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AN EXPERIMENTAL INVESTIGATION OF GLASS BREAKAGE IN COMPARTMENT FIRES

Michael J. Skelly

Virginia Polytechnic Institute
and State University
Blacksburg, VA 24061

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Center for Fire Research
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Notice

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AN EXPERIMENTAL INVESTIGATION OF GLASS BREAKAGE IN COMPARTMENT FIRES

by

Michael J. Skelly

Thesis submitted to the Graduate Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
Mechanical Engineering

APPROVED:

Richard J. Roby, Chairman

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by

Michael J. Skelly
Committee Chairman: Richard J. Roby
Mechanical Engineering

(ABSTRACT)

An experimental investigation has been completed which studied the breaking of window glass by fire. The experiments were carried out in a specially designed compartment to achieve two-layer flows characteristic of normal building fires. The experimental data was collected from two test groups: the first for windows with their edges insulated from the fire (edge-protected) and the second for windows uniformly heated by the fire (edge-unprotected).

The results of the edge-protected window tests indicated that the glass breakage was caused by a critical temperature difference between the central heated portion of the pane and the glass edge. The experimental work showed the critical value to be approximately 90C. After the material properties of the glass were determined, the theoretical findings of Keski-Rahkonen were used to obtain a value of 70C; the difference attributed to radiative heating. The test results also demonstrated a distinctive loss of integrity by the windows. When breakage occurred, the cracks spread throughout the glass, joined together and caused at least partial collapse of the pane.

The results from the edge-unprotected window tests were quite different. There were relatively few cracks developed and almost no propagation across the glass. Consequently, there was no window collapse in any of these cases. The breakage did initiate at a consistent glass temperature value, however, the mechanism for these tests is not known.

ACKNOWLEDGEMENTS

My first and heartiest note of thanks goes to Dr. Richard J. Roby, my thesis advisor. To anyone who knows him though, he's just Rick. His easy-going attitude and sincere interest in getting to know his students, not to mention his mastery of combustion, makes him one of the university's best. His encouragement in certain matters was greatly appreciated by me.

I would also like to thank some of Tech's other fine people. I am especially grateful to Ms. Willie Hylton for her tireless efforts in ordering all of the equipment that I needed. Johnny Cox and his men, especially Shorty, were just as invaluable. Their work was always of the highest quality.

And of course, I would like to thank the graduate students that I had the good fortune to work with. Foremost among them is Dan Gottuk. We worked together to set up the combustion lab and now the project is in his competent hands. Dave Foss, Andrew Hamer and Doug Wirth have gone before me but were very good company while they were here. The airport men, Scott Stouffer and Ted Anderson, always made the office a little more lively (and crowded) whenever they decided to come in. And I am glad to have known, even for such a short time, Rik (not Rick) Johnson and Linda Blevins. I wish you all the best of success.

Finally, I would like to acknowledge the support of the Center for Fire Research of the National Institute of Standards and Technology under Grant No. 60NANB8DO829; scientific officer, Henry Mitler. Without the Center's support, this contribution to Fire Research would not have been possible.

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NOMENCLATURE

σ_y	Tensile strength of the glass
E	Modulus of elasticity for the glass
ß	Glass coefficient of linear thermal expansion
T_∞	Heated glass temperature
T_o	Measured insulated edge temperature
f	Crack length
T_f	Glass temperature at inner edge of crack
T_o	Glass temperature at outer edge of crack
M_o	Initial moment before crack occurs
P_o	Initial normal force before crack occurs
σ_x	Normal stress on top of edge beam
τ_{xy}	Shear stress on top of edge beam
P	Normal force on edge beam section
V	Beam section shear
ν	$= [\ 3*G / \kappa*E*f^2\ ]^{1/2}$
G	Glass Shear Modulus
κ	thermal conductivity of glass
delt	distance from the edge to the thermocouple
h	convection coefficient
T_o	thermocouple temperature
Ta	air temperature
Te	true edge temperature

1. INTRODUCTION

1.1 Background

The most recent U.S. fire loss statistics, compiled for the year 1987, describe a compelling need for engineering advancement in the field of fire science: The 2.3 million fires responded to by public fire departments in that year killed 5,810 civilians and 126 firefighters, injured 28,215 civilians and created 7.2 billion dollars in property losses [1]. This thesis addresses one seriously neglected aspect of fire science: the prediction of window glass breakage by fire.

The breaking of window glass during a fire is significant in that the new wall openings produced, provide an inlet for fresh air and an exit for the hot fire gases. The increased ventilation changes the equivalence ratio for the system and consequently the composition of the escaping combustion gases. These hot gases serve to spread fire throughout a structure, contributing to the staggering property losses suffered each year. Also, the gases themselves are a major cause of fire fatalities because, according to the U.S. Consumer Products Safety Commission, more than half of the people who die in building fires in the U.S. each year are killed by the toxic products from the combustion and not the flames or the high temperatures [2]. A systematic study in the United Kingdom between 1976 and 1982 [3] of the results of autopsies of fire victims and a similar study in Maryland [4] have shown that a majority of the deaths occurred because the smoke and fumes released by the fire disabled the victim, preventing flight from contact with the flames and high temperatures.

Regarding the lack of study addressed to the problem of window failure in fires, Howard Emmons observed in his paper ,"The Needed Fire Science" in the First International Symposium on Fire Safety Science [5], that the only work on the subject to date was an experimental project conducted by two Harvard University students in 1977 [6].

Since Emmons' 1986 paper, there have been three theoretical papers published on glass breaking in fires [7-9]. However, no experimental studies in actual fire conditions have been reported in the literature. The purpose of this thesis is to present experimental data for window glass breakage in a compartment fire and test the previous experimental and theoretical developments against these new results. The experimental data was collected from two test groups: the first for windows with their edges insulated from the fire (edge-protected) and the second for windows uniformly heated by the fire (edge-unprotected). Therefore, a thorough review of the earlier work is presented here along with an assessment of the need for this research in the fire engineering developments taking place today. First, however, the general characteristics of compartment fires are reviewed.

1.2 Compartment Fire Fundamentals

When a solid or liquid fuel is burned, flammable gases are produced and continue to burn directly above the fuel. The less reactive gases produced from this combustion rise in a plume and form a hot layer at the top of the enclosure. If the fire continues, stoked by entrained air, the layer is fed and the depth increases until a ventilation opening such as a door or window is encountered. The hot layer gases will flow out the opening driven by bouyancy and pressure inside the enclosure and regulated by the plume air entrainment rate below the hot layer. The depth and chemical composition of the hot layer in the enclosure are determined by the vent flow dynamics, the layer temperature, the air entrainment rate, and the rate of production and nature of the combustion products.

When more than the stoichiometric amount of air is entrained into the compartment, complete combustion of the fuel will take place. However, when insufficient air is entrained, the combustion will be incomplete, the yields of carbon monoxide (CO) and carbon dioxide (CO_2) will increase and potentially flammable gases will be fed to the hot layer. If the flammable gas concentrations rise high enough, the layer will burn. The onset of layer burning has been taken to be the definition of "flashover" [10]. The fire is now ventilation controlled as opposed to fuel controlled and has undergone a transition from a localized condition to a general conflagration where the flames pass out the ventilation openings. A condition of "flameover" is reached when the compartment becomes fully involved with flame until all the fuel surfaces are burning [10]. This can occur through normal flame spread, or either piloted or spontaneous ignition. However, the additional heat release from flashover can also enhance flame spread and burning rate to cause flameover.

1.3 Earlier Developments

This thesis examines the surface temperature conditions under which window glass will break during a room fire. Edge-protected and edge-exposed windows were installed in a compartment and tested during a fire to check the theory that the windows break at relatively low temperatures when a specific temperature difference between the center and edge surfaces is reached. Also, the manner in which the windows broke was studied. These two areas have been studied both theoretically [7-9] and experimentally [6] with the similar conclusion that edge-protected windows will be affected differently in fire conditions than edge-unprotected windows.

The three theoretical papers referred to above all are concerned with the mechanism of glass breakage. The most comprehensive of the three is the paper by Keski-Rahkonen [7]. This study used the heat conduction equation with linearized radiation boundary conditions to calculate the thermal field in an edge-protected window pane that was heated by fire. The temperature field was then used to determine the thermal stress field in the pane. These results indicated that the stresses were proportional to the difference between the average and local temperatures. Keski-Rahkonen generalized his stress results at the pane edge since this is where the maximum temperature difference occurs. His work indicates that the stress at the edge is very close to:

$$\sigma_y = E\beta(T_\infty - T_o) \qquad [1.1]$$

where:

σ_y	is the normal failure stress
E	is Young's Modulus
β	is the coefficient of linear thermal expansion
T_∞	is the heated glass temperature
T_o	is the insulated edge temperature

He obtained a rough value for the breakpoint temperature difference of soda glass, taking for maximum tensile stress σ_y = 50 MPa, linear thermal expansion coefficient $\beta = 8 \cdot 10^{-6} C^{-1}$ and Young's Modulus E = 80 GPa, which yield $T_\infty - T_o$ = 80C.

Emmons, in his paper reviewing the work done on glass breakage by fire [8], provides a simpler derivation of the above formula: the central part of a glass plate heated from temperature T_o to T_∞ will expand by $\varepsilon = \beta\Delta T$. A narrow strip of cool edge must expand equally if it is to remain attached. However, the cool edge expansion is produced by a normal stress σ_y rather than by the temperature, thus the normal stress is equal to the expansion multiplied by Young's Modulus. The glass edge, where the original glass sheet was cut to fit the frame, contains irregularities which cause a crack to start at a tension lower than the normal breaking stress for the rest of the glass.

In the third of the three theoretical papers [9], Pagni explains the Edge-protected window breakage phenomenon with an analogy:

> A window breaks in a fire for the same reason that an ice cube cracks when placed in a liquid. Thermal expansion places the cooler portion in tension. The exposed window heats and expands placing its cooler shaded edge in tension until it cracks at a small defect, usually at the top inner edge.

The formulations that Pagni develops to estimate the glass temperature difference at breakage are the same as those in Emmons work and are equivalent to the simplified version of Keski-Rahkonen's heat conduction equation. However, because Pagni uses slightly different material constants, he obtains a temperature difference at breakage of 58K. Pagni also relates the results of a fracture mechanics computer simulation test of this theory. A two-dimensional unsteady version of this problem was run on a Cray computer with the resultant temperature difference obtained of 60K with the same property values. Pagni assumes that the 2K increase in the window temperature difference at fracture is due to conduction into the cooler edge region.

There have been two important studies done concerning window glass breakage patterns. The first was an experimental study done by two Harvard University seniors P.K. Barth and H.T. Sung in 1977 [6]. They heated glass plates using a radiation panel. The plate sizes were varied (6"x7" or 6" square) as were the heating conditions. Uniformly heated plates sometimes did not break at all, while when they did break, the break always started at the edge [9]. Some of the plates had definite surface scratches, but in no instance did the fractures follow these scratches, or originate there. The original crack often bifurcated (split into two diverging cracks) at a distance away from the edge (usually 1 cm or more). In the case of uniform heating, there was never more than one bifurcation.

In the case of nonuniform heating, the results were quite different. In these experiments, where the glass edge was shaded by a mask, the plates broke in every test. As with the uniform heating, all of the cracks originated at the edge (usually on the top or bottom), however, multiple bifurcations were the rule as the original fracture split within 1 cm of the edge and each of the new breaks soon split, resulting in five or more cracks. This type of break pattern was important because the cracks moved through the glass and joined together, causing the window to collapse.

In the second study concerning window glass breakage patterns, Emmons considered crack growth as distinct from its initiation, suggesting a cause for the multiple cracks [8]. His solution analyzes the edge crack using beam theory.

Emmons considers a crack starting at the edge of a glass plate (Fig. 1) and growing along y = constant. As the crack grows, the σ_y tension is relieved and after advancing a distance.f, a beam is produced as shown. The beam is at a temperature of T_f along its inner edge and T_o along the outer edge. Initially, the beam has a resultant moment M_o and a normal force P_o due to the σ_y stress distribution. However, after the crack forms and the beam is cut loose (Fig 2), the moment and the force are removed from the cracked end. Just before the beam is cut loose, however, and after the crack has removed the stress, the beam is held in place by tension σ_x and shear τ_{xy} forces on the inner edge of the beam. Since these forces both increase as the crack advances and the σ_y stresses decrease, the crack is more likely to bifurcate than advance in the original direction.

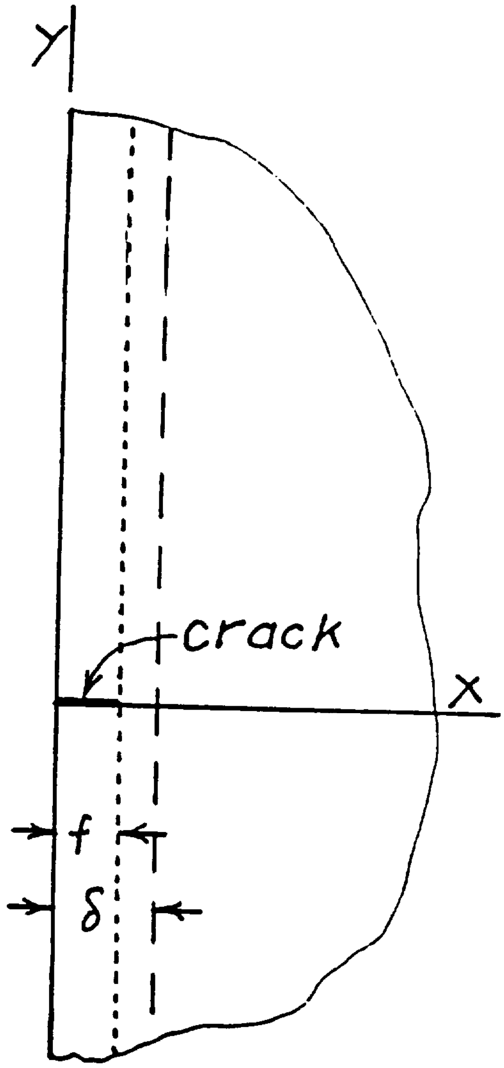


Figure 1. Edge Beam Representation [10]

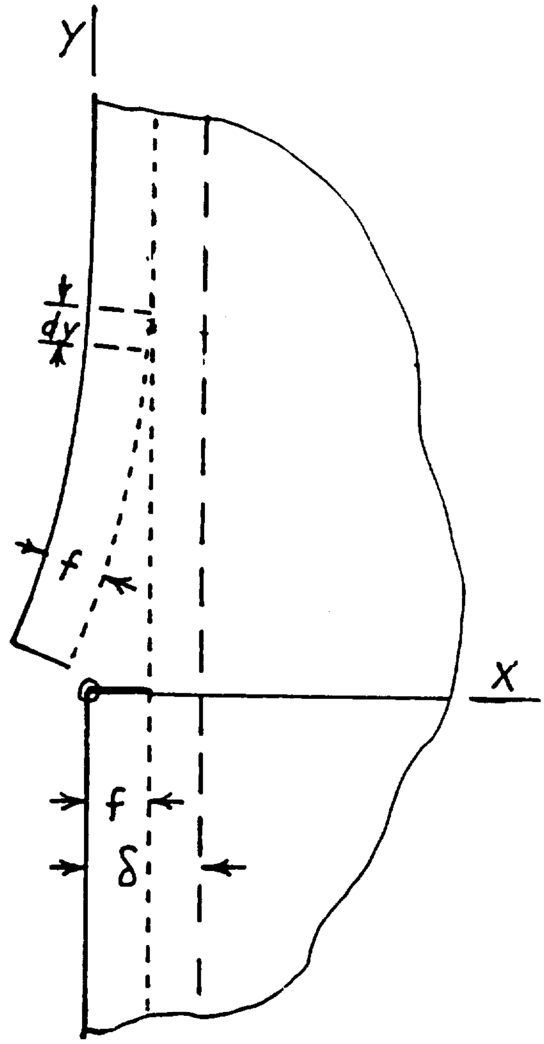


Figure 2. Upper Edge Beam Cut Loose (Exaggerated) [10]

Emmons provides a quantitative basis for his solution using the methods of solid mechanics. His work shows that a horizontal force **P** and a vertical tensile shear **V** are responsible for the crack growth and bifurcation:

$$\mathbf{P = Ef\beta(T_\infty - T_f)} \qquad [1.2]$$

$$\mathbf{V = Ef^2\beta(T_f - T_o)(\nu/12)} \qquad [1.3]$$

The horizontal force at the crack tip that would normally drive its growth decreases as $\mathbf{T_f}$ approaches $\mathbf{T_\infty}$ ($\mathbf{P \propto T_\infty - T_f}$) but increases proportional to the length of the crack ($\mathbf{P \propto f}$). The vertical tensile force required to keep the beam in place increases as the square of the crack length ($\mathbf{V \propto f^2}$) and in proportion to the rising temperature differential across the beam ($\mathbf{V \propto T_f - T_o}$). Together, these forces restrain the growth of the original crack and encourage bifurcation.

1.4 Applications

In Howard Emmons' paper "The Needed Fire Science" [5], in which he focuses on those less developed aspects of fire science, he provides his perspective on the outlook for this field and notes: "By now (1985), it has become broadly accepted that the way of the future in Fire Engineering is through various levels of modeling, aided by the modern computer." Emmons' words were right on the mark. This decade has witnessed impressive efforts to develop computer models simulating both the physical and chemical aspects of compartment fires. However, there has been one crucial element omitted from the various models. The effects due to changing equivalence ratio have been consistently neglected by the modellers.

From the program FIRST [11], which models a single closed room, to ASET [12] which allows for a small amount of leakage into the room, and on to FAST [13] which simulates a multiroom environment with buoyancy driven flows through open windows and doors, the computer models do not have the capabilities to consider closed room fires suddenly provided with new sources of oxygen due to breaking windows. Even the most recent work by the Center for Fire Research only partially addresses this problem. Their Consolidated Compartment Fire Model [14] features forced and unforced vent flows but arbitrarily imposes these conditions onto the model. There has not been enough information to allow new window vent flows to be integrated naturally into the program.

However, this element can be modelled successfully if an understanding is obtained of how edge-protected and edge-exposed windows react to various surface temperature conditions. The surface temperature conditions can be modelled using an approach developed by two scientists from the Center for Fire Research at the National Institute of Standards and Technology: J.R. Lawson and J.G. Quintiere [15]. In their method, as well as in any of the computer models being created, the type of fuel and the approximate amount in the compartment must be known in order to obtain any results. The burning rate of the material can then be determined from experimental formulas or more typically from actual test data collected by the Consumer Products Safety Commission [16] or the Center for Fire Research [13]. With the total heat release rate known as well as the compartment dimensions, a simple calculation allows for the determination of the radiant heat flux reaching the window. The surface temperature conditions of the window can then be found using radiation heat transfer equations with the material properties of the glass. In this way, experimental discoveries concerning window glass breakage can be integrated into any of the compartment fire models being developed today.

1.5 Format of Thesis

This thesis is composed of five chapters. Following this introduction, chapter two provides a description of the experimental apparatus used to conduct the tests and details of the procedures followed in all of the work. Chapter three presents the test results. A preliminary section presents test results concerning the two-layer environment. After this, the time-temperature histories for selected tests are documented graphically. Next, the times and temperatures at breakage for the edge-protected and edge-exposed experiments are given in tabular form. Window breakage patterns from each of the two test sets are then provided for analysis and comparison. Chapter three ends with a section on the material properties of the window glass used here. These values are then used to calculate a representative breakpoint temperature from the theoretical stress equation. Chapter four is the discussion section. The general trends in the data are highlighted here. Also, an examination of the experimental errors and their sources is contributed. Finally, chapter five provides conclusions and recommendations. This section summarizes the important findings of chapter 4 in the interest of assessing the practical applications of the work. Suggestions are made as well, concerning new information that may further this work and the corresponding tests that should be performed.

2. EXPERIMENTS

2.1 Introduction

The experiments performed to investigate window breakage were made under conditions closely resembling those found in building fires. All tests were made within a compartment fire setting. This chapter describes the design of the compartment used in the tests. Also, the work done in preparing a combustion facility is presented. This test site was developed to analyze toxic species generation rates in compartment fires. Finally, the experimental procedures followed in the window breakage investigation as well as descriptions of the instrumentation are documented here.

2.2 Fire Test Compartment

Figure 3 shows the setting in which both the window breakage tests and toxic species generation tests were performed. The entire assembly consists of the fire compartment constructed on top of a distribution plenum with the two vents dividing the inlet and exhaust flows. In a typical building fire, the inlet and exhaust flows are through the same vent. They are separated in this arrangement because a measurement of the total inlet flow is needed in the toxic species generation tests. The plenum has been designed to distribute the incoming air and assure that the two-layer effect is achieved during the fires. In this way, the compartment serves as a scale model room, with the tests now being conducted under floor-ventilated conditions.

