EVALUATION OF SUPERCRITICAL CARBON DIOXIDE TECHNOLOGY TO REDUCE SOLVENT IN SPRAY COATING APPLICATIONS

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, Superfund-related activities, and pollution prevention. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

Passage of the Pollution Prevention Act of 1990 marked a significant change in U.S. policies concerning the generation of hazardous and nonhazardous wastes. This bill implements the national objective of pollution prevention by establishing a source reduction program at the EPA and by assisting States in providing information and technical assistance regarding source reduction. In support of the emphasis on pollution prevention, the Clean Technology Demonstration (CTD) program is designed to identify, evaluate, and/or demonstrate new ideas and technologies that lead to waste reduction. It continues the efforts of the Waste Reduction Innovative Technology Evaluation (WRITE) Program. CTD focuses on evaluating and demonstrating technologies available to a particular industry to minimize pollution at the source. These methods reduce or eliminate transportation, handling, treatment, and disposal of hazardous materials in the environment. The technology evaluation project discussed in this report emphasizes the study and development of methods to reduce waste and prevent pollution.

E. Timothy Oppelt, Director
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ABSTRACT

This evaluation addresses the product quality, waste reduction, and economic issues of spray paint application using supercritical carbon dioxide (CO_2). In the UNICARB™ process developed by Union Carbide, supercritical CO_2 is used to replace some of the solvents in conventional coating formulations. The CO_2 acts as a diluent to reduce the viscosity of the reduced solvent coating formulation for spray application; it also aids in the spray atomization process. CO_2 is introduced into the paint stream by means of specialized equipment which meters and mixes the CO_2 in the proportions selected for optimum coating application. Using this process in the application of nitrocellulose lacquer finish on a chair-finishing line, Pennsylvania House Furniture Company, in White Deer, Pennsylvania, has been able to move from a two-coat to a one-coat finish while maintaining product quality. Product quality evaluation included gloss and hardness measurements, subject ratings by three groups of evaluators, and Pennsylvania House records concerning levels of customer acceptance of furniture units. Pennsylvania House has more than a year's experience producing high-quality products using this technology. VOC emission is reduced because supercritical CO_2, recovered from the wastestreams of other industrial processes, replaces most of the volatile fast- and medium-drying solvents in the solvent-borne coating being applied, and one coat is applied instead of two. Solid wastes from the conventional process and from the supercritical CO_2 spray process are approximately the same per furniture unit sprayed. The equipment costs and other factors that affect the return on investment for this process can be variable, but a payback period of 5 years is estimated for the process as implemented at the White Deer facility.

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CONTENTS

CONTENTS (Cont'd)

FIGURES

TABLES

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SECTION 1

PROJECT DESCRIPTION

This program was conducted by Battelle for the Pollution Prevention Research Branch (PPRB) of the U.S. Environmental Protection Agency with the cooperation of Union Carbide Corporation, Nordson Corporation, and Pennsylvania House Furniture Company. The PPRB is evaluating and demonstrating new technologies for pollution prevention through the Pollution Prevention Clean Technology Demonstration (CTD) Program. The goal of this program is to promote the use of clean technologies that reduce or eliminate sources of pollution in a particular industry. The CTD program is a continuation of efforts of the Process Engineering Section (PES) of PPRB, which directed the efforts of the Waste Reduction Innovative Technology Evaluation (WRITE) Program.

In this particular evaluation, the use of supercritical CO_2 (carbon dioxide) technology for paint spray application is reviewed. Specifically, this technology is evaluated as it is used by Pennsylvania House to apply a nitrocellulose lacquer finish on a chair-finishing line. This process is not specific to the application of nitrocellulose lacquer finishes used by Pennsylvania House. It is used with other coating formulations to coat baking utensils, automotive components, and metal.

If the supercritical CO_2 spray technology process is to be considered a commercially viable alternative for coating applications, it must be capable of producing a product of equal or better quality than the spray process it is replacing. Furthermore, to be considered a candidate for the CTD program, the technology must be environmentally friendly, offering advantages in waste reduction or pollution prevention. The economics of the technology must be quantified and compared with the economics of the existing technology. However, reduction of operating costs is not an absolute criterion for the use of this or any other technology. Other justifications, such as a demonstrated favorable impact on the environment via waste reduction or pollution prevention, would encourage adoption of new operating approaches. This document addresses issues associated with the environmental impact of using supercritical CO_2 technology in paint spray applications, effects on product quality, and the economic ramifications of implementing this technology in the finishing operation at Pennsylvania House.

PROJECT OBJECTIVES

The goal of this study is to provide an independent evaluation of the use of supercritical CO_2 technology for paint spray applications. Specifically, this is an evaluation of the UNICARB™* process as it is used to apply nitrocellulose lacquer on a chair-finishing line at Pennsylvania House Furniture. This study has the following critical objectives:

- Product Quality: Show that coating applied by this spray technology meets company standards for a quality finish.
- Pollution Prevention Potential: Demonstrate that use of this spray application technology to replace solvents in coatings reduces VOCs released in finishing operations.
- Economic Ramifications: Document the cost to install and operate this pollution prevention technology on an existing spray coating finish line.

DESCRIPTION OF THE SITE

The site selected for evaluating this new technology is Pennsylvania House Furniture Company in White Deer, Pennsylvania. The White Deer facility produces cherry and oak chairs, stools, mirrors, dining room tables, and four-poster beds. Pennsylvania House has been using supercritical CO_2 coating technology at its White Deer plant for more than a year to apply a nitrocellulose lacquer finish to wood furniture on its chair line. At current production rates, more than 250 furniture units per day are coated with nitrocellulose lacquer by this process. Plans are under way to expand the use of the technology to a second finish line in the next year.

DESCRIPTION OF THE TECHNOLOGY

Union Carbide Corporation developed the use of supercritical CO_2 for spray coating applications, introducing this technology commercially in 1988 under the UNICARB™ trademark. A number of publications provide thorough descriptions of this process. (See the Reference List, Section 7). Union Carbide claims that the UNICARB™ process is an environmentally friendly way to reduce VOC emissions by using supercritical CO_2 to replace some of the volatile organic solvents that are used conventionally to dilute coatings for spray application. Additionally, Union Carbide

*Mention of tradenames or commercial products does not constitute endorsement or recommendation for use.

claims that expansion of the supercritical CO_2 as it leaves the spray gun nozzle aids in the paint spray atomization process. The net result is a process that makes possible the application of high-quality coatings at reduced levels of VOC emissions.

Supercritical fluids are gases that exist at temperatures and pressures near or above the critical point of the fluid as depicted on a phase diagram (Figure 1). At the critical point, the properties of the liquid and the gas are similar or identical. The resulting single-phase fluid exhibits solvent-like properties that can be altered by adjusting temperature and pressure. A number of gases have been examined for use as supercritical fluids in applications such as industrial and analytical separation processes, cleaning, chromatography, and coating. The UNICARB™ process for coating uses nontoxic, nonflammable carbon dioxide as the supercritical fluid for coating dilution. Carbon dioxide, readily available as a by-product of a variety of industrial processes, has a critical temperature of 31.3°C (88°F) and a critical pressure of 72.9 atm (1070 psi), falling within the ranges already used for heated paint systems and airless spray equipment.

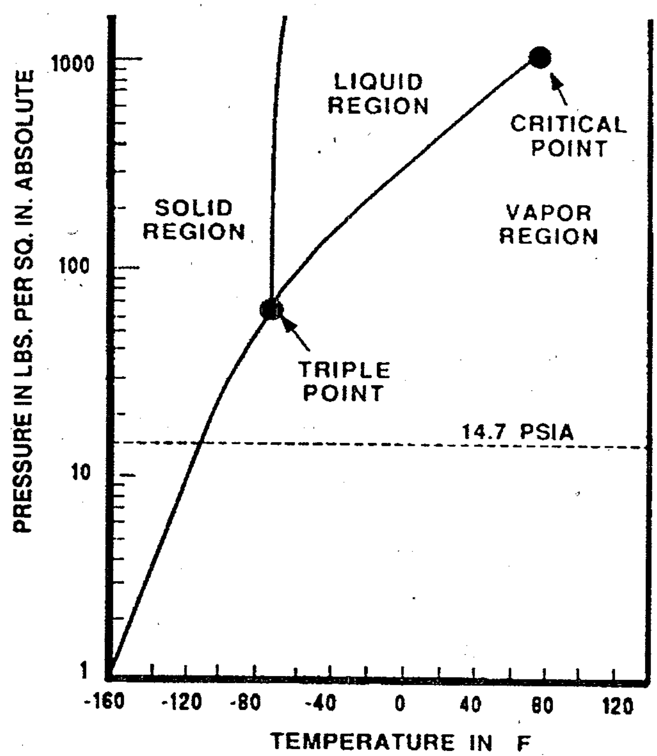

Figure 1. Phase Diagram for Carbon Dioxide.*

* Nielsen, K.A., Busby, D.C., Glancy, C.W., Hoy, K.L., Kuo, A.C., and Lee, C., "Supercritical Fluid Spray Application Technology: A Pollution Prevention Technology for the Future," Union Carbide Chemicals and Plastics Company, Inc. Presented at the 17th Water-Borne & Higher-Solids Coatings Symposium, February 21-23, 1990, New Orleans, LA.

In the UNICARB™ process, the solvent-like properties of supercritical CO_2 are exploited to replace a portion of the organic solvent in the conventional solvent-borne coating formulation. The supercritical CO_2 acts as a diluent solvent to thin the viscous coating just prior to application, so that the coating can be atomized and applied with a modified spray gun. According to Union Carbide, 30 to 80% of the organic solvent in a coating formulation can be replaced with supercritical fluid. Typically, most of the volatile, fast-drying solvents and some of the medium-drying solvents are eliminated, retaining enough medium- and slow-evaporating solvents to obtain proper leveling and film coalescence. The solvent blends may need to be adjusted to optimize performance with the supercritical CO_2 spray technology. This usually can be done without changing the resin chemistry or pigment-loading levels. The solvent level of even conventional high-solids coatings can be reduced further when applied by this process. The actual reduction in solvent content that can be achieved is dictated by a number of factors. These include the type of coating being applied and its exact formulation, the desired film thickness and properties of the applied coating, and the environment in which the coating is being applied.

Thermosetting, thermoplastic, air-dry, and two-component formulations, in clear, pigmented, and metallic coating systems, have been developed successfully for application by supercritical CO_2 spray technology. Limitations exist with pigmented systems because some of the pigments, (e.g., carbon black), may be soluble in the supercritical CO_2. However, other pigments, including aluminum flake, titanium dioxide, and calcium carbonate, have been included successfully in formulations applied using this process. Nitrocellulose, silicone alkyds, acrylics, and a two-part urethane formulation have been developed for supercritical CO_2 application. Union Carbide is currently working on a two-part epoxy system and a phenolic resin formulation.

The supercritical temperature and pressure of CO_2 are within the ranges already used for heated paint systems and airless spray equipment, but special equipment is needed to introduce the CO_2 into the reduced solvent formulations and then heat and pressurize the resultant mixture prior to spraying. Typically, 10 to 50% carbon dioxide by weight may be introduced depending on the solubility in the coating, the solids level, the pigment loading, and the ambient conditions in the spray booth. Heating lowers the coating viscosity for easier pumping but decreases the solubility of the CO_2 in the coating concentrate. Therefore, optimum operating temperature and pressure must be determined and maintained to achieve the best results in each application.

Usually, the coating is heated to 40° to 70°C with spray pressures of 1200 to 1600 psi. The specially formulated coatings are applied with spray guns similar to those used for airless applications. However, because the decompression of supercritical CO_2 results in finer atomization of the sprayed coating and smaller particles than is common with use of airless spray equipment, slight modification of the spray gun nozzle design was required to optimize the spray pattern. The result is a more finely dispersed and more uniform pattern than typically is achieved with conventional air spray equipment.

