WINDOW BREAKAGE INDUCED BY EXTERIOR FIRES

by

Frederick W. Mowrer
Department of Fire Protection Engineering
University of Maryland
College Park, MD 20742, USA

Reprinted from the Second (2nd) International Conference on Fire Research and Engineering (ICFRE2), August 3-8, 1997, Gaithersburg, MD. Proceedings. Sponsored by the National Institute of Standards and Technology (NIST) and Society of Fire Protection Engineers (SFPE). Published by the Society of Fire Protection Engineers, Boston, MA, 1998.

WINDOW BREAKAGE INDUCED BY EXTERIOR FIRES

Frederick W. Mowrer, Ph.D.
Department of Fire Protection Engineering
University of Maryland
College Park, MD 20742

Abstract

One pathway for exterior fires to penetrate building envelopes is through windows and other glazed openings that have been broken by fire-induced stresses. A number of small- and large-scale experiments have been conducted to evaluate the performance of various window assemblies, glazing materials and potential protective treatments under the influence of imposed radiant heat fluxes ranging from 0.2 to 1.8 W/cm^2. Window assemblies include single- and double-pane windows with wood, vinyl and vinyl-clad wood frames. Glazing materials include ordinary single- and double-strength plate glass, tempered glass, a heat-resistant ceramic glass and a wind-resistant laminated glass. Potential protective treatments include insect screens, vinyl film sun shades, aluminum foil and reflective paint. The application of aluminum foil over the exterior side of a window was found to be an effective treatment to prevent window breakage induced by an exterior fire. This simple treatment could be implemented by homeowners or other occupants of existing buildings in advance of an approaching exterior fire. Tempered glass and heat-resistant ceramic glass did not break under the influence of the imposed heat fluxes; mounted in a suitable fire resistant frame, they could be candidates for use in new windows where exposure to an exterior fire is anticipated. Vinyl-frame windows did not perform well under the exposure of imposed heat fluxes. The vinyl frames and sashes of these windows lost strength, distorted and sagged, permitting openings to develop even when the glazing remained intact. Consequently, vinyl-frame windows would not be suitable for use, even with fire resistant glazing materials.

Keywords: glass breakage; window fire tests; building envelope; wildland-urban interface

INTRODUCTION

Fire transmission from the exterior to the interior of a building is a significant aspect of wildland-urban interface fires, earthquake-induced fires and other conflagrations in developed areas. Exterior fires may penetrate a building envelope via a number of pathways, including through windows and other glazed openings. This mode of fire transmission is the subject of this study. The purpose of this study is to identify and assess potential methods, including occupant self-help strategies, to improve residential window performance in response to exterior fires. The methods are intended to be consistent with the overall level of protection of the building envelope.

The fire scenario contemplated here is a wildland or other exterior fire approaching a building from some distance, such that the exposure to the target building envelope is a fairly uniform radiant heat flux. For the performance of windows to be critical, this imposed heat flux must be high enough to break the window, but too low to ignite the siding, eaves, roof or other combustible exterior elements. The broken window then provides a potential pathway for burning brands to enter the building and ignite light combustible interior furnishings, such as window treatments, upholstered furniture or bedding.

Failure mechanisms and potential remedial measures for windows exposed to uniform radiant heat fluxes have been addressed experimentally. This experimental program is described along with observations, findings and conclusions based on the experiments. A number of small- and real-scale experiments have been performed. Small-scale screening experiments with representative window assemblies and various treatments have been conducted to evaluate expected performance under simulated radiant exposure conditions and to identify potential treatments to prevent exterior fire-induced window breakage and fire transmission to the interior. Baseline real-scale tests using commercially available residential double-hung window assemblies have also been conducted to evaluate the performance of real-scale residential windows and to assess the applicability of the small-scale experiments. The treatments that seemed most promising based on the screening experiments were then subjected to real-scale exposures using commercially available residential window assemblies.

