


PPG Flat Glass
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Flat Glass Production Using the Float Process

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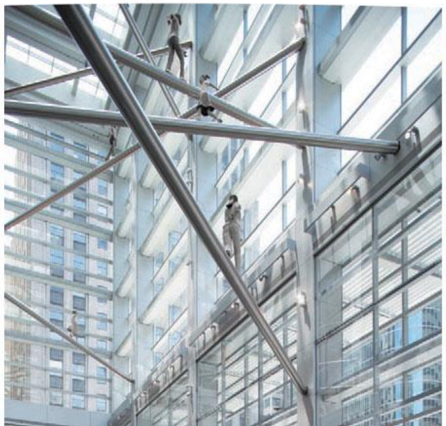
Contributions by Chuck Edge



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Presentation Outline

Float Process History

Process Tour

- Glass Delivery System
- The Float Bath
- The Bath Exit

The Equilibrium Thickness Concept

Ribbon Forming

Optical Distortion

Heat Transfer

Bath Chemistry

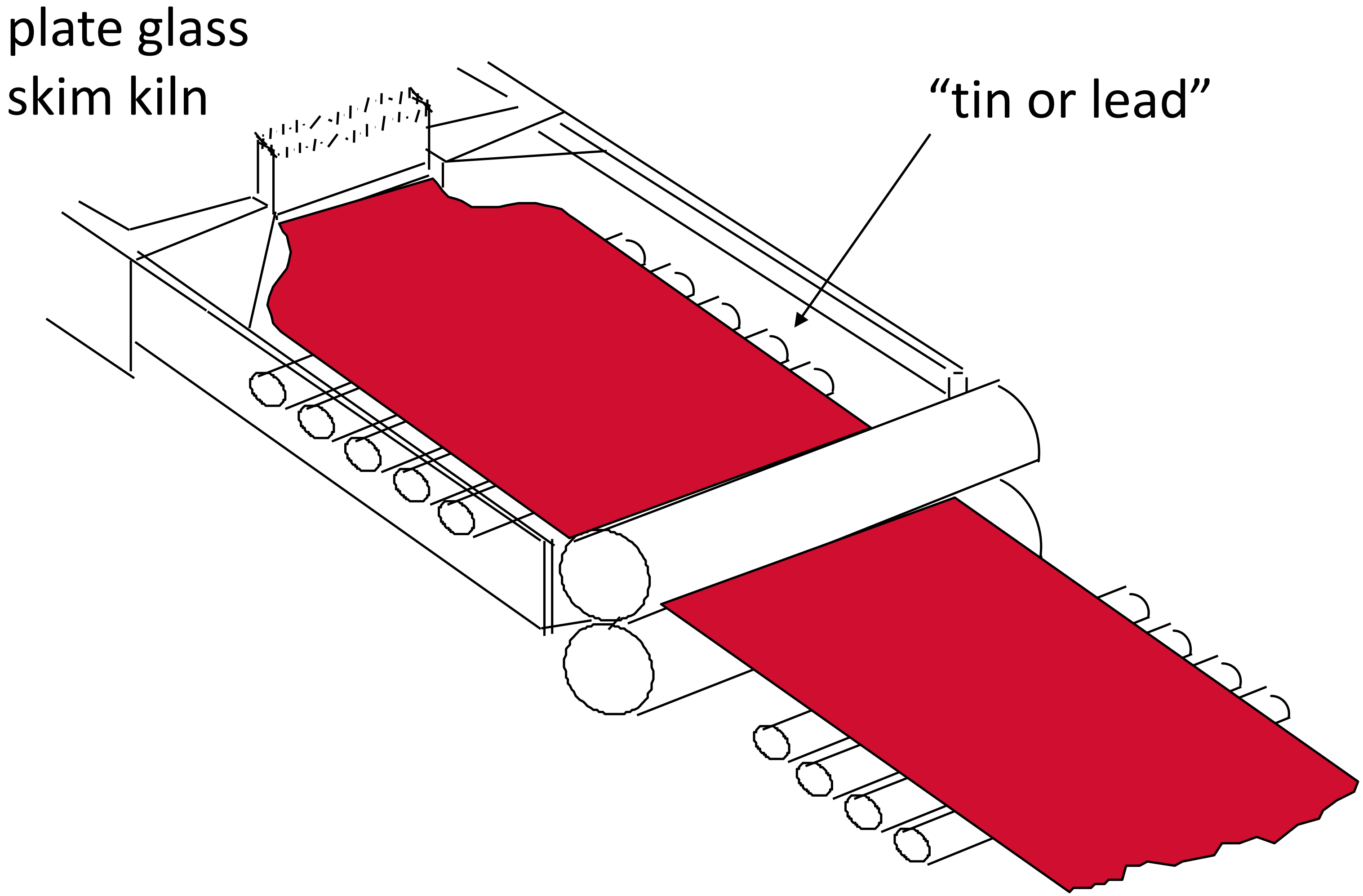
Bath Modeling

Float Process History

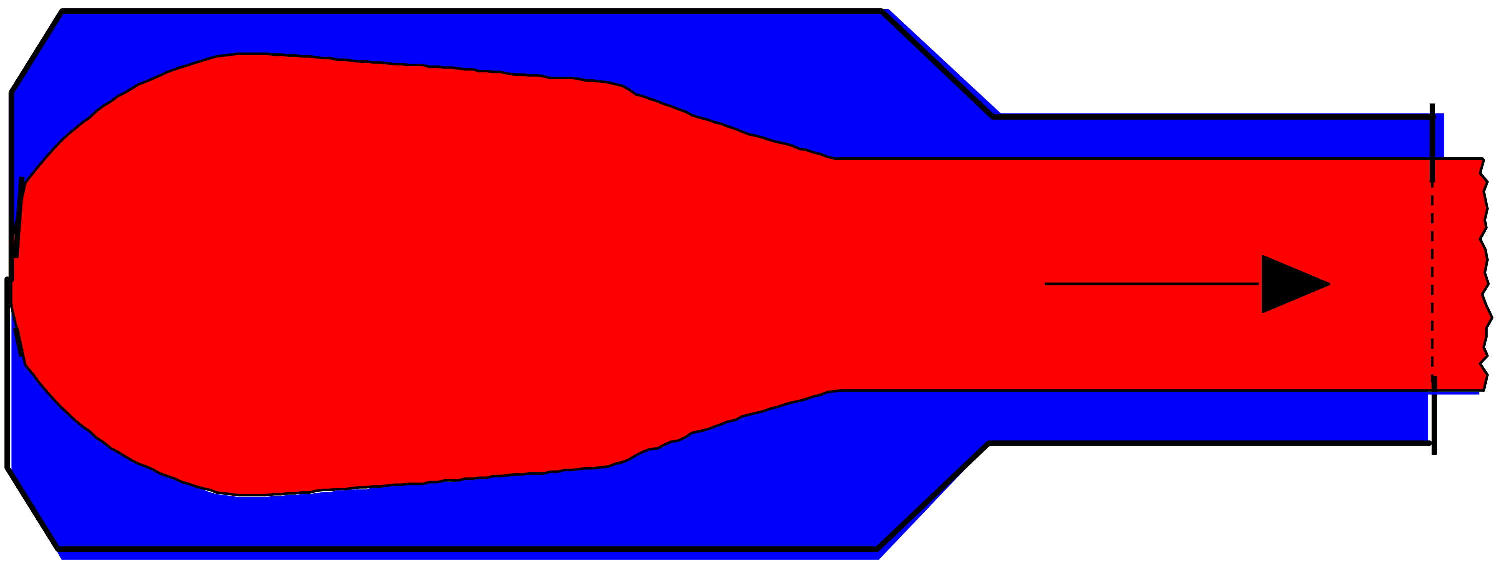
Float Glass Manufacture (A Brief Patent History)

Inventor	Year	Comments
Bessemer (Brit.)	1848	annealer, fire-polisher
Lombardi (Ital.)	1900	capacitors
Heal	1902	first "float glass" patent
Hitchcock	1905	direct stretch concept
Heal	1925	melt directly on tin
Hitchcock	1928	unhindered lateral flow
Pilkington	1965	first Pilkington patent (U. S.)
Edge et. al.	1974	PPG process

