Innovations Deserving
Exploratory Analysis Programs

Transit IDEA Program

Transit Scratchitti Removal by Controlled Fire Polishing

Final Report for
Transit IDEA Project 28

Prepared by:
Shane Y. Hong, Ph.D.
Columbia University
New York, New York

March 2002

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board

This Transit IDEA project was funded by the Transit IDEA Program, which fosters development and testing of innovative concepts and methods for advancing transit practice. The Transit IDEA Program is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP), a cooperative effort of the FTA, the Transportation Research Board (TRB) and the Transit Development Corporation, a nonprofit educational and research organization of the American Public Transportation Association (APTA).

The Transit IDEA Program is one of four IDEA programs managed by TRB. The other IDEA programs are listed below.

- NCHRP Highway IDEA Program, which focuses on advances in the design, construction, safety, and maintenance of highway systems, is part of the National Cooperative Highway Research Program.
- High-Speed Rail IDEA Program, which focuses on innovative methods and technology in support of the Federal Railroad Administration's (FRA) next-generation high-speed rail technology development program.
- Safety IDEA Program, which focuses on innovative approaches for improving railroad safety and intercity bus and truck safety. The Safety IDEA program is funded by the Federal Motor Carrier Safety Administration and the FRA.

Management of the four IDEA programs is coordinated to promote the development and testing of innovative concepts, methods, and technologies.

For information on the IDEA programs, look on the Internet at www.trb.org/idea or contact the IDEA programs office by telephone at (202) 334-3310 or by fax at (202) 334-3471.

IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

Transit Scratchitti Removal by Controlled Fire Polishing

Final Report

Transit IDEA Project 28

Prepared for

Transit IDEA Program

Transportation Research Board

National Research Council

Prepared by

Shane Y. Hong, Ph.D.

Columbia University

New York, New York

March 16, 2002

ACKNOWLEDGEMENT

This project was funded by the Transit IDEA Program of the Transportation Research Board. Cost sharing was provided by Columbia University of $21,000. As collaborator of the project, New York City Transit (NYCT) provided labor and materials to evaluate and characterize the scratchitti, and samples of scratched glass windows for testing.

TABLE OF CONTENTS

EXCUTIVE SUMMARY

Graffiti vandalism on rail transit car windows is a serious problem.

A new type of graffiti vandalism has emerged and prevails -- the scratching or etching of polycarbonate and glass windows, referred to as “scratchitti.” The “scratchitti” gives passengers the impression that vandals are in control on the transit system and that passengers are not secure and safe. But unlike paint graffiti, the scratches, which cannot be wiped away or hidden by a coating, cause permanent damage. Usually, the glass panel must be replaced. Transit authorities have tried polishing the glass as well as patching the glass with optical grade epoxy. However, the quality of the repair is not acceptable and the cost of operation is prohibitive, leaving no satisfactory, cost effective options. On some subway systems or transit buses, transit officials have tried to install a removable polyester film as a protective cover. Once it is etched, a new piece of polyester film replaces the damaged one. Polyester film has several disadvantages: it cannot repair already damaged glass, it degrades the optical property of the glass, and it is expensive to replace, which adds to the operation costs.

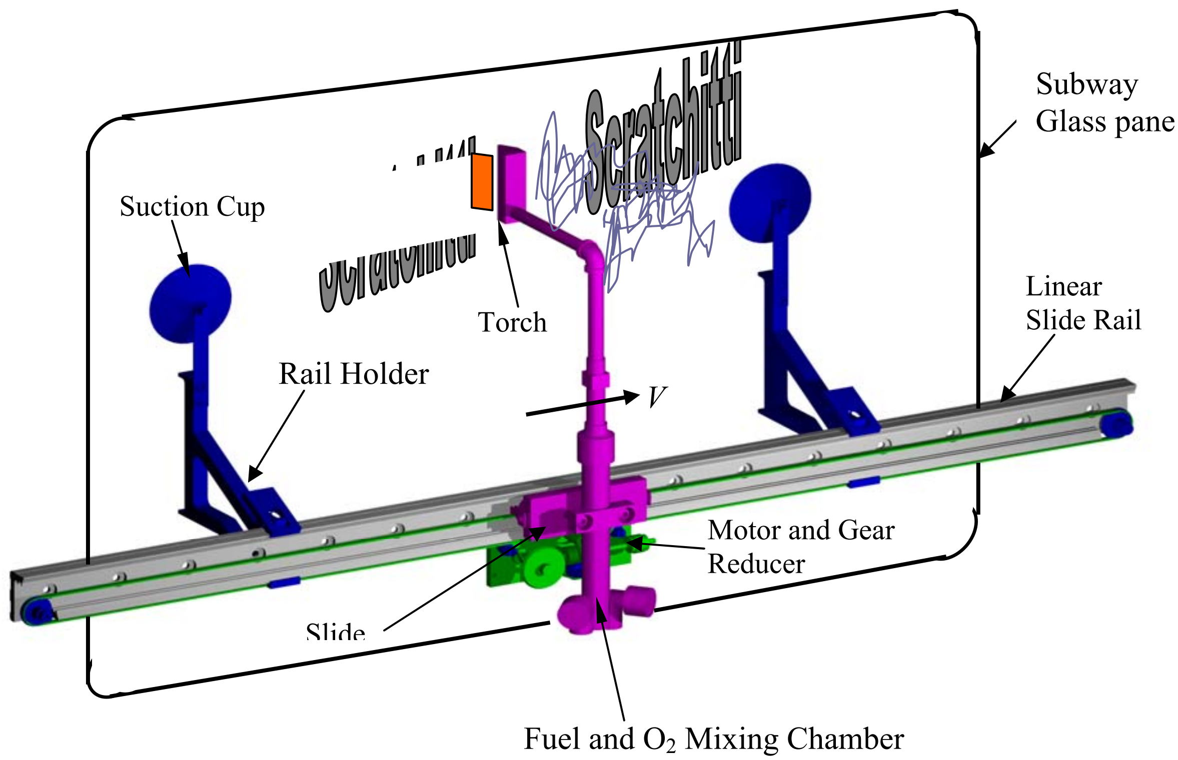
To solve this problem, we applied an innovative approach – controlled fire polishing, which incorporates a technique of localized softening and surface tension. Intensive heat is positioned near to the scratch marks on the glass panel. The heat melts a thin layer of glass into liquid, changing the glass’s viscosity to a formable state. The glass is melted to a level close to the depth of the scratch, and allowed to cool down naturally. During the cooling process, the surface tension of the melted glass evens out the scratching indent. After cooling and without grinding or polishing it, the glass is as even and smooth as it was originally. In this process, except the thin and small scratched surface area being repaired, the glass remains solid and structurally sound during this operation to prevent any distortion of the glass panel. When well controlled, this operation will work on both horizontally and vertically placed glass, such as glass framed in the windows or doors of subway cars.

This Transit IDEA project has successfully demonstrated the feasibility of this innovative process. We have surveyed and characterized the scratchitti, investigated the glass or polycarbonate properties, designed the heat source, ran a heat transfer analysis and temperature computer simulation, and designed and built a motor driven prototype tool for removing scratchitti for initial test. The project has demonstrated the feasibility of our proposed system and collected the necessary data and parameters for controlling the process. Following this project, we propose to develop a well-controlled operational instrument or tool for removing glass graffiti, based on the results of this study. The final effort will deal with automating this graffiti removal system.

To facilitate the smooth operation, a uniform, linear, narrow, and high temperature flame as the heat source provide cost effective tool for fire polishing. This was achieved through our three iterations of nozzle development. The machine we designed and built, *Scratchitti Buster*, is a motor driven slider controlled by a computer to move the nozzle at a constant speed during the polishing process. Light and portable, this machine has suction cups to cling to the glass panel for positioning. It uses the glass surface as reference by a pair of brackets so that the nozzle will keep a constant distance while moving. The brackets are adjustable to fit the machine with different sizes of windows. Oxy-fuel used can be acetylene-oxygen for high speed fire polishing or propane-oxygen for convenient and easy operation.

Analytical and numerical heat transfer simulations of the flame and glass pane interaction yield satisfactory operational parameters for the desirable steady-state temperature distribution. The control parameters include the flow rates of the fuel and oxygen and their mixing ratio, the flame travel speed and distance from glass surface. The desirable temperature distribution enables the glass surface to re-flow and remove etches, while preventing glass distortion and cracking. Experimental testing of the fire polishing process was performed, and the feasibility of the process was demonstrated by glass samples that recover from heavy scratches to a smooth, clear and transparent state. The ranges of optimum operating parameters for high polishing quality have been identified through a range of testing conditions. Common defects of the glass polishing were investigated and their causes due to improper control operating parameters was located and fixed.

This project addressed the pressing vandalism issue faced by transit agencies across the country. The results from this Transit IDEA project have demonstrated the feasibility of this process, and produced important information for final product design in commercialization stages. It is ready to move onto development.



The conceptual design of the Scratchitti Buster as mounted on glass panel

1. INTRODUCTION

1.1 PROJECT OBJECTIVES AND SCOPE

The objective of this project is to develop an environmentally benign, novel re-manufacturing process and product to relief the bothersome scratchitti vandalism- permanent scratches on the glass surface. In this project, an innovative approach, controlled fire polishing, has been used. Intensive heat melts only a thin layer of the glass panel. During the cooling process, the surface tension evens out the scratching indent. The process is to enable the reuse of the damaged window/door and eliminate the otherwise waste by replacement new glass. It allows a better living environment for people, rid of the unpleasant and annoying scratchitti vandalism**.**

1.2 PROJECT BACKGROUND

1.2.1The Need for Scratchitti Removal System

New York City Transit (NYCT) currently operates 5,792 passenger railcars and provides service seven days a week, twenty-four hours a day to approximately 1.1 billion customers a year.

NYCT has operated a graffiti free fleet since May 1989 when the last graffitied railcar was removed from service. Graffiti free, that is, in terms of paint or ink graffiti since paint or ink graffiti markings are removed from cars within 24 hours. However, with the conquering of one type of graffiti, a new type of graffiti vandalism emerged - the scratching/etching of polycarbonate and glass windows, sometimes referred to as "scratchitti."

Polycarbonate windows, which were first installed in railcars and provided in new cars in the early 1980's, solved the problem of glass window breakage but it was discovered that polycarbonate could be easily scratched with anything from knives to a paper clip. Vandals made heavy use of this new type of canvas for their "art" and polycarbonate windows were being replaced in epidemic proportions. Eventually, it was decided that New York City Transit needed a glass that was stable enough to prevent breakage and less easy to scratch than polycarbonate. A new type of impact resistant glass that met FRA requirements and was more resistant to scratches was developed and installed on the railcars.

However, even though this new type of glass is more scratch resistant than polycarbonate, vandals have discovered that it can be scratched and they have been very creative in their choice of tools, which range from emery cloths to diamond dust encrusted pen styluses. As with the paint and ink graffiti, the "scratchitti" gives passengers the impression that vandals are running wild in the transit system. Unlike paint graffiti, the scratches cannot be wiped away and cause permanent damage. Currently scratchitti is so prevalent that it is on almost every window and door of every rail car of New York City's (NYC) subway lines.

It has been estimated that in order to run a scratch free fleet, NYCT would have to spend $60 - 70 million per year, replacing window glass. At the present time, NYCT replaces glass only when it is so scratched it cannot be seen through, or has obscenities or racial slurs etched into it. In 1997, NYCT replaced approximately 62,000 pieces of damaged glass for a material and labor cost of $2.6 million. The cost of the glass ranges from $20 to $100 per piece depending on the size (i.e. side door glass or picture (side) window glass with the labor cost being $26.36/hour). NYCT has approximately 174,000 pieces of glass in the subway fleet.

Scratchitti occurs not only in New York City, but in all United States cities and it is not limited to subways. Windows and doors (often large and expensive) of public buses, residential homes, and business buildings also suffer severely from this type of vandalism. Citing a federal study, a Philadelphia newspaper, *The Inquirer*, reported that the cleanup costs for scratchitti runs to $1 billion a year nationally. This project offers a viable solution for glass vandalism, benefiting all transit agencies and other property owners.

(a) Scratchitti on polycarbonate glass

(b) on tempered high strength soda-lime safety glass

Fig. 1 Scratchitti is a severe problem in the NYC subway system and many other places.

1.2.2 The Technical Challenges

Since manufacturing unscratchable glass is technically impossible, many organizations have investigated potential methods to remove the scratches, such as grinding/polishing the scratches, applying plies of Mylar film (polyester film) to the glass, and patching with clear polymer coating. To date, no feasible solution has been found.

Grinding/polishing operations require that the glass be removed from the frame for the scratches to be polished out. Attempting to polish/grind the scratches at NYCT facilities was very labor intensive. The windows were shipped to a vendor who polished the glass to remove the scratches. However, deep scratches could not be removed without impairing the integrity of the glass. This process required removing the damaged window, and replacing it with a new or repaired window, accruing labor, material and storage costs.

Covering windows with plies of Mylar (polyester) film was slightly more successful. The film could be applied to the window while it was in place in the frame. For the most part, the film protected the window glass from being scratched. However, because the film itself was more susceptible to scratching than the glass, it had to be replaced often, which again resulted in a material and labor costs. In addition, this approach cannot restore glass windows already etched.

Epoxy or polyurethane coatings, when applied to the glass, filled in the scratches making them seemingly disappear. However, the window had to be removed from the frame as the coating had to be applied to the glass when it was in a horizontal position. Applying the coating vertically resulted in the material dripping and running. The coating also had to be applied in a clean environment to prevent dust and dirt from being trapped between the coating and glass, which meant the windows must be shipped to the vendor. When the coating became scratched, the window again had to be removed, and to comply with flammability regulations, the first coating was removed before another coating could be applied. Again this was a labor and material intensive process.

Optimum requirements for a workable solution to the "scratchitti" problem include:

- Glass should be able to be repaired, or a protective coating or process applied while it is in the frame on the railcar or building;
- The repair/protection process should not be labor intensive and should be able to be completed within 5 minutes;
- If the window must be removed from the frame the repair/replacement time should be approximately 5 -10 minutes;
- The repaired/protected glass must be able to fit into the window frame;
- The structural integrity (impact resistance, strength) of the glass should not be impaired by the repair/protection process;
- The optical quality of the glass should not be changed;
- There should be no distortion, drips or runs;
- Any coating used must meet flammability and smoke toxicity requirements;
- The repair/protection process should not add any additional significant weight to the glass;
- Any coating/film used should not be detectable --no edges should be apparent;
- The repair/protection process should be able to be performed without the need for extra ordinary equipment;
- The protective process should provide the glass with not less scratch resistance than the glass currently has;
- Any coating/film used should be resistant to the cleaners and solvents used to clean and maintain the railcars.

