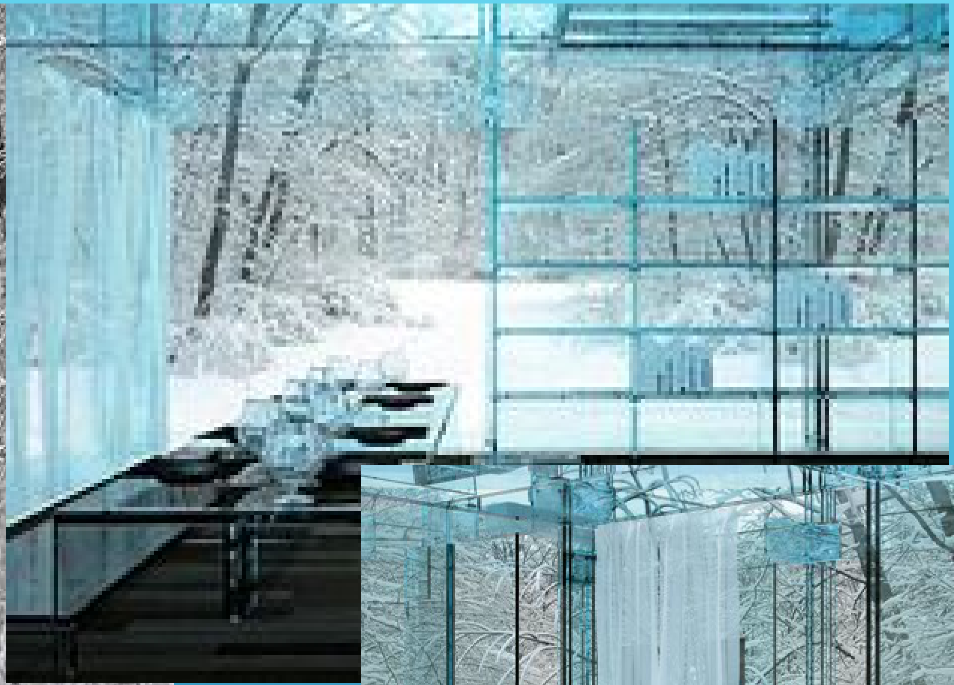
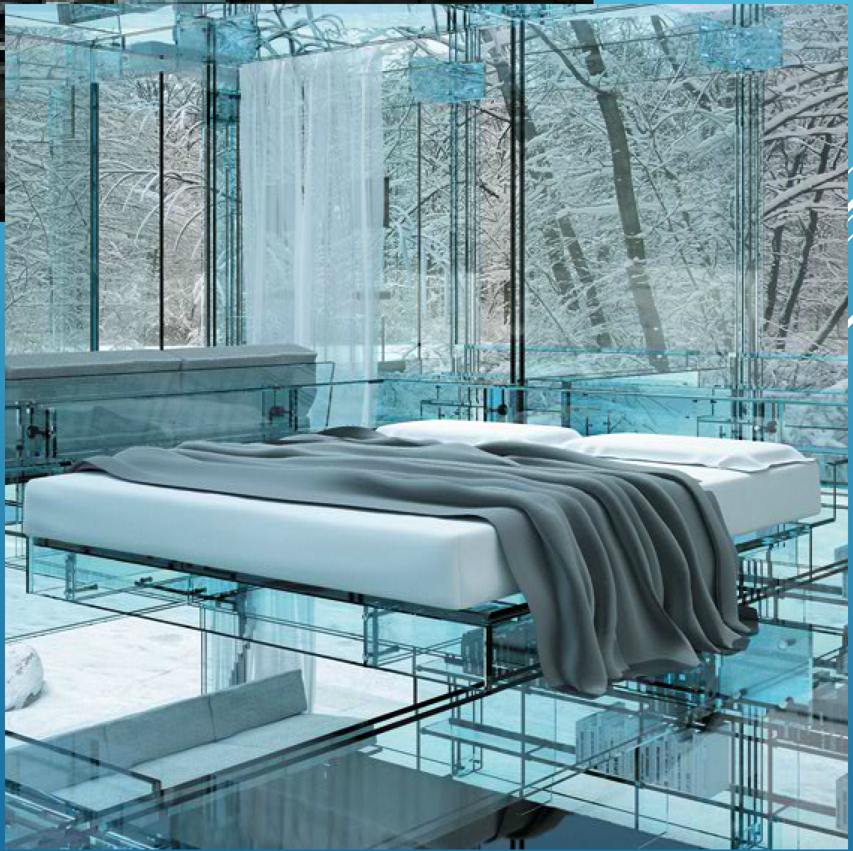
BREAKING GLASS

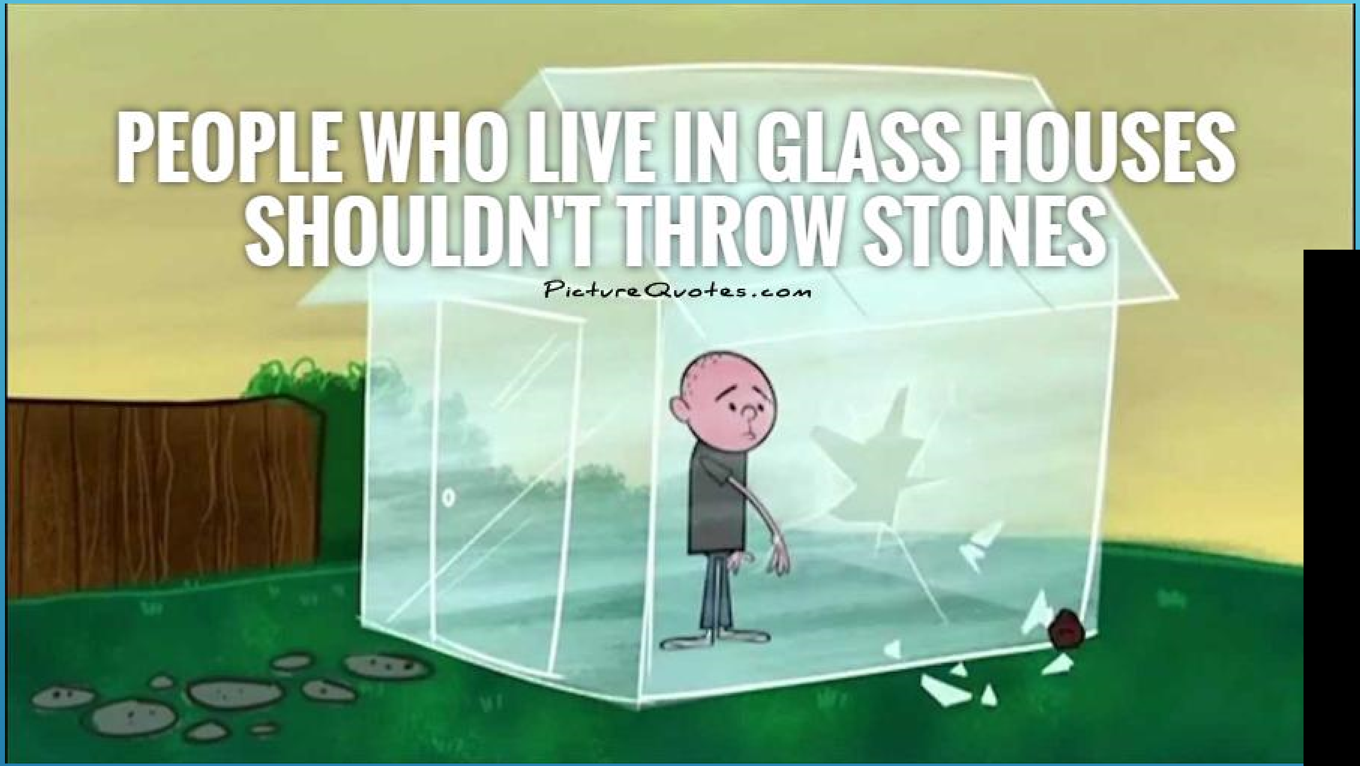
Mark Brook, P. Eng.

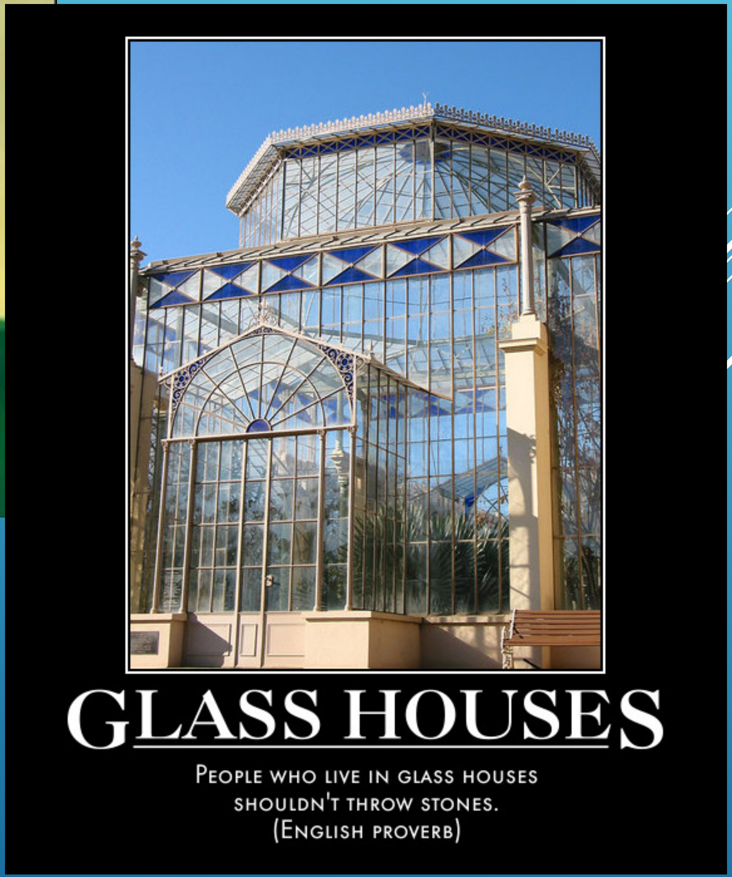
BVDA Façade Engineering





HOW TO BUILD A GLASS HOUSE


PEOPLE WHO LIVE IN GLASS HOUSES
SHOULDN'T THROW STONES
PictureQuotes.com

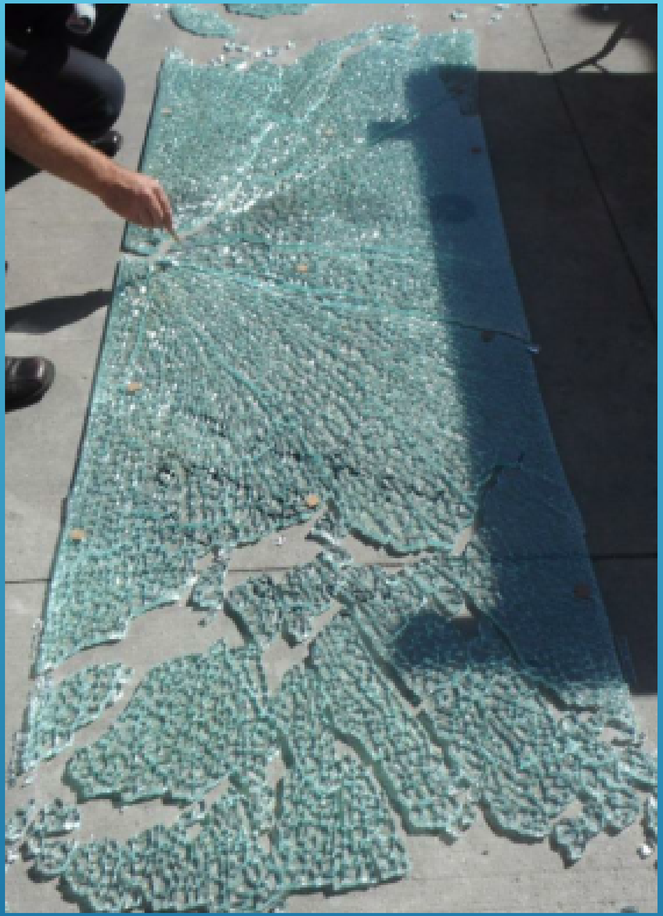

GLASS HOUSES
People who live in glass houses
shouldn't throw stones.
(English proverb)

- Common misconceptions regarding glass breakage
- Two case studies
- Summer of 2011- Sky Fall(ing) spontaneous breakage
- Spandrel breakage
- Glass doesn't just break.