Previous research on window breakage under fire exposure is reviewed. Most of this previous work has addressed glass exposure to interior fires, not to exterior fires. The distinction is in the exposure conditions to which the window is subjected. In interior fires a layer of hot, buoyant gases forms beneath the ceiling and descends, subjecting the inside of the windows to a two-layer convective and radiative environment. In exterior fires, other than facade fires, the fire source is typically located some distance from the exposed window and consequently the exterior of the window is subjected to fairly uniform, purely radiative heating. This changes to combined convective and radiative heating when flames contact the window, as in floor-to-floor fire spread along a building facade. This research has focused on the case of purely radiative, fairly uniform exposure of the exterior side of window assemblies. Direct flame impingement on a window is not addressed here.

BACKGROUND

A number of investigators have studied glass breakage in compartment fires. Emmons (1986) pointed out that very little was known scientifically about this topic. He referred to a senior thesis paper prepared at Harvard by Barth and Sung (1977) as the first scientific study of this topic. Subsequent to Emmons's identification of this topic as one of many outstanding issues in fire science, experimental and theoretical studies of window breakage due to fire have been conducted by Keski-Rahkonen (1988, 1991), Pagni (1988) and Joshi (1991), Joshi and Pagni (1994, 1994a), Skelly, et al. (1991), and Silcock and Shields (1993).

These studies have addressed the response of window glass to interior compartment fires. In this scenario, an enclosure fire produces a heat flux on a window assembly from the inside. The window assembly consists of a plate of glass supported in a frame such that the frame shields the border of the glass from the incident heat flux. The heat flux absorbed by the field of the glass causes the exposed glass to heat up, while the shielded glass border remains cool. The temperature difference between the glass field and the glass border induces tension stresses in the cool glass border as the field tries to expand but is constrained by the border. With sufficient heating, these thermally induced stresses exceed the yield stress of the glass and the glass cracks.

In this scenario of a window in a frame, the glass initially cracks at points of stress concentration along its edge. This is typically at locations where imperfections exist, such as at notches caused by cutting of the glass, or where the glass is already under some stress, such as at locations where glazing points hold the glass in place. Once the glass begins to fail, a bifurcating fracture pattern typically develops, with cracks propagating from the perimeter of the glass into the field. Cracks may merge in the field of the glass and may fully surround sections of the glass. This sometimes leads to some or all of the glass falling out of the window, causing a new vent to occur in the compartment boundary. In other cases, however, the glass fractures but remains in place. The conditions under which window glass will crack and fall out remain unresolved.

Concern about bushfires and wildland-urban interface fires has resulted in at least two experimental evaluations of window performance under exterior fire conditions. As a result of the 'Ash Wednesday' fire in Australia on 16 February 1983, McArthur (1991) undertook an investigation of the performance of aluminum- and timber-framed windows subjected to a furnace exposure intended to represent an exterior fire. Cohen (1994) has begun to address experimentally window breakage from exterior fires in support of the Structural Ignition Assessment Model (SIAM) being developed by Cohen and coworkers at the USDA Forest Service (1991) to address wildland-urban interface fires.

Pagni (1988) suggests a simple strain criterion for the glass temperature increase required to break windows in fires, $\Delta T = g(\sigma_b / E\beta)$, where g is a geometric factor of order one, σ_b is the tensile strength at breakage, E is Young's Modulus of Elasticity for the glass and β is the thermal coefficient of linear expansion. Pagni and Joshi (1991) report representative window glass (soda-lime) properties gleaned from the literature and calculate breaking strains and associated temperature increases at breakage based on these properties:

$\beta\times10^6$ (K^{-1})	$\sigma_b\times10\text{-}7$ (N/m^2)	$E\times10^{-7}$ (N/m^2)	strain (%)	ΔT (K)
9.5	4.7	7.0	0.07	70
9.2	2.0-5.0	7.2	0.03-0.07	30-75
8.5	5.5-13.8	7.24	0.08-0.19	90-220
9.0	3.5-7.0	7	0.05-0.10	55-110

Pagni and Joshi note that the relatively large range of values is due to the uncertainty in the tensile stress at breakage, σ_b. Joshi and Pagni (1994a) observe that glass strength depends strongly on the treatment and handling of its surface, where tiny flaws lead to weakening and failure by brittle fracture. Larger surfaces are more likely to have more severe flaws, so the strength of glass generally decreases with increasing size.

