Flat Glass Manufacture and Fabrication

Glass Engineering 150:312
Ceramics and Materials Engineering

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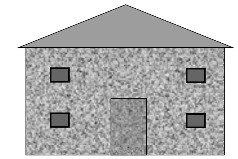
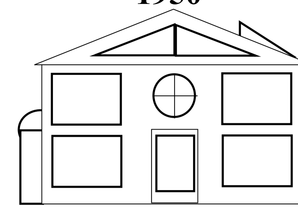
Technology Revolution

- **Float Glass Process**
  - → Inexpensive
  - → High Quality
- **Coatings**
  - → Thermal Performance
  - → Windows are as good as walls
- **Result: Drastic change in the way we live**
- **And the same for automobiles.**



1950



2003

Introductory History

- **Egyptians**
  - → First people to realize what could be done with glass when it is hot and plastic.
  - → Made vessels for cosmetics and perfumes by forming molten glass around a shaped core.
- **Romans**
  - → By Roman times glass being blown and molded, cut and engraved, and painted.
- **Middle Ages**
  - → Main achievements were colored glass windows.
- **Last 50 to 70 Years**
  - → Only then was there any appreciable advances in the development of flat glass for windows.
- **Only two basic methods of forming flat glass through the ages (prior to float glass):**
  - → Window glass processes
  - → Plate glass process

Window Glass

- **General Features**
  - → Window glass processes have all depended on forming a sheet by stretching a lump of molten glass.
  - → They all have the characteristics of brilliant fire finish.
  - → Three processes - crown, cylinder, and drawn - have been used.
- **Crown Process:**
  - → Developed by Syrians in 7th Century.
  - → Blow bubble- attached iron punty opposite the blow pipe, remove blow pipe, spinning-centrifugal force flattens bubble to circular disk.
  - → Most commonly used up to the middle of the 19th century (i.e., mid-1800's).
  - → The crown or disk was spun after the initial blowing and shaping stages on the end of an iron rod.
  - → Thin, transparent, circular plate of glass - attached at center - result of heat and centrifugal force.
  - → Disk diameter size 1.4 meters (55") usual - 1.8 meters (71") maximum.
  - → Waste high - cutting square panes from circular disk.
  - → Each crown had a bullion in the center where rod was attached.

Cylinder Glass

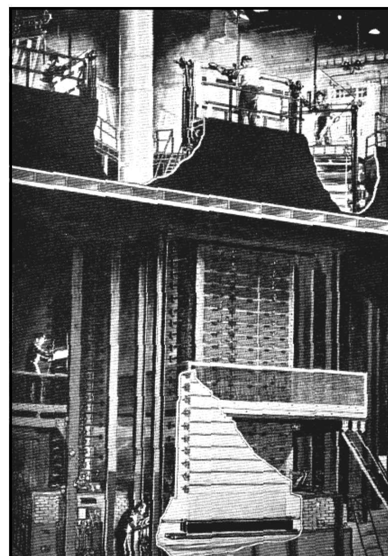
- **Handblown**
  - → First introduced in 12th or 13th century.
  - → Next advance came in mid-19th century.
  - → Removed size limitations of crown - could make much bigger panes.
  - → Process involved blowing a large cylinder which was allowed to cool before being split and flattened by heavy wood block.
  - → Cylinders were blown and then swung in a trench: the cylinder became longer and air was blown into it to maintain its shape.
  - → Cylinders usually about 1.6 meters (63") long and 0.3 meters (12") across.
  - → Process mechanized somewhat until cylinders up to 4 meters (13') long and 0.6 meters (24") in diameter could be blown.

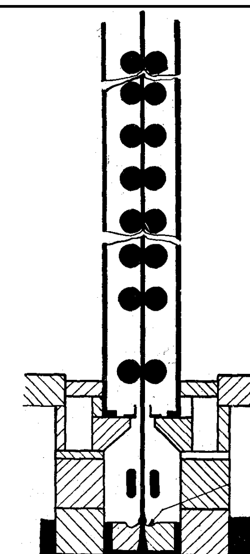
Cylinder Glass

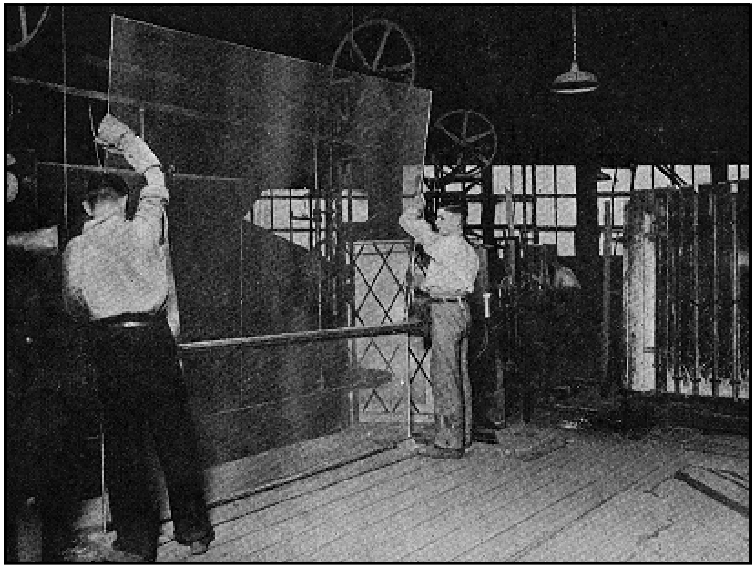
- **Machine**
  - → Sheet or window glass production was first mechanized on a large scale in early 20th century (circa 1903).
  - → American Window Glass Company developed method for mechanical blowing of cylinders.
  - → Up to 13.4 meters (44') long and 1 meter (40" = 3') diameter.
  - → A blowpipe with a flanged metal disk or bait fixed to it, lowered into molten glass
    - ✓ bait slowly raised between guiding shafts drawing up a cylinder of glass with it
    - ✓ compressed air blown down the pipe, kept diameter constant
    - ✓ speed of drawing determined thickness
    - ✓ glass lowered to form, split, flattened, and annealed.
  - → Although very large quantities of sheet glass could be produced, quality inconsistent, relatively slow and laborious, considerable waste of time and material.
  - → Process was discontinuous, cylinders had to be split and flattened, which was both costly and harmful to the surface.
  - → Quality poor
    - ✓ gatherer introduced cord and bubble
    - ✓ flattening operation introduced surface defects.

Machine Draw Processes

- **The logical evolution was to draw a flat sheet rather than a cylinder.**
- **Fourcault Sheet Draw Process**
  - → The modern sheet glass process was first developed by Fourcault circa 1914 in Belgium.
  - → Sheet of glass is drawn vertically through a "debiteuse", a refractory block with a slit across its width immersed in the molten glass.
  - → Glass rises through the slit under hydrostatic pressure and a bait is used to raise the sheet.
  - → Main problem is to prevent "waisting in" - achieved by passing edges of ribbon between cooled rollers.
  - → Thickness determined mainly by speed of draw and glass temperature in the drawing kiln.







