Thermal Glass Breakage

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ABSTRACT

The problem considered here is "When does a window exposed to fire become a vent?" Both compartment fires and urban/wildland interface fires provide applications for this work, which was chosen for the 2002 Howard W. Emmons Lecture because he introduced that topic to fire research. Glass breaks when exposed to fire because the temperature difference between the exposed pane and its shaded perimeter produces a strain at the edge due to the excess thermal expansion of the central heated pane. When the stress induced by that strain exceeds the glass breaking stress, a brittle fracture crack is initiated at the edge which travels, usually on multiple paths, through the pane at ~ 1.5 km/s. Practical examples of real fires where glass breaking played a critical role are cited. The literature is reviewed. Multipane windows are discussed. Techniques are presented for calculating the glass breaking time as a boundary condition in field and zone models for fire safe designs. The primary difficulties in application are identifying the pane's proper glass properties and the fire's radiative and convective heating coefficients. Suggested properties at 50°C for the soda lime float glass common in windows include: density $\rho = 2500$ kg/m^3, specific heat capacity $c_p = 820$ J/kgK, thermal conductivity k = 0.95 W/mK, Young's Modulus E = 72 GPa, thermal coefficient of linear expansion $\beta = 9\text{x}10^{-6}$ K^{-1} and breaking stress $\sigma_b = 10$ to 50 MPa. The breaking stress has a wide range because it is a function of the glass edge condition and history. Comparisons are made with experimental results from the Building Research Institute in Japan, the University of Maryland in the USA and the University of Ulster's FireSERT Centre in the UK. The glass fall-out problem is formulated.

KEYWORDS: glass breaking, thermal stresses in glass, compartment fire venting, glass fall-out, boundary conditions, radiation.

NOMENCLATURE

a	apparatus dimension
c_p	specific heat
E	Young's modulus
g	geometry factor of order unity
H	half-length of the window
$H_v(y,z)$	Heaviside function = 0, for y or z shaded, and 1 otherwise
h	heat transfer coefficient
I	absorbed radiant heat flux
k	thermal conductivity
L	glass thickness
ℓ	decay length, length
m	Weibull parameter
q	heat flux
s	shaded length
T	temperature
T_c	$\sigma_b/E\beta$
t	time
x	dimension into glass
y	away from edge
z	along edge
subscripts	
0	fire side of glass pane
L	ambient side of glass pane

b	breakage
c	characteristic
e	edge
i	initial
t	test
u,o	Weibull parameters
λ	spectral
∞	ambient

Greek

α	thermal diffusivity, absorptivity
β	thermal expansion coefficient
Δ	difference
ε	emissivity, strain
λ	wavelength
θ	dimensionless temperature, $(T-T_i)/T_c$
ρ	density, reflectivity
σ	stress, radiation constant
τ	dimensionless time, t/t_c with $t_c = L^2/\alpha$

1. INTRODUCTION

History

When Professor Emmons retired from Harvard University in 1983, I asked him what we could do to acknowledge his enormous lifetime contributions to fire research. He said that he had recently won the American Physical Society's Office of Naval Research Prize for which the honoree gave a lecture and in return received a plaque and an honorarium and, if we were going to do anything, that is what he would like to have done. So the Howard W. Emmons Lectureship was established at the 1983 NBS Annual Fire Research Conference honoring Professor Emmons. Those proceedings were published in *Combustion Science and Technology* and subsequently in the book *Fire Science for Fire Safety* [1]. Table 1 lists the Howard W. Emmons Lectures given to date.

Table 1. Howard W. Emmons Invited Plenary Lectureships

Lecture	Date	IAFSS Symposia	Awardee	Title
1	1984	NBS Conf.	J. deRis	A Scientific Approach to Flame Radiation and Material Flammability
2	1985	1	E.E. Zukoski	Fluid Dynamic Aspects of Room Fires
3	1986	NBS Conf.	J.G. Quintiere	State of Fire Research and Safety
4	1988	2	K. Kawagoe	Real Fire and Fire Modeling
5	1991	3	P. Thomas	Fire, Flames and Dimensional Analysis
6	1994	4	O. Pettersson	Rational Structural Fire Engineering Design, Based on Simulated Real Fire Exposure
7	1997	5	T. Jin	Studies on Human Behavior and Tenability in Fire Smoke
8	1999	6	Y. Hasemi	Diffusion Flame Modeling as a Basis for the Rational Fire Safety Design of Built Environments
9	2002	7	P.J. Pagni	Thermal Glass Breakage

The Combustion Institute followed the lead of the International Association for Fire Safety Science by recently naming its symposia's plenary lecture for Professor Hoyt C. Hottel [2].

Professor Emmons' contributions to fire research have been reviewed [3]; permit me to share some of my experiences with him. Every sabbatical away from Berkeley, I went to Harvard to work with him. On my first day there in 1974, he outlined a well thought out program of experimental work on cellular urethane, which was exactly in tune with my flame spread interests at the time [4]. I have never been able to discern how he knew just what I wanted to do. During a 1980 sabbatical, his ground-breaking 1956 ZAMM article [5], describing forced flow boundary layer combustion, now known as the "Emmons Problem", was generalized to boundary layer combustion in any geometry and flow field. That article appeared in the *Fire Safety Journal* Special Issue honoring Dr. Philip Thomas [6].

Glass Breaking Overview

The earliest reference to window glass breaking due to fire was by Professor Emmons in "The Needed Fire Science" in the proceedings of the First Symposium [7] where he described undergraduate experiments at Harvard [8]. Glass breaking was quantified in the Second Symposium invited review, "Fire Physics – Promises, Problems and Progress" [9]:

$$\varepsilon_b = \sigma_b/E = \beta\Delta T_b \, . \qquad (1)$$

See the nomenclature for symbol definitions. Each term in Eq. (1) is the thermally induced strain at the edge of the glass at the breaking point. The first equation is Hook's Law and the second is the definition of the thermal coefficient of linear expansion, $\beta = d\ell/dT\ell$. Using typical values, $10 < \sigma_b < 50$ MPa and $E \sim 72$ GPa in Hook's Law gives small breaking strains, $1.5 \times 10^{-4} < \varepsilon_b < 7 \times 10^{-4}$; i.e., 0.015% to 0.07% thermal expansion suffices to break the glass. The frame offers no restraint to the glass since the maximum expansion, <1 mm, is less than the normal gap of several mm between the frame and the pane [10]. What is the glass temperature rise at breaking? From Eq. (1), with $\beta \sim 9 \times 10^{-6}$ K^{-1}, $20°C < \Delta T_b < 80°C$. Since the gas temperature rise to produce flashover is 500°C, glass breaking precedes flashover for ordinary window glass.