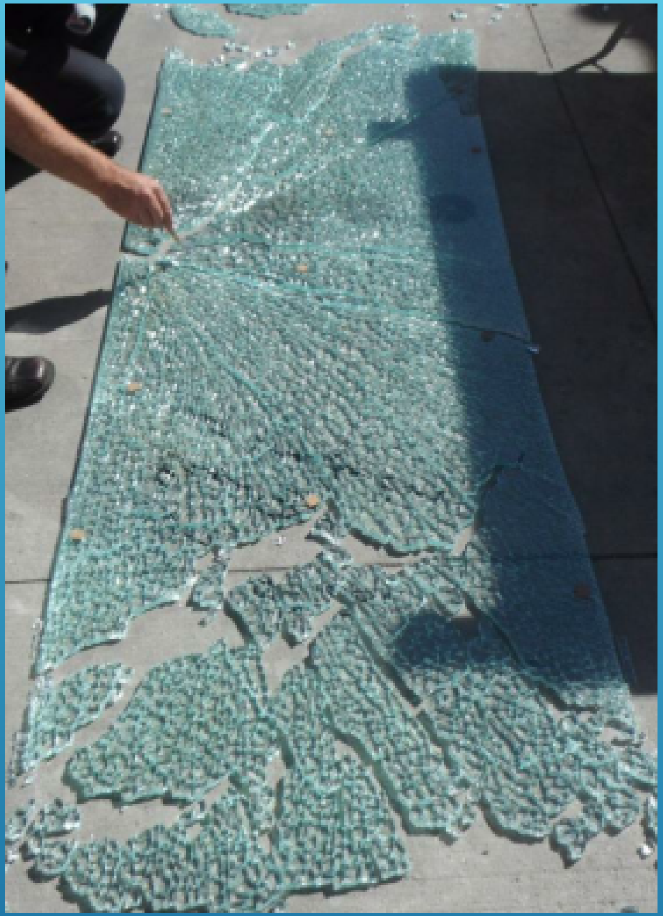
IT IS THE FATE OF GLASS TO BREAK







BREAK ON PURPOSE FRAGMENTATION TEST



BREAK ON PURPOSE FRAGMENTATION TEST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JAN. 13, 2004

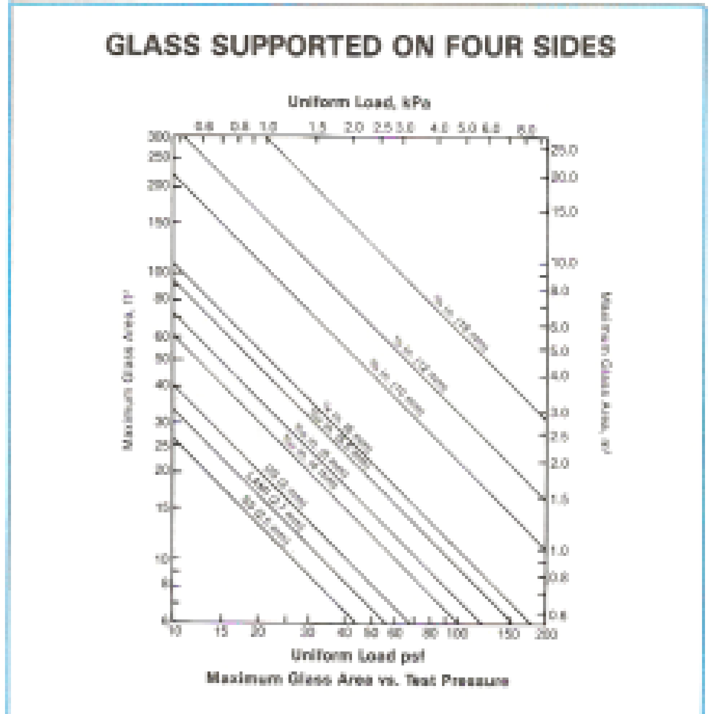


Fig. 1

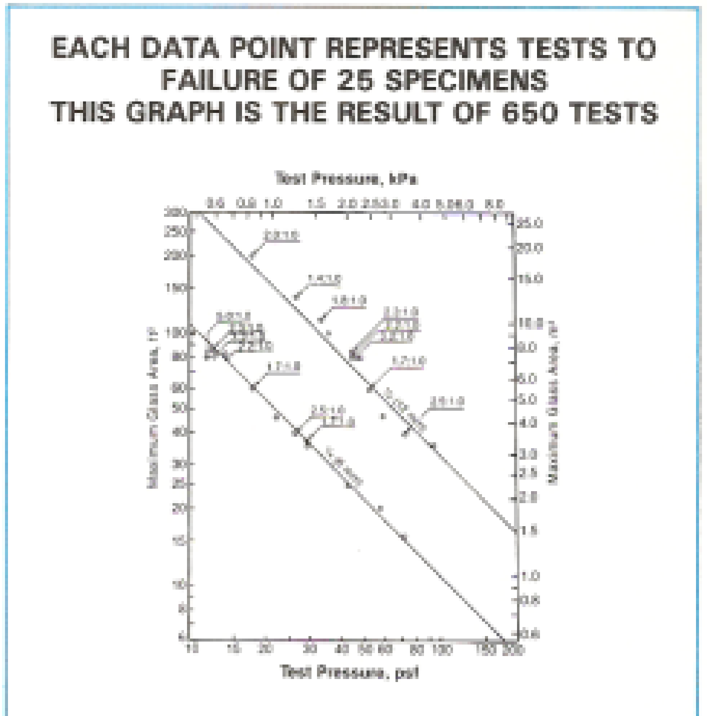


Fig. 2

HOW OFTEN SHOULD GLASS BREAK?

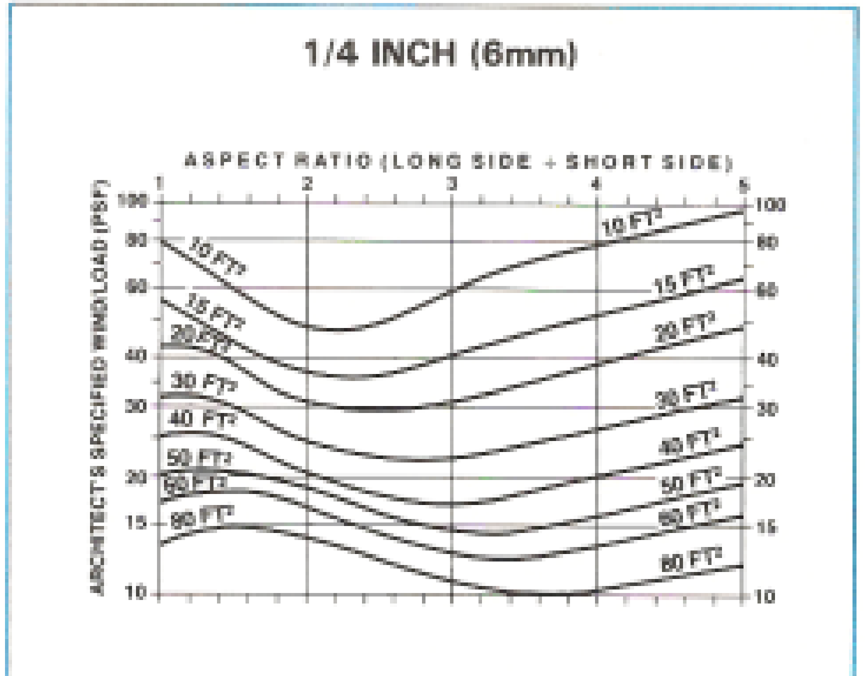
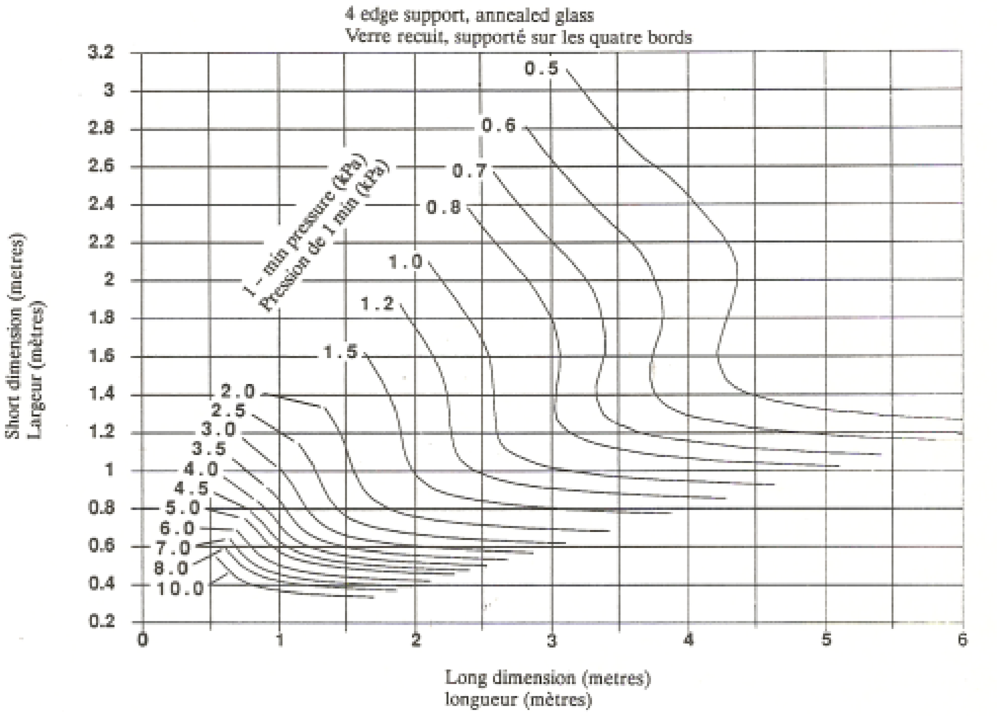


Fig. 3



Design Criterion: Factored Load < Factored Resistance
Critère de calcul: Charge pondérée < Résistance pondérée

FIGURE 4

HOW OFTEN SHOULD GLASS BREAK?