An Early “Float” Concept

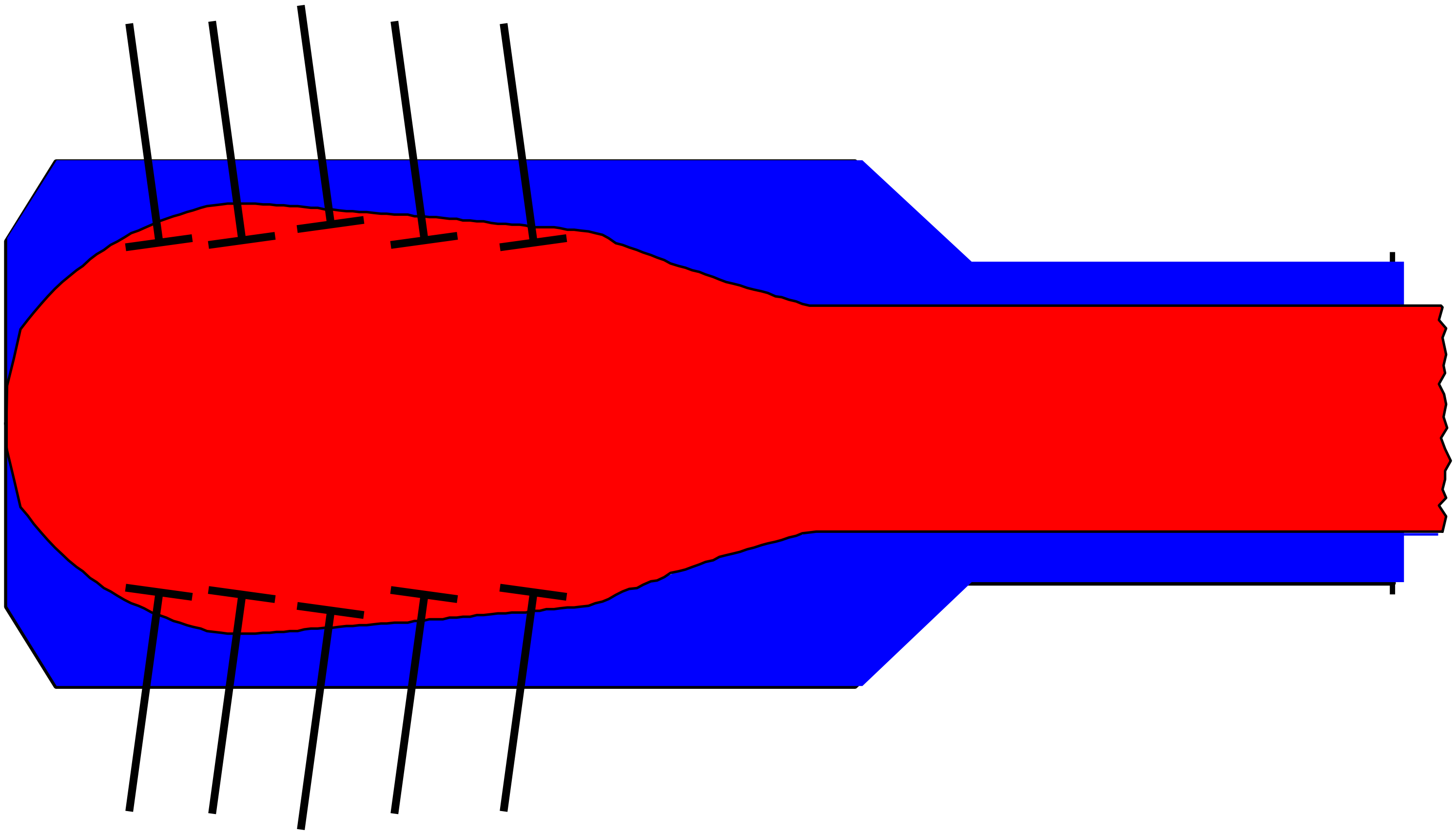


The Direct Stretch Process



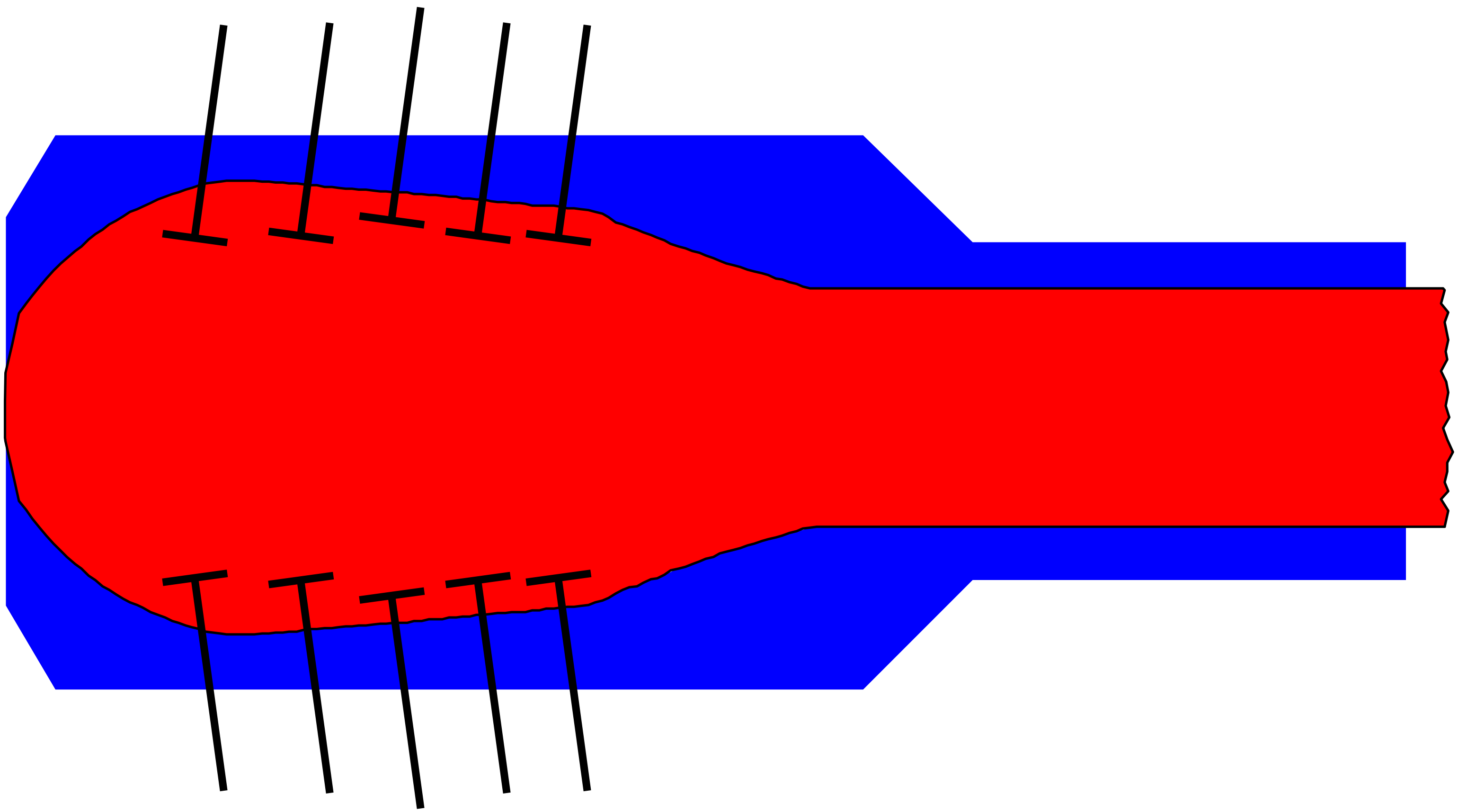
The Assisted Direct Stretch (ADS) Process

(*to produce glass <equilibrium thickness)*

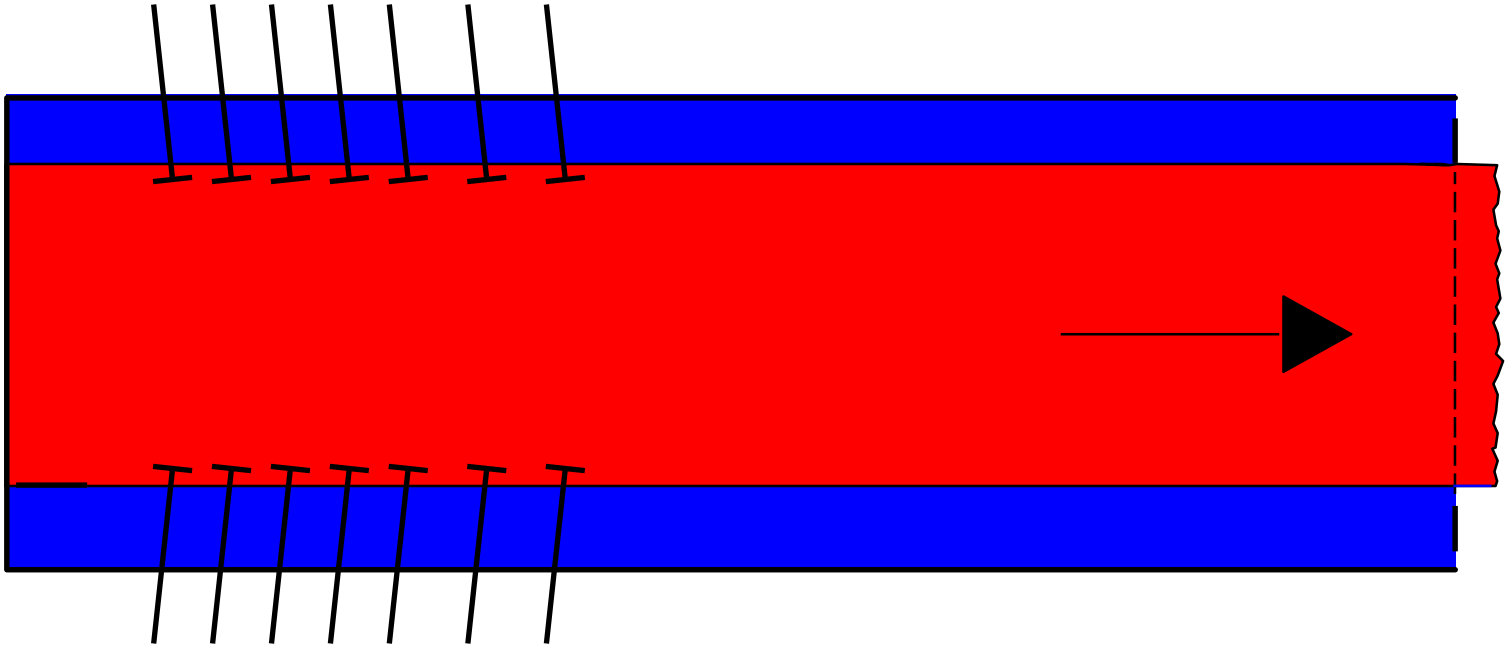


The Reverse Assisted Direct Stretch (RADS) Process

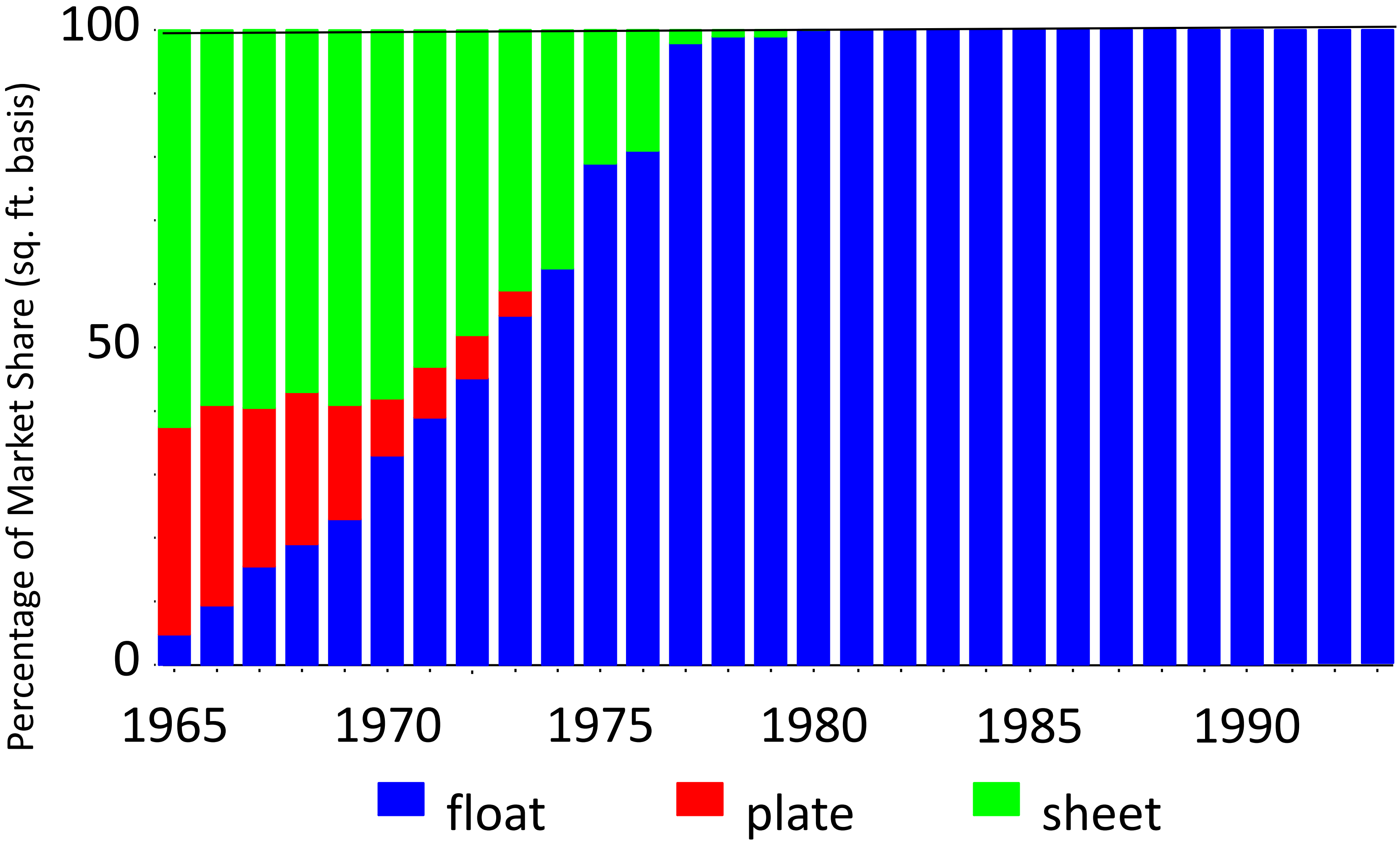
(*to produce glass $\geq$ equilibrium thickness)*