1.3 PROJECT ORGANIZATION

This project has been conducted mainly at Columbia University with collaboration of New York City Transit. Columbia used its theoretical and experimental expertise to carry out the in-depth study, and developed the design for a working system. New York City Transit was responsible for the statistical evaluation and characterization of the scratchitti, as well as for gathering samples from their 25 subway lines, providing advice and guidance during the course of the study, and for actively participating in testing the process after the system is constructed.

This project, as covered in this report, is to conduct the feasibility study, that includes to characterize the problem, to computer simulate and design a prototype or a setup for testing. The NYCT and CU are jointly responsible for conducting the tasks. After the idea is successfully demonstrated, we will develop a well-controlled scratchitti removal instrument or tool for manual operation based on the feasibility study result. The last step will be the development of automatic system for scratchitti removal. Once the system is automated, an efficient and convenient scratchitti buster will be available for the use by all transit agencies.

2. PRINCIPLE OF NEW TECHNICAL APPROACH

This project uses an innovative approach to restore the scratched glass to a smoothly finished, optically transparent state. This approach is environmentally safe: it does not generate hazardous waste or use caustic chemicals.

This approach, called controlled fire polishing, incorporates a technique of localized softening and surface tension. Intensive heat is positioned to near the scratch marks on the glass panel. The heat melts a thin layer of glass into liquid, or changes the glass's viscosity to a formable state. The glass is melted to a level close to the depth of the scratch, and allowed to cool down naturally. During the cooling process, the surface tension of the melted glass will even out the scratching indent. After cooling and without grinding or polishing it, the glass will be as even and smooth as it was originally.

In this process, except the thin and small scratched surface area being repaired, the glass remains solid and structurally sound during this operation, not allowing the distortion of the glass panel. If well controlled, this operation can be done not only glass placed horizontally, but also repair the vertically as framed in the window or door of the subway cars.

Technically, this approach can be justified easily. Glass is generally shaped at elevated temperatures where the viscosity can be controlled. The glass properties make this approach very feasible. Glass has low thermal expansion (0.54 to 9 x 10^{-6} cm/cm^{o}C); local heating by our approach may not crack the glass. Glass has low thermal conductivity (3 to 10 X 10^{-3} cal/sec/cm^{2}/^{o}C/cm); therefore, it is possible to create the temperature gradient at which the scratched surface re-flows while the back panels stay solid strong. Glass manufacturers use a process similar to fire polishing, to round and polish the sharp edges of cut glass.

This process renews old glass, with or without scratching marks. Based on engineering principles, this process can restore 100 percent of the surface smoothness and optical transparency, with no chemical waste, no glass disposal, and no protective film requirements. Unlike grinding, this process does not reduce the amount of material in the glass panel, which could weaken the panel structure. Nor does it produce grinding debris or powder to contaminate the environment. Furthermore, our process reduces the amount of glass scrape and protective film waste disposal.

Therefore, once developed, this quick, easy, and environmentally safe process can even and smooth the glass surface to restore the high optical transparency. Our approach will not only improve the passengers' impressions of the transit system, it will reduce costs for labor, materials, and waste.

3. TECHNICAL INVESTIGATIONS

Controlled fire polishing is our proposed new approach to solve the scratchitti removal problem. While the approach provides many advantages, there are some technical problems to be addressed. If glass is placed horizontally on a table, this process would achieve the desired smoothness and evenness of the glass surface easily. However, our goal is to repair the glass at the site, without removing the glass panel. When glass panels are in a vertical position, as in rail car doors and windows, the molten or softened glass tends to sag due to gravity. Therefore, it must be well controlled. First, the softened layer will be no deeper than the scratch, minimizing the amount of flowable mass. By controlling the temperature, we can improve the viscosity of the glass so that it will not sag. Because the unaffected area of the glass sustains the softened glass, we will limit the size of the heated area to maintain the overall strength of the glass, which will also reduce repair time.

For vehicle glazing, a laminate consisting of two glass plates (soda lime), 1/8 in. thick, bonded with an interlayer of 0.015 plastic sheet (such as plasticized polyvinyl butyral resin), is commonly used. Soda lime window glass has a low softening point of 696^{o}C (1274^{o}F), making it one of the easiest types of glass to heat to its appropriate surface temperature. However, what we do not know is which heat source will be most effective. During the feasibility phase, our study will consider higher temperature and less heating time to be the desirable characteristics for creating the sharp temperature gradient. Although cooling the front and back of the surrounding glass panel may not be needed to keep its temperature low temperature, it will be considered during the study to achieve the most desirable temperature distribution. Even though the plastic film inside is confined, it is wise to keep this plastic layer at a low enough temperature to prevent degradation.

The objective of Phase 1 is to conduct a feasibility study. The elements of the technical aspects and conceptual development include: discrete experiments and analysis to obtain the control parameters based on material properties, heat transfer, thermal cracking avoidance, heat source study, patching with molten glass, ironing /rolling enhancement, temperature requirement, temperature distribution pattern on the glass, area coverage, control parameters, gravity effect, depth of glass softening, surface tension, cooling rate, material re-flow, time control, thermal expansion and thermal stress and crack. The technical investigations are categorized into the following five tasks:

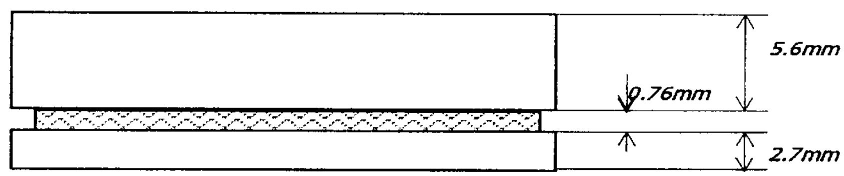
3.1 SURVEY AND CHARACTERIZATION OF GLASS/PC ETCHINGS

In order to design the most feasible system to remove glass scratchitti, it must be studied using statistical methods to determine the depth, texture, and profile of the etching. To characterize the etchings, we examined them using an optical microscope and SEM (scanning electron microscope) to study the severity of the etching. Surface analyzer is used to measure the roughness and the exact dimensions of etches. The NYCT provides glass samples with scratchitti from New York City's 26 subway lines, which are comprised of 5865 rail cars. Thus, based on our samples, the scratches can be grouped into the following three categories:

1. Wide, uniform scratches that cannot be divided into single scratches; their width ranges from 0.4 to 1.3 inches and length: 2.5 to 3.5 inches.
2. Clearly single scratches; their width: 0.001 to 0.003 inches and length varies, but generally extends over a substantial part of the entire glass surface.
3. Large, continuous scratches, clearly made up of smaller single scratches; however, not as continuous as the first kind, as these contain spaces of an unscratched-glass in-between the single scratches they consist of; their width: 1.1 to 1.7 inches and length: 3.5 to 6.0 inches.

The depth of the scratches does not differ much among the three kinds. They ranges from 400 to 600 micro inches. Aside from the 3 above-mentioned types, there are also few scratches that are short (about 1 inch) and thin (similarly to the single scratches). Those depth ranges from 1000 to 4000 micro inches.

The depth of the scratch will determine the level of thickness of the glass surface that will need to be softened. The statistical results of the scratching/etching mark profiling will provide a fundamental task statement for the glass graffiti removal. The width or the distance of adjacent scratches will determine how large an area the heat source must cover. Using the characterization results, we selected the appropriate cooling strategy and temperature distribution.



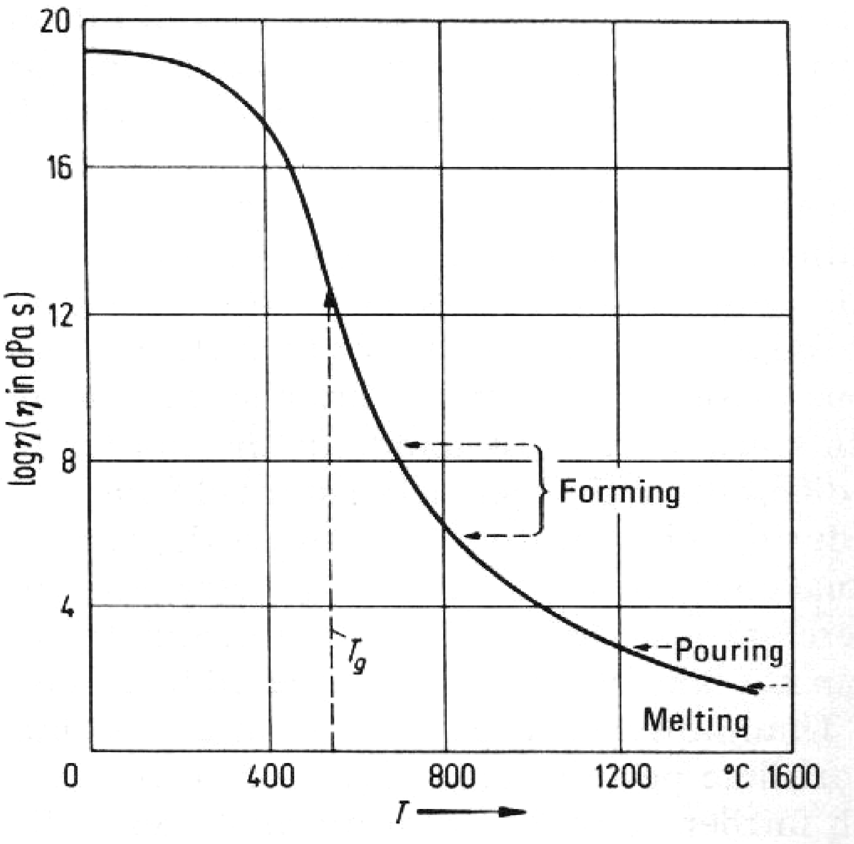


Figure 3: The glass property: the viscosity drops dramatically at glass transition temperature

3.2 GLASS AND POLYCARBONATE PROPERTY INVESTIGATION

The window panes of safety glass are made with two plates of thermally and chemically tempered soda-lime glass (ordinary window glass) held together by a plasticized polyvinyl butyral (PVB) resin film as shown in Fig.2 (*1*). Autoclaving the glass-PVB assembly at approximately 110°C and 15 atm usually achieve an extremely good adhesion (*2*). PVB is a very stable substance at room temperature, however, it pyrolyzes at temperatures close to 300°C, as may be judged from the pyrogravimetric curve in air (*3*), which shows a sudden increase in decomposition rate around this temperature. In our case, the critical temperature may be slightly higher because PVB will be subjected to high temperatures only for short time intervals as well as because the system is of constant volume (for the area away from pane edges). Therefore gases produced at initial stages of decomposition may be expected to dramatically increase the pressure on PVB and shift the decomposition equilibrium to the side of decomposing material. Because the system is also air-tight, it prevents oxidation and eliminates the problem of burning of PVB. In summary, the temperature of the PVB laminate must be maintained below a certain critical temperature that is significantly lower than the temperature required to melt glass.

Although, specific details on the composition, properties, and manufacturing process of the glass plates used for the window panes are mostly proprietary, information on the basic properties of glass is available. Glass used for plates and practically all windows is ordinary soda-lime glass. The compositions of commercial soda lime glass (*4*) by approximate weight are SiO_2, 72.6%, Na_2O, 15.2%, CaO 4.6%, MgO, 3.6%, Al_2O_3, 1.7% and B_2O_3, 0.8%. Temperature dependence of viscosity of this glass is illustrated in Figure 3. Since glass is very nearly a Newtonian fluid, there is a possibility of finding the maximum viscosity and minimum temperature at which the surface tension and gravity will be sufficient to smooth out the crevices in the glass. This temperature minimum will be highly dependent on the shape and depth of cracks.

The types of glass used on transportation vehicles are typically tempered, which affects their properties dramatically. The purpose of tempering is to subject the surface to compressive stress. Since breakage is generally caused by an expansion of microscopic surface defects due to tensile stresses, breakage can be prevented if the applied tensile stresses are balanced by the permanent compressive stress of the surface. Tempering involves uniform rapid cooling of a glass object from temperatures above its glass transformation temperature, T_g. T_g is defined as the temperature at which $\eta = 10^{13}$poise. It characterizes a temperature range within which glass transforms from melting with viscosity sufficiently low for any internal stress relaxation to occur in a relatively short time (i.e. glass behaves like a viscous liquid on the time scale of the experiment) to relaxation times being sufficiently long for residual stresses to remain. Chemical tempering produces a similar effect by alkali ion exchange. A glass product is dipped into a melt of potassium nitrate (KNO_3), where Na^+ ions at the glass surface are replaced by much larger K^+ ions. Larger space requirements for K^+ ions result in larger surface stress. Exchange depths usually reach 10-100μm. Thus, tempering produces surface compressions up to 1000MN/m^2. High compressive stresses are kept relatively close to the surface, and the tensile stresses inside the glass are several times smaller in magnitude. However, this causes a major challenge in the application of controlled fire polishing, i.e., cracking of glass due to thermal expansion.

From our own preliminary experimental study, there are two types of cracks that form by different mechanisms. The first type, body cracks, generally form in the plane normal to the surface of glass and extend from surface to surface. These cracks probably result from thermal expansion of the glass surface, thereby increasing the tensile stress of the internal layers past the breaking point. Body cracks are always produced during the initial stages of heating. Low temperature flames and larger flame diameters are more inclined to cause body cracks than high temperature small flames. Hence, the problem of body cracks can be solved by reducing the heated area, thereby reducing the total thermal stress in the pane. The second type of cracks, surface chips, may form as follows: When a small, rapidly heated area begins to cool, adjacent material is heated by heat conduction. Hence, while the center of heated area contracts, the underlying layers expand producing high tensile stresses on the boundaries of the volume initially heated. Such cracks are characteristic of very hot heating flames, heating and cooling rates, and small heating areas as a result of local temperature gradients. Note that the cracking phenomena are of concern only when no substantial portion of glass is above its T_g. Above T_g the modulus of elasticity of glass drops practically to zero (*5)*, therefore, all local stresses can be relieved by a sufficiently large mass of glass plate. Our solutions to resolve the glass crack are:

1. The viscosity of a sufficient volume of glass around a crevice must be low enough for surface tension to maximally fill the crack.
2. The temperature of the remaining surface of the glass plate must not exceed a certain critical value for more than a specified period of time.
3. Thermal stresses due to temperature gradients must not exceed a critical value. This implies that a certain maximum value of the temperature gradient cannot be exceeded.

3.3 HEAT SOURCE DESIGN AND CHARACTERIZATION

3.3.1 Heat Source Requirements

The general requirements for the optimal heat source appear to be the following:

1. It must be of maximal attainable temperature, well above 1000°C. High temperatures will produce high surface heating rates, therefore, increasing the T gradient normal to the surface, will allow PVB laminate to be preserved while melting the surface layers of glass. In general, the temperatures should be above T_g at a location only slightly below the scratch depth (~50μm total depth). This requirement may be satisfied by many oxygen-fuel gas mixtures (Table 1):
2. It must have at least one dimension in a plane of glass that is extremely small. Heating only a small total area appears to be the only way to reduce overall thermal stress in a glass plate below its critical value.