PROBABILITY

TABLE A

PROBABILITY FUNCTIONS

NORMAL PROBABILITY FUNCTION—VALUES OF x IN TERMS OF $P(x)$ AND $Q(x)$

$Q(x)$	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010	
0.00	∞	3.09023	2.87816	2.74778	2.65207	2.57583	2.51214	2.45726	2.40892	2.36562	2.32635	0.99
0.01	2.32635	2.29037	2.25713	2.22621	2.19729	2.17009	2.14441	2.12007	2.09693	2.07485	2.05375	0.98
0.02	2.05375	2.03352	2.01409	1.99539	1.97737	1.95996	1.94313	1.92684	1.91104	1.89570	1.88079	0.97
0.03	1.88079	1.86630	1.85218	1.83842	1.82501	1.81191	1.79912	1.78661	1.77438	1.76241	1.75069	0.96
0.04	1.75069	1.73920	1.72793	1.71689	1.70604	1.69540	1.68494	1.67466	1.66456	1.65463	1.64485	0.95
0.05	1.64485	1.63523	1.62576	1.61644	1.60725	1.59819	1.58927	1.58047	1.57179	1.56322	1.55477	0.94
0.06	1.55477	1.54643	1.53820	1.53007	1.52204	1.51410	1.50626	1.49851	1.49085	1.48328	1.47579	0.93
0.07	1.47579	1.46838	1.46106	1.45381	1.44663	1.43953	1.43250	1.42554	1.41885	1.41183	1.40507	0.92
0.08	1.40507	1.39838	1.39174	1.38517	1.37866	1.37220	1.36581	1.35946	1.35317	1.34694	1.34076	0.91
0.09	1.34076	1.33462	1.32854	1.32251	1.31652	1.31058	1.30469	1.29884	1.29303	1.28727	1.28155	0.90
0.10	1.28155	1.27587	1.27024	1.26464	1.25908	1.25357	1.24808	1.24264	1.23723	1.23186	1.22653	0.89
0.11	1.22653	1.22123	1.21596	1.21072	1.20553	1.20036	1.19522	1.19012	1.18504	1.18000	1.17499	0.88
0.12	1.17499	1.17000	1.16505	1.16012	1.15522	1.15035	1.14551	1.14069	1.13590	1.13113	1.12639	0.87
0.13	1.12639	1.12168	1.11699	1.11232	1.10768	1.10306	1.09847	1.09390	1.08935	1.08482	1.08032	0.86
0.14	1.08032	1.07584	1.07138	1.06694	1.06252	1.05812	1.05374	1.04939	1.04505	1.04073	1.03643	0.85
0.15	1.03643	1.03215	1.02789	1.02365	1.01943	1.01522	1.01103	1.00686	1.00271	0.99858	0.99446	0.84
0.16	0.99446	0.99036	0.98627	0.98220	0.97815	0.97411	0.97009	0.96609	0.96210	0.95812	0.95416	0.83
0.17	0.95416	0.95022	0.94629	0.94238	0.93848	0.93458	0.93072	0.92686	0.92301	0.91918	0.91537	0.82
0.18	0.91537	0.91156	0.90777	0.90399	0.90023	0.89647	0.89273	0.88901	0.88529	0.88159	0.87790	0.81
0.19	0.87790	0.87422	0.87055	0.86689	0.86325	0.85962	0.85600	0.85239	0.84879	0.84520	0.84162	0.80
0.20	0.84162	0.83805	0.83450	0.83095	0.82742	0.82390	0.82038	0.81687	0.81338	0.80990	0.80642	0.79
0.21	0.80642	0.80296	0.79950	0.79606	0.79262	0.78919	0.78577	0.78237	0.77897	0.77557	0.77219	0.78
0.22	0.77219	0.76882	0.76546	0.76210	0.75875	0.75542	0.75208	0.74876	0.74545	0.74214	0.73885	0.77
0.23	0.73885	0.73556	0.73228	0.72900	0.72574	0.72248	0.71923	0.71599	0.71275	0.70952	0.70630	0.76
0.24	0.70630	0.70309	0.69988	0.69668	0.69349	0.69031	0.68713	0.68396	0.68080	0.67764	0.67449	0.75
0.25	0.67449	0.67135	0.66821	0.66508	0.66196	0.65884	0.65573	0.65262	0.64952	0.64643	0.64335	0.74
0.26	0.64335	0.64027	0.63719	0.63412	0.63106	0.62801	0.62496	0.62191	0.61887	0.61584	0.61281	0.73
0.27	0.61281	0.60979	0.60678	0.60376	0.60076	0.59776	0.59477	0.59178	0.58879	0.58581	0.58284	0.72
0.28	0.58284	0.57987	0.57691	0.57395	0.57100	0.56805	0.56511	0.56217	0.55924	0.55631	0.55338	0.71
0.29	0.55338	0.55047	0.54755	0.54464	0.54174	0.53884	0.53594	0.53305	0.53016	0.52728	0.52440	0.70
0.30	0.52440	0.52153	0.51866	0.51579	0.51293	0.51007	0.50722	0.50437	0.50153	0.49869	0.49585	0.69
0.31	0.49585	0.49302	0.49019	0.48736	0.48454	0.48173	0.47891	0.47610	0.47330	0.47050	0.46770	0.68
0.32	0.46770	0.46490	0.46211	0.45933	0.45654	0.45376	0.45099	0.44821	0.44544	0.44268	0.43991	0.67
0.33	0.43991	0.43715	0.43440	0.43164	0.42889	0.42615	0.42340	0.42066	0.41793	0.41519	0.41246	0.66
0.34	0.41246	0.40974	0.40701	0.40429	0.40157	0.39886	0.39614	0.39343	0.39073	0.38802	0.38532	0.65
0.35	0.38532	0.38262	0.37993	0.37723	0.37454	0.37186	0.36917	0.36649	0.36381	0.36113	0.35846	0.64
0.36	0.35846	0.35579	0.35312	0.35045	0.34779	0.34513	0.34247	0.33981	0.33716	0.33450	0.33185	0.63
0.37	0.33185	0.32921	0.32656	0.32392	0.32128	0.31864	0.31600	0.31337	0.31074	0.30811	0.30548	0.62
0.38	0.30548	0.30286	0.30023	0.29761	0.29499	0.29237	0.28976	0.28715	0.23454	0.28193	0.27932	0.61
0.39	0.27932	0.27671	0.27411	0.27151	0.26891	0.26631	0.26371	0.26112	0.25853	0.25594	0.25335	0.60
0.40	0.25335	0.25076	0.24817	0.24559	0.24301	0.24043	0.23785	0.23527	0.23269	0.23012	0.22754	0.59
0.41	0.22754	0.22497	0.22240	0.21983	0.21727	0.21470	0.21214	0.20957	0.20701	0.20445	0.20189	0.58
0.42	0.20189	0.19934	0.19678	0.19422	0.19167	0.18912	0.18657	0.18402	0.18147	0.17892	0.17637	0.57
0.43	0.17637	0.17383	0.17128	0.16874	0.16620	0.16366	0.16112	0.15858	0.15601	0.15351	0.15097	0.56
0.44	0.15097	0.14843	0.14590	0.14337	0.14084	0.13830	0.13577	0.13324	0.13072	0.12819	0.12566	0.55
0.45	0.12566	0.12314	0.12061	0.11809	0.11556	0.11304	0.11052	0.10799	0.10547	0.10295	0.10043	0.54
0.46	0.10043	0.09791	0.09540	0.09288	0.09036	0.08784	0.08533	0.08261	0.08030	0.07778	0.07527	0.53
0.47	0.07527	0.07276	0.07024	0.06773	0.06522	0.06271	0.06020	0.05768	0.05517	0.05266	0.05015	0.52
0.48	0.05015	0.04764	0.04513	0.04263	0.04012	0.03761	0.03510	0.03259	0.03008	0.02758	0.02507	0.51
0.49	0.02507	0.02256	0.02005	0.01755	0.01504	0.01253	0.01003	0.00752	0.00501	0.00251	0.00000	0.50
	0.010	0.009	0.008	0.007	0.006	0.005	0.004	0.003	0.002	0.001	0.000	$P(x)$

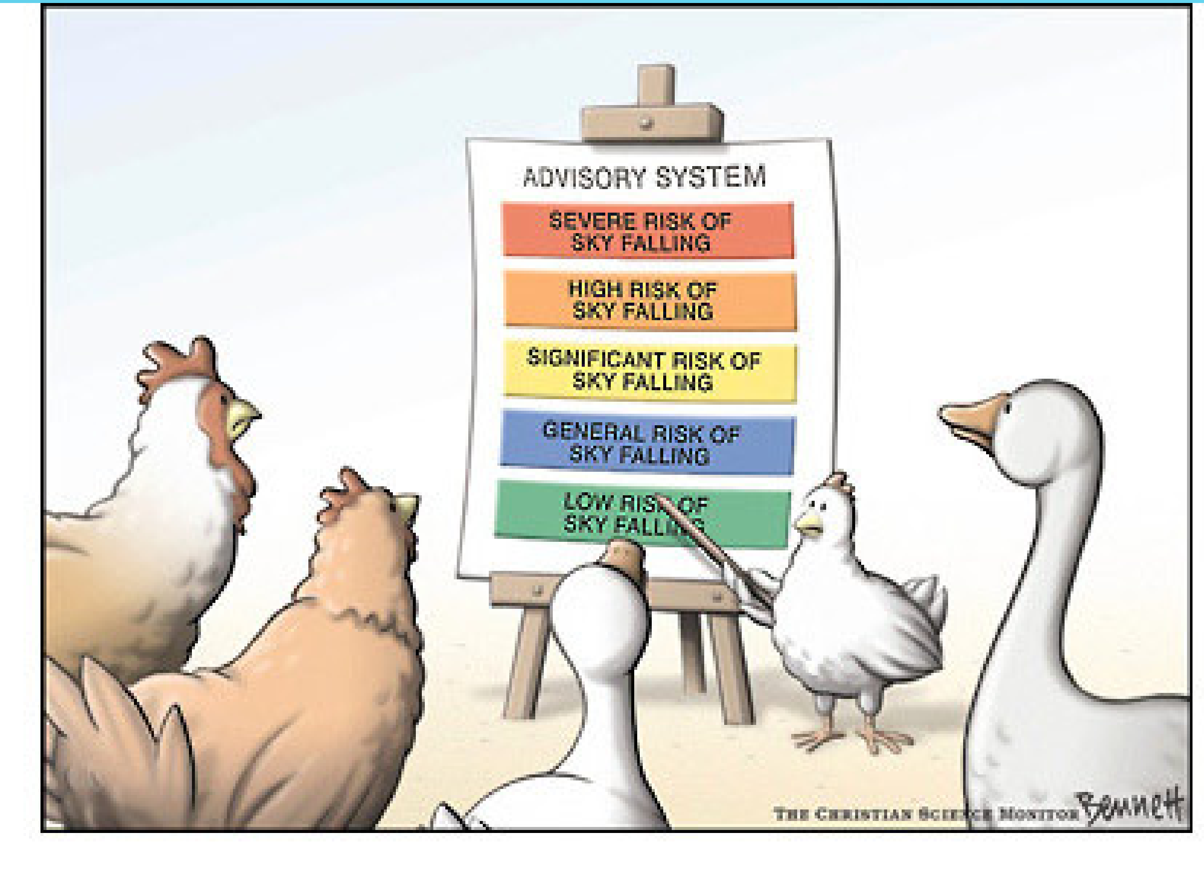
For $Q(x) > 0.007$, linear interpolation yields an error of one unit in the third decimal place; five-point interpolation is necessary to obtain full accuracy.

$$P(x) = 1 - Q(x) = \int_{-\infty}^{x} Z(t)dt$$

Compiled from T. L. Kelley, The Kelley Statistical Tables. Harvard Univ. Press, Cambridge, Mass., 1948 (with permission).

PROBABILITY OF BREAKAGE

- <1/1000
- 2/1000
- 5/1000
- 8/1000
- 100/1000
- 750/1000



It is worth noting that the published glass strength information is based on glass subjected to uniform one (1) minute loading and not subjected to other factors that might affect its performance. Factors that can affect a glass's ability to perform in an architectural application, such as surface and edge damage, mechanical stresses, and thermal stresses, are discussed in detail in Section 6. This published information is also based on a design factor of 2.5 or a breakage probability of 8/1000. The design factor of 2.5 is not a recommendation, but rather the design factor commonly used by designers when selecting glass for buildings. If the design professional wishes to use a design factor greater than 2.5, the equations presented in Section 3 can be used. If a design factor of less than 2.5 is being considered, the glass manufacturer should be consulted.

B3. CALCULATION OF RESISTANCE TO NORMAL PRESSURE

B3.1 **Risk of Failure — Calibration Procedure —** In the past it has been the practice to define a probability of failure in terms of the breakage rate per thousand lights. This practice has not been continued in the standard because it includes no reflection of the reliability of the model predicting the capacity of the glass, or the statistical character of the loading.

B3.1.1 Instead, a second moment reliability model has been used (Canadian Standards Association 1981) to assess the level of safety provided. Lind (1987) suggests an optimum reliability index of 3.0 for a nominal lifetime of 50 years. A preliminary assessment of several designs based on Table 2 of this standard suggests, however, that the nominal lifetime for a reliability index of 3.0 may be closer to 10 years on average (or expressed another way, for a nominal life of 50 years, the reliability index is somewhat lower than 3.0).

B3.2 **Reference Factored Resistance — Table 2 and Figures 1 to 9 —** This is the resistance of in-service annealed single rectangular glass plates simply supported and free to slip in plane, to the one-minute equivalent pressure at which 0.8% of the units tested are expected to fail, multiplied by a resistance factor of one.