Keski-Rahkonen did elegant analyses [10,11] of the stress fields induced in window glass by heating. Since his focus was on the stress field, he looked only at the limiting case where: 1.) there are no temperature gradients across the glass thickness so a constant radiative input can be treated as a volumetric heat source; 2.) convective and linearized radiative heat loss is treated as a volumetric heat sink and 3.) all gas temperatures, the initial temperature and the temperature of the outer edge are constant and identical. It is important that his analytic results confirm Eq. (1) for all geometries. It may be difficult to apply his analyses directly to compartment fires. However, they could describe small-scale experiments with a constant radiative flux [12,13]. Joshi and Pagni [14-16] derived two-dimensional temperature histories for single pane windows heated by fires and showed that for many fire applications, one dimensional fields sufficed, T(x,t), where x is the coordinate along the primary heat flux through the glass thickness. They developed a glass breaking program, BREAK1 [17], which is available without charge at the NIST Building and Fire Research Laboratory website. Good agreement with the data of Skelly, et al. [18] has been reported (see Fig. 6 of Ref. 16). Sincaglia and Barnett [19] incorporated glass breaking into the zone compartment fire model, FIRST [20].

Extension of glass breaking analyses to double-pane windows is described by Cuzzillo, et al. in the paper [21] which won SFPE's 1999 Bono Award. Double pane windows may play a role in fire hardening structures exposed to urban/wildland interface fires [22,23]. The largest data set on thermal breakage of glazing by fire has been obtained at the FireSERT Center of the University of Ulster at Jordanstown [24]. Time to glass breaking and fall-out, glass temperatures and stresses have been obtained for single pane, double pane and laminated windows in an ISO compartment [25-30]. Pool fires in square pans ranging from 0.5 to 1.0 m are placed in the center and far corner of the room. Higher gas layer temperatures and glass heating rates are obtained for the corner placement due to decreased entrainment. Comparisons with analyses will be discussed in a later section.

Outline

Next, several real fires will be described where glass breaking played a critical role in the fire growth. Then the physics of glass breaking will be discussed. The properties of glass and the interaction of radiation with glass will be examined in detail. Comparisons will be made with existing experimental data. Possible approaches to the glass fall-out problem will be discussed.

2. PRACTICAL EXAMPLES

A zone compartment fire model was first used to describe a fatal fire in Prof. Emmons' reconstruction of the MGM Grand Fire [31]. Glass breaking did not play a role there; however, it was critical in the San Juan DuPont Plaza Hotel Fire [32-34]. Ninety-seven people lost their lives on New Year's Eve 1986. An arsonist used a can of sterno to ignite stored furniture in a room with glass walls. The fire spread through the broken glass into the room above. When that room flashed over, it sent a corridor filling hot smoke plume to block both exits of the people-filled casino. Table 2 from Ref. 32 shows a timeline of the glass breakage in this fire. Time zero is the same as in Ref. 33.

The Cathedral Hill Hotel Fire in San Francisco on 18 December 1983 had as its outstanding feature the witnesses' observations of sequential breaking of all sixteen windows on both sides of its ballroom. Stacked foam padded chairs provided sufficient excess pyrolyzates [35] to support a backdraft [36] after thermal stresses broke the corner window closest to the fire. The rearward facing step, formed by the window sill, ensured good mixing (see Fig. 3 of Ref. 37) of the cold oxygen-rich gravity current flowing in the window with the fuel-rich room gas [38]. The subsequent deflagration broke the windows sequentially. Four people died as the fire swept through the hotel.

Large pieces of window glass striking the sidewalk below were a significant life hazard in the One Meridian Plaza Fire in Philadelphia on 23 February 1991. The fire began by self-heating to ignition of a stored pile of cotton rags lightly coated with linseed oil in an office under renovation on the twenty-first floor of a thirty-six floor high rise near the historic Philadelphia City Hall. The initial furniture-fueled fire thermally stressed the high-rise window glass to breakage. Fall-out of parts of the room of origin window provided sufficient ventilation to flashover that room. Delayed detection and improperly set standpipe valves allowed the fire to grow beyond the floor of origin. Propagation up the building, both internally and externally, continued for 19 hours until the newly installed sprinklers on the thirty-fourth floor extinguished the fire. Three firefighters were killed [39-41].

Table 2. Timeline for the San Juan DuPont Plaza Hotel Fire, 31 December 1986

Clock Time	Analysis Time, s	Events
Before 15:32		Sterno ignited by arsonist.
15:34:30	150	Exponential fire growth begins in the initial fuel package.
15:38:40	400	Flames lap over edges of balconies.
15:39:10	430	Material on North Ballroom balcony begins exponential growth.
15:39:10	430	Glass breaks between South Ballroom and Foyer.
15:39:15	435	Hot flow from South Ballroom enters Lobby through door at top of Foyer stairway.
15:39:35	455	First hot smoke reaches west door of Casino and west Lobby exit at top of spiral staircase.
15:35:35	455	Glass breaks between the Lobby and Foyer east of the Foyer staircase.
15:39:55	475	Hot black smoke reaches the west end of the Lobby.
15:40:30	510	Glass breaks in sidelights on balcony door to Foyer.
15:41:10	550	Glass breaks between Rio Lama Room and the Foyer.
15:41:30	570	Flashover occurs in the Rio Lama Room.
15:42:00	600	Glass breaks in southeast corner of Casino.
15:42:20	620	Hot smoke fills the Casino and flows out the southwest windows previously broken by occupants.
After 15:43		Flames traverse Casino.