Machine Draw Processes

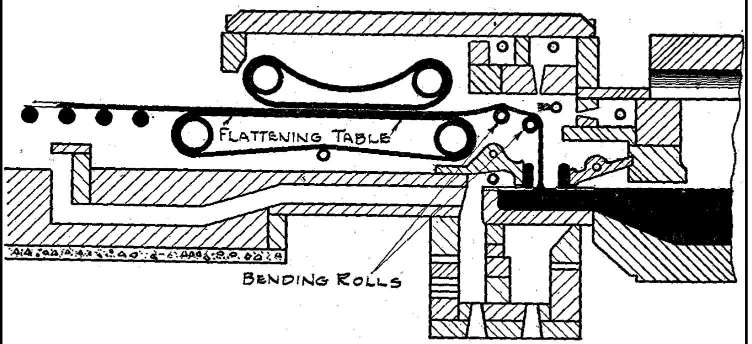
- **Fourcault Process Disadvantages**
  - → Because of temperature conditions in drawing chambers and tendency of glass to devitrify, process has to be stopped at frequent intervals and drawing chamber temperatures raised to remove accumulated devitrified glass.
  - → Because of erosion and corrosion, "debi" had to be replaced every 3 to 4 months.
  - → Solidified ribbon of glass has a certain amount of distortion that cannot be avoided because of small differences in viscosity due to chemical and thermal inhomogeneities.
  - → The thickness of the ribbon of glass drawn is controlled by the viscosity so that even small inhomogeneities cause variations in thickness of the finished sheet.

Machine Draw Processes

- **Fourcault Process Advantages**
  - → Machine is relatively simple and the glass is therefore inexpensive.
  - → Surface of glass has "fire-finish”
  - → The fire-finish surface is achieved by letting the glass cool down on its own without touching anything solid while soft.

Machine Draw Processes

- **Colburn Process**
  - → Running in parallel development with the Fourcault process in Belgium was the Colburn process in the U.S.A.
  - → 1916-1917 Libbey-Owens Sheet Glass Co. Installed several machines.
  - → Process
    - ✓ molten glass is cooled in its passage from the melting tank to the drawing chamber
    - ✓ reheated for a straight upward pull of about 1 meter
    - ✓ subsequent bending over a roller
    - ✓ moved horizontally into a lehr.
  - → Sheet widths range from 2.54 to 4.0 meters (8.3 to 13.2'), the maximum being about 1 meter greater than is possible on the Fourcault process.
  - → Glass had an “orange-peel” texture on one surface



Machine Draw Processes

- **Pennvernon (or PPG Process)**
  - → Developed by PPG
  - → Patented in 1926
  - → Generally recognized as the most successful of the sheet drawing processes.
  - → Like the Fourcault process, it is a vertical drawing process, but the debiteuse with its slit is replaced by a submerged refractory slab called a drawbar.
  - → The glass ribbon is drawn freely from the surface of the molten pool with the drawbar allowing more flexible temperature adjustment since it acts as a radiation shield.
  - → Pairs of coolers can be inserted on top of each other and this permits a higher working temperature in the channel - so there is less tendency to devitrify than in the Fourcault Process.
  - → Glass at approximately 750^{o} C [1380^{o} F].
  - → Drawn up annealing tower approximately 13 meters (42.7') high.
  - → Width is maintained by knurled water cooled rollers which mark only the edges.

Machine Draw Processes

- **Asahi Process - Asahi Glass Co. - Japan**
  - → Patent filed 10/20/70; patent issued 6/19/73.
  - → Principal feature is that high quality sheet glass in a wide range of thickness (0.7 to 6 mm) can be produced efficiently through a simple and low-cost remodeling of a Fourcault plant.
  - → Licensed to 13 sheet makers around the world (128 machines).
  - → Drawing elements are pair of refractory rollers submerged called A-block and an edge former called Edge-block.
  - → West Virginia Sheet Glass, Clarksburg, W.V., purchased by Asahi Glass, converted Fourcault to Asahi Process, production started in 1980.

Machine Draw Processes

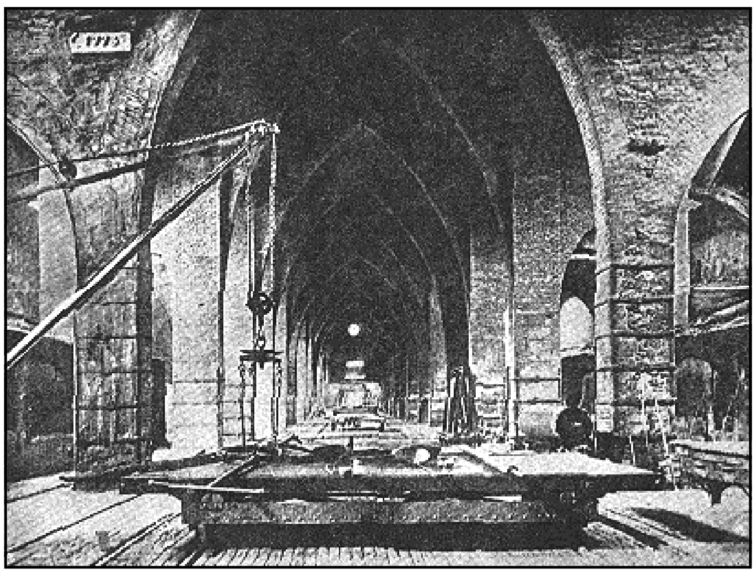
- **Corning Overflow Process (Down draw process)**
  - → Glass enters a long narrow trough.
  - → Glass flows over both sides and joins together as it is drawn downward.
  - → Use for technical sheet glass
  - → Modified and used extensively for LCD screens.

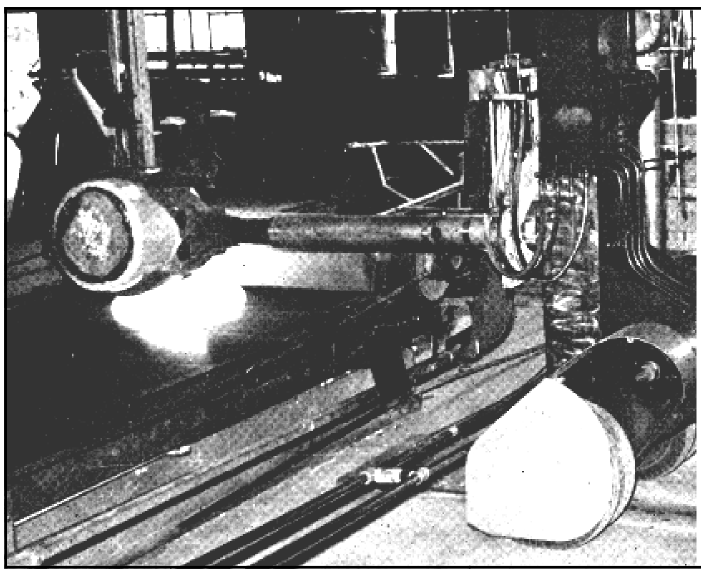
The Development of Plate Glass

- **Glass made by the window processes was it was full of distortion.**
  - → All window methods involved stretching the molten glass whether by spinning, blowing or pulling it, and this stretching converted inhomogeneities into distortion.
  - → The window processes also made only a comparatively thin glass.
- **Coaches and large shop windows required distortion-free glass.**
  - → The Plate Process was developed to meet these requirements.
  - → Plate glass had ground and polished sides -- no distortion
  - → Plate glass was thick and had the necessary strength