Table 1: Temperatures reached by various fuel and oxygen level

Fuel Gas	**Temperature (°C)** O2		Air	
	Actual	***Calculated***	***Actual***	***Calculated***
Acetylene	3100	2600	2325	1879
Propane	2815	1876	1900	1436
Methane	2770			
Hydrogen	2825			
Propylene	2930	2035		1535

*Propylene data are from [6], others from [7]

3.3.2 The Design of The Heat Source:

There are a number of different types of heat sources that could be used for melting glass, including electrical, laser, and traditional fuel gas torch. The gas torch is perhaps the cheapest, most accessible heat source. Hence, our preferred heat sources are based on hydrocarbon gas combustion.

The torch in which a fuel burns determines the temperature distribution configuration and heat delivery rate at the glass surface. There are two basic choices of torch design: premixed and diffusion flame torch. Ideal torch for the application would be an infinitely thin line extending from one edge of the glass to the other that would produce surface temperatures of around 1200°C sharp temperature change in the direction perpendicular to the glass surface. This would minimize the volume of glass heated above T_g and thus minimize the distortion in the internal stress pattern. The sharp gradient is not critical for the annealed glass applications, however, it is essential for laminated safety glass since the laminate can be preserved only by minimizing the total amount of heat transferred to the glass (temperature at the glass-laminate interface).

For ambient temperature operation, the minimal dimension of the flames as approximately 3-5mm for point Propane-Oxygen and Acetylene-Oxygen flames. With estimated flame temperature well above 2000°C, these flames produce hot spots (areas where temperature is sufficient to polish the surface) of approximately 5 mm in smallest dimension.

The nozzle design to produce a uniform linear heat source is critical for the success of the scratchitti removal. Following the study of glass material study, we have investigated the characteristics of various heat sources and explored different designs of the heat source for the purpose of scratchitti removal. While continuous improvement is still in progress, we have three nozzle designs that satisfy the heat source requirement.

3.3.2.1. Nozzle Design 1: Solid, Linear Acetylene-Oxygen Torch.

Shown in Figure 4, the first nozzle design consists of two aluminum plates with a liner between them shaped so as to produce a wide rectangular channel. The channel connects one of the edges of the assembly with a redistribution chamber. The chamber is a rectangular void in the assembly of the same width as the channel that ensures equal pressure along the channel width. A premixed acetylene-oxygen mixture is supplied to the redistribution chamber. Currently, we have used a channel of 2.5x2.5cm (width x distance from the chamber to the outlet). The maximum thickness of the channel is on the order of 0.1cm; for larger values Re of the acetylene-oxygen stream exceeds the critical value, stream becomes turbulent and either flash back occurs or flame extinguishes. At sufficiently low channel thickness stable, essentially cylindrical flames (parallel to the outlet) of dimensions of 1mm, uniform along the outlet were produced.

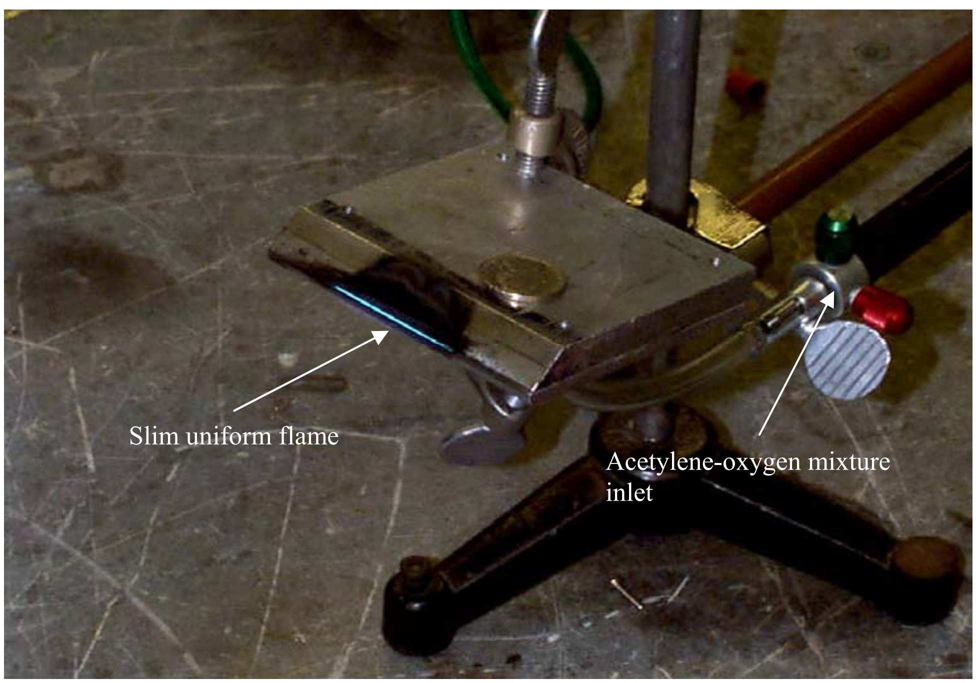


Figure 4: The solid linear acetylene-oxygen torch produces a uniform and slim flame.

3.3.2.2 Nozzle Design 2: Mixed Tube Array Torch

Shown in Figure 5 and 6, two sets of thin tubes (0.9mm, 1.2mm prototypes have been built) to a fuel or oxygen supply at one end and welded in a one-dimensional, alternating array at the other. The result is a series of small burners spaced close enough to produce uniform linear hot spots on the glass. The system uses ideas from our original Propane-Oxygen burner combined with a robust design that utilizes commercially available steel tubing. Mixing between the parallel stream of oxygen and fuel is sufficient to produce satisfactory temperatures. Because the velocity of oxygen can be controlled independently from the velocity of the fuel, velocity of the flames may be increased above the usual v_f, thus decreasing the buoyancy effects on the flame. The burner is safe since there are no enclosed volumes with the premixed gases. Satisfactory temperatures have been achieved with propane and hence we will be able to use the cleaner, safer, and cheaper fuel.

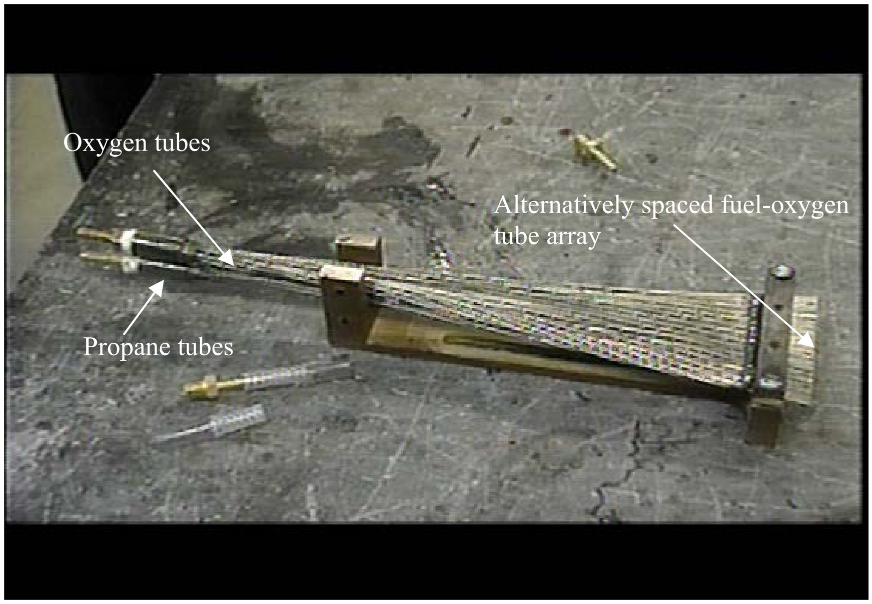


Figure 5. The construction of mixed tube array torch.

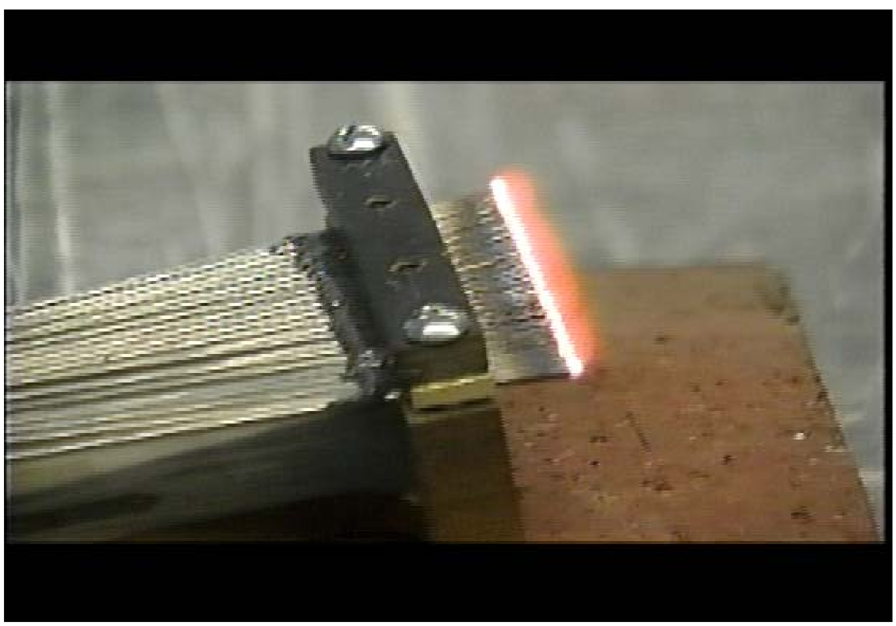


Figure 6. A uniform, stable linear flame has been achieved in this mixed tube array torch with a temperature high enough for glass treatment.

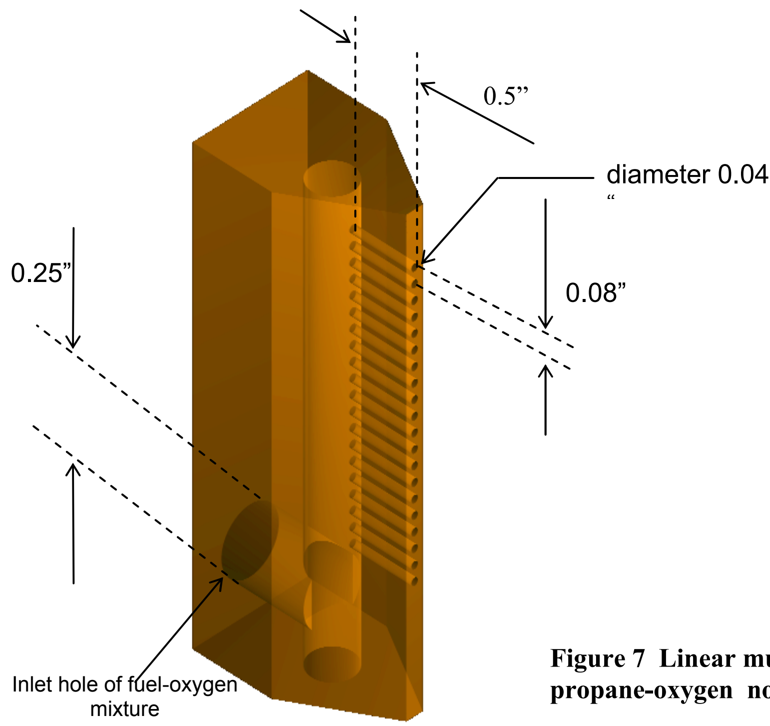


Figure 7 Linear multi-orifice premixed propane-oxygen nozzle

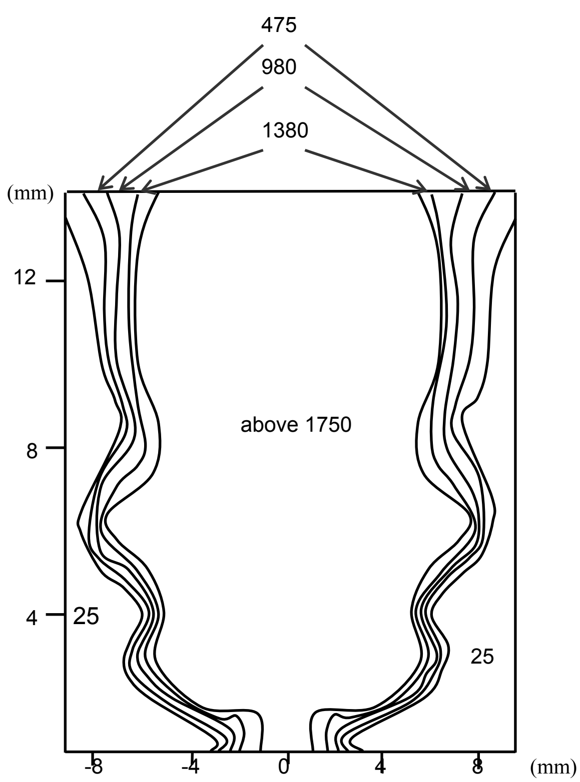


Figure 8: Measured temperature distribution in ^oC across the flame from linear multi-orifice nozzle

3.3.2.3. Nozzle Design 3: Linear Multi-Orifice Premixed Propane-Oxygen Nozzle

The nozzle, shown in Figure 7, has a series of holes spaced 0.08" apart linearly on center. These through holes have a diameter of 0.04" and are approximately 0.5" long. They are connected to the fuel supply by a 0.25" hole drilled perpendicular to the holes and along the length of the row. The pre-mixed propane and oxygen gases leave the tip through a small orifice and are ignited in the air, which create a flame of uniform temperature at a short distance about 0.3" from the surface of the torch.

3.3.3 Heat Source Characterization

The two-dimensional temperature profile of the flame cross section for this nozzle was studied experimentally under the volume flow rate of 6.0 liter/min for propane and 20.4 liter/min for oxygen (mixing ratio 1:3.4) at room temperature 25^{o}C. The temperatures of the flame were measured using B-type high temperature thermocouple, which was mounted on the moving slide at 2 mm/sec and scanned across the flame. The procedure repeated for different distances from the nozzle, at 2 mm increment up to 20 mm. From the tabulated data of measurements, the temperature profile of the flame is plotted in Figure 8. Due to the limitation of the thermal couple, the highest temperature measured was 1750^{o}C. The fuel (either propane or acetylene) and the oxygen are supplied from the gas tanks with the regulator output pressure set to 10 psi and 20 psi respectively. The fuel and oxygen are mixed in a commercial welding torch handle, Harris Torch-MEFS-098 which is mounted on the slide of the machine. The range of fuel flow rate is approximately 1 to 8 (liter/min) and oxygen rate is 3 to 28 (liter/min), and in most of optimum combustion cases the ratio of fuel and oxygen is 3 to 3.5: 1. In order to make repeatable operation the fine flow control valve can be set for repeatability.