EXPERIMENTAL PROGRAM

The experimental program undertaken to evaluate window breakage induced by exterior fires includes two elements:

- Small-scale screening experiments of representative glazing systems and potential protective treatments;
- Large-scale experiments of baseline configurations and promising protective treatments using commercially available residential double-hung window assemblies.

Small-scale screening experiments

Seventy-two small-scale screening experiments were conducted in the gas-fired radiant heat exposure apparatus shown schematically in Figure 1. These experiments were conducted to evaluate the performance of different exemplar glazing systems and potential protective treatments under imposed radiant heat fluxes ranging from approximately 0.2 to 1.6 W/cm^2. At the low end of this range, windows did not break under the imposed heat flux, while at the high end, the wood frames used for the window assemblies charred and smoked, and in some cases smoldered, indicating the onset of ignition.

The gas-fired radiant heat exposure apparatus used for the small-scale experiments includes two vertical banks of gas-fired burners located opposite the test window assembly. Each bank consists of five porous ceramic panels and measures 38 cm wide by 83 cm high. The panels are each oriented at an angle of 30 degrees with respect to the window assembly to produce a fairly uniform radiant heat flux at the window assembly. The side panels were covered with aluminum foil to reflect heat back into the test chamber and thus maximize exposure to the test assembly. The outside walls of the test chamber consist of water-cooled copper plates. Test window assemblies are oriented at the center height of the gas panels. A shutter protects the test assemblies from the incident heat flux until it is opened at the start of a test.

The glazing materials evaluated include single-strength (SS) and double-strength (DS) ordinary plate glass, tempered glass, a heat-resistant ceramic glass and a wind-resistant laminated glass. Potential protective treatments evaluated include insect screening, vinyl film sun shade, aluminum foil and reflective paint. These treatments were applied to the exposed side of the window assembly, except for the vinyl film sun shade tests and two tests in which aluminum foil was attached to the inside (unexposed) side of the window. Table 2 summarizes the different configurations used and results of the small-scale experiments.

Large-scale experiments

Nineteen experiments were conducted with commercially available residential window assemblies. In these experiments, double hung windows, nominally 61 cm wide by 81 cm high, were mounted in the center of a 1.2 m wide by 2.4 m tall wall. The wall and window assemblies were constructed to be representative of typical wood frame residential construction in the United States. The wall frame was constructed with nominal 2x4 lumber. During preliminary calibration experiments, the exterior (exposed) side of the wall was sheathed with 12.7 mm thick gypsum wallboard, but the paper facer degraded under the imposed heat flux, so the gypsum wallboard was replaced with 12.7 mm thick calcium silicate board for subsequent tests. The interior side of the wall assembly was not sheathed.

A number of different commercially-available window assemblies were evaluated. These included single- and double-pane windows with frames of wood, vinyl and vinyl-covered wood. For two of the experiments, the exterior (exposed) side of the windows were covered with aluminum foil. The large-scale experiments are summarized in Table 1.

The windows were subjected to fairly uniform radiant heat fluxes using a large-scale electrical resistance radiant panel described by Ohlemiller, et al (1993). The arrangement of the wall assembly and the large-scale radiant panel is shown schematically in Figure 2. The radiant panel consists of two separate panels nominally 38 cm wide by 198 cm tall. The two panels are oriented at an angle of approximately 15°; the panels are separated by a space approximately 16 cm wide. The radiant panel was positioned to be centered along the vertical centerline of the test wall, with the edges of the panels located 30 cm away from the surface of the test wall. The bottom of the radiant panel is located 30 cm above the floor.

The wall panels were instrumented with four thermocouples and two heat flux meters. For window assemblies with single glazing, two thermocouples were attached to the glass on the exposed side of the upper and the lower panes of the double hung windows, while the other two thermocouples were embedded in the adjacent window frames. The frames were drilled to the depth of the glazing on the unexposed side of the assembly and the thermocouples were inserted in the drilled holes. For window assemblies with double glazing, the four thermocouples were attached to each of the panes of glass, the exposed and unexposed lights of both the top and bottom windows. One of the heat flux meters was used to measure the heat flux being transmitted through the lower window of the double hung window assembly. This meter was placed 5 cm behind the glass at the center of the lower window. The other heat flux meter was used to measure the heat flux at the lower edge of the window assembly along the vertical centerline. For wood-frame windows, this meter was mounted in a hole drilled in the bottom sash of the lower window. For vinyl-frame windows, this meter was mounted in the wall assembly, directly below the window assembly.