The compartment, with dimensions of 60 x 48 x 39 inches, was framed using 1/4 inch angle iron with 1/4 inch thick, 4 inch wide iron slats welded onto the frame to

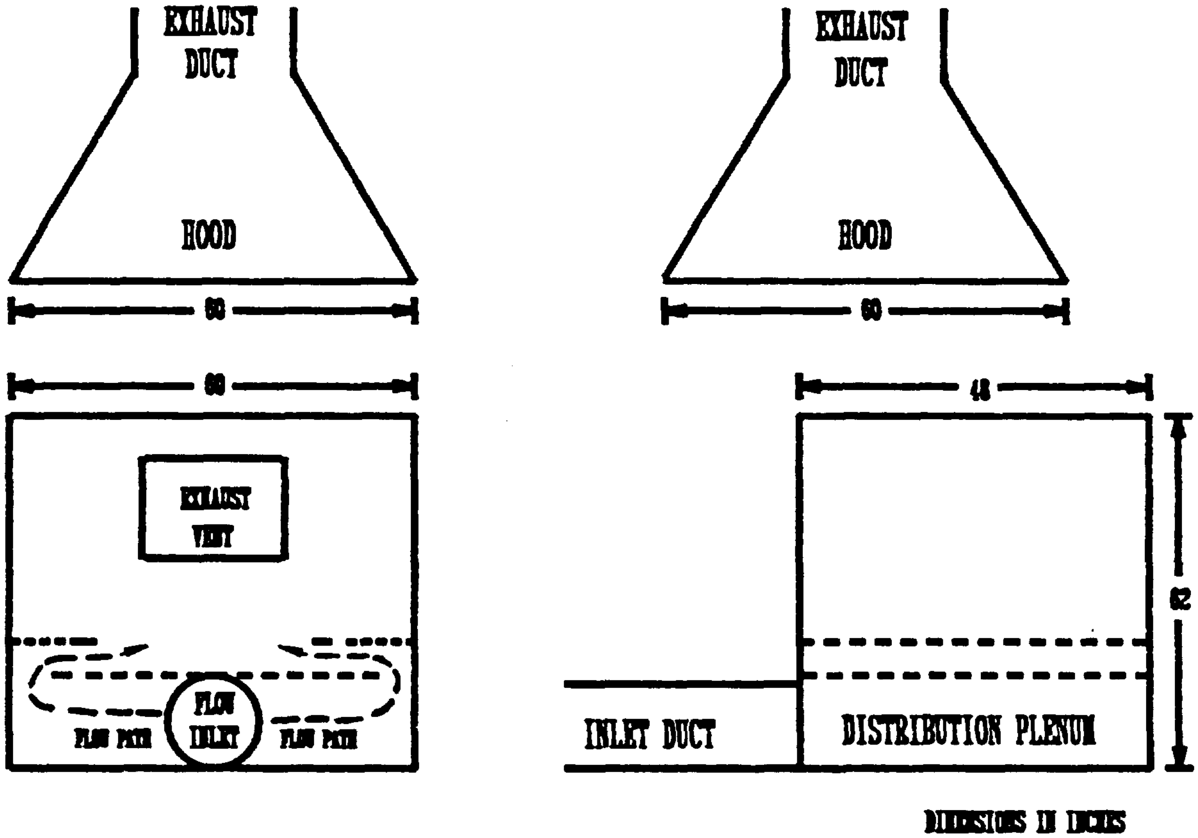


Figure 3. Fire Compartment Schematic

provide support for fire insulating board. Thermal Ceramics brand Kaowool ceramic fiber board was the insulating material bolted to the frame to close off the walls and the ceiling. The 1 inch thick boards were bolted onto the iron slats inside the compartment. The ventilation path allowing the combustion gases to flow from the compartment was provided by cutting a rectangular window into the center insulating board in the front of the box. The height and area of the window were maintained constant throughout all of the tests. The area of the opening was 20 x 23 in. with the bottom of the vent 14.5 inches from the floor of the compartment and the top 8 inches from the compartment roof.

The plenum was also framed using the 1/4 inch angle iron but was sealed with 1/8 inch steel plate surrounding the frame up to the full plenum height of 23 inches. A 12 inch diameter hole was cut into the front plate to provide the ventilation path into the plenum. The plenum guide vanes were constructed of 1/16 inch steel plate. The design was such that the incoming air flowed around the sides of the lower plate up into the combustion zone guided toward the center of the compartment by the two side vanes.

2.3 Experimental Facility

2.3.1 Combustion Lab

Prior to the window breakage project, preparations were made to investigate toxic species generation within the compartment fire setting. The fire test compartment was also used for these experiments. This section describes the development of the facility and the experimental setup for the tests.

The experiments were conducted on the site of the Price's Fork Rocket Lab. The facility consists of the measurement trailer, the fire lab and the fire wall, however, the buildings were remodeled, setting the compartment in the fire lab and adding a complete exhaust system, to create the new Combustion Lab Facility (Figs. 4 and 5).

A hood was installed in the fire lab to collect the exhaust from the compartment. The hood was 31 inches high with 60 inch sides and was constructed of 22 gage galvanized sheet metal. The ceiling of the hood was 24 inches square. The circular opening in the hood ceiling was 18 inches in diameter.

The hood was connected to the ceiling of the fire lab by a 6 inch high, 24 inch diameter flange that also coupled the hood to the 18 inch diameter, 22 gage, galvanized steel ductwork that ran from the roof of the fire lab 10 feet down to the pavement and then traveled 30 feet straight to the blower with a 46 inch orifice plate section in between.

The section with orifice plate was constructed according to ASME standards [17]. The section upstream from the plate is 30 inches long with the 1/8 inch diameter pressure tap 18 inches from the plate. The downstream section is 16 inches long with the second 1/8 inch pressure tap just 9 inches from the orifice plate. The plate itself is 18 inches in diameter with the center hole of 9 inches and is positioned so that there is at least 16 feet of straight ductwork upstream and at least 7 feet downstream.

The orifice plate provided a pressure drop proportional to the flow passing through the duct at that point. The apparatus used to measure the pressure drop was a Barocel-type (Model 590) pressure transducer from Edwards High Vacuum Inc.. The transducer was designed to read a 100 Torr (54 inches of water) differential pressure with an accuracy of .15 % of reading. The power supply and readout was a type 1450 also from Edwards and provided an analog output of 0-10 volts dc that was read by the data acquisition system.

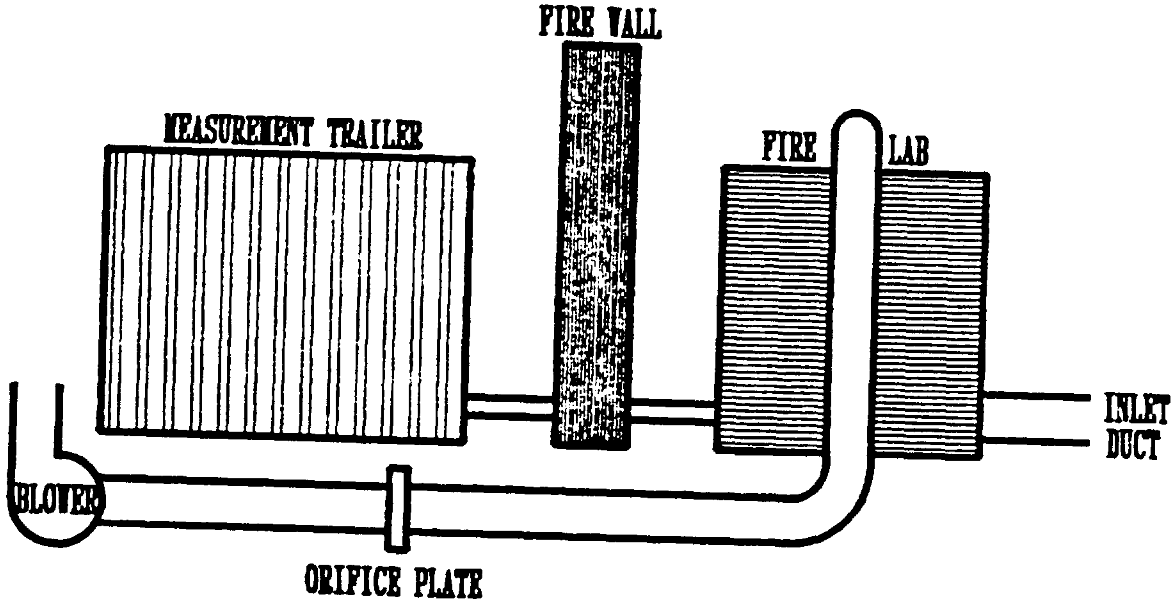


Figure 4. Combustion Lab Facility

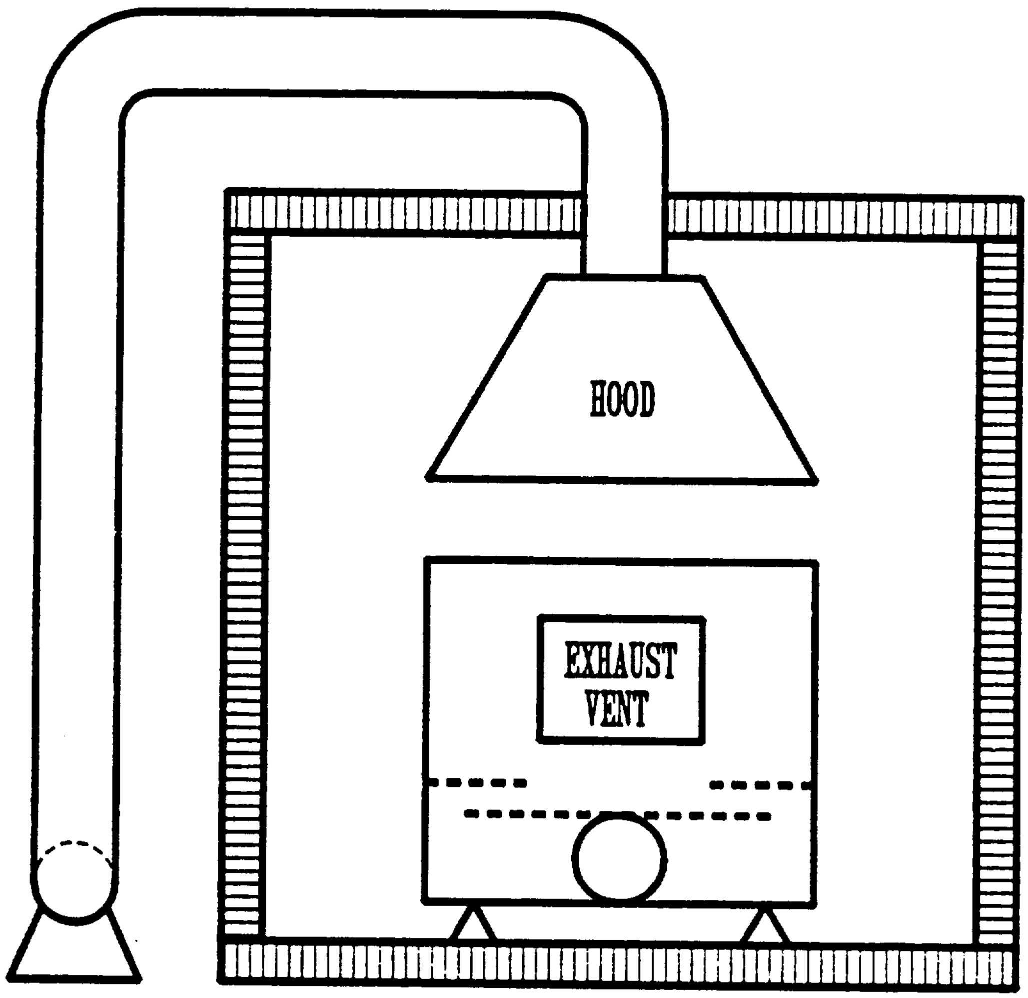


Figure 5. Fire Lab

The calibration of the transducer was performed using the fan lab test facility in Randolph Hall. Static, velocity and total pressure measurements, generated with a pitot tube, were made both with the test facility's calibrated manometer and the Edwards transducer. Static pressure measurements were different by 3% between the two instruments. The velocity pressure measurements were also 3% different. The total pressure measurements varied by only 2%. All of these measurements were in the range of 0-3 Torr (0-1.5 inches of water) and the range expected for the actual measurements is 0-20 Torr (0-10 inches of water).

The blower for the system was sized according to the pressure drop expected across the orifice plate and through the ductwork. The head loss due to the contraction of the hood was found to be negligible. The blower selected for the facility was an IAP type A, size 182, backward inclined fan. The fan was equipped with a TEFC (totally-enclosed fan-cooled) 15 hp motor that pulled 5000 SCFM at a pressure drop of 6.4 inches of water (corrected to 12 inches at 500°F). The fan was also designed with a vortex inlet damper to adjust the flow.

2.3.2 Gas Sampling System

Figure 6 shows the general positioning of the gas sampling system. The compartment probe was a 50 inch long, hollow, stainless steel shaft with a 1/4 inch inner diameter. The exhaust probe, located 3 feet upstream of the orifice plate, was a 16 inch long hollow stainless steel shaft (12 inches were fluted) with a 1/4 inch inner diameter. The gas collected by both probes was then pulled by sample pumps into the analyzers.

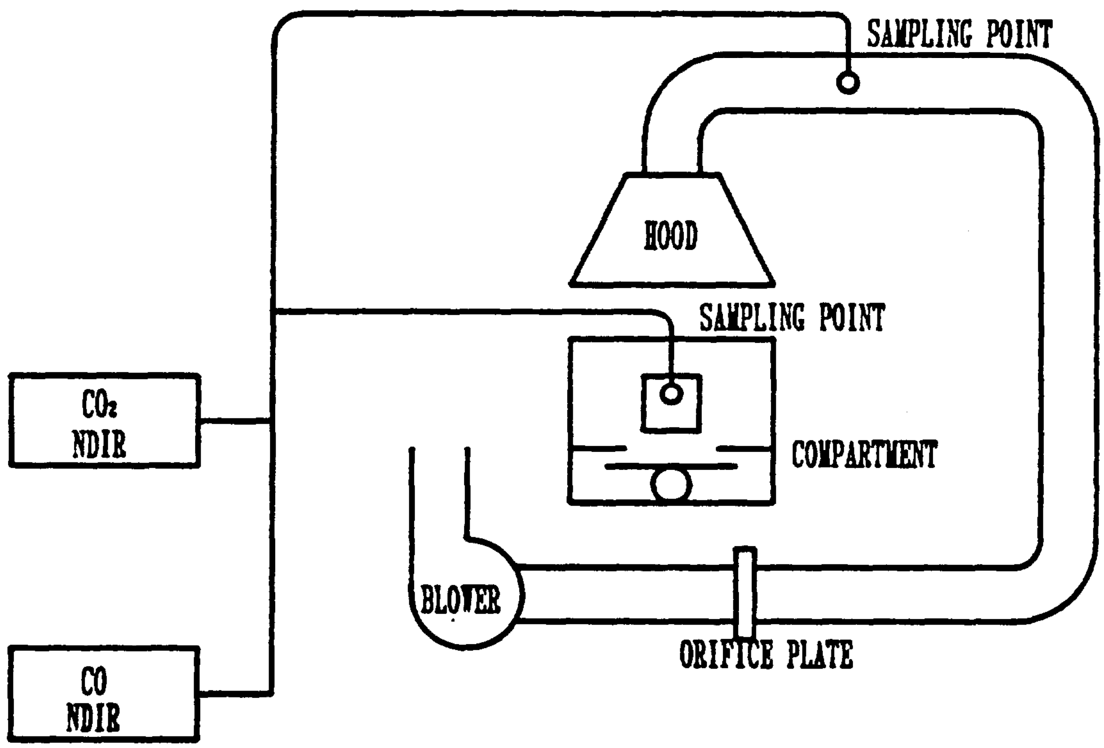


Figure 6. Gas Sampling System

The initial experiments were run using Rosemount Analytical CO and CO_2 NDIR analyzers. Both of the instruments were designed to measure gas concentrations in three separate ranges: the CO_2 analyzer for 0-5000 ppm, 0-15% and 0-20%; the CO analyzer for 0-1000 ppm, 0-1% and 0-10%.

2.3.3 Inlet Measurement System

The air-fuel ratio was determined in the tests by measuring the inlet and exhaust flows. The total flow of air leaving the compartment (plus whatever is entrained) was indirectly measured by the pressure transducer, and the volume of air entering the compartment was measured with a linear velocity transducer.

To facilitate the inlet measurements, a 13 foot duct was attached to the distribution plenum. This 12 inch diameter pipe was constructed of 22 gage sheet metal. The length of the duct was necessary because of flow requirements and specifications of the velocity probe.

The point measurement of the gas velocity in the duct was made using a 2-wire linear velocity transducer from Kurz Instruments; the system was specified to work in the range of 0-2 standard meters per second. The specifications for the velocity transducer dictated that the probe be mounted 10 pipe diameters downstream and 3 upstream from the nearest obstructions. The probe was, therefore, mounted 3 feet from the compartment on the topside of the duct and set in place with a compression fitting. The insertion depth of the probe was determined so that the velocity measured represents the average velocity within the duct. Knowing the average velocity, the volumetric flow rate into the compartment was then calculated.

The calibration of the transducer was performed by the manufacturer but the determination of the probe depth was found using the fan lab test facility. The inlet duct was attached to the existing pipe section and a variable-speed room fan was used to provide the air flow. By traversing the sensor across the center line of the duct, from the far wall to the center, the average point was found. Seven of these half-traverse tests were performed. The fan speed was different for all of them. In each of the tests, there were velocity measurements taken at five points within the duct. Of the points 2 inches, 3 inches, 4 inches, 5 inches and 6 inches (the center) from the duct wall, the 4 inch point proved to give a velocity value closest to the average from all of the five points. Therefore, the probe was fixed at this point for all of the tests.

2.4 Experimental Setup For Window Tests

2.4.1 General Parameters

The window breakage tests were conducted using standard 3/32 inch thick, 11 x 20 inch soda-ash glass windows. The glass was cut by hand with a scribe and the edges were not ground in any way. The windows were mounted in a 14 x 22 inch aluminum window frame that was installed on the side of the compartment (Fig. 7). The fires were created in the compartment by burning liquid hexane. Four different sized aluminum trays were used as containers to hold the fuel: the 12" x 8", 8" x 8", 8" x 4" and 8 inch diameter pans were filled with the hexane and allowed to burn in the center of the compartment. There were a total of 17 experiments performed, divided into 11 edge-protected and 6 edge-unprotected tests.