As a last example, consider a fire discussed in my graduate class ME290F/FP580L “Case Studies in Fire Safety Engineering Science” offered to distant learners jointly by WPI and UCB. In the winter of 1983, a music teacher woke in the middle of the night to find her bed in flames. She barely survived and her insurance company sued the manufacturer of her electric blanket. The expert for the manufacturer ran a zone compartment fire model without considering glass breaking. The calculation showed that a bed fire would self extinguish for lack of oxygen. On that basis, the expert built an exact replica of the room including a manikin in the bed and a glass transom over the door. In the full-scale test, the blanket was ignited with a match. The fire grew rapidly utilizing the oxygen in the room. Sufficient heat was generated to crack the transom glass at 150 s. Transom pieces fell out, ventilating the fire, which then, as other windows cracked and fell out, grew to flashover, a great surprise to the expert. This example illustrates the critical role of proper boundary conditions in zone or field compartment fire calculations. Probably the most important time-dependent boundary condition is the change in geometry when a window changes from part of the wall to one of the vents. The physics of glass breaking due to thermal stresses which controls that timing is discussed in the next section.

3. PHYSICS OF GLASS BREAKING

Consider the framed window pane shown in Fig. 1. The coordinate origin is placed at the inner edge of the shaded region of width s. x is into the glass with zero on the fire side and the glass thickness is L so that $0 \le x \le L$. y is toward the center of the pane and z is along the edge of the shaded region.

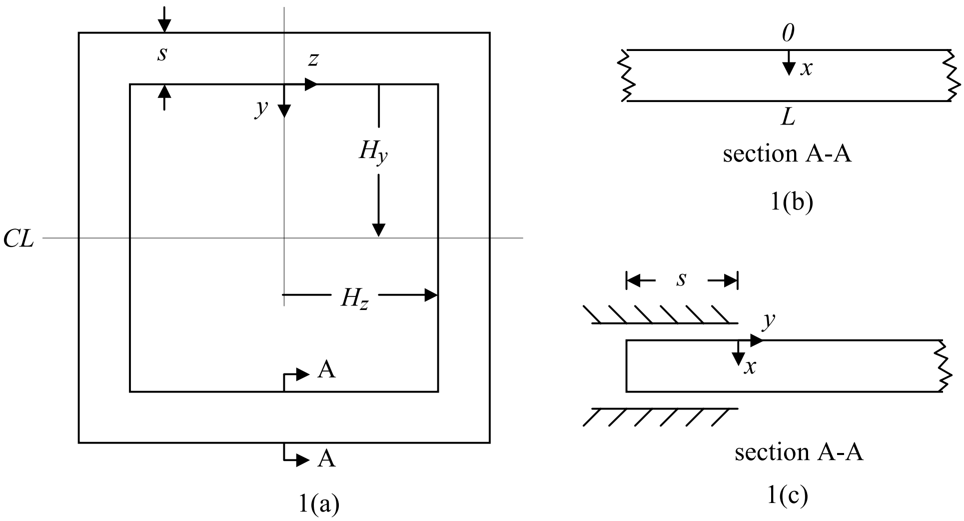

Fig. 1. Window geometry. x is the depth, y is normal to the shaded region, z is along the shading, s is the width of the shading, H_y and H_z are the exposed pane half-lengths and L is the glass thickness.

The governing energy equation for this system is

$$\rho c_p \frac{\partial T}{\partial t} = k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] + \frac{I(y,z,t)}{\ell} e^{-x/\ell}\, H_v(y,z)\,, \tag{2}$$

where $H_v(y,z)$ is a two-dimensional Heaviside function = 0, for y or z in the shaded region and = 1 otherwise. I(y,z,t) is the absorbed fraction of the incident radiative flux directly from the fire which is at sufficiently short wavelengths that its distributed internal absorption needs to be included and ℓ is the decay length in the glass [42]. The initial and boundary conditions are:

$$\text{at} \quad t = 0,\ T = T_i\,, \tag{3}$$

$$y \to \pm\infty \ \ \frac{\partial T}{\partial y} = 0\,, \quad z \to \pm\infty \ \ \frac{\partial T}{\partial z} = 0\,, \tag{4,5}$$

$$x = 0\,,\ -k\frac{\partial T}{\partial x} = q(0,y,z,t)\,H_v(y,z); \quad x = L\,,\ -k\frac{\partial T}{\partial x} = q(L,y,z,t)\,H_v(y,z). \tag{6,7}$$

where H_v accounts for the shading at the pane edge and q represents the net heat flux in the positive x direction at each surface, excluding the absorbed flame radiation represented by I in Eq. (2). The q's will depend on the temperatures, velocities and non-flame radiation adjacent to each point on both sides of the pane. This is a difficult computational problem. Fortunately, there are limiting cases which can be invoked in practical applications [21].

The greatest simplification comes from recognizing that it is the difference between the integrated bulk temperature over the central pane and the coldest temperature on the pane edge which produces the strain that leads to cracking [11,14]. That is, the ΔT_b in Eq. (1) is

$$\Delta T_b = \overline{T}_{exposed} - T_{coldest} \,, \tag{8}$$

where

$$\overline{T}_{exposed} \equiv \int_0^L \int_0^{H_y} \int_0^{H_z} T(x,y,z,t_b)\,dxdydz \,/\, L\,H_y\,H_z \,, \tag{9}$$

with the upper right quadrant assumed to represent the whole pane. As Keski-Rahkonen says, "maximum stresses are located at cold spots" [11]. The point of crack origin will be the edge cold spot with the largest stress-concentrating defect.

