	2	1425	22
A S S 4	1404	1406	2	1427	21
A S S 5 0	1408	1410	2	1439	29
A S S 6 0	1411	1413	2	1441	28
A S S 7 0	1419	1421	2	1443	22
A S S 8 0	1423	1425	2	1453	28
A S S 9 0	1430	1433	3	1500	27
Average			2		24

“Total application times were rounded up to the nearest minute. For example, since it took less than one minute total to apply adhesive to both board and laminate for assembly **A3S7O,** the total application time was rounded up to one minute.

Equations and Examples:

Total application time for assembling **A3S 1,** min = Adhesive application end time - adhesive application start time
= 1437 - 1438
= lmin

Dry time for **A1S1,** min = Time laminated - adhesive application end time
= 1525 - 1438
= 47min

TABLE D-4. APPLIED SOLIDS TO ASSEMBLIES A#S(1-9)

Assembly identification	Board and laminate weight, g [a]	Weight of board, laminate, and adhesive, g	Applied solids, g
A 1 S 1	5,630.8	5,670.3	39.5
A 1 S 2	5,582.0	5,627.6	45.6
A 1 S 3	5,630.5	5,678.8	48.3
A 1 S 4	5,573.7	5,623.4	49.7
A 1 S 5 0	5,593.2	5,637.0	43.8
A 1 S 6 O	5,614.4	5,662.2	47.8
A 1 S 7 O	5,523.2	5,569.9	46.7
A 1 S 8 O	5,529.2	5,577.2	48.0
A 1 S 9 O	5,528.1	5,593.2	65.1
Average	**5,578.3**	**5,626.6**	48.3
A 2 S 1	5,556.2	5,595.5	39.3
A 2 S 2	5,578.6	5,616.2	37.6
A 2 S 3	5,545.2	5,595.2	50.0
A 2 S 4	5,575.1	5,616.1	41.0
A 2 S 5 O	5,613.0	5,652.4	39.4
A 2 S 6 O	5,622.5	5,660.1	37.6
A 2 S 7 O	5,519.5	5,565.0	45.5
A 2 S 8 O	5,489.9	5,541.5	51.6
A 2 S 9 O	5,525.3	5,579.3	54.0
Average	**5,558.4**	**5,602.4**	44.0

“Weights taken from Table D- 1.
1 g = 0.0022 lb.

Eauations and Examples:

Applied solids for assembly Al S 1, in g = weight of board, laminate, and adhesive, g - board and laminate wt., g
= **5,670.3 g - 5,630.8 g**
= 39.5 g

(continued)

TABLE D-4. (Continued)

Assembly identification	Board and laminate weight, g [a]	Weight of board, laminate, and adhesive, g	Applied solids, g
A 3 S 1	5,562.2	5,641.1	78.9
A 3 S 2	5,574.6	5,655.3	80.7
A 3 S 3	5,577.5	5,667.0	89.5
A 3 S 4	5,604.3	5,700.3	96.0
A 3 S 5 0	5,572.3	5,660.7	88.4
A 3 S 6 0	5,678.1	5,735.2	57.1
A 3 S 7 0	5,430.8	5,484.0	53.2
A 3 S 8 O	5,426.3	5,484.6	58.3
A 3 S 9 0	5,467.1	5,533.7	66.6
Average	**5,543.7**	5,618.0	74.3
A S S 1	5,649.6	5,654.2	4.6
A S S 2	5,708.9	5,714.4	5.5
A S S 3	5,739.7	5,745.1	5.4
A S S 4	5,729.0	5,734.2	5.2
A S S 5 0	5,707.5	5,714.7	7.2
A S S 6 0	5,765.4	5,770.3	4.9
A S S 7 0	5,640.3	5,644.7	4.4
A S S 8 0	5,577.2	5,582.5	5.3
A S S 9 0	5.635.0	5.643.1	8.1
Average	**5,683.6**	**5,689.2**	5.6

[a] Weights taken from Table D-l.
1 g = 0.0022 lb.

Equations and Examples:

Applied solids for assembly A3S 1, in g = weight of board, laminate, and adhesive, g - board and laminate wt., g
= 5,641.1 g - 5,562.2 g
= 78.9 g

Appendix E
Physical Property Data

DENSITY, WATER CONTENT, NON-VOLATILE MATTER CONTENT, AND VOC CONTENT

	Adhesive 1				
Physical Property	Part A [a]	Part B [b]	Adhesive 2	Adhesive 3	Control
Density, g/L [c]	1,163	1,101	1,085	1,107	791
Water content, g/g [d]	0.8240 [e]	0.4084	0.406 1	0.4055	0.0038
Non-volatile matter content, g/g [f]	0.1381	0.4596	0.5 146	0.5153	0.1714
Method 24 VOC content, g/g	0.0379	0.1320	0.0793	0.0792	0.8248
VOC content,gVOC/ L of adhesive	44	145	86	88	653
VOC contentg VOC/L of adhesive minus water	1134	265	154	160	655

[a] Adhesive 1 Part A is the activator. It is a zinc solution.
[b] Adhesive 1 Part B is the adhesive.
[c] Values are measured values and are averages of three results from three samples (or six results averaged) of each adhesive, except for Adhesive 1. Densities were measured according to ASTM D 1875-90 at 25°C (77°F).
[d] Values are measured values and are averages of two results from two samples (or four results averaged) of each adhesive, except for Adhesive 1. Water contents are shown in weight fractions and were measured according to ASTM D 3792.
[e] Values are measured values and are averages of one result from three samples (or three results averaged). Water contents are shown in weight fractions and were measured according to the Karl Fischer Titration method.
[f] Values are measured values and are averages of four results from four samples (or eight results averaged) of each adhesive. Non-volatile matter contents are shown in weight fractions and were measured according to ASTM D 2369