The Development of Plate Glass

- **Table Cast**
  - → Molten glass was poured onto the table and then rolled by a traveling roller into a plate.
  - → Annealed, ground flat, and then polished.
  - → Grinding involved several stages using finer and finer sand, and polishing was done with rouge.
  - → Results were good, but process was time-consuming and expensive



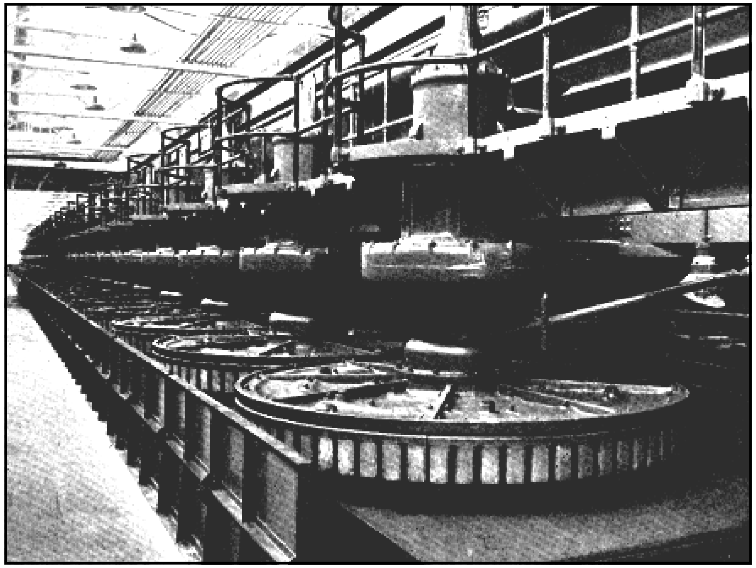


The Development of Plate Glass

- **Bicheroux Process**
  - → Introduced in 1920's (just after 1st World War).
  - → Glass still melted in pots - but it was then rolled into a sheet between mechanical rollers, rather than being cast onto a table and then rolled.
  - → Made smoother sheet with a consequent saving in time and material in the grinding process.
- **Continuous Rolled**
  - → First breakthrough came from Ford in America, where it was shown that glass could be rolled continuously.
  - → Pilkington developed a process that successfully combined a continuous melting furnace with the continuous rolling of a ribbon of glass.

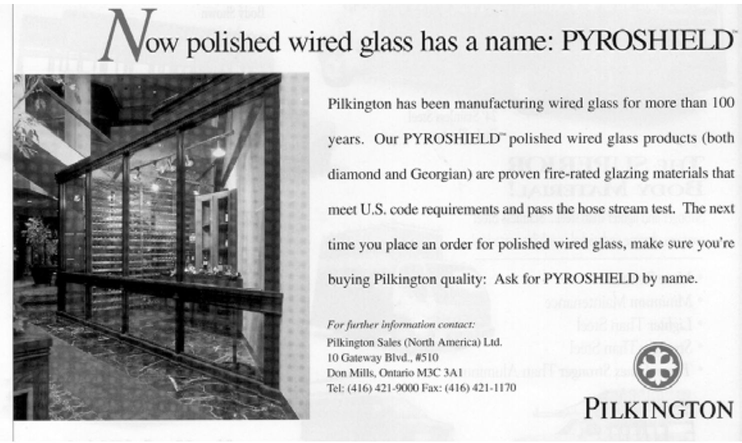
The Development of Plate Glass

- **Continuous Grinding and Polishing:**
  - → In 1923 Pilkington introduced the first continuous grinding and polishing machine.
  - → Cut glass plates mounted onto a series of tables which moved through the grinders and polishers; at end of process, table dropped into a tunnel and returned to accept another plate of glass.
- **Twin Grinding:**
  - → During the early 1930's, developed by Pilkington - first used in 1935.
  - → A machine that could grind the ribbon of glass on both sides simultaneously as it came out of the annealing lehr before it was cut into plates.
  - → Acknowledged as the final and most remarkable development in the long history of plate glass manufacture.
  - → In the machine a continuous ribbon of glass about 300 meters long was ground on both surfaces at the same time with enormous grinding wheels fed with progressively finer sand.
  - → Process speed started at 66 m/h; improvements led to speed of 300 m/h in 1946.



Patterned and Wire Glass

- **Table Cast**
  - → Developed along similar lines as plate glass.
  - → James Hartley developed a method for patent rolled plate glass in 1847.
  - → Glass ladled straight from melting pot onto casting table and rolled flat (also a pattern could be engraved on the table and transferred to the glass on rolling).
  - → Hartley had eliminated the stage of refining the glass (in a cuvette) before pouring it; and as a result was able to patent the process although it was just like plate otherwise.
  - → Hartley's glass was translucent, but not transparent.
  - → Filled a need for a strong, cheap product for skylights and for roofing railway stations, and when colored, was in great demand for churches.
  - → Wire glass was developed later
    - ✓ Catastrophic failure protection
    - ✓ Still used widely today as security glass



Patterned and Wire Glass

- **Rolled and Continuous Rolled:**
  - → By 1884 double roller machines were in use.
  - → A second pair of rollers impressed a pattern on one side of the sheet after it had been formed by the first pair of rollers.
  - → Developments of this double rolling machine continued to be used until the 1950's when the continuous casting process (for plate) quickly led to continuous rolling of patterned and wired glasses.
  - → Pattern glass very popular in Europe, less so in USA
  - → Pattern glass manufacturing continues by roll processing
  - → Some secondary patterning of float glass

The Transition to Float Glass

- **Plate Glass**
  - → Met all demands for thick and thin distortion-free windows, but
  - → glass wastage was 20% of production; loss from grinding and polishing.
  - → high capital and operating costs.
- **Sheet Glass-(Window Glass)**
  - → Was inexpensive
  - → Could make glass which retained its natural brilliance without the need for grinding and polishing, but:
  - → Could not make the high quality products free from distortion
- **Dream:**
  - → Combine the best of the two.
  - → Make glass with fire polish inexpensively and with the distortion-free quality of polished plate.
  - → Dream achieved in 1959 with the commercialization of the Float process.