It is the integrated thermal expansion of the whole pane which causes strain at the cold edge. This fact can be utilized by averaging the boundary conditions over the exposed pane before the temperature field is calculated. Then only the x variable, in the direction of maximum flux from the hot side to the cold side of the pane, remains. The governing equation is then

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + I(t) \frac{e^{-x/\ell}}{\ell} \,, \tag{10}$$

where data suggest the decay length is $\ell = 1$ mm [42] and the source term is the derivative of Beer's Law [21]. With the assumption that the glass is gray to nonflame radiation, the conditions are:

$$\text{at } t = 0 \;,\; T = T_i \,, \tag{11}$$

$$\text{at } \; x = 0, -k\frac{\partial T}{\partial x} = h_0(t)(T_{0\infty}(t) - T(0,t)) + \varepsilon_{0\infty}(t)\,\sigma T_{0\infty}^4(t) - \varepsilon\sigma T^4(0,t) = q_0(t) \,, \tag{12}$$

$$\text{at } \; x = L, -k\frac{\partial T}{\partial x} = h_L(t)(T(L,t) - T_{L\infty}) + \varepsilon\sigma T^4(L,t) - \varepsilon_{L\infty}\sigma T_{L\infty}^4 = q_L(t) \,, \tag{13}$$

where ε is the glass emissivity, $\varepsilon_{0\infty}(t)$ is the hot layer emissivity and $\varepsilon_{L\infty}$ is the cold ambient emissivity. An approximate solution to this set of equations has been reported [14-17,21]. See Ref. 14 for the details. Every variable in Eqs. (10-13) represents an average over a glass surface, x = 0 (hot) or x = L (cold). Once this solution is obtained, a further average is made,

$$\overline{T}_{exposed}(t) = \int_0^L T(x,t)dx / L , \tag{14}$$

to use in Eqs. (8 and 1).

The two-dimensional profiles shown in Fig. 3 of Ref. 14 indicate that $T_{coldest} \sim T_i$, provided that s/L > 2, i.e., large shading exists and the heating is sufficiently fast that the Fourier number is small, i.e., $\alpha t_b/s^2 < 1$. In that limit, Eq. (1) becomes

$$\Delta T_b(t_b) = \overline{T}_{exposed}(t_b) - T_i = g\sigma_b/E\beta . \tag{15}$$

The net force on the free standing pane is zero. Locations on the pane above the average temperature are in compression while those below the average temperature are in tension (see, e.g., Fig. 4 of Ref. 14). The right side of Eq. (15) is multiplied by a factor slightly greater than unity, $g \sim 1+s/H_y$, to account for this compressive effect of the shaded region on the exposed pane (see Eq. (40) and Fig. 6 of Ref. 14). To apply even this approximate analysis to practical fires, using a model such as BREAK1 [17], several input variables are required, as discussed in the next section.

4. GLASS PROPERTIES AND HEAT TRANSFER

The reason glass windows exist in the first place is their transparency; however, the interaction of radiation with glass is a strong function of wavelength. See e.g. Fig. 12.24 of Ref. 43. To be accurate in the treatment of glass breaking, the spectral transmittance, $\tau_\lambda(\lambda)$, needs to be known for that particular glass specimen. While $\tau_\lambda(\lambda)$ will depend on the formulation and thickness of the glass, all samples will be largely transparent in the visible and near infrared and opaque at large and small wavelengths. Recall that

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1 \quad \text{and} \quad \varepsilon_\lambda = \alpha_\lambda . \tag{16}$$

A typical spectral transmittance for soda lime float glass is

$$\begin{aligned} &\tau_\lambda \sim 0 , \ \lambda < 0.3\ \mu m \ \text{and}\ \lambda > 2.4\ \mu m , \\ &\tau_\lambda \sim 0.9 , \ 0.3\ \mu m \le \lambda \le 2.4\ \mu m . \end{aligned} \tag{17}$$

Assume $\rho_\lambda \sim 0.1$ for all λ then Eq. (16) gives $\alpha_\lambda \sim 0.9$ when $\tau_\lambda \sim 0$. Figure 2 shows a typical piecewise gray approximation to the spectral properties of glass. An important fire safety question is: How much radiation is transmitted through glass? It is also important to glass breaking, since any transmitted radiation does not heat the glass. Use Planck's Law for the spectral emissive power as a function of temperature (see, e.g., Fig. 12.13 and Table 12.1 of Ref. 43) along with Fig. 2 to calculate the transmitted fraction of the incident radiation as a function of the source temperature. The results are shown in

Table 3 for temperatures covering both flames and hot emitting layers. For T<600K, there is no transmission. At typical flame temperatures, ~ 1250K, 25% of the incident radiation is transmitted, 10% is reflected and 65% is absorbed. Measurements suggesting higher transmission [44] are incorrect, since they do not distinguish between direct transmission and glass emission as the glass heats up. For experiments in which glass is heated by high temperature radiant panels [12,13], Table 3 suggests that the glass is heated by only ~ 65% of the radiation measured with a black, opaque heat flux gauge. This agrees well with the transmission measurements in Ref. 13. The reflected and transmitted fractions of the incident radiation may confuse infrared surface temperature measurements.

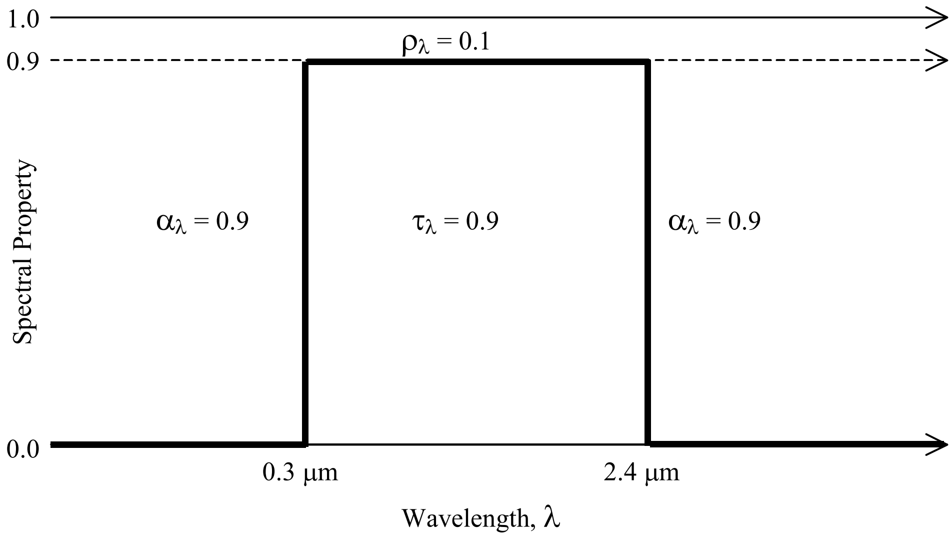

Fig. 2. Piecewise gray approximation to the spectral properties of soda lime float glass.

