Final Technical Report Draft

Project Title: Energy Saving Glass Lamination via Selective Radio Frequency Heating

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List of Acronyms

EVA – ethylene vinyl acetate
LSG – laminated safety glass
NDE – non-destructive evaluation
PVB – polyvinyl butyral
RF – Radio Frequency
TAW – transparent armor window
TPU – thermoplastic polyurethane
UT – ultrasonic testing
T BTU – trillion British Thermal Unit
kWh – kilowatt hours
B sq ft. – billion square feet
FastFuse – Ceralink tradename for RF Lamination

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Executive Summary

Purpose:

This project focused on advancing radio-frequency (RF) lamination technology closer to commercial implementation, in order to reduce the energy intensity of glass lamination by up to 90%. Lamination comprises a wide range of products including autoglass, architectural safety and innovative design glass, transparent armor (e.g. bullet proof glass), smart glass, mirrors, and encapsulation of photovoltaics. Lamination is also the fastest growing segment of glass manufacturing, with photovoltaics, architectural needs, and an anticipated transition to laminated side windows in vehicles. The state-of-the-art for glass lamination is to use autoclaves, which apply heat and uniform gas pressure to bond the laminates over the course of 1 to 18 hours. Laminates consist of layers of glass or other materials bonded with vinyl or urethane interlayers. In autoclaving, significant heat energy is lost heating the chamber, pressurized air, glass racks, and the glass. In RF lamination, the heat is generated directly in the vinyl interlayer, causing it to heat and melt quickly, in just 1 to 10 minutes, without significantly heating the glass or the equipment. The main purpose of this project was to provide evidence that low energy, rapid RF lamination quality met the same standards as conventionally autoclaved windows. The development of concepts for laminating curved glass with RF lamination was a major goal. Other primary goals included developing a stronger understanding of the lamination product markets described above, and to refine the potential benefits of commercial implementation.

Scope:

The scope of the project was to complete implementation concept studies in preparation for continuation into advanced development, pilot studies, and commercial implementation. The project consisted of 6 main tasks. The first dealt with lamination with poly-vinyl butyral (PVB) interlayers, which prior work had shown difficulties in achieving good quality laminates, working with Pilkington North America. The second task dealt with a study of current lamination processes in the various laminate industries, and development of concepts for integrating RF lamination into new or existing processes. The third task explored the use of a non-destructive technique for analyzing laminate adhesion with the University of Illinois at Urbana-Champaign. The fourth task focused on developing concepts for curved glass lamination using RF lamination. The fifth and sixth tasks together comprised an analysis of laminate product markets, ranking for applicability and commercialization potential, and the development of commercialization strategies for those products. In addition, throughout the project as new experimental data and conventional process data were obtained, the benefits analysis of RF lamination was refined.

Results:

The goals of the project described above were achieved, positioning RF lamination for the next stage growth envisioned in the original Industrial Grand Challenge proposal. Working with Pilkington North America, lamination of flat autoglass with PVB was achieved, meeting all 16 stringent industry tests. In particular, PVB laminates made with RF lamination passed environmental tests including the high temperature, 120 °C bake test, without significant formation of bubbles (defects). The adhesion of PVB to glass was measured using the pummel method. Adhesion values ranging from 1 to 7 out of 10 were obtained. The significant process parameters affecting the environmental and adhesion performance were identified through a designed experiment. Pre-lamination process variables including PVB storage humidity and the de-airing process (vacuum or nip rolling) were significant, as well as the level of pressure applied to the laminate during the RF process. Analysis of manufacturing with RF lamination equipment, based on the processes developed indicated that 3 RF presses could replace a typical auto-industry autoclave to achieve equal or greater throughput with possibly less capital cost and smaller footprint. Concepts for curved lamination identifying castable molds for prototyping were developed, which allowed Ceralink to obtain commitment to begin curved tooling development.

Conclusions:
The project significantly helped to advance RF lamination past the feasibility and novelty stage and into the realm of commercial acceptance as a viable alternative to autoclaves. The demonstration of autoclave-quality autoglass produced in just 1 minute with RF lamination, with validation by Pilkington, has fueled industry motivation to seriously consider RF lamination. The industry and other contacts and outreach made in the study of laminate markets (including 3 technical publications and 5 conference presentations), has resulted in a recent surge in RF lamination activity.

Recommendations:
The next technical challenge for RF lamination is the development of curved lamination. Curved lamination is a critical advancement for enabling implementation in the large automotive glass industry. Demonstration within the autoglass industry on smaller vehicle windows will enable support by glass companies to pursue investments in larger RF equipment for handling very large architectural glass. Opportunities for establishing a larger RF lamination demonstration facility at Ceralink are being pursued to enable lower cost, faster demonstrations and manufacturing validations.

For the transparent armor market, which deals in window sizes already feasible with current RF capabilities, a targeted focus on transitioning to commercial and other Federal agency support of RF lamination is envisioned, with implementation feasible in the next two years.

Commercialization Plan and Status:
The commercialization plan for RF lamination involves further development in the key autoglass sector, via curved lamination, and nearer term implementation of RF lamination in the transparent armor market. A U.S. patent application on the technology remains pending. Ceralink, developer of RF lamination processing and the commercial interest in the technology, has partnered with a major RF equipment manufacturer to supply RF press equipment to RF lamination customers, with licenses to use the technology sold with the equipment. Ceralink envisions developing the curved lamination technology, and supplying the curved platen tooling to industry.

Ceralink’s marketing strategy focuses on targeted conference presentations, maintaining an active internet presence, and utilizing the RF testing capabilities at Ceralink and the RF equipment supplier to provide feasibility studies, demonstrations, and manufacturing validation studies to laminators.

Introduction

This project investigated the merits of applying Radio Frequency (RF) processing to the glass lamination industries to achieve significant energy and processing time savings. The target industries for early adoption of this emerging and enabling technology are the autoglass, architectural glass, transparent armor, and photovoltaics market segments. The primary objective of the project was to demonstrate manufacturability potential for RF lamination in order to provide a basis for commercial implementation. The project tasks were crafted based on the perceived requirements for proving the viability of RF lamination as a replacement to the state of the art autoclave. These included:

- demonstrating laminated glass quality comparable to autoclaved glass using industry standards testing,
- demonstrating how RF lamination can fit into process flow and maintain autoclave throughputs,
- developing concepts for laminating curved windows such as autoglass,
- and identifying important metrics from industry for considering implementation of the new RF lamination process as a substitute for autoclaving.

This was accomplished by studying conventional processing and the markets that utilize lamination, further analyzing benefits of RF lamination, and researching the mechanical, optical, and environmental quality of RF processed laminates compared against industry standards. The experimental portion of this effort was designed to identify and minimize technical and economic risks as the RF lamination technology is becoming positioned for rapid uptake by the target industries.

Using Ceralink's FastFuse™ RF lamination technology, the required heat for laminating (fusing) multiple layers of different materials together is produced directly in the thin interlayers, and as a result the thicker structural layers of the laminate remain relatively cool. The novel attribute to the technology lies in exploiting the inherent material properties and their behavior in an intense and highly targeted RF field. Glass, acrylic, polycarbonate, solar cells, and some transparent ceramics inherently are not affected (heated) by the RF energy, while the thin interlayer films of vinyl or polyurethane quickly heat to melting temperatures. By simultaneously combining the application of both highly efficient RF energy and mechanical pressure, an RF press can displace the inefficient autoclaves that are the current state-of-the-art in the industry. Thus, the RF process drastically reduces energy consumption of the lamination process, in many cases as much as 90%, and reduces the lamination time from hours using autoclaves to just several minutes via FastFuse.

RF glass lamination technology has potential to dramatically alter the laminate manufacturing industries through lower energy costs, faster cycle time and better process flow, improved quality, and lower capital equipment costs. Existing manufacturing sites are likely to keep using autoclave lamination, however new manufacturing in growing industries such as autoglass, transparent armor, and photovoltaics offer opportunities for building laminate manufacturing infrastructure with lower long term cost of operation through significant energy and time savings.

Background

The Industrial Grand Challenge mission includes driving a "25% reduction in U.S. industrial energy intensity by 2020 in support of EPAct 2005". As a Next-Generation Manufacturing Concept (IGC Topic Area 1), RF lamination far exceeds this goal for lamination processes used in the glass and transportation equipment (automotive) industries. Energy savings will come primarily from reduced electricity consumption. Corresponding greenhouse gas reductions will occur with respect to the electricity reduction. In addition to energy savings, the RF process greatly reduces process time for lamination. The most recent results indicate that lamination can be completed in just 1 to 3 minutes, and multiple sheets can be laminated at one time, without increasing the cycle time. This compares with the 1-18 hours required conventionally using autoclave (high pressure) or vacuum systems. State of the art autoclave and vacuum systems necessitate batch processing, while the speed of RF lamination opens the door to semi-continuous process flow in lamination lines. This could revolutionize the laminated product industries, which include automotive and architectural glass, rapidly growing photovoltaic panels, and security/armor windows.

The objective of this project was to develop the manufacturability concepts needed to move energy saving radio frequency (RF) lamination closer to commercial reality. This was accomplished by studying conventional processing and the markets that utilize lamination, further analyzing benefits of RF lamination, and researching the quality of RF processed laminates compared against industry standards. The mechanical, optical, and environmental quality of laminates produced by RF lamination were examined. The project was poised for success with a strong team including Ceralink, inventor of the RF lamination technology, a world leading glass manufacturer, a leading microwave and RF equipment manufacturer and builder of large RF presses, and the University of Illinois, with unique capabilities of non-destructive evaluation for laminated safety glass. The project strongly positioned RF lamination technology to advance toward industrial uptake.

Technology Motivation and Concept

A core technical problem in the glass industry is the necessity for extensive heat in all stages of processing from raw materials to final forming. This study addressed heat in glass lamination, the fastest growing segment of the glass industry, representing over 25% of glass sold in the US. Despite recent declines in U.S. glass production, demand for laminated glass is expected to grow significantly over the next 10 years. Rapid growth in lamination is resulting from the rise of solar power (laminated solar panels and solar concentrator mirrors), security, and energy saving regulations in the automotive industry. A new technique, RF lamination, reduces energy consumption and the related CO_2 emissions of this process by over 90%[1].

The RF lamination process is applicable to all of the most commonly laminated products including photovoltaics, safety and security glass, transparent armor, autoglass, and architectural glass. Demonstrated materials include glass, ceramics, acrylic, polycarbonate, metallized low-E glass, solar cells, glass containing sensors and light emitting diodes (LEDs), and polyester (PET) films (Figure 1). Laminated glass is bonded using polymer interlayers including polyvinyl butyral (PVB), ethylene vinyl acetate (EVA), and thermoplastic polyurethane (TPU). PVB is the most common, used in autoglass, architectural laminates, hurricane glass, and most safety glass applications. EVA is primarily used in photovoltaics, and more decorative architectural applications, with some grades suitable for structural applications. TPU is primarily used in lamination of plastics (polycarbonate, acrylic) and bullet resistant glass or transparent armor. All of these materials have been demonstrated using RF lamination.

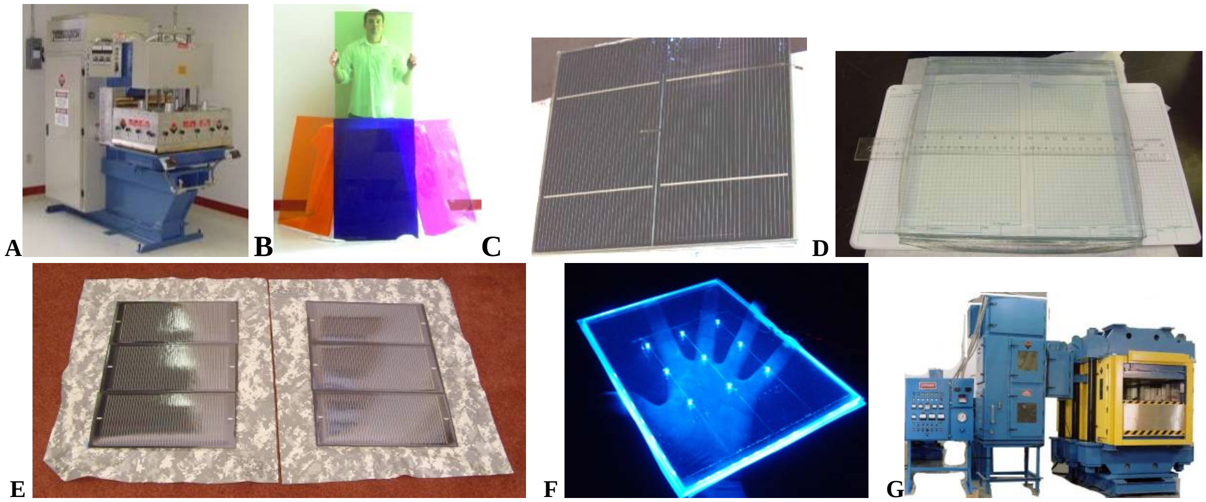


Figure 1. Photographs of samples laminated by Ceralink using the RF lamination process, A) The first RF press (18"x20") built for FastFuse through Ceralink's NY state funded program, used for all lamination experiments in this project. B) 4 panels laminated simultaneously in 3 minute process (2'x3' each, colored EVA interlayers)[2], C) silicon solar panel lamination with solderless leads laminated with PVB[2], and D) Transparent armor (12"x12"x1.75") with TPG using TPU interlayers[3], E) flexible photovoltaics laminated to camouflage tent fabric (13.5 x 19" each), F) "smart glass" with embedded blue LEDs laminated into glass using PVB interlayer[4], and G) Very large RF press (4'x10') built for other composite applications showing scale up infrastructure.

The current state of the art method is the use of autoclaves (Figure 2A), which apply heat and pressure to laminate most products, or vacuum laminators (Figure 2B), which are used for photovoltaics and some architectural products. The autoclave method relies on convection to deliver heat to the glass, and thermal conduction through the glass to heat the interlayer, while vacuum laminators rely primarily on thermal conduction. Only a small fraction of the heat in either system is responsible for melting the interlayers, which essentially comprises the laminating process. The majority of energy is lost to heating the glass, the chamber, furniture, and atmosphere within the autoclave. Autoclaves operate in batch-type processes and can take 1-18 hours depending on the loading, thickness of the glass, and the autoclave characteristics. Vacuum laminators are generally only used for EVA lamination, which depending on the grade, can be laminated in 20 to 120 minutes, with higher quality grades requiring longer times. The vacuum laminator shown in Figure 2B is a new model, advertised in October 2009 issue of Glass Magazine, as capable of laminating individual EVA-bonded windows in just 30-90 minutes. By comparison, RF lamination can produce the same size windows, up to at least 4 at a time, in just 3 minutes. Vacuum laminators are typically limited to either just one panel or a few panels at a time.

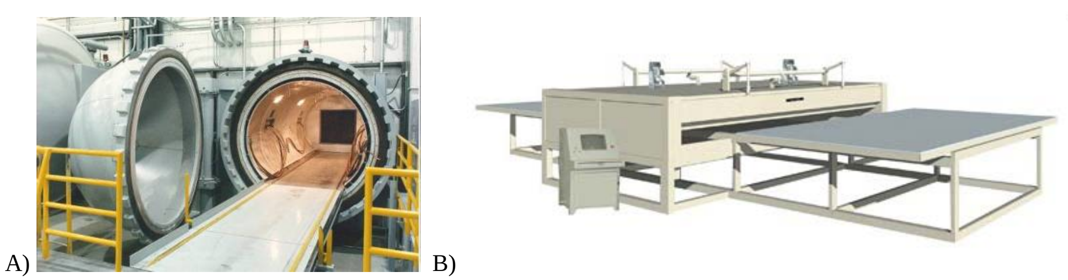


Figure 2. State of the art lamination equipment A) autoclaves, heated pressure vessels, and B) vacuum laminators.

Innovation, originality, feasibility

Ceralink invented an innovative ultra-fast, energy saving process for laminating glass and composites in 1-3 minutes, using a radio frequency (RF) press in 2005, and applied for a U.S. patent on the innovation[5]. RF Lamination technology has the potential to revolutionize the laminate manufacturing industries through lower capital equipment costs, lower energy costs, faster cycle time, and improved process flow. The development has been supported by Ceralink, the Department of Energy through a prior Inventions & Innovations grant (DE-FG36-GO16043), the New York State Energy Research & Development Authority (NYSERDA), the primary RF equipment manufacturer, Thermex Thermatron, and various industrial partners, representing major glass, autoglass (Pilkington North America), photovoltaics (FTL Solar and PVilion), transparent armor (The Protective Group), and also underutilized non-RF lamination applications for RF heating, such as RF curing of phenolics and opaque thermoplastic composites .

Before RF glass lamination was discovered, RF technology successfully decreased the time, energy, and cost of manufacturing in composites, wood, paper, and packaging industries for many years, from very small to very large scale (Figure 1G). RF processing has decreased the time and energy required for many processes such as manufacture of plywood, from many days to a few hours. Energy savings greater than 90% is typical in many RF processes. Ceralink’s effort is the first to apply this technology, for which equipment infrastructure already exists, to the glass industry.

Prior to this project, Ceralink demonstrated single pane laminations up to the size of automotive side windows demonstrated (2’ x 3’), 1 to 3” thick multilayer transparent armor up to 18” x 18”, and photovoltaics up to 18” x 20”[2-4]. For this wide range of materials and relatively large sizes, RF lamination was shown to require less than 5% of the energy (a 95% savings) compared to the current state of the art autoclave method. This presented a hypothetical opportunity to save 10 trillion BTU each year by 2020 in the glass industry in the United States.

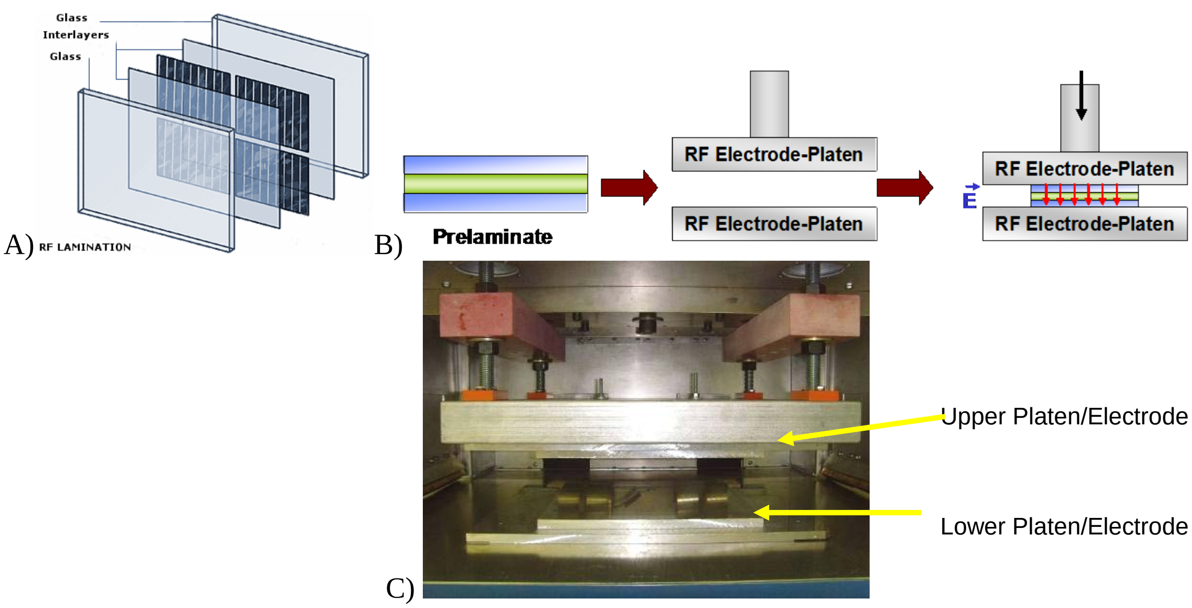


Figure 3. A) Schematic of the typical layers of a laminated panel. In this example, the structural layers are glass, with two polymer interlayers with a solar cell in the center. B) Schematic of the FastFuse™ lamination process. The prelaminate is placed in the RF press, and the press simultaneously applies force and RF energy. C) Photograph of upper and lower platens in an RF press.

The RF Lamination process works by dielectric heating of the vinyl or polyurethane interlayers used to bond glass layers together. Dielectric heating occurs when the vinyl is placed in a radio frequency (RF) field and the RF energy causes dipoles and weak bonds in the vinyl to vibrate and move. As a result, micro-friction occurs and heat is produced. The glass surrounding the interlayer does not react significantly with the RF field, and therefore does not heat. In the RF Press, the field is generated between parallel metal electrodes. At the same time, pressure is applied by the electrodes (also called platens), usually uniaxially, onto the laminate, as shown in Figure 3. The pressure promotes removal of air from between the interlayer and the glass, and facilitates flow of the hot molten (or softened) interlayer to conform and adhere to the glass.

In conventional lamination thicker panels take longer to laminate due to slow conduction of heat through glass to the interlayers. In RF lamination, because the glass is essentially transparent to the RF energy, the RF immediately heats all of the interlayers simultaneously. Thicker glass actually makes the RF process more efficient by thermally insulating the interlayers as they are heated. This reduces the total power required for lamination. RF lamination studies of 2’ x 3’ panels indicate that a thick stack of four laminates requires the same amount of time as just one panel.

Path to industry adoption

RF lamination has excellent potential for commercial success in manufacturing. Manufacturers have an investment in existing autoclave processes, so transitions will be gradual for RF to replace autoclaving. In circumstances of new manufacturing capacity, RF will be more strongly considered. Autoclaves are used out of necessity, but carry burdens of the bottleneck created by the slow batch processing, and safety concerns associated with pressure vessels. The industry is receptive to exploring new technologies that can produce glass meeting the required safety and quality standards. New production lines will be the first places that implementation is expected. Manufacturers of custom laminated products, such as solar and armor materials, have greater flexibility to try new processes, providing paths to initial market entry.