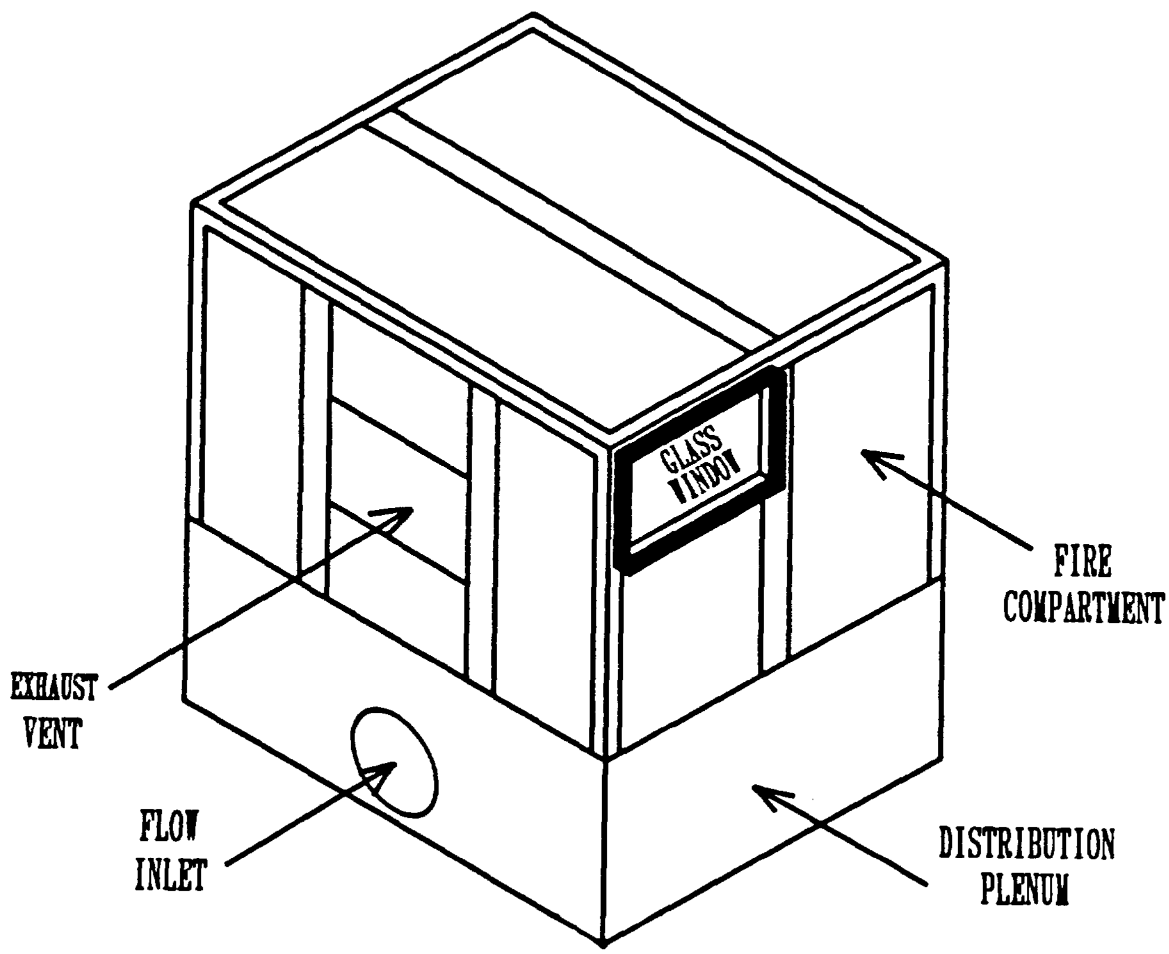


Figure 7. Compartment Setting for Window Tests

2.4.2 Edge-protected Tests

The initial set of experiments tested the edge-protected window glass. Figure 8 shows the placement of the window pane in the frame for these tests. The insulation used was 3/8 inch wide cellular rubber weather stripping. The window was held in place against the weather stripping by the metal washers. Figure 8 also indicates the positioning of the thermocouples used to measure the temperatures. The glass temperature was measured using an Omega brand chromel-alumel "cement-on" thermocouple (K-type) attached to the inside center of the window. The glass edge temperature was also measured with a chromel-alumel thermocouple (K-type). The exposed junction was positioned between the window and the weather stripping. Omega electronic ice points were used as references for both thermocouples.

2.4.3 Edge-unprotected Tests

In the final set of experiments, edge-unprotected windows were tested. In these tests the windows were mounted on the opposite side of the window frame inside the compartment and held fixed by reversing washers. In this way, the entire glass plate was exposed to the heat source. The glass temperature was again measured with a "cement-on" chromelalumel thermocouple (K-type) attached at the same point as the edge-protected tests. There was no edge temperature to be measured in these tests, instead, the compartment gas temperature was measured. Figure 8 shows the point at which the thermocouple was inserted. The exposed junction was set at a position 4 inches deep into the compartment, where subsequent tests showed the gases to be well mixed. Again, electronic ice points were used as references for both thermocouples.

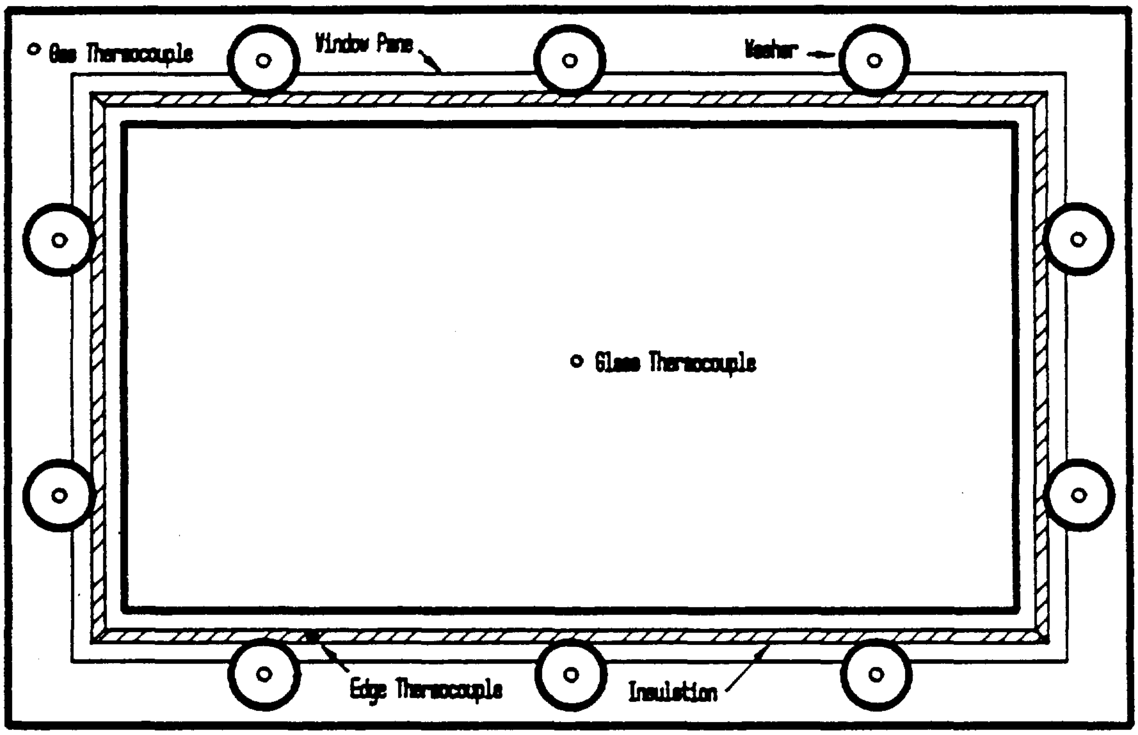


Figure 8. Edge-Protected Window Placement and Thermocouple Positioning

2.4.4 Data Reduction

In all tests, digital voltmeters were used to record the thermocouple outputs. To obtain a complete record of all the data, each of the tests was videotaped. These tapes provide a record of the thermocouple outputs throughout the tests as well as a picture of the breakage patterns at the time of failure. The final tabulated and graphical results were obtained by viewing each test in real time, clocking the recording with a stopwatch and compiling data pairs of thermocouple voltages (later converted to temperatures) vs time. The qualitative breakage pattern results were obtained through viewing both real-time and stop-action footage of both the total glass failures and the crack initiations.

3. RESULTS

3.1 Introduction

This chapter presents the experimental results from the edge-protected and edge-unprotected window breakage tests. Representative tests are displayed graphically and evaluated in this context. The tabular results for all of the tests are then documented with the relevant numerical analysis. Following this, a study of the glass breakage patterns is presented along with figures of typical fractures. Finally, the experimentally determined material properties are provided for use in calculating the breakpoint temperature difference representative of these tests. First, however, the results are given from the test that was performed to examine the compartment flow conditions during a fire.

3.2 Confirmation of Two-Layer Environment

An initial experiment was done to verify the presence of the two-layer environment. The compartment was prepared with the inlet duct attached to the plenum and the velocity probe was installed for flow measurements. The fire was set in the 8" x 8" pan using hexane as fuel. When the fire was started, the exhaust vent size was at a maximum of 20" x 22". The two-layer system was apparent immediately. The air flow around the vents was traced using smoke to create patterns revealing a hot layer of gases driven out of the vent above a colder layer fed by entrained air through the opening and a marked boundary between the two. As the vent size was decreased, the smoke patterns indicated that less air was entrained, confirmed by increased flow rates through the inlet duct, until finally, with the vent size at 14" x 20", no further entrainment was observed.

3.3 Window Breakage Test Results

3.3.1 Time-Temperature Histories

The complete time histories for selected edge-protected and edge-unprotected tests are plotted together in Figures 9 and 10, with the remainder of the test histories in Appendix A. Figure 9 graphs the 12" x 8" pan fire data from tests 3 and 14. The compartment gas profile is plotted along with the edge-unprotected glass temperature record and the edge-protected test data of heated glass and edge temperature histories. The most conspicuous feature of the graph is the compartment gas temperature curve. This plot rises faster and higher than any of the glass temperature curves reaching a peak of 720C. The final data point represents the temperature and time at which the fuel was exhausted. The continuously rising curve indicates that the fire diminished very little in intensity before extinction. Below this, the identical shapes of the two heated glass temperature curves show that there were very similar fire conditions in these two tests. The edge-unprotected curve extends further and only ends where the crack initiation occurs. At this point, the compartment is still heating up, as the rising compartment gas curve indicates. The edge-protected curve ends at the 49 second mark where, as Table 1 indicates, the catastrophic window failure occurred. The lowest curve, the plot of the edge temperature for test 3, shows that almost no heating of the edge took place.

Figure 10 graphs the 8" x 8" pan fire data from tests 4 and 15. The same variables are plotted as in Figure 9. In this case, the compartment gas curve rises more slowly and for a longer time than for the 12" x 8" gas temperature curve. Also, after reaching a peak temperature of 600C, the gas curve falls for 80 seconds before the fire goes out. This size pan fire burns with less intensity and diminishes over a longer period of time than the 12" x 8" size. The two heated glass temperature curves behave very much like those

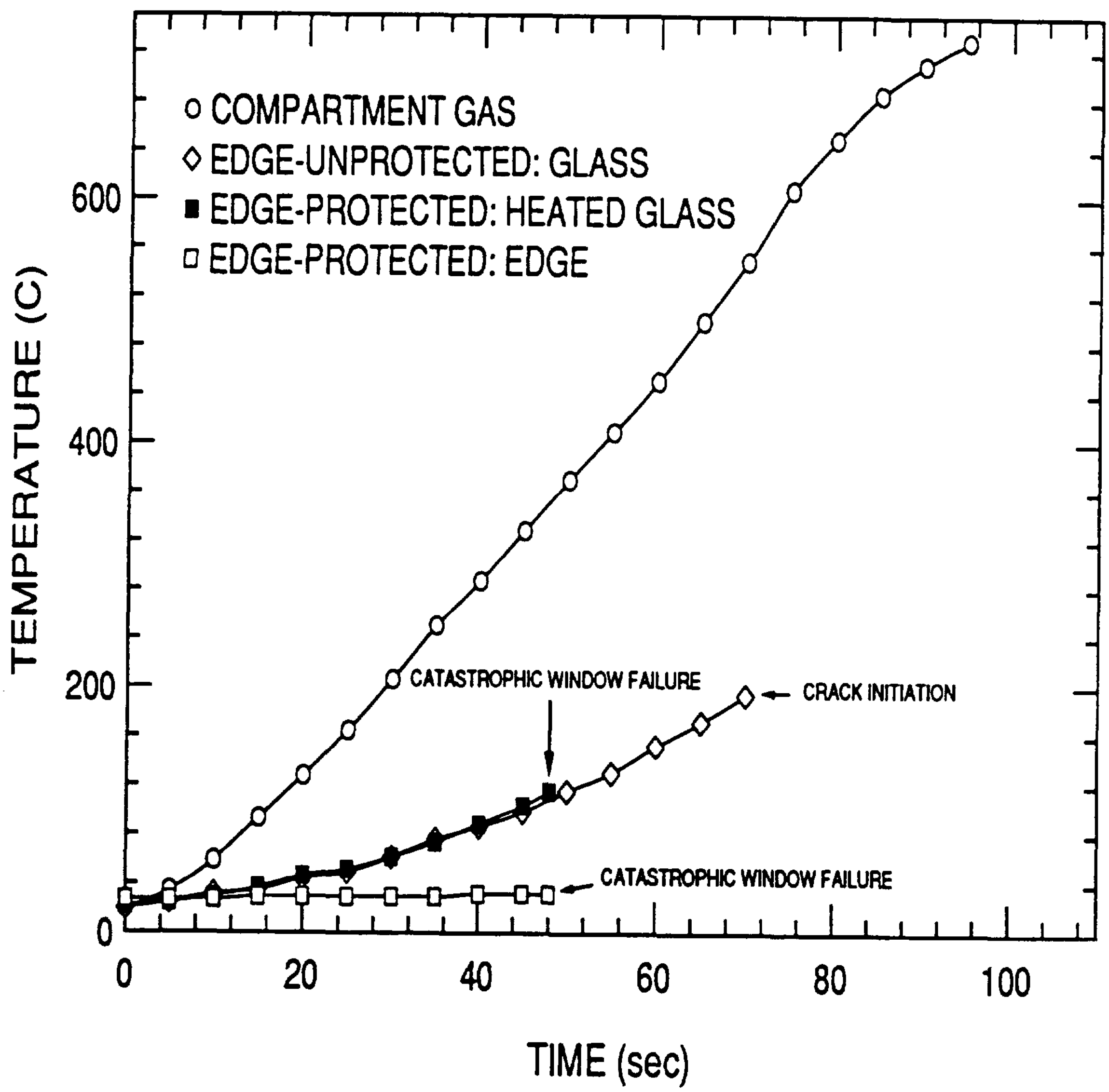


Figure 9. Time-Temperature History
12" x 8" Pan Fire Data
Window Tests Number 3 (Edge-Protected)
and Number 14 (Edge-Unprotected)

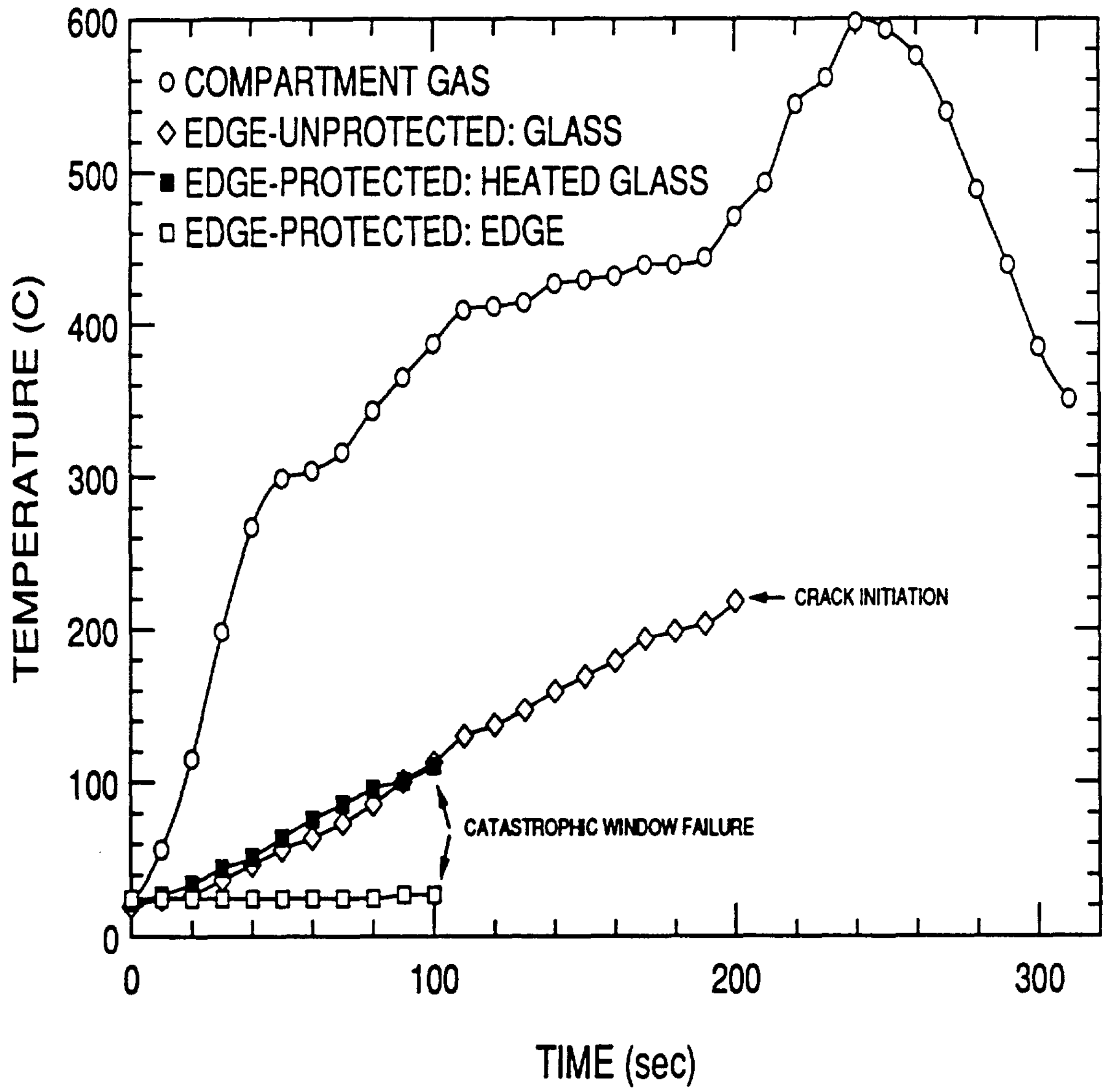


Figure 10. Time-Temperature History
8" x 8" Pan Fire Data
Window Tests Number 4 (Edge-Protected)
and Number 15 (Edge-Unprotected)

in Figure 9. For the amount of time that there is common data, the two curves run closely together. However, while the edge-protected heated glass curve undergoes failure at 100 seconds, the edge-unprotected plot continues for another 100 seconds until the crack initiation occurs. These values are more than twice as high as the corresponding times in the 12" x 8" tests of Figure 9. Again, the lowest curve is the plot of the edge-protected data. As in the last figure, the nearly constant temperature curve shows that virtually no heating has taken place.

Figure 11 differs from the previous two graphs in that the data from two edge-protected window tests are now plotted together as opposed to that from one edge-protected and one edge-unprotected. The data for these curves is from tests number 9 and 11, both performed with an 8" x 4" pan fire. Test number 11 represents the only one of the edge-protected tests where there was no glass breakage. Both time scales are similar, extending out past 300 seconds. The glass temperature curves are of similar shape and follow together closely. The values for test 9 are 5-10C cooler at each point and the curve reaches out to its highest temperature of 101C before the failure occurs but the glass temperature plot for test 11 continues on for about 120 seconds more, rising to a maximum temperature of about 120C before falling slightly before the fire is extinguished. The two edge temperature curves are even more similar, overlapping for most of their common length and showing a temperature rise of 15C. When failure occurs in test 9, the breakpoint temperature difference is quite low at approximately 60C. This is the lowest of all tests. When the fire is extinguished in test 11, the temperature difference is 70C. However, the maximum difference is 80C and occurs about 60 seconds before this point.