Table 3. Transmission through Piecewise Gray Glass as f(T).

Temp., K	2.4 μmT, μmK	Transmitted, %	Absorbed, %	Reflected, %
600	1440	1	89	10
800	1920	5	85	10
1000	2400	13	77	10
1200	2880	22	68	10
1400	3360	31	59	10

Note that for multipane windows of the same glass, the first pane acts as a band pass filter only transmitting incident radiation which is also transmitted through subsequent panes. The consequence is that flames and hot layers do not radiatively heat panes beyond the first exposed in multipane windows.

From Fig. 2 and Eq. (16), the total hemispherical emissivity for glass near 300K is $\varepsilon \sim 0.9$, in good agreement with data [45]. The indepth radiation absorption [46], shown as an exponential in Eqs. (2 and 10), varies with the wavelength of the incident radiation. The λ dependence is accounted for by only allowing the shorter λ flame radiation in I(t). The longer λ hot layer radiation is assumed to be absorbed at the surface.

Window glass is primarily soda-lime float glass with an approximate by weight composition of 70% SiO_2, silica, 15% Na_2O, soda, and 15% CaO, lime, and other oxides [47]. The thermal transport properties are well known, e.g., density, $\rho = 2500 \pm 100$ kg/m^3 [48]. The thermal conductivity, k, and specific heat capacity, c_p, both increase as T increases [49]. At 50°C, c_p = 820 J/kgK and k = 0.95 W/mK are good values for soda-lime glass. These properties give a 50°C glass thermal diffusivity of $\alpha = k/\rho c_p = 4.6\text{x}10^{-7}$ m^2/s. The range of values from the literature are 0.7 < k < 1.4 W/mK, for fused silica, and 750 < c_p < 950 J/kgK for 0°-300°C. The range of thermal diffusivities is then $2.9 \text{ x } 10^{-7} < \alpha < 7.8 \text{ x } 10^{-7}$ m^2/s. The manufacturers' material data sheets can provide improvements on these values for particular window glasses. A parameter of critical importance to glass breaking in compartment fires is the thermal coefficient of linear expansion, $\beta \equiv d\ell/dT\ell$. The value for soda-lime glass, in the range 0-300°C, is $\beta = 9.0 \pm 0.5 \text{ x } 10^{-6}$ K^{-1}. For borosilicate (Pyrex) glass, where B_2O_3 replaces CaO, values as low as $\beta = 3 \text{ x } 10^{-6}$ K^{-1} can be obtained [48].

The mechanical properties of interest here are the Modulus of Elasticity or Young's Modulus, E, and the tensile stress at brittle fracture, σ_b. If the glass is rigidly clamped at its edge, bending moments become important and Poisson's Ratio, $\nu = 0.23 \pm 0.03$ and the Modulus of Rigidity, $G = E/2(1+\nu)$ are also needed. Here the glass is assumed to be annealed, i.e., initially stress free, and isotropic with no moments. Young's modulus for soda-lime glass decreases with temperature [50]; at 50°C, E = 72 GPa. Glass is much stronger in compression than in tension so failure will always occur in tension by brittle fracture. Microscopic flaws in the glass surface or edge concentrate stress and provide a point of origin for failure. Bansal and Doremus [51] say "because the strength depends strongly on the history of treatment, handling of the surface and relative humidity… strength is not an intrinsic property of glass and a table of strengths of different glass compositions is not useful." While the strength of typical new soda-lime glass in a waterless atmosphere is 70 MPa, they recommend "the maximum design strength for glass pieces in ambient air is … 20 MPa or less."

It is, however, possible to obtain an estimate of σ_b for use in models [11,17] from experimental breaking stress distributions. Data from 59 soda-lime float glass samples (178 x 25.4 x 2.5 mm) in a four-point flexure apparatus is shown in Fig. 3 [16]. The data are well fit with a three-parameter cumulative Weibull function [52]:

$$G(\sigma_b) = 1 - \exp((\sigma_b - \sigma_u)/\sigma_o)^m, \tag{18}$$

for $\sigma_b \geq \sigma_u$ with m = 1.21, σ_o = 33 MPa and σ_u = 35.8 MPa. Additional data, taken on the same apparatus by Prime [53], on thicker glass yielded m = 1.23, σ_o = 34.3 MPa and σ_u = 37.9 MPa for 20 specimens of 6.4 mm glass and m = 1.27, σ_o = 29 MPa and σ_u = 39.3 MPa for 23 specimens of 9.5 mm glass.