The PPG Process



Primary Glass Processes
U. S. Market Share



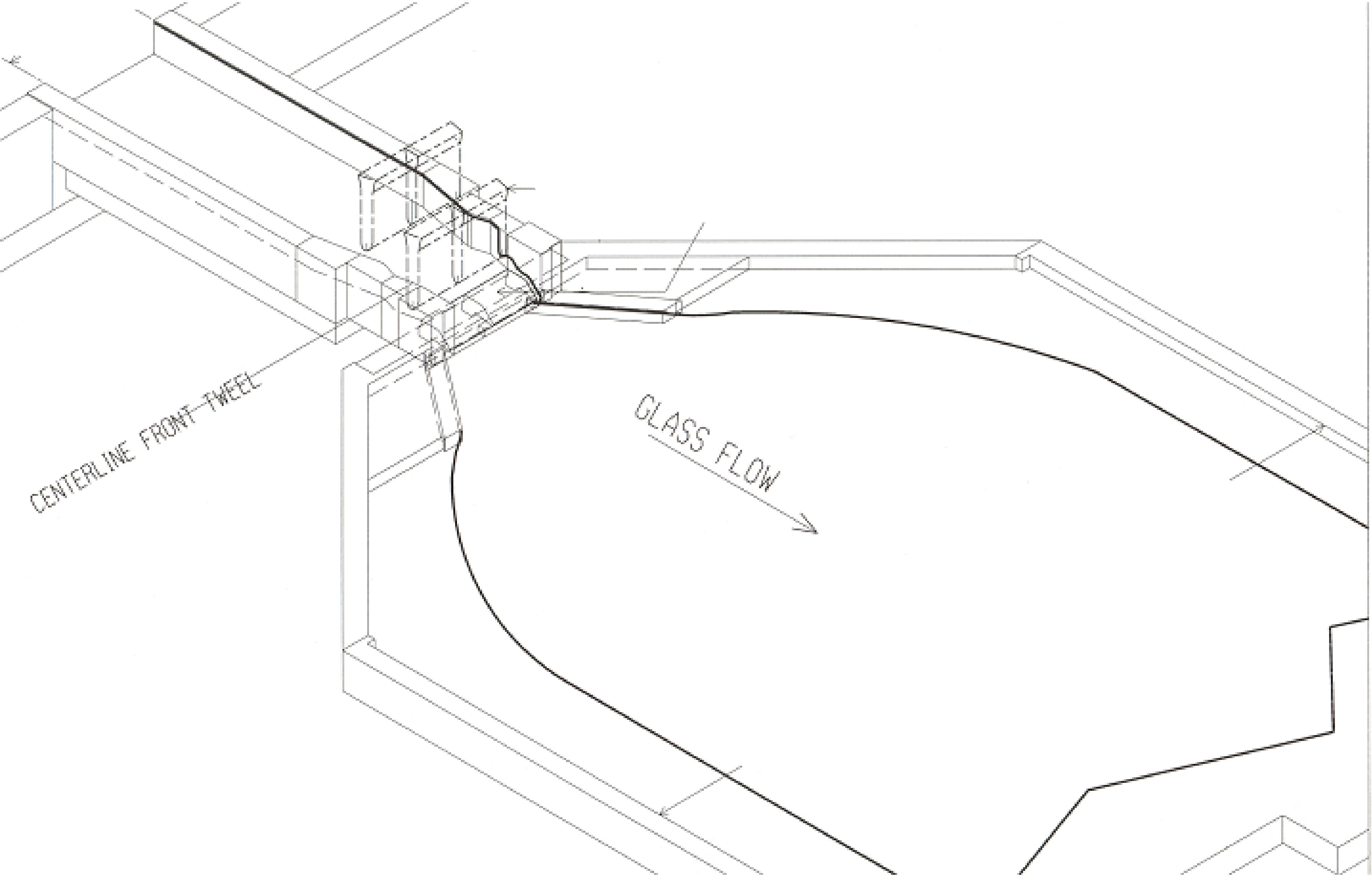
Process Tour

Functions of a Float Bath

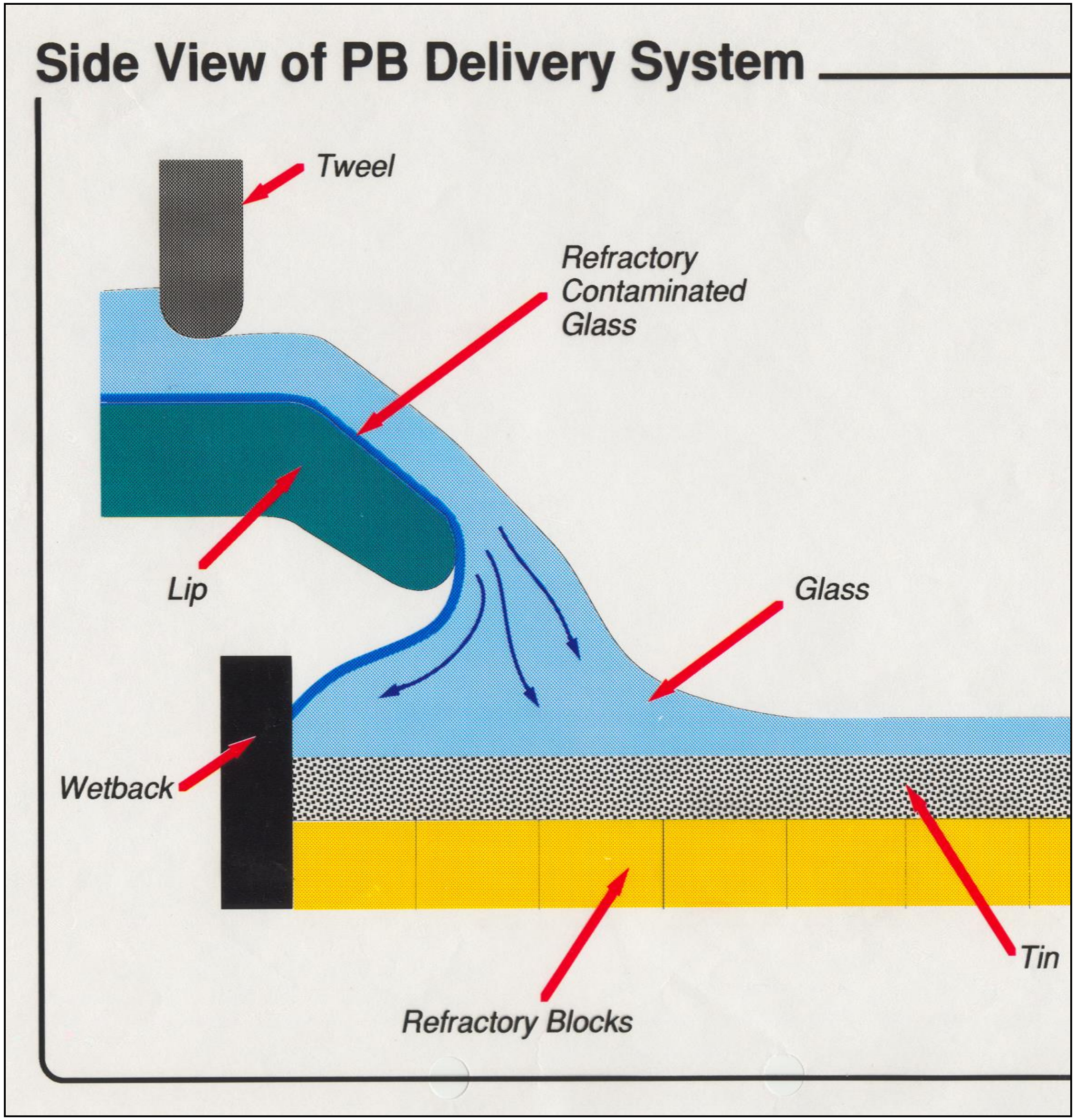
- Need to produce glass as flat as possible
  - Bottom surface becomes flat since liquid tin (very dense) provides flat surface
  - Top surface becomes flat by glass flow due to gravity
- Need to produce glass to needed thickness and width
  - ADS machines are used
- Need to cool glass from 1100 C to 600 C
  - Coolers are used at appropriate locations
- Tin must not get oxidized
  - Bath atmosphere kept reducing 95% N_2 + 5% H_2