OLD DISCLAIMER

BREAKAGE PATTERN – HOW IT BREAKS

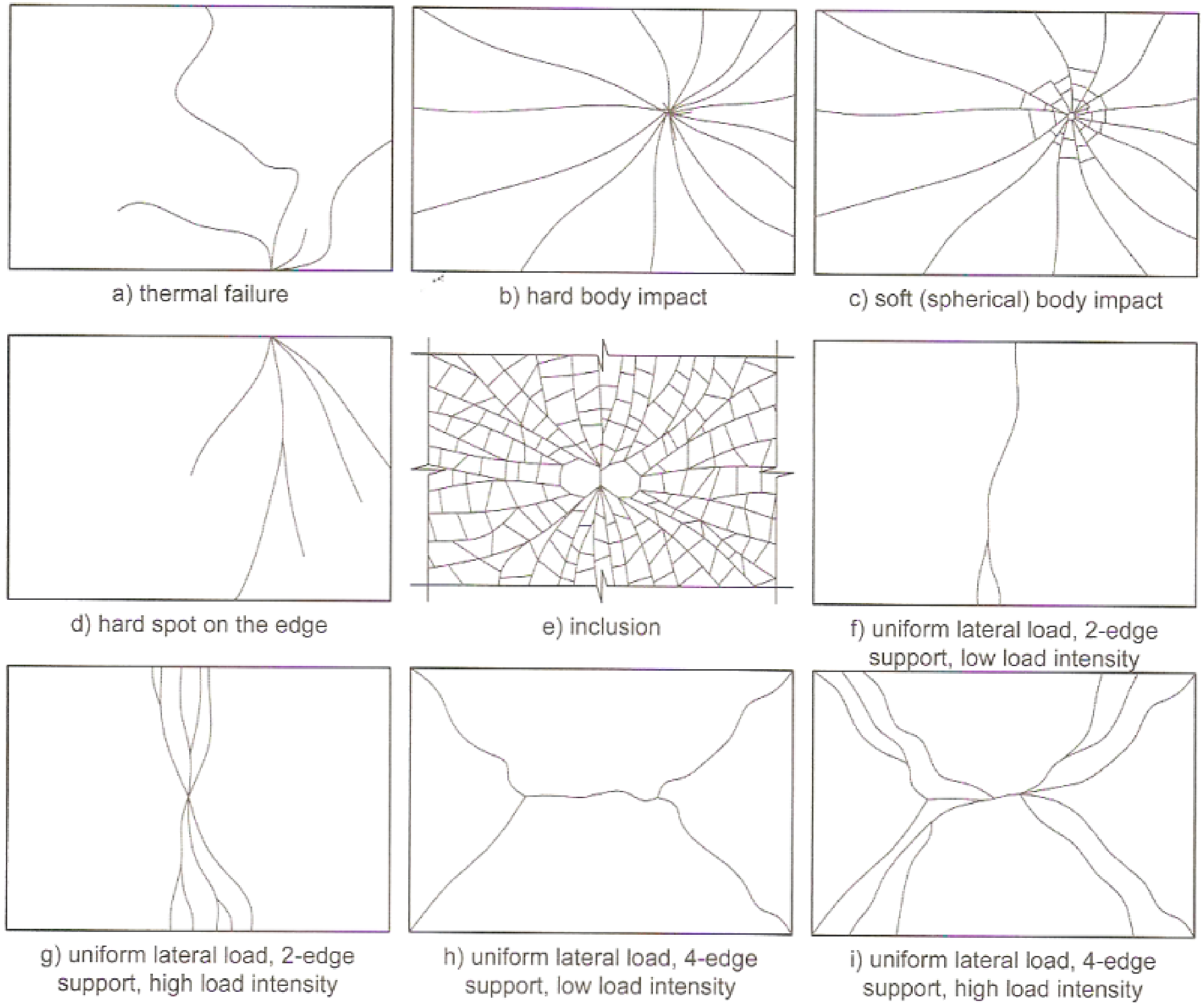
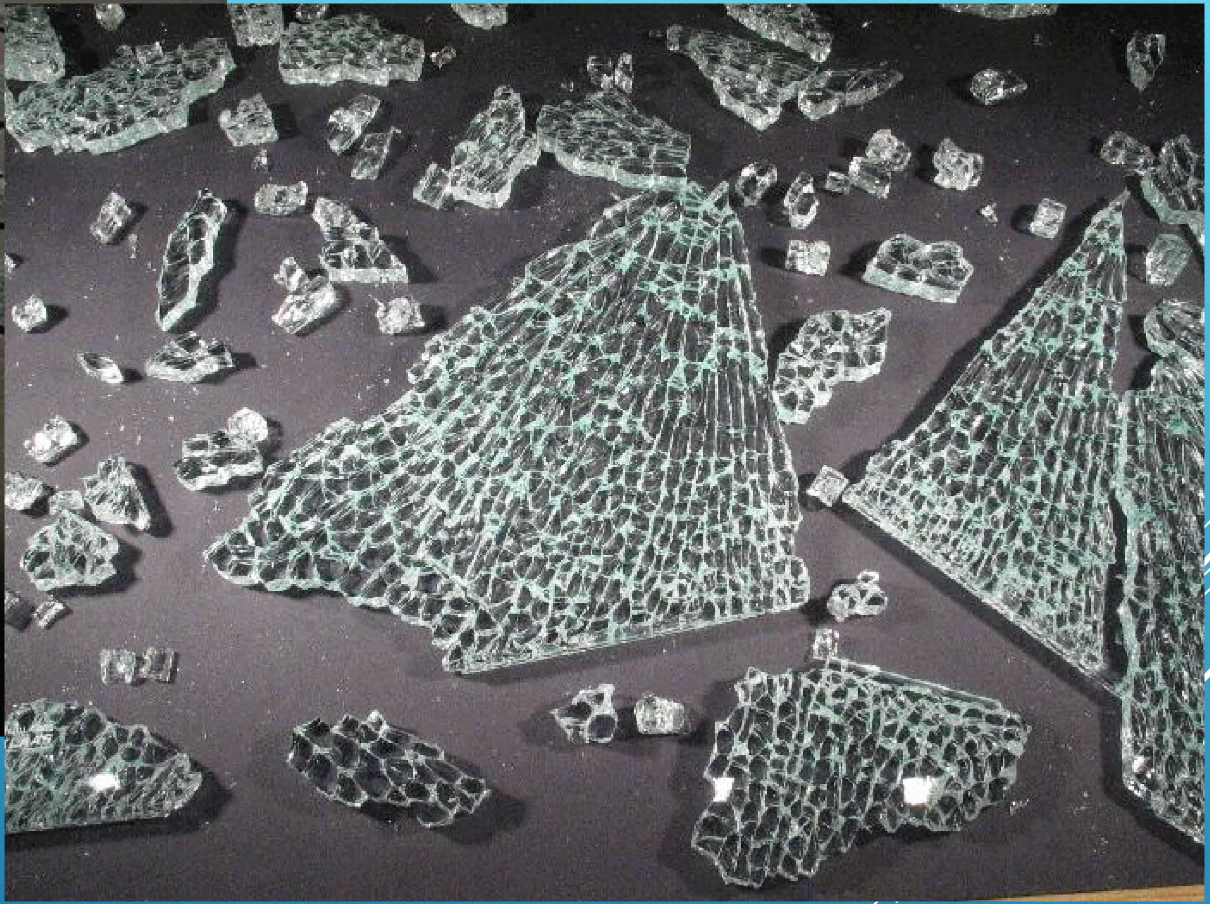


Figure 8.4: Schematic representation of typical glass failures [265].

BREAKAGE BEHAVIOR FT GLASS



BREAKAGE BEHAVIOR FT GLASS

BREAKAGE BEHAVIOUR OF FT GLASS

2011 SKY IS FALLING CASE 1


Facebook.com/ FreeRangeComic
©COPYRIGHT 2013 BY Bill Whitehead DISTRIBUTED BY CREATORS.COM
8-5
NICE TRY, CHICKEN LITTLE! WE'RE NOT FALLING FOR THAT ONE AGAIN!


NEWS
THE SKY IS FALLING!! THE SKY IS FALLING!!


THE SKY IS FALLING! THE SKY IS FALLING!
THAT'S MY LINE..


THE WORLD NEWS
Since 1883
YOUR NUMBER ONE SOURCE FOR HEADLINES
THE SKY IS FALLING!
CHICKEN LITTLE NOWHERE TO BE FOUND

- Glass edges
- Glass thickness
- Surface compression
- Fragmentation test
- Code/standard compliance

GLASS EXAMINATION

- Use of brokers, global supply
- Domestic
- North American/Europe
- Asia

GLASS SUPPLY

- Code compliance 1996
- Wind loads

RAILING INVESTIGATIONS

Appendix C

TASK GROUP ON LIVE LOADS DUE TO USE AND OCCUPANCY MEMORANDUM

National Research Council Canada | Conseil national de recherches Canada

Institute for Research in Construction | Institut de recherche en construction

MEMORANDUM

DATE March 8, 2012

TO Expert Advisory Panel on Glass Panels in Balcony Guards via J.P. Ferron

FROM Technical Advisor, Standing Committee on Structural Design Cathy Taraschuk

RE: **Loads on Balcony Guards**

The Task Group on Live Loads Due to Use and Occupancy of the Standing Committee on Structural Design held their tenth meeting on March 1, 2012, in Toronto. At the request of the Expert Advisory Panel on Glass Panels in Balcony Guards, the Task Group considered the question of which load combinations on exterior balcony guards should be considered.

The relevant load combination table from the NBC 2010 is

Table 4.1.3.2.A.
Load Combinations Without Crane Loads for Ultimate Limit States
Forming Part of Sentences 4.1.3.2.(2) and (5) to (10)

Case	Load Combination	
	Principal Loads	Companion Loads
1	1.4D	—
2	(1.25D or 0.9D) + 1.5L	0.5S or 0.4W
3	(1.25D or 0.9D) + 1.5S	0.5L or 0.4W
4	(1.25D or 0.9D) + 1.4W	0.5L or 0.5S
5	1.0D + 1.0E	0.5L + 0.25S

The question posed was whether or not the live load should be considered in combination with the wind load. The Expert Panel's assertion was that it is unlikely that the full live load will be realized during the design wind event.

In discussing the appropriate combination, the Task Group noted that case 2, with the full live load coupled with a reduced wind load (via the 0.4 factor) is a plausible scenario. By extension, it is also plausible that some fraction of the live load may be present during the design wind event as per load combination 4. As such, the opinion of the Task Group on Live Load Due to Use and Occupancy regarding exterior balcony guards is that **the live load needs to be considered in combination with the wind load via load combinations 2 and 4**.

The Task Group did note that the wind load, when combined with the live load, should be the outward wind load (i.e. acting as a suction load on the guard) that is applied in combination with the outward guard load, and as a separate case, the inward wind load (i.e. acting as a pressure load on the guard) that is applied in combination with the inward guard load. The Task Group is in the process of revising Sentence 4.1.5.14.(1) to maintain the outward guard live load at the stated values, but prescribe lower inward guard loads.

NICKEL SULPHIDE INCLUSIONS

- Pilkington – rare
- Guardian – rare, extremely rare
- Saint Gobain – very rare
- PPG – very rare, extremely rare

HOW RARE IS RARE

- Pilkington – rare
- Guardian – rare, extremely rare
- Saint Gobain – very rare
- PPG – very rare, extremely rare
- 1/7.38 tonnes
- 1/8.7 tonnes 1/5000 sq. ft. of 6mm thick

HOW RARE IS RARE

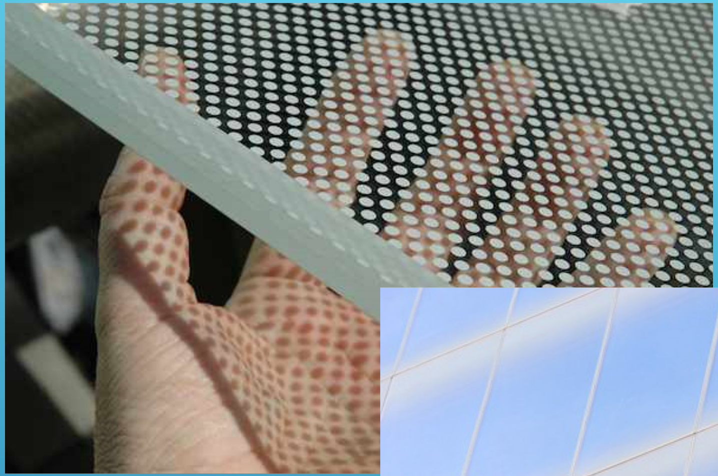
- SB 13 Ontario
- CSA A500 Building Guards
- Recognition of post breakage behavior
- Recognition of wind as load case
- Laminated glass