OBSERVATIONS AND FINDINGS

A number of observations have been made with respect to the small-scale and large-scale experiments that have been conducted. For the small-scale experiments, these observations include:

- The breakage of ordinary glass in window frames is generally consistent with the theory propounded by Emmons and developed in detail by Pagni and Joshi, although the heating of the window glass shielded by the frame seems to be more significant than considered by Pagni and Joshi. The effect of this is to increase the temperature at breakage of the exposed glass, such that the temperature differences at breakage between the exposed field and the shielded edge are consistent with the values suggested by Pagni and Joshi.

- The critical imposed heat flux needed to cause the single-strength glass windows without protective treatments to fail is somewhere in the range of 0.4 to 0.5 W/cm^2. At lower heat fluxes of approximately 0.33 W/cm^2, these window assemblies did not fail, while at higher heat fluxes, they always failed. Within this critical range, some window assemblies failed, while others did not. For exposed glass supported around its edge in a shielded frame, fracture initiates at the edges, most likely at locations where imperfections or other points of stress concentration exist.

- For single-strength glass windows without protective treatments, the heat load at failure, defined as the product of the imposed heat flux by the breakage time, had an average value of approximately 96 J/cm^2 for cases where glass breakage occurred, and a range of 27 to 161 J/cm^2 for these cases, as shown in Figure 21. While there appears to be a slight trend towards lower heat loads at higher heat fluxes, the scatter in the data make this observation inconclusive. The data scatter is consistent with the range of breakage strengths noted above.

- For single-strength glass windows without protective treatments, the total heat flux transmitted through the glass reached approximately one-third of the radiant flux imposed on the glass as steady-state conditions were approached. For the heat fluxes considered here, this total transmitted flux would be inadequate to cause ignition of light combustibles behind the window, such as draperies or curtains.

- When windows did break in these experiments, the glass remained in place for the most part. Breakage typically occurred with cracks initiating along one or more edges of a window. These cracks would bifurcate in the field of the window. In some cases, cracks with different origins would merge, creating sections of glass completely surrounded by cracks, but these sections typically remained in place nonetheless.

- Breakage did not occur when aluminum foil was applied to the exterior, exposed side of the window. For these cases, the aluminum foil reflected the incident heat back into the test chamber, keeping the window relatively cool. Less than 2% of the imposed heat flux was transmitted through windows for these cases.

- Breakage did occur when aluminum foil was attached to the interior, unexposed side of a window. This breakage occurred when the imposed heat load at breakage was approximately 70-78 J/cm^2, a value approximately 75% of the average value for exposed glass. This result is consistent with the reflection of transmitted heat back into the glass from the unexposed side, which would cause the window to heat up faster and break more quickly. In this case, the transmitted heat flux was less than 2% of the imposed heat flux.

- Breakage occurred when aluminum foil with a 127 mm square hole at the center was attached to the exposed side of the window frame; the imposed heat load at glass failure ranged from 136 to 371 J/cm^2 for these cases. In these cases, the breakage pattern was different from the other cases, suggesting a different failure mechanism. For these cases, the breakage initiated at the center of the window, directly behind the hole in the aluminum foil, with a fracture pattern resembling fish scales, suggesting compression failure rather than tension failure. A few cracks propagated from this central region to the edges of the window.

- Bright aluminum and black fiberglass insect screens attached to the exposed side of the window frame did not prevent glass breakage for single strength windows, but they did increase the average imposed heat load at breakage to approximately 116 J/cm^2, an increase of 21% compared with exposed single strength windows. This increase is consistent with the 'shading factor' provided by insect screens. Both types of insect screen remained in place during exposure. Thus, insect screens may prevent the passage of burning brands through a window opening and may have some benefit where flying brands are the mode of fire transport (Boral, undated).