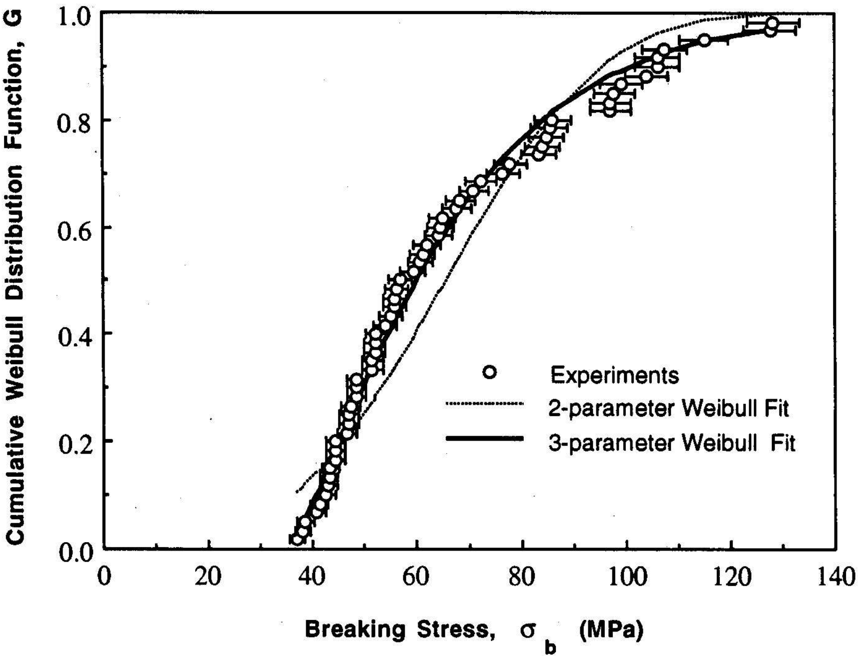

Fig. 3 Weibull cumulative distribution function with data points for glass breaking stress.

Prime shows that the mean breaking stress in full-scale windows, σ_b, is related to the mean test breaking stress, σ_t, by

$$\sigma_b = (\sigma_t - \sigma_u)(2a/\ell_e)^{1/m} + \sigma_u , \qquad (19)$$

where σ_u is the lower limit strength from the Weibull distribution, a is the length of the uniform bending moment in the four point test apparatus, here a = 38.6 mm, and ℓ_e is the total length of the window edges [53]. For the three distributions listed here, σ_t = 60.4 MPa (1/8"), 63.4 MPa (1/4") and 61.0 MPa (3/8"). Assuming a 1m square window gives ℓ_e = 8 m, since each side has four edges. The factor $(2a/\ell_e)^{1/m}$ would be ~0.02 and $\sigma_b \sim \sigma_u + 0.5$ MPa, illustrating that, in the usual limit of windows much larger than the test samples, $\sigma_b \rightarrow \sigma_u$. Thus, the Weibull distribution gives $\sigma_b = \sigma_u$; here $\sigma_b \sim 38$ MPa. This value is a good starting point for comparisons with experiments, fire safe design calculations or fire reconstructions. The careful examination of fracture surfaces themselves can also provide insight into the causes and characteristics of glass fracture as described in the article "Fractology" by Prof. Frechette [54].

It remains to discuss the convective and radiative heating parameters in compartment fire scenarios. On the exterior side, the radiation loss is simply $\varepsilon\sigma T^4(L,t)$ where $\varepsilon = 0.9$, $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4 and T(L,t) is the exterior glass temperature. The convective loss is $h_L(t)(T(L,t) - T_{L\infty})$ where $T_{L\infty}$ is the ambient temperature and $h_L(t)$ is the average free or forced heat transfer coefficient [43]. In the case of free convection of air on a vertical plate, e.g., a window, the convective coefficient can be approximated by

$$h_L \approx 1.24(\Delta T/2H_y)^{1/4} \quad \text{if} \quad (2H_y)^3\,\Delta T < 15\,,$$
$$h_L \approx 1.27\,\Delta T^{1/3} \quad \text{if} \quad (2H_y)^3\,\Delta T \geq 15\,, \tag{20}$$

where H_y is in meters and ΔT is in degrees C. For large windows with $\Delta T = 60°C$, $h_L \approx 5$ W/m^2K. On the interior, the glass radiates to the compartment with $0.9\ \sigma\ T(0,t)^4$. The interior convective heating of the glass is $h_o(t)\ (T_{o\infty}(t) - T(0,t))$ where $T_{o\infty}(t)$ is the interior gas temperature. Emmons [55] suggests

$$h_o(t) = 5 + 45\ (T_{o\infty}(t) - T(0,t))/100\ , \tag{21}$$

until h_o reaches 50 W/m^2K when it is fixed to that value. Dembsey's experimental results for h_o are also in that range [56]. Correlations [57] for $h_o(t)$ for turbulent forced flow past the window may be used. Empirical correlations also exist for the total heat flux from flames adjacent to windows or walls [58]. For double pane windows, $h_{gap} \sim 2.5$ W/m^2K [21].

The radiant emission from the flame may be calculated assuming a flame temperature of ~1200 K [59], using the Hottel Charts [43] for the gas emission and employing soot volume fraction estimates [60] for the soot emission. Similar methods can be applied to the emissivity of the hot layer, $\varepsilon_{o\infty}(t)$. Shape factors may be calculated for the geometries involved [43]; however, shrinking the flame to a point source and calculating the radiant flux as $Q_{rad}/4\pi R^2$ where R is the distance between the window and the fire point source often suffices [61]. Q_{rad} can also be obtained as the radiative fraction of the fire heat release rate [62]. Recall that I(t) is only the absorbed fraction of the incident flux from the flame.

5. COMPARISON WITH EXPERIMENT

Steep temperature gradients, and therefore steep stress gradients, exist in the thermal boundary layer in the shaded region, see e.g. Figs. 3 to 5 of Ref. 14 and Figs. 8 and 9 of Ref. 10. Two consequences follow. 1.) Thermocouples in the shaded region will always overestimate the true cold spot temperature at the initial point of fracture on the edge. 2.) Strain gauges applied to an area of the glass surface within the shaded region boundary layer will always underestimate the true breaking stress, σ_b, at the initial point of fracture. Because of these experimental difficulties, comparisons will be limited here to the time to the first crack in the window pane.