Figure 12 shows two graphs of edge-protected window test data. These tests were performed using an 8 inch diameter pan. On each of the graphs there is a curve

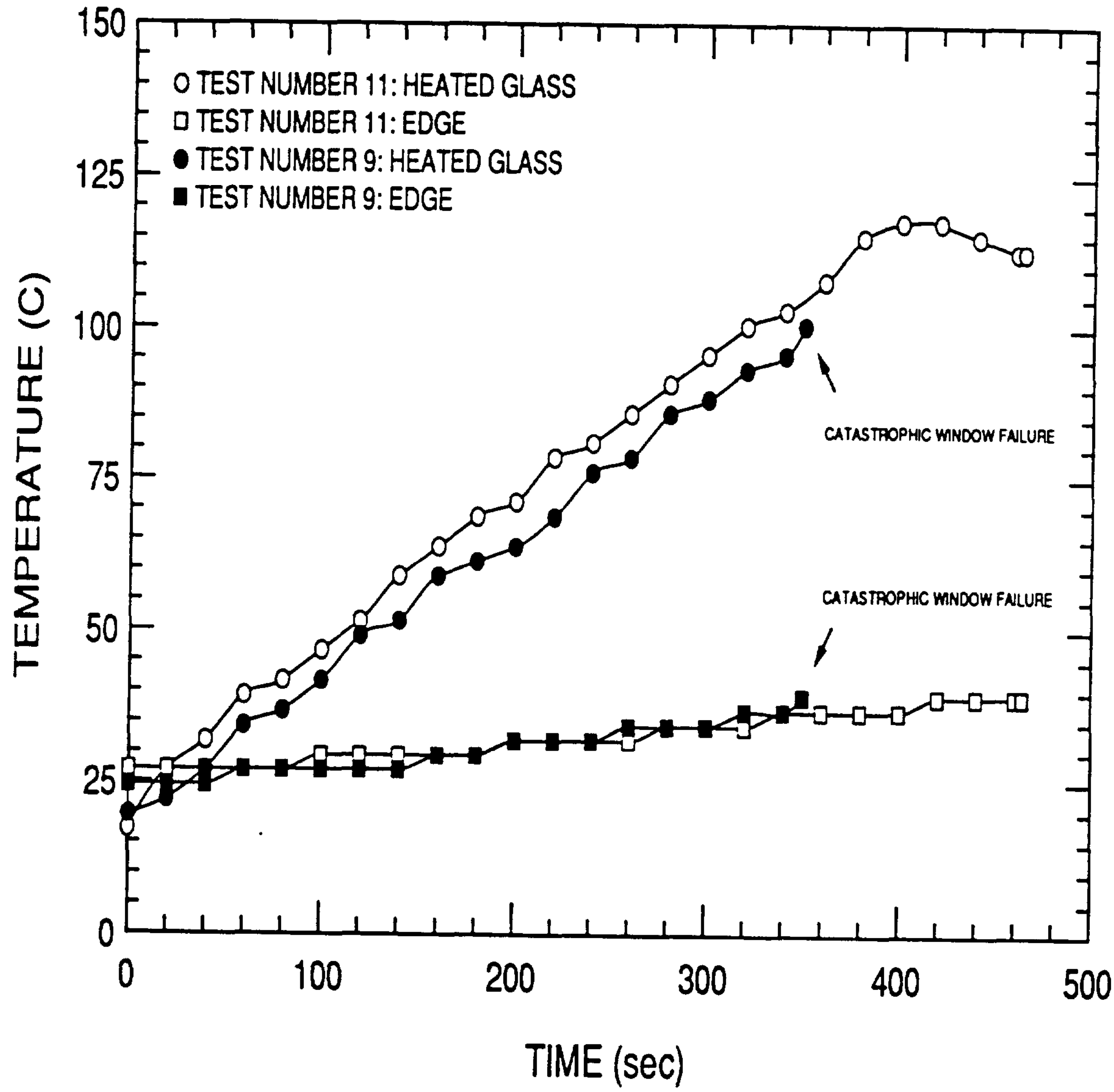


Figure 11. Time-Temperature History
8" x 4" Pan Fire Data
Edge-Protected Window Tests
Number 9 (Glass Breakage) and
Number 11 (No Glass Breakage)

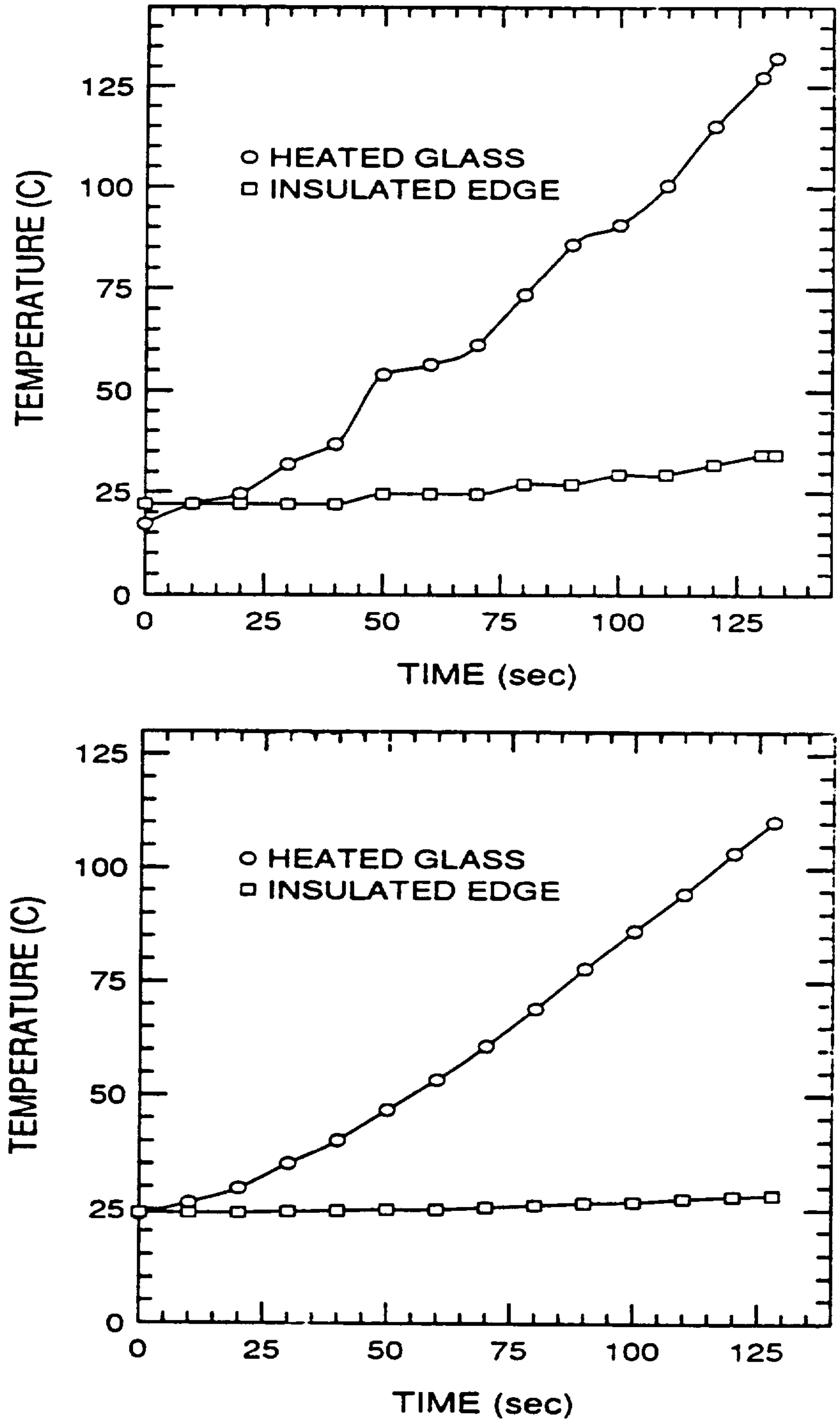


Figure 12. Time-Temperature Histories
8" Round Pan Fire Data
Top: Test Number 8 (Edge-Protected)
Bottom: Test Number 7 (Edge-Protected)

representing the heated glass temperature history and another for the protected edge temperature. The window failure occurs near the 130 second mark in each test. The initial glass temperatures are approximately the same for both tests, however, the glass temperature at breakage in test 8 is somewhat higher than in test 7. This gives an indication of the test to test variation in the fire development. The glass temperature curve in test 8 also demonstrates a pattern of sharp and sudden temperature increases. As for the protected edge curve, there is a greater than expected temperature rise. In comparison to the other edge-protected tests, the nearly 15C rise is slightly high. For test 7, the heated glass temperature curve rises very smoothly and the temperature rise for the protected edge is very close to 5C.

The final two graphs in this section are plots of time to window breakage vs pan area. Figure 13 was produced using the data from the 10 edge-protected tests where breakage occurred. Figure 14 uses the data from all 6 of the edge-unprotected tests. The curve for Figure 13 represents an inverse relationship between the breakage time and pan area. The breakage times are lowest for the largest sized pan and grow steadily higher as the areas are decreased. The individual data points are very consistent. There is little scatter among them and the least-fit analysis produces a smooth curve. An inverse relationship is also apparent in the edge-protected data of Figure 14. The largest area, for the 12" x 8" (96 in^2) pan, produces the lowest time for the initiation of cracks. As the area is decreased, the time to cracking increases linearly. As in Figure 13, the data is very consistent. There is even a repeated point at 64 in^2 and 200 seconds. In the 10 edge-protected tests represented here, the breakage occurred instantaneously, however, in the edge-unprotected tests, there was additional breakage throughout the experiment after the crack initiation. The data plotted in Figure 14 represent the first appearance of cracks in the windows.

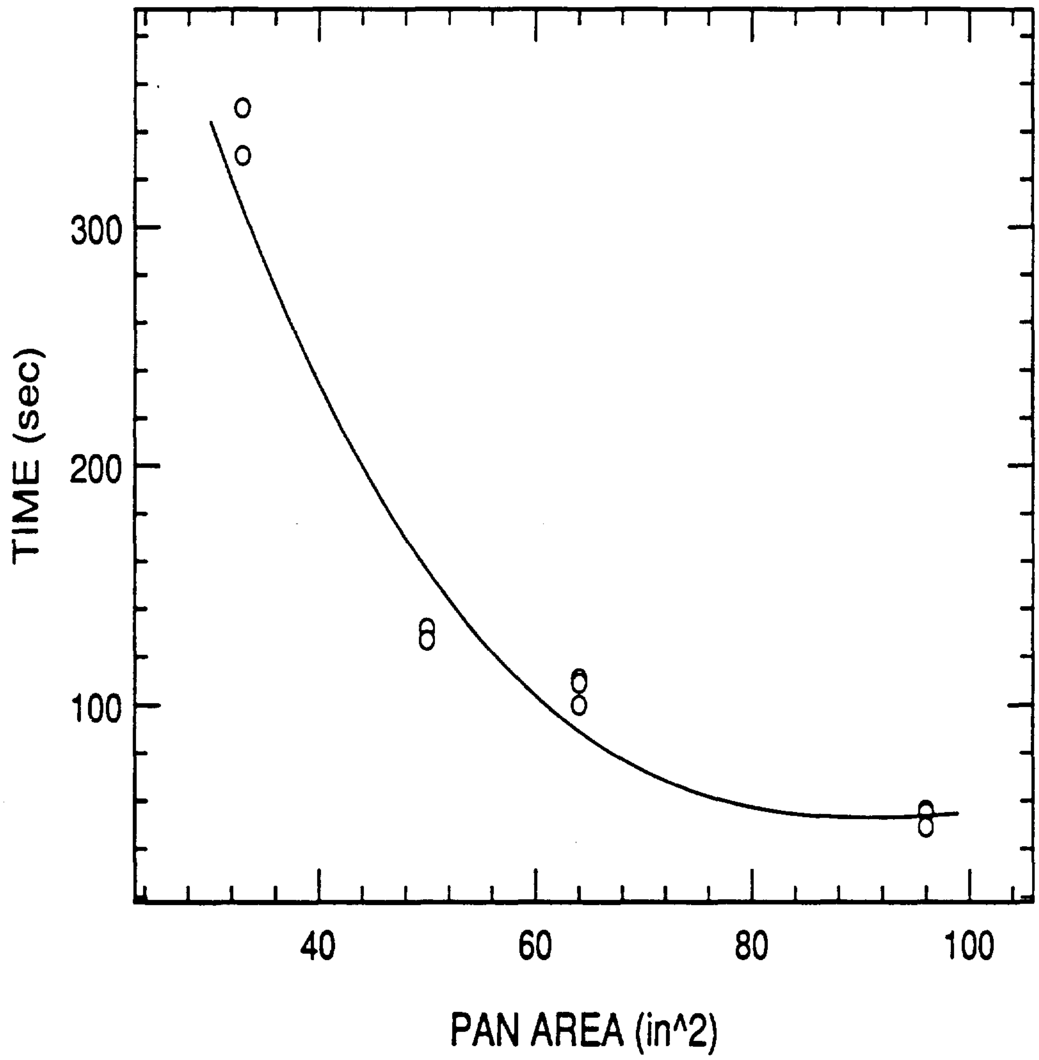


Figure 13. Breakage Time versus Pan Area
Edge-Protected Test Data

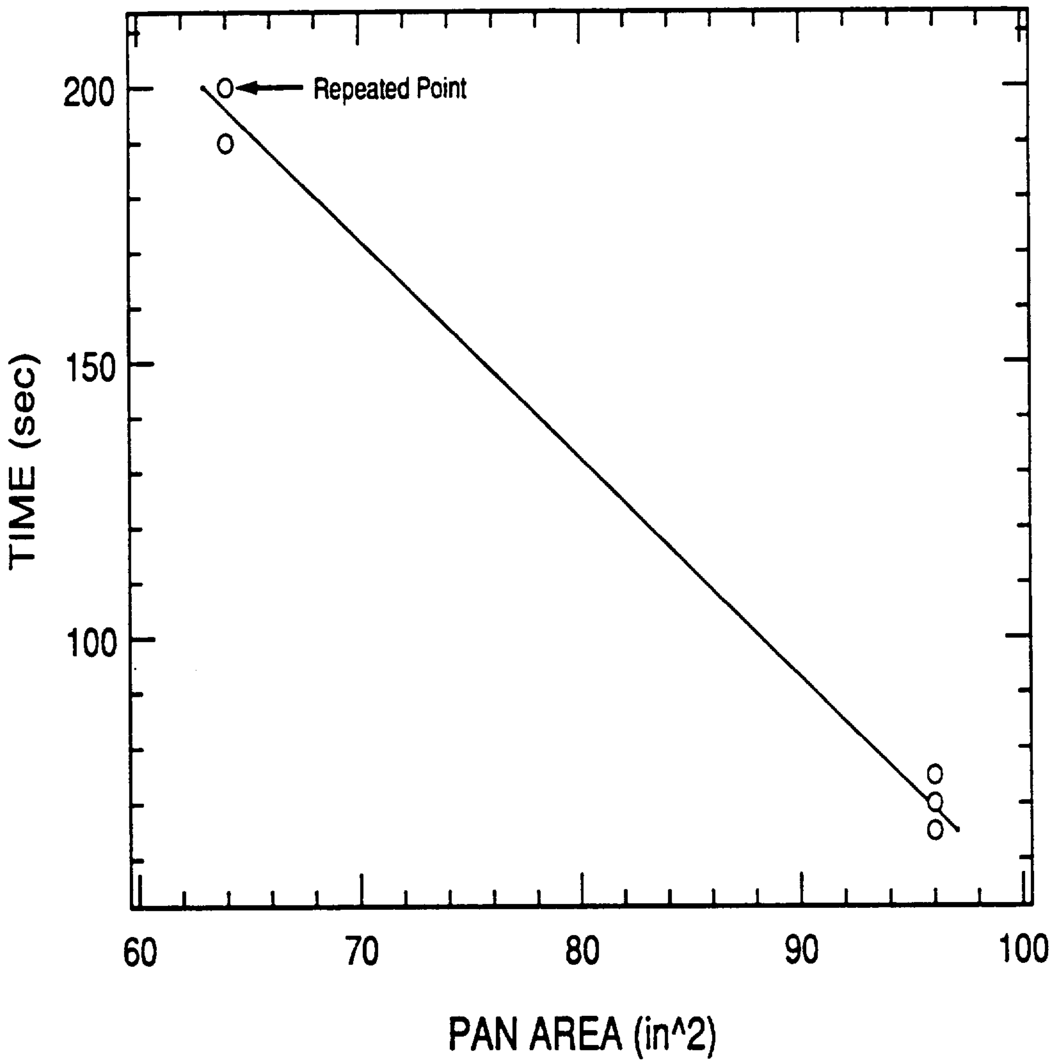


Figure 14. Time to Cracking versus Pan Area Edge-Unprotected Test Data

3.3.2 Times And Temperatures At Breakage

Table 1 summarizes the results from the edge-protected window tests. There were a total of eleven tests performed using four different pan sizes and in ten of the cases there was a catastrophic window failure. In test number 11, with the 8" x 4" pan fire, there was no cracking observed. Each of the other ten tests resulted in multiple bifurcations which joined together causing partial window collapse. For each of the tests, the pan fire size, the temperatures at glass breakage and the time to breakage are listed in the table. The table averages are provided for the center temperature, edge temperature and the breakpoint temperature difference. The standard deviations are listed as well, in parentheses. The complete numerical time histories for these tests are listed in Appendix B.

The three tests with the 12" x 8" pans provided the lowest average time to breakage of 53 seconds, with all three values within 4 seconds (8%) of this time. The mean edge temperature value of 27C is 20% lower than the table average with the high and low percent differences within the set being 40 and 3, respectively. In this case all of the temperatures were below the table average. The other results are slightly better. The mean center temperature of 131C is only 6% lower than the table average and the largest percent difference within the set is 25. The average temperature difference of 104C is 15% lower than the table average. The 132C individual value, highest out of all the tests, was 38% above the table average. Values for both the center temperature and the temperature difference were scattered on both sides of the table averages.

The three 8" x 8" pan tests had an average time to breakage of 1 minute and 47 seconds with even more consistent individual values. The greatest difference from this average was 6%. The mean edge temperature for this group, at 32C, almost exactly

Table 1. Window Test Results: Edge-Protected

Test No.	PanFire Size	TEMPERATURES AT GLASS BREAKAGE (C) Edge,TE	Center,TC	Difference,(TC-TE)	Time Until Breakage
1	12" x 8"	22	117	95	55 seconds
2	12" x 8"	27	159	132	56 seconds
3	12" x 8"	32	116	84	48 seconds
4	8" x 8"	27	110	83	100 seconds
5	8" x 8"	35	135	100	112 seconds
6	8" x 8"	35	115	80	109 seconds
7	8" round	29	110	81	127 seconds
8	8" round	35	132	97	132 seconds
9	8" x 4"	40	101	61	350 seconds
10	8" x 4"	50	137	87	330 seconds
11	8" x 4"	37*	118*	81	No Cracks
AVG.(SD)		33(8)	123(16)	90(18)	

* At Maximum Temperature Difference

matches the table average (3% difference). The greatest difference from the group is -20%. The average center temperature of 120C is only 2% off the table average. The highest individual difference was -12%. The group's temperature difference average of 88C represents a 2% difference from the table value and the biggest individual difference was -12%. For this pan size, the data in all three temperature categories was scattered on both sides of the table averages.

There were only two tests done with the 8" diameter pans and the results were quite similar to those from the 8" x 8" pan fires. The average time to breakage was slightly higher at 2 minute and 10 seconds but the other three averages were almost identical. The edge temperature average was, in fact, exactly the same at 32C. The greatest individual difference from the table average was slightly lower, though, at -6%. The average center temperature was 121C (1C above the 8" x 8" value). This represents less than a 2 percent difference from the table value. The highest individual difference in center temperatures was also similar to the 8" x 8" value at 11%. The temperature difference average for this set was 89C (1C above the 8" x 8" value). This represented a 1% difference from the total average while the largest individual difference was -11%. And as in the last set of data, the values in each temperature category were on both sides of the table mean.

There were three tests performed with the 8" x 4" pans, however, only two of these produced a window failure. Tests 9 and 10 had by far the highest time to breakage among all experiments. The mean time was 5 minutes and 40 seconds, with both values within 3% of this average. The highest overall edge temperature values also came from these two tests. The main reason for this is that test number 10 represents a rerun of test 11 after that test failed to produce any breakage. The intact window was reused and the test was started while the glass temperature was still warm at 38C. The average edge temperature of 45C was 31% higher than the table average and the greatest individual difference was, due to the previous heating, very high at +41%. While the average center temperature at 119C was only 3% from the table average, there was a great deal of individual scatter with one value 20% lower and the other 11% higher. Both temperature difference values were below the table value and combined to produce the lowest average of any set, at 74C. This was 20% below the overall. The 61C individual value, lowest of any test, was 38% below the table average. Test number 11 was the longest test of all, lasting 7 minutes and 50 seconds and the only test not to produce a window failure. The maximum temperature difference from this test was 10% below the table average and occurred at 6 minutes and 40 seconds. This was 50 seconds later than the greatest time to breakage (from test number 9).

Table 2 summarizes the results from the edge-unprotected window glass tests. The values were compiled from the complete test listings in Appendix B. There were three tests performed with the 12" x 8" pan fires and three with the 8" x 8" pan fires. In all of the tests, there were cracks developed in the glass plates, however, there were no catastrophic failures as in the edge-protected tests. For each test, the time to crack initiation, and the temperatures at that time are listed in the table. The table average for the glass temperature is calculated along with the standard deviation. There is no average for the compartment gas temperature because the values differ uniformly between the two pan sizes.

The 12" x 8" Pan Fires produced the lowest average time to cracking of 1 minute and 10 seconds. All three tests were within five seconds (7%) of this time. The compartment gas temperatures were less consistent producing an average of 604C with the deviations of -9%, +5%, and +4%. There was similar scatter in the glass temperature values. The mean of the three was 197C with deviations of -7%, -1%, and +8%.

Table 2. Window Test Results: Edge-Unprotected

Test No.	PanFire Size	TEMPERATURES AT GLASS CRACKING (C) Center,TC	Gas,TG	Time of Crack Initiation
12	12" x 8"	184	632	75 seconds
13	12" x 8"	215	630	65 seconds
14	12" x 8"	195	550	70 seconds
15	8" x 8"	218	470	200 seconds
16	8" x 8"	186	404	190 seconds
17	8" x 8"	186	426	200 seconds
AVG.(SD)		197(15)		

The times to cracking for the 8" x 8" pan fires were significantly higher than in the 12" x 8" tests. The average time for these tests was 3 minutes and 17 seconds. The individual values were also consistent with differences of +2%, +2%, and -4% from the set average. The compartment gas temperatures were lower than in the 12" x 8" tests. The average temperature for the group was 433C and the individual differences were -7%, -2% and +8% from this average. The glass temperature values were similar to the previous tests with the same group average of 197C. The scatter was greater with differences of +10%, -6% and -6% from the mean.