- Vinyl sun shade film adhered to the unexposed (inside) side of a window did not prevent glass breakage. If anything, the data suggest that this treatment may expedite breakage.

- Neither heat resistant ceramic glass or tempered glass failed when exposed to heat fluxes of approximately 1.6 W/cm^2 for periods of up to 15 minutes. In these experiments, the wood frame and glazing putty began smoking. The wood frames charred under this exposure and the glazing putty puffed up and developed voids, suggesting that failure of the window frame would likely occur before failure of the glazing.

- The application of high temperature silver paint to the exposed side of a window increased the heat load at breakage to 384-525 J/cm^2, approximately a 4- to 5-fold increase compared with unprotected window assemblies.

- The wind-resistant laminated glass, consisting of a thermoplastic film adhered to a single pane of plate glass, demonstrated approximately a 2-fold increase in the heat load at breakage, with an average value of 190 J/cm^2 and a range of 146-238 J/cm^2. Under the imposed heat fluxes, the thermoplastic film softened and delaminated from the glass; thus it would not be expected to hold the glass in place after fracture.

For the large-scale experiments with commercial double-hung residential window assemblies, the following observations are made:

- The single-pane wood-frame windows always failed at heat fluxes above 1.0 W/cm^2 and did not fail at heat fluxes of less than 0.70 W/cm^2. For those cases where failure occurred, the average measured glass temperature at failure was 157C for the upper light and 123C for the lower light. The measured frame temperatures at first failure were 61C for the upper light and 55C for the lower light. Thus, the average temperature differences between the glass and the frame at failure were 96C for the upper light and 68C for the lower light, respectively. The average imposed heat load at failure was 97 J/cm^2 for the upper light and 77 J/cm^2 for the lower light, with a range of 44 to 167 J/cm^2 for the upper light and 42 to 123 J/cm^2 for the lower light, respectively.

- The exposed (outside) lights of double-pane wood-frame and wood-frame with vinyl trim windows failed in all tests of these windows, in which imposed heat fluxes ranged from 1.05 to 1.8 W/cm^2. The average measured temperature at failure was 149C for the upper light and 143C for the lower light, with a range of 134 to 162C for the upper light and 119 to 174C for the lower light, respectively.

- The unexposed (inside) lights of double-pane wood-frame windows failed in all tests of these windows, in which imposed heat fluxes ranged from 1.05 to 1.8 W/cm^2.

- The unexposed (inside) lights of double-pane wood-frame with vinyl trim windows did not fail in any tests of these windows, in which imposed heat fluxes ranged from 1.10 to 1.45 W/cm^2.

- Double-pane vinyl-frame windows failed catastrophically, with the development of large through penetrations caused by sagging and collapse of the window frames, in all tests of these windows. Heat fluxes for these tests ranged from 0.8 to 1.6 W/cm^2.

- For the double-pane vinyl-frame windows, the imposed heat load at breakage of the exposed panes averaged 22 J/cm^2 for the upper light and 61 J/cm^2 for the lower light, with ranges of 16 to 25 J/cm^2 for the upper light and 47 to 68 J/cm^2 for the lower light. The measured temperature at breakage of the exposed panes averaged 97C for the upper light and 145C for the lower light, with a range of 93 to 100C for the upper light and 130 to 161C for the lower light, respectively.

- The unexposed lights of the double-pane vinyl-frame windows did not always fracture, but through penetrations always formed. In some cases, the unexposed lights slipped out of the vinyl sashes as the sashes and frames distorted, sagged and lost strength due to the imposed heat flux. The upper window frames sagged considerably under all imposed heat fluxes, ranging from 0.8 to 1.6 W/cm^2. This sagging permitted through openings to form between the top rail of the window sash and the window frame and between the window glazing and the top rail of the sash. Sagging and distortion of the upper windows would have been worse had the lock between the upper and lower windows not been engaged.