Time to First Crack

An excellent study of glass breaking under radiant heating by Harada et al. was reported at the Sixth Symposium [12]. Their incident heat fluxes of 2.7 to 9.7 kW/m^2 were measured with a black, opaque total heat flux gauge. The transmission and reflection effects shown in Fig. 2 reduce the radiant energy absorbed by the glass to ~

65% of the reported values, i.e., 1.8 to 6.2 kW/m^2. The times to first crack calculated by BREAK1 are in good agreement with the average experimental times over a wide range of conditions as shown in Table 4. No cracking in the 0.5m square float glass panes was observed for absorbed fluxes < 3.3 kW/m^2. The shading was 15mm. Fixed values of the breaking stress were used for the 3 mm float glass, σ_b = 40 MPa, and the 6.8 mm rolled wire glass, σ_b = 12 MPa. The rolled wire glass has many more flaws on its edges, reducing σ_b. The reported temperature differences for the float glass may be low since the unexposed glass surface temperatures appear to have been used rather than the average of the x = 0 and x = L surface temperatures. The average is appropriate since it is the bulk temperature increase that generates the stress at the cold edge. Placing the thermocouples and strain gauges in the center of the shaded region causes high edge temperature and low breaking stress measurements. Sample BREAK1 inputs and outputs for the medium flux restrained float glass are shown in Appendix A. Restraints were observed to have no effect on the time to first crack. The values for E and β in Ref. 12, should read 73 GPa and 8.75 x 10^{-6} K^{-1}, respectively.

Table 4. Comparisons between BREAK1 Calculated Time to First Crack and BRI Data.

Average over	Flux (kW/m^2)		Time (s)		Temperature Difference (K)	
	Incident	Absorbed	Experiment	Calculated	Experiment	Calculated
1 to 3	5.48	3.56	207	196	45.3	66.7
7 to 9	6.69	4.35	144	144	53.3	66.7
15 to 17	9.11	5.92	90	95	57.9	66.7
4,5 & 30	5.45	3.54	231	198	43.2	66.7
10 to 14, 18,22&23	7.40	4.81	128	124	55.0	66.7
19 to 21	9.09	5.91	81	95	51.9	66.7
31 to 33	2.83	1.84	290	239	21.0	20.3
38 to 40	5.41	3.52	101	113	22.0	20.3
44 to 46	9.51	6.18	50	68	21.6	20.3
34 to 37	2.84	1.85	293	237	19.2	20.3
41 to 43	5.35	3.48	120	115	23.3	20.3
47 to 49	9.48	6.16	56	68	24.3	20.3

Another interesting study of radiant heating of windows was performed at the University of Maryland [13]. The emphasis was on urban/wildland interface fires where windows are the weak points allowing entry of a wildfire into a structure. The ingenious solution of securing aluminum foil on the outside of the window by staples or glue was experimentally tested and proved effective. In the small scale portion of this study, radiant panel burners, similar to those in Ref. 12, were used to radiantly heat 340 x 230 x 2.4 mm glass panes mounted with 13 mm shaded edges to replicate real windows. Good agreement was obtained between BREAK1 predictions for the time to first crack and these results, for slightly higher flux levels than in Ref. 12, as shown in Table 5. The BREAK1 inputs were similar to Appendix A with the following changes [13]: h_o = 10 W/m^{2}K, α = 4.2 x 10^{-7} m^2/s, E = 72 GPa, β = 8.5 x 10^{-6} K^{-1} and σ_b = 42 MPa so that ΔT_b = 74°C.

Table 5. Comparisons between BREAK1 Calculated Time to First Crack and Small-Scale UMD Data

Average Over	Flux (kW/m^2)		Time (s)	
	Incident	Absorbed	Experiment	Calculated
G9 to G12	7.33	4.76	143	150
G3 to G5	9.50	6.15	109	101
G13 to G16	12.55	8.16	61	69

The most extensive data set on window breaking in actual compartment fires has been developed at the FireSERT Center of the University of Ulster at Jordanstown [24-30]. Experiments in an ISO compartment with three windows, as shown in Fig. 4, have been performed on single, double and laminated glazing. The shaded region thickness is s = 20 mm and the glass thickness is L = 6 mm. The fuel is mineralized methylated spirits in square pans with sides ranging from 0.5 m to 1.0 m, placed either in the center of the room or in the corner furthest from the windows and door.

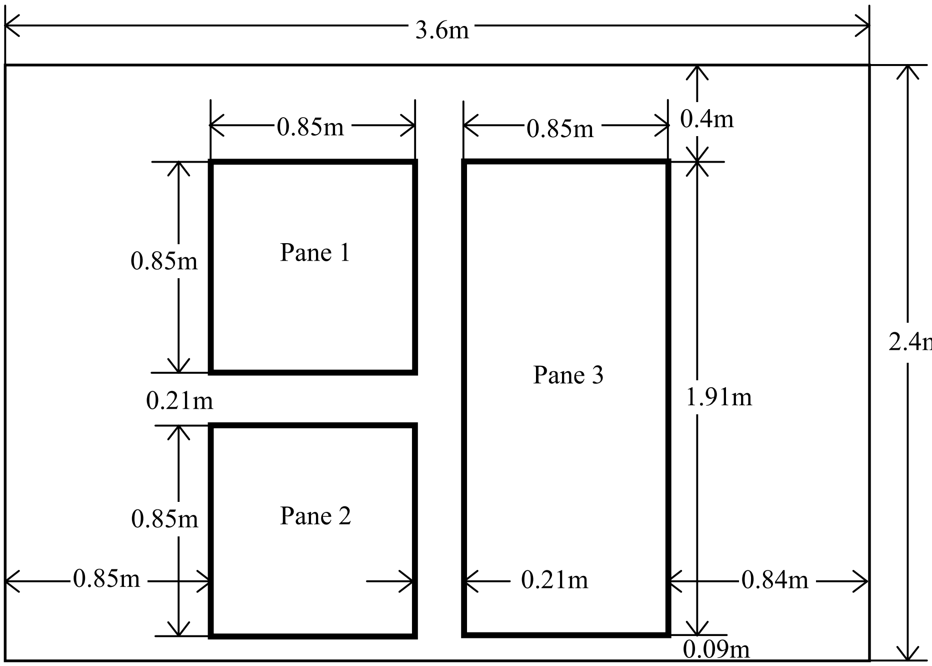

Fig. 4. External elevation of the windowed wall of the FireSERT ISO compartment.