Glass Delivery to the Tin Bath

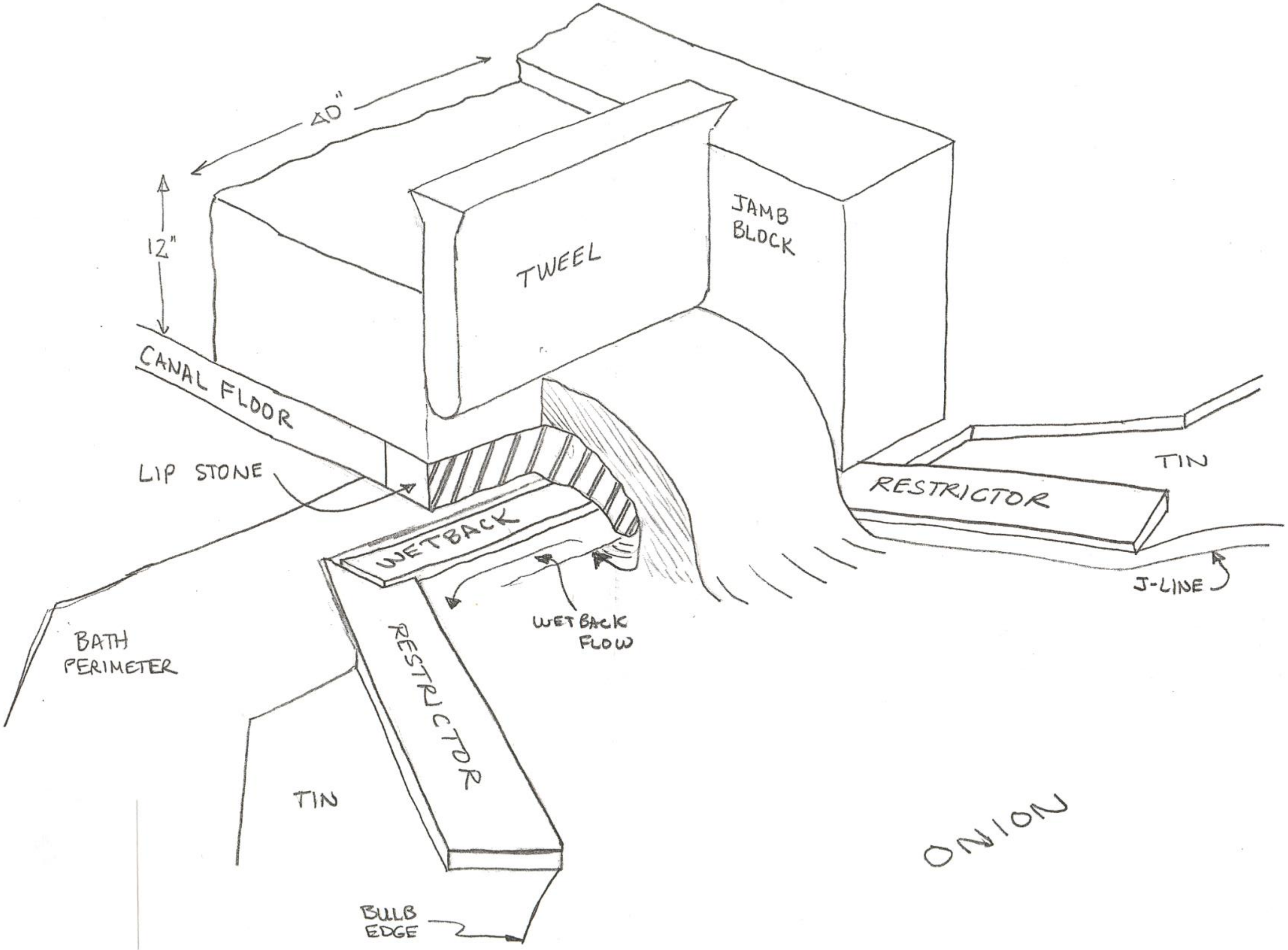
Glass Delivery



Glass Delivery System

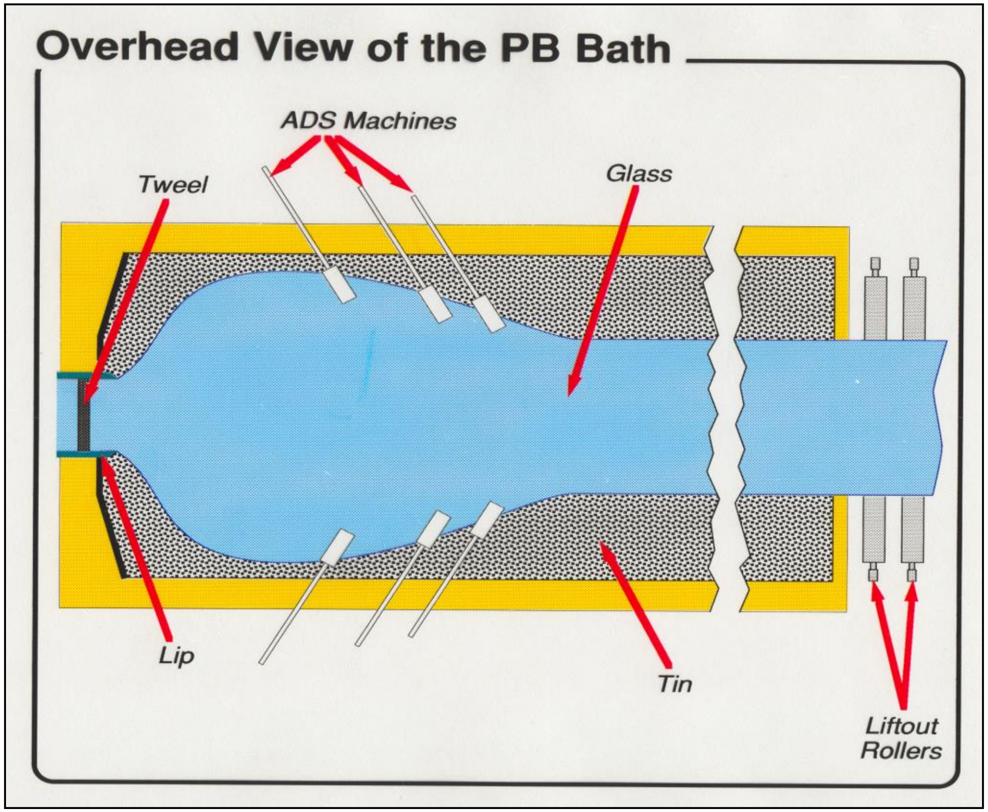


Glass Delivery System



The Float Bath

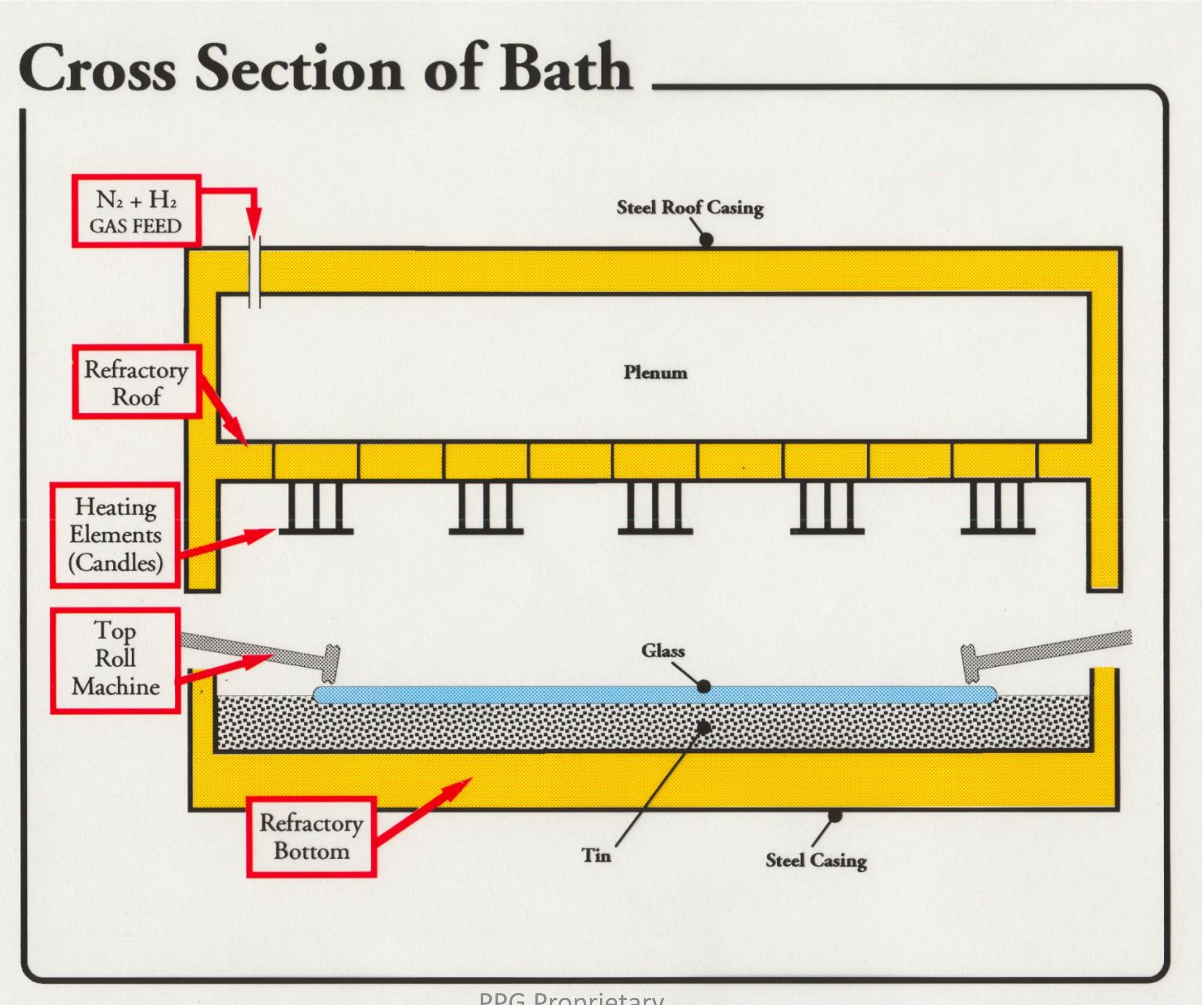
Overhead View of Ribbon on Tin



Glass flows onto the tin at a thickness of approximately 5 cm and spreads to achieve an equilibrium thickness of .6909 cm.

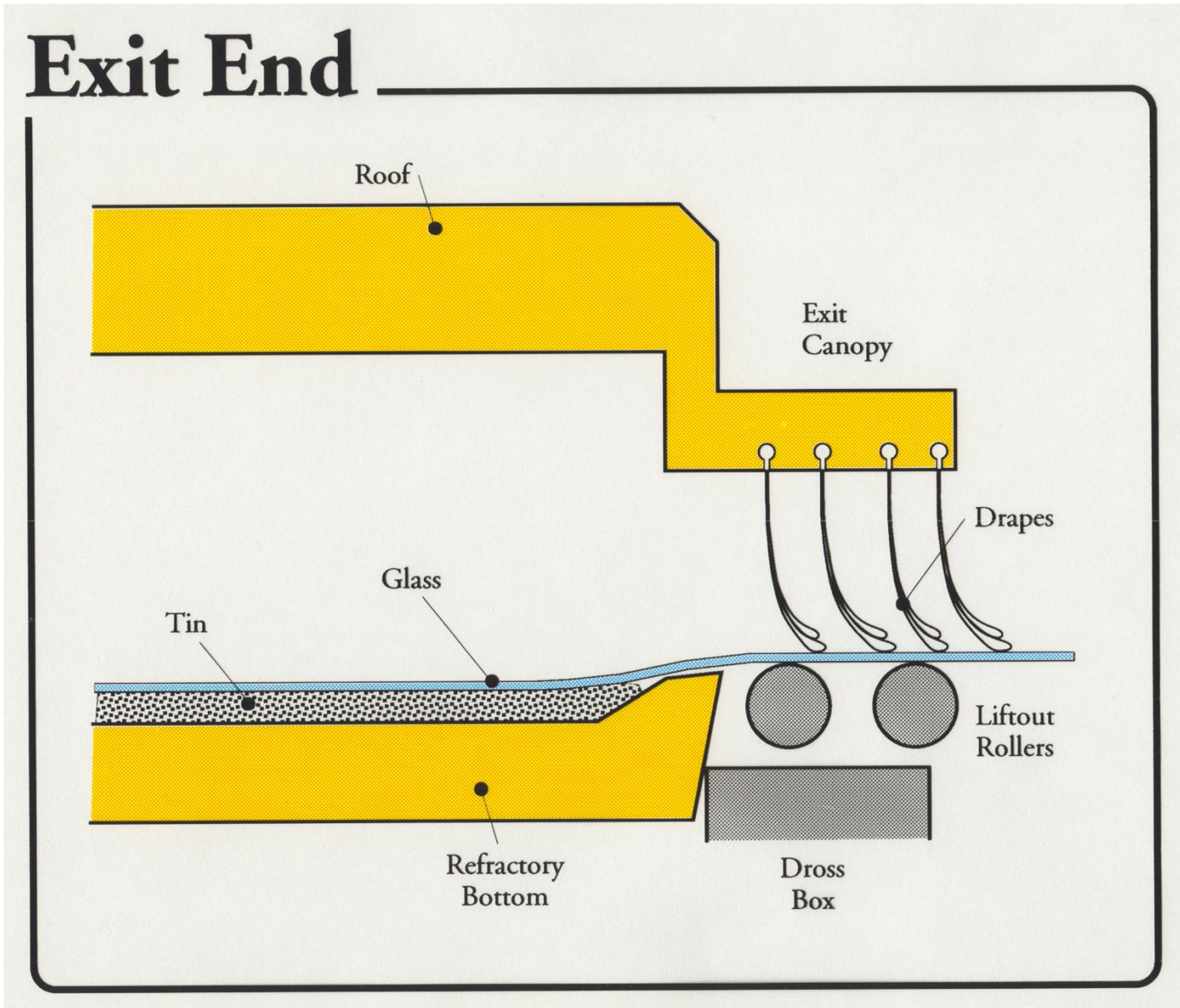
The lehr force is attenuating the glass to a final thickness less than equilibrium. The internal stress in the glass attempts to narrow the ribbon back to equilibrium thickness. The outward force imposed by the ADS machines minimizes the collapse to produce a ribbon of desired thickness and width.

Float Bath Cross Section



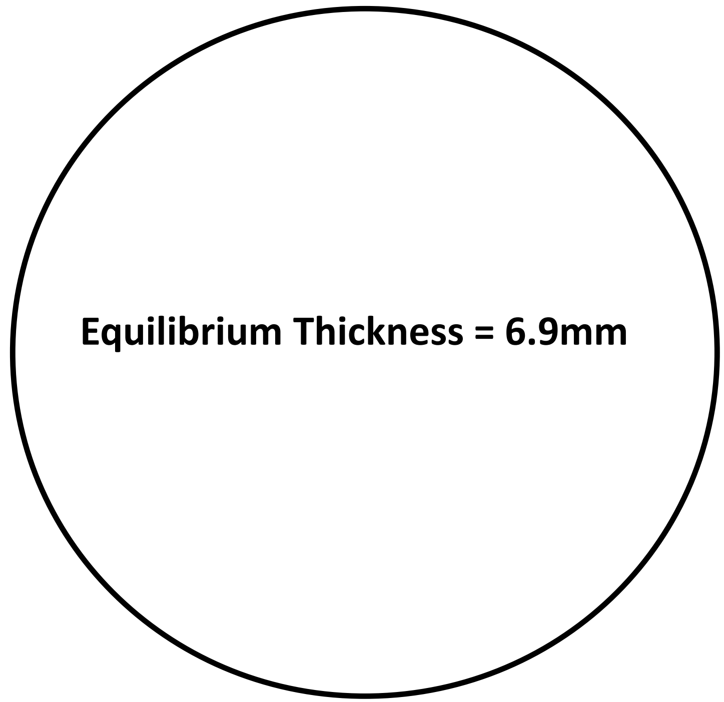
The Bath Exit

Ribbon Removal from Float Bath



Equilibrium Thickness

Equilibrium Thickness



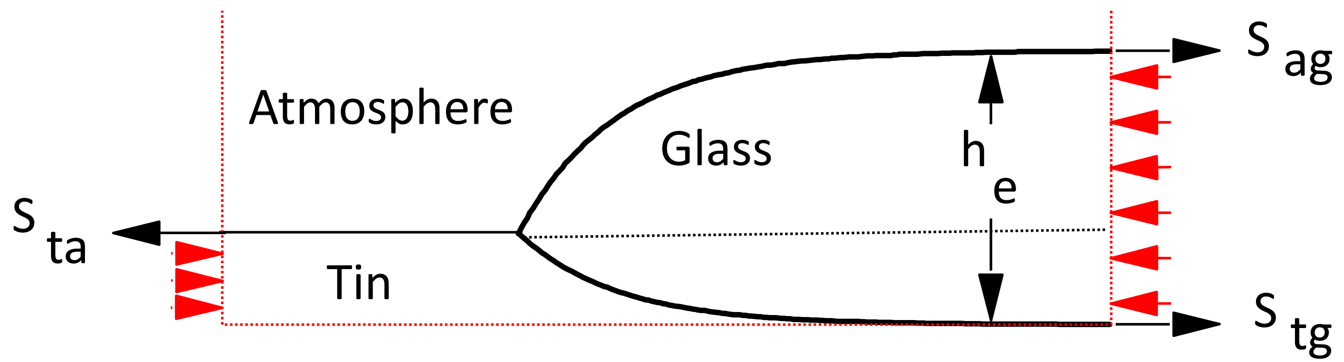
When molten glass is poured onto tin, it will spread until the interfacial tensions and gravitational forces are balanced, resulting in a circular glass-tin interfacial shape with an equilibrium thickness of 6.9mm.

When forming a continuous ribbon, the glass will always attempt to achieve equilibrium thickness.

If the glass thickness is less than 6.9mm, the ribbon will collapse to become thicker.

If the glass thickness is greater than 6.9mm, the ribbon will spread to become thinner.