SUMMARY

Failure mechanisms of windows subjected to radiant heating from exterior fires have been addressed experimentally. The performance of such windows has proven to be generally consistent with the theory of glass breakage described by previous investigators. The question of when a broken window will fall out after it breaks remains unanswered. In the experiments conducted for this program, windows tended to remain in place after fracturing, but field experience suggests that broken windows frequently fall out. Further work is needed to investigate this question as well as questions regarding the effects of direct flame impingement on window assemblies.

A number of potential remedial strategies have been considered to prevent or delay glass breakage. For existing window installations, the application of aluminum foil to the outside of the window surface appears to be highly effective. This is a simple remedy that could be implemented by homeowners and other building occupants on relatively short notice. For new installations, the use of tempered glass or ceramic glass appears to offer a high level of protection, without the need for active intervention in the path of an advancing conflagration. Such glazing materials need to be installed in fire resistant window assemblies that will not fail during the expected period of exposure. Vinyl-frame windows are inappropriate for such applications because the vinyl sashes and frames distort and lose strength under the influence of moderate imposed heat fluxes.

Either of these solutions would increase the fire endurance of ordinary windows considerably, to the point where fire transmission through windows becomes much less likely. Without similar upgrades in the fire endurance of other vulnerable fire transmission paths, however, efforts to increase the fire endurance of windows may largely be in vain. Finally, the implications of any upgrades to other fire scenarios should be considered before any changes are implemented.

ACKNOWLEDGEMENTS

This work was conducted with the support of the Building and Fire Research Laboratory at the National Institute of Standards and Technology under contract COMMIP4024. The advice and consideration extended by Doug Walton are gratefully acknowledged. The laboratory supervision provided by Dan Madryzkowski and the laboratory support provided by Bill Twilley, Loren DeLauter and Gary Roadarmel were indispensible.

REFERENCES

Barth, P.K. and H. Sung, 1977, "Glass Fracture under Intense Heating," *Senior Project*, Harvard University, Cambridge, MA.

BORAL, "The Design of Bushfire Resistant Homes," ed. C. Ramsay, J. Barber, T. Crichton and J. Keogh, CSIRO Building Research, Australia.

Cohen, J.D., 1994, "Structural Ignition Assessment Model," presented at Biswell Symposium, Feb. 15-17, 1994, Walnut Creek, CA.

Emmons, H.W., 1986, "The Needed Fire Science," *Fire Safety Science-Proceedings of the First International Symposium*, eds. C.E. Grant and P.J. Pagni, Hemisphere, Washington, DC, pp. 33-53.

Joshi, A.A. and P.J. Pagni, , 1994, "Fire-Induced Thermal Fields in Window Glass. I - Theory," *Fire Safety Journal*, **22** (1), pp. 25-43.

Joshi, A.A. and P.J. Pagni, , 1994a, "Fire-Induced Thermal Fields in Window Glass. II - Experiments," *Fire Safety Journal*, **22** (1), pp. 45-65.

Keski-Rahkonen, O., 1988, "Breaking of Window Glass Close to Fire," *Fire and Materials*, **12**, pp. 61-69.

Keski-Rahkonen, O., 1991, "Breaking of Window Glass Close to Fire, II: Circular Panes" *Fire and Materials*, **15**, pp. 11-16.

McArthur, N.A., 1991, "The Performance of Aluminium Building Products in Bushfires," *Fire and Materials*, **15**, pp. 117-125.

Ohlemiller, T.J., T.G. Cleary, J.E. Brown and J.R. Shields, 1993, "Assessing the Flammability of Composite Materials," *Journal of Fire Sciences*, Vol. 11, No. 4, pp. 308-319.

Pagni, P.J., 1988, "Fire Physics - Promises, Problems, and Progress," *Fire Safety Science-Proceedings of the Second International Symposium*, eds. C.E. Grant and P.J. Pagni, Hemisphere, Washington, DC, pp. 49-66.

Pagni, P.J. and A.A. Joshi, 1991, "Glass Breaking in Fires," *Fire Safety Science-Proceedings of the Third International Symposium*, eds. G. Cox and B. Longford, Hemisphere, Washington, DC, pp. 791-802.

Silcock, G.W. and T.J. Shields, 1993, "An Experimental Evaluation of Glazing in Compartment Fires," *Interflam '93*, pp. 747-756.