Nordson Corporation has developed a complete line of special equipment for the UNICARB™ process (Figure 2) and designed the equipment used by Pennsylvania House. A supply unit mixes coating concentrate and carbon dioxide to a desired ratio, pressure, and temperature, and delivers the solution to specially designed spray guns. The size of the supply unit is dictated by production requirements. A microprocessor-based controller continuously monitors the system and allows the operator to adjust the ratio of coating concentrate to carbon dioxide for best results. The supply unit and controller are placed adjacent to, but outside of, the spray booth. The system equipment is available for either manual or automatic operation. Manual and automatic spray guns for electrostatic and non-electrostatic applications can be used with minor modifications to the nozzle. Because the reduced solvent coating is more viscous, a special pumping station is required.

DESCRIPTION OF THE FINISHING PROCESS

Pennsylvania House uses the UNICARB™ process on the chair-finishing line at its plant in White Deer, Pennsylvania, to apply nitrocellulose lacquer finishes. This supercritical CO_2 spray technology has allowed Pennsylvania House to continue using the solvent-borne nitrocellulose lacquer coating that is used widely in the U.S. wood-finishing industry, while reducing VOC emissions from their finishing operation. To bring this technology to production-line use, Pennsylvania House worked closely with Union Carbide to optimize the basic process, Nordson for equipment-related issues, and with Guardsman and Lilly to optimize the formulations of reduced solvent coatings.

The chair-finishing line at the White Deer facility carries chairs, stools, and mirrors from assembly through the finishing process and to packaging. A schematic representation of the finishing operation appears as Figure 3. The finishing process is labor intensive, with manned stations for staining, wiping, rubbing, sanding, polishing, and inspection. The overhead conveyor system runs through the various work stations at 6 to 7 ft per minute; 6 ft per minute is approximately 60-70% of capacity. At this speed, 250-300 units per day are produced. Total time on the line from start to finish is about 4 hours.

Two color stains usually are used to highlight the natural grain and provide color to the wood. Toner stain is sprayed on first, followed by a sprayed mineral-spirit wiping stain, which then is wiped off by hand. Some pieces get a spatter stain for special effects before entering the oven for the first drying step. Oven temperature is maintained at 110°F for all heating steps. The next

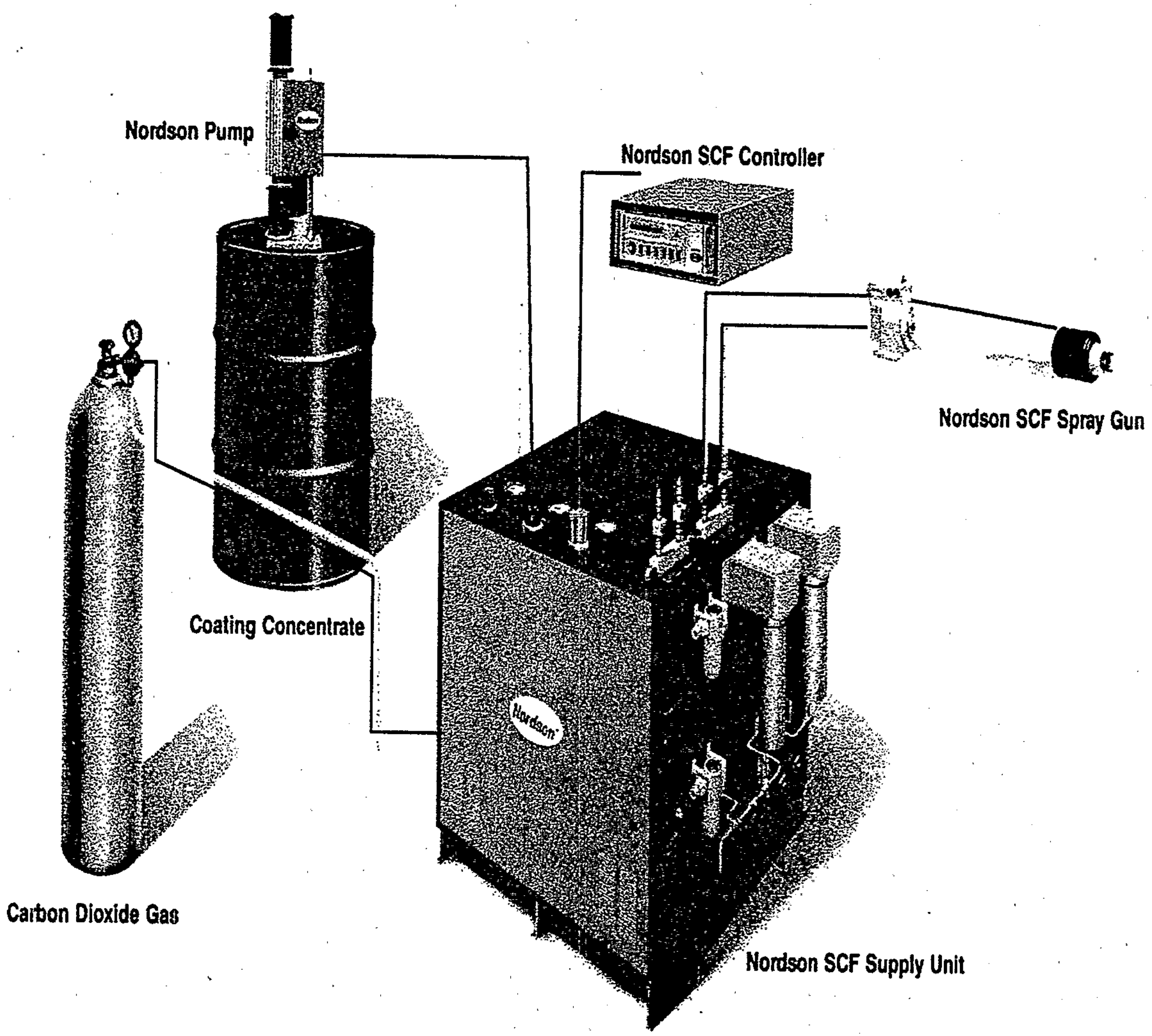

Figure 2. The UNICARB™ system.*

* The UNICARB™ System, Nordson Corporation, 555 Jackson Street, Amherst, Ohio 44001, Telephone: 800-241-8777.

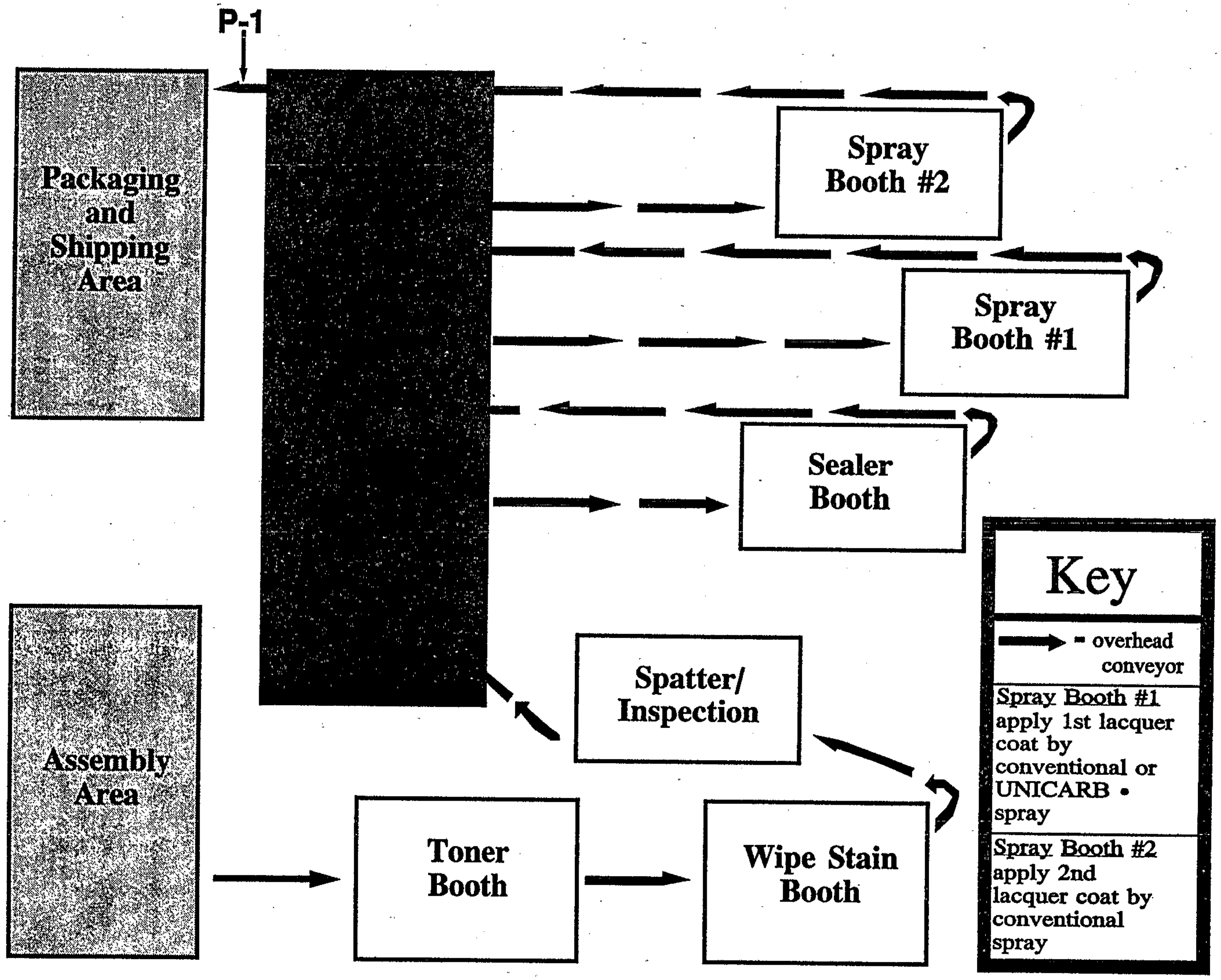

Figure 3. Schematic of chair-finish line at Pennsylvania House White Deer Facility.

step is spray application of a 20%-solids nitrocellulose sealer followed by a second pass through the oven. Light hand sanding is performed if needed before or after application of the sealer.

The nitrocellulose lacquer is spray applied next. In the conventional finishing process, nitrocellulose lacquer (21-23%-solids) is applied manually using airless spray equipment in two coats, with a pass through the oven between the coats. Flash-off time between spraying the coating and entering the oven is 10 to 12 minutes. Oven residence time is 7 minutes. The same flash-off and oven-time intervals are used after the second coat of lacquer. Furniture units remain on the line at ambient temperatures for one hour and forty-five minutes after the last oven pass before they are packaged. When the supercritical CO_2 finishing process is used, only one coat of nitrocellulose lacquer is needed to achieve the desired film build and finish quality. The nitrocellulose lacquer formulation optimized for the Pennsylvania House production line has approximately a 41%-solids content. This coating is applied using the UNICARB™ equipment in spray booth #1, followed by a 10- to 12-minute flash-off period, and a 7-minute pass through the oven. Because Pennsylvania House has not reconfigured the chair conveyor line, the UNICARB™ line follows the existing conveyor line through the unused spray booth #2 and the final stage of the oven before reaching inspection and packaging for shipment. The second oven pass is not required for this process but has no negative effect on the cured finish coat.

Conventional and reformulated nitrocellulose lacquer coatings used by Pennsylvania House are supplied to the spray guns directly from the shipping drums. The drums of coating are equilibrated and mixed in the Pennsylvania House paint room before being pumped through lines to the spray booths. Temperature and humidity changes in the plant sometimes require adjustments in the solvent blend of the formulations for optimal spray results. With conventional lacquer, solvent is added to the drum of coating, which then takes about 1 hour to reach the spray booth. This adjustment process sometimes must be repeated to get the desired results. Once extra solvent has been added to a drum of coating, the contents of the drum have a higher volatile content. With the supercritical CO_2 spray system, the operator simply adjusts the ratio of CO_2 to coating concentrate at the control unit located just outside the spray booth. No additional solvents are introduced into the process, and adjustments are immediately evident.