The Transition to Float Glass

- **Float Process Description**
  - → A continuous ribbon of glass moves out of the melting furnace and flows along the surface of an enclosed bath of molten tin.
  - → Ribbon is held in chemically controlled atmosphere at a high enough temperature for a long enough time for the irregularities to melt out and for the surfaces to become flat and parallel.
  - → Because the surface of the molten tin is flat, so is the glass.
  - → Ribbon is then cooled while on the molten tin until the surfaces are rigid.
  - → A ribbon is produced with a uniform thickness and bright fire polished surfaces with no need for grinding and polishing.

Key Issues in Flat Glass Processing

- **Defect origins:** tank, forming machinery, forming process
- **Glass surface contact**
  - → Fire polish; handle when cool or by edges for drawn glass
  - → Smooth metal rollers for rolled glass
  - → Float on molten tin for float glass
- **Forming**
  - → Draw, roll or float
  - → Cool to freeze in new geometry
- **Principal Forming Forces**
  - → Viscosity/gravity
  - → Traction
  - → Friction
  - → Surface tension

Key Issues in Flat Glass Processing

- **Each process has optimum forming viscosity (and temperature)**
- **Liquidus temperature**
  - → below Tliq, crystals start to grow spontaneously (devitrification)
  - → the greater the time spent by the glass under Tliq, the greater the chance of devitrification
  - → must avoid for product quality issues
- **Problem: stationary glass in melter and forehearths below Tliq**

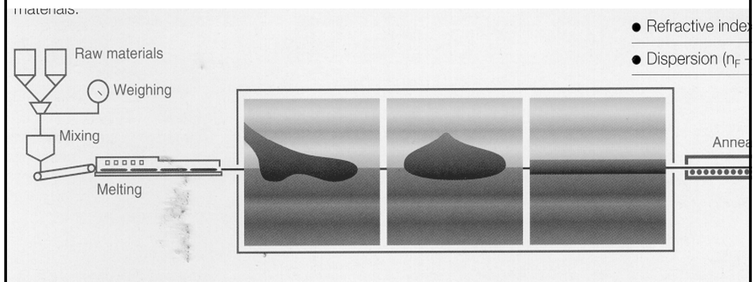
The Float Process

- → Conditioned glass falls freely over spout lip onto molten tin bath
- → Flat bath is steel casing lined with refractories
- → Nitrogen-hydrogen atmosphere prevents oxidation
- → Temperature profile is maintained in the bath by radiant heaters and water coolers
- → Guides, barriers, edge rolls and top rolls control ribbon position
- → The glass ribbon, when sufficiently cool, is taken off the tin bath and travels to a horizontal annealing lehr
- → Entrance temperature is 1050^o ; 10^4 poise; liquidus is 995^o C. Exit temperature is 600^o ; 10^{11} poise.
- → Equilibrium thickness of glass-ribbon is 7 mm.
- → Key to patent: glass delivery and wetback area. Thin skin of glass that has passed over refractory flows preferentially outward and ends up in outer border of ribbon, where it eventually is cut off.

Typical Float Furnace Parameters

- **Area:** **165 m^2 [1777 ft^2]**
- **Pull:** **500 tonnes/day**
- **Pull/Area:** **3 tonnes/m^2**
- **Salt Cake:** **1.0 - 2.7% of sand**
- **Hot Spot:** **1620° C**
- **Backwall:** **1480° C**
- **Difference:** **140° C**
- **Redox Number:** **20 - 30**

FLOAT GLASS PROCESS



Float glass advantages

- **High Optical Quality**
  - → No waviness
  - → Fire polished surface
  - → Thickness range 0.4-30 mm
  - → Widths to 3.5 m
  - → Capacity 150-700 tons/day
- **Efficient Process**
  - → Couples well to melting furnace
  - → Ribbon width can be set to match product requirements
  - → Only waste is 5 cm strip on ribbon edges
  - → But, color changes are still inefficient
- **Horizontal Ribbon -Annealing, Cutting and Handling Simplified**
- **Low Labor Requirements, but High Capital Costs**

The Tin Bath

- **Tin is the only suitable material based on:**
  - → Cost
  - → Vapor pressure
  - → Toxicity
  - → Chemical inertness to glass
  - → Commercial grade
- **Oxygen Cycle**
  - → To prevent tin oxidation, a protective atmosphere is used [N_2, H_2], the bath is sealed.
  - → Nevertheless, some oxygen can enter the bath, increasing the tin vapor pressure.
  - → Tin speck: tin compounds condense on the cooler parts of the bath roof and fall onto the ribbon.
  - → DROSS: Solubility of oxygen in tin increases with temperature. At the hot end tin dissolves oxygen, which is precipitated as stannic oxide dross at the cold end. The dross floats on the tin under the glass ribbon.
  - → TIN BLOOM: Bottom of glass ribbon takes up thin layer of stannous oxide. On reheating for bending or tempering this can oxidize to give a wrinkled surface with a bluish haze. UV fluorescence.

The Tin Bath

- **Sulfur Cycle**
  - → Sulfur is extracted from the glass and vaporizes as tin sulfide.
  - → Hydrogen reduces it to tin
  - → Tin condenses and drops onto the glass surface.
- **Remedies**
  - → reduce sulfur in glass compositions
  - → minimize cold surface availability by proper bath roof design
  - → remove tin sulfide from vapor

Criteria Determining the Choice of A Support Metal for the Float Bath

	Melting point C	**Boiling point C**	**Estimated Density at 1050 C [g/cc]**	**Vapor Pressure at 1027 C [torr]**
Required value	<600	>1050	>2.5	<0.1
bismuth	271	1680	9.1	27
gallium	30	2420	5.5	7.6×10^{-3}
indium	156	2075	6.5	7.9×10^{-2}
lithium	179	1329	0.5	55
lead	328	1740	9.8	1.9
thallium	303	1460	10.9	16
tin	232	2623	6.5	1.9×10^{-4}

Volatilization of Oxygen and Sulfur from Dilute Solutions In Tin

	Impurity in tin	Main component of vapor	Tin in saturated Vapor at 1027 [mg/m^3]
none		tin	0.3
oxygen	1000 ppm by weight	stannous oxide	3
sulfur	1000 ppm by weight	stannous sulfide	100

Flat Glass Fabrication

Flat glass products and their application in architecture and automotives

Table 1. Insulating Glass Sealant Comparison Chart[1]

Physical Property/ Test Attribute	Butyl Extrusion[2]	Hot Melt Butyl	Mercaptan Terminated Polypropylene Glycol[3]	Polysulfide[4]	Silicone	Urethane
Chemical Resistance (Glazing Compatibility)	Fair	Fair	Good	Excellent	Very Good	Good
Chemical Resistance (Wood Preservatives)	Poor	Poor	Fair	Excellent	Good	Good
Moisture Vapor Transmission	Excellent	Excellent	Good	Good	Poor	Very Good
Gas Retention (Argon)	Excellent	Excellent	Very Good	Very Good	Poor	Good
Low-Temperature Properties (–40° F)	Fair	Fair	Very Good	Very Good	Very Good	Very Good
High-Temperature Properties (180° F)	Fair	Fair	Very Good	Very Good	Excellent	Very Good
Accelerated Aging (QUV 2,000 hrs)	Very Good	Very Good	Fair	Very Good	Excellent	Fair
Outdoor Aging	Fair	Good	Fair	Very Good	Excellent	Fair
Structural Strength	Fair	Fair	Very Good	Very Good	Excellent	Very Good