3.3.3 Breakage Patterns

Figures 15 and 16 show representative breakage patterns from the ten edge-protected window tests where cracking occurred. In all of the tests, the cracks initiated at the edges of the glass and they propagated rapidly, such that all breakage was complete in less than one second. The remaining patterns (Appendix C) are similar to these figures. The figures show that there were many single and multiple bifurcations, with the cracks spreading throughout the pane and joining together. In all ten of the tests, there was at least partial window collapse. In the majority of the cases, more than half of the window was removed from the frame.

Breakage patterns for the edge-unprotected window tests are presented in Figures 17 and 18. For the edge-unprotected tests, crack propagation across the pane lasted from less than one second to more than a minute. The two patterns in Figure 17 (test 13 on top and test 15 below) represent the minimum amount of cracking that occurred in the tests. Figure 18 shows more extensive cracking with the window in test number 14 (top) sustaining the most damage. Tests 16 and 17 (Appendix C) produced patterns very similar to those shown from Figure 18 in regard to the absence of multiple bifurcations

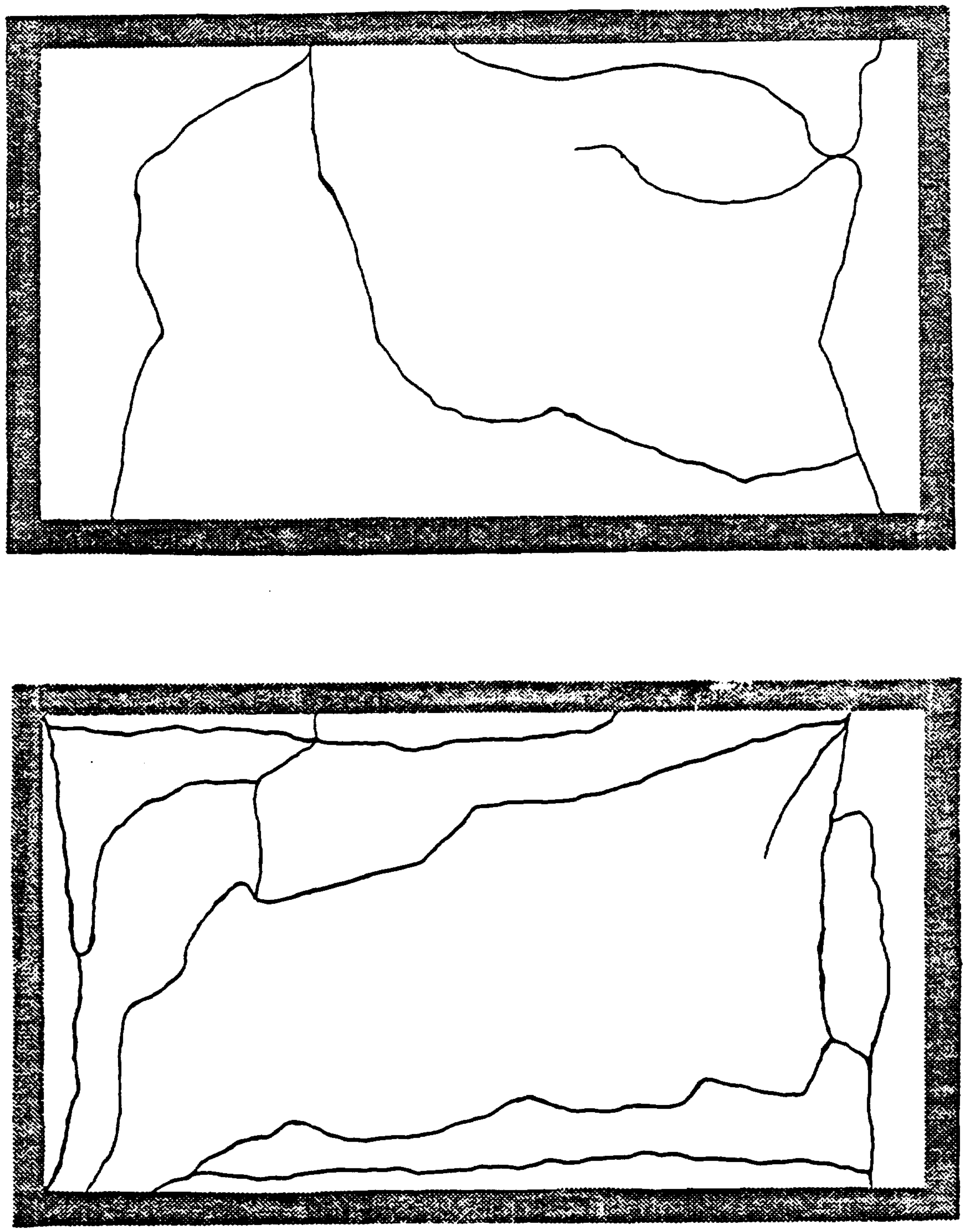


Figure 15. Edge-Protected Window Breakage Patterns
Top: Test Number 2
Bottom: Test Number 7

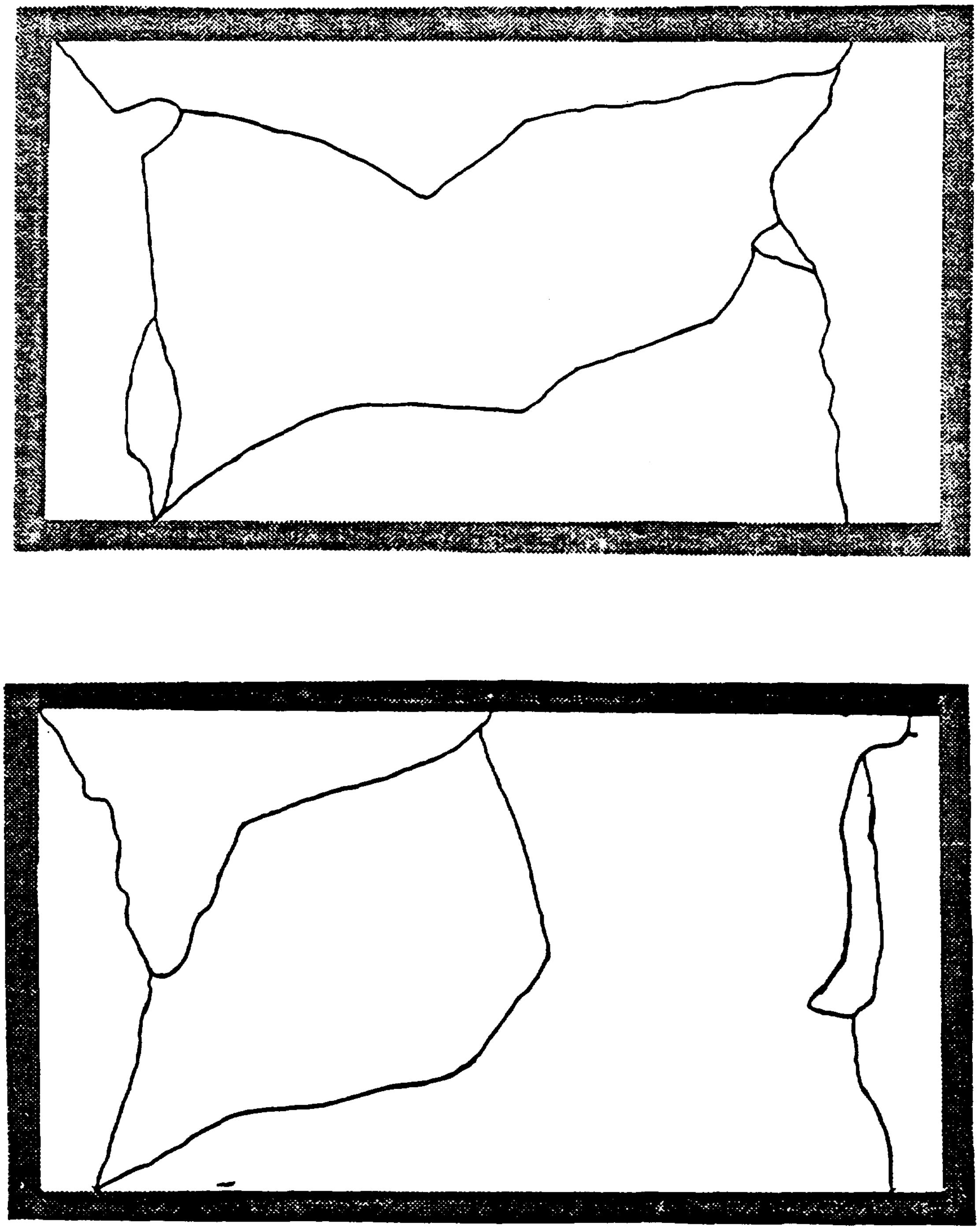
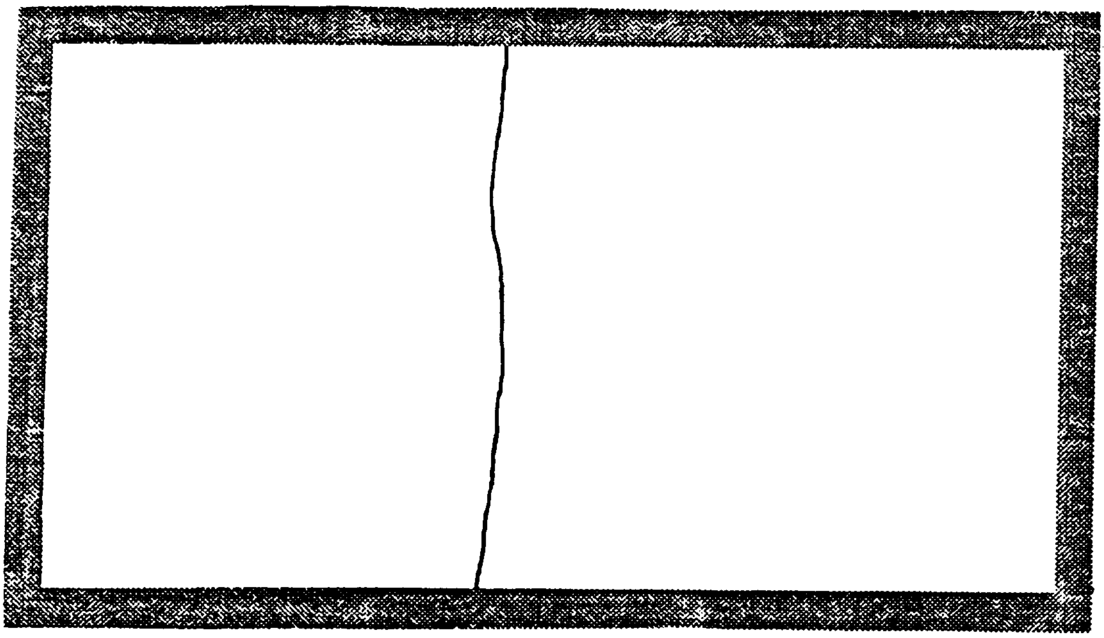


Figure 16. Edge-Protected Window Breakage Patterns
Top: Test Number 9
Bottom: Test Number 10



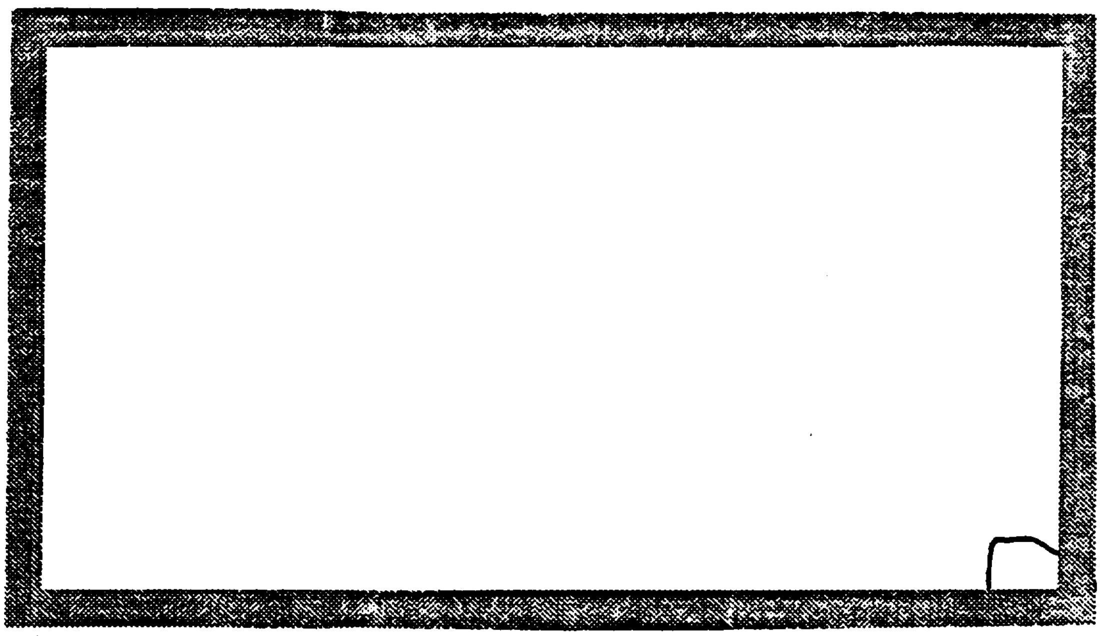


Figure 17. Edge-Unprotected Window Breakage Patterns
Top: Test Number 13
Bottom: Test Number 15

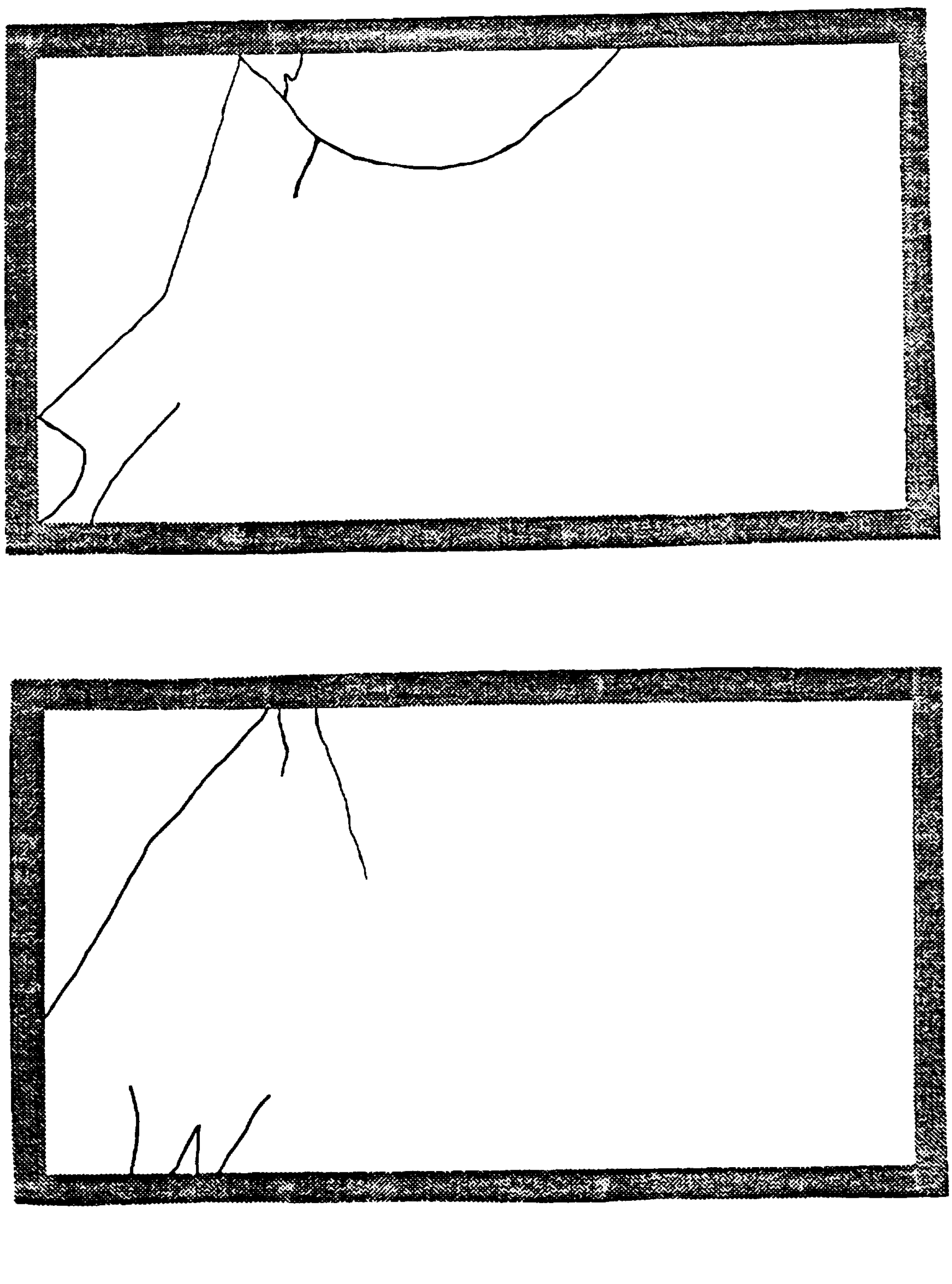


Figure 18. Edge-Unprotected Window Breakage Patterns
Top: Test Number 14
Bottom: Test Number 12

and in the isolation of the individual cracks. There are some bifurcations present in the top pattern of figure 18, however, the resulting cracks do not continue to split. Also, in certain tests, numbers 12, 14, and 15, small portions of the window were removed because of the cracking. In none of the three cases did the newly created openings exceed 3 cm^2 in area. Even in the case of test number 13 with the glass split completely in half, the window remained intact. And, just as in the edge-protected tests, all the cracks initiated at the edges of the glass.

3.4 Material Properties

In the research reviewed earlier, a formula developed independently by Keski-Rahkonen, Emmons and Pagni [7-9] was applied by all three men to determine the theoretical breakpoint temperature difference across a pane of glass. That work required the use of material properties for the glass and in all three cases, the values used were taken from reference books listing the properties for an average sample of soda-ash glass. For this thesis, the material properties were determined for the particular samples that were used in the tests. In this section, these properties are used in the stress equation to evaluate a reference breakpoint temperature difference for this work.

The first material property obtained was the coefficient of linear thermal expansion, β. The coefficient was determined from tests made with a Netzsch Dilatometer. Two samples were measured and each had the same coefficient value of $9.5 \cdot 10^{-6}$ %/C. This is 17% greater than the value of $8 \cdot 10^{-6}$ %/C used by Keski-Rahkonen and Emmons.

The glass modulus of elasticity, E, and tensile strength, σ_y, were both measured on a universal testing machine. Tensile loads were applied to samples of the glass until the breaking point was reached. The modulus was determined from the stress-strain diagram that was produced for each sample. The modulus is the slope of the elastic portion of the curve. The strain was monitored using a strain gage fixed to the sample and the load applied to the glass was measured and recorded by the machine. The results from the tests were used to calculate an average modulus of 70 GPa ±10%. This is 13% less than the literature reference value of 80 GPa.

The ultimate strength of the glass, σ_y, was calculated as the breakpoint load divided by the cross-sectional area of the sample where the break occurred. Because of the difficulty in cutting them, the dog-bone shaped samples were produced with more edge imperfections than the panes of glass. For this reason, the highest tensile strength of any test, 47 MPa, was taken as the truest measure of the window strength. This is 6% less than the reference value of 50 MPa.

Using these properties in the stress equation from chapter 1:

$$\sigma_y = E\beta(T_\infty - T_o) \qquad [1.1]$$

yields $T_\infty - T_o \approx 70C$. This temperature difference is 13% lower than the 80C value determined by Keski-Rahkonen and Emmons and it is 17% greater than the 60C value calculated by Pagni.

4. DISCUSSION

4.1 Introduction

This chapter presents an analysis of the work in chapter 3. After studying the results, the significant findings as well as the general trends are discussed here. Within this context, comparisons have been made to the theoretical and experimental work done by other researchers. The final section is a consideration of the errors in the work and an assessment of their effect on the results.

4.2 Analysis

4.2.1 Two-Layer Effects

The first experimental result was the confirmation of two-layer effects during a compartment fire. The initial test demonstrated that there was a clear boundary within the compartment between the combustion gases and the air feeding the fire. These characteristics, along with the evidence of no entrainment through the exhaust vent, indicated that floor-ventilated room fire conditions were being simulated.