SUMMARY OF APPROACH

A Quality Assurance Project Plan (QAPP), prepared at the beginning of this study (Battelle, 1993), describes the detailed approach and scientific rationale used to evaluate the UNICARB™ process. The process evaluation included a product quality assessment, an estimation of the pollution prevention potential of this technology, and an economic analysis. A summary of the data used to address each of these issues is presented in Table 1.

TABLE 1. SUMMARY OF EVALUATION CRITERIA

Objective of Evaluation	Sample Type	Property	Criteria	Critical
Product Quality	wooden (cherry) chair-back splats*	gloss	measurement	no
		pencil hardness	measurement	no
		total appearance	subjective:	
			1. Pennsylvania House	yes
			2. Battelle Test Groups	no
Pollution Prevention Potential	conventional coating formulation	percent volatiles/ percent solids	measurement	yes
	UNICARB™ formulation	percent volatiles/ percent solids	measurement	yes
	carbon dioxide	volume used	company records	no
	solid waste	volume disposed	company records	no
Economic Ramifications	UNICARB™ process	capital cost	Nordson Corporation†	yes
		operating cost	company records	yes
		waste disposal	company records	yes

* Substitute for oak panels in QAPP. See Section 2, "On-Site Sample Preparation" for complete explanation.
† 1993 equipment cost figures from Nordson Corporation. See Section 4 for complete explanation.

Product Quality Evaluation

The objective of the product quality evaluation was to determine whether a coating applied by the supercritical CO_2 spray process provides a finish of equal or better quality than the finish achieved by the conventional coating process. Specifically, the objective was to find out whether nitrocellulose lacquer applied by the UNICARB™ process provides a wood finish of equal or better quality than does the conventional nitrocellulose formulation and spray technique previously used by Pennsylvania House Furniture Company. This was accomplished by comparing three sets of chair-back splats that were finished on the Pennsylvania House chair line in an identical manner except for the nitrocellulose lacquer finish—one set of samples was finished using the one-coat supercritical CO_2 spray process and the other two sets of samples were finished using one and two coats (respectively) of the old nitrocellulose formulation and the airless spray equipment still in place on the chair-finishing line.

Pollution Prevention Potential

The pollution prevention potential of this technology is based on reduction in emission of organic solvents added to a coating formulation to control viscosity for spray application. In conventional spray coatings, a blend of solvents is used. Fast-evaporating solvents reduce viscosity for good atomization; medium-evaporating solvents aid in leveling; and slow-evaporating solvents allow time for final film formation. In the supercritical CO_2 spray process, most of the fast- and medium-drying solvents are removed from the formulation, and the slow-drying solvents are adjusted slightly for better film formation. Supercritical CO_2 is used to replace the fast- and medium-drying solvents. Thus, the supercritical CO_2 spray process was expected to reduce VOC emissions from the chair-finishing line at the White Deer Plant. It was important to verify that this technology did not add to other wastestreams while it reduced VOC emissions.

Economic Analysis

The objective of the economic analysis was to determine the payback period for the switch to the supercritical spray process from the conventional system previously used at the White Deer facility. This was accomplished by comparing the operating costs of the UNICARB™ process to the conventional finishing process. The initial investment by Pennsylvania House in capital equipment and installation costs was considered, as were operating costs, which include materials, waste disposal, labor, and utilities. A return on investment (ROI) and payback period for the conversion was calculated.

SECTION 2

PRODUCT QUALITY EVALUATION

Nitrocellulose coating formulations have been used with good results in the U.S. wood finishing industry for many years to give a warm, rich, defect-free appearance. Criteria for judging a quality wood finish are subjective and unique to each company, but the natural beauty of the wood typically is emphasized for stained and clear coat finishes. At Pennsylvania House, the final appearance and quality of the finish are judged through visual examination by inspectors on the coating line. Special attention is given to gloss, smoothness, and lack of surface defects such as blisters or pinholes. The evaluation of product quality is strictly subjective in nature; it is up to the discretion of Pennsylvania House and ultimately the customers who purchase their products. No physical tests are used to generate a quantitative measure of product quality.

In this study, product quality was assessed through independent subjective evaluations of nine test panels (three sample sets) prepared by Pennsylvania House staff on the chair-finishing line. All panels were finished by the same production methods that typically are used on the chair line at Pennsylvania House. Three test panels were finished using the one-coat nitrocellulose UNICARB™ process currently used in production on the chair line at Pennsylvania House, three panels received one coat of the conventional nitrocellulose applied by the conventional airless equipment, and the remaining three chair splats received the full two-coat finish by the conventional process previously used on the chair-finishing line at Pennsylvania House.

Product quality, as discussed in this document, was evaluated through independent evaluations performed by Pennsylvania House staff members, coatings experts in the Battelle Advanced Organic Coatings Group, and other Battelle staff members making up a panel considered representative of the consumer market. The product quality evaluation demonstrated that a coating applied by the UNICARB™ spray process yields a product with a finish quality equal to or better than the quality finish obtained by conventional methods.

ON-SITE SAMPLE PREPARATION

Finished samples for the product quality evaluation were prepared on site by experienced Pennsylvania House staff at the White Deer facility (Table 2). Care was taken to ensure all samples were prepared by the same methods typically used by Pennsylvania House on their chair-finishing line. Because actual furniture units were too costly to be used as samples for the project evaluation, cherry chair-back splats were finished on the chair line in the same way the

TABLE 2. ON-SITE SAMPLING

Field Sample Description	Field Sample Number and Size	Field Sampling Method	Storage Conditions
Wood Panels one coat conventional nitrocellulose	three cherry chair-back splats (7" x 21")	spray on finish line	ambient
Wood Panels two coats conventional nitrocellulose	three cherry chair-back splats (7" x 21")	spray on finish line	ambient
Wood Panels one coat UNICARB™ nitrocellulose	three cherry chair-back splats (7" x 21")	spray on finish line	ambient
Nitrocellulose lacquer conventional formulation	three (450 mL each)†	pump from drum as received	ambient, protect from freezing*
Nitrocellulose lacquer UNICARB™ formulation	three (450 mL each)†	pump from drum as received	ambient, protect from freezing*

* Samples were analyzed within 14 days after sample collection. Unopened reserve samples could be used up to 6 months after collection.
† Two 450-mL field samples collected from each formulation were used for testing. The third was held in reserve.

chair units are routinely finished. Nine panels (splats) were treated with toner stain, dried, sealed, and sanded by staff on the chair line. Then three splats were sprayed with one coat of nitrocellulose lacquer using the UNICARB™ process. The conventional process requires two coats of nitrocellulose lacquer to achieve the desired appearance and film quality; the second coating is applied after the first coating is dried in the oven. Six splats were sprayed with a single coat of conventional nitrocellulose lacquer using airless equipment. After drying, three of these splats were sprayed with a second coat of nitrocellulose lacquer using the conventional airless spray process. The single-coat samples were retained for comparison to the UNICARB™ splats. All three sets of splats made a total of four 7-minute passes through the 110°F oven in the same sequence actually followed during production (Figure 3). After the sample splats reached point P-1 on Figure 3, they were inspected by employees of Pennsylvania House Furniture Company for production defects.

It was possible to spray sample chair splats using the conventional lacquer and equipment because the White Deer facility continues to use conventional nitrocellulose/airless spray equipment on its table finishing line and still has the airless spray equipment in place on the chair line, although it is no longer used in production. The formulation currently used on the table line is the same as that used on the chair line before conversion to the UNICARB™ process. Pennsylvania House is beginning to convert the table line to supercritical CO_2 spray technology also.

At the time of the site visit and under direction of the Battelle Study Leader, two changes were made in the sampling procedure outlined in the QAPP. The first change was the substitution of 7" x 21" cherry chair-back splats for the flat oak 1' x 3' panels described in the QAPP. Pennsylvania House employees suggested the use of cherry instead of oak because the quality of the final finish is somewhat easier to determine on dark stained cherry than on the lighter oak. Because both oak and cherry are used routinely in chairs at White Deer, the employees are skilled in handling both. In addition, the chair-back splats simulate the geometry of the furniture surfaces coated on the chair line better than do flat, rectangular panels. The second change in procedure compensated for the fact that the sample splats could not be hung on the chair conveyor and had to be manually transported. In order to simulate the processing sequence and timing intervals, a marker was attached to an empty hanger on the conveyor line and followed through the production process. These deviations from the sampling procedures specified in Section 3.0 of the QAPP were approved by the Battelle Study Leader in the field and are documented in the laboratory record book.

QUALITY EVALUATIONS

The objective of the product quality evaluation was to determine whether the nitrocellulose lacquer finish applied using the UNICARB™ process provides a wood finish of equal or better quality than that of the conventional nitrocellulose formulation and spray technique previously used by Pennsylvania House Furniture Company. This was accomplished by performing three independent evaluations of the three sets of chair splats that were finished by Pennsylvania House for this study. Pennsylvania House experts provided a visual judgment of the finish quality of each of the nine sample splats just as they typically would do for their furniture units. The ratings of the Pennsylvania House experts were considered the critical factor in judging finish quality. To provide an additional perspective on product quality, the coated sample splats also were evaluated subjectively for gloss, smoothness, and overall appearance by two test groups at Battelle: a group of three coating experts from Battelle's Advanced Organic Coatings Group, experienced in coatings technology; and a second test group made up of ten Battelle staff members having no professional expertise in coatings. This second group was considered representative of general consumer interests. While the results of the viewer evaluations at Battelle are not considered critical to the product quality evaluation, they are presented as an objective comparison to the ratings given by the Pennsylvania House experts.

The Finish Quality Evaluation Sample Panel Rating Form completed for each of the sample splats by the Pennsylvania House experts and the members of the Battelle test groups is presented in Figure 4. The subjective evaluation of "total appearance" is largely dependent on visual observation of two factors—gloss and smoothness (tactile). A rating of "1" indicates high quality, a rating of "2" is acceptable quality, and a rating of "3" means unacceptable quality.

FINISH QUALITY EVALUATION SAMPLE PANEL RATING FORM

Please rate the sample panel identified on this sheet on the following scale of 1 to 3 for gloss, smoothness, and overall appearance:

1 = high quality
2 = acceptable quality
3 = unacceptable quality

Sample ID Number ______________________

Observer Name ______________________

Company ______________________

Date ______________________

Property	Rating
Gloss	________
Smoothness	________
Total Appearance	________

Reviewed By ______________ **Date** ________

Figure 4. Rating sheet for subjective evaluation of finish quality.

The results of the Finish Quality evaluations are presented in Tables 3, 4, and 5, and then summarized in Table 6. The total appearance of each of the splats is summarized by a pass/fail criteria. A single rating of "3" (unacceptable quality) in total appearance by any expert (Pennsylvania House or Battelle) merited a "fail," indicating that the quality of the sample finish was unacceptable. Two ratings of "3" by the non-expert group were taken as sufficient criteria for failure, indicating that the product would not meet consumer appeal. The results of the independent quality evaluations clearly demonstrate that sample panels finished by the UNICARB™ process are of consistently better quality.

TABLE 3. FINISH QUALITY EVALUATION RESULTS BY PENNSYLVANIA HOUSE REPRESENTATIVES

Process	Sample Number	Gloss		Smoothness		Total Appearance		Total Appearance (Pass/Fail)
		PH-1	PH-2	PH-1	PH-2	PH-1	PH-2	
Conventional One Coat Process	46482-9-1	3	3	3	2	3	3	Fail
	46482-9-2	1	1	2	1	2	1	Pass
	46482-9-3	3	3	2	3	3	3	Fail
Conventional Two-Coat Process	46482-10-1	2	1	3	2	3	2	Fail
	46482-10-2	1	1	1	1	1	1	Pass
	46482-10-3	1	1	3	3	3	2	Fail
UNICARB™ Process	46482-11-1	1	2	2	2	1	2	Pass
	46482-11-2	1	2	2	3	2	2	Pass
	46482-11-3	1	2	1	2	1	2	Pass

Note: A single rating of "3" for TOTAL APPEARANCE by any expert resulted in a fail.