[1] Testing done by Morton International, Chicago, Ill.
[2] Commonly referred to as Swiggle®
[3] Commonly referred to as Permapol®
[4] Commonly referred to as Thiokol®

Single Lite Processes

- **Heat Treating**
  - → Fully Tempered
    - ✓ Surface Compression 10,000 psi or more
    - ✓ Edge Compression 9,700 psi or more
  - → Heat-Strengthened
    - ✓ Surface Compression 3,500 to 7,500 psi
    - ✓ (Edge Compression not in standard)
- **Chemically strengthening**
  - → Ion exchange between small sodium ions and larger potassium ions
  - → Performed in a molten salt bath
  - → Applications
    - ✓ Thin glass (less than 1/8")
    - ✓ Cannot be strengthened by thermal tempering.

Single Lite Processes

- **Coatings**
  - → Pyrolytic
    - ✓ Fired coating applied during manufacturing or in a tempering oven
    - ✓ Hard, durable, medium performance.
  - → Sputtered
    - ✓ Ar^+ ions hit a negatively charged target of coating material. Atoms are ejected and land on glass. Line of sight.
    - ✓ Planar-magnetron sputtering
    - ✓ Vacuum, room-temperature
    - ✓ These are high performance coatings
    - ✓ Large capital expense for Leybold-Heraeus equipment, or equiv.
  - → Enameling
    - ✓ Spandrel
    - ✓ Decorative
    - ✓ Industrial

Tinting of Glass with Films

Films can:

- **Cut 12% to 93% of the incoming light**
- **Eliminate 99% of ultraviolet**
- **Cut up to 76% of the solar heat gain**
- **Apply to #2 surface.**

Single Lite Processes

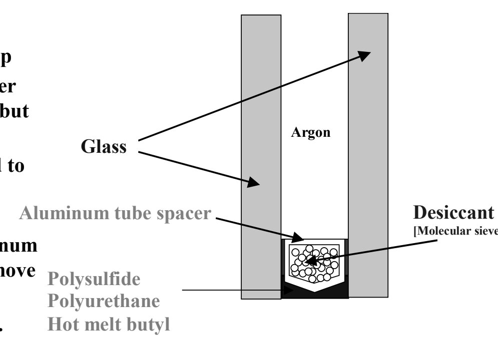
- **Other Unit Operations**
  - → Bending
    - ✓ Annealed
    - ✓ Heat-treated
  - → Edge Work
    - ✓ Grinding
    - ✓ Polishing
  - → Cutting --Rectangles, Circles, Other shapes
    - ✓ Conventional vs. Water Jet
    - ✓ Manual, Automated, Computer
  - → Drilling - Holes, Notches, Slots

Multi-Lite Processes

- **Laminating - Glass-Glass**
  - → PVB
  - → Resin
  - → Glass-Polycarbonate
  - → Artistic- Colors, Pictures, Patterns
- **Insulating Glass [IG] Units - Double, Triple, Quad, etc.**
  - → Air vs. Gas filled
  - → Films -- Suspended, Applied
- **Bending - Laminated, Insulating**

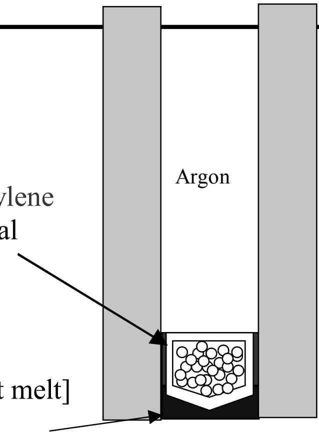
Double Pane Insulating Glass [IG] Units

- **Air or gas gap for thermal isolation**
- **For 6 mm glass, typically 12 mm gap**
- **Argon gas is a better insulator than air, but more expensive**
- **Good seal required to retain argon**
- **Desiccant beads (alumina) in aluminum spacer channel remove moisture**
- **Seal failure is fatal.**



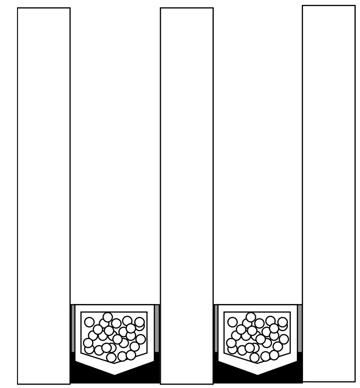
Double Pane Insulating Units

- Double seal for enhanced unit integrity



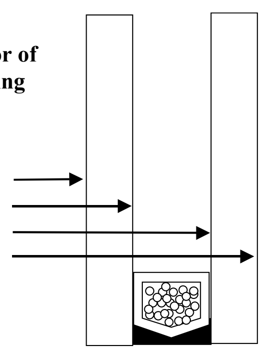
Triple Pane Insulating Units

- Double seal construction
- Third pane provides greater insulation
- Surface reflections are 50% higher
- Principally used in cold climates, e.g. Canada and Scandinavia.



Surface Identification in Architectural Units

- #1 Surface faces the exterior, must be durable.
- Coatings applied to this surface give maximum visual impact, but can weather.
- Surfaces #2 and #3 are retained in pristine state.
- #2 & #3 add strength and are useful for fragile coatings.



Glass for Commercial and Residential Architecture

- **Vision Glass**
  - → Color
    - ✓ clear
    - ✓ tint
    - ✓ reflective
  - → Thermal Performance
    - ✓ insulating glass units
    - ✓ low-E coatings
    - ✓ reflective coatings
    - ✓ films
  - → Acoustical Performance
    - ✓ insulating glass units
    - ✓ laminated glass
  - → Safety Glazing Codes
    - ✓ Fully tempered
    - ✓ laminated
    - ✓ films
  - → Security
    - ✓ bullet-resisting
    - ✓ detention/prison glazing
  - → Fire Rated
    - ✓ Wired Glass
    - ✓ Low Expansion transparent Ceramics
    - ✓ Gels
    - ✓ Laminates

Glass for Commercial and Residential Architecture

- **Spandrel Glass (Non-vision areas)**
  - → Ceramic frit
    - ✓ Fired-on Lead or Lead-free
    - ✓ Can apply to any surface
  - → Silicone Paint-Water-based
    - ✓ Drying oven
    - ✓ Many colors
    - ✓ Soft
    - ✓ 2nd surface only
- **Opacifiers**
  - → Polyethylene
  - → Polyester
  - → Water-based adhesive vs. Solvent-based adhesive
  - → 2nd surface only
- **Duranar DTG**
  - → Duranar paint colors baked on
  - → Intermediate strength
  - → 1st or 2nd surface