4.2.2 Edge-Protected Data Trends

The edge-protected window data also indicated important relationships. Specifically, window breakage was seen to be a function of the temperature difference across the pane. With the exception of tests number 2 and number 9, the temperature differentials were concentrated around the table average of 90C. As for the 132C difference of test number 2 and the 61C difference of test number 9, they represent serious deviations, however, they do not indicate that the benchmark value of 90C for breakage should be moved in any particular direction as they are almost evenly spaced on either side of this average. This trend of the glass breakage occurring when a consistent temperature difference is reached, is exactly what is predicted by Keski-Rahkonen, Emmons, and Pagni [7-9].

More evidence for regarding the temperature difference as the mechanism of glass breakage can be found by considering the lone test in which the window remained intact (test number 11) along with test number 10, which followed immediately after and used the same window pane. The fact that the window broke at a temperature difference of 87C after remaining intact at a temperature difference of 81C in a previous test, run under the same conditions, strongly indicates that the particular temperature difference caused the breakage.

However, the experimental average of 90C is 30% greater than the expected value of 70C, formulated using the stress equation. The 61C temperature difference from test number 2 is 13% lower, the closest indvidual value and the only one below the expected figure. The other nine values are from 14% to 89% greater. In order to consider the stress equation a valid means of predicting the breakpoint temperature difference, these large discrepancies must be explained. The final section of this chapter, the error assessment, provides this explanation.

4.2.3 Edge-Unprotected Data Trends

A similar pattern of the windows cracking as a function of the glass temperature can be detected in the numerical data from the edge-unprotected window tests. Although the times to breakage and the compartment gas temperatures vary with pan fire size, the glass temperatures at crack initiation do not show this pattern. For these experiments, the standard temperature was 197C with individual values spaced evenly on both sides of this number. This temperature is probably a function of a number of other variables including the window size and the compartment itself, but there does seem to be a direct relationship with the time to crack initiation. There is, however, no theoretical or experimental research describing the temperature conditions under which this might take place.

4.2.4 Breakage Times And Pan Sizes

The graphical results presented in chapter 3 revealed that there is an inverse relationship between the time to breakage or cracking and the pan size. These results simply support the theory that the breakage is a direct function of either the glass temperature or temperature difference. The larger the pan area, the greater the heat flux directed toward the window and, therefore, the glass temperature will rise more quickly, resulting in smaller breakage times.

4.2.5 Breakage Patterns

The breakage patterns produced in both the edge-protected and edge-unprotected window tests represent a more qualitative trend in the data. Although there was breakage in all but one of the experiments (test number 11), there were important differences between the breakage patterns for the two types of tests. There were single and multiple bifurcations in the edge-protected tests with partial window collapse in all ten cases. The edge-unprotected windows, while cracking in all six cases, held together and remained firmly in the frame. In most of the cases there were multiple cracks but these rarely extended more than 3-4 inches beyond their point of initiation. There was also a small number of bifurcations but these bifucations did not multiply. This is the essential difference between the two sets of experiments. The bifurcations effectively double (at least) the number of cracks which, under edge-protected conditions, travel with less restraint through the heated part of the glass plate often joining together and causing the window to collapse.

The ten edge-protected tests show the multiple bifurcations that the Harvard experimental work [6] and Emmons' theoretical work [8] predict. And in each case, the tests confirm Emmons' observation that this situation is most conducive to window collapse. The edge-unprotected results are similar to those from the Harvard work in that there was no window collapse and the bifurcations that occurred did not multiply. Also, the fact that the edge-unprotected cracks did not, in general, travel extensively throughout the glass can be inferred from the crack growth derivations of Emmons.

4.3 Error Assessment

The focus of the window breakage testing process was on accurately measuring the glass temperatures. The thermocouples provided this accuracy along with fast response. However, certain factors still restricted the measurement capabilities. Radiative heating was foremost among the problems.

The thermocouples used to measure the heated glass temperatures were embedded between two paper thin, glass reinforced, high temperature polymer laminates. They were then glued to the inside center of the window. The covering was not sufficient to eliminate the radiation heat transfer from the fire. Because of the positioning of the edge thermocouple, radiative heating did not affect these measurements. This means that, since the heated glass temperature is actually smaller than what was measured, the true breakpoint temperature differences are also smaller than the tabulated values. The radiative heating effects were, therefore, one reason for the difference between the experimental values and the theoretical breakpoint temperature difference calculated for this thesis.

A second factor that was initially considered to have decreased the accuracy of the measurements was the positioning of the thermocouple used to measure the edge temperatures. The thermocouple was set between the window and the weather stripping. The problem with this arrangement was that the thermocouple bead was actually 1 cm away from the edge of the window. The magnitude of this effect was estimated in Appendix D using a 1-D conduction-convection heat transfer model. It was found that the edge temperature values decrease by 2C in one case, 1C in five cases and not at all in the other four. This lowers the table average by 1C and therefore, increases the table difference average by 1C. The effect here can be considered negligible because, with the voltmeter only measuring to the tenths place, the temperature measurements themselves were not accurate to more than 1C.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

There have been three prominent topics throughout the thesis; and the findings in each area have been sufficiently complementary to allow a number of conclusions to be drawn from this work.

1. The presence of a two-layer system was regarded as essential to reproducing those conditions found in typical building fires. Since the stated objective of this work is to present experimental data on window glass breakage collected under actual room fire conditions, the initial emphasis was on confirming a two-layer environment during a fire in the test compartment.

The first test performed, before any of the window experiments, set about this task of confirmation. And the results did prove that there was a two-layer system in the compartment. There was a clear demarcation of the hot and cold layers in the distinct absence of smoke below the height of the vent opening. At that stage, the fire was fed entirely from air entering through the inlet duct and the combustion products were the only gases flowing through the exhaust vent.

2. The first chapter reviewed the previous work done on the subject of edge-protected window breakage in fires. The most extensive theoretical studies were directed toward determining the breakage mechanism and, consequently, developing quantitative methods of predicting when the window pane will break. The temperature difference across the pane was proposed as the cause of the breakage and a stress equation was derived to predict this breakpoint difference. The second area of

importance in this thesis was in testing the validity of the suggested mechanism and, therefore, the stress equation as well.

Ten of the edge-protected tests resulted in breakage at an average temperature difference of 90C. The consistency of this value supports the theory of the temperature difference as the cause of breakage. The fact that the window pane from the eleventh test did not break until a retest under the same conditions produced a higher temperature difference also strongly supports this theory. Using the material properties specific to the glass tested in these experiments, a theoretical breakpoint temperature difference of 70C was determined using the stress equation. The experimental average for the breakpoint difference taken from the test data was 90C. This value is 30% higher and nine of the ten individual test values are from 14% to 89% greater. However, these differences should be considered as the result of the radiative heating problems discussed in chapter 4. This type of heating causes the measured heated glass temperature (and thus the temperature difference) to be greater than the actual value. In light of these results, the proposed breakage mechanism and the stress equation should be considered valid.

3. Also in the earlier literature review, the work by Emmons [8] and the Harvard students [6] was discussed. The work dealt with the types of breakage patterns that result from either protecting the edges of the window or exposing them to the fire. The main work on the subject suggested that the edge-protected windows will develop more cracks and that these cracks will be more extensive, with multiple bifurcations and thus, a greater likelihood for window collapse due to cracks joining together. This theory was supported by a previous experimental study. The final emphasis of this thesis has been on confirming that there is a true difference in breakage patterns between the edge-protected and edge-exposed windows.

The tests were filmed and all breakage patterns were recorded on tape. The results were very plain. The edge-protected windows collapsed in all 10 cases where there was breakage. There was considerable cracking and numerous bifurcations with the collapses resulting from the cracks joining together. Also, the cracks behaved as theorized in bifurcating at a short distance from the original crack and moving off at sharp angles. On the other hand, in the six edge-exposed tests the largest piece of glass removed from any window was 3 cm^2. There were relatively few single bifurcations and no multiple bifurcations. And nearly all of the cracks halted their progress within 4-5 inches of their point of initiation. Based on these results, the theory on the differences between window breakage patterns does agree with the experimental results.

4. It was mentioned earlier that there is broad acceptance of computer modelling as the way of the future in fire engineering [5]. The limitations of these models in regard to incorporating new vent flows were also noted. Based upon the findings here, it is safe to conclude that these new vent flows can be integrated into these models using the 70C breakpoint difference value from this work as a benchmark figure with the results of these experiments very likely representing the high end of the scale.

5.2 Recommendations

The suggestions offered here are concerned with eliminating the problems discussed in chapter 4 and in extending the experimental work into unexplored areas.

1. The difficulties with radiative heating were considered to be the most significant problem encountered in the tests. This complication very likely accounted for the difference between the experimental breakpoint temperature difference average and the stress equation value calculated for this glass. Since this type of heating was possible

due to the absorption properties of the thermocouple covering, a solution is to shroud the thermocouple in a material such as aluminum that will reflect more of the radiation.

2. Another point that may be of importance in subsequent experiments is detecting any uneven heating of the window. This would be most important in situations where there is a fire of relatively low intensity. Part of the theory reviewed in this thesis is based on the assumption that the central portion of the window will be heated to a uniform temperature. In order to discover any gradients that may exist, and obtain the true maximum temperature difference across the glass, an array of thermocouples should be spread across the pane.

3. A related issue is the presence of a temperature gradient between the inside and outside of the window. Such a gradient could cause the window to break by a completely different mechanism than that discussed here. There would actually be torsion bending as opposed to tensile stress. This might be of consequence with thicker windows. To detect this type of gradient, thermocouples should be attached to the window in pairs, with one on the heated side and the other directly across from it on the unheated side.

4. Finally, regarding the observation of the breakage patterns, the method used by the Harvard students of catching the glass pieces as they are removed from the frame would be helpful in circumstances where the patterns are not clearly distinct on video or where the collapse of the window occurs so suddenly as to prevent an accurate picture from being obtained. The pieces could, in many cases, be reconstructed to see an accurate breakage pattern.

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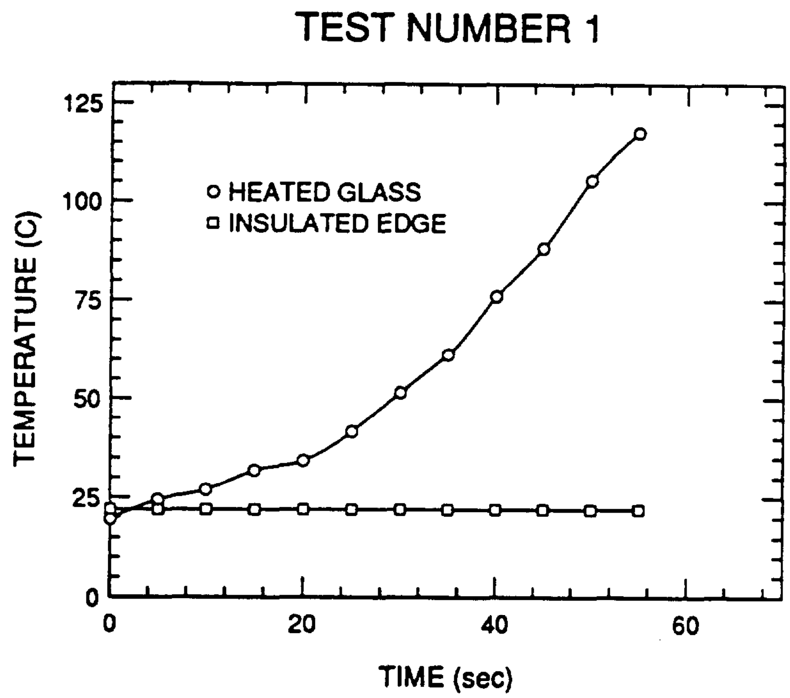
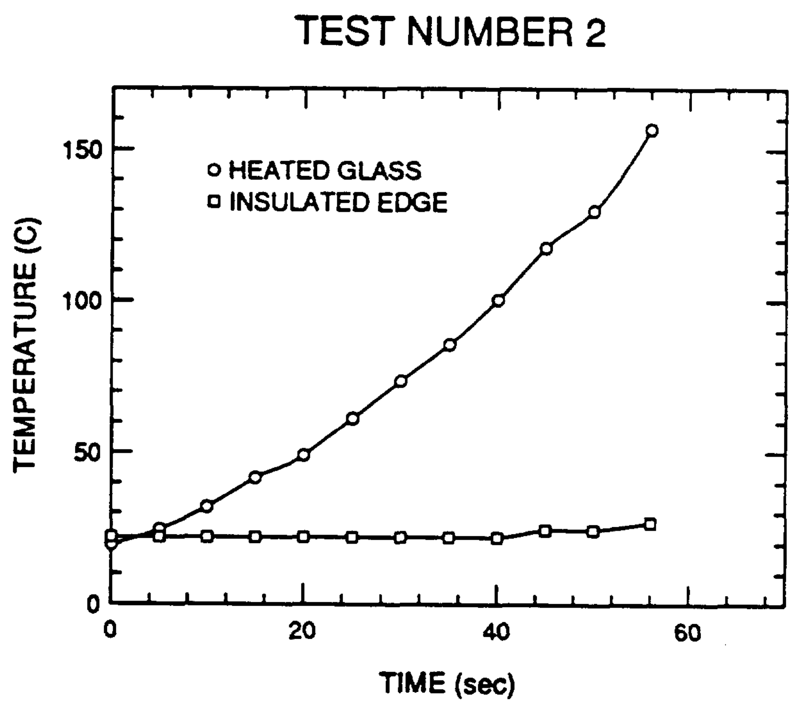
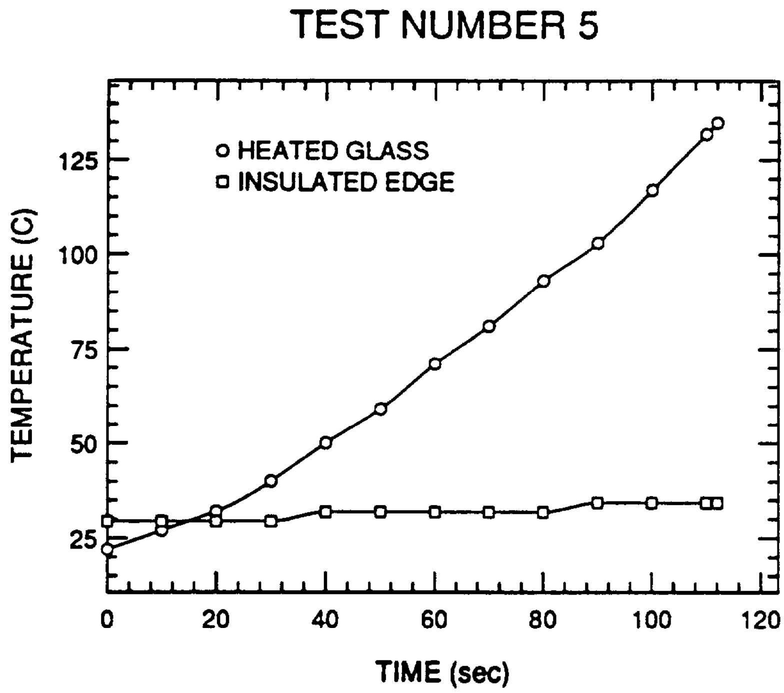
APPENDIX A

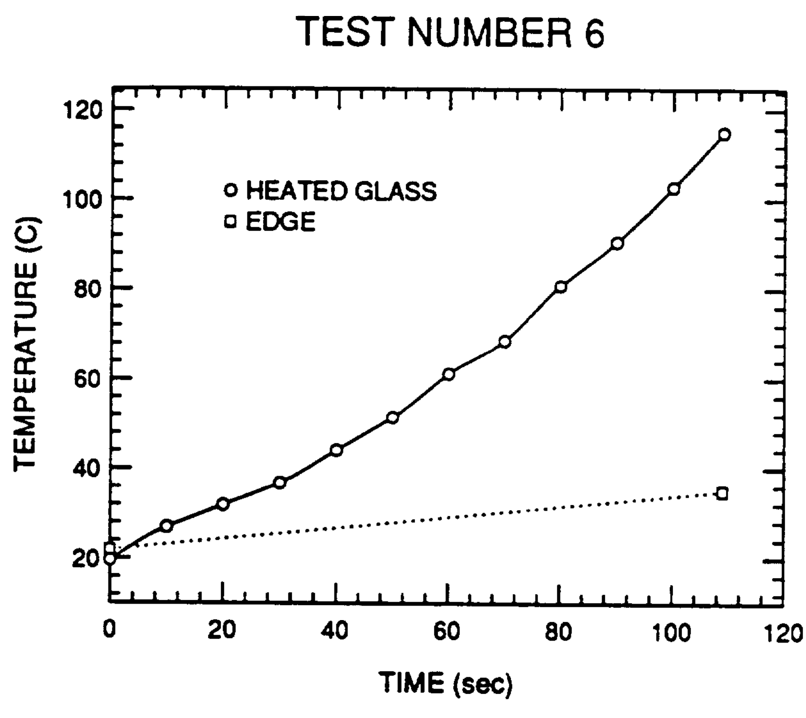
This appendix contains the graphical Time-Temperature histories for the five edge-protected window tests and the four edge-unprotected tests not presented in chapter 3.



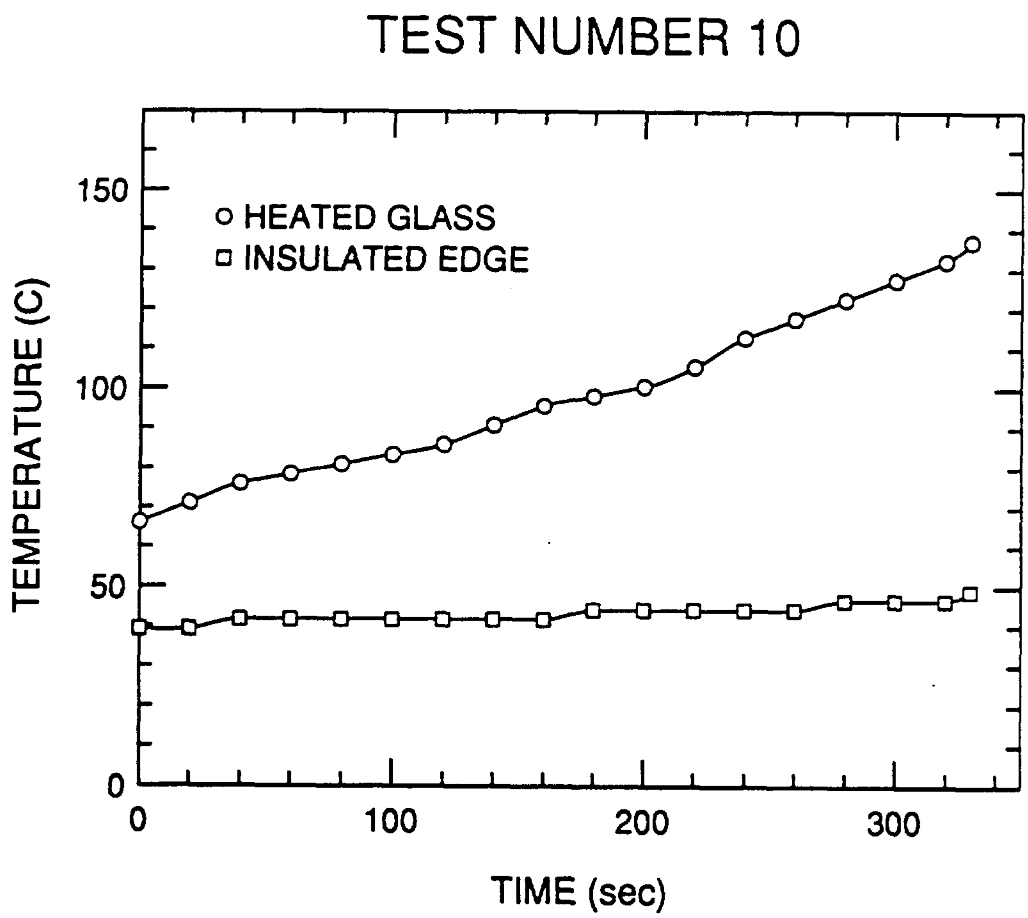


Top: Edge-Protected Window Test (12" x 8" Pan Fire)
Bottom: Edge-Protected Window Test (12" x 8" Pan Fire)