In addition to evaluating individual sample splats, the test groups at Battelle were asked to view three groups of three mixed spats, and to chose the panel with the best overall appearance (Table 7). Each group of mixed splats included a splat sprayed with the supercritical CO_2 technology, a splat with one coat of conventionally applied nitrocellulose lacquer, and a splat finished with two coats of conventionally applied nitrocellulose lacquer. Once again, the results of this comparative evaluation demonstrated a preference for the UNICARB™-finished splats.

TABLE 4. FINISH QUALITY EVALUATION RESULTS BY BATTELLE COATINGS EXPERTS

Process	Sample Number	Gloss			Smoothness			Total Appearance			Total Appearance (Pass/Fail)*
		A	B	C	A	B	C	A	B	C	
Conventional One-Coat Process	46482-9-1	3	3	3	2	1	2	2	2	3	Fail
	46482-9-2	2	2	2	2	2	2	2	2	2	Pass
	46482-9-3	3	2	3	2	2	3	2	2	3	Fail
Conventional Two-Coat Process	46482-10-1	2	2	1	3	3	1	3	2	1	Fail
	46482-10-2	2	2	1	3	2	1	3	2	2	Fail
	46482-10-3	2	2	2	3	1	2	3	2	2	Fail
UNICARB™ Process	46482-11-1	2	2	2	3	3	2	2	2	2	Pass
	46482-11-2	2	2	2	2	2	2	2	2	2	Pass
	46482-11-3	1	1	2	2	2	2	2	2	3	Fail

* One rating of "3" for TOTAL APPEARANCE by any expert resulted in a fail.

TABLE 5. FINISH QUALITY EVALUATION RESULTS BY NON-EXPERT BATTELLE TEST GROUP

Sample Number	Gloss										Smoothness										Total Appearance										Total Appearance (Pass/Fail)*
	A	B	C	D	E	F	G	H	I	J	A	B	C	D	E	F	G	H	I	J	A	B	C	D	E	F	G	H	I	J	
46482-9-1	2	1	3	1	3	2	2	3	2	2	2	3	2	1	1	2	1	2	2	2	2	3	2	1	3	2	2	3	2	2	Fail
46482-9-1	1	1	2	1	3	3	1	2	2	2	2	3	3	2	2	2	2	1	1	2	2	2	2	2	2	2	1	2	2	2	Pass
46482-9-3	2	1	3	1	3	3	2	2	3	2	2	3	3	1	2	3	2	1	2	2	2	2	3	1	2	3	2	2	2	2	Fail
46482-10-1	1	2	2	2	2	3	1	1	1	2	2	1	2	1	3	3	2	1	2	2	2	1	2	2	3	3	1	1	2	2	Fail
46482-10-2	1	2	2	2	2	2	2	2	2	2	2	1	2	3	1	3	2	2	3	2	2	2	3	3	2	2	2	2	3	2	Fail
46482-10-3	2	2	2	2	3	2	2	2	2	2	2	1	3	3	3	3	3	3	2	2	2	1	3	3	3	2	2	2	2	3	Fail
46482-11-1	1	2	2	2	2	2	1	2	2	2	2	2	1	2	1	3	2	1	1	1	2	3	1	2	2	2	2	1	2	2	Pass
46482-11-2	1	2	2	2	2	3	1	2	1	2	2	3	2	1	2	3	2	1	2	2	2	2	2	2	2	3	1	2	2	2	Pass
46482-11-3	1	3	2	2	2	2	1	2	1	1	2	2	2	1	2	2	2	1	1	2	2	2	2	2	2	2	1	2	1	1	Pass

* Two ratings of "3" for TOTAL APPEARANCE by any non-expert resulted in a fail.

TABLE 6. SUMMARY OF FINISH QUALITY RESULTS

Process	Sample Number	Battelle Experts*	Battelle Non-Experts†	Pennsylvania House Experts*
Conventional One-Coat Process	46482-9-1	Fail	Fail	Fail
	46482-9-2	Pass	Pass	Pass
	46482-9-3	Fail	Fail	Fail
Conventional Two-Coat Process	46482-10-1	Fail	Fail	Fail
	46482-10-2	Fail	Fail	Pass
	46482-10-3	Fail	Fail	Fail
UNICARB™ Process	46482-11-1	Pass	Pass	Pass
	46482-11-2	Pass	Pass	Pass
	46482-11-3	Fail	Pass	Pass

* A single rating of "3" for TOTAL APPEARANCE by any expert resulted in a fail.
† Two ratings of "3" for TOTAL APPEARANCE by any non-expert resulted in a fail.

TABLE 7. BEST OVERALL PANEL SELECTED BY THE NON-EXPERT BATTELLE TEST GROUP

Process	Sample Number	Number Times Rated as Best
Conventional One-Coat Process	46482-9-1	4
	46482-9-2	2
	46482-9-3	2
Conventional Two-Coat Process	46482-10-1	2
	46482-10-2	1
	46482-10-3	1
UNICARB™ Process	46482-11-1	6
	46482-11-2	5
	46482-11-3	7

In addition to the subjective visual inspections of the test samples, Battelle wanted to determine some of the physical attributes of the finished samples for comparative purposes. Measurements of gloss (Table 8) and pencil hardness (Table 9), using standard ASTM test methods, were taken to generate additional data on the physical attributes of the coating. Although these measurements are not critical to the product quality evaluation, they do provide some quantitative insight into the physical attributes of the finish of each of the coating processes.

TABLE 8. GLOSS DATA ON SAMPLE PANELS

Finishing Process	Sample Number	Average Gloss Data/Panel	Average Gloss Data/Set
Conventional One Coat	46482-9-1	20.3 ± 4.3	20.3
	46482-9-2	20.4 ± 3.1	
	46482-9-3	20.3 ± 3.1	
Conventional Two Coat	46482-10-1	33.2 ± 1.6	32.3
	46482-10-2	35.0 ± 2.2	
	46482-10-3	28.7 ± 2.8	
UNICARB™	46482-11-1	35.3 ± 3.2	31.5
	46482-11-2	30.5 ± 3.1	
	46482-11-3	28.7 ± 2.9	

The number of gloss measurements taken on each splat differed from that specified in the QAPP. The splats evaluated measured approximately 7 inches x 21 inches. The test procedures outlined in ASTM D529 recommend averaging six gloss measurements for a 3-inch x 6-inch sample area, which correlates to 49 measurements on the 7-inch x 21-inch splat. The mean and standard deviation of the 49 data points represent the overall gloss appearance of each sample, alleviating subjective biases of the person performing the measurements while still incorporating the assessment of any nonuniformity in the gloss across the sample surface. The breadth in standard deviation of the data can be used as a gauge of the uniformity of the sample finish. Gloss test results for each of the nine panels are reported as the mean of 49 determinations and then averaged for each of the sample sets for easy comparison among each of the finishing processes in Table 8. The averaged gloss data for the UNICARB™ samples are statistically the same as those for the conventional two-coat process. The gloss data of both of these sets show that they are substantially glossier than the one-coat conventional finish sample set.

TABLE 9. PENCIL HARDNESS TEST RESULTS

Finishing Process	Sample Number	Hardness Values			Range
Conventional One Coat	46482-9-1	3B	3B	2B	3B-2B
	46482-9-2	3B	3B	2B	
	46482-9-3	2B	3B	3B	
Conventional Two Coat	46482-10-1	B	HB	HB	B-HB
	46482-10-2	B	HB	B	
	46482-10-3	B	B	B	
UNICARB™	46482-11-1	3B	3B	2B	3B-2B
	46482-11-2	3B	3B	3B	
	46482-11-3	3B	3B	3B	

The hardness of the finish on the wood samples was measured on each of the nine coated wood panels using ASTM D3363. Three readings were taken on each panel. The results did not differ by more than one hardness unit for each panel and each type of coating. The degree of hardness is determined using the following scale (from soft to hard): 6B-5B-4B-3B-2B-B-HB-F-H-2H-3H-4H-5H-6H. The conventional two-coat system appears harder than the other samples by approximately 2 hardness units. The one-coat conventional and the UNICARB™ coatings are essentially the same hardness. The difference in the hardness data could be attributed to a difference in film thickness between the two-coat conventional process and the one-coat applications. Because accurate measurement of film thickness on wood substrates is difficult to obtain, film thickness data are not available to substantiate further comment.

PRODUCT QUALITY ASSESSMENT

The results of the product quality assessment indicate clearly that the nitrocellulose lacquer finish applied by the supercritical CO_2 process is of equal or better quality than the finish obtained by conventional methods. Product quality verification was supported by coating experts, who typically will be more critical of the more subtle aspects of the coating finish, and by non-expert examinations. Both groups indicate that the UNICARB™ process will provide a finish with acceptable consumer appeal. Thus, it is concluded that the use of this process for the application of nitrocellulose lacquer finishes on the chair line at Pennsylvania House in no way compromises the quality of the finished product. These results are supported by the fact that Pennsylvania House has not seen an increase in returns since the inception of the UNICARB™ process. Further, the number of chairs that have to be reworked in the plant to remove finish defects before shipping has decreased, indicating that the production efficiency has remained the same or increased slightly since the UNICARB™ process was implemented.

SECTION 3

POLLUTION PREVENTION POTENTIAL

The primary impetus for considering any technology for evaluation under the Clean Technology Demonstration Program is that the technology have a measurable and positive impact on the environment. This effect may be measured in terms of pollution prevention or waste volume reduction. Pollution prevention addresses the specific hazards of individual pollutants (e.g., solvent) in the gross wastestream, whereas volume reduction addresses the effects of waste products on environmental resources (e.g., landfill space).

POLLUTION PREVENTION

The pollution prevention potential of the UNICARB™ process is manifested by the reduction in emissions of organic solvents that are added to a coating formulation to control the viscosity for spray application. Because the UNICARB™ process uses supercritical CO_2 to replace most of the fast- and medium-drying solvents in the conventional formulation, a reduction in VOC emissions from the chair-finishing line at the White Deer facility is expected. Although reducing VOC emissions is important, it is equally important to demonstrate that the UNICARB™ process does not add pollutants to other wastestreams.

In this evaluation, the pollution prevention potential of the UNICARB™ process was determined by carefully considering all wastestreams. The nitrocellulose lacquer finishing process used on the chair line can contribute to pollution in two ways: VOC emissions from the coating formulation, and spray booth wastes, including solvent-laden filters and nitrocellulose dust.

VOC EMISSIONS

VOC emissions using the conventional and UNICARB™ process were estimated in terms of the total amount of volatile compounds emitted on an annual basis, considering a constant volume of production. The total amount of VOCs emitted by each process was calculated using the percent volatile content of the respective coating systems and the amount of each coating needed to coat the same number of furniture units. By using the UNICARB™ process, Pennsylvania House has been able to reduce the number of coats of nitrocellulose lacquer from two to one. Therefore, the calculation of VOCs emitted must take into account the difference in the amount of coating actually sprayed to coat a furniture unit by the conventional and by the UNICARB™ process. Pennsylvania House records were used in conjunction with test measurements to determine the amount of VOCs emitted using the conventional and UNICARB™ processes.

The volume of nitrocellulose lacquer used in each finishing operation was determined during the initial phases of implementing the UNICARB™ process at Pennsylvania House. Metering devices were placed in line on the airless spray guns used to apply the conventional nitrocellulose formulation, and on the coating inlet line to the supercritical fluid (SCF) supply unit used to feed the mixture of coating concentrate and supercritical CO_2 to the modified spray guns used with the UNICARB™ process. Pennsylvania House records indicate that it takes approximately 16 oz of the conventional formulation to apply the two coats needed to achieve the desired quality in the finished product. The UNICARB™ process required about 7 oz of the reduced solvent formulation per furniture unit to achieve the same quality. Less volume of coating is required using the UNICARB™ process for two reasons: the higher solids content of the UNICARB™ formulation means more resin is transferred to the substrate per volume of formulation sprayed; and the increased viscosity of the film deposited by the UNICARB™ process inhibits film buildup by soaking into the wood substrate.