Glass for Commercial and Residential Architecture

- **Mirrors**
  - → Wet-chemical deposition
  - → Sputtered
  - → Transparent (2-way) mirrors
- **Decorative**
  - → Sand-blasted
  - → Chemical etching
  - → Colored
  - → Leaded
  - → Edge work - ground, polished, beveled, shapes
  - → Glue chip
  - → Molded
  - → Coatings

Automotive Products

- **Automotive**
  - → Tempered
  - → Laminated
  - → Heat-Strengthened
  - → Silk-screened
  - → Coatings
  - → Films
- **New Products and Trends**
  - → Electrically-heated windshield
  - → Head-up display
  - → Encapsulation
  - → Larger, complicated shapes
  - → Color coordinated glass parts
  - → Moisture sensing windshields

New Architectural Products

- **Switchable Glazings (Variable light transmission)**
  - → Liquid crystal laminates
  - → Suspended particle displays
  - → Electrochromics
  - → Photochromics
- **Improved Thermal Performance**
  - → Lower emissivity pyrolytic coatings
  - → New spacer materials for insulating glass units
  - → Aero-gels - transparent insulating materials
  - → Films - suspended, applied
- **Aesthetics**
  - → More color selection, base glasses and/or coatings
  - → Self-cleaning - non-stick coatings
  - → Glass walls can be used to create images -decorative, advertising, logos

Uncoated Architectural Glass Products -- USA

Glass Type	PPG	LOF	Visteon [Ford]	Guardian	AFG	Cardinal
Clear	Clear	Clear	--	Clear	Clear	Clear
Bronze	Solarbronze	Bronze	Versalux Bronze	Bronze	Bronze	--
Gray	Solargray	Gray	Versalux Gray	Gray	Gray	--
Green	Solex	Blue-green	Versalux Green	Green	Green	--
Black	Graylite 14 Optigray 23	SuperGray	Versalux Gray 2000	--	--	--
Blue	Azurlite	Arctic Blue	Versalux Blue Versalux Blue 2000	--	--	--
Dark Green	Solargreen	Evergreen	Versalux Green 2000	--	--	--
Water White	Starphire	Optiwhite	--	--	Crystal Clear	--

Pyrolytic Architectural Glass Products -- USA

Coating Type	PPG	LOF	Visteon [Ford]	AFG
Reflective	Solarcool [Bronze, Gray, Graylite, Azurlite]	Eclipse [Clear, Bronze, Gray, Blue-Green, Evergreen, Arctic Blue, Gold]	Versalux [Bronze, Gray, Blue, Green] RC [Blue, Green] 2000R, B1200T	
Low E	Sungate 500 Solarban 55	Energy Advantage, Solar E		Comfort-E Comfort-E2

Sputter Coated Architectural Glass Products -- USA

Coating Type	PPG	Guardian	AFG	Cardinal
Reflective		Reflective Sun-Guard (Clear, Green)	Hi-Performance	
Low-E	Sungate 100, 100T Solarban 60 Solarban 60T	Performance Plus, Perform. Plus HT	Comfort-ES Comfort-Ti	LoE 178 LoE 172 LoE 145

Fabricators who sputter coat:

Interpane (Reflective, Vari-Tran, Low-E, Iplus)
Viracon (Reflective and Low-E, Solarscreen)

Light and Solar Transmission and Reflectance of Selected Products

Process	Single or Double	Glass	Light Trans	Light Reflect	Solar Heat Trans	Solar Heat Reflect
Body Tint	SG	Antisun Green	75	6	46	5
	SG	Antisun Bronze	50	5	44	5
	SG	Antisun Gray	41	5	44	5
	DG	Antisun Green	65	10	36	6
	DG	Antisun Bronze	44	7	34	7
	DG	Antisun Gray	36	6	34	7
Wet Process	DG	PPG Solarban 550-20 Clear	20	18	15	15
Pyrolitic	SG	Reflectafloat	33	43	43	28
	DG	Reflectafloat	29	43	34	29
	SG	Glaverbel Stopsol	42	32	50	26
	DG	Glaverbel Stopsol	38	34	42	29
Vacuum coating	SG	Suncool Silver 20/34	20	23	16	18
	SG	Suncool blue 30/39	30	16	21	18
Electro-float	SG	Spectrafloat	51	10	54	10
	DG	Spectrafloat	44	12	42	12

US Glass Standards/Specifications

- **Annealed Glass**
  - → ASTM C 1036-91 (Reapproved 1997), Standard Specification for Flat Glass
- **Fully Tempered and Heat-Strengthened Glass**
  - → ASTM C 1048-97b, Standard Specification for Heat-Treated Flat Glass - Kind HS, Kind FT Coated and Uncoated Glass
- **Laminated Glass**
  - → ASTM C 1172-96, Standard Specification for Laminated Architectural Flat Glass
- **Glass Clad Polycarbonate**
  - → ASTM C 1349-96, Standard Specification for Architectural Flat Glass Clad Polycarbonate
- **Reflective Glass**
  - → ASTM C 1376-97, Standard Specification for Pyrolytic and Vacuum Deposition Coatings on Glass
- **Stress Measurement**
  - → ASTM C 1279-94, Standard Test Method for Non-Destructive Photoelastic Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened, and Fully Tempered Flat Glass

US Glass Standards/Specifications

- **Calibration of Stress Equipment**
  - → ASTM C 1377-97, Standard Test Method for Calibration of Surface Stress Measuring Devices
- **Glass Strength**
  - → ASTM E 1300-97, Standard Practice for Determining the Minimum Thickness and Type of Glass Required to Resist a Specified Load
- **Safety Glazing**
  - → CPSC 16CFR1201, Safety Standard for Architectural Glazing Materials
  - → ANSI Z97.1 - 1984 (R1994) Standard for Safety Glazing Materials Used in Building -- Safety Performance Specification and Methods of Test
- **Design Loads**
  - → ASCE 7-95, Minimum Design Loads for Buildings and Other Structures
- **Impact (Dade, Broward and Palm Beach Counties in Florida)**
  - → SBCCI Standard for Windborne Debris Impact Tests (Southern Building Code Congress International, Inc.)
  - → ASTM E 6.51.17 Task Groups
- **Insulating Glass**
  - → ASTM E-773, Standard Test Method for Seal Durability of Sealed Insulating Glass Units.
  - → ASTM E774, Standard Specification for Sealed Insulating Glass Units

Industry Association Address Listings

ANSI: American National Standards Institute	11 West 42nd Street, 13~ Floor New York, NY 10036 PH: 212 6424900 FX: 212 398-0023
ASCE: American Society for Civil Engineers	345 East 47th Street New York, NY 10017-2398 PH: 212 705-7496 FX: 212 355-0608
ASTM -- American Society for Testing and Materials	100 Barr Harbor Drive West Conshohocken, PA 19428-2959 PH: 610 832-9500 FX: 610 832-9555
CPSC: Consumer Products Safety Commission	Division of Regulatory Management Washington, D.C. 20207 PH: 301 504 0400 FX: 301 504-0124