Significant development is needed to develop RF lamination for curved and large area glass, which will ultimately deliver large industry wide energy and cost savings. Automotive glass (which is relatively small but curved) and architectural glass (which is generally flat but large) represent the vast majority of the laminated glass industry today, and together comprise 85% of all flat glass. Glass laminated by the RF method must pass stringent quality standards for automotive and building use. The transparent armor (e.g., security glass) market is smaller and more fragmented, but is much more energy intensive per unit of production than larger autoglass manufacturers. Transparent armor provides numerous opportunities for near term industry adoption with significant energy savings possible for many manufacturers. The rapidly evolving photovoltaics market, which lacks significant standards for laminate quality, presents more non-manufacturing related challenges making adoption potential a case-by-case situation.

Laminated glass products can contribute to numerous in-use energy benefits. By lowering the cost of manufacturing with RF lamination, these ongoing benefits can be realized more quickly. For example, the vinyl interlayers contribute UV blocking ability, which reduces greenhouse effect in cars and buildings, thereby reducing the energy and CO_2 burden of air conditioning. The California Air Resources Board identified that increased use of laminated glass for side windows in automobiles could decrease CO_2 emissions up to 1.9 million metric tons per year nationwide[6], equivalent to reducing annual gasoline consumption by 225 million gallons[7]. The additional cost of laminated side windows would be offset by lower cost RF lamination, and accelerate industry’s transition to laminated side windows.

The growth of the photovoltaics industry is rapidly increasing the volume of laminate manufacturing, as virtually all PV is laminated (also called “encapsulation” in the PV industry). Estimates of PV growth rate of solar at 20-30% per year through 2012[8, 9]. With PV production doubling every 2 to 3 years, new energy burdens from lamination are created. Significant opportunities for growth in the glass, interlayer, and laminating equipment industries are being generated. RF lamination can provide a step change in the solar industry, cutting production time and energy costs, thereby facilitating greater consumer uptake through reduced capital cost of solar power.

Project Goals and Plan

The anticipated outcomes of the project included:

- Demonstration of successful PVB lamination with RF lamination
- Quantitative determination of RF laminated glass quality
- Development of concepts for technical methods to achieve curved glass lamination with RF (primarily for automotive products)
- Development of concepts for industrial scale RF lamination and manufacturing integration
- Clarification of standards for laminated glass products
- Development of understanding of diverse needs of technology users in auto, architectural, solar, and specialty laminate applications.
- Development of preliminary strategies to deploy RF lamination technology to users in the industries that will realize energy benefits.

RF laminate quality

A major focus of the project was to research the quality of visibly "good" laminates, by testing and analysis of environmental durability, mechanical performance, and adhesion bond strength. This testing provided empirical relationships of performance and RF lamination variables, which will facilitate further process development, short and long term performance analysis, and quality control for manufacturing.

Prior work focused on demonstrating a wide range of laminate types, sizes, and obtaining visibly "good", defect-free laminates. Characterization of optically clear laminates, free of visible defects, was not extensively studied. Certain environmental tests (boiling and baking the samples) were conducted, that demonstrated passing characteristics for EVA and TPU. PVB laminated with the RF process failed these tests, as a result of dissolved air, and/or water, evolving from the PVB during the environmental tests[2]. The failure was most likely associated with the bypassing of air removal steps used in conventional lamination of PVB, and from moisture absorbed by the PVB prior to lamination. PVB comprises the vast majority of laminates, and therefore the greatest energy and greenhouse gas impact. Therefore it was critical to resolve the PVB environmental performance issue. This was accomplished in cooperation with Pilkington.

Curved RF lamination

Curved glass lamination is challenging conventionally, with relatively high reworking rates in industry (averaging 3%)[10] corresponding to a proportional excess energy burden. Curved glass has not yet been investigated using RF lamination. Pilkington and Thermex-Thermatron were consulted to develop concepts for curved glass lamination using RF, and to identify resources to test those concepts The concepts deemed most likely to succeed will be included in the Project Continuation Plan for Stage 3.

Laminate market research and strategies

Ceralink interfaced with engineers and management of companies that are potential users of RF lamination. The feedback from these companies will be critical in developing commercialization strategies into each of the markets where RF lamination will fit, including automotive glass, architectural & building products, solar materials (photovoltaic panels and solar concentrating mirrors), laminated plastic windows, and transparent armor for security and defense applications. Each market will present unique challenges and opportunities.

Project Team

Contractor

Ceralink's technical team was composed of the scientist and engineers who developed RF glass lamination and have raised the technology to its current level. Ceralink initially developed and demonstrated a wide range of general applicability for the RF lamination technology, using equipment at the RF equipment partner. The initial work was partially supported by the Department of Energy Inventions and Innovations program under grant DEFG36-06GO16043. Feasibility of RF lamination up to 2' x 3' (approximate automotive side window size, and larger than many residential window panes), using EVA, PVB, and TPU interlayers were demonstrated. Lamination of PVB without post-processing defects (ie., proper air removal), was not achieved, and targeted as a key objective of this project. Ceralink has pursued US patent protection for RF lamination, and has cultivated industry awareness of RF lamination as an alternative manufacturing technology.

Glass Industry Partner

Ceralink teamed with Pilkington North America, part of NSG Group, the 2nd largest glass company worldwide, to study RF lamination in and the standard industry equipment and practices for fabricating and evaluating laminated glass for the auto industry[11]. The glass company contributed materials, analysis by industry standards, feedback on the capabilities of RF lamination with respect to industry expectations, and information on the autoclave process. Pilkington's expertise in large flat architectural glass lamination, and automotive curved glass lamination was significant in determining important factors for RF lamination to compete with autoclaving. Pilkington's analytical capabilities include physical testing of glass, microscopy, x-ray analysis, spectrophotometry, and accelerated weathering. The company's technology center serves as the platform for testing and developing new designs and processes, supporting products used by several of the major automakers.

University Partner

Ceralink teamed with the University of Illinois at Urbana-Champaign to explore fundamental adhesion mechanisms and performance in RF laminated glass through non-destructive ultrasonic evaluation (NDE). The collaboration added important analytic expertise and an NDE experience with laminated glass to the project. The University of Illinois previously developed methods for NDE of adhesion in laminated glass, using ultrasonic acoustic wave methods[12, 13]. This work was partially supported by the Department of Energy under grant DEFG02-91-ER45439. The bond strength is determined by analyzing energy velocities of a wide frequency ultrasonic pulse, and comparing to modeled adhesion levels and destructive adhesion tests. This type of NDE will be useful in quickly evaluating the differences between optically clear/defect free samples produced with RF lamination, without being tied to subjective pummel tests. As the NDE method is refined, empirical models of adhesion strength can be created to study variations in the RF process.

RF Equipment Partner

Thermex-Thermatron, LLC (Louisville, KY) has over a 60 year history of designing RF systems and optimizing RF processing. Skilled RF engineers, experienced in RF systems design and control, were invaluable for developing RF process variations to study effects of voltage, current, RF power, and system design. The company has experience building large RF systems for the composites and wood products industries, and has regularly built systems over 10 ft long and 4 ft wide.

Results and Discussion

The project plan focused on meeting certain technical goals to advance RF lamination technology. The goals, which are listed below, were designed to progress RF lamination toward commercial acceptability. Ceralink’s statement of project objectives was produced to allow these goals to be achieved.

Original Goals & Objectives of this project:

- Demonstrate successful PVB lamination with RF lamination
- Demonstrate scientific models and method for quantitatively determining adhesion in RF laminated glass
- Develop concepts for approaching curved glass lamination
- Develop concepts for industrial scale RF lamination and manufacturing integration
- Develop plan for meeting safety and regulatory hurdles for laminated glass products
- Develop understanding of diverse needs of customers in auto, architectural, solar, and specialty laminate applications.

Task 1. Study RF Lamination with polyvinyl butyral (PVB) Interlayer
Polyvinyl butyrate (PVB) is the largest volume interlayer for lamination, and therefore has the highest cumulative energy demand. This task focused on validating that RF laminated glass with PVB performs as well as conventionally laminated glass. Prior to this project, Ceralink performed successful laminations with PVB; however, upon environmental testing with 100 °C bake and boil tests, the samples would fail through severe bubbling. The potential causes of the failures were narrowed to failure to fully de-air the laminates, moisture absorbed in the PVB due to poor storage conditions, removal of pressure with the PVB still hot, or an inadequacy in the RF lamination process itself. The task was structured to allow observation of PVB lamination in the conventional autoclave manufacturing environment, and studies involving fabricating and testing samples of PVB laminated glass made using the RF process.

Subtask 1.1 Research on RF lamination in a PVB manufacturing environment.
The technical process of conventional glass lamination manufacturing process using PVB was studied. Through site visits to the Pilkington manufacturing and R&D facilities, conventional lamination methods, analytical methods, and process flow were studied. The study of process flow will be discussed later in Task 2. In conventional process, complete air removal and proper storage of PVB are essential to producing windows that meet the environmental testing requirements of the autoglass industry.

PVB Storage
In manufacturing, the PVB is stored in low temperature and low humidity (below 50 °F and 26% relative humidity), with the entire PVB interlayer cutting and lay-up operation performed in the same environment. This is due to the hygroscopic nature of PVB. Previous RF lamination work had been performed with PVB stored in ambient laboratory conditions, and therefore likely had significant adsorbed moisture leading to environmental test failure through bubbling. A dry storage solution was obtained to permit proper PVB storage at the RF lamination facility. The interlayer manufacturers indicated that room temperature was adequate for storage; however, the dry box was retrofitted with cooling coils to allow control over the chamber temperature below ambient.

Figure 4. Controlled humidity storage for PVB interlayers at the RF lamination facility for maintaining humidity levels below 20%.

Air Removal

Also in previous RF lamination work, air removal was accomplished simply through the action of pressing the glass panels together. This method produced environmentally passable samples made with other interlayers (ethylene vinyl acetate, EVA, and thermoplastic polyurethane, TPU), which are less prone to moisture absorption. Industry takes certain steps to ensure that air is removed from windows before they are even placed in the autoclave for lamination. These “pre-lamination” steps comprise one of two methods, nip-rolling or vacuum de-airing. In nip-rolling, the glass-vinyl lay-up is heated enough to make the vinyl tacky, but not hot enough to fully laminate. The window is then passed through rollers to squeeze out air between the vinyl and the glass. The interlayers used typically have surface patterns meant to aid the removal of air during nip-rolling. A typical industry process uses up to three sets of nip rollers, one cold and two hot, to seal the windows prior to autoclaving. The vacuum method involves placing the window in a vacuum bag, or using a vacuum-ring tool around the edge of the window. Vacuum is pulled and the glass is heated to remove the air and seal the window before autoclave lamination. Nip rolling and vacuum bagging capabilities were set-up as pre-lamination steps for RF lamination testing in this project.

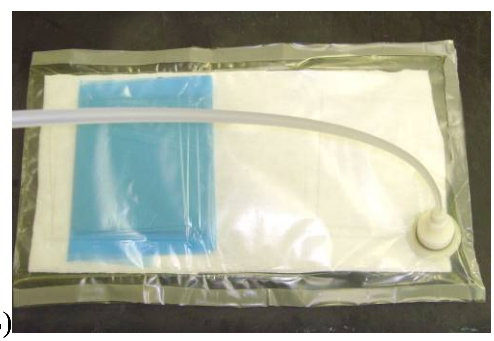
A)  B) 

Figure 5. Air removal systems set up during this project for PVB lamination including A) nip roller, and B) 6” square glass panel wrapped in blue release film, in nylon vacuum bag.

Test Methods

Ceralink was introduced to the autoglass industry test methods used by Pilkington. The tests covered optical, mechanical, and environmental performance of the laminates, following the ANSI/SAE Z26-1996 and Pilkington’s own Indicative Test Protocol (Table I). These tests were used in Subtask 1.3 for analyzing the performance of RF laminated glass. Demonstration of RF laminate performance meeting these requirements is a major step in proving commercial viability of the process.

Table I. Table of quality tests performed on RF laminated glass, following ANSI/SAE Z26-1996 and Pilkington North America's Indicative Test Protocol. Tests marked with an (*) did not pass the initial round of testing, but were later passed after designed experiments to address the issues.

Optical Testing	Mechanical Testing	Environmental Testing
Haze	Abrasion resistance	Humidity
Light Stability	Dart drop impact (7 oz., 30 ft)	Cyclic humidity
Luminous Transmission	Ball drop impact (8 oz., 30 ft)	Thermal cycling
	Pummel adhesion*	UV exposure
		Boil test
		Bake test, 90 °C, 4 days
		Stepwise bake test, 120 °C 2 hours*
		24 month exposure – Florida
		24 month exposure – Arizona

Subtasks 1.2 Fabricate test coupons & 1.3 Perform analysis of performance of test coupons

Subtasks 1.2 and 1.3 are discussed together, as these tasks were interdependent during the project. Analysis performed on sets of fabricated coupons provided feedback for new experimental designs and targeted testing for subsequent samples.

Pilkington provided glass and PVB interlayer materials throughout the project for fabrication of laminated glass test coupons using RF pressing. Ceralink performed the lamination using a 10 kW, 18"x20", 3 ton RF press (Figure 6). Aluminum platens measuring 13" x 13" were fabricated to allow lamination of up to 12" square glass panels. Throughout the project, over 300 laminate test coupons were fabricated. Both pre-lamination methods, nip-rolling and vacuum de-airing, were used in fabricating the test coupons. Throughout the project other variables were addressed. The full list of studied variables is provided in Table II.

A)  B) 

Figure 6. Photographs of A) the RF press used for fabricating test coupons, and B) the press opened, with a sample loaded on the lower platen.

Table II. List of RF lamination variables studied in Task 1

Variable	**Range**
RF pressure	40 to 160 psi
RF power level	2.7 to 4.5 kW
RF lamination time	25 to 70 seconds
Prelamination method	Nip rolling and vacuum bagging
Initial sample temperature in RF	Room temperature, 60 °C
Cooling time under pressure	No cool under pressure, 5 minute cool under pressure
PVB type	Regular adhesion and high adhesion

An initial set of 70 12" square panels was laminated using the maximum pressing force of the press (41 psi on the windows, compared to 100 to 150 psi used in autoclaving) were laminated. These windows were fabricated by preheating and nip rolling prior to lamination. Each window was placed in the RF press at approximately 60 °C, and heated via RF for 40 seconds, resulting in visually good laminates. These windows were subjected to the 16 tests listed above. The only failing tests were Pummel Adhesion (very low), and the bake test to 120 °C. Boil and bake tests at 100 °C passed, unlike prior samples produced by Ceralink. This indicated that PVB storage addressed a significant portion of the environmental performance concerns. Because the samples formed bubbles at 120 and 110 °C, but not at 100 °C, indicated that trapped air, and not moisture, caused the environmental failures with properly stored PVB.

Description of Tests

The initial testing results are summarized in Table III. The testing is further described following the table.

Haze and Abrasion resistance

The passing haze test indicated that the RF lamination process completely eliminated the surface pattern on the PVB. A haze value of less than 1% is required, and RF laminated samples ranged from 0.1 to 0.4%. The haze samples were also tested after abrasion, which just affected the outside of the glass, and therefore did not significantly relate to the RF process; however, the abrasion test did pass as well.

Table III. Table of analytical testing and results for initial 12" square PVB window study.

Test	# of Samples	Duration	Result
Ball drop, 226 g	12	1 day	Passed
Pummel	5	1 day	**Failed – Pummel of 0 to 1** Target: Pummel rating of 3-8
Haze Target, < 1%	5	1 hour	Passed 0.4%
Luminous Transmission <1% degradation after irradiation	5		
Cyclic Humidity 3x - 2 wks 50°C/95% RH, 2 wks ambient	5	12 weeks	Passed
Boil/Stepwise Bake	5	2 days	Passed after 2 hour boil (100 °C) **Fine bubbles at 110 °C** **Failed (bubbles) at 120 °C**
UV test	5	6 weeks	Passed.
Temp. Cycling	5	10 days	Passed with no failures with cycling between 80 °C and -40 °C
High Temp Stability, 90 °C	5	4 days	Passed No bubbles after 4 days at 90 °C
High Temp Stability, 120 °C	5	2 hours	Passed No bubbles after 2 hours at 120 °C
Long Term Exposure Florida	9	2 years	Passed at 6 months TBD at 12, and 24 months
Long Term Exposure Arizona	9	2 years	Passed at 6 months TBD at 12, and 24 months

Light stability and luminous transmittance

This test is performed by first measuring light transmittance through the window, followed by high intensity lamp exposure, for example with a xenon lamp, followed by re-measuring of transmittance. The initial transmittance test indicated an acceptable level of transmittance for the particular glass & PVB combination used. The reduction in transmittance after irradiation is related to the affect of the high intensity light on the PVB, and is shown in Table IV. Table of the results of light stability and luminous transmittance testing.. The reduction in transmittance of less than 1 % indicated a passing mark for this test.

Table IV. Table of the results of light stability and luminous transmittance testing.

	Percent transmittance		
Specimen No.	**Before Irradiation**	**After Irradiation**	**Reduction of Transmittance**
1	74.48	74.26	0.22
2	74.68	74.39	0.29
3	74.55	74.37	0.18

Ball drop and dart drop tests
In the dart impact test, a sharp tipped steel dart weighing 7 oz is dropped onto the glass from a height of 30 feet. A failure is recognized as a penetration through the laminate by the dart. This test is indicative of the safety performance of the laminate. 5 panels were tested and all passed.

In the ball impact test, a steel sphere weighing 8 oz is dropped onto the glass from a height of 30 feet. A failure is recognized as a penetration through the laminate by the ball. This test is indicative of the safety performance of the laminate. 12 panels were tested and all passed.

A)  **B)** 

Figure 7. Photographs of A) dart impact specimen, and B) ball drop impact specimen showing the damage pattern, but no penetration through the glass, indicating a “Pass”.

Pummel adhesion test: In this test, a skilled person uses a hammer to strike the surface of a laminated glass sample that has been chilled to 0 °F, held against an angled steel plate. After smashing the glass, the tester observes the appearance of the glass, and compares against standards to give a subjective ranking from 0 to 10. Increasing rank numbers indicate higher levels of adhesion. 5 samples were tested, resulting in pummel values of 0 to 1, indicating that very little glass remained adhered to the PVB after pummeling (Figure 8). Variables of interest included RF pressure, RF process time, PVB storage, and the adhesion of the PVB interlayer itself.

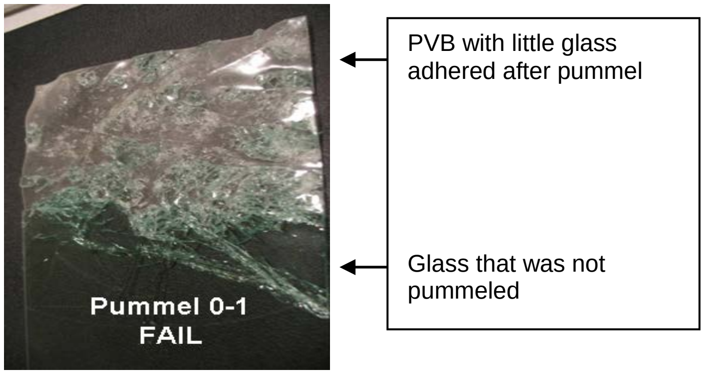


Figure 8. Photograph of pummeled sample from initial pummel test with low PVB adhesion to the glass.

Cyclic humidity test: In this test, panels were cycled for 12 weeks between 2 weeks at 50 °C, 95% relative humidity, and 2 weeks at ambient conditions. All samples passed without delamination, bubbles or hazing.

Thermal cycling test: In this test, 10 cycles were made between 80 °C, 80% relative humidity and -40 °C. All samples passed without delamination, bubbles or hazing.

UV cycling: In this test, the target is to have less than 1.5% loss in transmission after 400 hours of high intensity UV exposure. The reduction in transmission was below 0.3% for all samples.

Bake test: Bake tests at 90 °C for 4 days and 100 °C for 2 hours passed without delamination, bubbles or hazing.

Boil test: Samples boiled in water for 2 hours passed without delamination, bubbles or hazing.

Stepwise high temperature bake test: Samples baked at 110 °C for 2 hours developed fine edge bubbles, which is still considered passing, however at 120 °C, bubbles formed throughout the glass (Figure 9), indicating failure of the test. No haze or delamination was observed. The formation of bubbles at 120 °C indicated the presence of air trapped in the PVB, suggesting incomplete air removal prior to lamination. Other variables of interest included cooling under pressure and the pressure level used during lamination.

Figure 9. Photograph of sample after 120 °C bake test showing bubbles throughout the PVB interlayer in the glass.

Environmental Test Success

The high temperature bake test was addressed through a series of designed experiments to identify parameters that positively affected the outcome of this test. Low humidity PVB storage clearly improved environmental performance. Variables selected to study for high temperature performance included RF process time, pressure, cooling under pressure, and vacuum vs. nip rolling for de-airing. A summary of the results of this study are shown in Figure 10. The low pressure level, which was used on the 12" square panels, was only 41 psi, compared to the 100 to 150 psi used in autoclaving. In order to reach high pressures, smaller 6" samples were used for these tests, allowing pressures up to 160 psi to be achieved. The primary difference between the samples on the top and the bottom row in Figure 10 is the higher pressure (160 psi), and the addition of cooling under pressure. The fine edge bubbles observed in the upper row samples are typical in autoclave lamination if pressure is released before the glass is cooled substantially. Therefore the elimination of the edge bubbles was due to adding a 5 minute cool time under pressure. The large bubbles throughout the sample were slightly reduced by extending the lamination time from 40 to 55 seconds, but nearly completely eliminated when high pressure was used. This suggested that 41 psi was insufficient to force all of the air out of the laminates, and appeared to be consistent with conventional processing. The nip-rolled sample exhibited only few small bubbles (lower left), which may have remained as a result of an un-optimized nip rolling process. With vacuum bagging, the 120 °C bake test passed without development of any bubbles in the interlayer. This result was even more significant given that the vacuum de-aired sample was heated in the RF press from room temperature, whereas the nip rolled sample was heated from 60 °C.