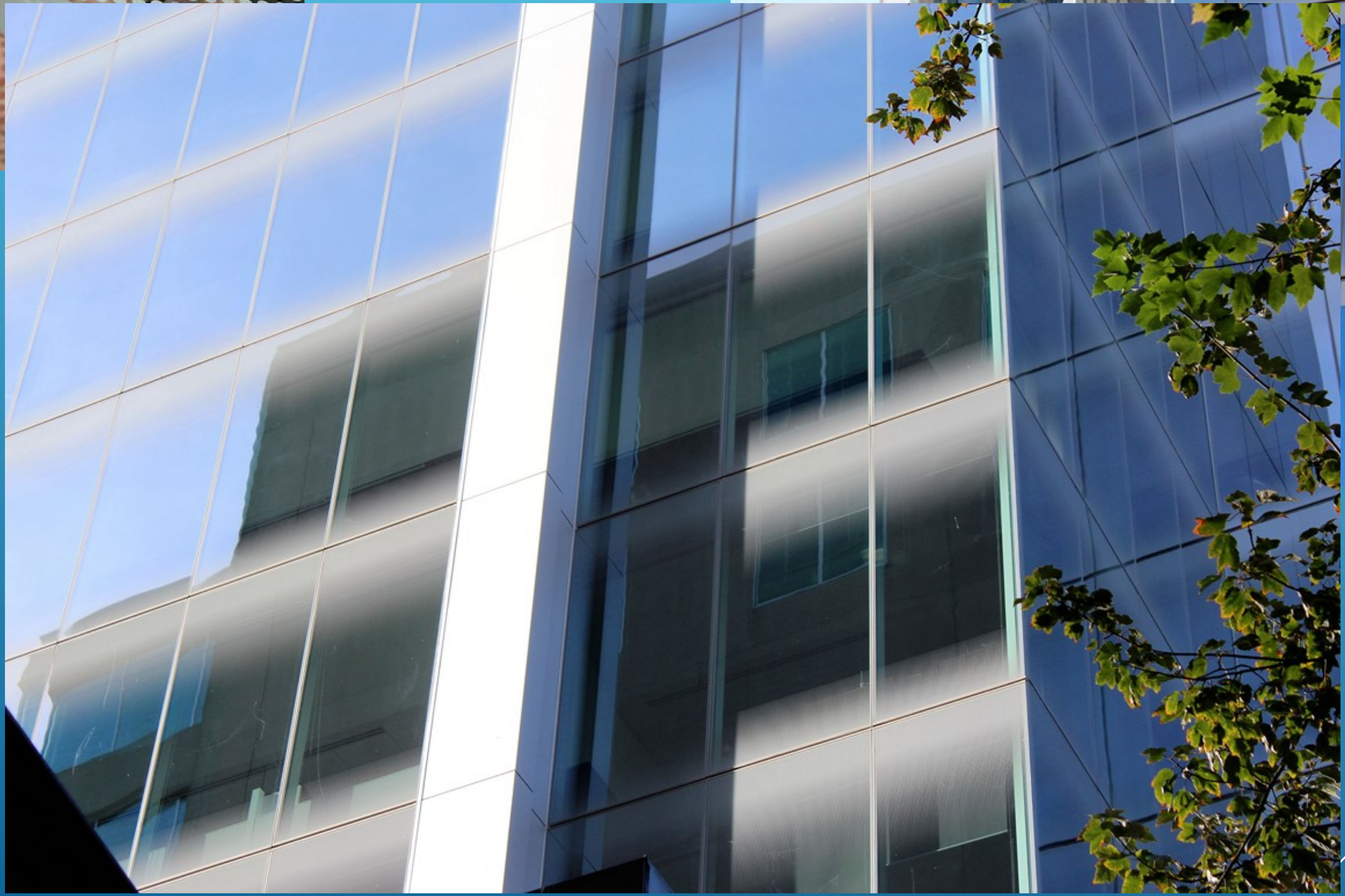
LEGISLATIVE CHANGES – FAR ENOUGH?

EVOLUTION OF GLASS SPANDRELS – CASE 2

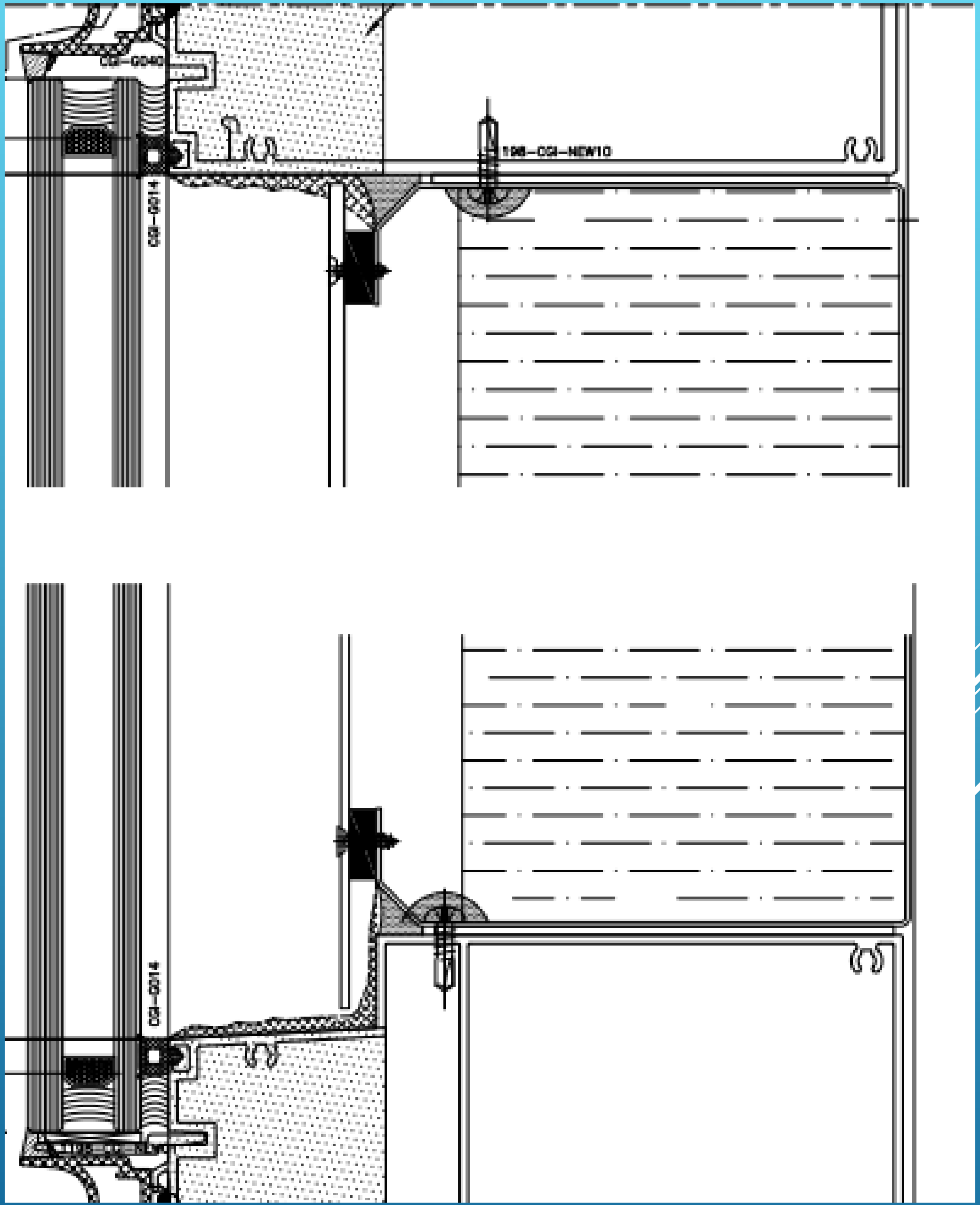


Microsoft
NORDSTROM





SPANDREL GLASS – FULL FRIT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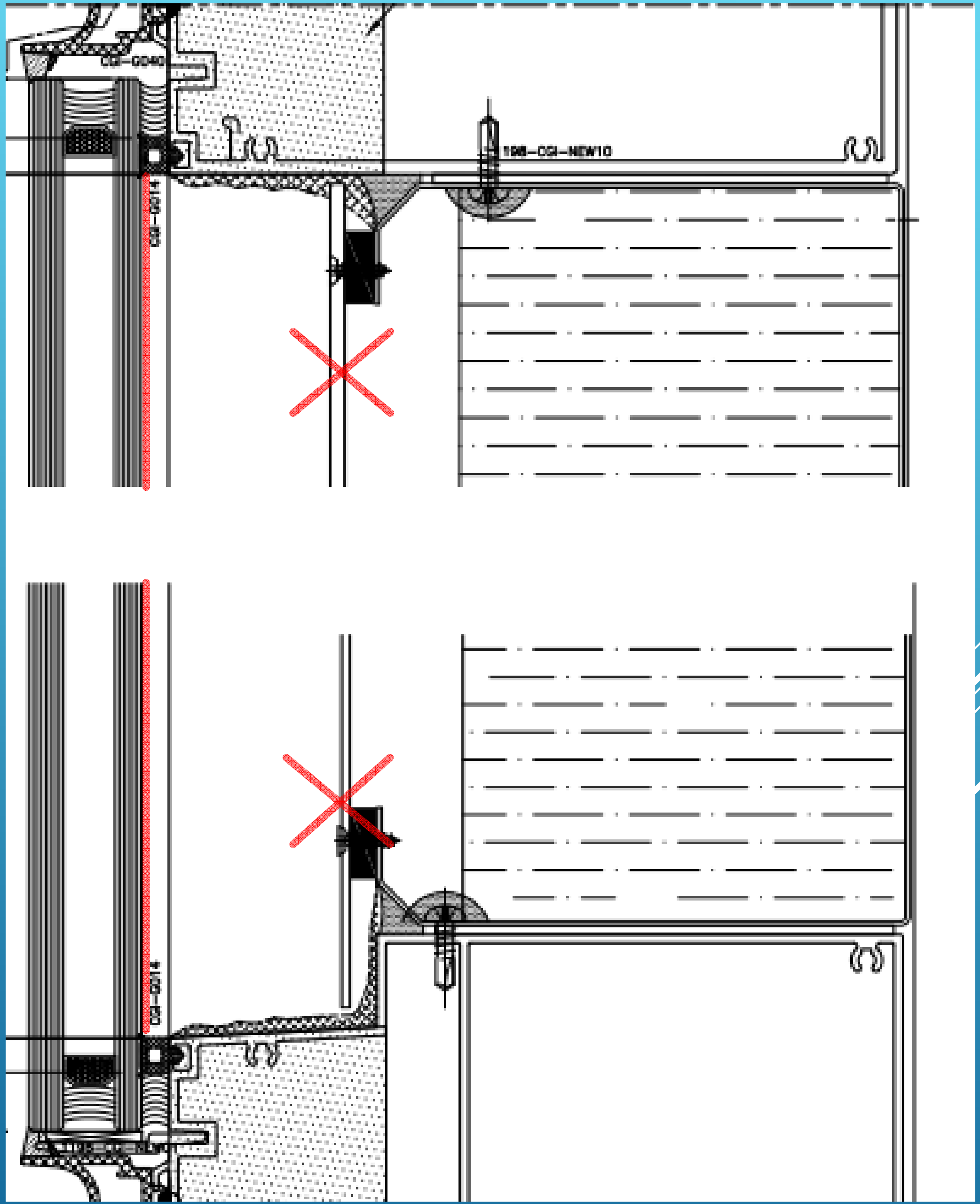
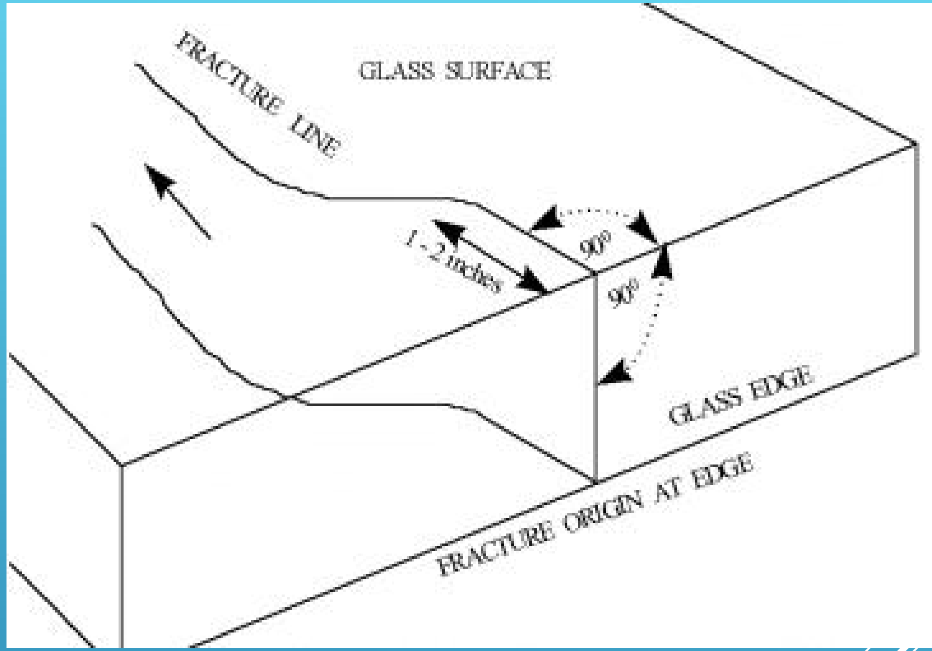


- Heat strengthened with low e #2
- Air space
- Heat strengthened with ceramic frit #4

SPANDREL GLASS

BREAKAGE OF SPANDRELS



THERMAL BREAKAGE OF SPANDRELS

THERMAL STRESS

CBD-129. Potential for Thermal Breakage of Sealed Double-GlazingUnits

Originally published September 1970.