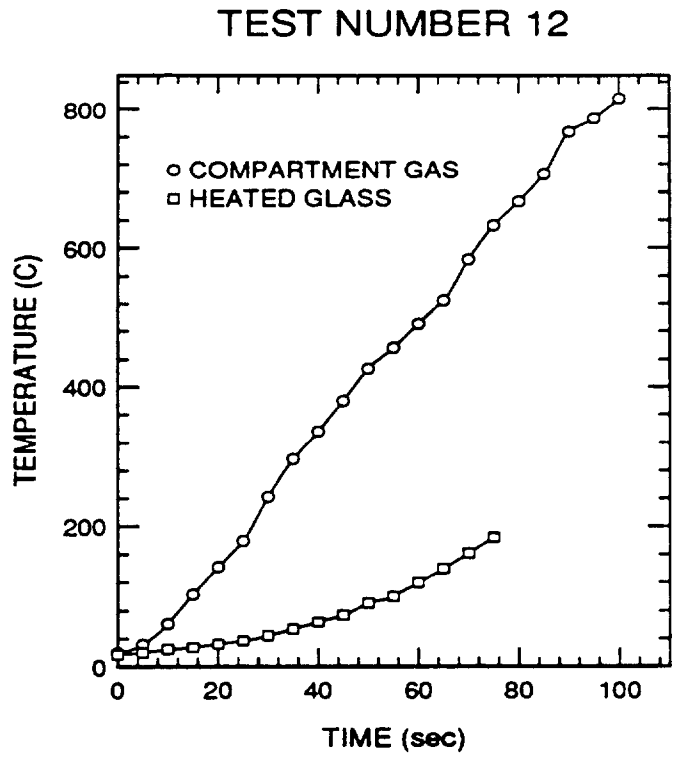


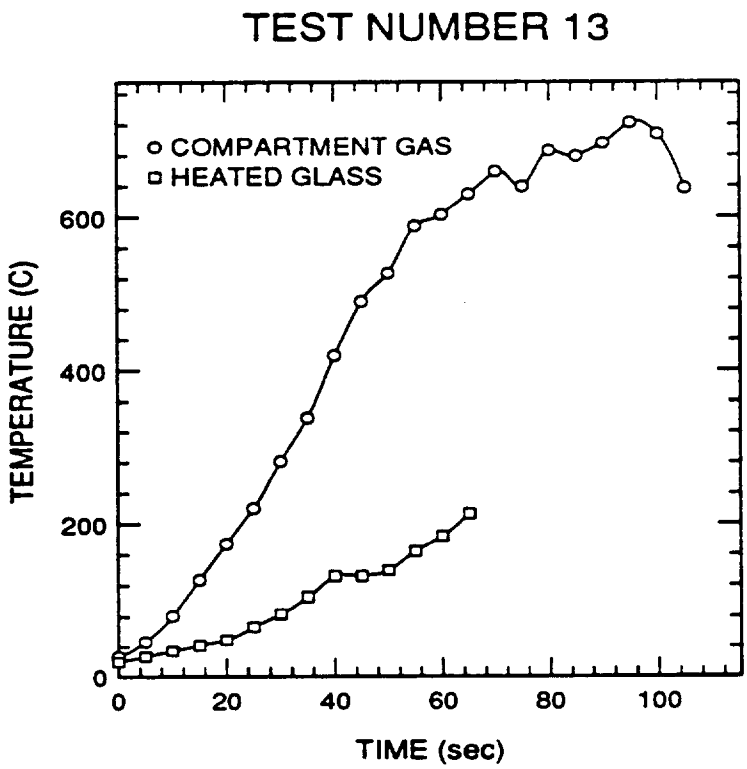


Top: Edge-Protected Window Test (8" x 8" Pan Fire)
Bottom: Edge-Protected Window Test (8" x 8" Pan Fire)

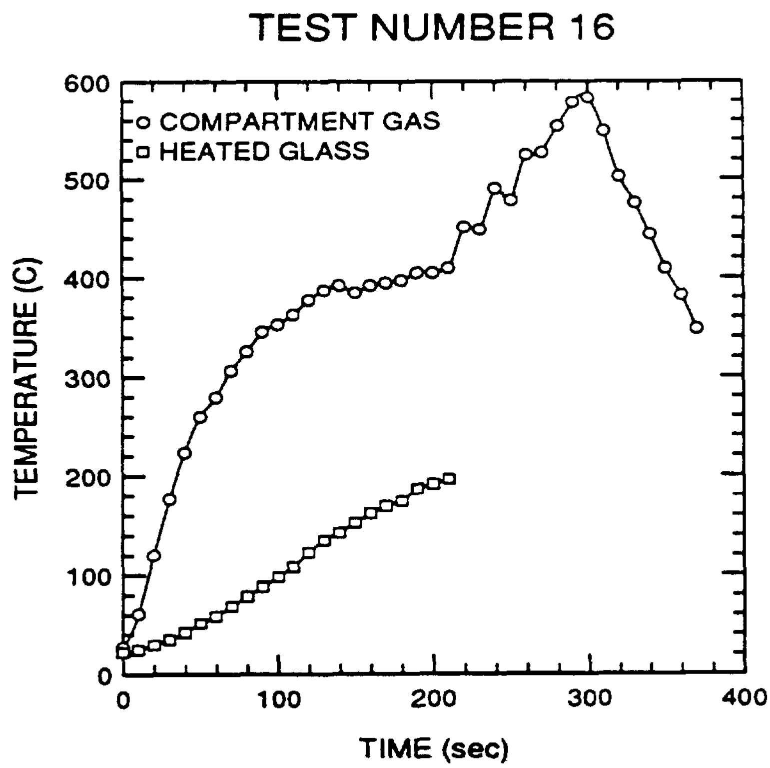


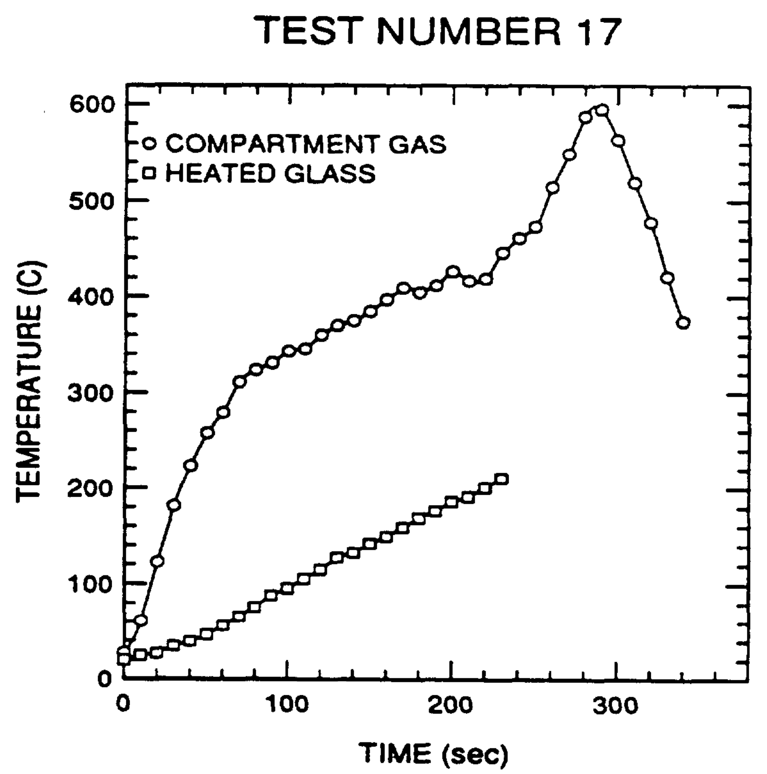
Edge-Protected Window Test (8" x 4" Pan Fire)





Top: Edge-Unprotected Window Test (12" x 8" Pan Fire)
Bottom: Edge-Unprotected Window Test (12" x 8" Pan Fire)





Top: Edge-Unprotected Window Test (8" x 8" Pan Fire)
Bottom: Edge-Unprotected Window Test (8" x 8" Pan Fire)

APPENDIX B

This appendix contains the numerical Time-Temperature histories for all seventeen window breakage tests. Tests number 1-11 are the edge-protected listings and tests 12-17 are the edge-unprotected results.

TEST NUMBER 1

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	0.9	22	0.8	20
5	0.9	22	1.0	25
10	0.9	22	1.1	27
15	0.9	22	1.3	32
20	0.9	22	1.4	35
25	0.9	22	1.7	42
30	0.9	22	2.1	51
35	0.9	22	2.5	61
40	0.9	22	3.1	76
45	0.9	22	3.6	88
50	0.9	22	4.3	105
55	0.9	22	4.8	118

TEST NUMBER 2

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	0.9	22	0.8	20
5	0.9	22	1.0	25
10	0.9	22	1.3	32
15	0.9	22	1.7	42
20	0.9	22	2.0	50
25	0.9	22	2.5	61
30	0.9	22	3.0	74
35	0.9	22	3.5	86
40	0.9	22	4.1	101
45	1.0	25	4.8	117
50	1.0	25	5.3	130
56	1.1	27	6.4	159

TEST NUMBER 3

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.1	27	0.9	22
5	1.1	27	1.0	25
10	1.1	27	1.2	29
15	1.2	29	1.5	37
20	1.2	29	1.9	47
25	1.2	29	2.1	51
30	1.2	29	2.5	61
35	1.2	29	3.0	74
40	1.3	32	3.6	88
45	1.3	32	4.2	103
48	1.3	32	4.7	115

TEST NUMBER 4

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.0	25	0.9	22
10	1.0	25	1.1	27
20	1.0	25	1.4	35
30	1.0	25	1.8	44
40	1.0	25	2.1	51
50	1.0	25	2.6	64
60	1.0	25	3.1	76
70	1.0	25	3.5	86
80	1.0	25	3.9	96
90	1.1	27	4.1	100
100	1.1	27	4.5	110

Test 1: Edge-Protected Window (12" x 8" Pan Fire)
Test 2: Edge-Protected Window (12" x 8" Pan Fire)
Test 3: Edge-Protected Window (12" x 8" Pan Fire)
Test 4: Edge-Protected Window (8" x 8" Pan Fire)

TEST NUMBER 5

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.2	29	0.9	22
10	1.2	29	1.1	27
20	1.2	29	1.3	32
30	1.2	29	1.6	40
40	1.3	32	2.0	50
50	1.3	32	2.4	59
60	1.3	32	2.9	71
70	1.3	32	3.3	81
80	1.3	32	3.8	93
90	1.4	35	4.2	103
100	1.4	35	4.8	117
110	1.4	35	5.4	132
112	1.4	35	5.5	135

TEST NUMBER 6*

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	0.9	22	0.8	20
10	-	-	1.1	27
20	-	-	1.3	32
30	-	-	1.5	37
40	-	-	1.8	44
50	-	-	2.1	51
60	-	-	2.5	61
70	-	-	2.8	69
80	-	-	3.3	81
90	-	-	3.7	91
100	-	-	4.2	103
109	1.4	35	4.7	115

* Thermocouple was displaced during test but reset before breakage

TEST NUMBER 7

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.0	25	1.0	25
10	1.0	25	1.1	27
20	1.0	25	1.2	29
30	1.0	25	1.4	35
40	1.0	25	1.6	40
50	1.0	25	1.9	47
60	1.0	25	2.2	55
70	1.0	25	2.5	61
80	1.1	27	2.8	69
90	1.1	27	3.2	79
100	1.1	27	3.5	86
110	1.1	27	3.9	96
120	1.1	27	4.2	103
128	1.2	29	4.5	110

TEST NUMBER 8

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	0.9	22	0.7	18
10	0.9	22	0.9	22
20	0.9	22	1.0	25
30	0.9	22	1.3	32
40	0.9	22	1.5	37
50	1.0	25	2.2	55
60	1.0	25	2.3	57
70	1.0	25	2.5	61
80	1.1	27	3.0	74
90	1.1	27	3.5	86
100	1.2	29	3.7	91
110	1.2	29	4.1	101
120	1.3	32	4.7	115
130	1.4	35	5.2	127
133	1.4	35	5.4	132

Test 5: Edge-Protected Window (8" x 8" Pan Fire)
Test 6: Edge-Protected Window (8" x 8" Pan Fire)
Test 7: Edge-Protected Window (8" Round Pan Fire)
Test 8: Edge-Protected Window (8" Round Pan Fire)

TEST NUMBER 9

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.0	25	0.8	20
20	1.0	25	0.9	22
40	1.0	25	1.1	27
60	1.1	27	1.4	35
80	1.1	27	1.5	37
100	1.1	27	1.7	42
120	1.1	27	2.0	50
140	1.1	27	2.1	51
160	1.2	29	2.4	59
180	1.2	29	2.5	61
200	1.3	32	2.6	64
220	1.3	32	2.8	69
240	1.3	32	3.1	76
260	1.4	35	3.2	79
280	1.4	35	3.5	86
300	1.4	35	3.6	88
320	1.5	37	3.8	93
340	1.5	37	3.9	96
350	1.6	40	4.1	101

TEST NUMBER 10

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.6	40	2.7	67
20	1.6	40	2.9	71
40	1.7	42	3.1	76
60	1.7	42	3.2	79
80	1.7	42	3.3	81
100	1.7	42	3.4	84
120	1.7	42	3.5	86
140	1.7	42	3.7	91
160	1.7	42	3.9	96
180	1.8	44	4.0	98
200	1.8	44	4.1	101
220	1.8	44	4.3	105
240	1.8	44	4.6	113
260	1.8	44	4.8	118
280	1.9	47	5.0	122
300	1.9	47	5.2	127
320	1.9	47	5.4	132
330	2.0	50	5.6	137

TEST NUMBER 11

TIME s	EDGE TEMP mv	EDGE TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.1	27	0.7	18
20	1.1	27	1.1	27
40	1.1	27	1.3	32
60	1.1	27	1.6	40
80	1.1	27	1.7	42
100	1.2	29	1.9	47
120	1.2	29	2.1	51
140	1.2	29	2.4	59
160	1.2	29	2.6	64
180	1.2	29	2.8	69
200	1.3	32	2.9	71
220	1.3	32	3.2	79
240	1.3	32	3.3	81
260	1.3	32	3.5	86
280	1.4	35	3.7	91
300	1.4	35	3.9	96
320	1.4	35	4.1	101
340	1.5	37	4.2	103
360	1.5	37	4.4	108
380	1.5	37	4.7	115
400	1.5	37	4.8	118
420	1.6	40	4.7	115
440	1.6	40	4.6	113
460	1.6	40	4.6	113
464	1.6	40	4.6	113

Test 9: Edge-Protected Window (8" x 4" Pan Fire)
Test 10: Edge-Protected Window (8" x 4" Pan Fire)
Test 11: Edge-Protected Window (8" x 4" Pan Fire)

TEST NUMBER 12

TIME s	GAS TEMP mv	GAS TEMP C	CENTER TEMP mv	CENTER TEMP C
0	0.8	20	0.7	18
5	1.3	32	0.8	20
10	2.5	61	1.0	25
15	4.2	103	1.1	27
20	5.8	142	1.3	32
25	7.3	180	1.5	37
30	9.9	244	1.8	44
35	12.1	298	2.2	55
40	13.7	336	2.6	64
45	15.5	379	3.0	74
50	17.4	424	3.7	91
55	18.6	453	4.1	101
60	20.0	485	4.9	120
65	21.4	518	5.7	140
70	23.8	575	6.6	162
75	25.8	622	7.5	184
80	27.2	655		
85	28.8	693		
90	31.3	753		
95	32.1	772		
100	33.3	801		

TEST NUMBER 13

TIME s	GAS TEMP mv	GAS TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.1	27	0.8	20
5	1.9	47	1.1	27
10	3.3	81	1.4	35
15	5.2	127	1.7	42
20	7.1	175	2.0	50
25	9.0	222	2.7	67
30	11.5	283	3.4	84
35	13.8	339	4.3	105
40	17.1	417	5.4	132
45	20.0	485	5.4	132
50	21.5	521	5.7	140
55	24.0	579	6.7	165
60	24.6	593	7.5	185
65	25.7	619	8.7	215
70	26.9	648		
75	26.1	629		
80	28.0	674		
85	27.7	667		
90	28.4	683		
95	29.5	709		
100	28.9	695		
105	26.0	626		

Test 12: Edge-Unprotected Window (12" x 8" Pan Fire)
Test 13: Edge-Unprotected Window (12" x 8" Pan Fire)

TEST NUMBER 14

TIME s	GAS TEMP mv	GAS TEMP C	CENTER TEMP mv	CENTER TEMP C
0	0.8	20	0.8	20
5	1.4	35	1.0	25
10	2.4	59	1.3	32
15	3.8	93	1.4	35
20	5.2	127	1.8	44
25	6.7	165	2.0	50
30	8.4	207	2.5	61
35	10.2	252	3.1	76
40	11.7	288	3.5	86
45	13.4	329	4.0	98
50	15.1	370	4.7	115
55	16.7	408	5.3	130
60	18.4	448	6.2	152
65	20.4	495	7.0	172
70	22.4	542	7.9	195
75	24.8	598		
80	26.5	638		
85	28.0	674		
90	29.0	697		
95	29.8	717		

TEST NUMBER 15

TIME s	GAS TEMP mv	GAS TEMP C	CENTER TEMP mv	CENTER TEMP C
0	0.9	22	0.8	20
10	2.3	57	1.0	25
20	4.7	115	1.1	27
30	8.1	200	1.5	37
40	10.9	269	1.9	47
50	12.2	300	2.3	57
60	12.4	305	2.6	64
70	12.9	317	3.0	74
80	14.0	344	3.5	86
90	14.9	365	4.1	101
100	15.8	386	4.6	113
110	16.7	408	5.3	130
120	16.7	408	5.6	137
130	16.9	412	6.0	147
140	17.4	424	6.5	159
150	17.5	427	6.9	170
160	17.6	429	7.3	180
170	17.9	436	7.9	195
180	17.9	436	8.1	200
190	18.1	441	8.3	205
200	19.2	467	8.9	220
210	20.1	488		
220	22.2	537		
230	22.9	553		
240	24.4	588		
250	24.2	584		
260	23.5	568		
270	22.0	532		
280	19.9	483		
290	17.9	437		
300	15.7	384		
310	14.3	351		

Test 14: Edge-Unprotected Window (12" x 8" Pan Fire)
Test 15: Edge-Unprotected Window (8" x 8" Pan Fire)

TEST NUMBER 16

TIME s	GAS TEMP mv	GAS TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.1	27	0.9	22
10	2.5	57	1.0	25
20	4.9	120	1.2	29
30	7.2	177	1.4	35
40	9.1	225	1.7	42
50	10.6	261	2.1	51
60	11.4	281	2.4	59
70	12.5	308	2.8	69
80	13.3	327	3.2	79
90	14.1	346	3.6	88
100	14.4	353	4.0	98
110	15.4	377	5.0	122
120	15.8	386	5.5	135
130	16.0	391	5.8	142
140	15.7	384	6.2	152
150	16.0	391	6.6	164
160	16.1	393	6.9	170
170	16.2	396	7.1	175
180	16.5	403	7.6	187
190	16.5	403		
200	16.7	408		
210	18.4	448		
220	18.3	445		
230	20.0	485		
240	19.5	474		
250	21.4	518		
260	21.5	521		
270	22.6	546		
280	23.6	570		
290	23.8	575		
300	22.4	542		
310	20.5	497		
320	19.4	471		
330	18.1	441		
340	16.7	408		
350	15.6	382		
360	14.2	348		