Data on the volatile content of the conventional nitrocellulose coating and the UNICARB™ coating were obtained from the coatings formulator (Lilly) and from direct determination of percent volatile/percent solids content of samples collected by the Battelle project team. VOC contents were determined by methods outlined in ASTM D2369. Liquid samples of both the conventional nitrocellulose coating and the nitrocellulose coating modified for the UNICARB™ process were collected for laboratory analysis. Coating formulation samples were taken from drums of coating material received by Pennsylvania House from Lilly. The supplier, lot number, and date were recorded in the laboratory record book for each field sample. At the White Deer facility, drums of coating are temperature equilibrated in the paint room for at least 24 hours before mixing and dispensing to the spray guns. Three samples were pumped into glass jars with Teflon® lid liners from a drum of conventional solvent-based nitrocellulose and three from a drum of the nitrocellulose coating reformulated for the UNICARB™ process. Sample containers were sealed to prevent evaporation during shipping.

A summary of the volatile compounds, extracted from the Material Safety Data Sheets (MSDSs), for each of the formulations (in the conventional system, coat one and coat two are the same formulation) is presented in Table 10 as a percentage of the weight of a gal of formulation. VOC data, as determined by laboratory analysis (ASTM D2369), are included for comparison. If the solvent listed is on the EPA's list of hazardous air pollutants (HAPs), a notation is made. 'Other' indicates unspecified volatile content, and is taken as the difference between the volatile content reported on the MSDSs and the sum of the solvent contents reported. The MSDSs indicate the UNICARB™ coating is formulated using 17.5% less solvents (on an absolute basis) than the conventional formulation, with only 9.67% of its formulation being comprised of HAP materials compared to 35.78% for the conventional formulation. On a per-gallon-of-coating-sprayed basis, this would result in a relative decrease in VOC emissions of 22.81%, with a 72.97% decrease in HAPs using the UNICARB™ formulation. VOC contents on a lb/gal basis are reported on the MSDSs as 4.7 lb/gal for the UNICARB™ formulation and 5.9 lb/gal for the conventional system.

TABLE 10. DESCRIPTION OF VOCS FROM MATERIAL SAFETY DATA SHEETS AND LABORATORY ANALYSIS

Materials Description	HAP (Y/N)	Conventional (% by weight)	UNICARB™ (% by weight)
MEK-heptanone	No		37.25
methoxypropylacetate	No	7.36	
xylene	Yes	16.80	
isopropanol	No	11.20	6.55
toluene	Yes	10.39	
N-butyl acetate	No	11.83	
isobutyl acetate	No	6.89	
2-butoxyethanol	Yes	3.27	9.67
MIBK	Yes	5.32	
isopropyl acetate	No	1.46	
Other		2.37	5.87
Total VOC (% by weight)	**MSDS:**	**76.88**	**59.34**
Total VOC (% by weight)	**Average of Analytical Data***	**66.69 ±0.067**	**64.23 ±0.186**

* Complete listing of raw data in the Appendix, Tables A-1 and A-2.

These data did not compare well with the ASTM D2369 results obtained from the laboratory analysis. The VOC content of each of the formulations was determined on each of the two replicate samples using ASTM D2369. Experiments were repeated on two different days. The raw data for all determinations are shown in the Appendix. The laboratory analysis indicated that the conventional formulation actually was higher in solids than it was supposed to have been formulated at, and the UNICARB™ formulation to be lower in solids. Results are listed in Table 10 as an average of the raw data for each formulation. By the laboratory results, a relative decrease in solvent content of only 3.69% was noted, or a difference of only 2.46% solvent per gal on an absolute basis. The reasons for the measured differences are not clear, because the data reported were generated according to standard procedures. Repeated analyses did not generate different results. The data may indeed be accurate representations of the samples collected, but may not be accurate representations of the formulations. Because Lilly routinely performs these determinations, and is bound to accurately report the results of these evaluations on their MSDSs, other factors must be responsible for the differences noted.

The conventional formulation was determined by Battelle in the laboratory analysis to be 33.31%-solids, compared to the 23.12%-solids level at which it is supposed to be formulated. Aside from the fact that higher solids coatings are more expensive to formulate, a higher solids coating would not spray the same as a formulation more diluted with solvent. The samples taken at Pennsylvania House were pumped from a drum that was on line and being used for production on the table line with satisfactory results. Therefore, it is highly unlikely the solvent blend of the formulation differed much from specification because the paint room operator would have been made aware of this when the coating applicators started getting bad product. The one reasonable explanation for the difference is the fast evaporation rate of the fast-drying solvents comprising a significant portion of the conventional formulation. Solvent evaporation could have occurred at two points in the evaluation: (1) as the sample formulations were being pumped into the sample jars during field collection; and (2) sample handling during the VOC determinations. Weight loss during the initial weighing of the samples for the VOC determinations was noted during laboratory analysis. Solvent evaporation at any step in the evaluation process would have the net result of increasing the measured solids content or decreasing the VOC levels.

Although some evaporation would be expected to occur with the UNICARB™ formulation also, it would not be expected to be as severe a factor because most of the fast-drying solvents were removed from the UNICARB™ formulation to begin with. The ASTM data indicate the volatile content in the UNICARB™ formulation to be higher (64.23) than reported in the MSDS by approximately 5%. The precision of the ASTM method may account for part of this. A relative difference of 4.7% is allowed between laboratories.

Undoubtedly, inaccurate determination of the VOC content of the formulations can affect the results of the pollution prevention potential evaluation. If the difference in VOC content is not very large between the two formulations, then the overall reduction in emissions will not be that significant on a gallon-per-gallon basis. If the actual difference in VOC content is reflected accurately by the data on the MSDSs, and the difference in VOC content is substantial, then the pollution prevention potential of the supercritical CO_2 spray process will be underestimated if the laboratory results are used in the evaluation. Because there are some probable reasons why the laboratory analysis may be inaccurate, the data from the MSDSs will be used for further calculations. These data are believed to be accurate for reasons previously stated.

In order to determine the reduction in VOC emissions on an annual basis, the number of gal of each formulation sprayed per year (Q) was estimated using the following equation:

$$Q = PV \times DOP \times OZ/16 \times 1/D$$

where PV is the daily production volume, DOP is the days of operation per year, OZ is the amount of coating sprayed per unit, and D is the density of the coating formulation. An average production rate of 250 chairs a day was assumed, with 200 production days a year. Pennsylvania House operates one shift a day. Density is reported on the MSDSs as 8.0 lb/gal for the UNICARB™ formulation and 7.7 lb/gal for the conventional formulation. The total volume of each coating sprayed per unit has been established at 7 oz for the one-coat UNICARB™ process and 16 oz for the two coats of conventional formulation. Under these assumptions, 2734 gal of UNICARB™ formulation are needed compared to the 6494 gal of the conventional formulation needed to finish the same number of units.

The difference between the volatile content of the conventional coating sprayed and the volatile content of the UNICARB™ coating sprayed represents the net change in volatiles emitted into the airstream.

$$V_c - V_s = R_v$$

V_c = VOC of conventional coatings sprayed annually (lb VOC/year)

V_s = VOC of UNICARB™ coatings sprayed annually (lb VOC/year)

R_v = net change annually in VOC emissions (lb VOC/year)

$$38{,}315 \text{ lb VOC/year} - 12{,}850 \text{ lb VOC/year} = 25{,}465 \text{ lb VOC/year}$$

$$R_v = 25{,}465 \text{ lb VOC/year}$$

Use of the UNICARB™ one-coat finish process could reduce VOCs by 25,465 lb/year at the White Deer Facility.

Using the VOC content reported on the MSDSs, this corresponds to an annual VOC emmision reduction of 67.5%. Even if the VOC content of the formulations were the same, an annual reduction in VOC emissions of 57.9% would be achieved simply due to the decreased amount of formulation needed per unit using the UNICARB™ process to achieve the same quality of finish.

CARBON DIOXIDE

Although a reduction in VOC emissions is important, it is equally important to demonstrate that the UNICARB™ process does not add pollutants to other wastestreams. Supercritical CO_2 is used in the UNICARB™ process to decrease VOC emissions. The reduced solvent formulation used by Pennsylvania House requires approximately 2.43 lb of CO_2 for every gal of coating concentrate sprayed with the UNICARB™ process. The actual quantity of CO_2 needed may require slight adjustment by the operator at the SCF control unit to compensate for changes in environmental conditions.

The amount of CO_2 released annually into the atmosphere can be determined based on annual usage of the UNICARB™ formulation. This has been determined previously to be 2734.4 gal for an annual production of 50,000 units. Using this as a basis, the annual emission of CO_2 from the finishing process is expected to be 6644 lbs (2.43 lb/gal x 2734 gal).

Any process that releases CO_2 into the atmosphere will be questioned in today's ecological environment. However, it is important to remember that carbon dioxide is not being "produced" through use of the UNICARB™ process; it is simply being used as a substitute solvent to thin and aid in the spray atomization process. The CO_2 used in this technology is supplied by various distributors of CO_2 which obtain and sometimes purify CO_2 generated as a by-product of other chemical processes. It is neither efficient nor economically favorable to "manufacture" CO_2. Thus, CO_2 used in processes such as supercritical CO_2 spray application of coatings does not actually contribute to the emission of CO_2 into the atmosphere. These methods simply use CO_2 that would have been released into the atmosphere as the result of other processes. The net result is that the UNICARB™ process does not contribute to the greenhouse effect. In fact, this process may actually help prevent CO_2 generation by reducing VOC emissions, because CO_2 is a natural by-product of the decomposition of many organic compounds, as well as a by-product of incineration methods used for reducing VOC emissions.

WASTE REDUCTION

Coating overspray at Pennsylvania House is collected on dry filters that are compressed and stored in 55-gal drums for disposal by landfill. One drum, at a disposal cost of $150/55 gal drum, can hold about 200 compacted filters and solid debris. Waste products generated will include dry and solvent-laden filters and nitrocellulose dust, both loose and trapped in the filters. No liquid waste was generated. Because Pennsylvania House does not separate waste by production lines, no physical data were available for the solid wastestream analysis. However, discussions with Pennsylvania House management and staff consistently indicated that the solid and liquid wastestreams were unaffected by the conversion to the supercritical CO_2 technology.

The chair-finishing process is the same except for the application of the nitrocellulose lacquer finish. Using the old process, two booths were in operation which required cleaning and maintenance. With the UNICARB™ process, only one booth is needed. The transfer efficiency of the modified UNICARB™ spray gun and the air-assisted spray gun are both approximately 50% based on Union Carbide records. However, due to the increased solids content of the UNICARB™ formulation, more solid waste is generated from the overspray by the UNICARB™ process. The 28 dry filters in each of the two spray booths needed for the conventional two-coat finishing process were changed once per week for a total disposal rate of 56 filters/week. The 28 dry filters in the one spray booth required for UNICARB™ finishing are changed twice per week for a total of 56 filters/week. Dry paint and dust from the booths is packed in the disposal drums with the filters, but no increase or decrease in the total volume of these products was noted. In conclusion, no change was observed by Pennsylvania House in the volume of solid waste generated by converting to the supercritical CO_2 spray process on the chair line.

POLLUTION PREVENTION ASSESSMENT

The results of the pollution prevention analysis clearly indicate that a reduction in VOC emissions occurred with use of the UNICARB™ process. The only new by-product of the process introduced into the wastestream is CO_2, but market information clearly indicates that the CO_2 sold commercially is itself a by-product of other production processes. Thus, the emission of CO_2 from the UNICARB™ process is not considered a detriment to the environment. Although the higher solids UNICARB™ formulation made it necessary to clean the spray booth more often, the difference in waste generation was offset by the fact that only one spray booth is needed with the UNICARB™ process.