3.4 HEAT TRANSFER AND TEMPERATURE DISTRIBUTION

In this project, both analytical and numerical methods have used for heat transfer and temperature distribution study.

In analytical approach, the thermal effects on glass due to an impinging flame are analyzed using the heat transfer mathematical model. The heat transfer to the glass de to a flame depends upon many parameters such as burning velocity, composition of post burning flame, geometry, etc. Precise analysis of the temperature fields and fluid flow in combustion flame is extremely difficult. Instead, an analysis of the forced convection heat transfer due to the impinging jet flow is assumed to suffice in the vicinity of the glass, where the thermo-flow field controls the heat transfer from combustion flame to glass panel. To simplify computational analysis, an impinging jet flow is substituted for a combustion flame, because of difficulty in analyzing the thermo-flow field both inside and outside the flame. The input heat fluxes for compute simulations are estimated from existing heat flux data under similar condition since heat flux measurement is a complex task. The temperature distribution on a glass pane is influenced by temperature dependent such as thermal conductivities, thermal diffusivity, specific heat, density, and emissivity. The analysis of temperature distribution of a glass pane is related existing theoretical approaches. This requires that the computational results can be made dimensionless parameters so that comparison with existing analytical results. Figure 9 shows the result of analysis, indicating the temperature response profile with varied travel speed.

We also accomplished the finite element procedure for the temperature analysis with the aid of the commercial general-purpose F. E. software, I-DEAS. The I-DEAAS performs the pre- and post- processes while the developed program carries out the computation of finite element matrices based on the heat transfer equations and solution of the assembled global equations. In order to select the best set-up for an ideal temperature distribution, we will simulate various heat source configurations, moving speeds, and air-cooling or water-cooling approaches using finite element analysis. The combination of ideal temperature distribution and glass surface tension will allow the glass to melt and cool to an even, smooth surface—restoring the glass to its original transparency. Some positive results have shown that we may be able to control the temperature to desirable distribution. Fig. 10 shows computer simulation that there is a possibility to obtain an ideal temperature distribution for controlled fire polishing. In this case, a 1700^{o}C flame of 3 mm wide travel at 0.001m/s with heat flux of 1.2 W/mm^{2} can melt top layer, but the glass body still remains below 300^{o}C. The glass thickness in this figure is 9 mm, regular thickness of subway rail car glass. Temperature measurement was conducted to verify the analytical and numerical temperature simulation result by imbedding a K type thermal couple of 0.005 inch diameter in engraved on one of the matching surfaces which were snapped from a piece of glass [11]. There are some differences between experiment and simulation data, but within acceptable error in engineering sense.

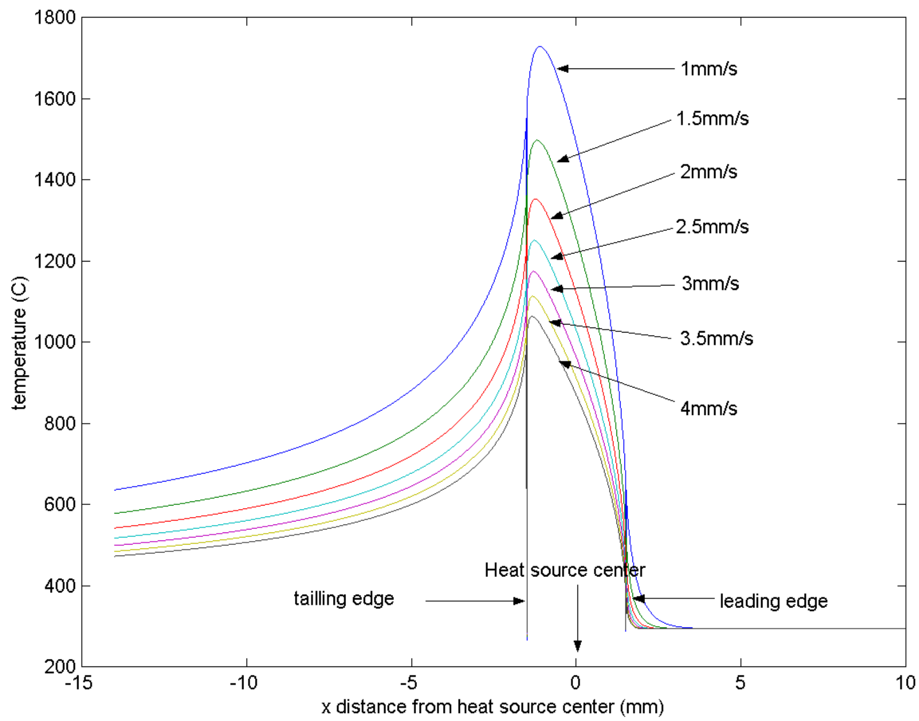
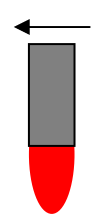


Figure 9 Surface temperature distribution along the direction of heat source motion (left to right) for source

speeds varying from 1mm/s to 4 mm/s



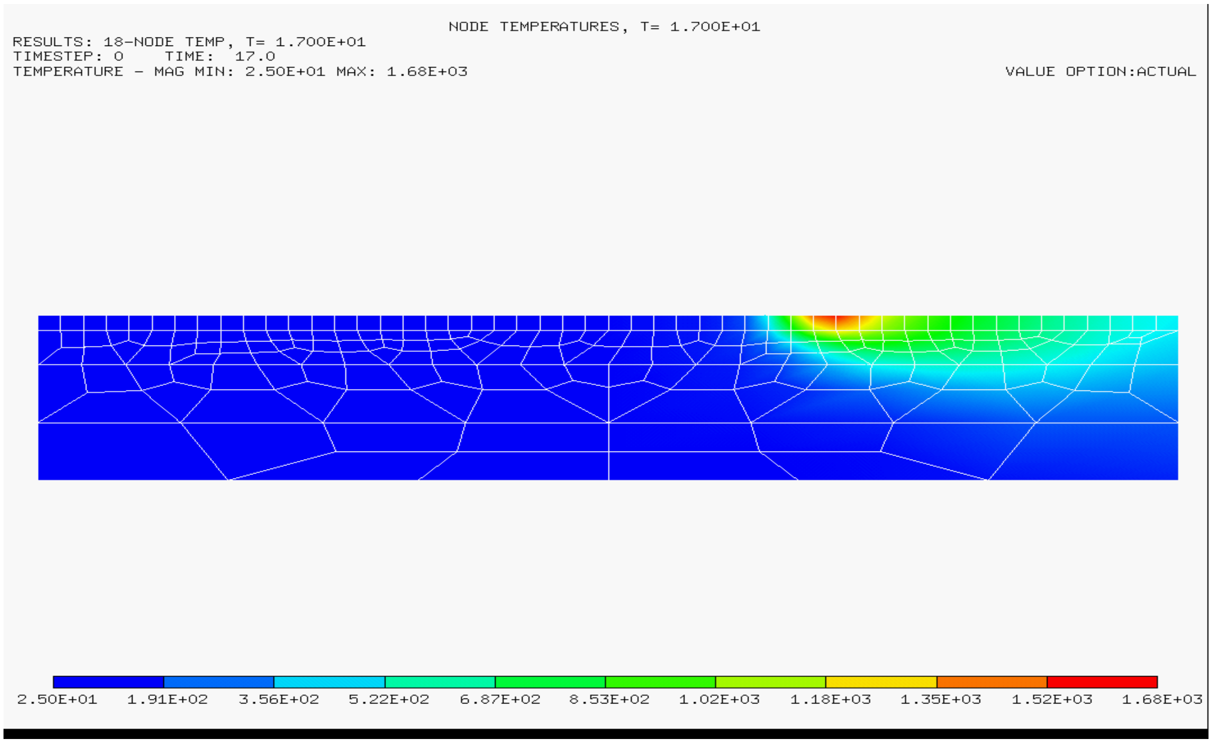


Figure10 Temperature distribution of the glass panel by finite element analysis with the working parameters of heat flux 3.1 W/mm^2, flame width 2 mm, flame temperature at surface flame 1700 ^{o}C, and travel velocity, 1mm/sec.

To avoid cracks, the internal stress within the glass panel must be controlled within the material strength. The internal stress of the glass is influenced by the temperature gradient and temperature distribution due to the thermal expansion effect. The material ability to resist cracking is also a function of temperature. Computational stress distribution can be obtained from the temperature distribution by finite element or finite difference method. To better understand the stress distribution within the glass, and to develop a strategy for cracking avoidance, various heat source arrangement, flame scanning speed, and pre-annealing or pre-warming or cooling arrangement can yield the internal stress distribution within the glass cracking strength. Combined consideration of temperature and stress distributions will provide the optimum solution for the controlled fire polishing.

3.5 DESIGN AND BUILD A PROTOTYPE SYSTEM TO DEMONSTRATE THE FEASIBILITY

Based on properties of glass, the heat source characteristics and the simulated temperature distribution pattern studies, a prototype or a simple set-up has been designed and built. Glass samples were used to test the glass graffiti removal process. The objective is to remove the etched graffiti without reducing the glass's transparency. Originally, auxiliary operations using external force such as ironing, or blowing to help the re-flow of the material at the glass surface was planed. The argument was that, when using external force, it is unnecessary to heat the glass to its melting temperature. But with the success of demonstrating the feasibility by pure fire polishing, there is no need to do so.

3.5.1 Design of the Scratchitti Removal Machine

To facilitate the controlled fire polishing approach, a simple but versatile machine has been designed and developed. Because the temperature distribution must be delicately controlled, the torch will not be handled by a human operator. Instead, the torch will be motor-driven, and its speed will be controlled electronically. Figure 11 illustrates the conceptual design of the "Scratchitti Buster" and Figure 12 is a photo of this machine in our laboratory.

This lightweight, portable machine can be positioned to the glass panel vertically or horizontally. It weights only 3.2 Kg or 7 lbs. This machine can rest on the window sash or cling to the glass pane using vacuum cups. Auxiliary support for this machine may be from an extendable leg similar to a tripod. Only the X-axis is motorized in the figure, the torch and the Y-axis is adjusted manually. A more sophisticate automation including the flame monitoring, and motion control for Y and Z-axis can be developed.

This machine uses the glass surface as reference by two reference brackets to control the distance between and flame torch and the glass surface. These reference brackets can be moved and adjusted for different locations on the X-axis linear rail to fit different size and shape of windows. The height of the bracket, 5 inches, separates the rail from the glass surface. So that the flame torch and the bracket can access the glass panel, while there is no interference between the machine rail and window frame for almost all subway cars and business and residential buildings. The bracket is designed in a way that it can slide freely along the rail external surfaces. It is locked into position by a spring-loaded lever, the top rail gripper. In use, the operator uses both hands to grasp the two brackets to hold the machine and to position the machine to where surface polishing to be performed. When relocating either bracket is needed, the operator's corresponding hand can press the lever at the other end of hinge, release the locking and slide that bracket to a new desirable location. By adjusting the two brackets distance and location, this machine can fit into different size of glass pane. The motorized slide, on which the Y-axis and the flame torch is mounted, can move between the two brackets or beyond the brackets. The X-linear rail in this particular design is 38 inches long, covers majority of the window sizes typically used in subway cars and residential houses. For extra large window size, or large glass wall such as in business buildings or glass bus shelters, this machine can be relocated to another area after treating an area.

3.5.2 Heat Source Motion Control

The motion of the slide is controlled by a small stepping motor with a wide speed range. The slower speed is for actual fire polishing process, while high speed with reciprocating motion allows the flame to pre-warm the glass panel for stress relief and heat treatment afterward. The motion control as well as the flame torch temperature control is computerized to suit different applications. For tempered glass with cracking tendency, the high-speed flame torch motion can pre-heat and warm up the glass pane so that it reaches the glass transition temperature uniformly. This process resolves the cracking issues normally encountered in treating tempered glass due to excessive thermal stress.