Skelly, M.J., R.J. Roby and C.L. Beyler, 1991, "An Experimental Investigation of Glass Breakage in Compartment Fires," *J. of Fire Prot. Engr.*, **3** (1), pp. 25-34.

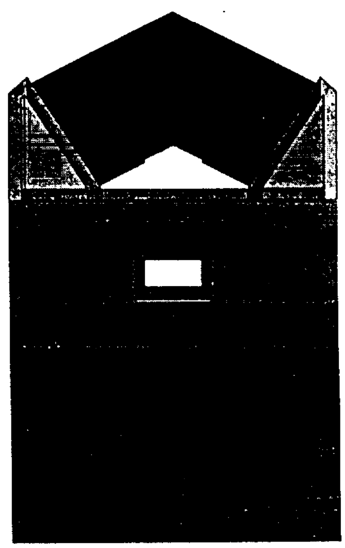

Figure 1. Schematic diagram of small-scale gas-fired radiant exposure apparatus.

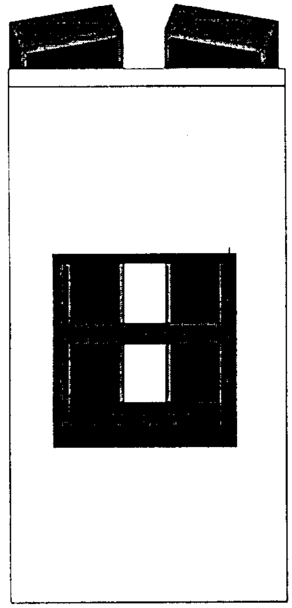

Figure 2. Perspective view of large-scale electric radiant panel apparatus.

Table 1. Summary of large-scale experiments

Test	Window description			Approx.	Initial glass breakage time (s)				Measured temperature at breakage time (C)			
No.	Panes	Frame	Covering	heat flux	Upper light		Lower light		Upper light		Lower light	
	(1 or 2)			(W/cm2)	Outside	Inside	Outside	Inside	Outside	Inside/frame	Outside	Inside/frame
1	1	Wood	None	1.10		#N/A	37	#N/A			83	40
2	1	Wood	None	1.80	90	#N/A	36	#N/A	202	90	110	48
3	2	Wood	None	1.80	32		32	116	157		119	87
4	2	Wood	None	1.10	56		78		138	50	152	52
5	1	Wood	None	0.40	0	#N/A	0	#N/A	128	85	134	113
6	1	Wood	None	0.70	0	#N/A	0	#N/A	181	90	172	134
7	1	Wood	None	0.90	0	#N/A	0	#N/A	228	115	210	116
8	1	Wood	None	1.20	40	#N/A	38	#N/A	119	30	117	34
9	2	Wood	None	1.20	45	295	90	255	142	149	174	118
10	2	Wood	None	1.45	36	201	40	218	162	140	127	131
11	2	Wood	None	1.45	55	224	46	130	158	137	133	87
12	1	Wood	Al foil	1.45	0	#N/A	0	#N/A	45	45	51	46
13	1	Wood	None	1.45	55	#N/A	85	#N/A	150	63	180	96
14	2	Wood/vinyl	None	1.20	50	0	63	0	134	267	155	250
15	2	Wood/vinyl	Al foil	1.45	0	0	0	0	Corrupt data file			
16	2	Wood/vinyl	None	1.45	35	0	37	0	Corrupt data file			
17	2	Vinyl	None	1.20	21	240	39	250	Corrupt data file			
18	2	Vinyl	None	1.60	10	288	42	0	100	172	161	262
19	2	Vinyl	None	0.90	31	0	85	0	93	265	130	246