Detailed gas and glass temperature histories, some strain and heat flux measurements as well as time to cracking, crack patterns and amount of fallout are obtained. Comparisons are made with the single pane, centered pan fires[30] to provide a counter example to the two previous radiation only cases, since here the heating is both convective and radiative. Table 6 shows good agreement for the average time to first crack for pool fire pans ranging from 0.6 m to 0.9 m. The glass properties were held constant for all comparisons with σ_b = 30 MPa. The shape factor from the centered pool fire to the upper square window, which usually broke first, was ~ 0.1. The pool fire heat release rate grew with time as the temperatures of the compartment walls and the pan increased. The hot layer appeared to be transparent. Average hot layer temperature histories throughout the upper compartment were used to calculate the convective heating. Zone [20] or field [63] models could be used for temperature history predictions, if $T_{0\infty}(t)$ were not available. In the future, comparisons will be made with corner fire single pane [29], double pane and laminated glazing data.

Table 6. Comparisons Between BREAK1 Calculated Time to First Crack and FireSERT Single Pane Center Fire Data

Average over	Pan size (m)	Time (s)	
		Experimental	Calculated
Sg 1 to 3	0.6	484	471
Sg 4 to 6	0.7	288	290
Sg 7 to 10	0.8	157	155
Sg 11 to 14	0.9	108	111

Fall-out

The above comparisons suggest that the initial crack formation in glass exposed to fire is reasonably well understood. It is perhaps an example of the kind of physics-based predictive capability that Professor Emmons had in mind when he first suggested performance based building codes [55]. However, the problem of fall-out remains to be solved. The University of Ulster data suggest one method for fall-out prediction to be pursued. After the first crack, additional cracks continue to develop. Each crack bifurcates as it moves from the edge into the heated region [7,64]. Glass appears to fall-out only after subsequent cracks achieve closure around a piece of glass isolating it from the frame. See e.g. Figs. 16 to 20 of Ref. 29. So it may be possible to calculate fall-out by continuing the breaking stress analyses until multiple cracks have formed. An experimentally determined number of cracks, e.g., two to four, could suffice to approximate the time to fall-out. Limited data on fall-out, shown in Table 7, indicate that frame details, window aspect ratio and heating intensity all play a role in glass fall-out.

Table 7. FireSERT Fall-Out Data Summary for Single Pane Center Fires.

	Average Percent of Pane Area that Eventually Fell Out		
Fuel Pan side, m	Pane 1	Pane 2	Pane 3
0.6	0	0	7
0.7	1	0	9
0.8	0	0	67
0.9	49	7	85

In many experiments, there are no significant pressure differentials acting on the glass panes. However, in real growing fires, pressure forces will exist to remove pieces of glass once they are isolated by cracking. It may be prudent to assume partial glass fall-out at the time of first crack in fire reconstructions. This is an important subject for future research.

CONCLUSIONS

1. Thermal glass breakage is well understood.
2. Glass thermal and mechanical properties, convective heat transfer coefficients and the interaction of radiation with glass are described here in detail.
3. True edge stresses and temperatures are difficult to measure accurately due to the steep temperature gradient in the shaded region.
4. The time to first crack in windows heated by compartment fires or wildfires can be determined reliably by analyses, such as that performed by BREAK1.
5. Successful comparisons of calculated glass breaking times with experimental times over a wide range of conditions are presented here.
6. Glass fall-out occurs when sequential cracking isolates islands of the glass pane away from the frame.
7. Pressure forces may play an important role in glass fall-out in real growing fires but have yet to be replicated in the laboratory.
8. Glass fall-out remains an important area for future work.

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APPENDIX A – Sample BREAK1 Input and Output

PHYSICAL AND MECHANICAL PROPERTIES OF GLASS FOR BRI COMPARISONS
1.Thermal conductivity [W/mK]= .9500E+00
2.Thermal diffusivity [m^2/s]= .4600E-06
3.Absorption length [m]= .1000E-02
4.Breaking stress [N/m^2]= .4000E+08
5.Youngs modulus [N/m^2]= .7300E+11
6.Linear coefficient of expansion [/deg C]= .8750E-05

GEOMETRY
1.Glass thickness [m]= .0030
2.Shading thickness [m]= .0150
3.Half-width [m]= .2350
COEFFICIENTS
1.Heat transfer coeff., unexposed [W/m^2-K]= 5.00
2.Ambient temp, unexposed [K]= 300.0
3.Emissivity of glass = .90
4.Emissivity of ambient (unexposed) = 1.00
FLAME RADIATION
Number of points used for flux input: 2

point #	time [s]	flux [W/m^2]
1	.00	4350.00
2	500.00	4350.00

GAS TEMPERATURE
Number of points used for temperature input: 2

point #	time [s]	temperature [K]
1	.00	300.00
2	500.00	300.00

HEAT TRANSFER COEFF. ON HOT LAYER SIDE
Number of points used for heat transfer coeff. input: 2

point #	time [s]	h2 [W/m^2-K]
1	.00	5.00
2	500.00	5.00

EMISSIVITY OF HOT LAYER
Number of points used for emissivity input: 2

point #	time [s]	emissivity
1	.00	.00
2	500.00	.00

NUMERICAL PARAMETERS
1.Maximum fractional error in soln= .000100
2.Size of time step [s]= 1.000
3.Maximum run time [s]= 500.00
4.Time interval for output [s]= 20.00

TEMPERATURE HISTORY

Time (s)	Exposed T(K)	Unexposed T(K)	Theta (Average)	Tau
.0	300.0	300.0	.000	.000
20.0	312.5	310.8	.157	1.022
40.0	323.4	321.6	.344	2.044
60.0	333.5	331.7	.513	3.067
80.0	342.8	341.0	.666	4.089
100.0	351.3	349.5	.804	5.111
120.0	359.1	357.3	.929	6.133
140.0	366.2	364.5	1.043	7.156
144.0	367.6	365.8	1.065	7.360

Window breaks at time = 144.00 [s]

$t_c = L^2/\alpha = 19.6$ s, $T_c = \sigma_b/E\beta = 62.6$ K,
$g = 1 + s/H_y = 1.06$, $\Delta T_b = gT_c = 66.7$ K