J.R. Sasaki

Sealed double-glazing units with low shading coefficients and low U-values (CBD 101) have been in use for some time (Table I). Unfortunately, designers often overlook the fact that sealed units with superior thermal performance experience greater thermally induced stresses than do ordinary sealed double-glazing units. These stresses, by themselves, will not cause good quality glass to break, but when they are added to other stress in the glass they can result in breakage. This Digest discusses the causes of thermally induced stresses and indicates how they can be kept to a minimum.

CBD-60. Characteristics of Window Glass

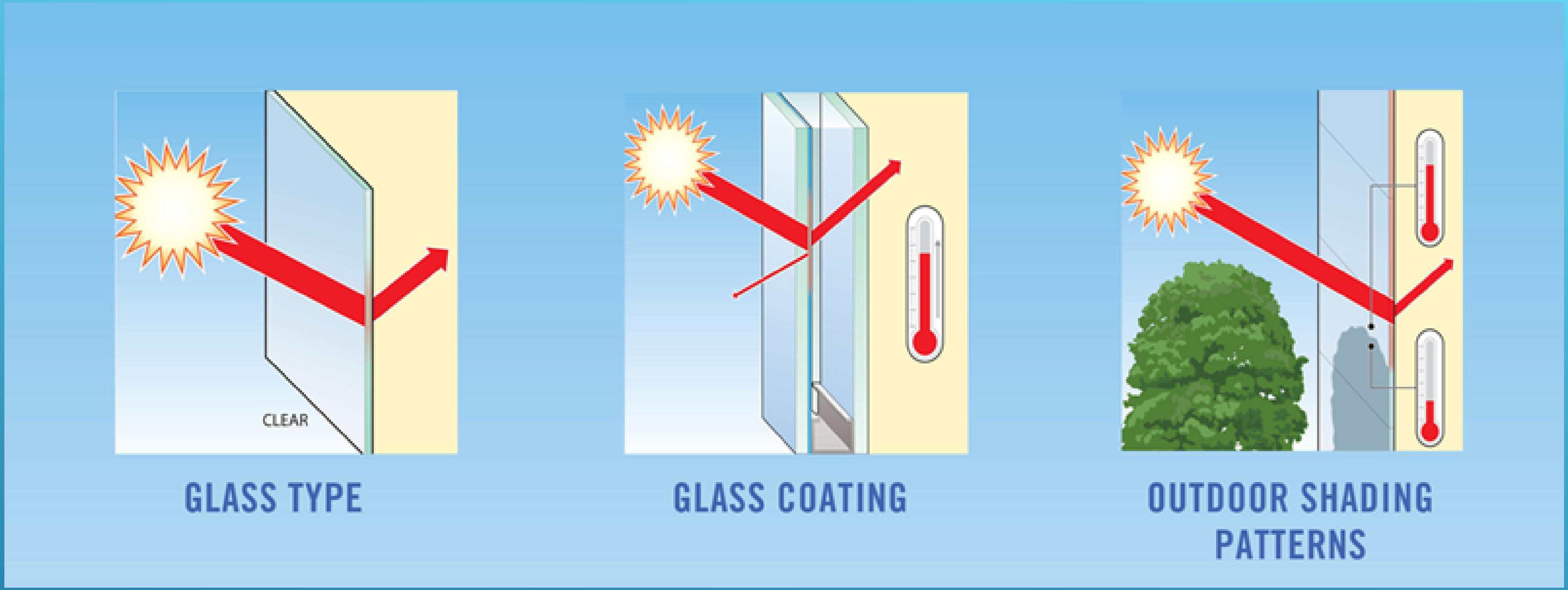
Originally published December 1964.

G.K. Garden

Although it was known before 2,000 B.C., glass found little use as a window material until Roman time. By the tenth century there was fairly high production of window glass in northern Europe, probably encouraged by the dictates of the climate. Through modern glass technology it is now used extensively in buildings for cladding and windows, not to mention a myriad of other applications.

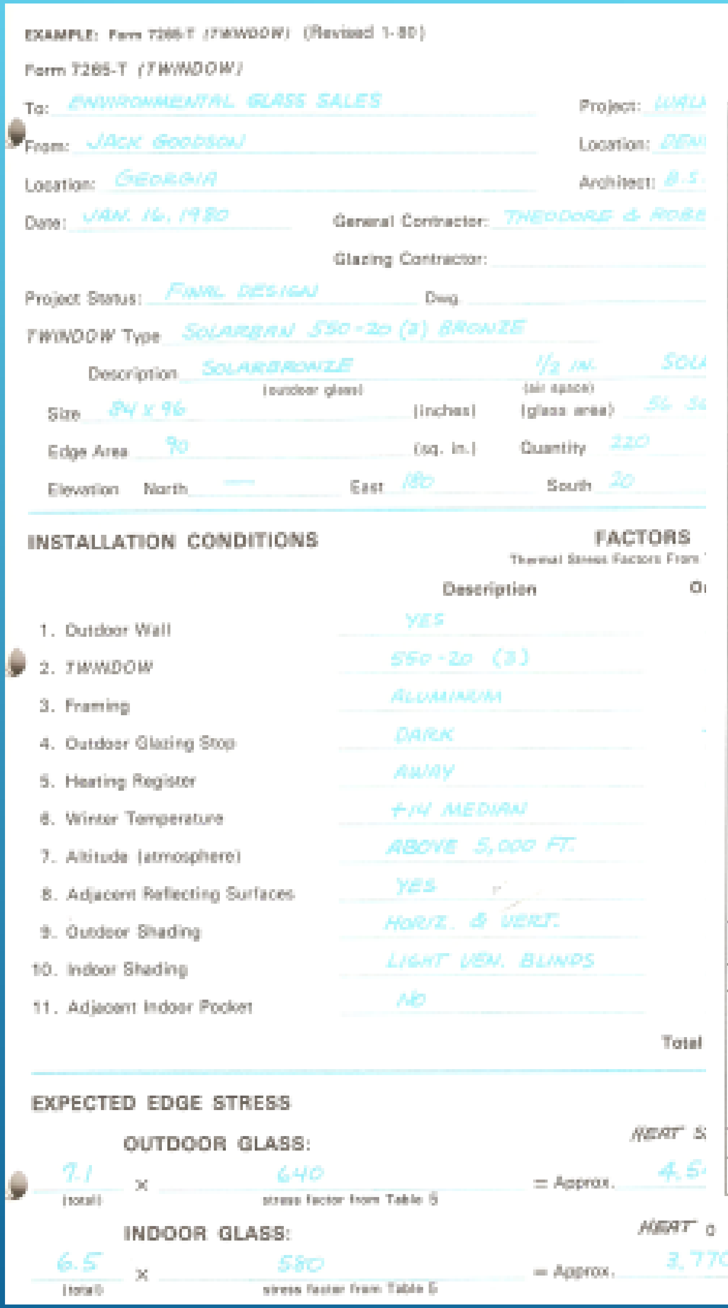
Glass is most vulnerable at its edges, with surface imperfections from cutting and handling adding to the risk of failure. The grinding and polishing of plate glass affects the surface condition of the glass, so that its usable strength is considerably less than that for firepolished sheet glass. Because the effect of stress raisers is indeterminate the allowable tensile strength of glass is determined statistically and a sizable safety factor included. By using the value thus established breakage can be reduced to an insignificant level but not eliminated.

Glass can be greatly strengthened by development of a "stressed skin" sandwich, where both surfaces are in compression and the middle is in tension. This can be accomplished by heating the glass to near its melting point and rapidly cooling both surfaces. The contraction of the middle (of the thickness) of the sheet develops the desired stress on final cooling. *Safety Toughened Glass*, as it is called, is three to five times more resistant to failure by bending, impact or thermal shock than annealed glass of the same thickness, although other properties such as durability, transparency (except for polarized light), elasticity, flexibility or coefficient of expansion are not changed. The "Achilles Heel" of safety toughened glass is its edges; even a relatively light impact with a sharp object can cause failure.



EXPOSURE

THERMAL STRESS ANALYSIS



EXAMPLE: Form 7265-T (TWINDOW) (Revised 1-80)

Form 7265-T (TWINDOW)

To: ENVIRONMENTAL GLASS SALES Project:
From: JACK GOODSON Location:
Location: GEORGIA Architect:
Date: JAN. 16, 1980 General Contractor: THEODORE & ROBE

Glazing Contractor:

Project Status: FINAL DESIGN Dwg.

TWINDOW Type SOLARBAN 550-20 (2) BRONZE

Description SOLARBRONZE (outdoor glass) 1/2 IN. (air space)

Size 84 x 96 (inches) (glass area)

Edge Area 90 (sq. in.) Quantity 220

Elevation North — East 180 South 20

INSTALLATION CONDITIONS **FACTORS**

Thermal Stress Factors From

	Description
1. Outdoor Wall	YES
2. TWINDOW	550-20 (2)
3. Framing	ALUMINUM
4. Outdoor Glazing Stop	DARK
5. Heating Register	AWAY
6. Winter Temperature	+14 MEDIAN
7. Altitude (atmosphere)	ABOVE 5,000 FT.
8. Adjacent Reflecting Surfaces	YES
9. Outdoor Shading	HORIZ. & VERT.
10. Indoor Shading	LIGHT VEN. BLINDS
11. Adjacent Indoor Pocket	NO

Total

EXPECTED EDGE STRESS

OUTDOOR GLASS: HEAT S

7.1 (total) × 640 stress factor from Table 5 = Approx. 4,5

INDOOR GLASS: HEAT

6.5 (total) × 580 stress factor from Table 5 = Approx. 3,770 psi

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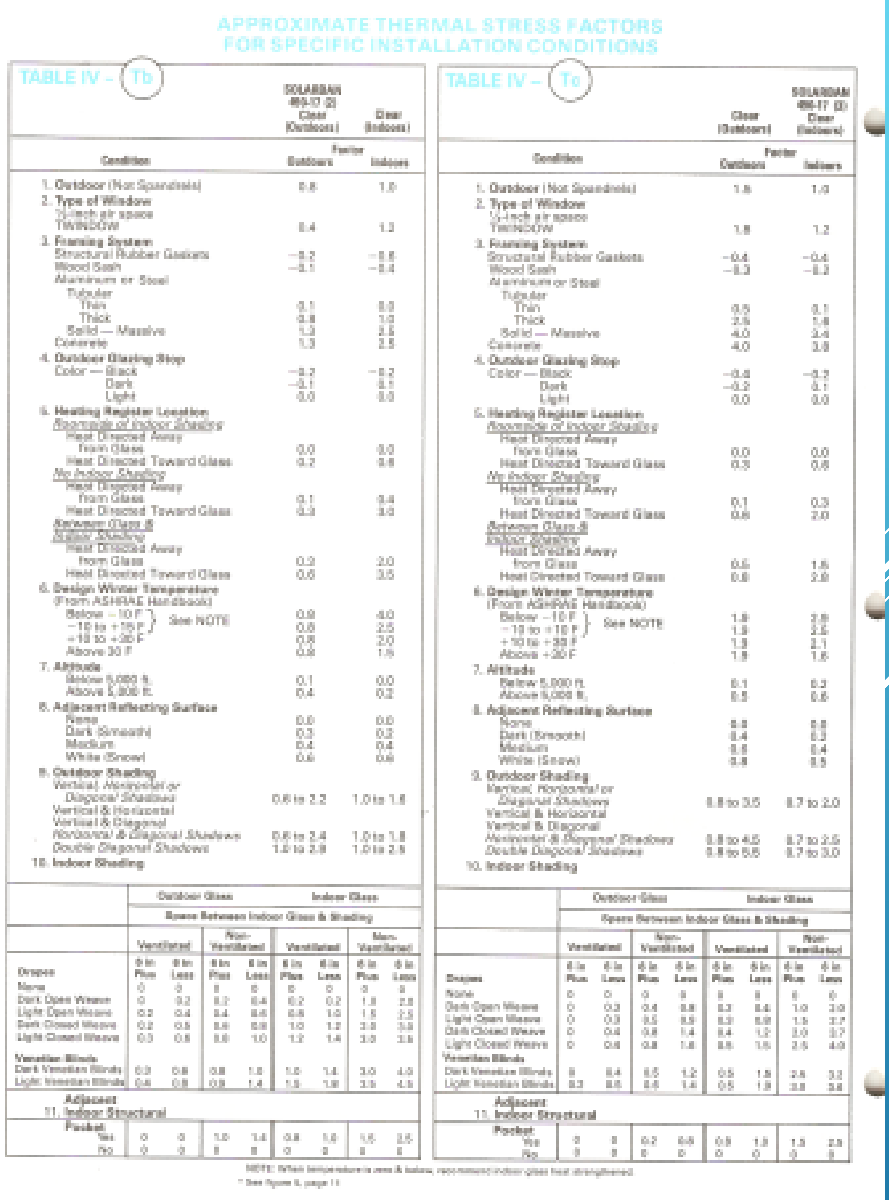