SECTION 4

ECONOMIC ANALYSIS

The economic evaluation of this technology involved comparing the cost of operating the chair-finishing line using the supercritical CO_2 spray process to the costs associated with operating the line using the conventional process. A return on investment (ROI) was determined for the conversion to the supercritical CO_2 spray process. The ROI was based on the costs associated with capital expenditures, including equipment and installation, and the return on this investment generated through lower personnel, operating, and materials costs. A summary of all costs used in computing the ROI is provided in Figure 5.

CAPITAL INVESTMENT

The UNICARB™ system equipment used by Pennsylvania House was supplied by Nordson Corporation. A schematic of this system is presented in Figure 2. The equipment used at Pennsylvania House was developmental and not reflective of cost of equipment now commercially available.

Nordson provided a current price quote for a system such as the one used in production at Pennsylvania House. The price quote included the SCF Supply Unit and Controller ($35,000) specially suited for wood finishing applications and an operating capacity of 4 gal/min, spray gun ($1,000), a supply pump for the reduced solvent coating ($10,000), and installation costs ($12,000), which included piping to the paint room and CO_2 tank, electrical supplies, and labor. Installation can be performed during one shift, if production is taken off line. The actual time to optimize use for production quality will vary depending on the actual finishing process. The CO_2 tank bulk storage used at Pennsylvania House is supplied by Cardox. The 16-ton tank rents for $500 a month, and the CO_2 pump rents for $250 a month. The current cost of CO_2 is $0.07 a lb.

CAPITAL COSTS

Initial Investment: $58,000

Equipment:

SCF Supply Unit/Controller:	$35,000
SCF Spray Guns (1)	$ 1,000
Special Pump for Reduced Solvent Coating:	$10,000
TOTAL:	$46,000

Installation Costs:

Electrical supplies/installation:	
Piping for CO_2 and coating/installation:	
TOTAL:	$12,000

OPERATING COSTS

Basis: 250 chairs/day x 1 shift/day x 200 working days/year = 50,000 chairs/year

UNICARB PROCESS ($/year): $45,546

Coating Formulation ($/year):

7 oz of coating/chair x 50,000 chairs = 350,000 oz/year

350,000 oz x 1 lb/16 oz x 1 gal/8.0 lb = 2,734.4 gal

2734.4 gal x $13.11/gal = $35,848

Carbon Dioxide ($/year):

Equipment Rental:

16 ton Storage Tank ($/year):	$6,000
CO_2 pump ($/year):	$3,000

Usage:

2.43 lb CO_2/gal of concentrate x 2734.4 gal/year = 6645 lb/year

6645 lb @ $0.07/lb ($/year) = $465

assume loss factor of 1.5 $ 698

CONVENTIONAL ($/year): $46,883

16 oz of coating/chair x 50,000 chairs = 800,000 oz/year

800,000 oz x 1 lb/16 oz x 1 gal/7.7 lb = 6493.5 gal

6494 gal x $7.22/gal = $46,883

OPERATIONAL SAVINGS AT PENNSYLVANIA HOUSE

Labor ($/year):$46,000

W/UNICARB: one less finisher @ $23,000/year
one less sander @ $23,000/year

Electricity ($/year):$11,000

W/UNICARB: one less booth to operate because only one coat is applied

Saving in Propane Possible ($/year):$18,000

W/UNICARB: one less coat is applied, last pass through oven is not needed, could partition off and turn off burners

Figure 5. Cost Analysis for CO_2 Program.

RAW MATERIALS

Raw material costs were provided by Pennsylvania House for the supercritical CO_2 adjusted formulation ($13.11/gal) and the conventional formulation ($7.22/gal). The annual costs of raw materials were determined using the previous estimates for the amount of each formulation needed to finish an annual production volume of 50,000 units (250 units/day, 200 units). The conventional formulation required 6,494 gal of coating, for an annual cost of $46,883. The UNICARB™ formulation required 2,734 gal at an annual cost of $35,848. However, the UNICARB™ process requires an additional expense for the CO_2. Assuming a use rate of 2.43 lb CO_2/gal concentrate, with 2734.4 gal of coating 6645 lb of CO_2 would be needed, at a total cost of $465/year. Some boil off and loss due to other factors is expected. Assuming a loss rate of 50%, the total annual cost would still be $698. Although a raw materials savings of $10,337 is realized annually for the actual formulations, this cost is almost offset by the $9,000 in leasing fees for the CO_2 tank and pump, for a net savings of $1,337. No change in cost is assumed for filters or other operating materials.

OPERATING COSTS

Conversion to the UNICARB™ process led to a decrease in operating costs. Most of the reduction came about because the finishing operation could be converted to a one-coat process using the UNICARB™ process, compared to the two-coat process previously used. Because of this reduction in finishing steps, Pennsylvania House was able to decrease its utility and labor costs. No change is assumed for line waste handling and disposal costs or finishing line maintenance.

As stated above, the UNICARB™ process requires only one spray booth. Shutting down the second booth results in a net annual savings of $11,000 for electricity costs. Additionally, because the one-coat process requires only one pass through the oven for final cure, savings could be made by sectioning off the last stage of the oven and turning off the burners used to heat this section. Although this option has not been implemented, Pennsylvania House has estimated the gas savings from doing this at about $18,000/year. The only costs that would have to be recovered would be those costs associated with bricking off the last stage of the oven.

Labor savings also were realized by converting to the UNICARB™ process. One less person is needed to operate the gun in the second spray booth, and one less sander is needed with the new process. One man-year for a person serving these functions is quoted at $23,000. Thus, a total labor savings of $46,000 is realized immediately.

ECONOMIC ASSESSMENT

The return on investment and payback period for the conversion to the UNICARB™ process were calculated based on worksheets provided in the Waste Minimization Opportunity Manual (U.S. EPA, 1988). Capital, materials, labor, and operating costs have already been outlined. Two analyses were performed. The first analysis includes the costs savings that would be realized if Pennsylvania House decides to turn off the gas to the final stages of the oven. This analysis ignores the costs incurred for actually sectioning off the oven, because no information was provided to estimate these costs. The second analysis reflects the actual expenditures and return realized in the current production operation. The following additional assumptions were made in the computations:

- No costs incurred in finance charges, i.e., the equipment was paid for in full by Pennsylvania House
- Depreciation period of 7 years
- Income tax rate of 43%
- An escalation rate of 5%
- Cost of capital return of 15%
- Plant overhead rate of 25%; labor burden of 28%
- Supervisory costs 10% of labor costs.

The first analysis included gas utilities savings of $18,000/year. Actual inputs and outputs of the worksheet for incorporating the assumptions used for that analysis are presented in Table A-4 (see Appendix). The resulting revenues and cost factors are reported in Table 11, along with the tabulated output for the return on investment. The resulting return on investment estimate is impressive, due primarily to the decrease in operating costs, with a 100% return on investment being achieved in the third year of operation.

The second analysis (Table 12) did not assume savings in gas utilities. The inputs for this second analysis are presented in Table A-5 in the Appendix. This analysis shows a 100% return on investment achieved in the fifth year of operation. This analysis reflects the economics of the actual operation currently in use on the chair line at the White Deer facility at the time of this evaluation.

TABLE 11. RESULTS OF ECONOMIC ANALYSIS - GAS UTILITIES SAVING

REVENUE AND COST FACTORS						
Operating Year Number		1	2	3	4	5
Escalation Factor	1.000	1.050	1.103	1.158	1.216	1.276
INCREASED REVENUES						
Increased Production		$0	$0	$0	$0	$0
Marketable By-products		$0	$0	$0	$0	$0
Annual Revenue		$0	$0	$0	$0	$0
OPERATING SAVINGS (Numbers in parentheses indicate net expense)						
Raw Materials		$374	$392	$412	$433	$454
Disposal Costs		$0	$0	$0	$0	$0
Maintenance Labor		$0	$0	$0	$0	$0
Maintenance Supplies		$0	$0	$0	$0	$0
Operating Labor		$48,317	$50,733	$53,269	$55,933	$58,729
Operating Supplies		$0	$0	$0	$0	$0
Utilities		$11,550	$12,128	$12,734	$13,371	$14,039
Supervision		$4,832	$5,073	$5,327	$5,593	$5,873
Labor Burden		$14,882	$15,626	$16,407	$17,227	$18,089
Plant Overhead		$13,287	$13,951	$14,649	$15,382	$16,151
Home Office Overhead		$0	$0	$0	$0	$0
Total Operating Savings		$93,241	$97,903	$102,798	$107,938	$113,335
RETURN ON INVESTMENT						
Construction Year	1					
Operating Year		1	2	3	4	5
Book Value	$58,000	$41,429	$29,592	$21,137	$12,851	$4,566
Depreciation (by straight-line)		$8,286	$8,286	$8,286	$8,286	$8,286
Depreciation (by double DB)		$16,571	$11,837	$8,455	$6,039	$3,672
Depreciation		$16,571	$11,837	$8,455	$8,286	$8,286
Cash Flows						
Operating Year		1	2	3	4	5
Revenues		$0	$0	$0	$0	$0
+ Operating Savings		$93,241	$97,903	$102,798	$107,938	$113,335
Net Revenues		$93,241	$97,903	$102,798	$107,938	$113,335
- Depreciation		$16,571	$11,837	$8,455	$8,286	$8,286
Taxable Income		$76,670	$86,066	$94,343	$99,652	$105,049
- Income Tax		$32,968	$37,009	$40,568	$42,851	$45,171
Profit after Tax		$43,702	$49,058	$53,776	$56,802	$59,878
+ Depreciation		$16,571	$11,837	$8,455	$8,286	$8,286
After-Tax Cash Flow		$60,273	$60,895	$62,231	$65,088	$68,164
Cash Flow for ROI	($58,000)	$60,273	$60,895	$62,231	$65,088	$68,164
Net Present Value	($58,000)	($5,589)	$40,456	$81,374	$118,588	$152,477
Return on Investment		**3.92%**	**66.85%**	**89.31%**	**98.44%**	**102.46%**

TABLE 12. RESULTS OF ECONOMIC ANALYSIS - NO GAS SAVINGS

REVENUE AND COST FACTORS				
Operating Year Number		1	2	3
Escalation Factor	1.000	1.050	1.103	1.158
INCREASED REVENUES				
Increased Production		$0	$0	$0
Marketable By-products		$0	$0	$0
Annual Revenue		$0	$0	$0
OPERATING SAVINGS (Numbers in parentheses indicate net expense)				
Raw Materials		$374	$392	$412
Disposal Costs		$0	$0	$0
Maintenance Labor		$0	$0	$0
Maintenance Supplies		$0	$0	$0
Operating Labor		$48,317	$50,733	$53,269
Operating Supplies		$0	$0	$0
Utilities		$30,450	$31,973	$33,571
Supervision		$4,832	$5,073	$5,327
Labor Burden		$14,882	$15,626	$16,407
Plant Overhead		$13,287	$13,951	$14,649
Home Office Overhead		$0	$0	$0
Total Operating Savings		$112,141	$117,748	$123,635
RETURN ON INVESTMENT				
Construction Year	1			
Operating Year		1	2	3
Book Value	$58,000	$41,429	$29,592	$21,137
Depreciation (by straight-line)		$8,286	$8,286	$8,286
Depreciation (by double DB)		$16,571	$11,837	$8,455
Depreciation		$16,571	$11,837	$8,455
Cash Flows				
Operating Year		1	2	3
Revenues		$0	$0	$0
+ Operating Savings		$112,141	$117,748	$123,635
Net Revenues		$112,141	$117,748	$123,635
- Depreciation		$16,571	$11,837	$8,455
Taxable Income		$95,570	$105,911	$115,181
- Income Tax		$41,095	$45,542	$49,528
Profit after Tax		$54,475	$60,369	$65,653
+ Depreciation		$16,571	$11,837	$8,455
After-Tax Cash Flow		$71,046	$72,206	$74,108
Cash Flow for ROI	($58,000)	$71,046	$72,206	$74,108
Net Present Value	($58,000)	$3,779	$58,377	$107,104
Return on Investment		**22.49%**	**88.53%**	**110.48%**

SECTION 5

QUALITY ASSURANCE

A Quality Assurance Project Plan (QAPP) was prepared and approved by the EPA before testing began (Battelle, 1993). This plan outlined a detailed design for conducting this technology evaluation, including parameters for field sampling, laboratory analysis, and data reduction. The quality assurance objectives of the QAPP are discussed below.