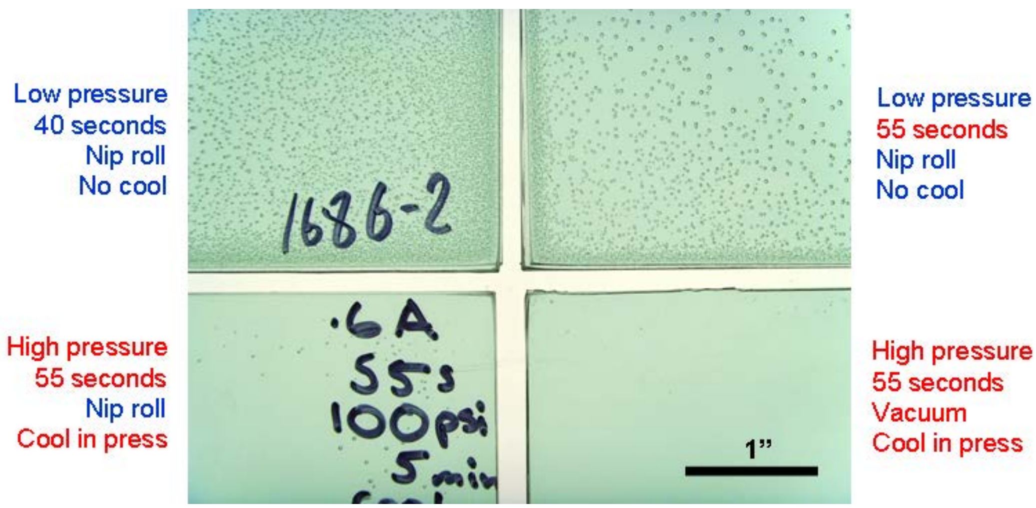


Figure 10. Photograph of 4 samples from a designed experiment to overcome high temperature bake test failures (top row). The top left sample was from the original sample set. The top right sample was processed slightly longer, resulting in minor, but measureable improvement. The bottom left sample showed greatly enhanced performance through increased pressure and cooling under pressure. The bottom right sample shows that vacuum de-airing eliminated all bubbles, compared to nip rolling.

Designed Experiment for Environmental Test Optimization

After obtaining these results, a large designed experiment was performed with Pilkington to refine understanding of the significant variables for the 2 hour bake test at 120 °C. A reduced 2^6 factorial experiment was designed with 3 levels of pressure included. A total of 108 samples were produced, with each parameter set in triplicate.

Six factors were evaluated in this experiment:

- **Storage** (Storage Conditions)
  The conditions (%RH) under which the PVB was stored. The actual time, temperature, and relative humidity was not submitted.
  - **4 =** target setting of 4%RH.
  - **20 =** target setting of 20%RH.
- **Type** (Type of PVB)
  The brand and type of PVB used.
  - **HAdh =** High Adhesion architectural PVB
  - **Sek =** Sekisui automotive PVB
- **Prelam** (Pre-lamination Method)
  The method used to prepare the samples for RF lamination.
  - **Nip =** Nip Roller (one pass)
  - **Vac =** Vacuum bag
- **Time** (Press Duration)
  The amount of time the RF was applied to the samples.
  - **40 =** 40 second duration
  - **55 =** 55 second duration
- **Pressure** (Gage Pressure)
  The pressure that was applied to the samples
  - **25** = 25 psi gage pressure
  - **50** = 50 psi gage pressure
  - **100** = 100 psi gage pressure
- **Cooling** (Cooling Duration)
  The amount of time after RF that the samples were allowed to cool while in press.
  - **No** = no cooling
  - **Yes** = 5 minutes in press

The RF power setting and glass preparation methods were held constant for the experiments. The actual glass temperatures were not measured. Three replicates of each treatment combination were produced. The samples were then treated at 120 °C for 2 hours. The bubbles present in each sample were counted and graded for severity, with low grades being free of bubbles, and high grades being severely bubbled.

In order to facilitate analysis, the 50 psi data was eliminated from the final data set. In all cases (main effect and all interactions) the 25 psi samples had a higher Bubble Grade average than the 50 psi samples, which had a higher average than the 100 psi. To put it another way, the Bubble Grade for the 50 psi samples was always between the 25 psi and the 100 psi samples. By eliminating the 50 psi data points, the design could be analyzed as a balanced 2^6 full factorial. The main and interaction effects plots for 'all data' have been included in the attachment for reference.

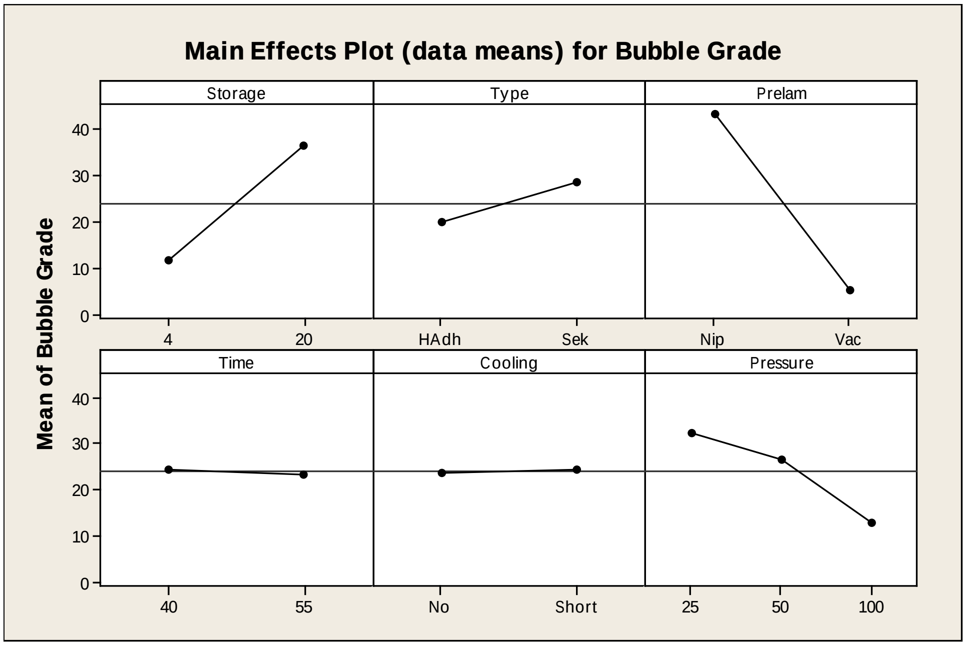


Figure 11. Plots of the affects of experimental variables on Bubble Grade.

Three of the factors had a significant impact on the Bubble Grade: Storage, pre-lamination, & pressure.

- Samples with a target storage humidity of 4% RH had a significantly lower average Bubble Grade than the samples with a 20%RH target.
- Vacuum bagged samples had a significantly lower average Bubble Grade than the samples that were nip rolled.
- Samples ran at 100 psi had a significantly lower average Bubble Grade than the samples at 25 psi.

The interactions involving 2 or 3 of the significant main effect variables had a statistically significant impact on Bubble Grade.

- Storage / Pre-lamination
- Storage / Pressure
- Pre-lamination / Pressure
- Storage / Pre-lamination / Pressure

Interactions with Type, Time, or Cooling variables were not statistically significant. The type of PVB, press time/duration, and cooling duration did not affect the amount of bubbles observed in the samples. The biggest surprise result was no effect from the 5 minute cooling, which indicates that fast lamination times will be achieved without needed long in-press cooling. The best conditions for lamination were determined to be high pressure, vacuum bag, and low humidity storage. The cube plot below shows the combination of high pressure, low humidity storage, and vacuum bagging giving the lowest Bubble Grade, while the opposite corner gave, by far, the worst Bubble Grade.

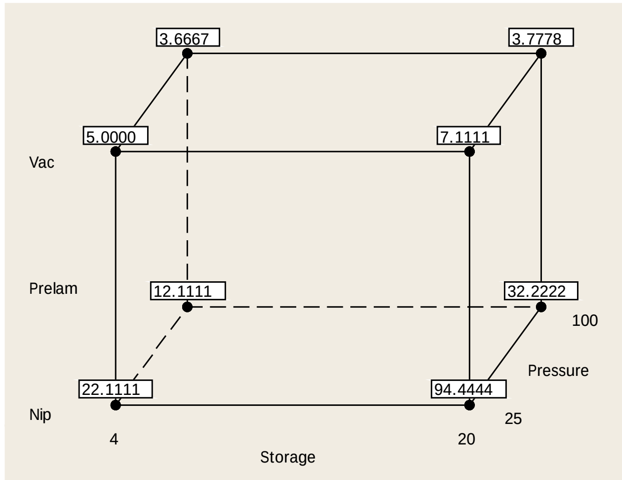


Figure 12. Cube plot of the mean Bubble Grades for the 3 significant variables, Pre-lamination type, Storage humidity, and Pressure.

Pummel Adhesion Success

The pummel adhesion test was addressed through a series of designed experiments to identify parameters that positively affected the outcome of this test. RF process time, pressure, cooling time, and vacuum de-airing were found to have small affects on adhesion, increasing the Pummel rating to 1-2. The greatest improvement of pummel adhesion was through the use of a high adhesion grade of PVB. Typical automotive PVBs have adhesion inhibitors added to provide moderate levels of adhesion, whereas architectural PVBs lack inhibitors, to give high adhesion in those applications. The high adhesion PVB resulted in pummel adhesion values in the industry acceptable range of 3 to 7 out of 10 (Figure 13).

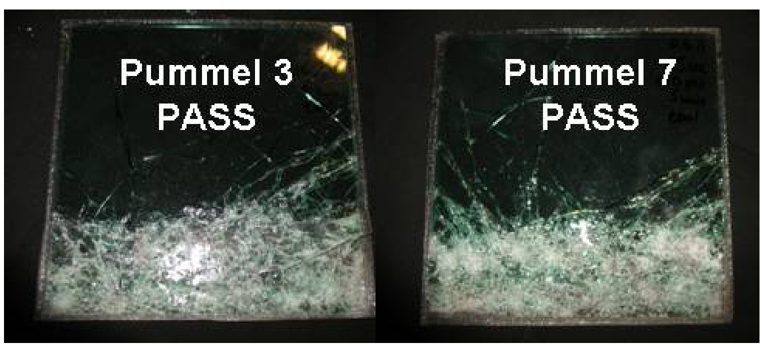


Figure 13. Photographs of pummeled glass samples with high adhesion PVB showing results in the low to high range acceptable to the autoglass industry.

The humidity of storage is likely to be a factor in Pummel adhesion strength, as it was in the environmental test case. PVB is hygroscopic material due to the highly polar vinyl alcohol groups of which it is comprised. As a result, PVB is not only attracted to the highly polar silanol groups of float glass but also the highly polar water compound. Therefore, PVB and water molecules compete for available bonding sites on the glass surface[14]. The general affect water content has on the adhesive bond strength in LSG is shown in Figure 14.

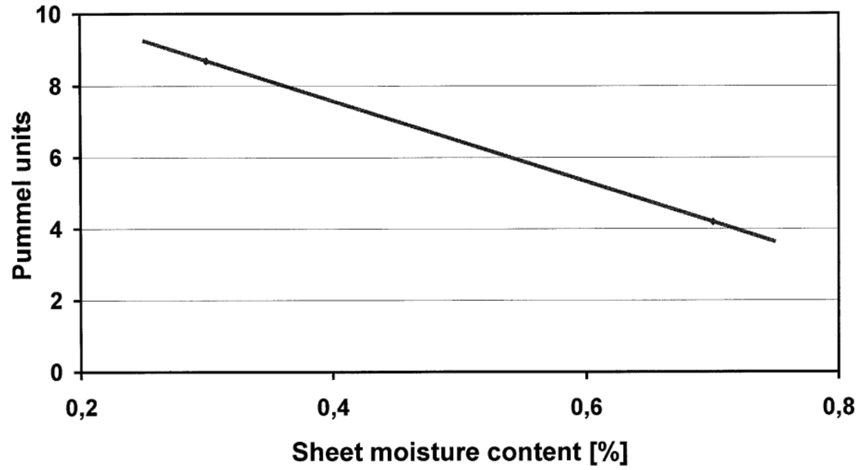


Figure 14. General relationship between adhesive bond strength and sheet moisture content in LSG. Figure extracted from[15].

Ultimately, RF lamination parameters that produce controlled adhesion levels for any grade of PVB should be developed. However, RF lamination has been proved feasible using alternative, commercially available interlayers. Future studies will investigate temperature control using optical temperature probes embedded in the glass. It is likely that reaching higher temperatures in the PVB in a controlled manner (without overshooting), could produce PVB adhesion within the desired range for any PVB. This will be pursued in future work with Pilkington.

Task 2. Study of current lamination process and requirements for integrating new process

Task 2 was designed to facilitate dialogue with Pilkington on integrating RF lamination into manufacturing flow. The major goal of this task was to develop understanding of the current manufacturing processes in lamination, and to envision how RF lamination would change the process.

The current process was studied through site visits, as described in Task 1. The lamination process included cutting the flat glass into the window shape, bending, cleaning, laminate lay-up, rolling, heating and nip-rolling, autoclave lamination, and quality inspection. Out of all the production steps, only autoclave lamination is a batch process. The other steps flow through the process both continuously and automated. The process is shown schematically in Figure 15. After nip rolling, the windows are typically loaded by hand onto autoclave racks, on which the glass is stored until the next autoclave batch cycle is ready. While waiting for the autoclave, the heat invested in the glass in the pre-heat oven and nip rolling stage is lost. The glass is then manually loaded into the autoclave, and after the autoclave cycle the glass is manually inserted back into the continuous process for the final processing stages.

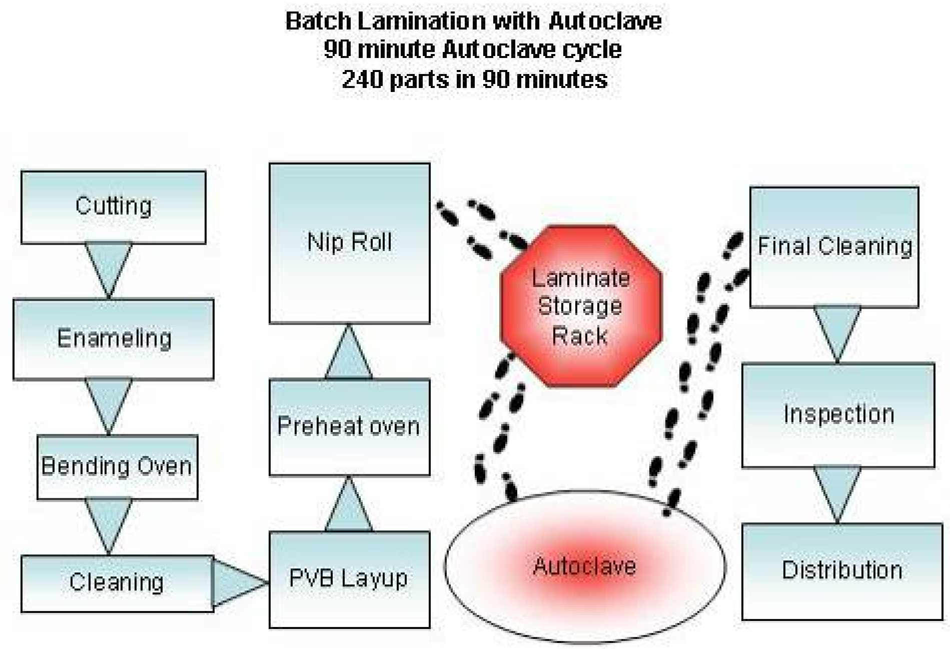


Figure 15. Diagram of autoclave based process flow for glass lamination. The entire lamination process is performed in a continuous, automated manner, except for the autoclave cycle. Continuous automated flow is represented by triangles, where footsteps represent operator movement of the products into the batch storage racks and autoclave. The large batch size of the autoclave allows for high throughput. If autoclave maintenance is required, the entire production flow stops.

Production target rates for throughput were also presented by Pilkington. This information was used to fit a hypothetical RF process into an industrial production flow. In autoclaving of automotive windows the autoclave process takes approximately 90 minutes, producing either 240 or 320 windshields in that time, depending on the size of the autoclave. The throughput rate of the total process is between 2 and 4 windows per minute. This high rate is not always maintained, as the process pauses for retooling as different windows are produced. However, while RF lamination provides in-press lamination times of less than 1 minute, clearly multiple windows must be in RF presses simultaneously to meet the high throughput of the autoglass process. This could be accomplished by using one press to laminate multiple windows (ideal for smaller side windows), or multiple presses to receive windows from the nip roll process in a staggered fashion. Using a staggered approach with a full 1 minute RF cycle time, 3 RF presses could take the place of a single autoclave, as shown schematically in Figure 16. When operated at a 20-second staggered interval, a continuous process flow could be maintained for up to 270 windshields every 90 minutes.

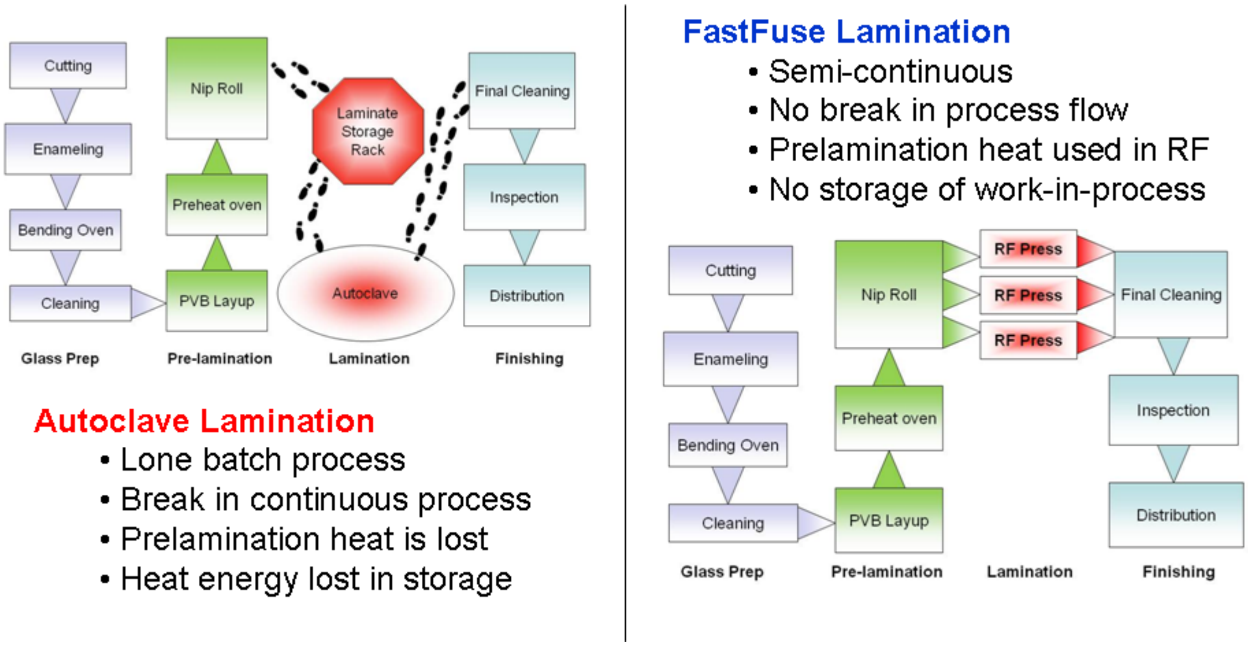


Figure 16. Diagrams of autoclave and FastFuse RF lamination process flows for autoglass for producing equivalent throughput. In the RF lamination (FastFuse) process, 3 RF presses, in a staggered, continuous process would meet the throughput of the current autoclave process.

Other direct impacts on the industrial process include that three RF presses would occupy significantly less factory space than the autoclave and the air compressors that support the autoclave. Maintenance of the RF presses would allow the manufacturing process to continue through the maintenance period. With multiple presses, two presses can keep running while one press is down for maintenance. With autoclaving, any maintenance requiring downtime will completely stop the manufacturing process.

Side windows present new challenges for autoclaving. Windshields, being large monolithic panels, require simple racks to support a large number of windows. Side windows, being much smaller, would require more complicated racking systems. The time required to rack the windows would be longer due to the quantity increase. As is common in many industrial processes, the many smaller components will have a lower ft^2 per hour production rate, than few larger components. RF lamination, however, requires no racking. A press with a large area relative to the size of the window can press multiple windows simultaneously, side-by-side. In the current bending processes for autoglass side windows, the press-bend tooling (described later in Task 4), often accommodate 2 or 4 windows in one tooling. This would likely be the case for the RF curved platen tooling as well (also described in more detail in Task 4 below).

Continuous flow in an RF press system has been demonstrated by the RF equipment manufacturer for a wide range of processes. Windows could pass through RF presses in a conveyorized fashion, with shuttles, or rotating tables. Continuous processing would bring auto windows from the nip roller directly into the press, and then moving from the press to quality inspection. By bringing the window still hot from the nip roller into the RF press, the temperature rise (and corresponding energy requirement) for lamination is dramatically reduced compared to laminating a cooled window. This results in a significantly greater energy savings than the shift from autoclave to RF lamination alone, by recovering and utilizing what was previously waste heat in the process.

Pilkington studied energy consumption in the lamination process. The data is variable based on the windows laminated, process parameters for various PVB interlayers, and different lamination lines. An average energy consumption of 0.45 kWh/ft^2 was determined. Energy information for the laminated glass industry as a whole was collected from glass industry statistics including Department of Energy Manufacturing Energy Consumption Statistics (MECS), which suggests an approximate average energy consumption of 1 kWh/ft^2. Pilkington's process is approximately twice as efficient as the industry average, but this average likely includes very large architectural glass and multilayer laminates. RF lamination energy data indicates an average energy consumption of 0.04 kWh/ft^2 for automotive side window sized glass. Pilkington's data showed a 80-90% energy savings potential for RF lamination versus a 90-95% energy savings in the industry as a whole (Figure 17).

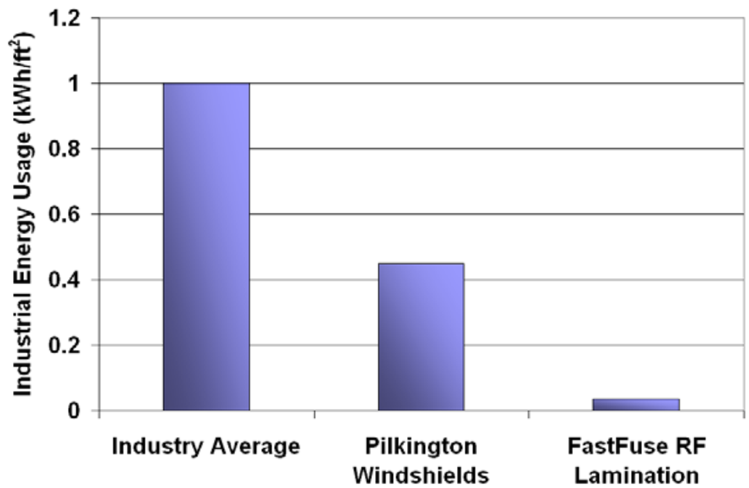


Figure 17. Graph of lamination industry energy usage for the industry average (based on industry reports), Pilkington's windshield manufacturing process, and FastFuse as demonstrated to-date by Ceralink.