APPROXIMATE THERMAL STRESS FACTORS FOR SPECIFIC INSTALLATION CONDITIONS

TABLE IV - Tb

TABLE IV - Tc

Condition	Factor Outdoors	Factor Indoors
1. Outdoor (Not Spandrels)		
2. Type of Window		
3. Framing System		
4. Outdoor Glazing Stop		
5. Heating Register Location		
6. Design Winter Temperature		
7. Altitude		
8. Adjacent Reflecting Surface		
9. Outdoor Shading		
10. Indoor Shading		
11. Adjacent Indoor Structural Pocket		

THERMAL STRESS ANALYSIS

PPG Thermal Stress Analysis

Project Information

Project:	
Location:	UXBRIDGE ONTARIO CANADA
Architect:	
Customer:	Mark Brook

PPG Product Information

Outdoor Lite:	0.25 IN Solarban 60 on Clear(2)
Airspace:	0.5 IN (12.7 MM)
Indoor Lite:	0.25 IN Clear
Glass Size:	60 IN x 80 IN (1524 MM x 2032 MM)
Glass Area:	33.33 SQ FT (3.0960 SQ M)
Edge Area:	70.00 SQ IN (42666.67 SQ MM)

Form 7265-IG -- Thermal Stress Factors From Table TG

Installation Conditions	Description	Outdoor Glass	Indoor Glass
Outdoor Wall	Yes - Not Spandrels	0.8	1.0
Insulating Glass Unit	With 0.5 IN Airspace	1.8	0.2
Framing	Tubular Alum/Steel Thin	0.5	0.2
Outdoor Glazing Stops	Dark Colors	-0.2	-0.1
Heating Register	Roomside of indoor shading - heat directed away from glass	0.0	0.0
Winter Temperature	-10 F to 10 F	1.5	0.8
Altitude (atmosphere)	Below 5,000 Feet	0.1	0.1
Adjacent Reflecting Surfaces	Medium (mix of dark/white colors)	0.5	0.3
Outdoor Shading	at 50%	2.2	1.2
Indoor Shading	Drapes - Light Open Weave (Ventilated Space Between, ≥ 6 inches)	0.0	0.1
Adjacent Indoor Pocket	None	0.0	0.0
	Factor Totals	7.2	3.8

Expected Edge Stress

Outdoor Glass:	7.2 x 470 = 3384 psi
Indoor Glass:	3.8 x 220 = 836 psi

Recommendation

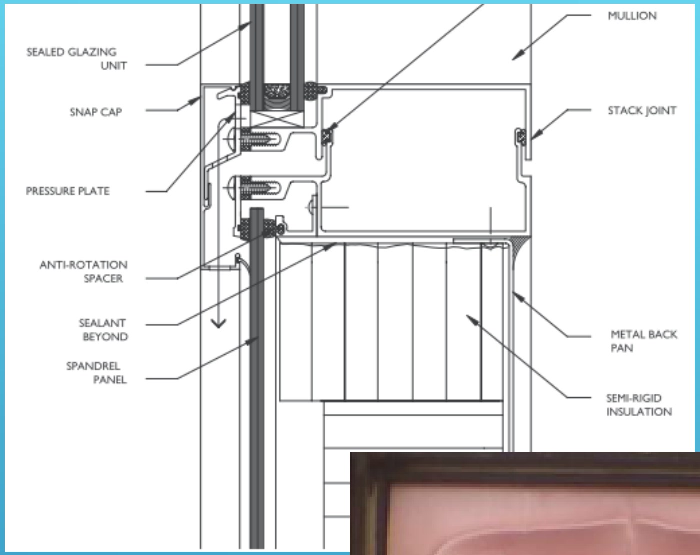
Outdoor Glass:	Heat Strengthened
Indoor Glass:	Annealed

Estimated Probability of Glass Breakage

	Outdoor Lite	Indoor Lite
Annealed	18 per 1000	less than 1 per 1000
Heat Strengthened	less than 1 per 1000	less than 1 per 1000

Notes

- Vary with construction
- Single glazing 60-80degC
- Double glazing 90-100degC
- Venting, insulation, air circulation

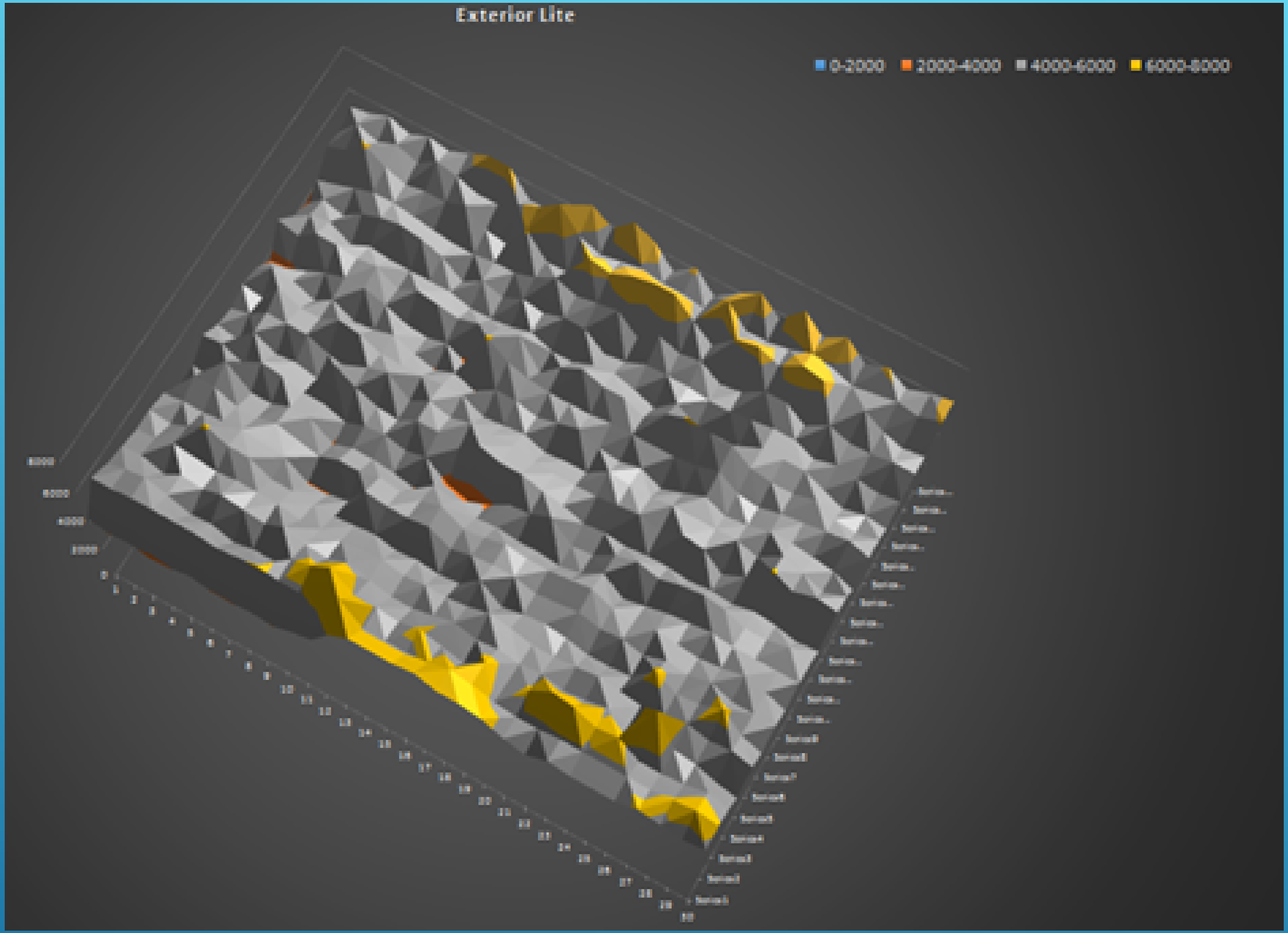


Credit Image Tim Moore

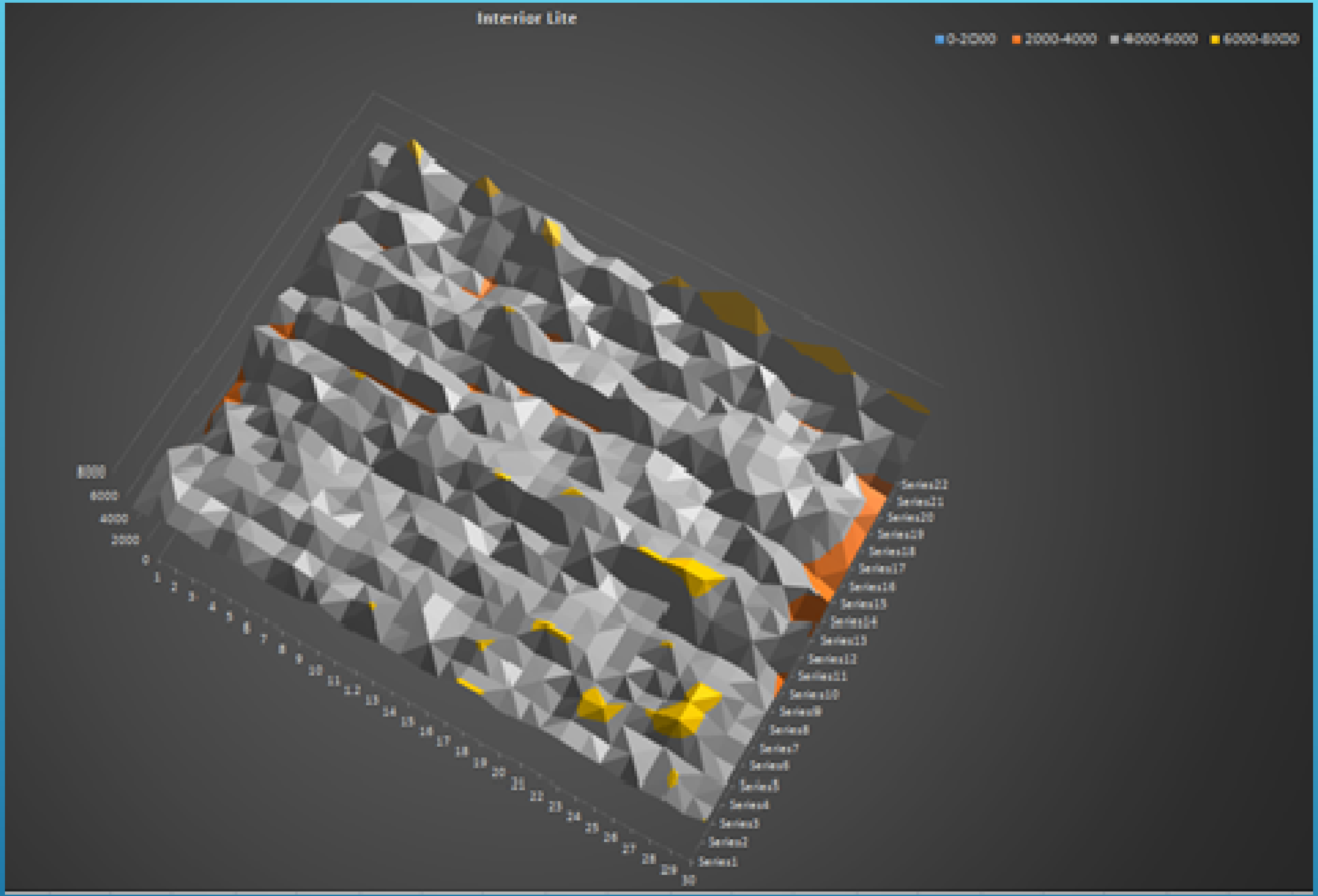
ACTUAL CAVITY TEMPERATURES

- Thermal simulation using field data as correlation
- Temperature gradient generates edge tensile stress
- Balloon with elastic band
- 4000-6000psi (20-40MPa)