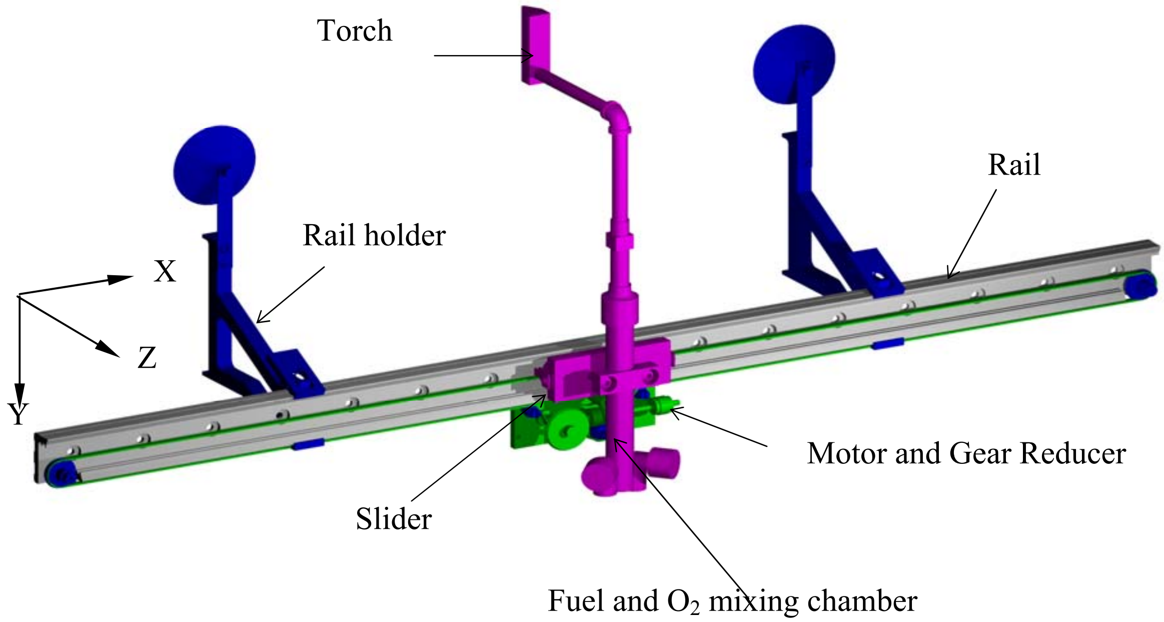


Figure 11 The design of the Scratchitti Buster

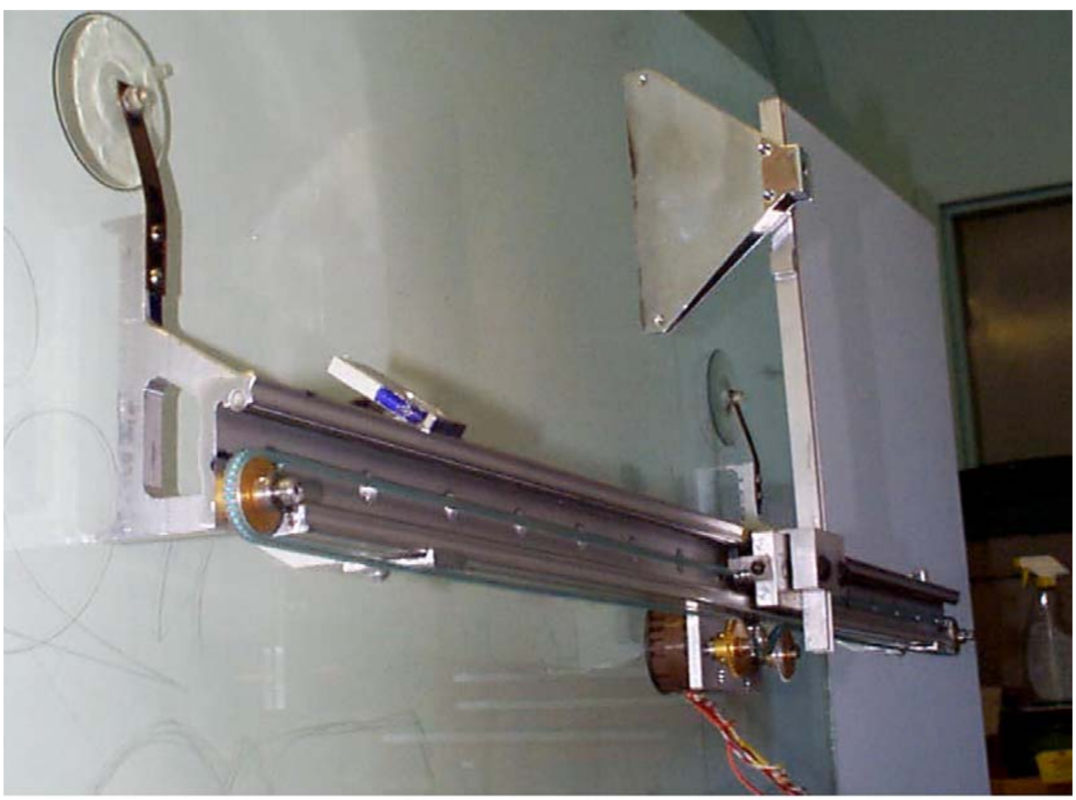


Figure 12 The photo of the scratchitti Buster as mounted on glass panel

A 24 oz-in (170 mNm) motor DC step motor (MST-D201-AFOS), with resolution of 100 steps per revolution controlled by APIMate DM-224i motor drive unit, provided the necessary power while remaining small and light enough to mount on the rail, which is enough to carry 5 lb of the torch to a certain velocity. The stepping is controlled by an intelligent drive that also has onboard memory for standalone operation. The motion speed of slider is set between 0.1 to 30 rev/s with a gear reduction ratio of 1:50. This allows a range of liner moving speeds approximately 0.1 to 30 mm/s.

3.5.3 Scratchitti Removal Experimental System

The pre-mixed propane and oxygen gases leave the tip through a small orifice and are ignited in the air, which create a flame of uniform temperature at a short distance about 0.3” from the surface of the torch. Shown in Figure 13 and 14, the fuel (either propane or acetylene) and the oxygen are supplied from the gas tanks with the regulator output pressure set to 10 psi and 20 psi respectively. The fuel and oxygen are mixed in a commercial welding torch handle, Harris Torch-MEFS-098 which is mounted on the slide of the machine. The range of fuel flow rate is approximately 1 to 8 (liter/min) and oxygen rate is 3 to 28 (liter/min), and in most of optimum combustion cases the ratio of fuel and oxygen is 3 to 3.5: 1. In order to make repeatable operation the fine flow control valve can be set for repeatability.

3.5.4 Initial Feasibility Demonstration

We have conducted an experimental evaluation of this invention; specimens of soda lime glass of 1/8 and 1/4 inches thick were scratched heavily on one surface. A flame of propane-oxygen mixture with the temperature more than 1600^{o}C was applied with a slow motion of 2 inches per minutes to the scratched specimen; the scratches on the top surface disappeared accordingly as shown in Figure 15. The sample has no distortion when the process is well controlled. The process can be done no matter whether the specimen was horizontally or vertically. The process also applied to a frosted glass specimen. The specimen became transparent. This experimental result demonstrates the feasibility of this invention.

3.6 QUALITY OF POLISHING RESULT

A successful fire polishing should not only remove the scratchitti on the glass surface, but also must meet several criteria: (1) The optical quality of glass should not be changed; (2) There should be no distortion, drips, or runs; (3) there should be no crack in the glass. The optical transparency is the key issue in glass polishing and is directly related to polishing quality. The resulting polishing quality also depends on the surface texture, the evenness of the polished glass surface, and the reformed structure of glass molecules. The parameters of the glass that yield optimal polishing results are identified.

If the polishing process is not well controlled many types of failures can occur. There are common defects in the process, including distortion of the glass panel, such as forming round edges of the glass specimen, or roughening of the glass panel surface, such as bubbles appearing on the glass surface, or cracking, still existing scratchitti, and so on. The polishing result can be divided into three categories: well-polished, under treated, and over-treated. They are defined as follows:

1. **Well-polished:** Under optimal operation condition in the fire polishing process, etches on the glass pane will be removed totally. The glass will recover its smoothness and transparency. There is neither distortion, nor cracking occurred. Figure 16 shows a heavily etched glass piece before and after a successful fire polishing process. This is the desirable result of fire polishing process. Other than this well-polished condition, the process result will not be considered as acceptable.

2. **Over-treated:** When the temperature is too high or the exposure too long, the glass is over treated. This may result in distortion of glass panel, such as forming round edges of the glass specimen or no flat glass panel surface (Fig. 17a), bubble appeared on the glass surface (Fig. 17c), severely burnt glass (Fig. 17d) and cracking when cooling (Fig. 17b).

3. **Under-treated:** Due to insufficient temperature or heating duration, the etched glass may be under-treated in the fire polishing process. It can be indicated by the full or partial existence of scratches still exist on surface of glass (Fig. 17e), crack when heating (Fig. 17 e), and reduced optical transparency and clarity (Fig. 17f).

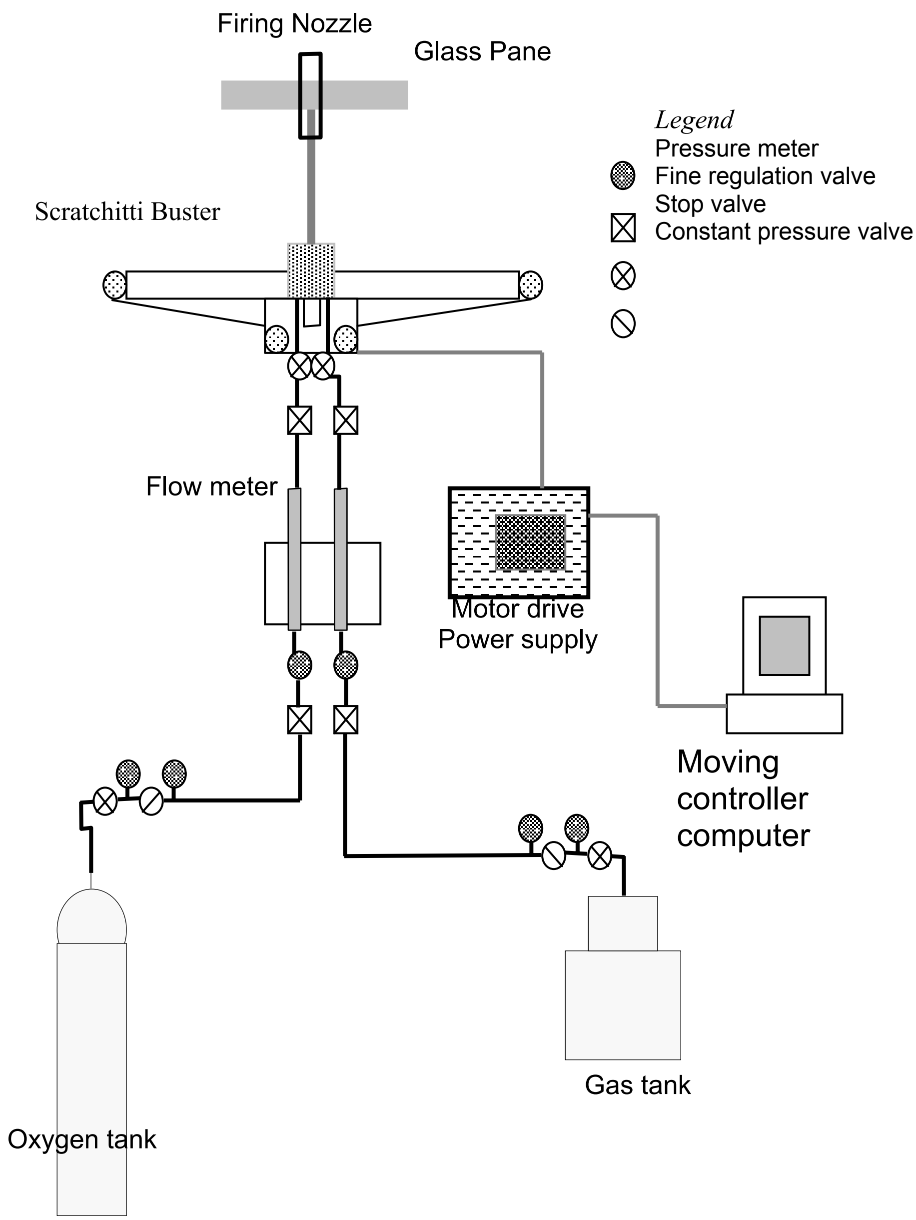


Figure 13 The schematics of the controlled fire polishing system for experiment

Figure 14 The photo of the fire polishing experiment system

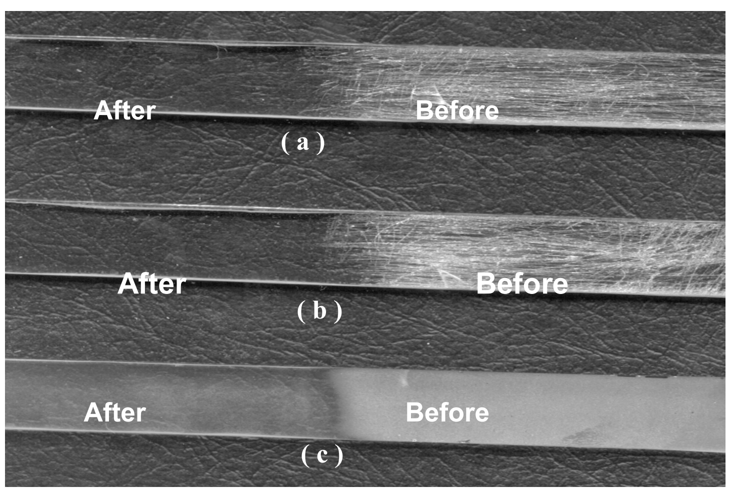
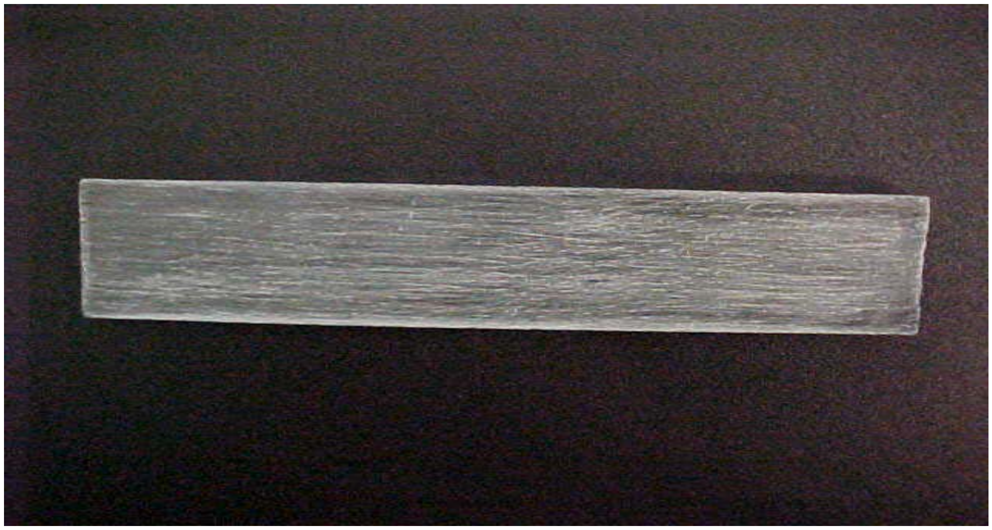


Figure 15 Initial tryout of the controlled fire polishing process yielded a result demonstrated the feasibility:

(a) and (b) Samples of heavily scratched glass (1/4 inches thick) were treated by our process to

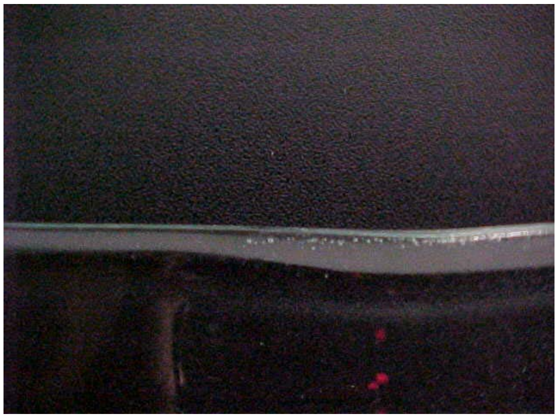
recover the transparency. (c) Sample of commercial frosted glass chemically etched (1/8 inches thick) was fire polished.