Equations and Examples for Adhesive 3:

Method 24 VOC content,
g of VOC / g of adhesive
= 1 - (non-volatile matter content, g/g) - (water content, g/g)
= 1 - 0.5153 - 0.4055
= 0.0792

VOC content,
g of VOC/L of adhesive
= (density, g/L) * (Method 24 VOC content)
= 0.7914 * 0.8248
= 652.75

VOC content,
g of VOC/L of adhesive,
minus water
= [(VOC content, g of VOC/L of adhesive) / (1 - (density, g/L * water content, g/g) / (density of water at 25 °C, g/L)]

= (1 * 88) / [1 -(1,107 * 0.4055)/997.07)]
= 160 g/L

Appendix F
Calculations for Table 3-7

APPLIED VOC EMISSIONS FOR EACH ADHESIVE [a]

	Adhesive 1 [b]	Adhesive 2	Adhesive 3	Control
VOC content, minus water, g/L	145	86	88	653
Density, g/L	1,101	1,085	1,107	791
Weight fraction solids, g/g	.4596	.5146	.5153	.1714
Wet adhesive usedg [c]	105	83	168	64
Wet adhesive used, L	0.0954	0.0765	0.1518	0.0809
Calculated VOC emissions g/m^2, of assembly based on weight of adhesive used	37	18	36	143
Theoretical coverage rate, g/m^2 per side [d]	32	32	32	22
Theoretical VOC emissions g/m^2, per assembly	19	10	10	207

[a] Emissions are expressed as grams per square meter for a constant assembly area of 0.37 m^2 (4 ft^2).
[b] Assumes properties of Part B, the adhesive, of Adhesive 1 since the applied mix ratio of adhesive to activator is 1 part of adhesive, Part B, to 15 parts of the activator, Part A.
[c] Wet adhesive used is the average amount of adhesive used per board/laminate assembly and includes overspray.
[d] Theoretical coverage rates taken from each adhesive manufacturer's technical data sheets which assumes 100 percent of the adhesive applied solids ends up on the substrate.

1 lb/gal = 119.8 g/L.
1 lb = 454 g.
1 gal = 3.7854 L.
1 g/ft^2 = 10.765 g/m^2.

Equations and Examples for Adhesive 3:

Wet adhesive used, L = (wet adhesive used, g) / (density, g/L)
= 168 g / 1,107 g/L
= 0.1518 L

Calculated VOC emissions, g/m', of assembly based on weight of adhesive used = [(VOC content, g/L) * (wet adhesive used, L)] / (assembly surface area adhesive applied to, m^2)

= (88 g/L * 0.1518 L) IO.37 m^2
= 36 g/m^2

Theoretical VOC emissions, g/m^2, per side = [(VOC content, g/L) * (theoretical coverage rate, g/m^2, per side) * 2 sides] / [(weight fraction solids, g/g) * (density, g/L)]

= (88 g/L * 32 g/m^2 * 2 sides) / (0.5153 * 1,107 g/L)
= 10 g/m^2

Appendix G
Calculations for Table 3-8

ADHESIVE COVERAGE AND COST INFORMATION

	Adhesive 1	Adhesive 2	Adhesive 3	Control
Density, g/L	1,101	1,085	1,107	791
Weight fraction solids, g/g	0.4596	0.5 146	0.5153	0.1714
Dry solids applied, g [a]	48	44	74	6
Dry solids applied per side, g/m^2	65	59	100	8
Theoretical dry solids applied, g/m^2	32	32	32	22
COVERAGE				
Theoretical coverage, m^2/L	15.67	17.30	17.66	6.30
Actual coverage, m^2/L	7.79	9.43	5.71	17.99
COSTS				
Cost, US dollars/L on a 208-L basis [b]	8.56	3.88	4.89	1.95
Theoretical cost, US dollars/m*	0.55	0.22	0.28	0.31
Actual cost, US dollars/m*	1.10	0.41	0.86	0.11

[a] Control applied at 22 g/m^2 dry adhesive solids per side. Theoretical coverage for the alternatives is calculated to be 32 g/m^2 dry adhesive solids applied per side.
[b] As of October 1996.
1 $ft^2/gal = 0.025\ m^2/L$.
1 gal = 3.7854 L.
1 $ft^2 = 0.093\ m^2$.

Equations and Examples for Adhesive 3:

Dry solids applied, g/m^2, per side = (Total solids deposited, g) / (2 sides) / (surface area per side, m^2)
= 74 g / 2 / 0.37 m^2
= 100 g/m^2

COVERAGE

Theoretical coverage, m^2/L, applied @ 32 g/m’ dry solids per side = (Weight fraction solids, g/g) * (density, g/L) / (theoretical dry solids applied per side, g/m^2)
= (0.5153 g/g) * (1,107 g/L) / 32 g/m^2
= 18 m^2/L

(continued)

Actual coverage, m^2/L	= (Weight fraction solids, g/g) * (density, g/L) / [(dry solids applied, g) / 2 sides / (surface area, m^2)]
	= (0.5153 g/g) * (1107 g/L) / (74 g / 2 / 0.37 m^2)
	= 6 m^2/L

COSTS

Theoretical cost US dollars/m^2	= (Cost, US dollars/L on a 208-L basis) / (theoretical coverage, m^2/L)
	= 4.9 \$/L / 18 m^2/L
	= 0.28 \$/m^2
Actual cost, US dollars/m^2	= (Cost, US dollars/L on a 208-L basis) / (actual coverage, m^2/L)
	= 4.89 \$/L / 5.71 m^2/L
	= 0.86 \$/m^2