Task 3. Non-destructive study of adhesion in RF laminated glass

The ultrasonic method used for non-destructive evaluation of laminated glass was performed at the University of Illinois at Urbana-Champaign as part of the 2011 Masters Thesis of Thomas Suchy[16], under the guidance of Professor Henrique Reis.

Laminated safety glass (LSG) is a ubiquitous composite material consisting of two or more glass plates adhered together by a viscoelastic copolymer interlayer such as polyvinyl butyral (PVB) or ethylene vinyl acetate (EVA)[17]. LSG is widely used in security, architectural and automotive industries as a transparent barrier providing safety from sudden impacts by absorbing energy while preventing penetration from intruding objects[18]. In addition to providing safety from impact, LSG is used for sound reduction, ultraviolet radiation protection and solar energy control[19]. Increased load bearing capacity and impact resistance make LSG superior to monolithic glass plates with identical thickness. Additionally, the adhesive bond between the copolymer interlayer and outer glass plates of LSG reduces the risk of injury by preventing glass shards from delaminating upon fracture. The performance of LSG is largely affected and controlled by the level of adhesion between the glass plates and copolymer interlayer[15]. When a laminate is struck by an external load, the copolymer interlayer absorbs kinetic energy through elastic deformation and transfers shear stresses between the outer glass plates[20]. Laminates with very high adhesion do not allow the copolymer interlayer to transfer shear stresses effectively, which reduces the impact resistance considerably. Therefore, laminates with too high adhesion act as monolithic glass plates when impacted by an external load. Conversely, when laminates with very low adhesion are impacted, large shards of glass are delaminated from the copolymer interlayer, resulting in high risk of injury[21]. As a result, it is imperative to find an optimal level of adhesion that will observe higher impact energy levels, while preventing delamination of fractured glass. The general tradeoff between impact resistance and adhesive bond strength in LSG is illustrated in Figure 18.

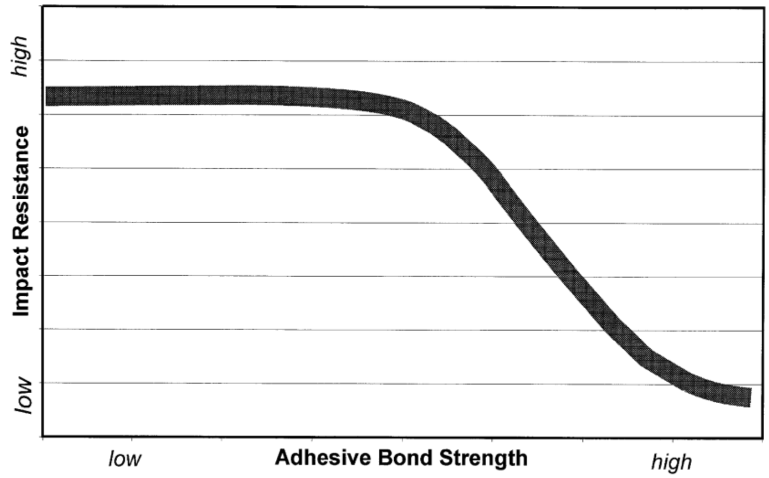


Figure 18. Relationship between impact resistance and adhesive bond strength in LSG. Figure extracted from the Keller, 1999 article in Glass Processing Days, "Adhesion in Laminated Safety Glass – What Makes it Work?"[15].

The non-destructive evaluation of glass adhesion was studied for two types of interlayers, EVA and PVB, by the University of Illinois. The EVA samples were provided by Ceralink using glass and interlayers obtained from vendors. The PVB samples were produced using automotive glass and PVB interlayers provided by Pilkington. The testing demonstrated similar results for non-destructive testing as for the destructive adhesion methods used at Ceralink for EVA (the 180° peel test), and at Pilkington for PVB (the pummel adhesion test). The NDE work resulted in a mid-project report from the University of Illinois on the EVA samples, and a Masters Thesis, primarily focused on the functioning of the NDE process and the PVB work[16].

The EVA interlayer work produced data showing a shift in ultrasonic acoustic properties in the glass as a function of increasing adhesion strength according to peel testing. This allowed a correlation between laminate process time and adhesion strength to be made for both destructive and non-destructive testing. The University of Illinois was previously familiar with testing laminates with PVB interlayers. The lower stiffness (elastic modulus) of the EVA interlayer presented new challenges to the University of Illinois, as lower stiffness materials have a stronger dampening effect on the ultrasonic waves, and therefore change the propagation characteristics.

NDE with PVB laminates was performed on autoglass laminated with RF. The University of Illinois, in previous work, developed the NDE process using glass and interlayers from a major PVB interlayer manufacturer. In this study, the University of Illinois reported very low adhesion levels in the majority of samples provided by Ceralink. This was not expected at the project on-set, but as was presented above in Task 1, the adhesion levels in the PVB laminates scored in the 0 to 1 out of 10 range on the pummel adhesion scale. The University of Illinois predicted levels in the 1 to 2 range for the same panels. After performing the adhesion studies described in Task 1, pummel adhesion values of 3 to 7 were obtained using a high adhesion PVB, at high pressure, with vacuum bagging. As described in Task 1, this combination of parameters led to reasonable levels of adhesion for 6" square samples. The NDE test requires longer distances between the ultrasonic transducers, therefore 12" x 6" samples were provided. However, these samples were laminated at only half the pressure as the 6" squares, due to being twice as large. As a result, the adhesion on these samples ranged only from pummel of 1 to 3. The NDE testing validated the Task 1 experimental indications that pressure was critical to achieving good adhesion.

NDE Introduction

The experimental estimation of the adhesion levels between the polyvinyl butyral (PVB) interlayer and the two adjacent glass plates in laminated safety glass (LSG) was performed using an ultrasonic guided wave approach. In this approach, the interfaces between the PVB interlayer and the two adjacent glass plates are modeled as layers of longitudinal and shear springs, as illustrated in Figure 19. The material properties of the PVB interlayer are provided in Table V, and the spring constants are provided in Table VI. The spring constants representing different levels of adhesion are estimated using concepts of fracture mechanics and surface characterization of the PVB interlayer and of the glass plates using atomic force microscopy (AFM). For an in-depth review of the estimation of these spring constants the reader is referred to Huo[19] and Suchy[20].

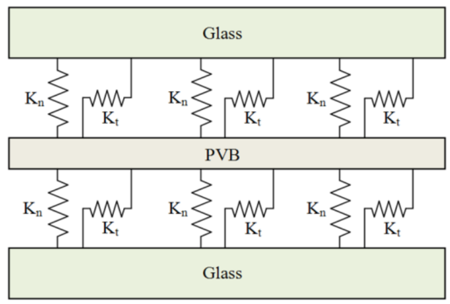


Figure 19. Spring model using normal and transverse spring layers to represent the adhesive bond in LSG.

The purpose of this study is to use mechanical guided waves to estimate the adhesive bond strength of laminates safety glass. Ceralink prepared and provided the first set of laminated specimens. Each laminated specimen consists of two layers of plate glass surrounding an ethylene vinyl acetate (EVA) interlayer. To obtain specimens with different levels of adhesive bond strength between the plastic interlayer and the two adjacent glass plates, Ceralink manufactured five groups of four specimens each with increasing RF lamination times. The RF lamination times for each of the five groups were 60, 75, 90, 120 and 150 seconds, respectively.

NDE Experimental Setup

Figure 20 illustrates a typical through-transmission set-up for mechanical guided wave ultrasonic measurements. Figure 21 shows two transducers mounted on angle-beam-wedges, one for sending and the other for receiving the ultrasonic signal, with the sending and receiving transducers, and analytical schematic shown. Both transducers are mounted on the same side of the test specimen.

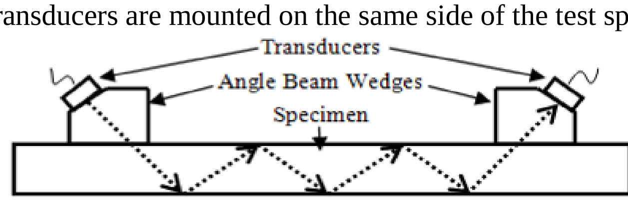


Figure 20. Typical trough-transmission ultrasonic set up for mechanical guided wave measurements.

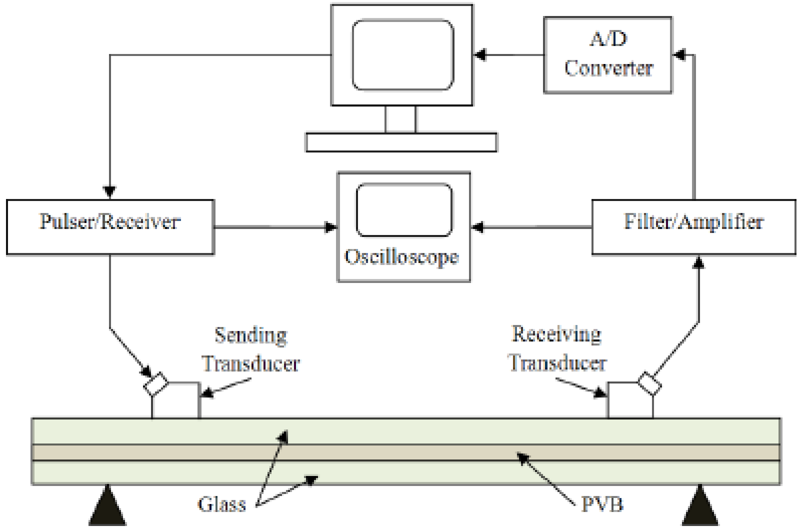


Figure 21. Schematic diagram of ultrasonic testing equipment and indirect through-transmission approach.

Panametrics longitudinal angle beam transducers with a central frequency of 500 kHz were used for this study. The transducers were mounted on Plexiglas angle-beam-wedges that can vary the angle of incidence from 0° to 60°. Figure 22 shows one angle-beam-wedge and transducer assembly connected to one of the two custom made holders manufactured in house. The distance between the two transducers (i.e., sending and receiving transducers) is controlled by connecting each of the custom holders to a metal bar with various marked distance as illustrated in Figure 23.

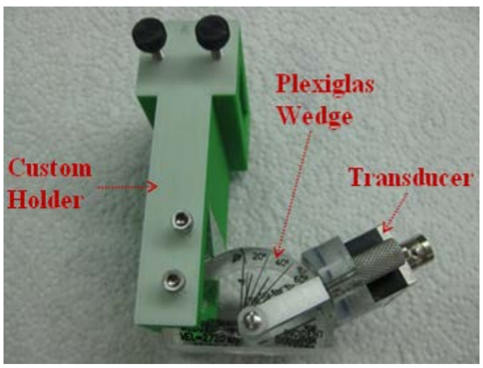


Figure 22. Ultrasonic transducer, angle beam wedge, and transducer holder assembly.

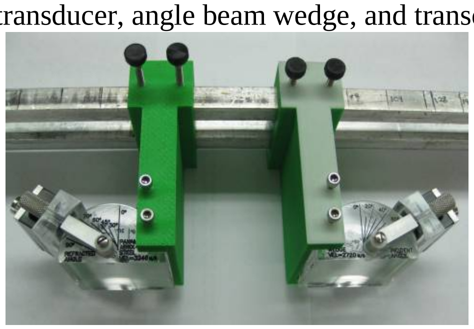


Figure 23. Transducer holder system showing the two transducers, the two wedges and the holding bar.

A stand used to support the laminated specimens for UT was constructed with three points of contact near the outer edges of the specimens. The sending transducer was excited using a Ritec RPR-4000 pulser/receiver. The signal from the receiving transducer was filtered using a Krohn-Hite 3945 analog filter/amplifier, before being digitized and stored in a computer for further analysis. LabVIEW software was used to control the entire data acquisition system to collect the ultrasonic waveforms.

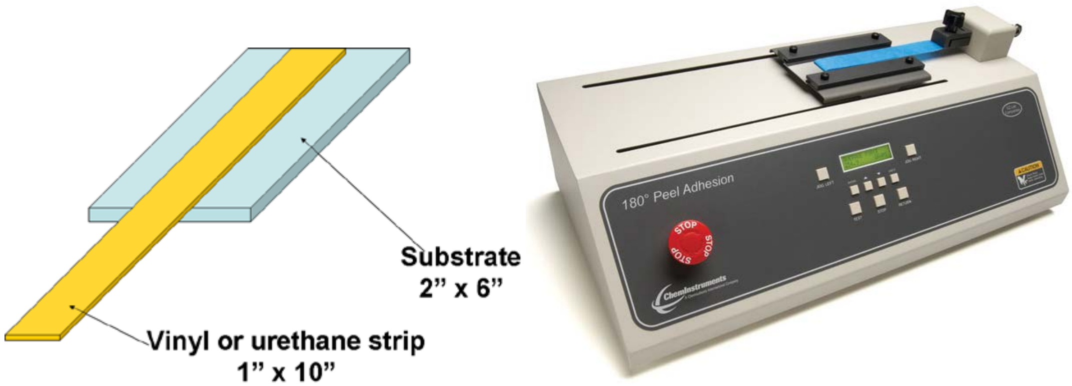
NDE Experimental Procedure

The laminate specimens corresponding to the five groups with increasing RF lamination times, i.e., RF lamination times of 60, 75, 90, 120 and 150 seconds, respectively, were tested on 12" x 12" glass panels. Four panels were made at each lamination time. Each laminate was investigated using identical testing parameters, with the exception of the excitation frequency, which was varied from 100 kHz to 500 kHz. The separation distance between sending and receiving transducers was held constant at 220 mm, and for each waveform, 2048 data points were collected with a sampling frequency of 8 MHz. The receiving time domain signal was averaged 25 times to eliminate any adverse signal noise. A 60° angle of incidence (using the variable angle wedge) was chosen to eliminate specific wave modes by means of the Snell's Law. The filter/amplifier was left open to collect all response frequencies, and a signal gain of 46 dB to the input signal was used. Ultrasonic couplant was applied at the interfaces of the transducers/angle-beam-wedges and the angle-beam-wedges/laminates to ensure proper transfer of acoustic energy. The power of the pulser and all other testing parameters was held constant for all the test data. A force was applied to the transducer holder until a saturation pressure was obtained. An excitation frequency sweep was used via the LabVIEW, which allowed the collection of the time signal waveforms at each frequency increment for later analysis.

Peel Strength Adhesion Testing

Experimental peel testing was performed using the ASTM D3330 standard on peel-adhesion. While the standards provide the method for performing the peel testing, no method existed for preparing the peel samples for glass lamination. Therefore Ceralink developed a new method for making peel samples using RF lamination.

Ceralink prepares peel samples for FastFuse by laminating a 1" x 10" test strip of interlayer to a single 2" x 6" piece of glass (Figure 24A). In order to make the process as similar as possible to regular FastFuse with 2 pieces of glass, a 2nd piece of glass is used, but a sheet of FEP or ETFE release film is placed between the interlayer and the top layer of glass. This allows the top layer of glass to participate in the dielectric heating, but then be easily removed for peel testing. Ceralink developed this approach to preparing peel test samples in our previous Department of Energy program. Ceralink also manipulates the buffer materials to avoid edge effects on the vinyl, and also to minimize spreading of the tape during melting and lamination.



A) B)

Figure 24. Schematic of 180° peel test sample. A) For this sample, an interlayer strip is bonded to the substrate material, leaving a tail of interlayer off of one end of the sample. The strip is attached to a load cell on the peel tester, and the force required to pull the interlayer off of the substrate is measured and converted to adhesion strength. B) the Chemsultants Instruments PA-1000-180 Peel Adhesion Tester at Ceralink.

Adhesion strength was measured for a 0.38 mm (15 mil) thick, Nanjing Kin Yong Fa EVA interlayer, K38BC, called "Better Clear." The adhesion measurement method was the 180° peel test, described in ASTM D3330 and ASTM D903. The peel test samples were prepared using 25 mm x 250 mm strips of EVA, bonded to glass substrates, measuring 50 mm x 150 mm. The extra length of EVA provided a tail for the peel tester to hold onto the vinyl. The samples were loaded into the Chemsultants International PA-1000-180, 180° Peel Adhesion machine (Figure 27B). Peel tests were performed using a displacement rate of 60 cm/min. Samples were laminated at various temperatures to determine the impact of lamination temperature on adhesion.

Ultrasonic Guided Wave Testing Results for EVA

The saved waveforms were processed using MATLAB software. A Chebyshev digital filter with a 2 kHz band pass window was applied for the waveforms corresponding to each excitation frequency. Figure 25 shows the energy velocity measurements for each laminate group as a function of frequency within the range of 295 kHz to 370 kHz.

The area underneath the energy velocity curves as a function of frequency was calculated using the trapezoidal rule. Figure 26 shows the area underneath each velocity curve a function of RF lamination time. The group velocity drop-off occurred at higher frequency as the lamination time increased. Figure 26Figure 25 shows a strong correlation between the calculated area under the group velocity curves in Figure 25 and RF lamination time. Figure 26Figure 28 shows the 180° peel adhesion strength, measured experimentally by Ceralink, which also increased with RF lamination time. RF lamination time led to higher temperatures on the glass as shown in Figure 27. Figure 27 demonstrates the relationship between RF lamination time and temperature, in which longer lamination times resulted in higher temperatures.

Ultimately, a model of adhesion strength as a function of processing parameters could be developed through experimental adhesion tests. By then correlating the ultrasonic guided wave frequency shift characteristics to adhesion strength, or lamination processing parameters (such as in Figure 26), the ultrasonic testing could then be used in lamination research. This would be particularly useful for testing panels non-destructively so that panels with known adhesion properties could be evaluated environmentally or in actual use conditions.

The controlled RF parameters are the lamination time, pressure, and RF power level. These three variables all affect the final temperature and adhesion levels. This work showed a correlation between energy velocity and one parameter, RF lamination time. A more detailed designed experiment will be required in the future to develop the adhesion strength model or any given interlayer.

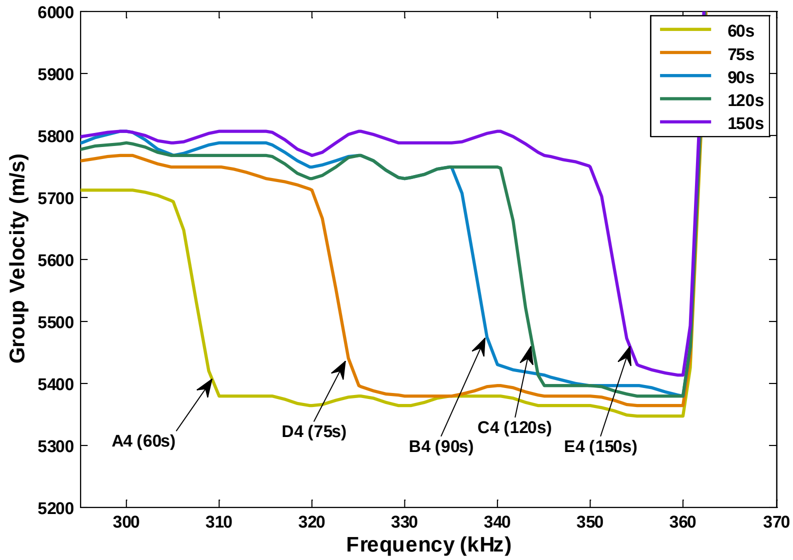


Figure 25. Energy velocity measurements as a function of frequency for each of the five laminate groups. The five laminate groups correspond to increasing RF lamination times of 60, 75, 90, 120, and 150 seconds.

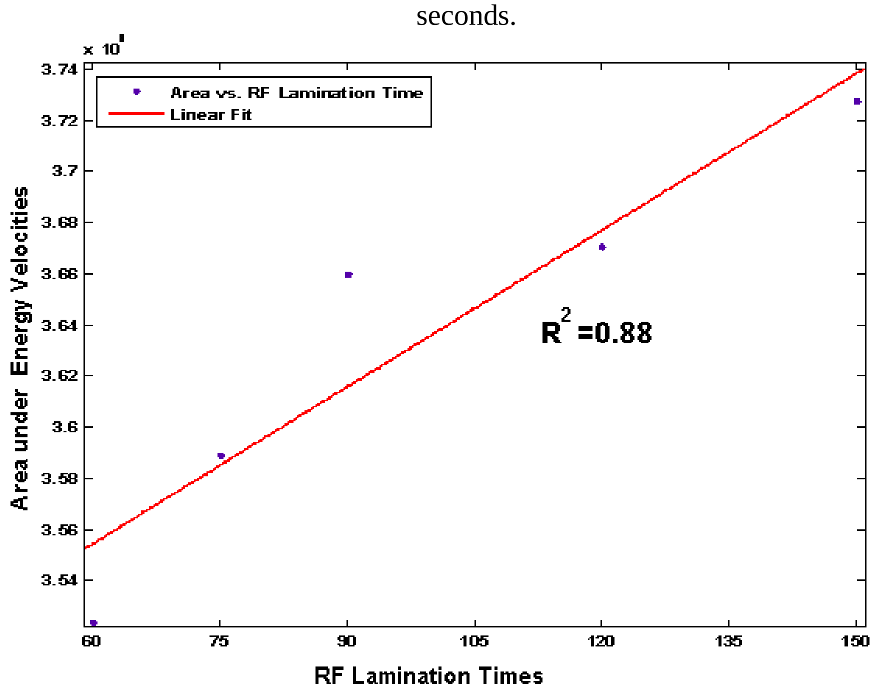


Figure 26. Graph of the area under the energy velocity curves plotted against the lamination times in the RF

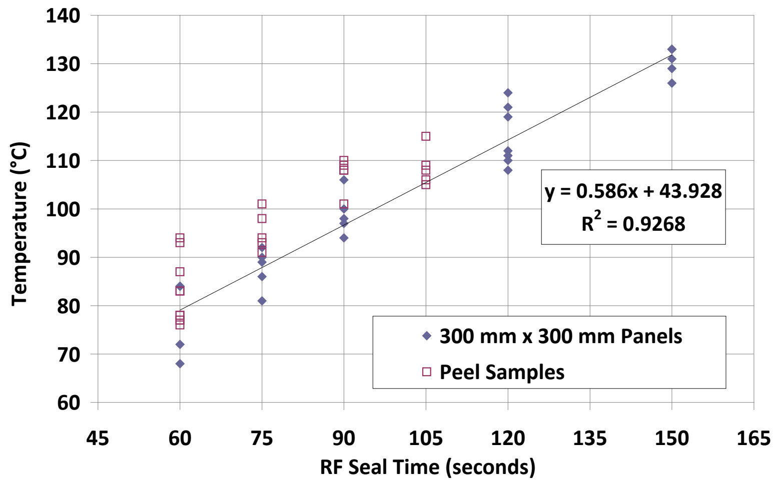


Figure 27. Plot of pyrometer measured temperatures for 300 mm square panels and 50 x 150 mm peel adhesion test samples, showing the correlation of increased temperature with increased RF lamination time. These samples were made with glass and 0.38 mm K38BC "Better Clear" EVA (from Nanjing Kin Yong Fa Mfg. Co.), using 1 Amp RF plate current.