ON-SITE SAMPLING

On-site sampling included collecting three samples each of the UNICARB™ and conventional nitrocellulose lacquer formulations for the pollution prevention evaluation, and finishing three sets of chair-back splats (panels) for the product quality evaluation. Each set was comprised of three samples. With the exception of the manner in which the nitrocellulose lacquer finish was applied, all samples were finished using the standard production methods for the chair line at the White Deer facility. Different nitrocellulose finishes were applied to each of the three sets: one set received one coat of the conventional nitrocellulose formulation, one set was finished using the conventional two-coat nitrocellulose lacquer finishing process, and one set was finished using the UNICARB™ production method currently on line at the White Deer facility.

The nitrocellulose lacquer formulations were collected and handled according to the procedures outlined in the QAPP and reviewed in Section 3 of this report for the environmental impact evaluation. The test panels finished for the product quality evaluation were finished according to methods outlined in the QAPP, with two exceptions. A review of the actual finishing process is presented in Section 1 of this report. Test panel preparation and explanations for the deviations from the QAPP were reviewed in Section 2. Deviations from the QAPP included finishing actual cherry chair-back splats instead of preparing special samples for the product quality evaluation, and carrying these samples from station to station instead of hanging them on the overhead conveyor line.

It was necessary to carry the samples because they could not be hung on the conveyor line and transported without falling off. Care was taken to ensure that all timing intervals between stations and during oven exposure were kept consistent with the transport rate of the production line. No impacts on the quality or accuracy of the results of this report are expected from this deviation.

Using cherry splats for the product quality evaluation can have only a positive impact on the results of this evaluations. They are part of the actual product finished at Pennsylvania House and are therefore more representative of the actual finished product than the test panels originally proposed. Using actual product for the quality evaluation was not considered when the QAPP was being prepared because it seemed an unnecessary inconvenience to Pennsylvania House.

LABORATORY ANALYSIS

All analyses were performed as proposed in the QAPP, with one exception: more gloss measurements were taken than previously proposed. Table 13 summarizes the achievement of the QA objectives for the critical measurements. Analytical data for pencil hardness and percent solids/percent volatiles are valid according to the criteria presented in the QAPP. The gloss data are invalid according to the precision requirements of the QAPP. Data for the critical measurements are included in the Appendix.

TABLE 13. QUANTITATIVE QA OBJECTIVES

Test Method	Number of Determinations	Completeness	Precision Valid Criteria; Results
Gloss Measurement* ASTM D523-89	49 determinations on each of the 9 coated 7 x 21-inch panels	Goal: 80% Actual: 100 %	Valid = 2 gloss units; Gloss data within a sample varied by as much as 11 units - <u>invalid</u> by QAPP criteria, see text for discussion
Pencil Hardness† ASTM D3363-74	3 determinations on each of the 9 coated 7 x 21-inch panels	Goal: 80% Actual: 100 %	Valid = 1 hardness units; Criteria met - results of data are <u>valid</u> for a given sample and within a sample set
Percent Solids/ Percent Volatiles* ASTM D23369-90	3 determinations on each of the 4 samples collected: 2 conventional, 2 UNICARB™	Goal: 80% Actual: 100 %	Valid = determinations on each sample should not differ by more than 1.5%; <u>Valid</u> criteria met for individual samples and between samples of same formulation.

* Data in Appendix.
† Data in Table 9.

PRODUCT QUALITY

The number of gloss measurements taken on each test panel differed from the number specified in the QAPP. The test panels evaluated measured approximately 7 x 21-inches. The test procedures outlined in ASTM D529 recommend averaging six gloss measurements for a 3 x 6-inch sample area, or one measurement for every 3 square inches. This corresponds to 49 measurements on a 7 x 21-inch panel. Measuring the gloss across the entire surface of the samples alleviated any subjective biases of the person performing the measurements and compensated for any nonuniformity in the gloss across the sample surface.

Nonuniformity in the gloss readings raw data on all of the samples was readily evident (Table A-3, Appendix). The values on a single panel varied by as much as 11 gloss units, well outside of the requirements for precision set in the QAPP. However, the large difference in values does not reflect technical problems encountered in coating the panels or in collecting the data, but rather is a reflection of the nature of the wood panels being coated. The natural wood finish allows for the character and grain of the wood substrate to show through, so that the finish on even, well-sanded and well-prepared panels will show some variation. This is part of the natural beauty of the wood and is not considered to be indicative of a deficient finishing process. Had the substrate been an impermeable and highly uniform, more consistent readings might be expected. The important factor in comparing the gloss measurements among the panels finished for this study is that the UNICARB™ panels are not statistically different from the panels coated using the conventional two-coat process. This was demonstrated by the statistical analysis of the results for mean and standard deviation. Both of these sample sets were shown to be quite different (glossier) from the one-coat conventional finish sample set (Table 8). In conclusion, although the gloss data are invalid according to the precision requirements of the QAPP, there is no negative impact on the objectives of the QAPP. The variation in gloss data is not a function of the finishing process but an artifact of the substrate being finished. This is supported by the fact that the scatter in the data is approximately the same for each set of panels. These gloss measurements were not a critical measurement for the product quality analysis.

Film hardness on wood samples using the pencil test was measured on the nine coated wood panels mentioned above (Table 9). Three readings were taken on each of the sample panels. The results did not differ by more than one hardness unit for each type of coating. The conventional spray (two coats) was harder than the other two coatings.

POLLUTION PREVENTION POTENTIAL

The pollution prevention potential analysis demonstrated a decrease in VOC emissions using the UNICARB™ process. This analysis required the VOC content of each of the coating formulations to be determined. Sample handling and the percent solids/percent volatiles determinations were performed according to the procedures outlined in the QAPP. The percent solids/percent volatiles are reported in Tables A-1 and A-2 in the Appendix as the mean for 12 determinations for the conventional formulation and 12 for the UNICARB™ formulation. The percent volatiles is statistically different between the two formulations. The mean for the conventional formulation is 66.69% and that for the UNICARB™ formulation is 64.23%. The results of the laboratory analysis on each sample replicate are valid when compared to other replicate data from the same sample and within a given sample set (same formulation).

As reported and discussed in Section 3 of this report, the difference in percent solids between the conventional and UNICARB™ formulations data differed substantially from the difference calculated according to the MSDS. This difference has a definite effect on the results of the pollution prevention potential evaluation. However, this incongruity was demonstrated not to have a profound effect on the objectives of this report, because a 57.9% reduction in VOC emissions would be achieved simply due to the fact that the UNICARB™ process requires only 7 oz of formulation per furniture unit compared to the 16 oz needed by the conventional process for the same quality of product. The 57.9% reduction in VOC emissions is based on formulations of equal VOC content.

RECORD DATA

The pollution prevention and economic analyses each required nonanalytical input and assumptions. These evaluations were performed in accord with the criteria and objectives of the QAPP, and as such the results of these evaluations are believed to be valid and in accord with the terms of the QAPP.

SECTION 6

DISCUSSION

The purpose of this evaluation was to provide an objective evaluation of the use of supercritical CO_2 as an alternative technology for spray applied in coating processes using reduced solvent formulations. Union Carbide has pioneered this technology under the UNICARB™ trademark. This evaluation was performed to answer questions regarding this technology which addressed the issues of product quality, pollution prevention potential, and process economics. Accomplishing the objectives of this evaluation required selecting a site that currently uses this process in a production process. The site selected was the White Deer Plant of Pennsylvania House Furniture. At the time of this evaluation, the White Deer Plant had been using the UNICARB™ process to apply nitrocellulose lacquer finish on their chair line for over a year with good results. While the results of this evaluation are specific to the production operation used at the White Deer Plant on their chair line, some limited comparisons should be able to be made to other production processes in which spray-applied solvent-borne coatings are used.

This evaluation found that conversion to the UNICARB™ process on the chair line at the White Deer Plant was favorable. Product quality evaluations demonstrated that the nitrocellulose finish applied using the UNICARB™ process was of equal or better quality than that of finish applied using the conventional two-coat process. Some concern was raised over the hardness of the UNICARB™ coat, which was determined by ASTM D3363 to be slightly softer than the conventional two-coat finish. However, arguments were presented which indicated that the low results could be related to coating thickness, because the UNICARB™ hardness was equal to that of the samples finished using a one-coat conventional process. This issue was not resolved because the pencil hardness measurements were not critical to the evaluation. The impact of reduced finish hardness on product quality or performance had not been defined.

The impact of converting to a supercritical CO_2 spray process for the application of coatings in other processes would have to be determined independently. Pennsylvania House used the resources of Union Carbide, Nordson, and two coatings suppliers to optimize their UNICARB™ coating process. As necessary when converting to any new coating formulation, the blend of diluent and film-forming solvents needed to be optimized for best performance along with changes in the parameters associated with the actual spray process. Because of the supercritical gas component, optimization of the supercritical CO_2 technology may require more time than optimizing conventional formulations and widely used spray application methods. A number of coating formulators have been licensed to formulate the reduced-solvent coatings, but they currently are not devoting resources to converting conventional formulations to formulations that will perform well using the UNICARB™ process. Union Carbide still provides this service for new customers. This situation is not unusual in an evolving technology, but it may affect the time required to convert new production processes to the UNICARB™ process, as some degree of experimentation will be required to optimize the technology to individual needs. The time required to implement this technology will decrease as the number of new formulations developed (with different resin chemistries and colorants) for use with the UNICARB™ process increases. Some technical problems, including formulations, equipment and application techniques, still exist in using this technology to apply coatings to large horizontal surfaces, but these issues are being addressed by the companies developing this technology. Pennsylvania House is pursuing solutions as it proceeds with implementation of the supercritical spray technology on its table line.

Although the pollution prevention potential of this technology can be evaluated only on an individual basis, the pollution prevention potential for the production process evaluated in this study demonstrated very favorable results. An annual reduction in VOC emissions in the range of 57% to 67% was demonstrated relative to the conventional finishing process. A large percentage of this reduction was attributed to the fact that the use of the UNICARB™ process on the chair line at the White Deer Plant required only one coat of the reduced solvent nitrocellulose formulation to achieve the same level of finish quality as the conventional two-coat process. This resulted in a decrease from 6494 gal/year of lacquer sprayed to 2734 gal/year. An additional reduction in VOC emissions was achieved through the decreased solvent content of the UNICARB™ nitrocellulose formulation. Solvent-loading levels are reportedly decreased by as much as 30 to 80% in some formulations. According to the MSDSs for the formulations used in this evaluation, a 23% reduction in solvent content per gal is achieved if supercritical CO_2 is used as a diluent. These results could not be substantiated by the laboratory analysis performed under this evaluation.

Capital equipment costs will vary according to production volume. The capital investment costs incurred by Pennsylvania House will be recovered in the first 5 years of operation. Although there is some reduction in raw material costs, most of the economic benefit gained from the conversion to the UNICARB™ process can be attributed to the reduction in labor and operating costs on the chair line at the White Deer Plant, as a result of reducing the nitrocellulose finishing process from a two-coat to a one-coat process.

SECTION 7

CONCLUSIONS

This evaluation of supercritical CO_2 spray technology for application of solvent-borne coating focused on three aspects: product quality, pollution prevention potential, and process economics.

The quality of the one-coat nitrocellulose lacquer finish applied at Pennsylvania House Furniture Company by supercritical CO_2 spray technology was demonstrated to be equal to or better than the quality of the two-coat finish applied by conventional air-assisted airless spray in this evaluation. In production, the furniture finish passes or fails on the basis of subjective evaluation of the total appearance by Pennsylvania House experts and ultimately by the customers. Quality of the supercritical CO_2 finish was supported by subjective evaluations by Pennsylvania House staff, coatings experts in the Battelle Coatings Group, and a group of non-experts, as well as by Pennsylvania House's records on customer acceptance and rates of in-plant defect corrections spanning more than one years's production line use of the supercritical CO_2 spray technology support.