Notes

- **Low Emissivity**
  - → Abs=Emiss, 1-e=Reflection
  - → Highly reflecting glasses
  - → Convective gas kilns better for Low E glass
    - ✓ heat by conduction
    - ✓ Low E film makes heating more difficult.
- **Far IR reflective**
  - → wavelength of body [37 C] and home
  - → Thin silver coating -- sputtered
    - ✓ Andersen [cardinal] sputter coats
    - ✓ Mutiple layers (10-12), durability layer, multiple silver layers (double silver)
  - → Pyrolytic coating
    - ✓ Applied by manufacturer in tin bath or just after
    - ✓ Tin
  - → Northern areas: put on #3 surface to keep heat in
  - → Southern areas: put on #2 surface to keep heat out

Notes

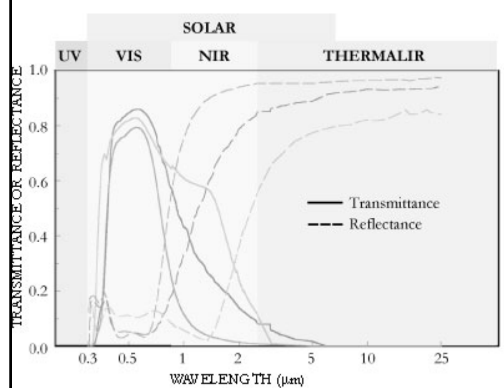
- **Near IR reflectance**
  - → Heat from sun
  - → Need high index, high reflectivity, TiO_2
- **Laminating**
  - → Resin process, UV cure from UCB
  - → Autoclave PVB film
- **Glass Stock Size**
  - → 130" x 204" standard
- **Performance Parameters**
  - → U Value
    - ✓ Low value corresponds to highly insulating
    - ✓ =1/R
  - → Shading Coefficient -- Measurement of heat entry
    - ✓ 3 mm glass with 85% transmission =1
    - ✓ Others scaled. 6 mm glass, perhaps 0.75, less heat enters
  - → Solar heat gain
    - ✓ Energy entering structure
    - ✓ I/Io

Notes

- **Intercept IG System**
  - → Coil of Al or Fe
  - → Form spacer
  - → Add desiccant
  - → Seal

Advanced Coatings for Window Glass

Low-Emissivity Window Coatings?



Oxides

Single-layer conducting oxide coating (gray)

Metals

Double metal layer (green)

Single metal layer (red).

Window Coatings – Energy Ratings

- Soft Coatings
  - ✓Applied after manufacture, can be sputtered or applied by sol-gel.
  - ✓Best performance coatings
- Hard Coatings
  - ✓Applied by fusing metal oxide to hot glass during manufacture
  - ✓Tough enough for exposed surfaces
- Heat Mirror
  - ✓Proprietary product applied to thin polyester sheet
  - ✓Suspended between to panes in IG unit.

Low-Emissivity Window Coatings

MARKET IMPACTS	
Total R&D Investment (current $ millions)	**$3**
Product market share in 1993 (% of units sold)	**36%**
Product market share in 2015 (% of units sold)	**79%**
Incr. value of product sales in 1993 (1993 $M)	**$630**
Incr. value of product sales in 2015 (1993 $M)	**$1100**

Low-Emissivity Window Coatings

CONSUMER BENEFITS ($ millions, present value in 1993 dollars)	
Value of energy savings "in the bank" as of year-end 1993	**$760**
Lifetime value of savings for technologies installed through 1993	**$6,300**
Lifetime value of savings for technologies installed through 2015	**$37,000**
Value of annual energy savings in 2015	**$5,300**
NET present value of technologies installed through 1993	**$400**
NET present value of technologies installed through 2015	**$17,400**

Low-Emissivity Window Coatings

ENVIRONMENTAL BENEFITS	
Carbon dioxide emissions avoided in 2015 (million tons/year)	**71**
Sulfur dioxide emissions avoided in 2015 (thousand tons/year)	**157**
Nitrogen oxide emissions avoided in 2015 (thousand tons/year)	**142**

Low-Emissivity Window Coatings

- Before 1973, nearly 5% of the national energy consumption was attributed to windows heating, cooling, and lighting required to compensate for the effect of windows.
- Advances in window technology have substantially reduced those losses and have the potential to make windows net sources rather than sinks of energy, especially in cold climates.
- Unlike insulated walls, which at their best prevent the outward flow of heat, optimal windows can accept solar gain and hence provide net heating.

Low-Emissivity Window Coatings

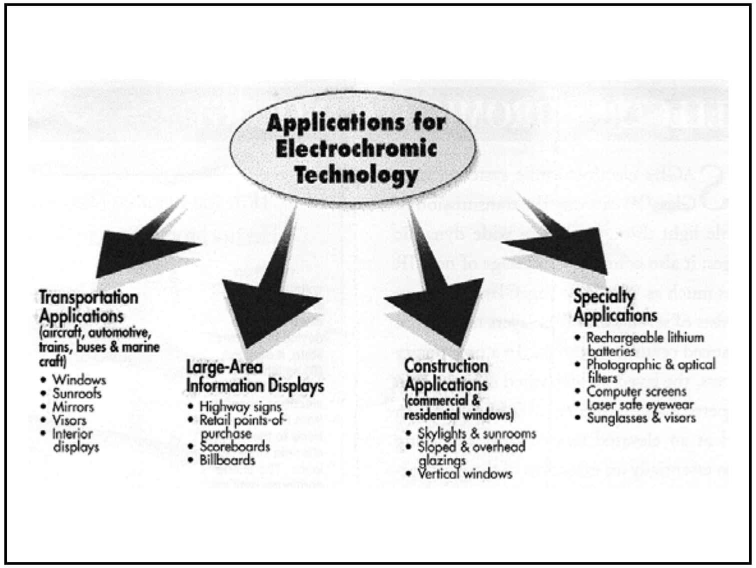
- High reflectance, hence low e, in the thermal infrared (IR)
- High transmittance (T) in the visible.
- Some coatings are designed to admit solar near IR (NIR) to help heat a building in a cold climate
- Some coatings are designed to reflect the NIR back in a warm climate.
- Introduced in 1981. Market share approximately 35% of sales
- Generated gas savings that are equivalent in energy to one-half the output of oil in Prudhoe Bay.