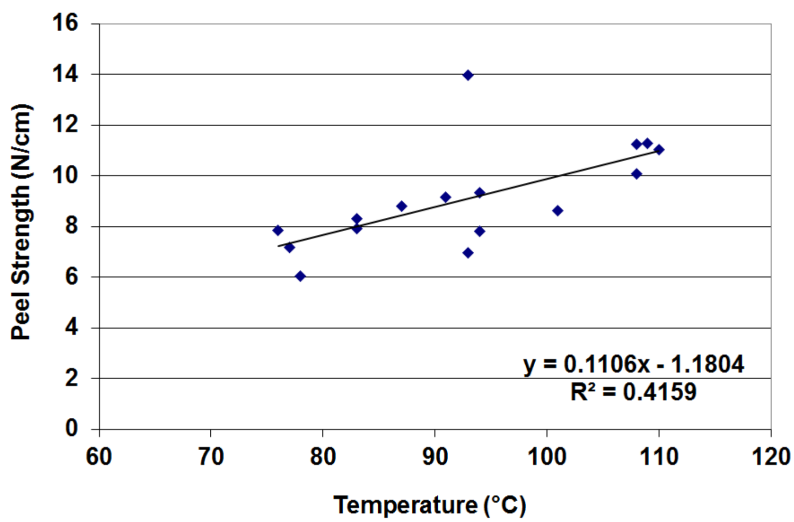


Figure 28. Plot of measured 180° peel adhesion strength as a function of temperature, showing upward trend with temperature (and therefore time, per Figure 27). The R^2 value of 0.4159 indicates a significant trend, however the scatter in the relationship between temperature and RF lamination time likely contributed to the relatively low significance. This data can be used to relate the energy velocity data in Figure 25 to physical measurements of adhesion strength.

NDE Conclusions - EVA

Based upon these preliminary test data, it appears that energy velocities will successfully separate laminates with different lamination times. However the test procedure still needs to be refined to further understand the different propagating modes, corresponding attenuations etc. Additionally, further tests need also to be carried out using specimens that have interlayers of different thicknesses. Further peel adhesion data from Ceralink will be used to develop correlations with energy velocities, resulting in empirical models of adhesion.

NDE Background - PVB

The material properties for float glass and PVB constituents and for the spring constants for an assortment of pummel numbers (adhesion levels) were extracted from Huo[22] and Suchy[20]. In order to represent an extremely weak adhesive bond, spring constants for pummel number 1 were approximated using a power regression fit on the spring constant values for laminates with higher pummel number values. Lamina thicknesses were measured from the experimental specimens supplied for ultrasonic guided wave testing (UT). Theoretical phase velocity, energy velocity and attenuation dispersion curves for different guided wave modes were computed and their values compared with experimentally obtained values for validation purposes.

Table V. Material properties of laminated safety glass constituents for theoretical model[19,20].

Specimen Label	Thickness (mm)	Density (g/cm^3)	Young’s Modulus (GPa)	Poisson’s Ratio	Longitudinal Attenuation (Np/m)	Shear Attenuation (Np/m)
Float Glass	2.10	2.5	72	0.25	0	0
PVB	0.793	1.1	3.9	0.34	8.51	43.5

Table VI. Spring Constants representing different levels of adhesion for spring model[19,20].

Pummel Number	Normal Spring Constant (N/m^3)	Transverse Spring Constant (N/m^3)
1	2.5315 E+11	8.8661 E+10
3	6.8785 E+11	2.4091 E+11
4	8.9754 E+11	3.1436 E+11
5	1.0778 E+12	3.7750 E+11
6	1.4933 E+12	5.2302 E+11
8	1.7010 E+12	5.9577 E+11

Ultrasonic Guided Wave Testing Experimental – PVB

Two groups of LSG specimens were prepared by Ceralink Inc. using a novel Fastfuse radio frequency (RF) lamination technology. Specimens from each group contain a polyvinyl butyral (PVB) interlayer sandwiched between two float glass outer layers. All specimens contain identical float glass plates, while the PVB interlayer was varied between specimen groups. Group 1 specimens contain an automotive grade PVB interlayer, while Group 2 specimens contain a stiffer architectural grade PVB interlayer. Furthermore, different lamination processing variables were controlled for each group. Therefore, experimental results for each specimen group are analyzed independently.

Six laminates with different lamination processing combinations were prepared for evaluation using the ultrasonic guided wave approach. Two variables were controlled during the lamination process for this study: RF lamination time and applied pressure during lamination. The RF lamination power was held constant for these specimens. Lamination processing parameters for each laminate in Group 1 are displayed in Table VII. Specimens in Group 2 contain an architectural grade PVB interlayer with a higher elastic modulus than the automotive grade PVB interlayer from Group 1. Table VIII exhibits the lamination processing variables for Group 2. RF lamination time and cooling time under pressure were varied, while the RF lamination power and pressure were held constant.

Table VII. RF Lamination Process variables for specimen Group 1, 12"x12" glass panels.

Specimen Label	RF Lamination Specimen ID	RF Lamination Time (s)	Applied Pressure (psi)	Cooling Time (s)
A	1680-3	40	20	0
B	1680-3	55	20	0
C	1697-2	70	20	0
D	1694-2	40	41	0
E	1695-2	55	41	0
F	1696-2	70	41	0

Table VIII. RF Lamination Process variables for specimen Group 2, 6"x6" glass panels.

Specimen Label	RF Lamination Specimen ID	RF Lamination Time (s)	Applied Pressure (psi)	Cooling Time (s)
AA	1792	40	82	0
BB	1793	40	82	0
CC	1794	55	82	0
DD	1795	55	82	0

Ultrasonic Guided Wave Testing Results for PVB

Figure 29 shows a schematic diagram of the guided wave testing set-up used to carry out ultrasonic energy velocity measurements. Figure 30 shows the theoretical energy velocity dispersion curves as well as experimental data. In Figure 30, the S0 and the S1curves represent the theoretical energy velocity dispersion curves of the fundamental and the first symmetric guided wave modes, respectively, and the A1 curve represents the dispersion curve of the first asymmetric guided wave mode. For an in-depth discussion of the various symmetric and asymmetric guided wave modes the reader is referred to Huo[19] and Suchy[20].

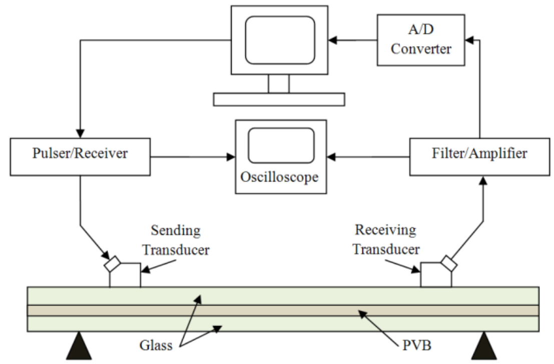


Figure 29. Schematic diagram of testing set-up for the ultrasonic guided wave evaluation approach.

Figure 30 shows the experimental mean of the five independent measurements versus frequency for Specimen B with 95% confidence intervals. Experimental measurements show nominal error at most frequencies. Measurements that approach the Rayleigh velocity (for higher frequencies) are very accurate because the A1 and S1 modes have completely converged into one wave envelope. Greater error occurred in regions where two wave modes converge or diverge from one another. Due to multiple wave modes interfering at lower frequencies, the arrival time of the A1 mode was likely distorted, creating discrepancies between independent measurements.

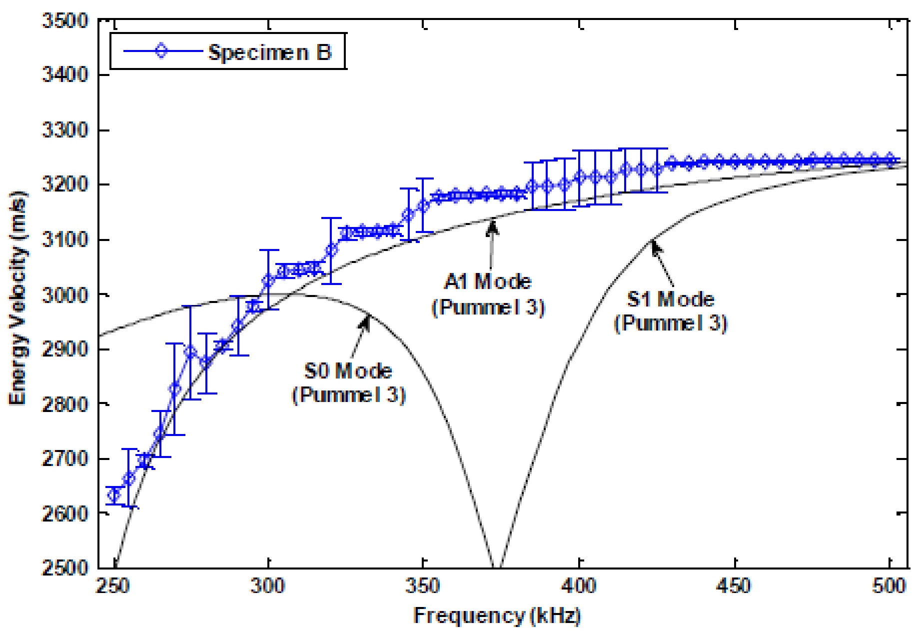


Figure 30. Experimental energy velocity measurements for laminated Specimen B from specimen Group 1 superimposed with theoretical dispersion curve model with pummel number 3 spring constants (See Table V and Table VI for material properties and spring constants, respectively). Error bars represent 95% confidence intervals.

Because all energy velocity measurements were carried out under identical testing conditions, it was determined that all specimens contain the same level of adhesion. Furthermore, all measurements lie along the A1 wave mode of the pummel number 3 dispersion curve. Based upon the ultrasonic energy velocity measurements in conjunction with the theoretical dispersion curves (solid lines), all LSG specimens from Group 1 are believed to have adhesion levels around or just under pummel number 3.

Experimental mean energy velocity measurements for all laminates in specimen Group 2 are presented in Figure 31. The theoretical dispersion curve model (solid curves) developed for specimen Group 1 is also presented with pummel number 3 spring constants, in order to observe any variances in measurements between specimen groups. Similarly to Group 1 results, the experimental energy velocities for each laminate in Group 2 follow the A1 dispersion curve. In addition, differences in energy velocity measurements between each laminate are negligible. Therefore, all four laminates in Group 2 are believed to hold comparable adhesion levels. As expected, the energy velocity data shows a noticeable shift toward higher frequencies. It cannot be resolved whether the resulting shift is due to the increase in PVB stiffness and/or a stronger adhesive bond at the glass/PVB interface. To help characterize shift in frequency, experimental mean energy velocity measurements for laminated Specimen B from Group 1 and Specimen DD from Group 2 are presented in Figure 32. Since identical float glass was used for all laminates, it was encouraging to find similar Rayleigh velocities (at higher frequencies) for specimens in Group 1 and 2. Furthermore, the initial energy velocity measurements used to predict the float glass stiffness were extremely consistent. Therefore, the float glass used for all LSG specimens has an estimated stiffness of 67 GPa.

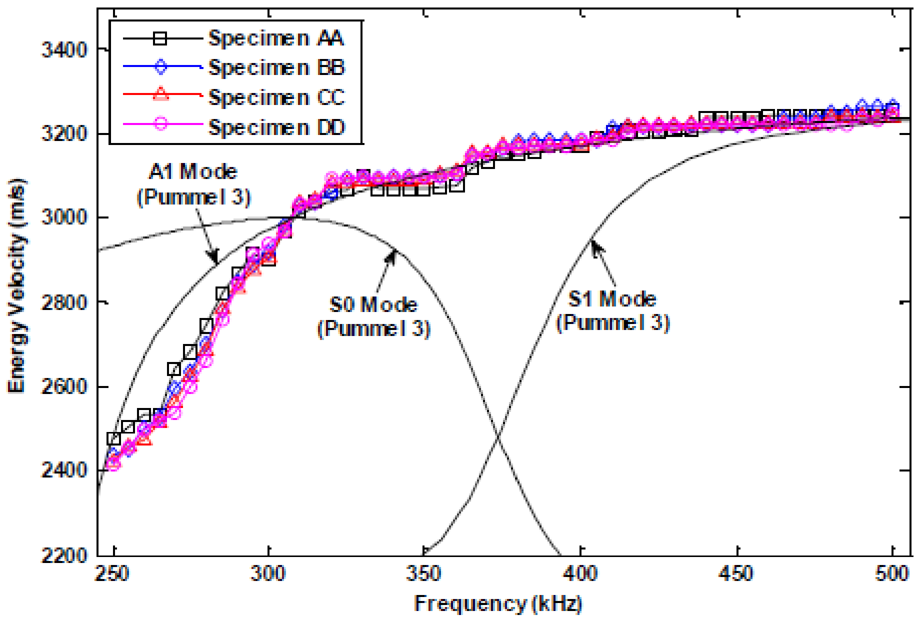


Figure 31. Experimental mean energy velocity measurements for all laminated specimens in Group 2. Analytical dispersion curve model from specimen Group 1 is presented with pummel number 3 spring constants.

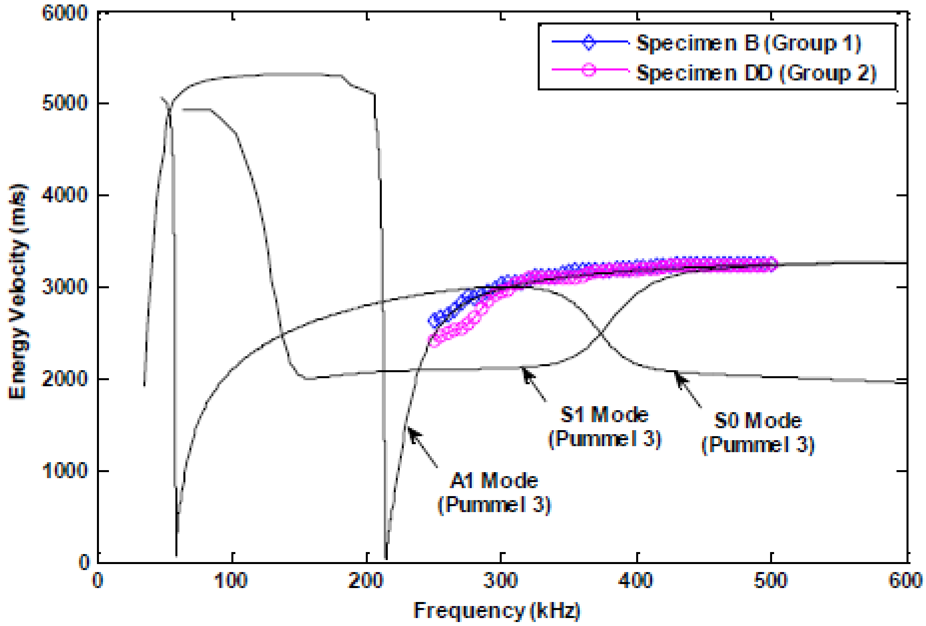


Figure 32. Experimental mean energy velocity measurements for laminated Specimen B from Group 1 and Specimen DD from Group 2. Analytical dispersion curve model from specimen Group 1 is presented with pummel number 3 spring constants.

NDE Conclusions – PVB

The energy velocity measurements on each specimen in this group produced very similar results. Therefore, the specimens in Group 2 are all believed to hold the same level of adhesion. The level of adhesion was more difficult to characterize for this group, as the stiffness of the PVB interlayer was increased by an unknown factor. Experimental results are presented with theoretical dispersion curves for a 20% increase Young's modulus for the PVB interlayer, and the empirical data follows the new model reasonably well. A few conclusions can be made from this discovery. If the architectural grade PVB does in fact have a 20% increase in stiffness from the automotive grade PVB, the adhesion level of laminates from Group 1 and Group 2 is believed to be identical. On the contrary, if the architectural grade PVB has less than 20% increase in stiffness, a moderate increase in adhesion was observed. A 20% increase in stiffness seems somewhat large; therefore a slight increase in adhesive bond strength is estimated. Pummel tests were not performed on these laminates, giving minimal support to experimental findings. However, the experimental results from Group 1 were encouraging and help uphold the conclusions made from Group 2 findings.

It is likely that the level of adhesion remained low in all specimens due to some deficient lamination processing variable. The adhesion process for LSG is very complex and contains a number of variables that may reduce adhesion drastically if not performed precisely to specification. In addition, lamination processes are not fully standardized leaving a large amount of tacit knowledge throughout the LSG industry. The level of adhesion may be increased by altering a few lamination processing variables. Three essential processing parameters that control the adhesion level in LSG are pressure, temperature, and time. Although the novel FastFuse RF lamination technology uses radio frequency energy as opposed to conventional heating techniques to heat the PVB interlayer, the required amount of heat for proper lamination of high adhesion laminates is believed to be unchanged. Typical target lamination temperature and pressure have been reported in the range from 130 – 150 °C and 140 - 220 psi, respectively[17, 18]. The maximum lamination temperature and pressure for any specimen from either experimental group reached approximately 100 – 130 °C and 40 to 80 psi, respectively. Therefore, the lamination temperature may have been low, while the lamination pressure was much too low. Although adequate temperature was provided to allow proper flow of the PVB interlayer, sufficient pressure was not applied in the lamination process to fill enough surface asperities permitting a strong chemical bond to form at the glass/PVB interface. The FastFuse RF technology as a whole shows great potential for replacing conventional autoclaving lamination, once appropriate laminating parameters are discovered. Considerable time and energy could be saved using the new lamination technology.

Overall, the use of ultrasonic guided waves shows potential for adhesion level characterization in LSG. The experimental work presented here may be supplemented with additional ultrasonic guided wave testing on LSG specimens with higher adhesion levels. Further testing would allow a complete set of analytical dispersion models for various pummel numbers to be created, which could then be used to predict adhesion levels directly with this guided wave approach. Once this method has been fine-tuned and developed further, it may be applied to more complicated LSG structures and geometry. Certain systems of interest may include LSG containing additional layers, e.g., transparent armor, LSG with different copolymer interlayers and LSG with curved surfaces.

NDE Extended Discussion

An extended discussion of the guided wave approach used in this study is available in the Master's Thesis of Mr. Thomas A. Suchy at the University of Illinois at Urbana-Champaign[16].

Task 4. Study concepts for curved lamination

As discussed in prior sections of the report, curved lamination is a critical technology to demonstrate for commercialization of RF lamination in the autoglass industry. Glass manufacturers including Pilkington, and the RF equipment manufacturer were engaged in discussions on curved laminates. Ceralink identified that curved platen tooling will be required for laminating curved glass. While such tooling is not used in autoclaving, the industry is familiar with tooling for bending glass.

Use of tooling in Glass Bending

The autoglass industry is familiar with tooling for curved glass. All curved autoglass starts as flat glass. The glass is heated on a mold up to the bending temperature (500-700 °C). Depending on the bending operation, the glass is either allowed to slump into the mold by gravity as the glass softens, or a two part mold is used that presses the glass into the mold. The press-bend method produces windows with close tolerances compared to slumping.

For laminated glass, in slumping the outer and inner curvature windows are bent together for a single window together creating a mated pair. Window-to-window variations can be significant, so the inner window from one pair can not be matched up to an outer window from another pair. This lack of tolerance suggests that producing exactly curved platens for slumped glass may not be possible. Some flexibility in the platen may be desirable.

The newer press-bend method uses two part precision molds that ensure that every piece of glass made fits tight specifications. With press-bent glass, the outer curvature windows and inner curvature windows can be made separately, and any outer and inner window combination will fit together. These new methods will produce windows that are highly uniform and will be very suitable for pressing in a mold for lamination. Most autoglass manufacturers are moving toward, if not already using the press-bend method. The tooling for press-bent glass can cost over $100,000 per window, so the cost of tooling is a recognized component of the window fabrication process. Industry confidence in their ability to create the tooling highly improves the likelihood of success for the RF process for curved windows in the auto industry.

Curved glass lamination

Currently, the autoglass industry does not use tooling to hold the shape of curved windows during lamination. These windows are prelaminated using nip rollers, or vacuum bagged, which holds the window tightly together. The hydrostatic air pressure in the autoclave then performs the lamination work without tooling. In RF lamination, pressure is applied in one direction (uniaxially) and requires platens that match the shape of the glass. For flat glass this is relatively simple to handle by using flat parallel platens. Curved windows require special tooling shaped to the exact curvature of the window.

In this task ideas for creating platens for the RF process were developed. The result is a basic design for RF compatibility of the platens, with numerous options for forming and structuring the curvature of the platen. In the RF press, a critical factor for platens is that the high voltage RF power is transmitted to the region of the platen where the glass and vinyl layers are located. This can be accomplished without exposing the materials of construction of the RF platens to RF energy, by creating a continuous, electrically conductive shell on the platen.