Equilibrium Thickness - A Free Body Diagram



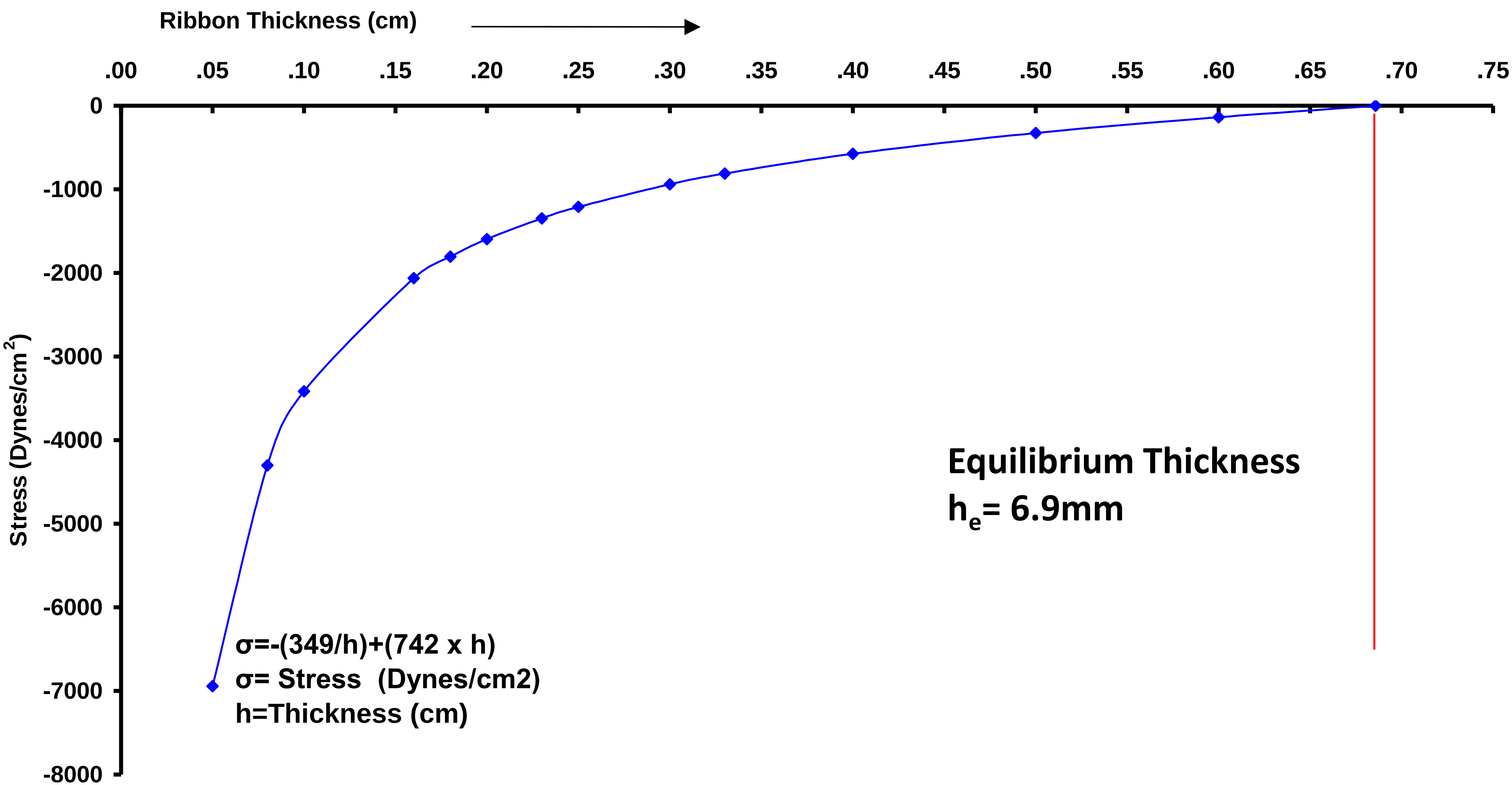
Equilibrium Thickness = 6.9mm

$$h_{eq}^2 = \left(S_{tg} + S_{ag} - S_{ta}\right)\frac{2\rho_t}{g\rho_g\left(\rho_t - \rho_g\right)}$$

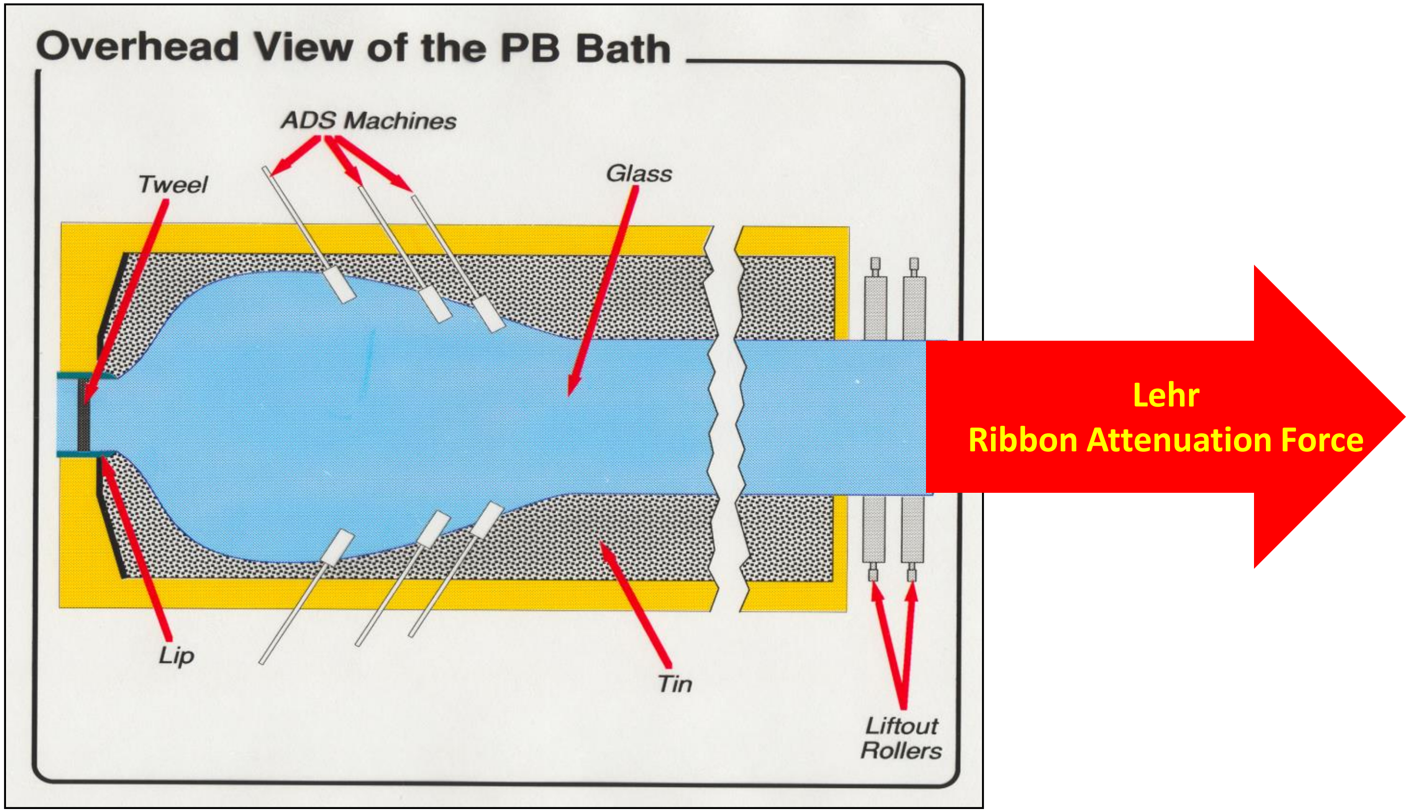
Some Material Properties

Density	
glass	2400 kg/m^3
tin	6500 kg/m^3
Surface Tension	
glass/air	.318 N/m
glass/tin	.528 N/m
tin/air	.497 N/m
Viscosity	
glass	10^2 to 10^9 Pa-s
tin	.001 Pa-s
Thermal Conductivity	
glass	1 W/m-K
tin	46 W/m-K
fused silica	1 W/m-K
Walsh 71 refractory	2 W/m-K

Ribbon Stress vs Thickness



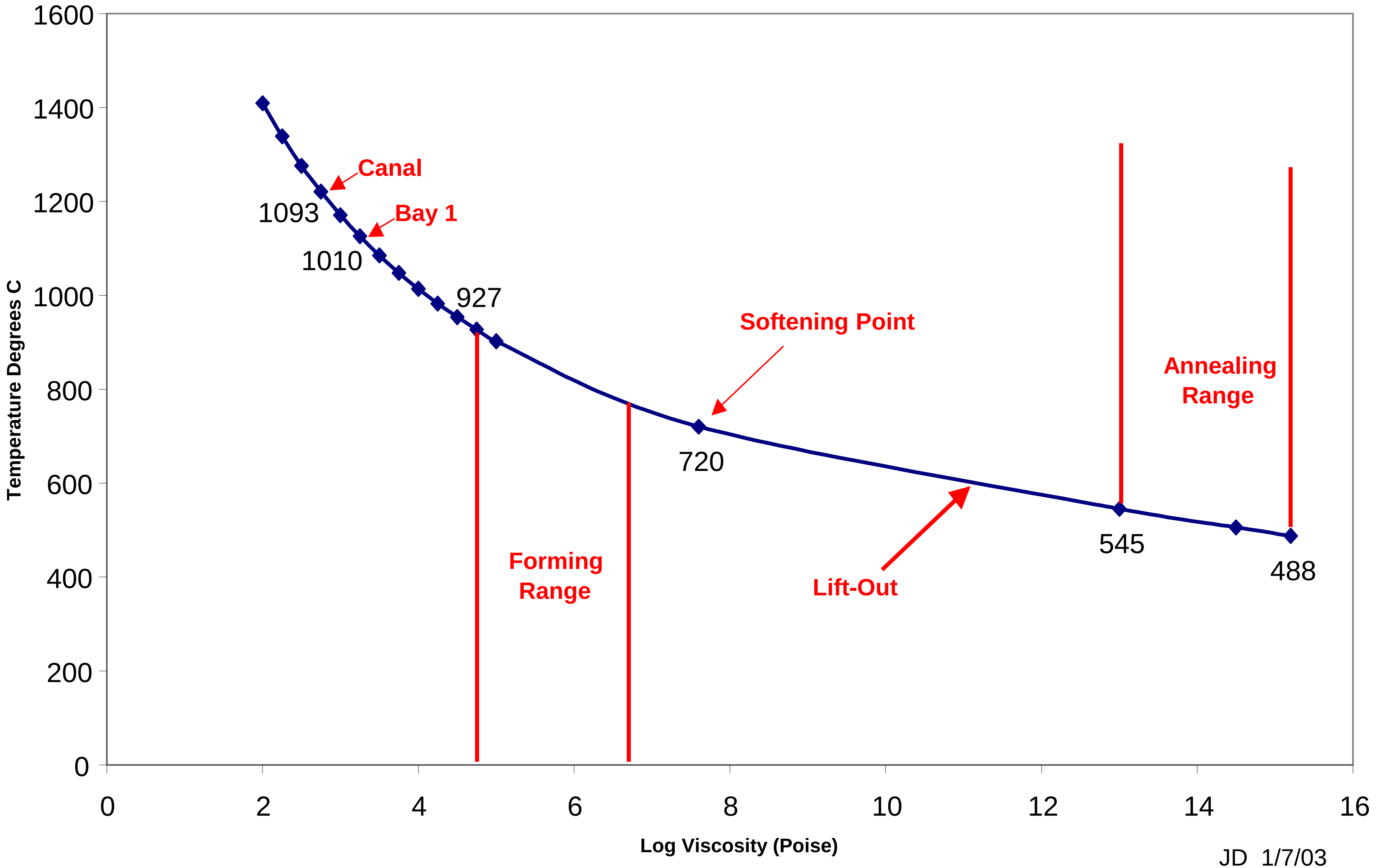
Ribbon Forming



Glass flows onto the tin at a thickness of approximately 5 cm and spreads to achieve an equilibrium thickness of .6858 cm.

The lehr force is attenuating the glass to a final thickness less than equilibrium. The internal stress in the glass attempts to narrow the ribbon back to equilibrium thickness. The outward force imposed by the ADS machines minimizes the collapse to produce a ribbon of desired thickness and width.