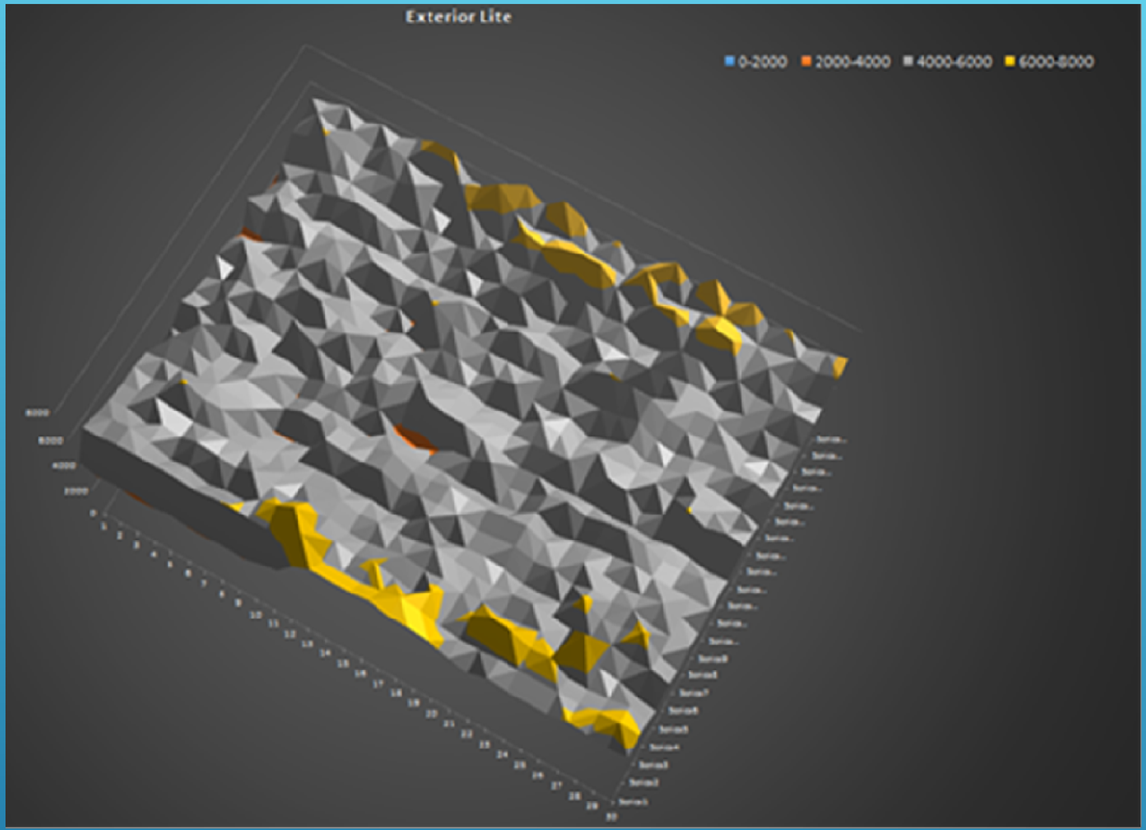
THERMAL STRESSES

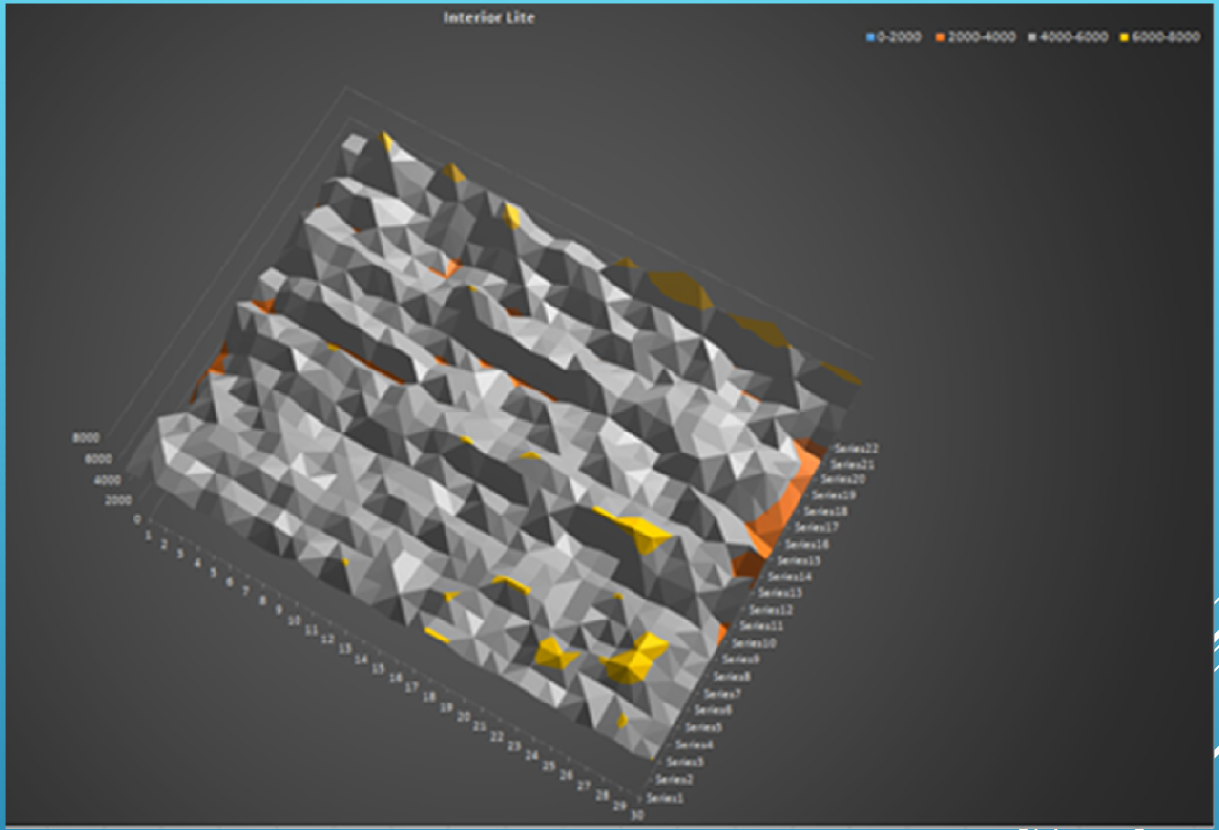


SURFACE COMPRESSION NO FRIT



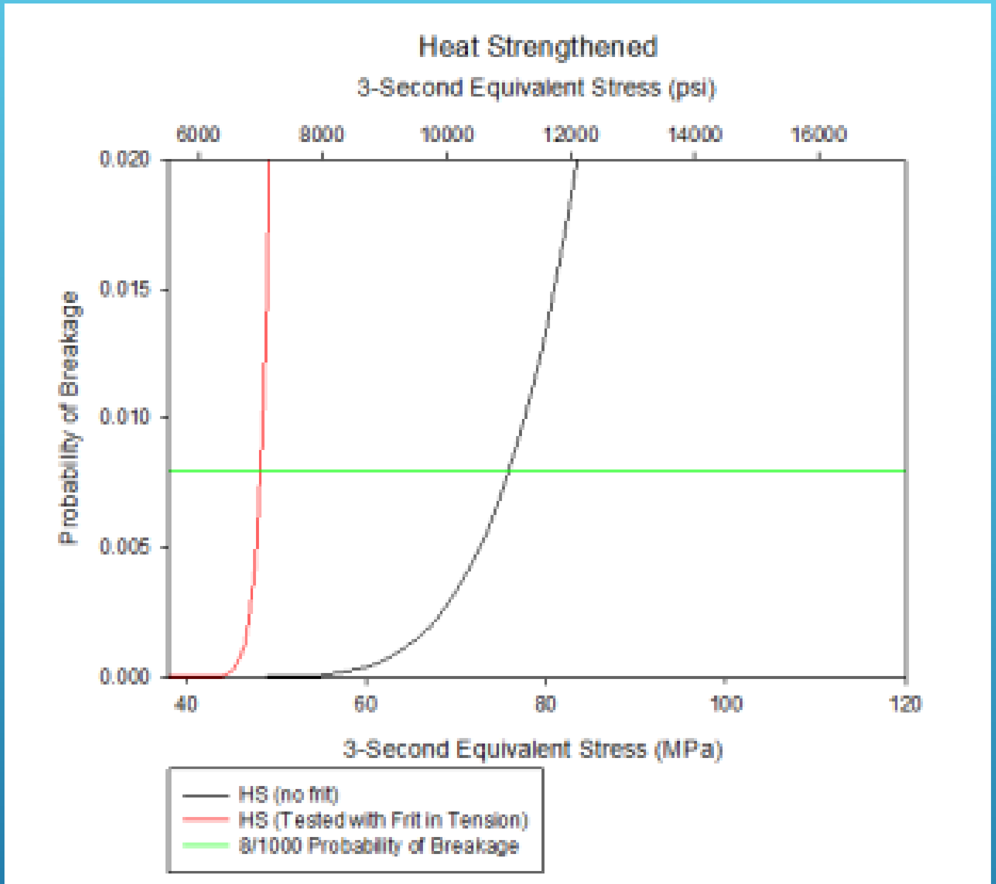
SURFACE COMPRESSION FRITTED

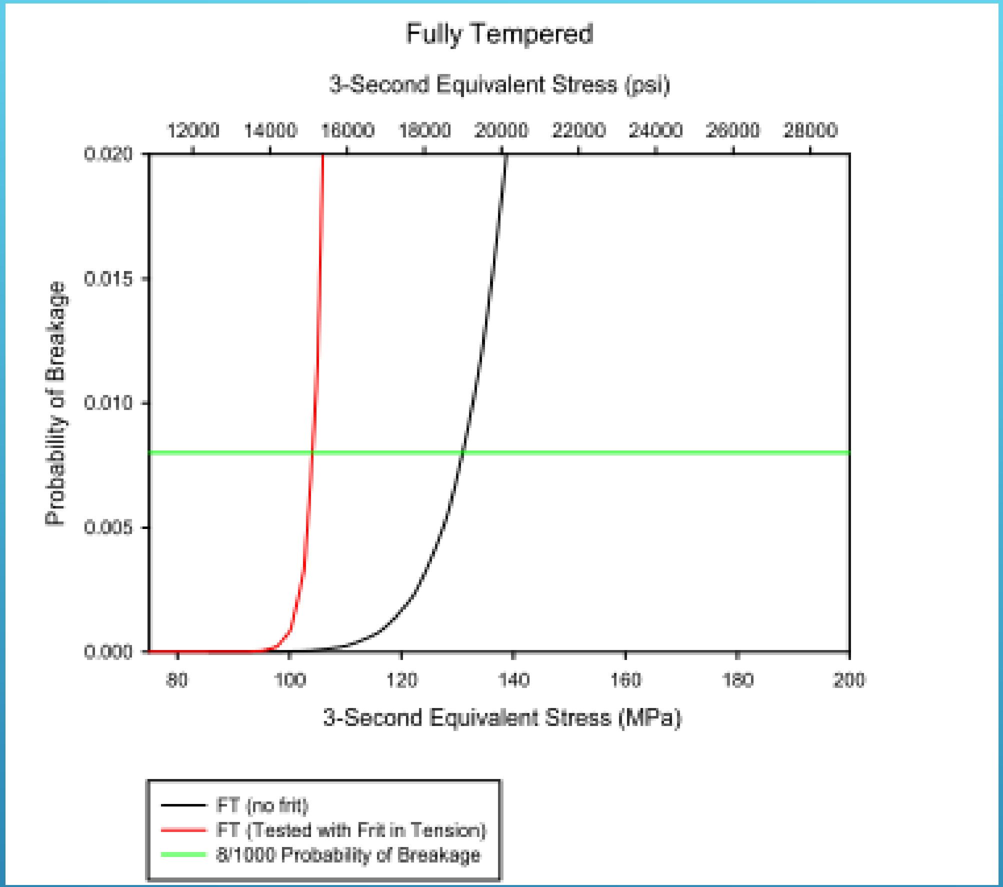

Exterior Lite
0-2000
2000-4000
4000-6000
6000-8000


Interior Lite
0-2000
2000-4000
4000-6000
6000-8000
8000
6000
4000
2000
0

- Impact on heat treating process
- Beam sample testing 60 – 70% as strong as non-fritted
- Consistent with international standards – not in Canada eh.
- Weakening effect of frit

EFFECT OF FRIT





Credit Image Barry/Norville

EFFECT OF FRIT

- Extreme temperatures and temperature gradients by design
- Manufacturing variances
- Weakening effect of frit

PERFECT STORM

- Revise architectural design to lessen stress
- Fully temper inboard lite – heat soak
- Consider non-ceramic frit coating*
- Modify ceramic coating application
- Revise edge treatments

SOLUTIONS

- ~~Revise architectural design to lessen stress~~
- Fully temper inboard lite – heat soak
- Consider non-ceramic frit coating*
- Modify ceramic coating application
- Revise edge treatments

SOLUTIONS

- It is the fate of glass to break.
- Glass doesn't just break – it breaks for a reason

THANK YOU