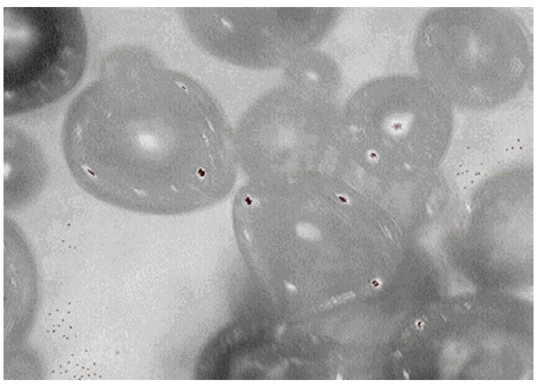
(a) Before treating

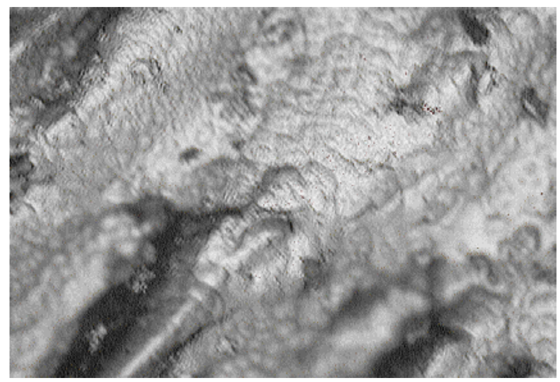
(b) After treating

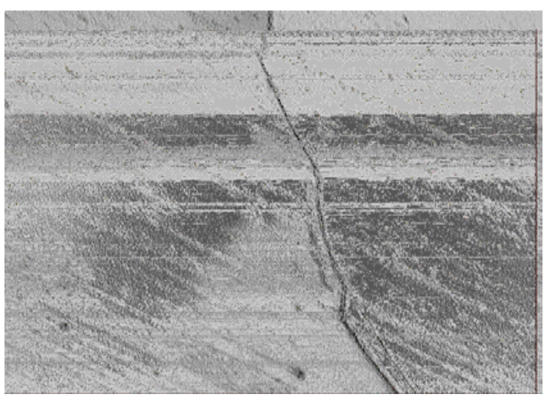
Figure 16 When well polished, the severely scratched glass piece, shown in (a), can recover the transparent state without distortion or crack shown in (b)


(a) Distortion of glass panel (6.2 l/min, 0.3mm/s)


(b) Crack occurred during cooling (6.6 l/min & 0.5mm/s)


(c) Bubbles in glass panel (6.7 l/min & 0.3mm/s)


(d) Severely burned glass surface (8.2 l/min &0.2 mm/s)


(e) Scratches still exist and with crack
(4.4 liter/min & 1.25 mm/s)


(f) Blackened scratches on glass surface
(6.0 l/min & 1.3 mm/s, mix ratio 1:2.9)

Figure 17. Common glass defects after the fire polishing (x100): (a) Distortion of glass (b) Crack occurred during cooling (c) Bubbles in glass panel (d) Severely burned glass surface (e) scratches still exist and with crack (f) Blackened scratches on glass surface. The propane flow rates and the nozzle speeds are indicated under each picture. The fuel-oxygen mix ratio is 1:3.4 for all except in (f).

Figure 18 indicates where those defective treatments occurred. By not doing the fire polishing process under those control parameters, those process defects can be avoid. Or preferably, the process should be conducted in the well-polished region for an optimum quality.

3.7 CONTROL PARAMETERS FOR SUCCESSFUL POLISHING

For a flame nozzle, the heat flux is controlled by the flow rate and mixing ratio of propane and oxygen. A specific local area of the glass is subjected to the heat flux influence for a period of time. The exposure time is a function of the flame thickness and its travel speed. In an effort to establish the operation region for successful fire polishing and scratchitti removal, a series of experiments were conducted. There are four main working parameters: (1) the flow rate of fuel gas, (2) the flow rate of oxygen, (3) The moving speed of heat source, (4) the working distance between the glass surface and torch with specified tilted angle.

Regular soda-lime glass panels were cut into specimens of ¼ inches thick, one inch wide and 4.5-6 inches long. The width of the glass was so selected that it will be covered fully by the full length of glass to avoid the flame edge effect. The glass samples were held vertically, so as the nozzle. Although it can be resolved in future advance nozzle design, the current linear flame has the tendency of higher temperature on top due to the convection effect. To compensate this, the glass is tilted a small angle, approximately 5^o. The distance between the center of the glass and the nozzle is then measured.

Figures 19-22 summarize the experiment results performed under different propane flow rates and propane-oxygen mixing ratios, and the nozzle-specimen separation, which represent the flame heat rate, and the nozzle moving speed, which controls the heat exposure time. The etched glass samples were examined about the quality of treatment after fire polishing, and were classified into one of the above three categories. In the test matrix, the chart can show the well-polished, under-treated, and over-treated regions. The testing results indicated that there is a specific region exists for optimal polishing region, which is composed of many operating parameters. In order to get optimum polishing results various operating parameters of the flow rate of propane and oxygen and the moving speed of torch have been attempted with constant working distance between the glass surface and tip.

The testing results indicated that the flow rate of gas and oxygen is close to linear relation for only specified region of operating parameters: higher flow rate of gas and oxygen which produce higher heat flux intensity requires the higher speed of torch for best polishing quality. The glass panel is placed with a tilted angle (5^o) and several working distances (0.7 ~ 2.7cm) between glass surface and torch surface. These settings are most appropriate for optimum polishing results.

Using acetylene instead of propane, the polishing speed can be much faster, approximately 6 times of that using propane. This is due to higher flame temperature produced by the reaction of acetylene and oxygen. Figures 23 and 24 shows the polishing parameter ranges that will remove scratchitti on the glass. Although acetylene can accelerate the fire polishing process, it is more difficult to handle. The control of the flame and the soot generated in the process challenge the skill of the operator.

Excessive heat treatment of glass surface such that the quality of the treated glass is unacceptable. The excessive heats can be resulted from factor such as excess flow rate of fuel and oxygen or the velocity being too slow for the polishing process. Which has been called as "over-treating". On the contrary, Usually not completely polished process, which is called "under-treating", happens in cause of either not enough heat flux intensity or too fast heat source moving speed. The defects (shown in Fig. 17) are indicated in Figure 18 where they occurred under what process parameters in the fire polishing process.

Polishing process is achieved only if the surface free energy becomes large than the energy of molecular level reorganization, however, less than required energy transferred to solid results under-treated working because not enough surface tension due to too low temperature cannot even out scratched surface, which process provide not flat surface. The boundary of interface between liquid state and solid state is too broad rather than steady formation. This causes to break down the medium of glass properties, the base of scratch layer and harm total integrity of glass panel. On the surface of glass the flat area are deformed due to irregular high-energized molecular flow, because of too much thermal energy is transferred molecular structure.

Experiments have shown that an increase in distance between the nozzle and the glass surface has a negative effect on the quality of polishing process; an increase in distance results in an increase of fuel consumption in order to produce same effect as if it were closer. In general, the surface quality of the glass after it has been processes can be more controllable if the distance is decreased. This is because an increase of distance is results turbulence effect caused by heat convection of ambient air and irregular heat flux of the flame. However, if the distance between the glass and torch is too short, the glass surface cannot be set to highest temperature region of flame and incomplete combustion may happen, which results to reduce the quality of glass polishing. Therefore, most reasonable conditions should be established with optimum distance between the glass panel and torch; which is around 1.3 to 1.6 cm. The region of operation parameter such as the flow rate of fuel and oxygen and traveling speed of heat source is identified with the distance between the glass panel and torch in comparison as shown figures.

These optimum conditions are dependent on the flow rate of fuel and oxygen and ratio of the oxygen and fuel, on which the optimum polishing conditions are dependent, because the flame temperature is determined by the flow rate and ratio of oxygen and fuel. In this study the ratio of oxygen to propane is set to 2.7 to 3.5 for operating range, however, approximately the ratio of 3.4 is best burning condition of polishing in order to achieve clean combustion and reduce soot, which is essential to optimum polishing condition. In less than this mixing ratio (~3.4) incomplete combustion happens, which produces soot, and more than this ratio the flame is blown off, because the velocity of mixture is higher than burning velocity.

The major difficulty of polishing processing is cracking phenomena and most of cracking phenomena appeared to be in state of cooling process. When a glass surface is heated by heat flux injection, the initial stress developed is compressive so that the hazards of fracture are relatively slight, but when suddenly chilled, the stresses are tensile so that the probability if fracture is increased greatly. The thermal stress on glass surface in steady state case can be expressed as follows,

$$\sigma_T = \frac{E\alpha(t - t')}{2(1 - \mu)}$$

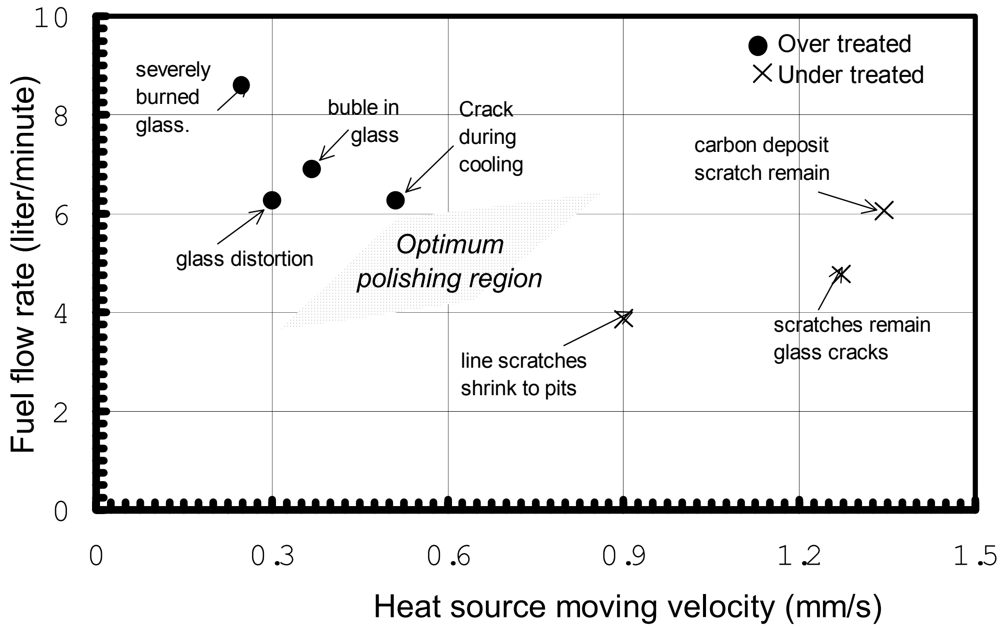


Figure 18 Common defects in fire polishing and the parameters associated with them.

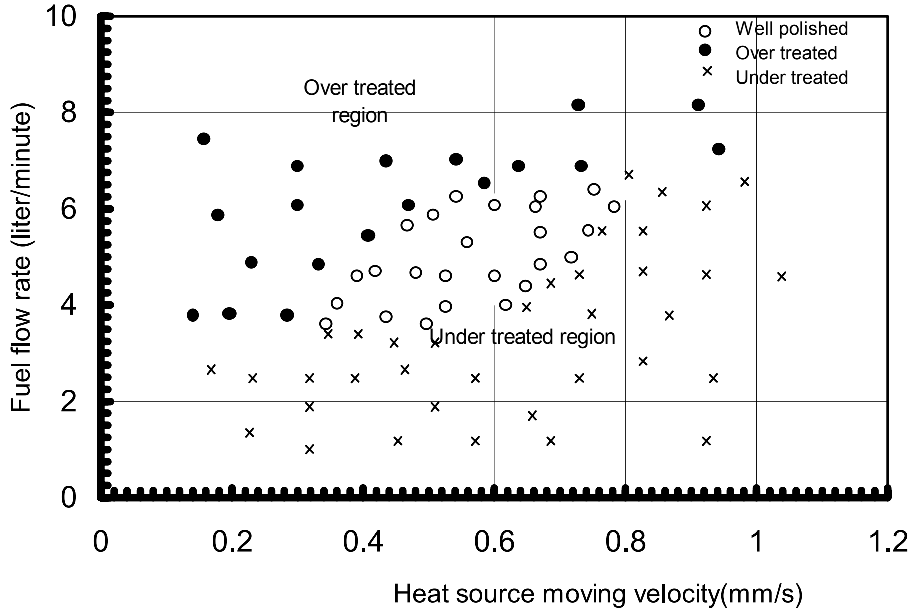


Figure 19 Result of fire polishing for scratchitti removal in terms of fuel flow rate and heat source moving speed. (Propane and oxygen mixing ratio, 1:3.4; nozzle distance, 1.3 cm)

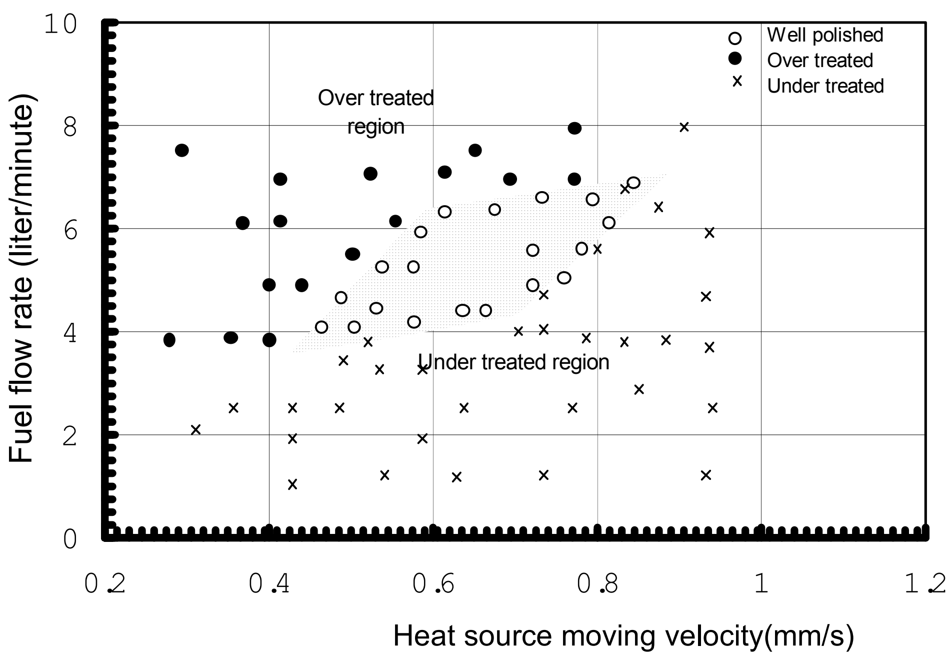


Figure 20. Result of fire polishing for scratchitti removal in terms of fuel flow rate and heat source moving speed. (Propane and oxygen mixing ratio, 1:2.9; nozzle distance, 1.1 cm)