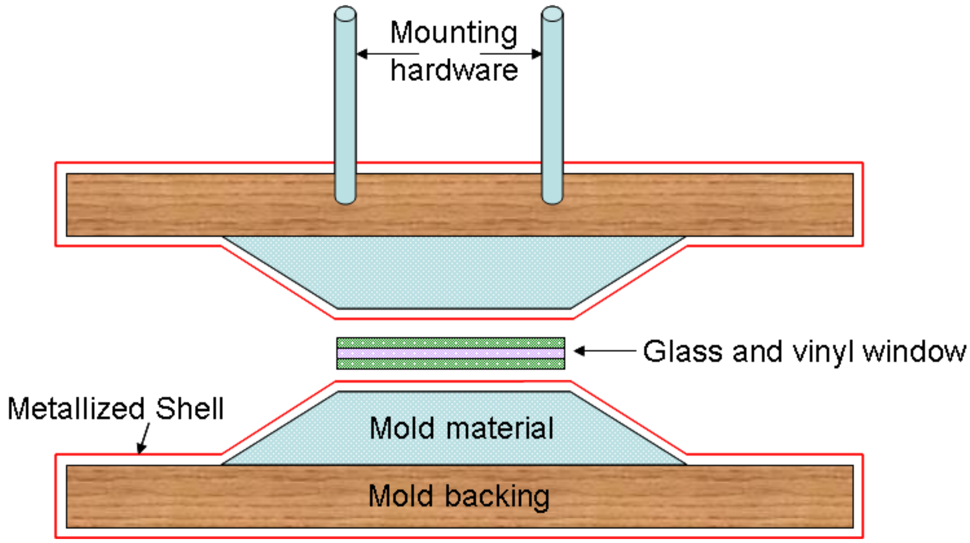


Figure 33. Schematic of platen design for molded platens. The mold material

Candidate curved platen designs

Several options were determined for curved platen fabrication, following the basic schematic devised and demonstrated in Figure 33. The characteristics of the platens must be sufficient to handle the 100-150 psi requirement of lamination, the 130-140 °C maximum laminating temperature, and allow uniform distribution of pressure. In flat panel work, it has been determined that thin conformable layers between the glass and platens ensure uniform distribution of pressure, and it is anticipated that similar set-ups will allow uniform pressure distribution when closely matched

Machined platens

Computer-aided machining (CAM) techniques may be suitable to create precision machined platens out of aluminum or other suitable materials, by using CAD drawings of the curved windows, supplied by the glass manufacturer, or obtained through 3-D scanning. This method is expected to produce high quality long-life platens; however, the cost of this work may be relatively high.

Castable platens

Another way to ensure perfectly matched platens is to direct cast the platens using moldable materials and the actual windows in order to produce a perfect fit. To accomplish this, several options exist include high strength (but heavy) plaster, rigid polymer foams (such as polyurethanes), and conforming materials such as hard silicones.

Functional platens

The metallized shell requirement leaves a great deal of freedom for the internal design of the curved platens. More complex designs can be envisioned to possibly use springs within the mold to allow one mold to conform to a range of window shapes. Other improvements could include fabricating plates with heaters or active cooling inside.

Cost of tooling

Based on the design options developed in this task, the cost of tooling is roughly estimated to range from \$1000 for a small (approximately 1 ft^2) window, with castable materials, and \$10,000 or more for larger (e.g. windshield size) or complex platens using CAM or functional platens.

Progress beyond Industrial Grand Challenge Scope
Using the concepts developed in this task, Ceralink Inc. obtained continuation funding from New York State Energy Research and Development Authority for initial development work on curved platens. Pilkington identified a specific rear-side window from a common car for initial testing. As of this report, two types of castable platens have been fabricated and will be tested for RF compatibility and demonstration of curved laminate feasibility.

Tasks 5 & 6. Analysis of market by sector and interlayer type, and approaches for implementation
As identified previously, glass lamination is divided into several classes of products, including autoglass, architectural safety glass, transparent armor, mirrors, furniture glass, smart glass, and photovoltaic encapsulation. These industries are also divided by the type of manufacturer doing the lamination. Most autoglass, perhaps half of architectural glass, and some photovoltaic and transparent armor glass are produced by the companies that manufacture the glass itself. These manufacturers are designated here as the "primary glass industry". However, a significant portion of lamination is performed by companies that produce products that include laminated components. These include manufacturers of photovoltaics, more customized architectural design, most transparent armor, smart glass, and many specialty laminated products produced by glass fabricators such as watch-glasses on chemical process equipment. The non-glass manufacturing laminators are designated here as "secondary glass fabricators". Many of the secondary fabricators are likely to be missing from the glass industry energy statistics, as the laminated component is one piece in a product, rather than the primary product itself. The main industries of interest are listed in Table IX. The different market segments are discussed in more detail below.

Table IX. Table of glass lamination industries, state-of-the-art, and common interlayers.

Industry	Interlayer	State-of-the-art Technology	Highlights
Primary glass industry – Autoglass, Architectural Glass	PVB -Polyvinyl butyral	Autoclaves	High automation, high volume, small windows (easier to implement),paves way for larger investment for very large flat glass (primary architectural) lamination
Photovoltaics	EVA -Ethylene vinyl acetate	Roll-to-roll and vacuum laminators	Energy efficient manufacturing of clean energy products, opportunity to reduce PV manufacturing cost
Security glass, Transparent armor	TPU - Thermoplastic Polyurethane	Autoclaves with vacuum bags	Largest unit energy savings (6-18 hour autoclave, vs. 5-10 minute RF) Significant commercial, government, and military markets
Secondary glass fabricator – architectural, furniture, signage	PVB EVA TPU	Vacuum laminators or autoclaves	Custom products with wide architectural applications have significant energy & time in product development → rapid development yields savings

Autoglass – The autoglass industry was the primary focus of the experimental work in this project. However the information obtained on laminated glass to PVB is equally applicable to any of the other markets. Autoglass accounted for nearly 60 percent of laminated and tempered flat glass in 2009 according to the Freedonia Group[23]. Declines in motor vehicle production since 1999 have weakened demand for this glass (and therefore also lowered the energy consumption of the industry). The length of ownership of vehicles has increased, and therefore the demand for replacement windows has actually increased over that time. Also over that time, the total area of glass used in vehicles has increased from approximately 51 ft^2/vehicle to over 60 ft^2/vehicle. In spite of the declines over the last decade, with economic recovery, the demand for glass in anticipated to grow strongly over the next 10 years.

Even as motor vehicle sales remain low, the volume of laminated glass in the auto industry will increase substantially as US autoglass manufacturers transition from tempered safety glass to laminated safety glass for side windows. Primarily spurred by federal safety regulations, in conjunction with environmental and energy pressure, particularly from the California Air Resources Board, the transition to laminated side windows is anticipated over the next 10 years. With an average of 60 ft^2 of glass in cars today, and currently only the windshield (about 25% of the glass area) that is laminated, the total volume of glass lamination may grow as much as 3-fold, even without an increase in the number of cars sold. US auto manufacturers lack the lamination capacity for side windows. The lack of capacity is slowing the transition, but also opens significant opportunities for new lamination technologies, such as RF lamination, to be considered. One benefit of RF lamination is that with its lower capital cost, and smaller footprint, RF lamination capacity can be built up gradually, starting with one press for a low volume production, and increasing as the demand for laminated side windows increases.

Information on RF lamination has reached many of the US autoglass makers. The original work on RF lamination was performed in conjunction with one major manufacturer, and the current work was supported by another. The demonstration of quality PVB laminates in this project was a critical first step to convince the industry of the manufacturability potential of RF. Curved lamination is the next necessary step. After demonstrating curved lamination, a prototype process should be established at Pilkington to prove out RF lamination in the manufacturing setting.

RF lamination has also been presented to energy efficiency leaders in the auto industry itself. Certain car manufacturers have indicated interest in supporting energy efficiency and process improvement initiatives by their suppliers. With successful implementation of RF lamination by Pilkington, the auto manufacturers themselves will be able to encourage the use of RF lamination as a best-practice for energy efficiency in lamination.

Primary Architectural Glass – The primary architectural glass market is generally composed of glass manufacturers that produce large sheets of laminated flat glass. The suppliers of these panels typically produce standard panel sizes, which fabricators then cut to size for installation in building construction. The laminated sheets can range up to extreme sizes of 15' x 20'. By contrast, the largest RF laminated glass panel to date is 2' x 3', and the largest RF press typically referenced in this work is 4'x 10'. Therefore the feasibility of RF lamination for this market is not necessarily proven, given the large size discrepancies. RF heating encounters technical challenges when the width of the laminated panel exceeds 4 feet. Reaching larger sizes will require investment for new RF equipment configurations to be developed. Therefore large architectural laminates have the most far-term potential for RF lamination. The companies that produce autoglass typically also produce this type of architectural glass. Successful demonstration of autoglass may help to spur investment in this area as well.

Photovoltaics – Several contacts have been made throughout the photovoltaics industry. The constant flux of PV manufacturers and PV market issues seem to place lamination as a lower end priority. However, some manufacturers, particularly those working with thin film and flexible photovoltaics, have taken interest in the potential for RF lamination to significantly reduce process times and the corresponding costs (including energy). For smaller photovoltaics manufacturers, the companies' own volume of production and currently invested capital equipment are limiting factors in RF implementation. Lamination issues remain a quality issue throughout the PV industry, however, with common occurrences of PV modules laminated too quickly using conventional processes. This produces the "visually good laminates" described in the Background section of this report, but with long term adhesion and environmental performance issues that appear later in the life of the panels[24].

Transparent Armor (e.g., Bullet Resistant and Bullet Proof Glass) – RF lamination has significant potential to reduce processing time of transparent armor windows (TAWs), through a dramatically changed dynamic from large batches to single-piece, semi-continuous processing. Current batch autoclave processes require up to 20 hours for thick multilayer structures like TAWs. TAW manufacturers realize that longer autoclave cycles produce higher adhesion, which improves performance in ballistic applications. Improved performance can allow thinner lighter weight windows to be used to deliver the same level of protection. However, the cost of the long autoclave cycles is a trade-off (e.g., 20 hours vs 6 hours). RF lamination may allow significant adhesion variation in shorter cycles (e.g., 10 minutes vs 5 minutes) to enhance adhesion[2]. The full effect of RF processing on adhesion must still be studied, as indicated in Tasks 1 and 3.

Transparent armor is assembled manually due to complex lay-up structures and comparatively small numbers of like-windows. With individual window assembly and vacuum bagging times of 10 to 20 minutes, windows in an autoclave batch cannot be laminated until all windows are prepped, vacuum bagged, and loaded into the autoclave. For a 200 window order, with a 15 minute per window prep and bag time, 2 workers would need 3 full days to prep the windows, followed by a long autoclave cycle, before any windows can be shipped. If problems were present in the lay-up or autoclave cycle, an entire order could be rejected or reworked. With RF lamination, the lamination process begins as soon as the first window is assembled. The full cycle time will be at par with the assembly rate of 10 to 15 minutes. Any problems that arise will be detected immediately and corrected prior to laminating additional windows. The manufacturer can also begin to ship the order on the first day of work. For a manufacturer with backlog and a need to achieve just-in-time manufacturing, the time savings of FastFuse is critical. A summary of the potential advantages for RF lamination of TAWs are summarized in Table X below.

Table X. Comparison of FastFuse RF Lamination vs. Standard Autoclave Lamination.

FastFuse RF Lamination of TAWs	**Autoclave Lamination of TAWs**
Processing Advantages	***Processing Limitations***
5-10 minute lamination cycle Very energy efficient – 90% reduction over current Heats interlayer directly – limited glass heating Rapid quality feedback Low capital cost Faster delivery schedule possible	Up to 20 hour lamination cycle Energy inefficient manufacturing process Heats glass first, then interlayer Batch manufacturing, slow quality feedback Cannot not mix laminate programs in one autoclave run Incomplete loading due to hold limitation after vacuum bagging results in high inefficiencies sometimes >50% High capital cost Long delivery lead-times
Quality Advantages	***Quality Limitations***
Potential for reduced haze through fast cooling Potential for reducing residual stresses due to much cooler temperatures in glass Potential to reduce weight due to lower residual stresses Easy integration of advanced heating and RCSR films	Must cool slowly, increasing haze Residual stresses introduced due to uneven heating/cooling Thicker laminates required due to high residual stresses

Laminated transparent armor windows are manufactured by approximately 30 companies in the U.S., and are of strategic interest to the Departments of Defense, Justice, Homeland Security, and State. In addition, a large portion of transparent armor is exported from the U.S. to security hot-zones including Mexico and the Middle East for use by foreign governments and companies doing business in those areas. By lowering the cost of transparent armor with FastFuse, the demand for TAW will further increase as it finds use in more applications. Even in current areas of use, such as military helicopters, the area of TAW per vehicle will increase with lower cost manufacturing, improving visibility and performance.

Application to other markets – The use of RF press technology in manufacturing is not new; however, its application to laminated glass is very recent. Even with a long history in plastics welding, composites, gluing, and wood and paper products, RF processing remains underutilized in many manufacturing settings. With typical process time and energy cost reductions in excess of 90%, RF glass lamination serves to raise the overall profile of RF processing. The recent establishment of the lab-scale RF testing center used in Task 1 and 3 RF lamination experiments just prior to this project has already resulted in several non-glass lamination industry initiatives. As RF lamination grows, other areas of improved manufacturing efficiency are anticipated to grow as well.

Benefits Assessment

A benefits assessment was compiled based on data obtained from several sources including the Freedonia Group "Focus on Flat Glass" Report #2074 (2006), a DOE Office of Industrial Technologies report, "Glass Industry of the Future: Energy and Environmental Profile of the U.S. Glass Industry" (2002), Energy Information Administration statistics, Ceralink's direct research on RF lamination energy consumption, and information gathered from direct communications with various laminated product industries on energy consumption.

Potential energy productivity improvement in comparison to the state of the art, and the timing of projected energy savings

The Freedonia Group reported in 2006 that laminated glass had higher growth rates than any other type of glass, at 6.7 %[25]. Based on this growth, US laminated glass production is forecast to reach 2.2 billion square feet by 2020 (Table XIV). In 2020, potential impact of RF lamination on the primary glass industry is up to 7 trillion BTU annually (Table XV) plus an additional 5 trillion BTU for photovoltaics, armor, and other secondary laminated glass products (Table XVI), for a total of 12-13 trillion BTU, assuming no major changes to the growth trends. Calculations made using industry data indicates an average energy consumption of approximately 1 kWh/ft^2 for autoclave lamination. The Appendix contains the following tables, which contain calculations for the growth and savings estimates in the Benefits section.

- Table XIV. Table showing an estimated scaling of laminated glass production comprising the automotive and architectural glass markets based on 2001 industry statistics and 2006 growth rates from the Freedonia Focus on Flat Glass report (Report #2074), 200625.

- Table XV. Table of general glass industry energy consumption data for 2012, 2020, and 2040 including potential/hypothetical savings using RF lamination.

- Table XVI. Table of Ceralink estimates for energy consumption in transparent armor, photovoltaic, and plastic window lamination industries with potential energy savings using RF lamination.

- Table XVII. Table of calculations for motor vehicle side and rear window transition from tempered to laminated glass, and the energy savings as a result of the use of lamination with autoclave and RF lamination. This data was used to produce Figure 34.

The potential impact of RF lamination is greater when anticipated transitioning of automotive side windows from tempered to laminated takes place over the next 10 to 15 years. Manufacturing capacity is not yet in place in the U.S. to handle this change. If the side windows are produced using autoclave lamination, an addition U.S. glass lamination energy burden of 18.7 T BTU a year will be incurred by 2020 (Table XVII**)**. Tempering is more energy intensive that traditional autoclave lamination, at approximately 8400 BTU/ft^2, compared to 3320 BTU/ft^2 for autoclaving. RF lamination, however requires just 136 BTU/ft^2 for single pane, automotive type laminates. As a result, significant energy savings will be achieved by transitioning from tempering to laminating side windows, with the greatest savings achieved when RF lamination is implemented (Figure 34). Some energy will be saved by not tempering, however the need for two sheets of glass per laminated window, and the plastic interlayer may offset some of the savings from eliminating the energy intensive tempering process. The lack of existing infrastructure for side window lamination presents a unique opportunity for market penetration of RF lamination.

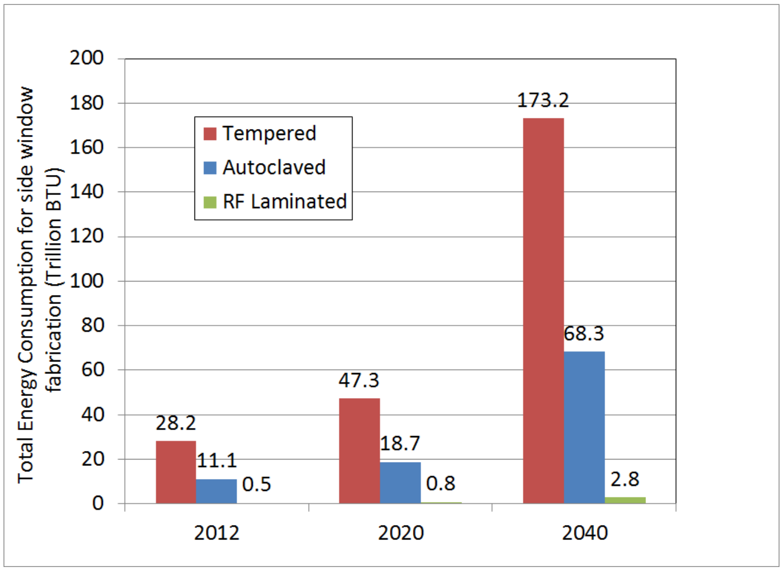


Figure 34. Chart of the energy required to process automobile side and rear windows by either tempering or by lamination with autoclave or RF processing. Tempering is much more energy intensive than lamination in general, however the difference between tempering and RF lamination is much greater than between tempering and autoclaving (Table XVII).

Safety and environmental regulations are prompting the auto industry to shift to laminated side windows, away from the tempered glass used now. Glass makers, including Pilkington, are anticipating the shift away from tempered glass to take place over the next 5 to 10 years. The shift will dramatically decrease the energy used in window manufacturing through the elimination of the tempering step. Meanwhile, the demand for lamination will triple the area of windows produced, and increase 4 or 5-fold in the actual number of windows, as side and rear windows are laminated. With autoclave lamination the primary glass market energy consumption add 11 trillion BTUs to the 2012 lamination energy consumption, and nearly 19 trillion additional BTUs by 2020. By facilitating earlier adoption of laminated auto side windows through easier scale-up, RF laminated glass will take market share from tempered glass. An estimated 47 Trillion BTU annually could be saved by laminating instead of tempering autoglass by 2020 (.

Table XI showed data on autoclave and RF lamination processing for a single production line of autoglass and transparent armor, based on industry survey and actual RF lamination experiments. Table XII shows hypothetical energy savings with RF lamination across the glass industry for the years 2012, 2020, and 2040, including ancillary energy benefits resulting from autoglass lamination and additional photovoltaics facilitated by lower manufacturing costs.

Table XI. Table of energy, process, and economic benefits for RF Lamination. This table provides examples of FastFuse vs. Autoclave costs for just 1 production line for autoglass windshields and transparent armor, two of the target markets of this proposal. Lower capital costs and ongoing energy benefits favor FastFuse.

Windshield Example			
	Autoclave	**FastFuse**	**Savings with RF**
Capital cost	$1-1.5 million	$300,000 x 3	$100-600k less capital cost
Cycle Time	60-90 minutes	<1 minute	95% less time
Energy per ft^2	0.45 kWh	0.04 kWh	90 % less energy
Peak electric demand	1700 kV	150 kV	Lower peak demand for RF
Annual Production ft^2/yr	22 million ft^2	25 million ft^2	Similar throughput
Annual Energy Cost for full time production	$1 million	$90,000	91% less energy consumption
Energy per million ft^2	1,000,000	40,000	**960,000 kWh (3.3 billion BTU)**
Transparent Armor Example			
Capital Cost	$1,000,000	$300,000	$700,000 lower for FastFuse
Cycle time	6-18 hours	5-15 minutes	95% less time for FastFuse
Energy per ft^2	15-30 kWh	0.9-1 kWh	93% less energy for FastFuse
Energy per million ft^2	15-30 million kWh	~1 million kWh	Up to 29 million kWh savings (99 billion BTU)

Table XII. Energy Savings from RF laminated glass in trillions of BTUs (T BTU). Assumes growth based on new market share taken from tempered glass, increased solar production, automotive sidelights, security and hurricane glass use as a result of lower cost.

Savings Mechanism	**Hypothetical Energy savings in 2012**	**Potential Energy savings in 2020**	**Potential Energy Savings in 2040**
Primary glass manufacturing	4.2 T BTU	7 T BTU	26 T BTU
PV, TA, and specialty glass	2 T BTU	5 T BTU	41 T BTU
Other composites (non-FastFuse)	-	10 T BTU	40 T BTU
Indirect benefit - Lower cost, faster solar panel production*	-	2 T BTU	18 T BTU
Indirect benefit - Increased automotive laminated sidelight**	-	2 T BTU	25 T BTU
Direct benefit – facilitation of laminating side windows instead of tempering	-	29 T BTU	105 T BTU
Direct benefit – RF lamination replaces side window autoclaving	-	18 T BTU	66 T BTU
Total Annual Energy Benefit from RF Lamination	6.6 T BTU	73 T BTU	321 T BTU
Total Annual CO_2 reduction equivalency from reduced electricity use (EPA	1.3 MMT	14.7 MMT	64 MMT

*****Additional solar energy production assuming RF lamination facilitates 3,000 MW total expansion of solar panels by 2040.
** Assumes RF lamination facilitates California Air Resources Board energy saving prediction for laminated sidelights and backlights in automobiles as a result of lower air conditioning energy usage in cars[6].

The reduction in electricity consumption from RF lamination is estimated as equivalent to 14.7 MMT CO_2 per year in 2020, based on the EPA Greenhouse Gas Equivalency Calculator, located online at, http://www.epa.gov/cleanenergy/energy-resources/calculator.html#results.