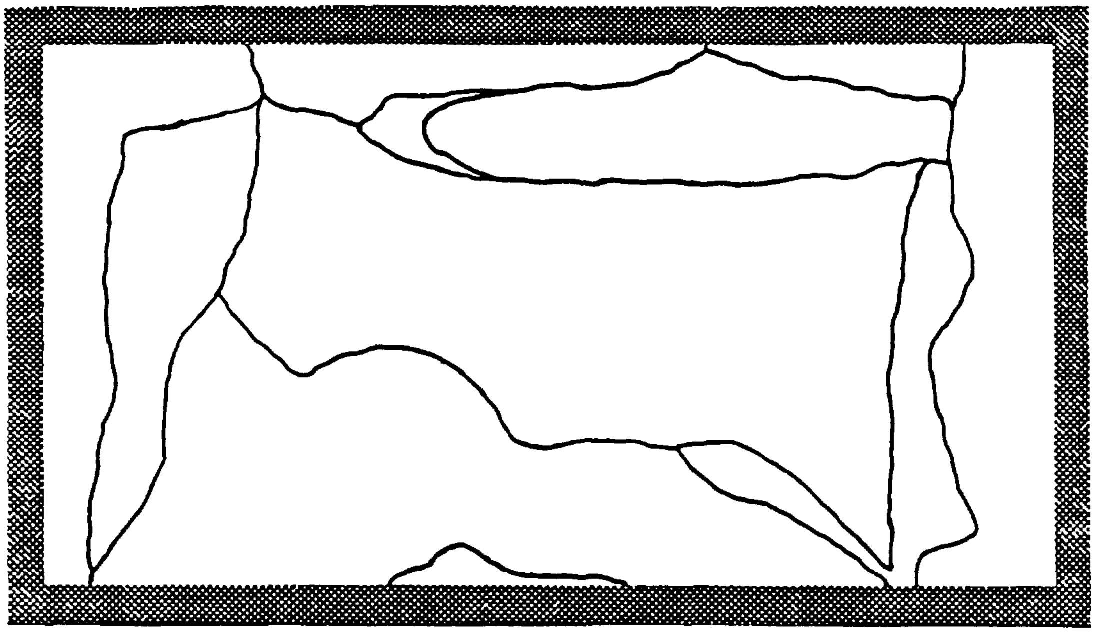
TEST NUMBER 17

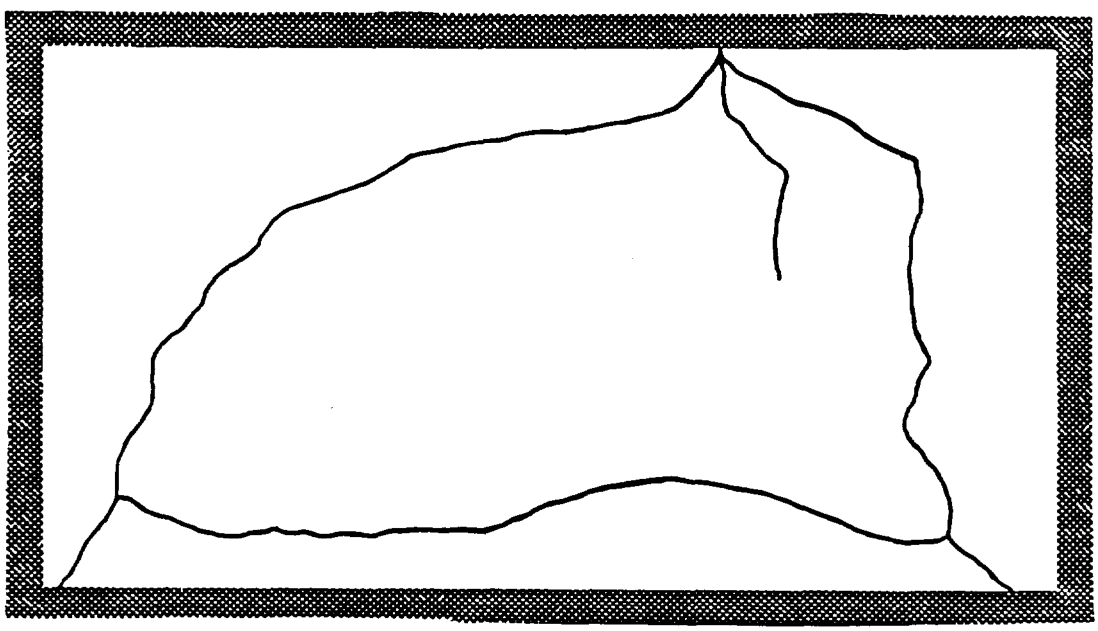
TIME s	GAS TEMP mv	GAS TEMP C	CENTER TEMP mv	CENTER TEMP C
0	1.1	27	0.8	20
10	2.5	61	1.0	25
20	5.0	122	1.1	27
30	7.4	182	1.4	35
40	9.1	225	1.6	40
50	10.5	259	1.9	47
60	11.4	281	2.3	57
70	12.7	312	2.7	67
80	13.2	324	3.1	76
90	13.5	332	3.6	88
100	14.0	344	3.9	96
110	14.1	346	4.3	105
120	14.7	360	4.7	115
130	15.1	370	5.2	127
140	15.3	374	5.4	132
150	15.7	384	5.8	142
160	16.2	396	6.1	150
170	16.7	408	6.5	160
180	16.5	403	6.9	170
190	16.8	410	7.2	177
200	17.4	424	7.6	187
210	17.0	415		
220	17.1	417		
230	18.2	443		
240	18.8	457		
250	19.3	469		
260	21.0	509		
270	22.4	542		
280	24.0	579		
290	24.3	586		
300	23.0	556		
310	21.2	514		
320	19.5	474		
330	17.2	420		
340	15.3	374		

Test 16: Edge-Unprotected Window (8" x 8" Pan Fire)
Test 17: Edge-Unprotected Window (8" x 8" Pan Fire)

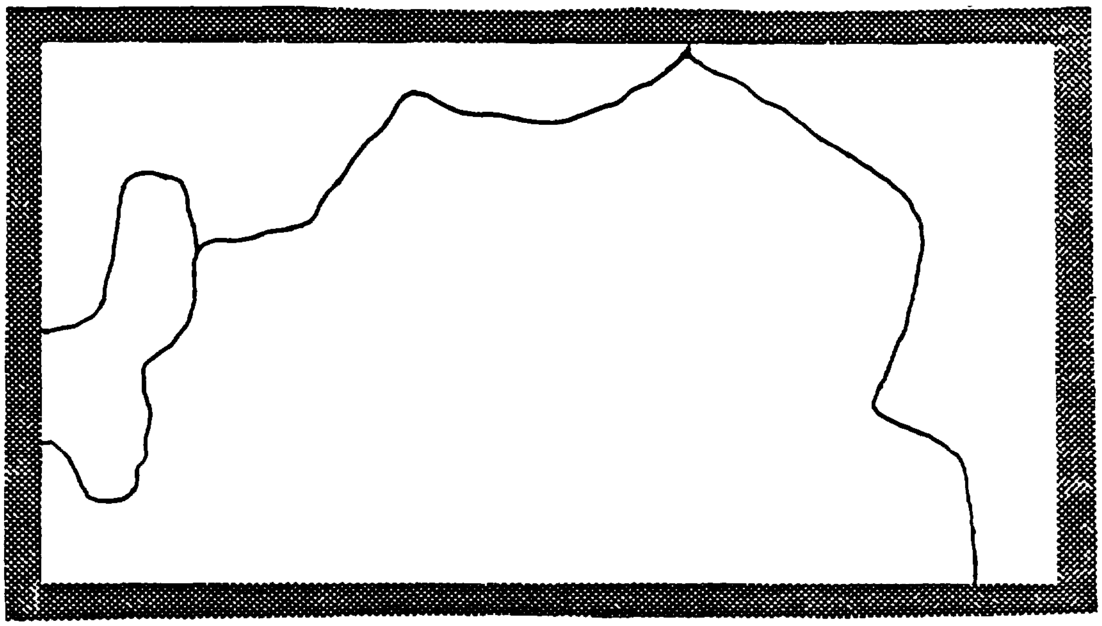
APPENDIX C

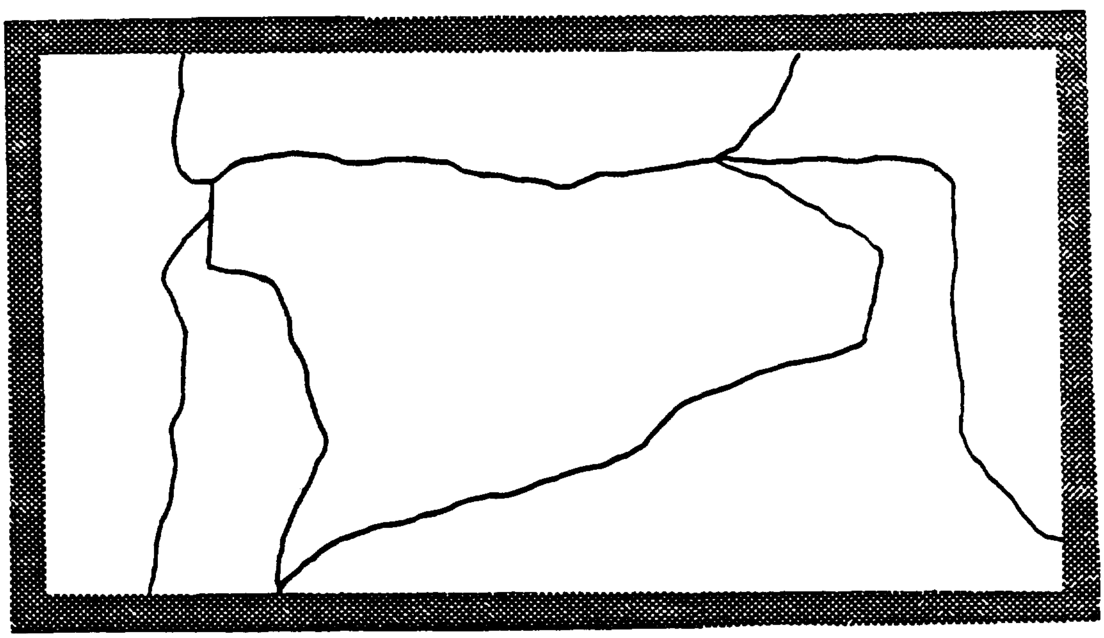
This appendix contains the window breakage patterns that were not presented in chapter 3. There were six remaining edge-protected breakage patterns and two from the edge-unprotected tests.



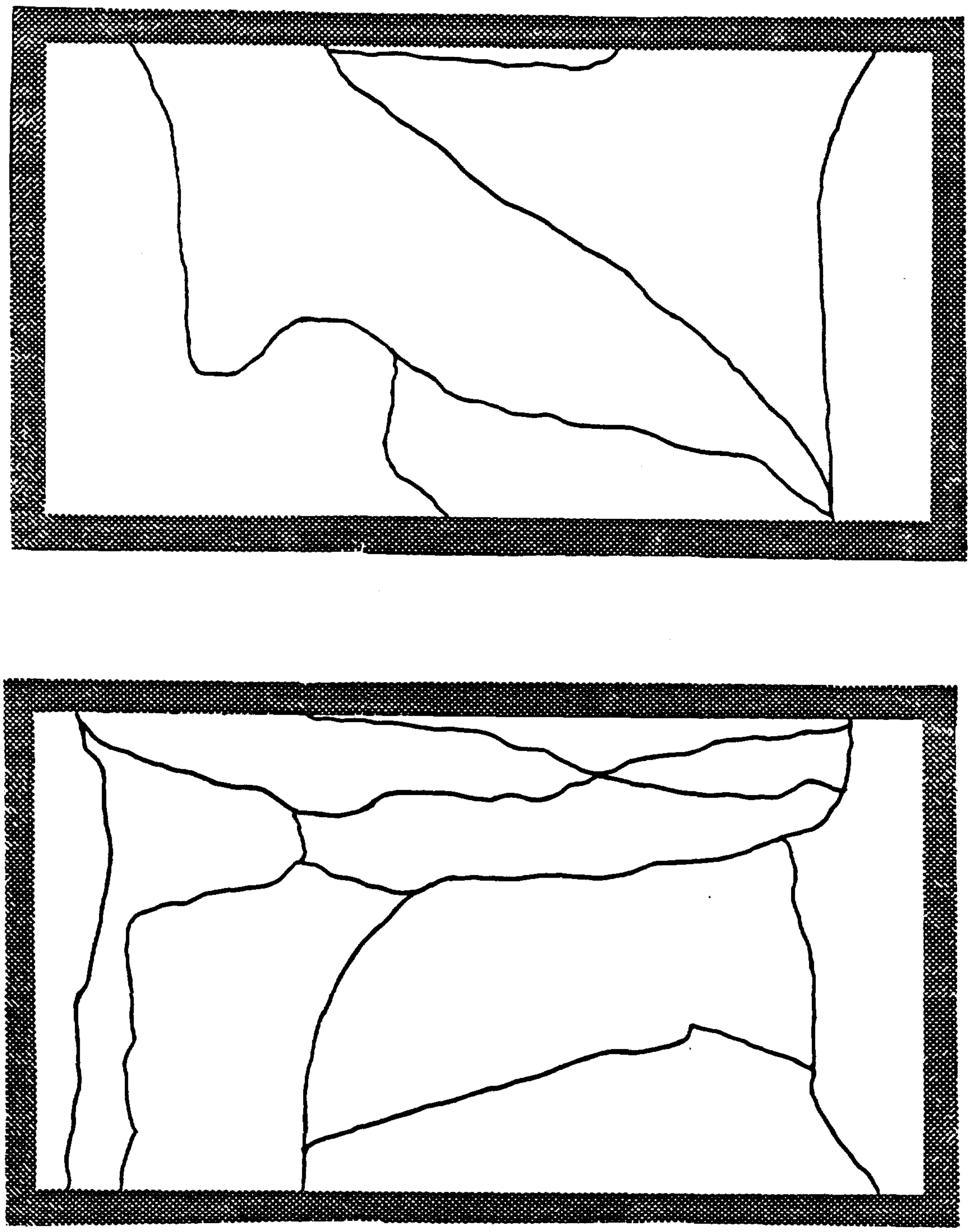


Top: Edge-Protected Breakage Pattern (Test Number 1)
Bottom: Edge-Protected Breakage Pattern (Test Number 3)

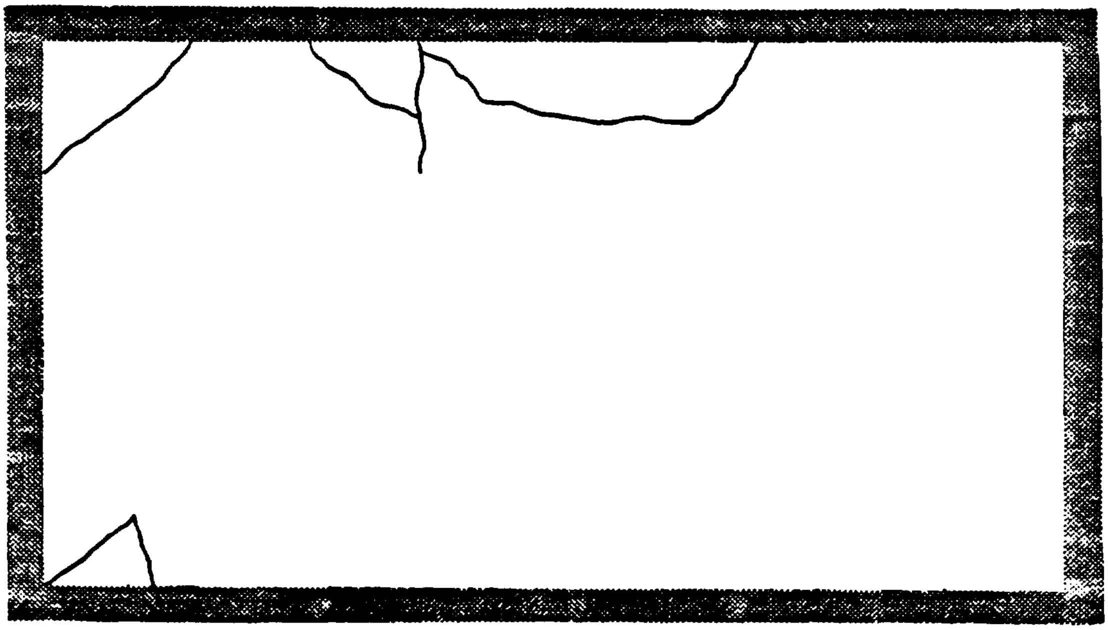


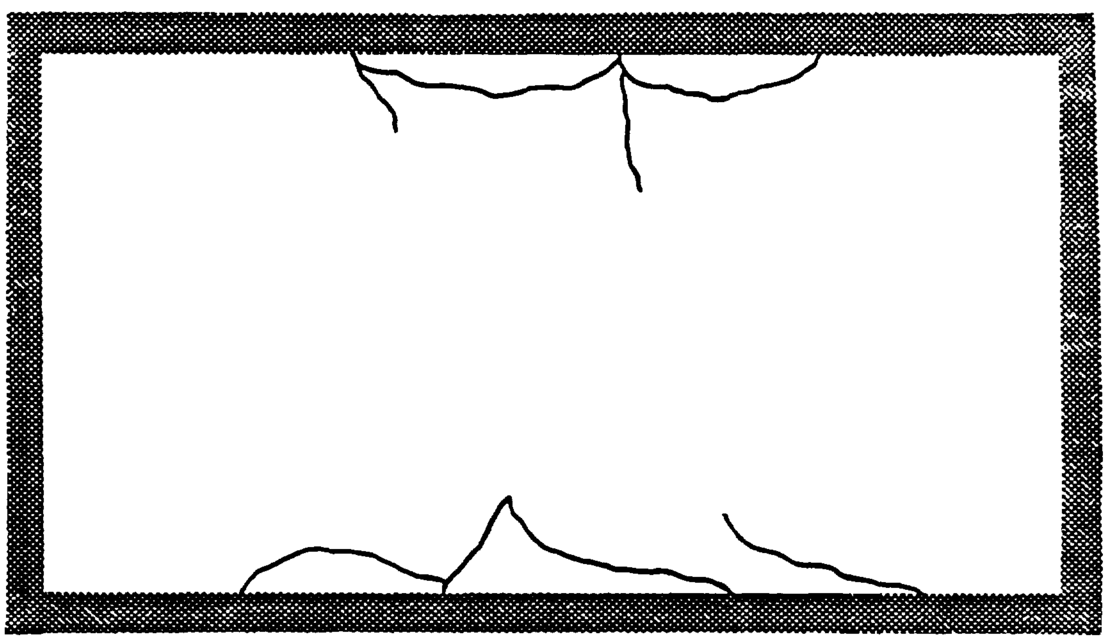


Top: Edge-Protected Breakage Pattern (Test Number 4)
Bottom: Edge-Protected Breakage Pattern (Test Number 5)



Top: Edge-Protected Breakage Pattern (Test Number 6)
Bottom: Edge-Protected Breakage Pattern (Test Number 8)





Top: Edge-Unprotected Breakage Pattern (Test Number 16)
Bottom: Edge-Unprotected Breakage Pattern (Test Number 17)

APPENDIX D

This appendix contains the results from the heat transfer analysis performed to determine the true edge temperatures. The edge thermocouple was actually measuring temperatures at a point 1 cm from the window edge.

A 1-D heat transfer model, incorporating convection and conduction, was used to solve for the true edge temperature values:

$$(\kappa/\text{delt})*(T_o - Te) = h*(Te - Ta)$$

where:

κ	is the thermal conductivity of glass
delt	is the distance from the edge to the thermocouple
h	is the convection coefficient
T_o	is the thermocouple temperature
Ta	is the air temperature
Te	is the true edge temperature

With the air temperature **Ta** = 20C, **κ** = 0.78 W/m, **h** = 4.5 W/m^2, and **delt** = 0.01 m, the true edge temperatures were calculated and are listed along with the thermocouple measurements:

Insulated Edge Temperatures

Measured Temp (C)	Actual Temp (C)
22	22
27	27
27	27
29	29
32	31
35	34
35	34
35	34
40	39
50	48

VITA

Michael J. Skelly was born on October 31, 1965 in Suffern, New York. He grew up in the nearby town of Nanuet and graduated from the senior high school there in 1983.

In the fall of 83, he enrolled at the State University of New York at Plattsburgh and attended school there for two years. He majored in pre-engineering and also found time to compete for the swim team.

He was accepted into Virginia Tech for the fall of 85. He was originally enrolled as an Aerospace and Ocean engineering major. He subsequently switched into ESM and then, finally, found his way into the Mechanical Engineering department. He graduated Magna Cum Laude in June of 87.

He stayed in Blacksburg during that summer and worked for Dr. Roby. He eventually decided to go to graduate school there and officially enrolled in August of that summer. He graduated in February, 1989. Currently, he is considering returning to school to pusue another degree.

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

An experimental investigation has been completed which studied the breaking of window glass by fire. The experiments were carred out in a specially designed compartment to achieve two-layer flows characteristic of normal building fires. The experimental data was collected from two test groups: the first for windows with their edges insulated from the fire (edge-protected) and the second for windows uniformly heated by the fire (edge-unprotected). The results of the edge-protected window tests indicated that the glass breakage was caused by a critical temperature difference between the central heated portion of the pane and the glass edge. The experimental work showed the critical value to be approximately 90C. After the material properties of the glass were determined, the theoretical findings of Keski-Rahkonen were used to obtain a value of 70C; the difference attributed to radiative heating. The test results also demonstrated a distinctive loss of integrity by the windows. When breakage occurred, the cracks spread throughout the glass, joined together and caused at least partial collapse of the pane. The results from the edge-unprotected window tests were quite different. There were relatively few cracks developed and almost no propagation across the glass. Consequently, there was no window collapse in any of these cases. The breakage did initiate at a consistent glass temperature value, however, the mechanism for these tests is now known.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

building fires; fire tests; glass; radiant heating

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