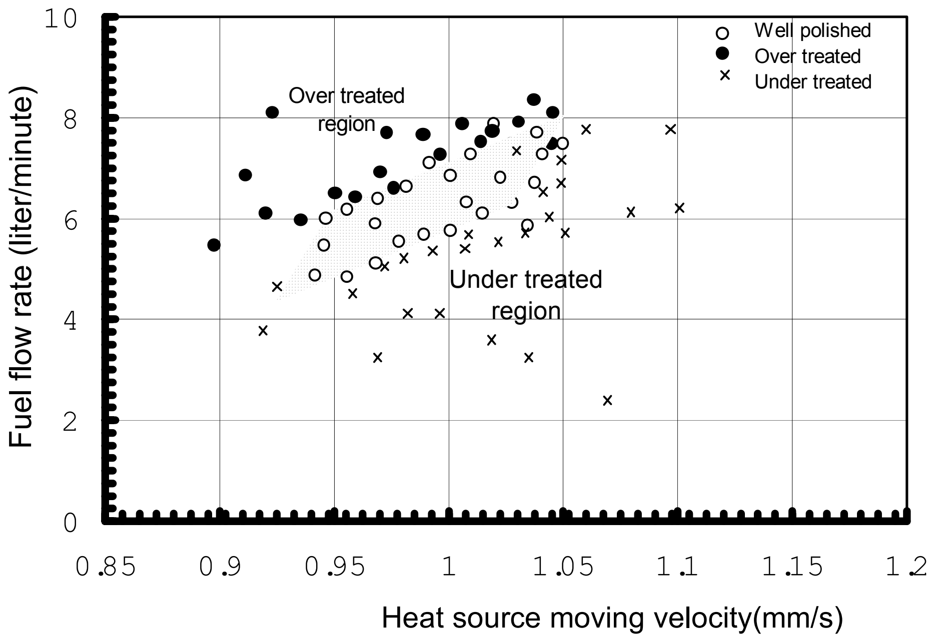


Figure 21 Result of fire polishing for scratchitti removal in terms of fuel flow rate and heat source moving speed. (Propane and oxygen mixing ratio, 1:3.9; nozzle distance, 1.0 cm)

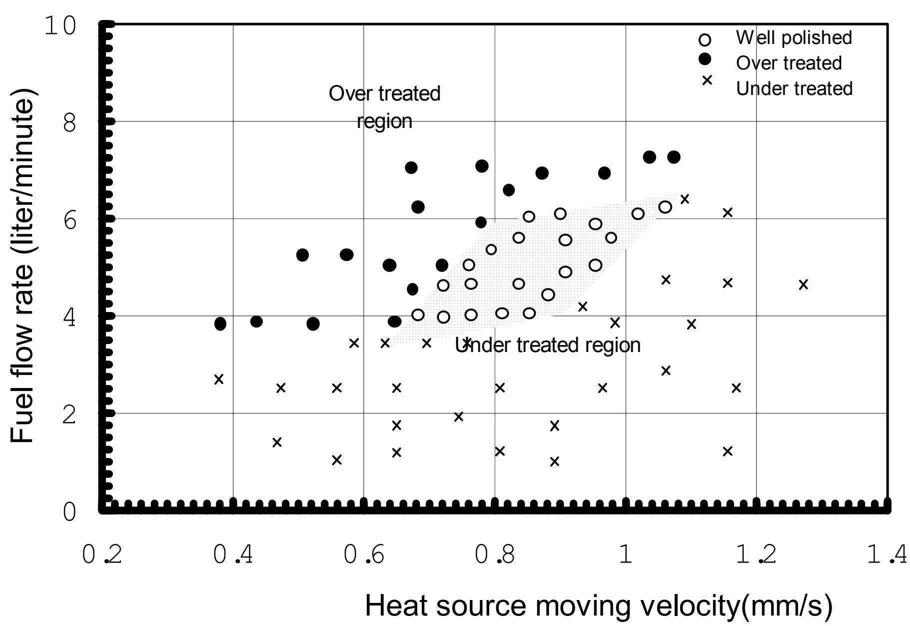


Figure 22. Result of fire polishing for scratchitti removal in terms of fuel flow rate and heat source moving speed. (Propane and oxygen mixing ratio, 1:3.3; nozzle distance, 0.9 cm)

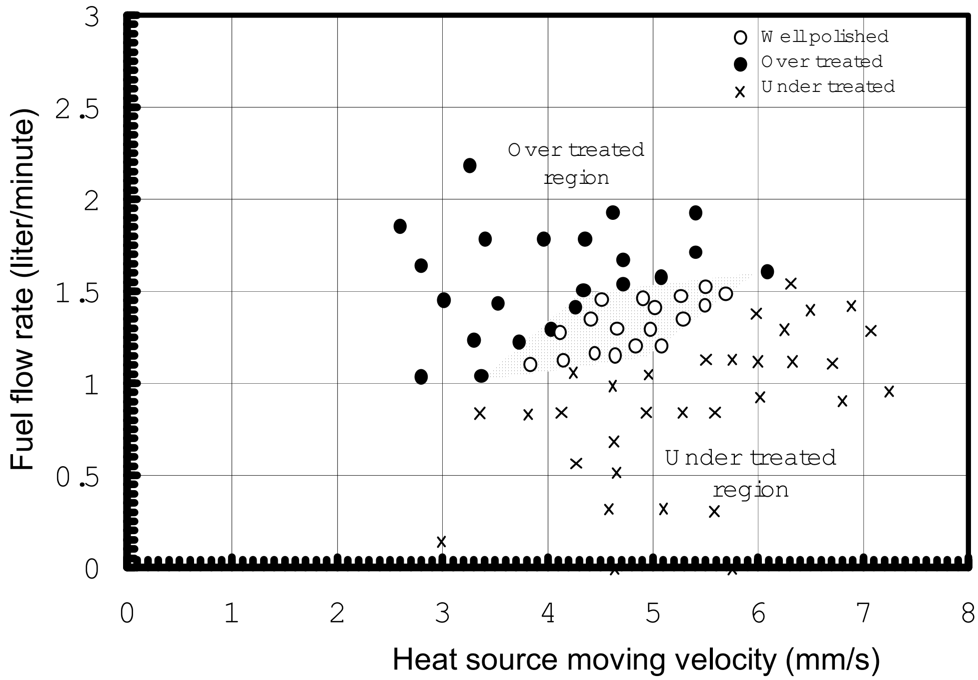


Figure 23 Result of fire polishing for scratchitti removal in terms of fuel flow rate and heat source moving speed. (Acetylene and oxygen mixing ratio, 1:1.2; nozzle distance, 5.8 cm; tilt angle 2^o)

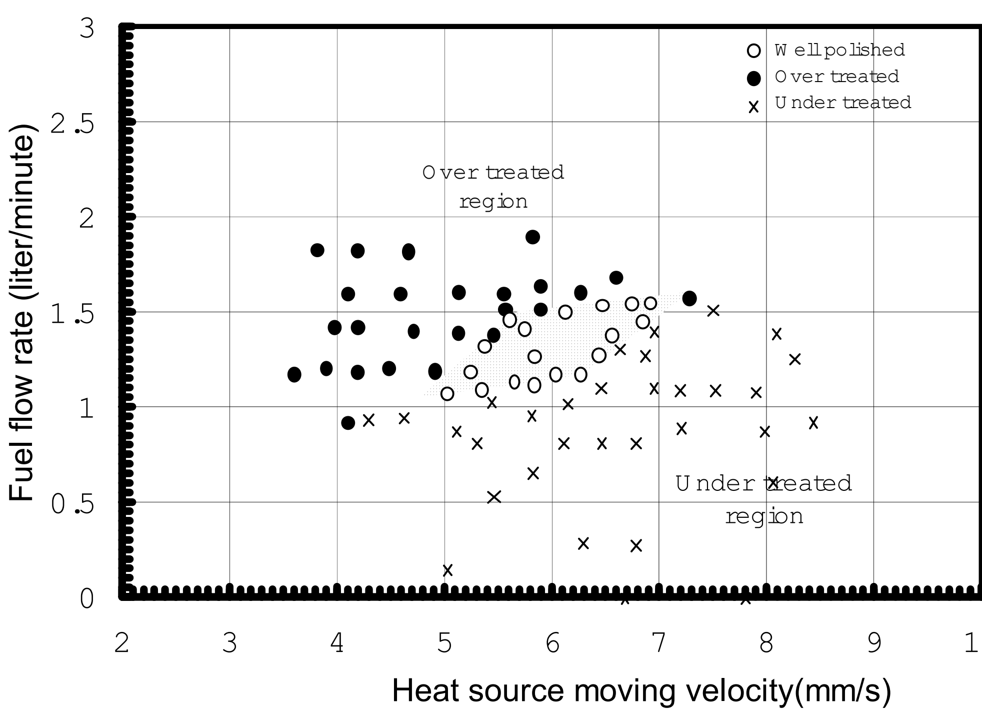


Figure 24 Result of fire polishing for scratchitti removal in terms of fuel flow rate and heat source moving speed. (Acetylene and oxygen mixing ratio, 1:1.2; nozzle distance, 3.5 cm; tilt angle 2^o)

In steady state condition, the thermal stress is proportional to the temperature differential and the coefficient of expansions of the glass but is independent of thickness. The surface stress could be about 10 kpi in case of the temperature difference of 1000^{o}C in glass properties based on the equation. However, the polishing process is absolutely transient status. So the above equation can only be treated as an approximation. The strength of soda-lime glass is approximately 9 to 14 kpi. Therefore, the crack may happen when the temperature changes between 0 to 600^{o}C.

To obtain a good polishing result, smooth thermal transition is very important. Because rapid cooling can cause severe thermal stress distribution in glass, to slow down the cooling rate, a wall backing glass pane can contain heat energy for a certain period during the polishing operations. Currently, there is some limitation regarding size of glass pane. If the size of glass pane is bigger than nozzle size, the glass is heated partially rather than uniformly. This can be address in the future nozzle design, with the end section of the nozzle progressively changing the heat intensity to prevent the high gradient of the temperature distribution and thermal stresses resulting crack propagation. Another approach, elongating the linear nozzle, not only will reduce the cracking possibility, but also boost the process productivity.

3.8 SUMMARY FROM TECHNICAL INVESTIGATION

This project presents the only economical and practical method to remove the scratchitti and to recondition the glass surface known today. The followings are the findings from this project:

- A method of controlled fire polishing that melts only a thin layer of the glass top surface to allow the material to re-flow in order to smooth the surface by the surface tension during the cooling down. This process takes place very locally so that glass maintains the strength and integrity without distortion.
- The aforementioned process is performed with a long and narrow linear heat source in a way like a wiper to clean the scratchitti in an efficient manner.
- The above linear heat source can be electric arc or laser beam, but preferred embodiment is an burner nozzle based on thin slot of burning pre-mixed oxy-fuel flow or a diffusion torch consisted of interlaid tube or channel arrays of oxygen and fuel.
- The heat source must be of intensive high temperature over the glass melting temperature, above 1200^{o}C, which is achievable by the propane-oxygen or acetylene-oxygen flame.
- A method of avoiding the crack due to thermal stress is by applying heat uniformly along a linear axis to reduce the temperature difference in that axis.
- In the other axis that the heat source moves, the heat is applied by very narrow heat source to minimize the amount of thermal expansion and to reduce the bulk glass thermal stress.
- The heating is intense in a very local area, so that the temperature of the glass material near the top surface will promptly reach and exceed the glass transition temperature T_g, therefore eliminate the internal stress may exist due to heating. The glass will not crack at temperatures above T_g.
- For tempered glass, uniform slow preheating may be applied to the glass body to release the internal stress and to reduce the cracking tendency.
- The movement of the heat source must be uniformly controlled with a speed that will create the localized heating zone reaching and exceed T_g and a thin layer of glass surface will reach the melting temperature, whereas the rest of glass body remain low temperature to retain the integrity and strength of the glass panel.
- A design of the machine, the *Scrachitti Buster*, has been developed to perform the fire polishing tasks is light, portable so that it can be relocated to the site and the glass area for the convenience of use.
- The design of the scratchitti buster has the bracket or fixture to separate itself from the glass surface at a constant distance, the distance will clear the obstacle of window frame or window recess.
- The design of the machine incorporates the vacuum cup so that the machine can cling to the glass for positioning. The reference is provided by the bracket foot-pads.
- The machine also can be positioned by sticks like a tripod legs.

- The brackets can slide on the machine X-axis by pressing the lock lever to adjust the bracket positions to fit the machine for different window size and glass treatment location.
- The speed of the machine is motorized and computer controlled so that the localized heating can attain the desired temperature distribution for the polishing process and to avoid the potential glass cracking.
- Above mentioned preheating to tempered glass may be performed by the heat source moved by the above mentioned machine in fast and reciprocating machine, and/or at more distance from the glass surface.

4. PLAN FOR TECHNOLOGY TRANSFER AND IMPLEMENTATION

4.1 Difference between Feasibility Study And Product Development

No doubt this feasibility study has cleared a few uncertainties of the application of fire polishing for transit scratchitti removal. It has proved that scratches on glass surface can be removed, while the glass is in a vertical position. In order to find the decent operating parameter, this study run the polishing tests with over 400 glass samples to identify the over-treating, under-treating, and decent treating zones. While NYCT provide some subway railcar glass panels, we do not have means to cut it into strips for the experiment. Regular soda-lime glass of the same thickness was used instead which is easy to scribe and snap into the samples sizes. The effect of glass tempering is awaiting further study in the next phase of development.

This study concludes the importance of a uniform linear heat source and well-controlled process such as the moving speed. Current nozzle is only 1.5 inch long. The sample's width is therefore can not exceed this limit. In order to treat the railcar window, a new longer nozzle with the length close to the window width need s to be developed, which will act like windshield wiper to clean the glass over a large area. In future product development, a narrower, higher intensity, and more uniform heat source will improve the quality of the polishing. And a transition heating must be provided at the two edges of the nozzle so that the nozzle can be used to treat partial area of a big glass panel to avoid glass cracking.

With limited funding and resources, this study is limited to demonstrate the feasibility of the scratchitti removal process. However, with initial success of developing a new technology for scratchitti removal, this project paves a way for starting the implementation phases.

4.2 Plan for Product Development and Field Implementation

The plan for implementation is divided into another two phases. They are described as follows.

PHASE II.

Objective:

To develop well-controlled glass graffiti removal instrument or tool based the experience from the feasibility study in this project.

In Phase II, we will develop a well-controlled instrument or tool for removing glass scratchitti, based on the results of this Phase I feasibility study. The nozzle will be refined to a mature design for field application. The longer linear nozzle to uniformly cover larger area will boost and productivity and reduce internal stress for crack avoidance. Although typically a manual operation, the moving speed of the heat source will be motorized and the heat source temperature will be well monitored and controlled during Phase II. Recognizing that skillful technicians are difficult to find and that training can be time intensive, our tool design must be operated easily. To insure quality outcomes from the scratchitti removal process; we will set the control parameters for the new tool. During this phase transit authorities in other United States cities may participate. These new partners will also be asked to share the development costs.

PHASE III.

Objective: Automation in the glass graffiti etching removal.