Increased use of RF laminated products will also contribute to secondary benefits, due to the new ability to automate continuous lamination processes, especially for smaller products. Photovoltaic, custom (secondary) architectural glass, and transparent armor lamination account for numerous smaller manufacturers that are rapidly growing and consume much more energy per unit of production than the highly streamlined autoglass manufacturing process. An estimate of the transparent armor and specialty lamination industries including photovoltaics, signage, and structural plastics lamination (e.g., polycarbonate and acrylic for shatter resistant laminated panels in detention centers, zoos, etc.), is estimated to represent a potential 2012 energy savings of 1.9 T BTU with RF lamination, rising to 4.8 T BTU savings by 2020 (Table XVI). Transparent armor or security glass has a higher estimated growth rate that standard glass at approximately 10%, while photovoltaic growth rates are estimated to be in the 20-30% range annually.

FastFuse implementation is possible by 2013 in areas such as transparent armor, with use in automotive glass in the next two to four years. Energy savings will be tied to uptake in production. Different sectors of glass lamination require different testing periods before new technology can be used in consumer products. For example in the automotive industry, long term environmental testing is required to show durability of laminated glass made using RF technology. This requires at least 2 years of testing for the automotive industry. This long term testing has already commenced in this project. Other applications, such as solar panels, which carry large manufacturing energy, clean energy generation, and economic benefits, will have shorter times to market. The energy savings are anticipated to be realized most quickly for auto side windows, transparent armor, and photovoltaics, for which new capacity and lower costs are currently a major issue. Windshield and primary architectural glass will require longer timeframes to transition from the existing autoclave capital expenditures at lamination factories. Energy savings in these applications is also derived from elimination of air compressors and waste heat utilization from pre-lamination processing steps.

Potential to reduce greenhouse gases, pollutants, and wastes, in comparison to the state-of-the-art

Direct greenhouse gas reductions are tied to reduced energy consumption, specifically for the fuel or electricity used to heat the large autoclaves. Based upon the 2006 Freedonia report reference above, the primary glass industry in 2012 will be using approximately 4.34 trillion BTU of energy to laminate glass in the U.S. This number is likely to be even higher considering rework rates averaging 3%, and the need to periodically run the autoclaves empty to burn out plasticizers that can cause dangerous autoclave fires[10]. This also does not account for the energy used in laminating acrylic and polycarbonate composite windows, photovoltaics, or transparent armor. The same volume of glass, if produced using RF lamination, would require only 0.18 trillion BTU (Table XV). This represents a savings of 4.26 trillion BTU out of the approximately 300 trillion total BTU used by the glass industry in 2012. The value of 300 trillion is calculated from an approximate industry growth rate of 4% per annum starting with 200 trillion BTU in 2002 from the Manufacturing Energy Consumption Survey by the Energy Information Administration[26], which covered primary glass manufacturing. With the adoption of lamination for side windows, RF Lamination could reduce the existing lamination energy consumption by approximately 96%, and eliminate a significant portion of tempering energy consumption. The total impact is estimated at 73 trillion BTU in 2020 (Table XII). The corresponding decrease in carbon dioxide emissions is 14.7 million metric tons.

The lower total energy consumption will also reduce the release of waste heat into the environment through the discharge of hot compressed air, and utilization of “waste” heat from prelamination de-airing steps. By facilitating earlier adoption of laminated auto side windows through easier scale-up, laminated glass will take market share from tempered glass. Earlier implementation of laminated side windows, facilitated by RF lamination, would lead to greater cumulative energy and greenhouse gas emission reductions.

Increased use of laminated products will also contribute to secondary benefits. For automobiles with laminated side windows, an estimated 1.9 million metric tons of CO_2 will be prevented every year by 2040, according to the California Air Resources Board[6]. Decreased cost of solar panels could result in many trillion additional BTUs of clean energy being generated from solar power. The DOE Solar Energy Technologies Program states, “The solar industry estimates that growth rates above 25% annually are possible, resulting in a $27 billion market by 2020.”[27] RF lamination’s ability to increase this growth rate by decreasing costs could lead to even faster CO_2 reductions, and greater economic benefits, as more energy is generated by solar.

Potential economic benefits of RF Lamination over the state-of-the-art

Lower cost RF lamination will reduce the cost of energy saving and clean energy producing laminated products, which comprise fast growing automotive sidelight and solar panel markets. RF equipment is manufactured in the U.S. by several manufacturers including Thermex-Thermatron, who was a participant in this project. Other U.S manufacturers have been made aware of the technology, and have expressed interest in supplying RF systems, as FastFuse RF Lamination is commercialized. These companies will benefit from domestic uptake of RF lamination, and first opportunity to supply RF lamination process technology worldwide, resulting in further domestic economic benefits of job growth and worldwide energy and greenhouse gas benefits. The worldwide market for lamination equipment, estimated by Ceralink based upon laminate market size, will be $523 million in 2012. Ceralink has partnered with RF press manufacturers in order for both Ceralink and the RF industry to profit together as demand for RF lamination grows.

The growth of RF and microwave heating in industry will result in a skilled workforce that is adapted to using these energy saving heating technologies. Currently, the biggest impediment to uptake of RF and microwave heating technologies is lack of familiarity in industry. The rise of RF lamination will produce engineers and technicians who are technically competent and comfortable working with dielectric (RF) heating. As these individuals move through industry, they will bring RF heating with them to other manufacturers and industries, creating long term energy efficiency opportunities.

In a market assessment report produced for Ceralink through the DOE Inventions and Innovations grant, glass industry experts stated that if laminated glass can suddenly be produced less expensively, with lower capital-cost burdens, it should capture additional market share from tempered glass. Tempered glass is often used where cost is an issue for laminated glass. RF lamination can cause a shift, making lamination a less costly option, as is the case with autoglass side windows, which are a prime example of this. Lamination without an autoclave will open numerous opportunities for small businesses to utilize lamination in applications that are currently inaccessible due to the capital, facility, and operational costs of autoclaving.

The solar industry is constantly striving to reach new, lower price points to facilitate uptake. Lamination is a critical part of solar module manufacture, and is often an expensive bottleneck in the process. Faster, lower cost RF lamination will lower the cost of photovoltaic solar panels. Solar concentrator mirrors are also laminated and with recent major installations of concentrating solar power plants in California, the potential manufacturing and long term energy and economic benefits of lower cost solar power products is significant. Every additional Megawatt of solar panel that is facilitated to reach the market by a cheaper process will produce on average 1.8 MWh of electricity each year, and prevent 1,250 metric tons of CO_2 release. Solar is growing faster than other lamination segments, at 20-30% per year, and is becoming a major portion of the glass lamination industry.

Lower cost manufacturing of laminated safety glass for automobiles will facilitate widespread, long term energy saving use of laminated glass in side windows, just through reduction in air conditioning. The CO_2 and fuel savings predicted by the California Air Resources Board, are equivalent to 220,000,000 gallons of gasoline, which is less than the current daily U.S. gasoline consumption rate, according to the DOE Energy Information Administration 2007 Petroleum Basic Statistics, but still equivalent to $660 million savings annually in gasoline for consumers at 2011 prices.

An analysis of throughput estimates and capital equipment costs shows significant potential for capital cost savings, and rapid return on investment with RF lamination (Table XI). The roughly equivalent cost of an autoclave and an RF press to manufacture similar sized products is quickly made up for by the estimated ability to yield nearly 10 times as much throughput with an RF press. In other words, the RF press technology requires just over 10% of the capital cost of autoclave systems. The 90% reduction in energy, assuming an average of 10 cents per kWh, would result in over $100,000 energy savings per million square feet of laminated glass. This corresponds to nearly $250 million per year for the entire glass lamination industry by 2020.

The potential of the technology to reduce process time:

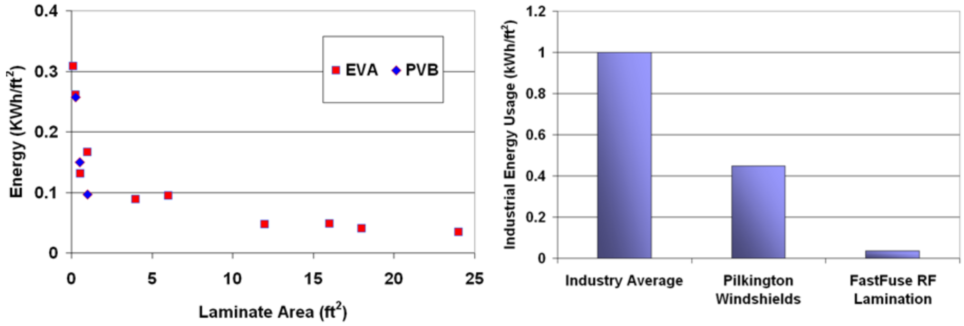
RF lamination has significant potential to reduce processing time, through a dramatically changed dynamics from large batches to single-piece, semi-continuous processing, as shown earlier in Figure 15 and Figure 16. Current batch autoclave processes require 90 minutes for simple laminates like autoglass, and up to 18 hours for thick multilayer structures like transparent armor. For automated autoglass processing, FastFuse studies indicate a lamination time in the press of 40 seconds, with glass entering pre-heated from the pre-lamination nip-rollers. In a car windshield example, 3 RF presses (~$300,000 each capital cost) using a 40 second cycle, would exceed the throughput of a 90 minute cycle in a autoclave ($1,500,000 capital cost) by over 40%.

Transparent armor is assembled manually due to complex lay-up structures and comparatively small numbers of like-windows. With individual window assembly and vacuum bagging times of 10 to 20 minutes, windows in an autoclave batch cannot be laminated until all windows are prepped, vacuum bagged, and loaded into the autoclave. For a 200 window order, with a 15 minute per window prep and bag time, 2 workers would need 3 full days to prep the windows, followed by a 6 to 8 hour autoclave cycle, before any windows can be shipped. If problems were present in the lay-up or autoclave cycle, an entire order could be rejected or reworked. With RF lamination, the lamination process begins as soon as the first window is assembled. The full cycle time will be on par with the assembly rate of 10 to 15 minutes. Any problems that arise will be detected immediately and correct prior to laminating additional windows. The manufacturer can also begin to ship the order on the first day of work. For a manufacturer with backlog and a need to achieve just-in-time manufacturing, the time savings of FastFuse is critical.

Like many products, new laminated glass designs can require several design iterations. With conventional autoclave lamination, this development can take weeks with just one autoclave cycle per day often competing against production needs. RF lamination provides the first ever rapid-prototyping for laminated products, which saves significant time and energy from the product development cycle, increasing competiveness of the manufacturing by bringing new products to market faster and lowering energy invested in the development portion of the manufacturing value chain.

Completeness and validity of assumptions used in developing the benefits

The assumptions used in the energy, environmental, and cost benefits described above have been refined by Ceralink since 2005 through DOE and industry manufacturing statistics, direct market research, including an internal energy analysis estimates by Pilkington and discussions with over 50 laminating manufacturers, and continued energy analysis of FastFuse lamination studies on autoglass, photovoltaics, architectural panels, transparent armor, and other products. FastFuse energy data comes from several studies by Ceralink investigating RF energy consumption for a wide range of laminate materials and sizes (Figure 35).



(A) (B)

Figure 35. A)Plot of FastFuse energy consumption as a function of laminate area for single pane windows (e.g. autoglass), showing improved efficiency with size. This data was used to develop industry energy benefits. B) Graph of lamination energy usage in kWh/ft^2 for the industry average (DOE & industry statistics), an internal review by Pilkington, and FastFuse RF lamination demonstrations.

Potential markets impacted by commercial implementation of RF lamination:

Four distinct markets will be directly impacted by the successful development and commercial implementation of FastFuse RF Lamination. These markets are: 1) Autoglass, 2) Architectural glass (primary glass companies and secondary glass fabricators), 3) Bullet resistant and ballistic/transparent armor, and 4) Photovoltaic modules. These markets will be accessed directly through the demonstrations planned in this project. Each of these markets possess attributes that are contributing to strong growth forecasts. Figure 36 shows the Technology Readiness progress of each market area, and the efforts responsible for that progress. The Industrial Grand Challenge proposal laid out a Project Continuation Plan that included a "Stage 3" development based on successful completion of this project. The Project Continuation Plan was closely followed in developing a proposal to the DOE Innovative Manufacturing Initiative.

The current TRL for laminated autoglass is 3, with flat glass lamination demonstrated at equivalent quality as autoclave lamination (TRL 4 for flat PVB interlayer laminates). Curved lamination is required to advance autoglass in general to TRL 4 and higher. Currently only front windshields are laminated. Rear and side car windows are tempered, causing them to break into tiny pieces when damaged. New safety standards favor measures to reduce passenger ejection from vehicles during accidents. Replacing side and rear windows with laminated glass is one solution to the ejection problem. Laminated side windows also block UV light from the sun, reducing the greenhouse effect in cars, and thereby reducing air conditioning use. Laminated windows can also be lighter weight than tempered windows. As indicated by the California Air Resources Board, a shift to laminated side windows will save 220 million gallons of gasoline each year. As the auto industry shifts to laminated windows, the demand for laminated glass will rise up to 300%. OEM autoglass manufacturers will add significant laminating capacity to meet these needs, and FastFuse will be poised to provide a sustainable alternative to new autoclaves, through lower capital expenditures, a more compact process and lower operating costs. Automakers are eager for suppliers to lower energy intensity and cost, and will promote successful energy efficient manufacturing technologies as best practices to other suppliers. FastFuse can accelerate the transition by providing a method to gradually increase side window capacity without installing additional large autoclaves.

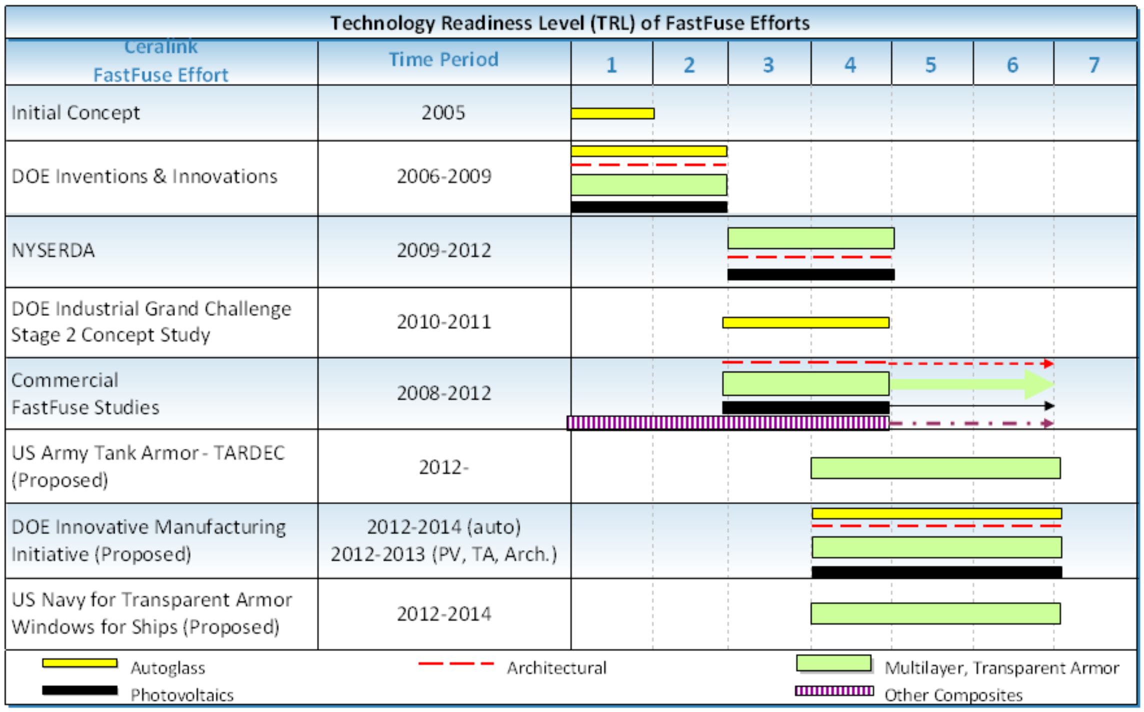


Figure 36. Chart of Technology Readiness Level for various industries studied in RF lamination. The chart follows the technical progress of each technology, however each project serves to advance the overall state of RF lamination.

Architectural glass typically comprises laminating large panels 8'x10' and larger. Applications include hurricane glass, curtain walls, sound protection, theft protection, furniture, and innumerable aesthetic designs that incorporate other materials including solar cells, light emitting diodes, printed media, mirrors, electrochromics, metal mesh, wire, cloth, and decorative natural materials, all of which have been tested with FastFuse. Tremendous customization of architectural design results in high value laminates, with a high level of invested development energy. One custom window may require 3 or 4 windows to perfect the design. Rapid prototyping and manufacturing with RF lamination can decrease the energy intensity of the final window by far more than just the direct manufacturing energy reduction. For very large architectural laminates, the RF press cost approaches autoclave costs, and is currently prohibitive for simply proving large-part feasibility. Successful implementation of smaller autoglass, PV, and transparent armor will encourage manufacturers like Pilkington, to invest in large RF equipment for architectural FastFuse.

Laminated transparent armor (TA) is manufactured by approximately 30 companies in the U.S., and is of strategic interest to the Departments of Defense, Justice, Homeland Security, and State. In addition, a large portion of transparent armor is exported from the U.S. to security hot-zones including Mexico and the Middle East for use by foreign governments and companies doing business in those areas. These products are highly energy intensive relying on thermal conductivity through thick, insulating glass and plastic layers, and currently account for approximately 4 trillion BTU of energy consumption annually. TA is lighter than opaque armor and provides more visual advantages, but significant costs limit use. By lowering the cost of transparent armor with FastFuse, the demand for TA will further increase. Therefore FastFuse will help the growth of this market. Work to date has advanced the TRL for TA by FastFuse to the 3-4 range, with equivalent ballistic performance as autoclaved panels. This work is also spurring RF investigations into the much larger market for opaque composite protection materials.

Despite recent troubles, the photovoltaic industry is undoubtedly on a long term growth path. This market is highly fragmented, like architectural and TA, but is less standardized in terms of materials and testing of laminated panels. This provides an excellent opportunity for FastFuse to allow PV companies to grow capacity while decreasing the time and cost of lamination. Ceralink’s work on PV has been demonstrated to TRL 3 (to early TRL 4) with thin film, silicon, and flexible photovoltaics.

In addition to Federal and State funded activities, commercially funded development is contributing to advances in the state of RF lamination technology in all areas. This work has implications for several other industries that continue to rely on conventional ovens, autoclaves, and hot pressing for manufacturing simple and advanced products ranging from abrasive grinding wheels to fiberglass composites. While not technically “FastFuse”, the manufacturing demonstration center established by this proposed project will spur development programs in these other areas, as is already occurring with the lab-scale FastFuse Testing Center inaugurated through a previous NYSERDA program.

Potential product improvements from RF lamination

Fast cooling is known to result in reduced haze, producing clearer windows, especially for certain interlayers like DuPont SentryGlas®[28]. In RF lamination, the heat is produced directly in the vinyl, and as a result the glass structural layers of the laminate remain relatively cool. By limiting the heat in the glass, RF lamination may improve the clarity of some windows in addition to dramatically reducing the energy and time for manufacturing. This may be especially significant for laminates constructed of thick glass, which due to their size and heat capacity cannot be cooled quickly once they are heated. Also, by cooling products such as armor windows in a flat press, better control over distortion in the plastic (polycarbonate, acrylic) layers is anticipated in comparison to autoclave lamination.

The short cycle time of RF lamination may allow some materials to be laminated that otherwise cannot withstand the long temperature soaks required in autoclave processing. For example, polyester films are used in glass laminates for adding mirrors, designs, embedding light emitting diodes, and other functions. Some of these films may degrade at temperatures of 130-140 °C for several hours, such as they would experience in the lamination of multilayer products. In RF lamination, the total time at temperature of 5 to 10 minutes for multilayer structures would allow lamination to occur without detrimental effects on the polyester inserts.

Another opportunity for improved product performance that was identified is in protective coatings particularly on polycarbonate and acrylic laminates. Many of these coatings are applied prior to lamination, but are susceptible to crazing (developing fine cracks) during the autoclave process. In RF lamination, the outer surface of the laminate can be kept much cooler than the interlayers, preventing crazing and improving product rejection rates and optical performance.

Commercialization Plan and Status

The commercialization plan for the FastFuse technology is a three-pronged approach for revenue generation and market penetration. First, Ceralink is pursuing intellectual property protection that would allow for ongoing license and royalty revenue in partnership with RF press manufacturers. Second, establishment of spin-off operations for custom tooling and non-destructive quality testing that are unique to each customer and product being laminated will lead to direct product sales to the end user. Additionally, Ceralink would offer application development consulting to customers on a project-by-project basis, in partnership with RF press sales agreements offered by suppliers. Third, market penetration will proceed with initial commercial sales in the smaller markets of armor and photovoltaics followed by curved glass tooling development that will lead to the larger markets for front and side window autoglass, opening up the large volume architectural glass market once the technology is mature.

Several major barriers to commercialization of RF lamination have been reduced as a direct result of this project. One is the decades long reputation that autoclave lamination has developed, which remains the industry standard for highest quality. Also, curved RF lamination technology must be demonstrated, particularly for the autoglass industry. The current glass bending tools often cost over $100,000 for one window, while the cost of similar tooling for RF lamination is anticipated to be below $10,000 per window. Addressing these two barriers in continued piloting and demonstration of FastFuse technology will be critical. Ceralink expects to begin overcoming these barriers, through the successful completion of this project.

How will RF lamination technology reach the market?
The commercialization plan for RF lamination includes:

- Marketing of FastFuse
  - Continued conference presentations by Ceralink Inc.
  - Websites as primary information dissemination tools (www.fastfuse.net and www.ceralink.com)
  - Responsive interest follow up, with phone conferences, web meetings/presentations, and site visits to prospective customers of FastFuse
  - Partnering with equipment manufacturers and end users in support of sponsored research and development opportunities
- Transfer of technology to industry
  - Ceralink is pursuing patent application (technology was applied for patent with priority date in 2006).
  - Intention to license directly to equipment manufacturer(s) to provide RF presses for FastFuse.
  - Ceralink will work with end-users on case-by-case process to reach development consultation agreements along with press sale.
- Market penetration path
  - Initial sales are anticipated in small products such as Transparent Armor, smaller photovoltaics, and in R&D groups at manufacturers.
  - Curved glass tooling development and validation will lead to incorporation into side window manufacturing in the U.S.
  - Commercial successes with these smaller product markets will encourage industry to invest in larger (and more capital intensive) RF presses to validate the technology on architecturally significant manufacturing operations.