Table 2. Summary of small-scale experiments

Test	Heat flux (W/cm2)		Break time	Heat load	Glass type	Protective treatment
	Imposed	Transmitted	(s)	(J/cm2)		
G1	1.40	0.54	79	111	DS	None
G2	0.90	0.29	195	176	DS	None
G3	0.95	0.31	129	123	SS	None
G4	0.95	0.31	92	87	SS	None
G5	0.95	0.33	106	101	SS	None
G6	1.00	0.38	115	115	SS	None
G7	1.00	No data	108	108	SS	None
G8	0.50	0.14	> 699	> 300	SS	None
G9	0.73	0.23	153	112	SS	None
G10	0.75	0.24	105	79	SS	None
G11	0.73	0.22	112	82	SS	None
G12	0.72	0.23	204	147	SS	None
G13	1.25	0.43	37	46	SS	None
G14	1.27	0.46	70	89	SS	None
G15	1.25	0.49	92	115	SS	None
G16	1.25	0.49	46	58	SS	None
G17	1.28	0.42	92	118	SS	Brite Al insect screen
G18	1.26	0.42	100	126	SS	Brite Al insect screen
G19	1.25	0.39	94	118	SS	Brite Al insect screen
G20	1.28	0.40	95	122	SS	None
G21	0.56	0.21	245	137	SS	None
G22	0.56	0.21	111	62	SS	None
G23	0.39	No data	380	148	SS	None
G24	0.50	0.18	321	161	SS	None
G25	0.50	0.15	72	36	SS	None
G26	1.18	0.44	71	84	SS	None
G27	1.18	0.01	> 900	> 1062	SS	Al foil
G28	1.15	0.39	117	135	SS	None
G29	1.02	No data	108	110	SS	Brite Al insect screen
G30	1.02	0.37	110	112	SS	Brite Al insect screen
G31	1.17	0.48	76	89	SS	None
G32	1.17	0.47	46	54	SS	None
G33	1.15	0.37	23	26	SS	None
G34	1.17	0.36	82	96	SS	None
G35	1.02	0.31	126	129	SS	Brite Al insect screen
G36	1.02	0.28	76	78	SS	Brite Al insect screen
G37	1.05	0.29	118	124	SS	Black FG insect screen
G38	1.02	0.25	130	133	SS	Black FG insect screen
G39	1.18	0.21	35	41	SS	Vinyl "Sun Shade"
G40	1.18	0.31	81	96	SS	Vinyl "Sun Shade"
G41	1.17	0.44	317	371	SS	Al foil w/5"x5" cutout
G42	1.52	0.45	40	61	SS	None
G43	1.53	0.48	89	136	SS	Al foil w/5"x5" cutout
G44	1.52	0.04	> 900	> 1368	SS	Al foil glued to glass
G45	1.52	0.04	> 900	> 1368	SS	Al foil glued to glass
G46	1.52	0.03	46	70	SS	Al foil glued to glass back
G47	1.52	0.53	110	167	SS	Al foil w/5"x5" cutout
G48	1.52	0.45	52	79	SS	None
G49	0.20	No data	> 1020	> 204	Ceramic	None
G50	0.33	0.12	> 1200	> 396	SS	None
G51	0.34	0.12	> 1200	> 408	SS	None
G52	0.48	0.18	297	141	SS	None
G53	0.48	0.16	208	100	SS	None
G54	0.48	0.19	> 1200	> 576	SS	None
G55	0.50	0.19	> 900	> 450	SS	None
G56	1.57	0.67	> 600	> 942	Ceramic	None
G57	1.56	0.71	> 900	> 1404	Ceramic	None
G58	1.60	No data	> 600	> 960	Tempered	None
G59	1.60	No data	240	384	SS	High temp. silver paint
G60	1.60	No data	54	86	SS	None
G61	1.60	No data	49	78	SS	Al foil glued to glass back
G62	1.60	No data	328	525	SS	High temp. silver paint
T1	1.05	0.40	>1200	> 1260	Tempered	None
T2	1.05	0.40	> 900	> 945	Tempered	None
T3	1.61	0.72	> 900	> 1449	Tempered	None
T4	1.60	0.72	> 900	> 1440	Tempered	None
L1	1.40	No data	104	146	Laminated	None
L2	1.40	No data	107	150	Laminated	None
L3	1.10	No data	142	156	Laminated	None
L4	1.00	No data	237	237	Laminated	None
L5	0.58	No data	364	211	Laminated	None
L6	0.55	No data	433	238	Laminated	None
L7	1.60	No data	136	218	Laminated	Lamination side exposed