Because of the extent of vandalism to NYC subway rail cars, tremendous staff time is needed to restore the quality of the glass windows and doors. For continuous maintenance of the subway's appearance, it is highly desirable to have an automatic system to do this work. The system will reduce the transit staff time required to repair the glass by automatically sensing and tracing the graffiti etching grooves, and repairing the damage. This system, designed as a robot on wheels, can be moved from windows to doors, repairing the glass with minimal human intervention. This phase is to be completed in the third year.

5. CONCLUSION

This project addresses the pressing issue of vandalism on subway car windows faced by transit agencies across the country. Unlike paint or ink graffiti, the glass etchings and scratches on subway car windows cause permanent damage. Because replacing the damaged window is so time consuming and costly, transit authorities have not been able to keep up with replacing window as a solution for "scratchitti."

For example, scratchitti is so prevalent it is on windows and doors of most rail cars of New York City's (NYC)subway lines. Transit officials estimates that to run a scratch free fleet, NYCT would need to spend $60-70 million per year, replacing window glass. Scratchitti occurs not only in New York City, but in many other United States cities, and it is not limited to subways. Windows and doors (often large and expensive) of public transit buses, residential homes, and business buildings also suffer from this type of vandalism. Citing a federal study, a Philadelphia newspaper, *The Inquirer*, reported that the cleanup costs for scratchitti runs to $1 billion a year nationally.

This project offers a viable solution for glass scratchitti vandalism, benefiting all transit agencies and other property owners. To solve this problem, the investigators working on this project developed an innovative approach – controlled fire polishing, which incorporates a technique of localized softening and surface tension. Intensive heat is positioned near the scratch marks on the glass panel. The heat melts a thin layer of glass to liquid, changing the glass's viscosity to a formable state. The glass is melted to a level close to the depth of the scratch, and allowed to cool down naturally. During the cooling process, the surface tension of the melted glass evens out the scratching indent. After cooling and without grinding or polishing it, the glass is as even and smooth as it was originally. In this process, the glass remains solid and structurally sound during this operation to prevent any distortion of the glass panel, except where thin and small scratched surface are being repaired.

To facilitate the smooth operation, a uniform, linear, narrow, and high temperature flame as the heat source provides a cost effective tool for fire polishing. The machine we designated *Scratchitti Buster*, is a motor driven slider controlled by a computer to move the nozzle at a constant speed during the polishing process. Light and portable, this machine has suction cups to cling to the glass panel for positioning. It uses the glass surface as reference by a pair of brackets so that the nozzle will keep a constant distance while moving. They are adjustable to fit the machine with different sizes of windows. Oxy-fuel used can be acetylene-oxygen for high speed fire polishing or propane-oxygen for convenient and easy operation.

The desirable temperature distribution enables the glass surface to re-flow and remove etches, while preventing glass distortion and cracking. Experimental testing of the fire polishing process was performed, and the feasibility of the process was demonstrated by glass samples that recover from heavy scratches to a smooth, clear and transparent state. The ranges of optimum operating parameters for high polishing quality have been identified through a range of testing conditions. Common defects of the glass polishing were investigated and their causes due to improper control operating parameters was located and fixed.

The results from this Transit IDEA project have successfully demonstrated the feasibility of this process, and produced important information for final product design in commercialization stages. It is ready to move onto development.

6. PROFILE OF THE PRINCIPAL INVESTIGATOR

Dr. Shane Y. Hong

Professor of Mechanical Engineering,

Columbia University,

500 W. 120th St., Room 234

New York, NY 10027
Tel: (212) 854-2957
Fax: (212) 854-3304
E-mail: sh295@columbia.edu

Dr. Shane Y. Hong joined Columbia University faculty as a full professor of mechanical engineering in 1996. He received his BS degree from National Taiwan University and his MS and Ph.D. degrees from University of Wisconsin, Madison, in 1975, 1981, and 1982, respectively.

He was an associate professor at Wright State University during 1990-1996, where he established the Center for Industrial Quality and Productivity, leading a consortium of 12 renowned companies in the development of economical cryogenic machining technology. His invention of the environmentally safe metal cutting process offers longer tool life, better product quality, higher productivity, and lower cost than conventional emulsion coolant method. His technology was subsequently licensed to Air Products and Chemicals, Inc. for full-scale commercialization.

Prior to his academic career, he was a member of the research staff at Bell Laboratories, where he joined the team developing ultra-high precision electron beam lithography system for VLSI processing, then lead the development of atomic force microscope for nanometer resolution 3-D metrology. During 1983-1985, he was a member of research staff of Western Electric's Engineering Research Center (currently called Lucent Technology), where he developed industrial robot systems and advanced automatic systems for manufacturing and inspection.

During his graduate study at University of Wisconsin, 1979-1982, Dr. Hong invented a versatile and intelligent machine, the Robotic Drilling Unit. The machine and the associated metal cutting sensing technology has been commercialized by a Dallas company and used in aerospace and automobile industries. It also won him a mechanical design award and made his Ph.D. dissertation one of the most sought after dissertations sold by University Microfilm Inc., Ann Arbor, Michigan.

Before he came to the United States in 1979, he already had a reputation for technological inventions. He won many award such as Dr. Yet-sen Sun National Technological Invention Award, Golden Brain Invention Award, CTS Young Inventor's Award, and was selected as one of the Ten Outstanding Young Men of the Republic of China. During 1977-1979, he engaged in military weapon research at Precision Gyro Plant in Chungshan Institute of Science & Technology, successfully led the development of two types of servo accelerometer for inertial guidance.

His creativity and research have won him more than 11 patents and over 50 technical papers in journals and conference proceedings and numerous proprietary technical reports.

7. REFERENCES

1. *Kirk-Othmer Encyclopedia of Chemical Technology*, “Lamination Process”, v. 14, 4th ed., ed. Howe-Grant, M. Wiley 1995.
2. “Vynil Acetal Polymers”, *Encyclopedia of Polymer Science and Engineering*, v.17, Wiley 1995.
3. Doremus, R.H. *Glass Science*. 2nd ed., Wiley, New York 1994
4. Kirillin et. al. *Engineering Thermodynamics*, trans. Semyonov, Mir Publishers, Moscow 1976.
5. Scholze, H. *Glass.* Transl. Lakin, M.J. Springer-Verlag, New York, 1991.
6. BTU Contracts, Inc. website www.btucontracts.com. Last access 2/15/00
7. Davies, A.C., *the Science and Practice of Welding*, 7th ed., Cambridge University Press, New York 1977.
8. Gerstein, et. al. “Fundamental Flame Velocities. I – Alkanes, Alkenes, Alkynes, Benzene, and Cyclohexane,” NACA Research Memorandum E50G24, NACA, Washington 1950
9. Levine, Gerstein. “Fundametal Flame Velocities. III- Acetylene” NACA RM E51J05, NACA, Washington, 1951
10. Fristrom, R. M. *Flame Structure and Processes*, Oxford University Press, New York 1995.
11. Seong-chan Jun, “Controlled Fire Polishing for Scratchitti Removal and Glass Resurfacing”, Ph.D. dissertation, Columbia University, 2002. P. 176-183

APPENDIX A: Preliminary Economic Analysis of Controlled Fire Polishing for Scratchitti Removal

Gas Consumption and Cost Estimation for Controlled Fire Polishing Process

Shane Y. Hong,
3.8.02

ESTIMATION OF GAS CONSUMPTION PER SQUARE METER

BASIS OF ANALYSIS

Glass surface area for controlled fire polishing	A (m^2)	1
Scratchitti depth	d(mm)	0.127
Thickness of glass layer to be melt on the surface	t(mm)	0.15
Volume needed to heat up to 1600^{O}C for 1 m^2 coverage	V(m^3)=A t	0.00015
Density of glass	r(g/cm^3)	2.3
Mass of glass to be melt	m(g)	345

Estimation by heat needed to melt the thin layer of glass surface:

Energy needed: dQ = m x C x (Ti-T)

Temperature T(^{o}C)	Specific heat C(J/K*g)	Heat needed dQ (J/m^2)
25	0.49513314	
100	1.689235492	12,812
200	2.834482742	58,279
300	3.649453247	97,790
400	4.250004783	125,906
500	4.705302549	146,625
600	5.058709271	162,333
700	5.338531348	174,525
800	5.563883764	184,179
900	5.748052701	191,954
1000	5.900505651	198,308
1100	6.028136852	203,567
1200	6.136063307	207,971
1300	6.228147634	211,694
1400	6.307349846	214,871
1500	6.375969183	217,604
1600	6.435813579	219,971
Total energy needed: H(J)		**2,628,389**

Estimation of the energy based on the heat flux needed to create the necessary temperature distribution profile in the finite element analysis of controlled fire polishing

Simulation data:	Option 1(C_3H_8)	Option 2(C_3H_8)	Option 3(C_2H_2)
Flame width, w (mm)	300	600	600
Flame thickness, t (mm)	3	6	5
Heat flux, Q (W/mm^2)	1.20	1.20	2.7
Flame moving speed, v (mm/s)	1	2	6
Time to treat 1 m^2 glass area, T (min.) T = A / (w x v)	56	14	4.6
Total energy consumption, H (J), H = Q x t x w xT	3,600,000	3,600,000	2,235,600

Theoretical Heat Requirement (the lager of the above two H's): 3,600,000 Joules

Heat Provided by Combustion of Propane with Oxygen

$C_3H_8+5O_2=3CO_2+4H_2O$

Heating value for propane, q(MJ/m^3):	94
q (kJ/kg)	46348
***Assume overall heating efficiency	50%
Amount of Propane needed Vp (m^3), V_p = H /q/50%,	0.08
Volume ratio between propane and oxygen=1:5	
Amount of oxygen needed Vo (m^3), Vo_2 =5Vp	0.38

Heat Provided by Combustion of Acetylene with Oxygen

$C_2H_2 + 2.5\ O_2 = 2\ CO_2 + H_2O$

Heating value for acetylene, q(MJ/m^3):	58
q (kJ/kg)	46348
***Assume overall heating efficiency	50%
Amount of acetylene needed Vp (m^3), V_p = H /q/50%,	0.062
Volume ratio between propane and oxygen=1:2.5	
Amount of oxygen needed Vo (m^3), Vo_2 =5Vp	0.16

Gas Pricing Information (*All-weld Products 914-592-3320)

Propane:in 20 lbs(9.07Kg) container $		$16.00
C_3H_8	$C_p$unit price per m^3	$1.76
	unit price per Kg	$1.76
Oxygen: in 244 ft^3 (10 kg)container $		$26.00
O_2	C_{o2}, unit price per m^3	$3.76
	unit price per Kg.	$2.60
Acetylene 40cft = 1.1m^3		$16.50
C_2H_2	C_a unit price per m^3	$14.56
	unit price per kg	$12.62

Cost of Gases for fire polishing 1 m^2 glass surface

Propane

Fuel cost, Cp ($/ m^2), $Cp = Vp \times c_p$	$0.14
Oxygen cost, Co_2 ($/ m^2), $Co_2 = Vo_2 \times c_{o2}$	$1.45

Acetylene

Fuel cost, C_e ($/ m^2), $C_e = V_e \times c_e$	$0.90
Oxygen cost, Co_2 ($/ m^2), $Co_2 = Vo_2 \times c_{o2}$	$0.58

Total cost for propane and oxygen usage to treat 1 square meter of glass: $1.58
Total cost for acetylene and oxygen usage to treat 1 square meter of glass: $1.49

Labor cost for treating 1 m^2 glass surface

Assume labor cost per hour C_{labor} : $20/hr

	Option 1	Option 2	Option 3
Time to treat 1 m^2 glass area, T (min.)	56	14	4.6
Labor cost to treat 1 m^2 , C_{labor}	$18.67	$4.67	$1.53
Depreciation of the equipment cost, C_e	$0.78	$0.78	$0.78

Total cost of treating 1 m^2 glass surface, C		($/$m^2$)		
Propane	$C_{total} = C_{labor} + C_{gas} + C_e$	$21.03	$7.03	
Acetylene	$C_{total} = C_{labor} + C_{gas} + C_e$			$2.31

Alternative approach by replace a new glass panel

New glass cost per $m^{2,}$ c_{glass} ($\$/m^2$) (43.76 Euro, or 84.50 Fr.)	$40.70
Time for labor to replace the glass (min)	15.00
Labor cost to replace the glass, C_{labor}	$5.00
Total cost if replace by a new glass	**$45.70**

Bus Shelter Glass Case Study:

The Bus Sheter in New York City: Five glass panels (two for posters on short wall, three for the long wall)
Panel size: Height, 6ft (1.828 m), Width, 4 ft (1.219 m).
Panel area: m^2 2.23

Propane

Vandal ratio percent area	Area to be treated (m^2)	Cost of Polishing Option 1 ($)	Cost of Polishing Option 2 ($)	Cost if replacement ($)
10%	0.22	$4.69	$1.57	$101.90
20%	0.45	$9.38	$3.14	$101.90
30%	0.67	$14.07	$4.70	$101.90
40%	0.89	$18.76	$6.27	$101.90
50%	1.12	$23.45	$7.84	$101.90
60%	1.34	$28.14	$9.41	$101.90
70%	1.56	$32.83	$10.97	$101.90
80%	1.78	$37.52	$12.54	$101.90
90%	2.01	$42.21	$14.11	$101.90
100%	2.23	$46.90	$15.68	$101.90

Acetylene

Vandal ratio percent area	Area to be treated (m^2)	Cost of Polishing Option 3 ($)	Cost of Polishing	Cost if replacement ($)
10%	0.22	$0.52		$0.00
20%	0.45	$1.03		$101.90
30%	0.67	$1.55		$101.90
40%	0.89	$2.06		$101.90
50%	1.12	$2.58		$101.90
60%	1.34	$3.09		$101.90
70%	1.56	$3.61		$101.90
80%	1.78	$4.12		$101.90
90%	2.01	$4.64		$101.90
100%	2.23	$5.15		$101.90

Equipment Cost

Nozzle		$200.00
Nozzle mount		$50.00
Fuel gas supply system		$2,000.00
Sensing and control system		$1,000.00
Motion generator, Mechanical System		$2,000.00
Motor control	$400	
motor	$100	
rail	$100	
slider	$100	
gears/cable	$300	
power supply	$100	
Subtotal	$1,100	
Total cost		**$5,200.00**

APPENDIX B: Project Review with New York City Transit Representatives

Mr. Keith Falk, Director, Car System Engineering, Service Delivery-Car Equipment, of New York City is watching the scratchitti removal by fire polishing process in Dr. Hong's laboratory in Columbia University on March 7, 2002

Visitors from NYCT, Mr. Falk and Mr. Chow, watched the fire polishing demo while graduate student Seongchan Jun and Paul Leung at side. 3/7/02