Viscosity vs Temperature



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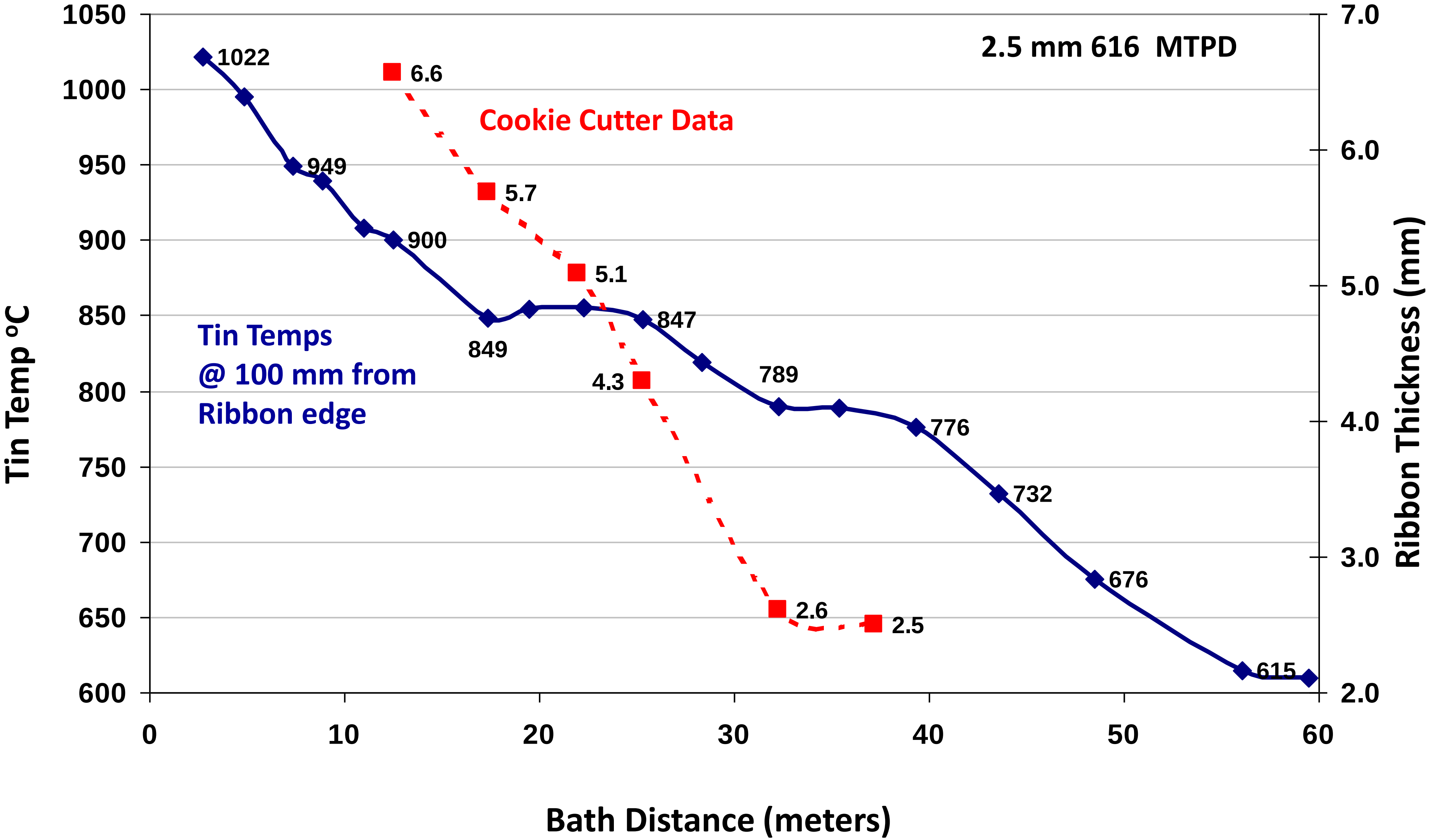
Forces: An Example Using a Typical Float Bath Setup

Force	First Machine (dynes)	Last Machine (dynes)
Inertia	0.04	0.47
Hydrostatic	590	317
Surface Tension	-590	-750
Net	0	-433
Tin Friction (bottom surface)	5.5	113
Longitudinal Lehr Force (ribbon attenuation)	161	5279

Tin Temperature and Ribbon Thickness

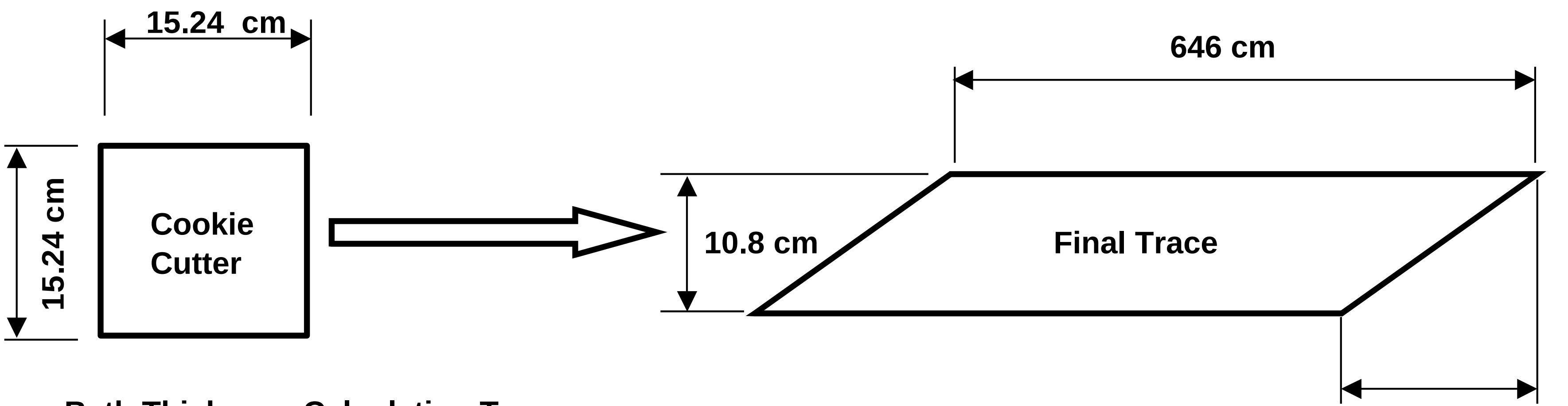


ADS Machines

- Work in conjunction with attenuating lehr force to form ribbon thickness and width
- Impart angular force to top surface of ribbon for controlling ribbon width and speed
- Affect ribbon thickness contour
- Used for less than equilibrium thickness: ADS “Assisted Direct Stretch”
- Used for greater than equilibrium thickness: RADS “ Reverse Assisted Direct Stretch”

Cookie Cutter Sample Trace and Calculation

2.5 mm 616 TPD Bay 5-1



<u>Bath Thickness Calculation</u> T_i

$V_i = V_f$

$T_i \times A_i = T_f \times A_f$

$T_i = T_f \times A_f/A_i$

$T_i = .086\text{ in.} \times (4\ 1/4\text{ in.} \times 25\ 7/16\text{ in.})/36\text{ in}^2.$

$T_i = .258\text{ in.}$

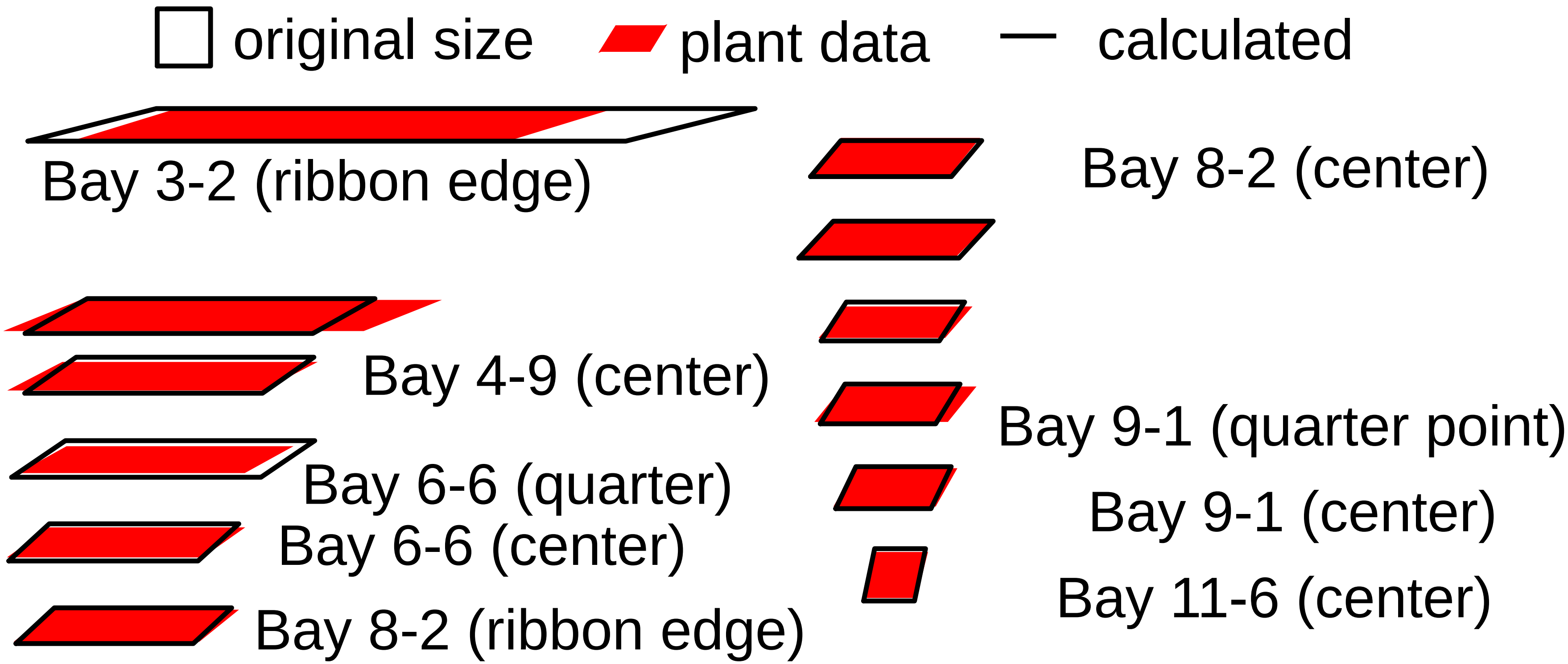
V_i = initial volume V_f = final volume

T_i = initial thickness T_f = final thickness

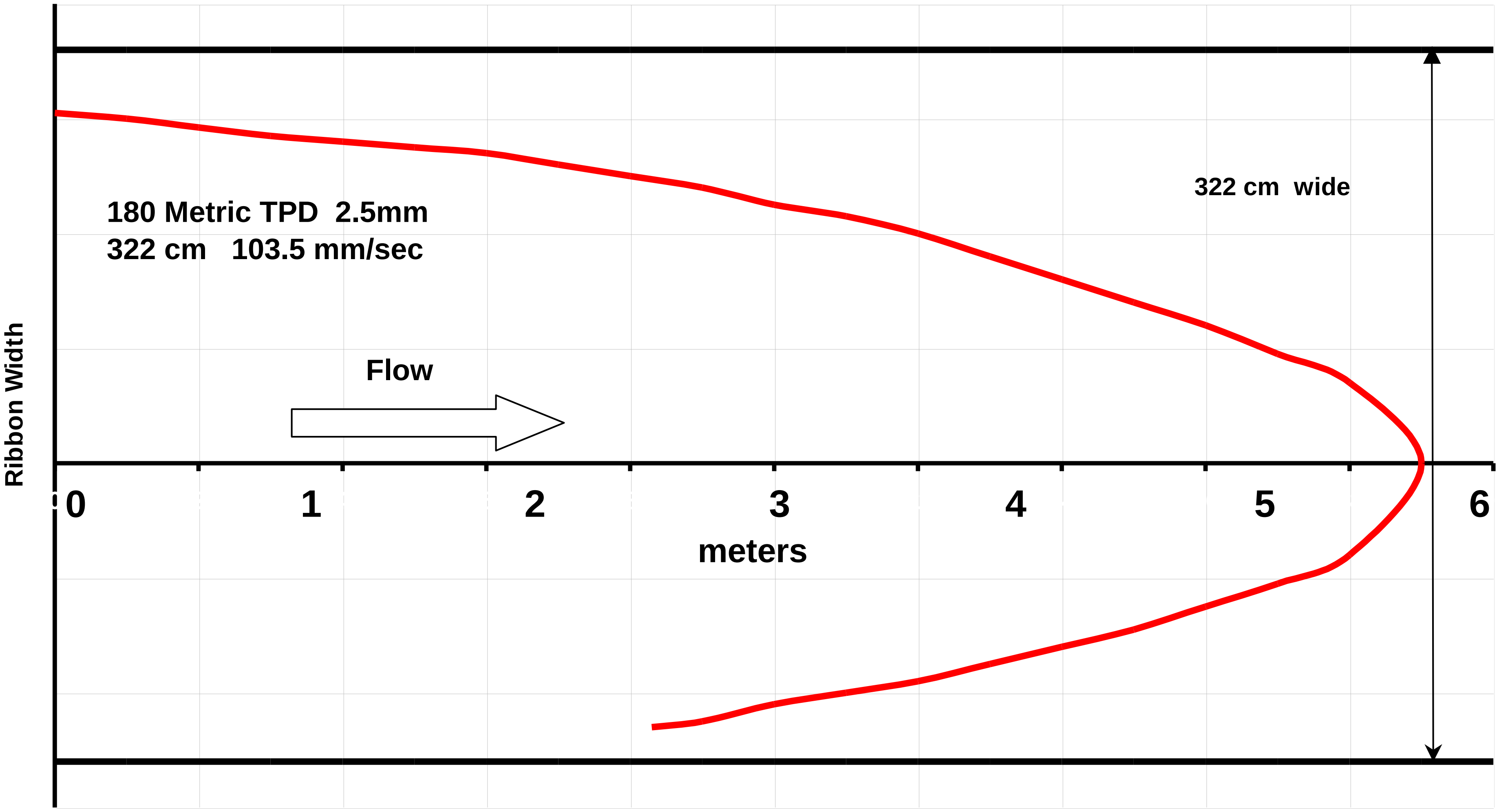
A_i = initial area A_f = final area

Cookie Cutter Tests

Prediction of cookie cutter data is a very sensitive test of the model, great for model validation