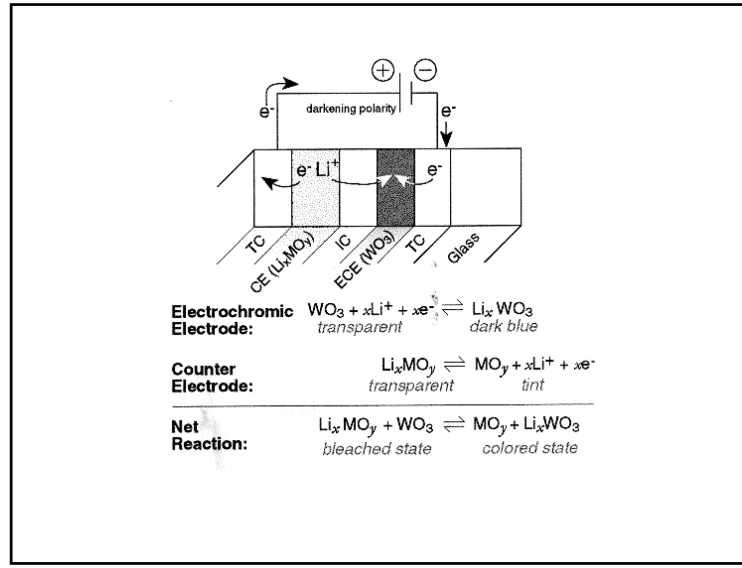
Low-Emissivity Window Coatings

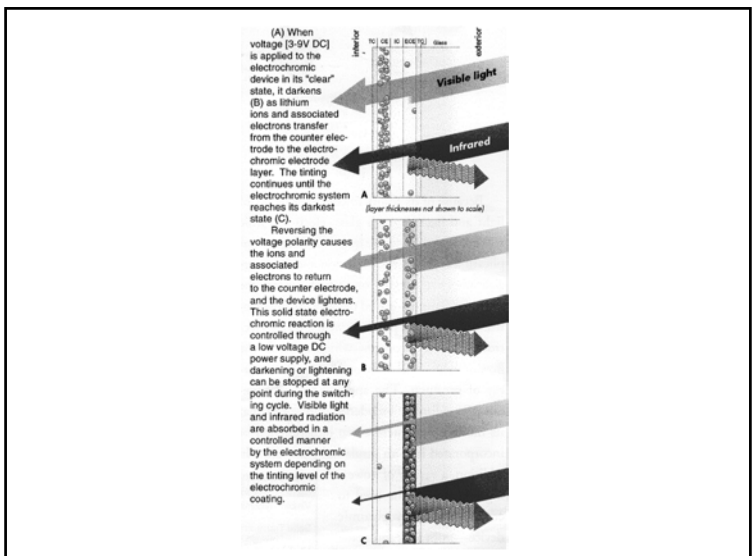
- One class of high-T, low-e materials consists of doped oxides of tin or indium, which are wide bandgap semiconductors. Adjusting the dopant level can tune the wavelength cutoff between transmittance and reflectance.
- Another class comprises very thin films of noble metals, especially silver. Although thick films of silver are highly reflective, the reflectance of very thin films (10-20 nm) can be suppressed by thin-film interference effects. Adding dielectric layers to the front and back of the metal layer thus reduces the reflectance of the thin film for a limited range of wavelengths. These coatings can be made highly transparent to visible radiation, but remain reflective in the NIR.

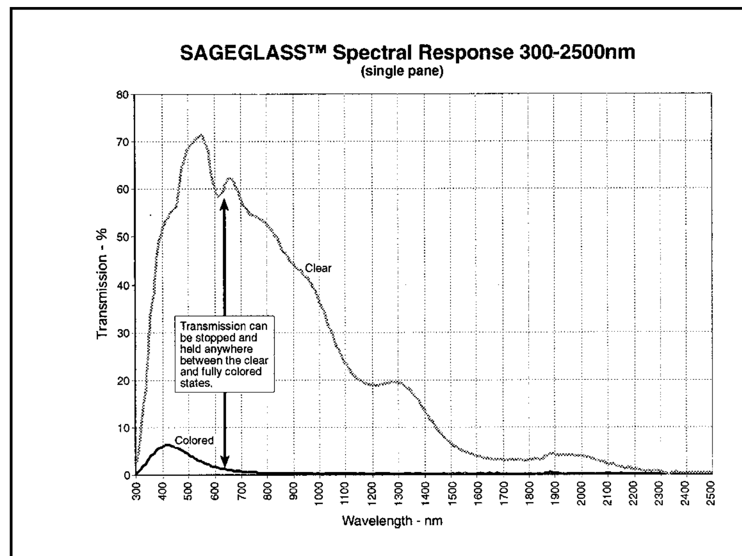
Low-Emissivity Window Coatings

- Optimum energy conservation results from combined effort
  - ✓Multiple panes
  - ✓Low conductance gas fill
  - ✓Insulating frames
- Electrochromic glass coatings
  - ✓Properties of coating can be changed to meet time of day needs
- Cost reductions needed in manufacturing to extend use.


Applications for Electrochromic Technology
Transportation Applications (aircraft, automotive, trains, buses & marine craft)
• Windows
• Sunroofs
• Mirrors
• Visors
• Interior displays
Large-Area Information Displays
• Highway signs
• Retail points-of-purchase
• Scoreboards
• Billboards
Construction Applications (commercial & residential windows)
• Skylights & sunrooms
• Sloped & overhead glazings
• Vertical windows
Specialty Applications
• Rechargeable lithium batteries
• Photographic & optical filters
• Computer screens
• Laser safe eyewear
• Sunglasses & visors


darkening polarity
e⁻ Li⁺
TC
CE (Li_xMO_y)
IC
ECE (WO_3)
TC
Glass
Electrochromic Electrode: $WO_3 + xLi^+ + xe^- \rightleftharpoons Li_xWO_3$ transparent dark blue
Counter Electrode: $Li_xMO_y \rightleftharpoons MO_y + xLi^+ + xe^-$ transparent tint
Net Reaction: $Li_xMO_y + WO_3 \rightleftharpoons MO_y + Li_xWO_3$ bleached state colored state


(A) When voltage [3-9V DC] is applied to the electrochromic device in its "clear" state, it darkens (B) as lithium ions and associated electrons transfer from the counter electrode to the electrochromic electrode layer. The tinting continues until the electrochromic system reaches its darkest state (C).
Reversing the voltage polarity causes the ions and associated electrons to return to the counter electrode, and the device lightens. This solid state electrochromic reaction is controlled through a low voltage DC power supply, and darkening or lightening can be stopped at any point during the switching cycle. Visible light and infrared radiation are absorbed in a controlled manner by the electrochromic system depending on the tinting level of the electrochromic coating.
interior
exterior
Visible light
Infrared
(layer thicknesses not shown to scale)
A
B
C


SAGEGLASS™ Spectral Response 300-2500nm
(single pane)
Transmission - %
Wavelength - nm
Clear
Colored
Transmission can be stopped and held anywhere between the clear and fully colored states.

Window Coatings – Energy Ratings

- U-factor
  - ✓Identifies the insulating performacne of the window
  - ✓Department of Energy [DOE] specifies performance.
  - ✓Less than 0.75 in Florida and Texas, for example
  - ✓Less than 0.35 in the North, Maine & Montana
- Solar heat gain coefficient [SHGC]
  - ✓In southern states, should be low, 0.40 or lower
  - ✓In northern states, can be much higher, heat is desired.

Window Coatings – Energy Ratings

- Visible transmittance
  - ✓Specifies the fraction of visible light passing through window
  - ✓Usually want 60 – 80% [0.6 – 0.8]