What will the technology developer's role be in commercialization? After implementation?
Ceralink plans to offer consulting to end users and assistance with new product development after implementation. Ceralink has a strategic role in developing initial market interest (which is actively

occurring) and in promoting the first sales of RF lamination equipment. The RF press sales will occur directly through the RF equipment manufacturer(s), with a referral or license fee to Ceralink. After implementation Ceralink will provide consultation support packages to end users for assistance with process development with RF lamination. As RF lamination sales become more common, it is anticipated that direct sales efforts by the RF equipment manufacturer(s) will increase. Likewise, the RF equipment manufacturer's familiarity with the specifics of RF glass lamination will grow, likely through technology transfer materials and direct collaboration with Ceralink. This will allow Ceralink to continue to benefit from implementation, with less direct involvement as the technology matures.

Spin-off possibilities from the Industrial Grand Challenge project

Curved Platens – Development of curved platens from concepts developed in this project could lead to a spin-off business for Ceralink to supply the industry with these platens. An alternative route is to train FastFuse end-users to make their own platens, however a standardized shop would ensure consistency among end-users. This business could operate by receiving samples of windows or CAD drawings from the end-user and fabricating RF compatible platens.

Non-destructive testing – The non-destructive testing technique developed by the University of Illinois is a potential spin-off business. The technique is applicable to any laminated glass whether prepared using conventional autoclave lamination or RF lamination. In RF lamination, where in-situ temperature measurement is difficult and process flow is nearly continuous, the NDT could serve as an in-line quality control tool. The University of Illinois reports that the physical tools used for the NDT are simple devices; however, the generation of useful data will require specialized training of engineers to properly perform the measurements and develop the technology as a commercially useable technology.

Realistic market share penetration rate

Penetration in the lamination markets will be gradual. Earlier uptake will occur for products of small size, in markets such as transparent armor, where numerous companies compete to find an edge over competition. Transparent armor is a market with little barrier to entry other than the initial capital cost of the autoclave. The lower cost of RF lamination equipment opens opportunities for new manufacturers of laminated products to emerge. RF lamination also provides an alternative to companies that do not laminate due to level of comfort with autoclaves.

In autoglass, a realistic potential for market intrusion is through new volumes of laminated side windows. With a lack of lamination infrastructure in the U.S. for side windows, a lower capital cost, lower energy alternative like RF lamination will be strongly considered. Uptake of RF lamination for side windows by Pilkington could lead to approximately 20% of US made auto side windows to be laminated with RF. Certain automakers highlight energy efficiency initiatives of their suppliers and encourage other suppliers to adopt best practices. With automaker backing, the use of RF lamination can spread further.

Barriers and potential approaches to overcome them

A major barrier to implementation is the decades long reputation that autoclave lamination has developed. Autoclaving provided the first high quality laminated windows, and remains the industry standard. Product development studies in which the quality and performance of RF laminated windows are measured are critical to building confidence in the ability of RF lamination to replace the autoclave.

Curved lamination presents another significant barrier, particularly for the autoglass industry. Virtually all autoglass is curved; therefore it is critical for this capability to be developed for RF lamination. Curved lamination will require special tooling for each window variation. This is not entirely significant, as unique tooling is already required for every window for bending the glass. The glass bending tools often cost over $100,000 for one window. The cost of tooling for RF lamination is anticipated to be significantly less at below $10,000 per window.

Transparent armor has perhaps the fewest barriers to market entry, although further long term environmental and performance testing should be performed. The size of windows demonstrated by FastFuse so far, with up to 2' x 3' flat panels, covers a large majority of transparent armor windows used for defense and security applications.

Commercialization activities

Routes to extend RF lamination development are continually in pursuit by Ceralink. These include Federal, State, and commercial opportunities. As a direct result of the curved platen concept task in this project, a New York State funded award was extended to allow initial development and feasibility testing for the concepts devised. Several commercial project proposals have been made, along with numerous phone meetings, site visits, and conference presentations. The 5 conference presentations made during this project have served to expand awareness of RF lamination among commercial end users, academia, government, and energy policy organizations.

These have led to collaborations on a prototype/pilot level proposed project very similar to the "Stage 3" 3 year effort that was outlined in the original Industrial Grand Challenge proposal. Other collaborations that have emerged include with the US Army Tank Armor Research, Development, and Evaluation Center (TARDEC), and strengthened relationships and market interest in the transparent armor industry in particular.

Metrics for decision to adopt process

The metrics to adopt the process vary by industry. In most industries, implementation is more likely to occur in the near term for new facilities rather than for retrofits of existing facilities. The metrics for adoption are not necessarily fixed, however quality, process flow, throughput, cost-benefit analysis, and end-user business decisions are equally critical. Table XIII shows a list of metrics for RF lamination adoption.

Table XIII. List of metrics for RF lamination adoption

Metric	Industry	Requirement	Motivation	RF Solution
Throughput	Autoglass	Equal or exceed current throughput Windshields – Approximately 240 every 90 minutes Side windows – smaller, throughput by ft^2 may be lower conventionally	Currently cutting, bending, cleaning, layup and quality control function at this rate, along with autoclaving. Any process that lowers the cost of lamination would have to at very least meet this rate.	Calculations of hypothetical process flow show that 3 RF presses could yield 10% higher throughput than 1 autoclave.
Throughput & process flow	Transparent Armor	Equivalent throughput is important. Ability to produce small order batches immediately may be more important	Current process requires 6 to 20 hours depending on thickness and materials used. Vacuum bagging systems severely limit autoclave loading capacity.	RF lamination time for armor is limited to 5 to 10 minutes of RF heating time. Small orders can be shipped same day.
Development Time	Transparent Armor		Development cycles take very long time with only 1 experiment per day regardless of number of samples	RF lamination allows numerous configurations and lamination parameters to be adjusted in a short time. Significantly lowers development cost.
Cost Benefit	Any			Cost benefit analyses based on capital equipment and energy suggest lower cost for RF
Quality	Any	Must meet or exceed current specifications	Product quality has to be at least equivalent	Continued testing shows RF performance in autoglass, armor, and photovoltaics meeting industry standards

Accomplishments

Technical Achievements
The most significant accomplishment in this project is that RF laminated glass has been demonstrated to achieve the same level of mechanical, environmental, and optical performance expected from state-of-the-art autoclaved glass. RF laminated glass has passed all 14 ANSI/SAE and autoglass industry standards tests to which it was subjected. A detailed experimental design found the variables most responsible for producing windows that met all of the environmental performance standards.

The demonstration of good air removal, with environmental stability of the laminates, and good PVB adhesion were major objectives of the Grand Challenge project, and have been achieved. This allows Ceralink to report energy savings and other RF lamination benefits with the confidence that products of equal quality are being compared.

Over 400 RF laminated panels were fabricated by Ceralink throughout the project for testing by Ceralink, Pilkington, and the University of Illinois.

Commercialization activities
The technical achievements of this project have allowed Ceralink to assemble teams including Pilkington, the University of Illinois, state level resources, and Federal agencies to pursue various routes of FastFuse commercial development. This has included commercially funded development projects, New York State supported development of curved lamination concepts produced in this project, a diverse industry and university supported team assembled for a prototype/pilot level demonstration in a range of lamination industries, and potential internally funded US Army evaluation of FastFuse product performance.

Facilitation of funding for continuation of work
Concepts for using FastFuse to laminate a small curved auto side-window were developed in this project. Based on these concepts, additional funding was secured from the New York State Energy Research & Development Authority (NYSERDA) for preliminary testing of the concepts in early 2012.

Conference Presentations and Publications
Six conference presentations and three conference proceedings were produced in relation to this project. The presentations and papers are available on the www.fastfuse.net and www.ceralink.com websites.

- A presentation was given at the Materials Science & Technology 2010 Conference in Houston, TX, in October 2010. A proceedings paper was published titled, “Novel Lamination Method for Large Armor Panels.”

- An RF lamination presentation was given at the Armor Symposium of the International Conference on Advanced Ceramics and Composites in Daytona Beach, FL, in January 2011.

- A presentation was given at the Composite Manufacturing & Process Technology II session of the SAMPE 2011 Annual Meeting (Society for Advanced Materials and Processing Engineering), on May 24, 2011 in Long Beach, CA. A proceedings paper was published titled, “Autoclave-free Radio Frequency Lamination for Armor and Other Transparent Windows.”

- A presentation was given at the ACEEE (American Council for an Energy-Efficient Economy) 2011 Summer Study in Niagara Falls, NY on July 28, 2011. A proceedings paper was published titled, “Optimizing Energy and Process Efficiency of Radio Frequency Glass Lamination.”

- A presentation on FastFuse RF manufacturing, entitled, "Industry Evaluation of Radio Frequency Lamination", was given at the Materials Science & Technology 2011 Conference in Columbus, OH in October 2011. This presentation detailed the PVB lamination quality accomplishments achieved in this project.

- A presentation on FastFuse called, "Radio Frequency Lamination for Curved Windows," will be presented at the International Advanced Ceramics and Composites in Daytona Beach, FL, in January 2012, based on the curved lamination concepts developed in this project.

Graduate Student Thesis
The University of Illinois at Urbana-Champaign produced a Master's Thesis on, "Adhesion Quality Control of Laminated Safety Glass Using Ultrasonic Velocity and Attenuation Measurements," based on work performed in this project[16]. The University of Illinois identified ultrasonic frequency ranges in which varying levels of adhesion between glass and EVA or PVB interlayers can be detected. The thesis focused on work with PVB and glass from Pilkington, laminated by Ceralink using RF lamination.

Conclusions

The project significantly helped to advance RF lamination past the feasibility and novelty stage and into the realm of commercial acceptance as a viable alternative to autoclaves. The demonstration of autoclave-quality autoglass produced in just 1 minute with RF lamination, with validation by Pilkington, has fueled industry motivation to seriously consider RF lamination. The industry and other contacts and outreach made in the study of laminate markets (including 3 technical publications and 5 conference presentations), has resulted in a recent surge in RF lamination activity. The information developed in this program will assist future commercialization efforts in autoglass, transparent armor and other laminated glass industries.

In this project, Ceralink has demonstrated 90% energy reduction with equivalent quality of autoglass laminates using its RF technology. Also, data suggests promise in improving the quality of some laminates such as security glass, due to the drastically reduced heating and cooling of the thick glass layers, as compared to that experienced in autoclave lamination. Another significant benefit that was demonstrated as a result of this project, relates to the significant improvement in processing time that is possible with commercialization of the FastFuse technology. In batch autoclaving, hundreds of windows may be laminated simultaneously. As a result, if defects occur during lamination, the defects cannot be detected until many windows have been produced. If the defects can be addressed by re-processing, the lamination energy & time investment is easily doubled. If the defects cannot be reworked, then the full energy value chain for that product is lost in scrap. RF lamination allows each window to be quality checked immediately after lamination and this rapid quality feedback thus can prevent significant losses in manufacturing. RF lamination will change process flow for current users of autoclaves or vacuum laminators. For example, in the automotive industry, laminated glass is currently produced in a highly automated, continuous process. The autoclave step is the only step in which the glass leaves the automated continuous process, and enters a manually handled, batch operation. Thus, RF lamination provides a logical next step to fully automate autoglass lamination.

Recommendations

The next technical challenge for RF lamination is the development of curved lamination. Curved lamination is a critical advancement for enabling implementation in the large automotive glass industry. Demonstration within the autoglass industry on smaller vehicle windows will enable support by glass companies to pursue investments in larger RF equipment for handling very large architectural glass. Opportunities for establishing a larger RF lamination demonstration facility at Ceralink are being pursued to enable lower cost, faster demonstrations and manufacturing validations.

For the transparent armor market, which deals in window sizes already feasible with current RF capabilities, a targeted focus on transitioning to commercial and other Federal agency support of RF lamination is envisioned, with implementation feasible in the next two years.

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Appendix: Potential Benefits Assessment Calculations

Table XIV. Table showing an estimated scaling of laminated glass production comprising the automotive and architectural glass markets based on 2001 industry statistics and 2006 growth rates from the Freedonia Focus on Flat Glass report (Report #2074), 2006[25].

Volume of Laminated Glass Produced	***Calculation***	***Result***	***Unit***
Square feet of flat glass laminated in 2001	6.4 B sq.ft * 25%	1.6	B sq ft
Square feet of laminated product (~2.5 sq ft of flat glass per 1 sq ft window)	1.6 B / 2.5	0.64	B sq ft
Growth rate of 6.7% from 2001 to 2012	$0.64B * (1.067)^{11}$	1.3	B sq ft
Growth rate of 6.7% from 2001 to 2020	$0.64B * (1.067)^{19}$	2.2	B sq ft
Growth rate of 6.7% from 2001 to 2040	$0.64B * (1.067)^{39}$	8.0	B sq ft

*Note: To calculate growth with a fixed growth rate over time, the following formula is used: $V = V_o(1+i)^t$, where V is the resultant value, V_o is the starting value, i is the growth rate, and the exponent t is the number of periods of growth, which in this case is years.

Table XV. Table of general glass industry energy consumption data for 2012, 2020, and 2040 including potential/hypothetical savings using RF lamination.

Autoclave industry energy consumption	***Calculation***	***Result***	***Unit***
Industry energy usage for lamination (From Pellegrino, 1997 data[29])		0.8	T BTU laminating (pre autoclave)
		0.84	T BTU laminating (autoclave)
Total glass lamination industry energy in 1997	0.8 + 0.84 T BTU	1.64	T BTU Total Lamination
Autoclave energy with 6.7% growth rate in 2001	1.64 T BTU * $(1.067)^{4}$	2.13	T BTU Total Lamination
Energy per sq ft based on Pellegrino and Freedonia data combined	2130 B BTU (2001) / 0.64 B sq ft (2001)	3321	BTU/sq ft
Energy per sq ft (kWh) based on Pellegrino and Freedonia	**2662.5 BTU / 3412 BTU/kWh**	**0.97**	**kWh/sq ft**
Energy per sq ft for single pane RF Lamination (Ceralink data)		0.04	kWh/sq ft
Energy per sq ft for single pane RF Lamination (Ceralink data)	0.04 kWh/sq ft * 3412 BTU/kWh	136	BTU/sq ft
Energy savings as percentage with RF Lamination compared to Autoclaving	**136 BTU/sq ft RF / 3321 BTU/sq ft Autoclave**	**4.1%**	**% Energy savings**
Autoclave energy with 6.7% growth rate in 2012	1.64 T BTU * $(1.067)^{15}$	4.34	T BTU
Hypothetical Energy Consumption in 2012 with all RF Lamination	**136 BTU/sq ft * 1.3 B sq ft**	**0.18**	**T BTU**
Hypothetical Energy Savings in 2012 with all RF Lamination	**4.34 T BTU - 0.18 T BTU**	**4.2**	**T BTU**
Autoclave energy with 6.7% growth rate in 2020	1.64 T BTU * $(1.067)^{23}$	7.29	T BTU
Hypothetical Energy Consumption in 2020 with all RF Lamination	**136 BTU/sq ft * 2.2 B sq ft**	**0.30**	**T BTU**
Hypothetical Energy Savings in 2020 with all RF Lamination	**4.34 T BTU - 0.18 T BTU**	**7.0**	**T BTU**
Autoclave energy with 6.7% growth rate in 2040	1.64 T BTU * $(1.067)^{43}$	27	T BTU
Hypothetical Energy Consumption in 2040 with all RF Lamination	**136 BTU/sq ft * 2.2 B sq ft**	**1.1**	**T BTU**
Hypothetical Energy Savings in 2040 with all RF Lamination	**4.34 T BTU - 0.18 T BTU**	**26**	**T BTU**

Table XVI. Table of Ceralink estimates for energy consumption in transparent armor, photovoltaic, and plastic window lamination industries with potential energy savings using RF lamination.

Note: The Pellegrino energy data appeared to refer only to PVB based automotive and architectural lamination, and likely did not include secondary laminators such as transparent armor and photovoltaics, which use thermoplastic polyurethane and ethylene vinyl acetate interlayers[29].

Estimate for transparent armor lamination based on Ceralink market research and interviews in Tasks 5 & 6.
Long autoclave cycles for transparent armor results in up to 15-30 times greater energy intensity that automotive PVB lamination.

	Calculations	***Result***	***Units***
Number of Armor/specialty laminators in U.S. (estimated)		75	Manufacturers
Average number of autoclaves each (estimated)		3	Autoclaves
Average number of cycles per day per autoclave (estimated)		1	Cycle/day
Estimated electricity cost per cycle (from industry estimates)		$ 500	$
Estimated number of production days per year for specialty laminators		300	Days
Estimated energy cost for industry per year for all manufacturers	75 * 3 * 1 * $500 * 300 days	$ 33,750,000	$
Energy consumption per year (kWh)	$33.75M / $0.0866/kWh	389,722,864	kWh
Energy consumption per year in 2012(T BTU)	389 M kWh * 3412 BTU/kWh	1.33	T BTU
Energy estimate for 2020 at 10% market growth rate	1.33 T BTU * $(1.10)^8$	2.85	T BTU
Energy estimate for 2040 at 10% market growth rate	2.85 T BTU * $(1.10)^{20}$	19.2	T BTU
Estimated Photovoltaic lamination (2012)		0.2	T BTU
Estimated Photovoltaic lamination (2020), 25% growth rate[30]	0.5 T BTU * $(1.25)^8$	1.19	T BTU
Energy estimate for 2040 at 15% growth rate	1.07 T BTU * $(1.15)^{20}$	19.5	T BTU
Estimated non-glass window lamination (polycarbonate, acrylic) in 2012		0.50	T BTU
Estimated non-glass window lamination (polycarbonate, acrylic) in 2020 (8% growth)	0.5 T BTU * $(1.08)^8$	0.93	T BTU
Estimated non-glass window lamination (polycarbonate, acrylic) in 2040 (8% growth)	0.93 T BTU * $(1.08)^{20}$	4.3	T BTU
Total Armor & PV conventional energy in 2012	**1.33 + 0.5 + 0.5 T BTU**	**2.0**	**T BTU**
Total Armor & PV conventional energy in 2020	**2.85 + 2.14 + 0.93 T BTU**	**5.0**	**T BTU**
Total Armor & PV conventional energy in 2040	**19.2 + 19.5 + 4.3 T BTU**	**43**	**T BTU**
Potential 2012 Energy Savings with RF Lamination at 96% lower energy	**2 T BTU * 96%**	**1.9**	**T BTU**
Potential 2020 Energy Savings with RF Lamination at 96% lower energy	**5 T BTU * 96%**	**4.8**	**T BTU**
Potential 2040 Energy Savings with RF Lamination at 96% lower energy	**43 T BTU * 96%**	**41.3**	**T BTU**

Table XVII. Table of calculations for motor vehicle side and rear window transition from tempered to laminated glass, and the energy savings as a result of the use of lamination with autoclave and RF lamination. This data was used to produce Figure 34.

Estimated increase in laminated glass for auto industry, from merging Freedonia & Pellegrino data.
Currently only front windshields are laminated, but each laminated window uses 2 sheets of glass.
Windshields make up approximately 20% of the window area in the average motor vehicle.

Freedonia indicated that 32% of all flat glass demand was for motor vehicles.	*Calculation*	*Result*	*Unit*
Volume of glass for motor vehicles in 2001[25]	6.4 B sq ft * 32%	2.048	B sq ft
So sq ft of laminated autoglass in 2001 was	2.048 B sq ft * 20 %	0.4096	B sq ft
And sq ft of tempered autoglass in 2001 was	2.048 B sq ft * 80 %	1.6	B sq ft
Freedonia indicated that 31% of all flat glass is tempered[25]	6.4 B sq ft * 31%	1.98	B sq ft
% of tempered glass used in motor vehicles	1.6 B sq ft in MV/1.98 B total	82.6%	%
Energy used in tempering glass industry wide, from Pellegrino 1997[29]		12.9	T BTU
Portion of tempering energy used in automotive, 1997	12.9 T BTU * 82.6%	10.7	T BTU
Total tempering energy in 2012 (6.7% growth)	**10.7 * $(1.067)^{15}$**	**28.2**	**T BTU**
Total tempering energy in 2020 (6.7% growth)	**10.7 * $(1.067)^{23}$**	**47.3**	**T BTU**
Total tempering energy in 2040 (6.7% growth)	**10.7 * $(1.067)^{43}$**	**173.2**	**T BTU**
Volume of tempered autoglass in 2012	**1.6 B sq ft * $(1.067)^{11}$**	**3.3**	**B sq ft**
Volume of tempered autoglass in 2020	**1.6 B sq ft * $(1.067)^{19}$**	**5.6**	**B sq ft**
Volume of tempered autoglass in 2040	**1.6 B sq ft * $(1.067)^{39}$**	**20.6**	**B sq ft**
Tempering energy per sq ft	**28.2 T BTU / 3.3 B sq ft**	**8427**	**BTU/sq ft**
Energy if autoclave laminated instead of tempered 2012	**3.3 B sq ft * 3321 BTU/sq ft autoclave**	**11.1**	**T BTU**
Energy if autoclave laminated instead of tempered 2020	**5.6 B sq ft * 3321 BTU/sq ft autoclave**	**18.7**	**T BTU**
Energy if autoclave laminated instead of tempered 2040	**20.6 B sq ft * 3321 BTU/sq ft autoclave**	**68.3**	**T BTU**
Energy if RF laminated instead of tempered, 2012	**3.3 B sq ft * 136 BTU/sq ft RF**	**0.5**	**T BTU**
Energy if RF laminated instead of tempered, 2020	**5.6 B sq ft * 136 BTU/sq ft RF**	**0.8**	**T BTU**
Energy if RF laminated instead of tempered, 2040	**20.6 B sq ft * 136 BTU/sq ft RF**	**2.8**	**T BTU**
Energy savings with RF Lamination vs Autoclave, 2012	**11.1 T BTU - 0.5 T BTU**	**10.7**	**T BTU**
Energy savings with RF Lamination vs Autoclave, 2020	**18.7 T BTU - 0.8 T BTU**	**17.9**	**T BTU**
Energy savings with RF Lamination vs Autoclave, 2040	**68.3 T BTU - 2.8 T BTU**	**65.5**	**T BTU**