Sand Trace Velocity Profile



Optical Distortion

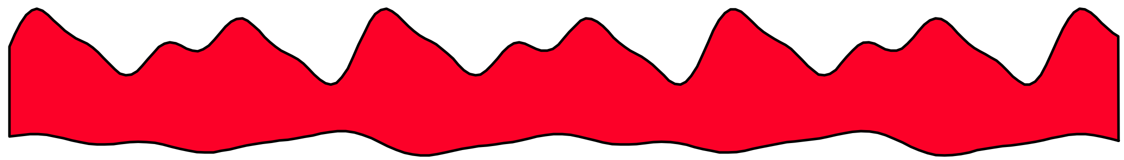
Float Glass: A Typical "Semi-Schlieren" Photo

The pattern is characterized by:

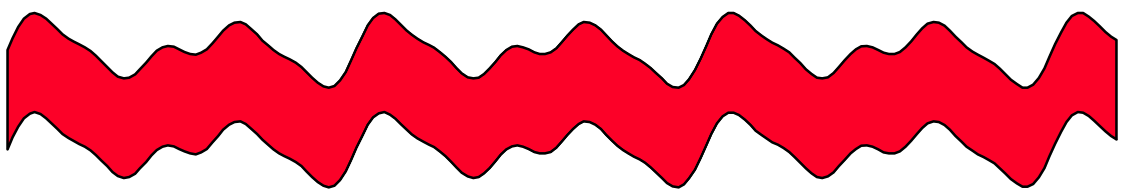
uniformity

directionality

Optical Distortion in Float Glass

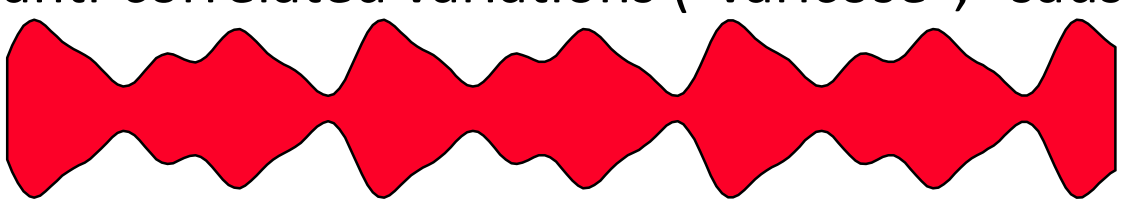


uncorrelated thickness variations

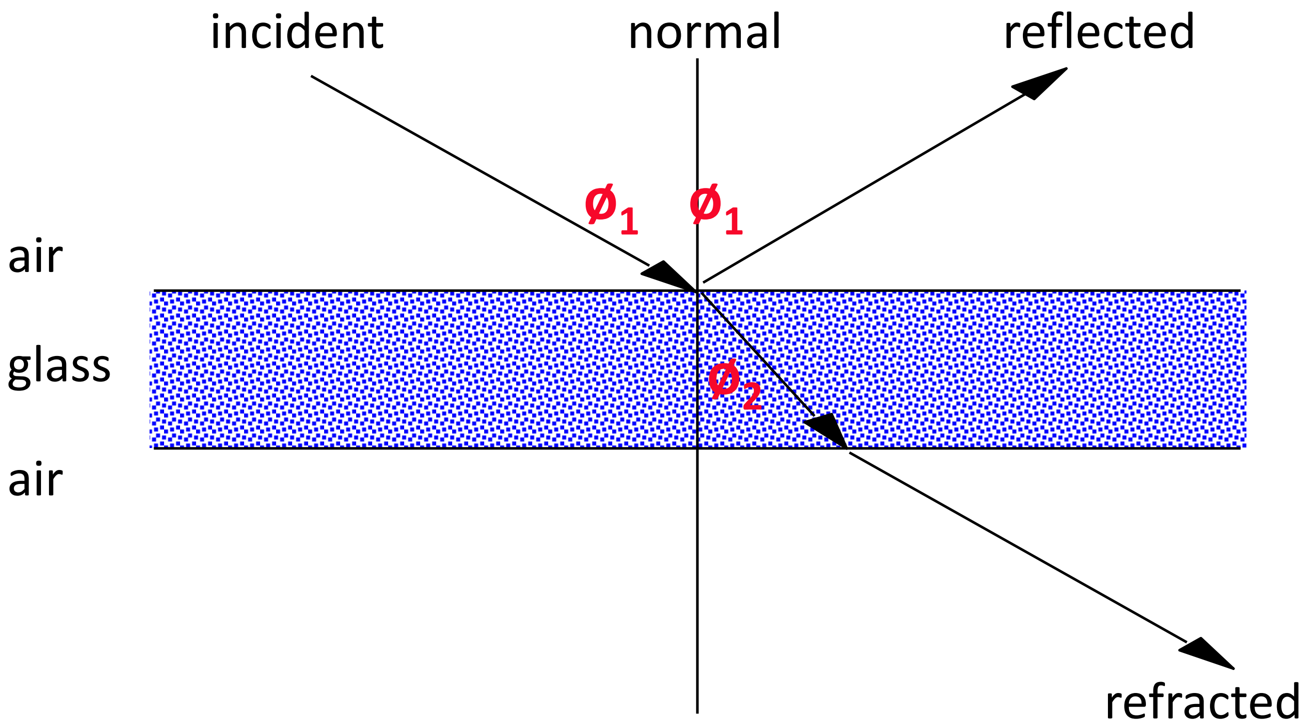


corrugations

highly anti-correlated variations ("varicose", "sausages")

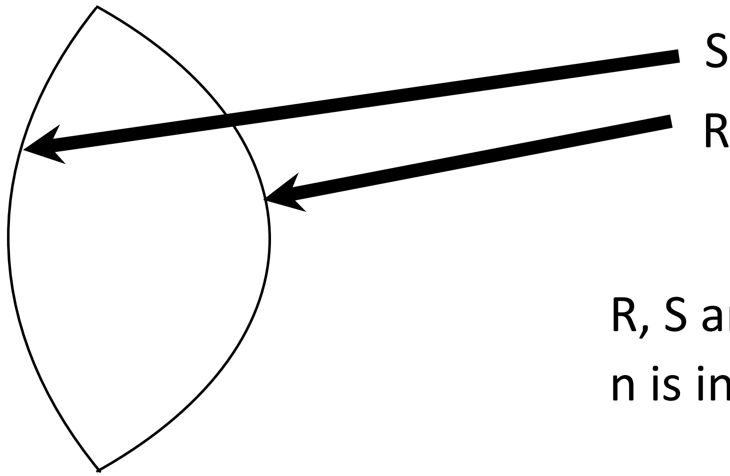


Refraction, Snell's Law



Snell's Law: $n_1 \sin \phi_1 = n_2 \sin \phi_2$

Properties of Lenses



R, S are radii of curvature

n is index of refraction

The lensmaker's equation:

$$1/f = (n - 1)(1/R + 1/S)$$

f = focal length

P = optical power (diopters)

$$P = 1/f$$

Float Glass Quality: Qualitative Features

- Reduced distortion levels over time
- Improved internal quality
- Optical quality degrades with reduced thickness
- Optical quality degrades with increased throughput
- Product standards are generally independent of thickness

Float Glass Manufacture

Sources of Optical Distortion

internal quality
poor refractories
bath hardware/machines
exit end

← "housekeeping", or passive variables

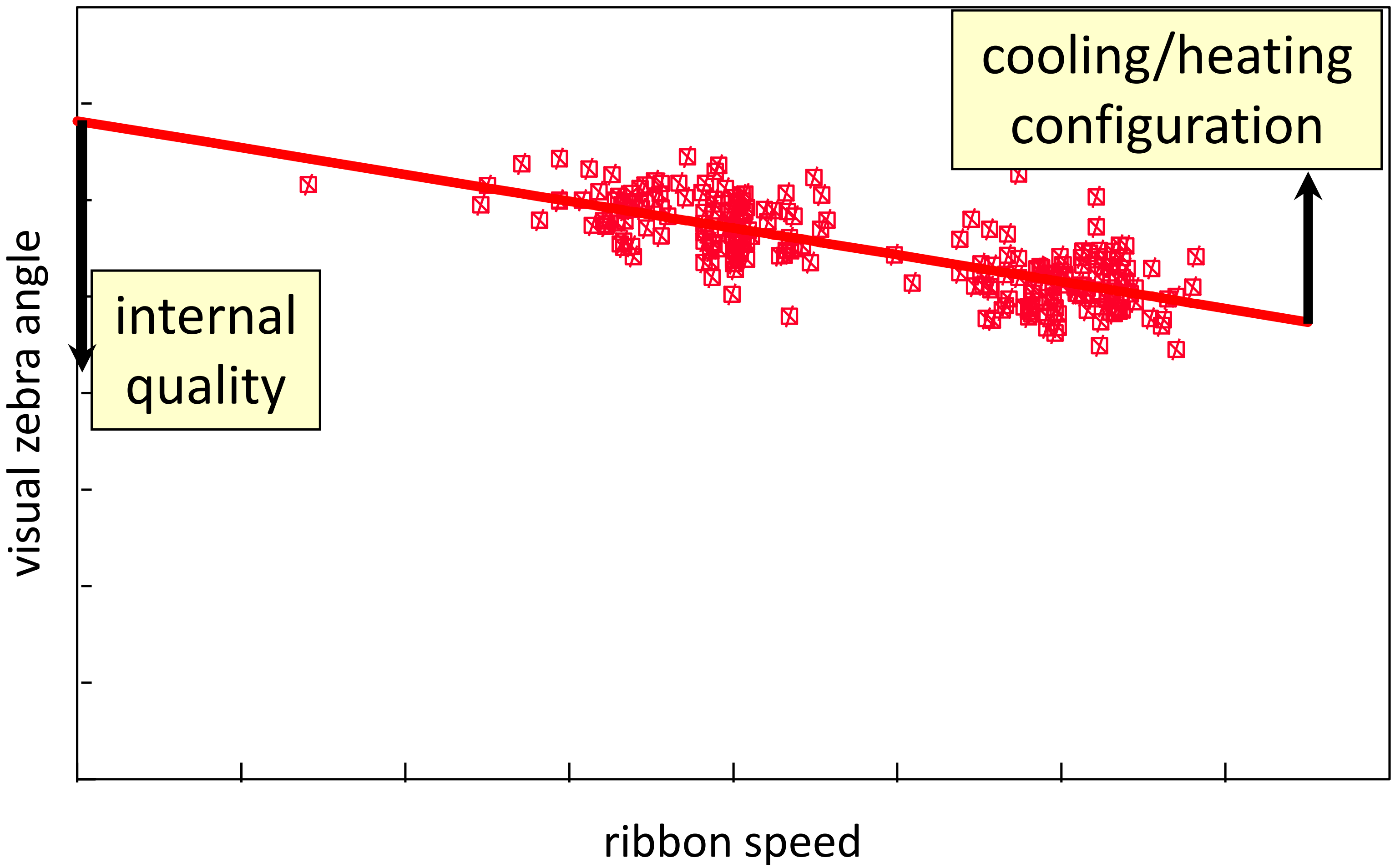
ribbon cooling
viscous stresses
tin flows