Release of volatile organic compounds during the finish process was reduced at Pennsylvania House by the supercritical CO_2 spray technology. The CO_2 used in this process is recovered from the wastestream of other industrial processes so it is not an additional contributor to global warming. Overall CO_2 may be decreased because many organic solvents that can add CO_2 to the wastestream are eliminated from the coating formulation. An annual reduction in VOC emissions in the range of 57% to 67% was demonstrated. Much of this reduction occurred because supercritical CO_2 is used at Pennsylvania House to apply a one-coat finish. The conventional finish process required two coats of nitrocellulose lacquer. Solid waste remained the same.

Capital investment costs incurred by Pennsylvania House will be recovered in the first 5 years of operation. Most of the economic benefit gained from conversion to the supercritical CO_2 process can be attributed to the reduction in labor and operating costs on the chair line at the White Deer plant.

This technology is one approach to reducing VOC emissions in the application of solvent-borne coatings. Product quality can be maintained and operating costs can be decreased.

Capital costs will vary with each implementation but a favorable payback period can be anticipated, in light of the findings of this evaluation.

This technology evaluation focused on a single product type and coating formulation wood furniture industry. However, this specific supercritical CO_2 spray technology seems adaptable to a number of solvent-borne coating formulations and products.

SECTION 8

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APPENDIX

RAW DATA FROM ANALYSIS OF FIELD SAMPLES

TABLE A-1. ANALYTICAL DATA FROM PERCENT VOLATILES/ PERCENT SOLIDS DETERMINATION ON UNICARB™

Sample No.	Percent Volatiles (%)	Percent Solids (%)
46482-12-2-A	63.66552	36.33448
2-B	64.24810	35.75190
2-C	64.35622	35.64378
2-D	64.22322	35.77678
2-E	64.27560	35.72440
2-F	64.25083	35.74917
46482-12-3-A	64.32866	35.67134
3-B	64.28932	35.71068
3-C	64.19441	35.80559
3-D	64.35120	35.64880
3-E	64.32956	35.67044
3-F	64.28883	35.71117
Average	64.233456	35.766544

TABLE A-2. ANALYTICAL DATA FROM PERCENT VOLATILES/ PERCENT SOLIDS DETERMINATION ON CONVENTIONAL NITROCELLULOSE FIELD SAMPLES

Sample No.	Percent Volatiles (%)	Percent Solids (%)
46482-13-2-A	66.65651	33.34349
2-B	66.71645	33.28355
2-C	66.59757	33.40243
2-D	66.67201	33.32799
2-E	66.72490	33.27510
2-F	66.70360	33.29640
46482-13-3-A	66.85705	33.14295
3-B	66.67916	33.32051
3-C	66.73917	33.26083
3-D	66.68234	33.31766
3-E	66.68787	33.31213
3-F	66.60912	33.39088
Average	66.693813	33.306160

TABLE A-3. 60 DEGREE GLOSS READINGS 9-24-93

46482-09-1	46482-09-2	46482-09-3	46482-10-1	46482-10-2	46482-10-3	46482-11-1	46482-11-2	46482-11-3
25.2	19.6	23.7	33.0	32.5	29.5	26.5	27.5	26.2
24.8	20.1	24.9	33.6	31.3	29.8	29.2	26.9	27.2
25.1	24.0	24.7	33.4	32.2	29.4	31.5	27.4	29.7
25.9	25.2	24.1	32.6	32.1	29.1	33.5	25.9	31.0
26.3	25.9	23.9	31.2	32.7	29.6	36.7	25.9	30.3
26.7	25.8	23.9	31.7	33.8	30.7	38.8	28.9	30.9
26.6	24.8	23.8	32.6	34.3	30.6	39.7	28.0	31.3
25.5	25.3	24.0	32.7	34.3	30.4	39.2	27.3	32.5
25.1	25.5	23.8	34.1	33.6	31.2	37.7	27.8	33.7
23.6	25.1	23.5	33.8	33.9	32.0	37.3	26.8	33.5
23.5	24.3	23.2	32.2	34.9	32.6	38.1	26.5	30.7
24.1	23.3	22.4	31.4	35.2	31.6	38.9	27.8	28.9
24.6	23.4	22.7	31.6	34.4	31.2	38.9	28.9	29.6
24.4	23.6	22.1	31.7	33.8	32.1	39.7	28.9	29.3
24.0	24.1	22.8	31.9	34.3	32.8	39.4	28.2	27.6
23.7	23.2	22.4	32.1	34.9	31.7	38.6	29.4	26.6
23.6	22.4	22.2	32.7	36.2	31.8	38.5	30.7	25.9
22.9	21.9	22.1	33.6	36.6	32.2	38.6	32.0	26.1
23.2	21.8	21.5	34.4	36.4	32.1	35.0	32.8	27.8
23.4	21.7	21.3	32.9	35.5	31.5	34.5	32.1	28.7
23.4	20.8	20.8	30.9	35.7	31.3	33.8	31.4	27.5
23.2	19.7	20.4	29.9	36.7	31.9	33.2	29.9	25.6
21.6	20.1	21.3	31.2	37.0	30.0	33.2	30.9	28.2
20.4	20.0	22.2	32.1	36.3	29.4	36.4	32.7	26.7
19.9	19.1	21.0	31.8	32.4	30.2	39.9	32.9	26.5
19.1	17.8	20.4	31.5	30.6	30.6	40.6	31.0	28.8
19.0	17.3	19.9	32.2	33.0	29.8	39.8	30.0	27.4
19.1	17.4	19.6	33.1	34.2	28.2	36.2	29.9	30.1
20.4	17.6	20.2	33.7	36.4	27.8	34.2	31.5	33.7
20.5	17.8	20.0	34.1	37.8	28.0	33.8	30.9	32.7
19.3	17.6	20.0	34.6	37.6	28.3	33.1	32.6	31.6
17.7	17.2	20.2	33.4	37.7	26.1	34.3	35.6	28.3
16.1	16.5	18.6	32.6	37.6	25.6	35.8	37.0	31.7
16.6	18.2	18.3	33.1	39.4	25.8	35.3	36.4	32.8

TABLE A-3. (Continued)

46482-09-1	46482-09-2	46482-09-3	46482-10-1	46482-10-2	46482-10-3	46482-11-1	46482-11-2	46482-11-3
16.8	15.0	17.9	33.9	37.2	27.3	35.9	35.3	31.9
16.7	17.4	16.6	34.7	31.0	26.7	31.8	36.7	26.0
16.3	17.6	15.6	35.2	34.6	23.0	34.4	36.8	28.7
15.9	17.2	14.7	34.5	36.9	22.9	34.1	34.2	27.9
15.5	16.6	15.0	33.4	38.7	22.4	29.8	34.8	31.1
15.4	17.9	16.5	33.3	38.3	26.6	31.2	33.6	31.0
15.8	18.7	17.8	32.3	37.0	24.9	30.2	30.7	28.9
15.9	18.1	18.0	33.5	37.5	24.7	32.3	29.5	31.5
16.0	18.4	18.1	35.0	37.1	26.4	36.1	29.4	28.4
15.2	18.8	18.3	35.4	35.0	26.6	35.0	30.2	27.9
16.3	21.5	18.0	33.6	34.0	25.9	34.4	30.5	25.4
13.8	19.2	16.9	34.3	33.0	25.9	34.9	27.6	23.3
13.4	18.6	15.7	35.1	31.7	26.6	32.9	29.3	22.3
13.0	17.5	14.8	34.3	32.3	26.3	33.0	27.4	21.5
11.7	16.6	12.9	39.5	33.0	27.1	32.3	27.9	23.6
20.3	20.4	20.3	33.2	35.0	28.6	35.3	30.5	28.7
+/-4.29	+/-3.10	+/-3.09	+/-1.55	+/-2.21	+/-2.80	+/-3.24	+/-3.06	+/-2.93

TABLE A-4. ECONOMIC ANALYSIS INPUTS - GAS UTILITIES SAVINGS

INPUT		OUTPUT	
Capital Cost		Capital Requirement	
Equipment	$46,000	Construction Year	1
Materials (incl.)	$0	Capital Expenditures	
Installation (incl.)	$12,000	Equipment	$46,000
Plant Engineering	$0	Materials	$0
Contractor/Engineering	$0	Installation	$12,000
Permitting Costs	$0	Plant Engineering	$0
Contingency	$0	Contractor/Engineering	$0
Working Capital	$0	Permitting Costs	$0
Startup Costs	$0	Contingency	$0
% Equity	100%	Startup Costs	$0
% Debt	0%	Depreciable Capital	$58,000
Interest Rate on Debt, %	0.00%	Working Capital	$0
Debt Repayment, years	0	Subtotal	$58,000
Depreciation period	7	Interest on Debt	$0
Income Tax Rate, %	43.00%	Total Capital Requirement	$58,000
Escalation Rates, %	5.0%	Equity Investment	$58,000
Cost of Capital	15.00%	Debt Principal	$0
		Interest on Debt	$0
		Total Financing	$58,000
Operating Cost/Revenue			
Marketable By-products		Operating Labor Savings	
Recycled Ink	$0	Operator hrs/shift	16
Recycled Solvent	$0	Shifts/yr	200
Total $/yr.	$0	Wage rate, $/hr.	$14.38
Utilities		Operating Supplies	0
Gas	$0	Total $/yr.	$0
Electric	($11,000)	Maintenance Costs	
Total $/yr.	($11,000)	(% of Capital Costs)	
Raw Materials		Labor	0.00%
Total, $/yr.	($1,337)	Materials	0.00%
Waste Disposal Savings		Supervision	
Offsite Fees, $	$0	(% of O&M Labor)	10.0%
Storage Drums $	$0	Overhead Costs	
Total Disposal Savings	$0	(% of O&M Labor + Super.)	
		Plant Overhead	25.0%
		Home Office	0.0%
		Labor Burden	28.0%

TABLE A-5. ECONOMIC ANALYSIS INPUTS - NO GAS UTILITIES SAVINGS

INPUT		OUTPUT	
Capital Cost		Capital Requirement	
Equipment	$46,000	Construction Year	1
Materials (incl.)	$0	Capital Expenditures	
Installation (incl.)	$12,000	Equipment	$46,000
Plant Engineering	$0	Materials	$0
Contractor/Engineering	$0	Installation	$12,000
Permitting Costs	$0	Plant Engineering	$0
Contingency	$0	Contractor/Engineering	$0
Working Capital	$0	Permitting Costs	$0
Startup Costs	$0	Contingency	$0
% Equity	100%	Startup Costs	$0
% Debt	0%	Depreciable Capital	$58,000
Interest Rate on Debt, %	0.00%	Working Capital	$0
Debt Repayment, years	0	Subtotal	$58,000
Depreciation period	7	Interest on Debt	$0
Income Tax Rate, %	43.00%	Total Capital Requirement	$58,000
Escalation Rates, %	5.0%	Equity Investment	$58,000
Cost of Capital	15.00%	Debt Principal	$0
		Interest on Debt	$0
		Total Financing	$58,000
Operating Cost/Revenue			
Marketable By-products		**Operating Labor Savings**	
Recycled Ink	$0	Operator hrs/shift	16
Recycled Solvent	$0	Shifts/yr	200
Total $/yr.	$0	Wage rate, $/hr.	$14.38
Utilities		Operating Supplies	0
Gas	($18,000)	Total $/yr.	$0
Electric	($11,000)	Maintenance Costs	
Total $/yr.	($29,000)	(% of Capital Costs)	
Raw Materials		Labor	0.00%
Total, $/yr.	($1,337)	Materials	0.00%
Waste Disposal Savings		Supervision	
Offsite Fees, $	$0	(% of O&M Labor)	10.0%
Storage Drums $	$0	Overhead Costs	
Total Disposal Savings	$0	(% of O&M Labor + Super.)	
		Plant Overhead	25.0%
		Home Office	0.0%
		Labor Burden	28.0%