← "process", or active variables

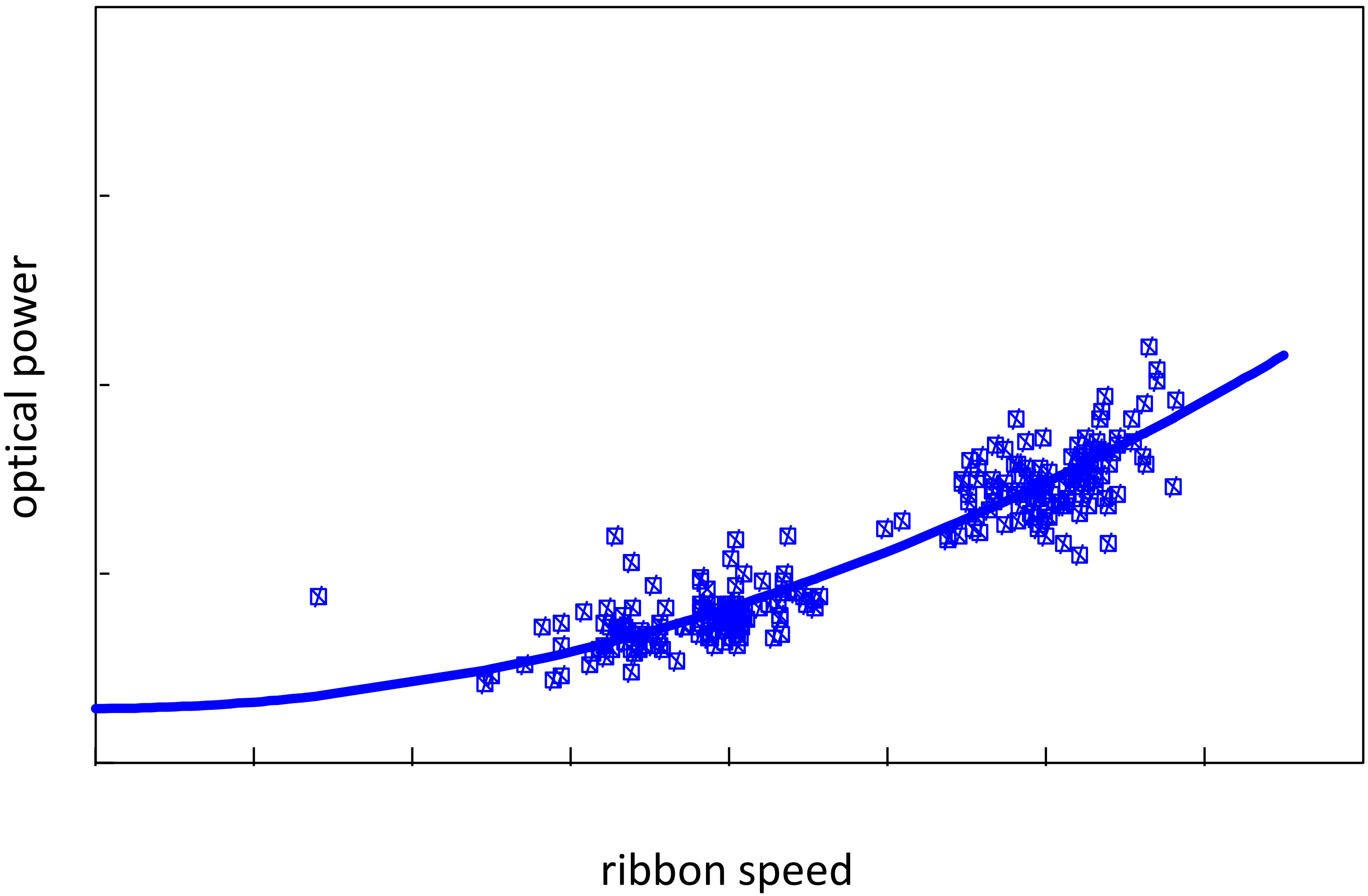
Float Glass: Transmitted Distortion

- There are two basic sources of transmitted distortion, glass inhomogeneities and surface irregularities.
- The glass inhomogeneities originate in the furnace.
- The surface irregularities originate in the hot end of the float bath, and are caused by cooling the ribbon.
- Both have a complex bath processing component.

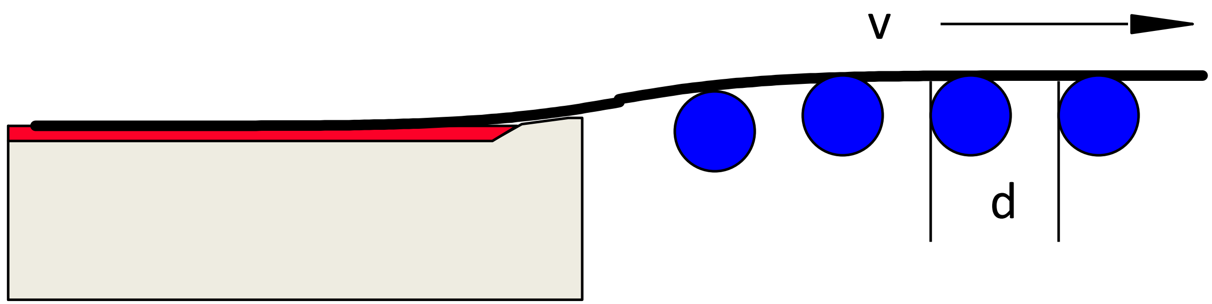
Model Validation:
Transmitted Distortion



Model Validation:
Reflected Distortion



Modeling the Exit End



Sag (distortion) $$= K\left(\frac{\rho g}{\mu}\right)\left(\frac{d^5}{vh^2}\right)$$

$$= K\left(\frac{\rho g}{\mu}\right)\left(\frac{Wd^5}{Qh}\right)$$

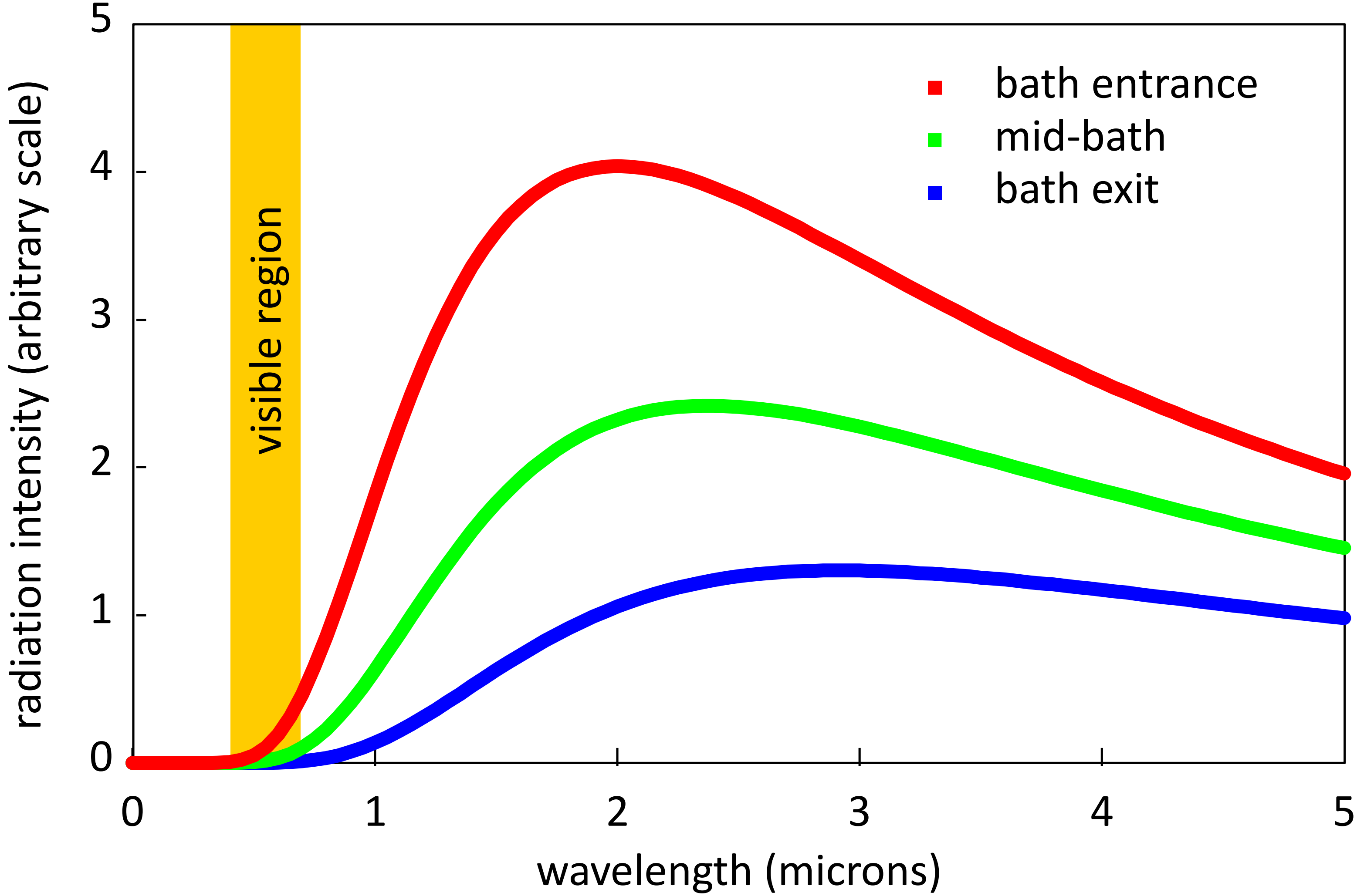
Thus, exit end distortion is inversely proportional to the ribbon viscosity and the ribbon thickness.

Heat Transfer

Heat Transfer – General Comments

- Heat transfer processes in the tin bath are quite complex
- All three modes of heat transfer (radiation, convection, and conduction) are taking place simultaneously.
- Glass is diathermaneous.

The Planck Radiation Distribution



Glass Ribbon Coolers

Bath Coolers

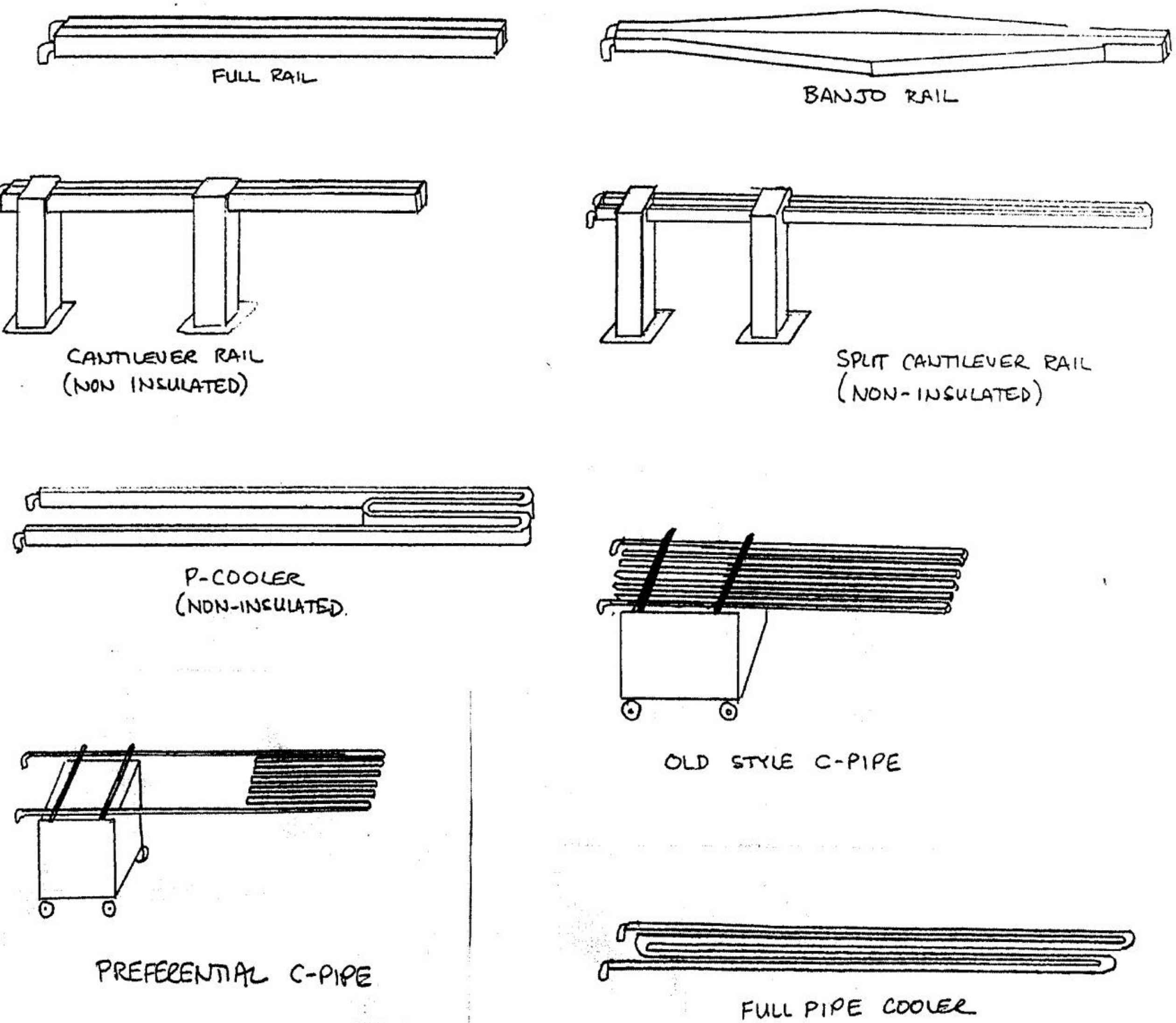


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Figure 46

Heat Removal by Water Coolers

$Q = MC\Delta T$

M = amount of water (kg)

C = specific heat of water: $\dfrac{1\ \text{cal}}{\text{g-}^{o}\text{C}} = \dfrac{1000\ \text{cal}}{\text{kg-}^{o}\text{C}}$

ΔT = temperature change of water (^{o}C)

Example: A cooler with a water flow of 378 l/min and a ΔT of 9^{0}C

Q =(378 l/min) x (1 kg/l) x (60 min/hr) x (1000 cal/kg-^{0}C) x (9^{0}C)

Q = 204,120,000 cal/hr = 854,650 kJ/hr 1kW = 3600 kJ/hr

Q = 238 kW

Shortcut

Q (kW) = l/min x ΔT x .07

Q = 378 l/min x 9 x .07

Q = 238 (kW)

Bath Chemistry

Metal Substrate Requirements

- Denser than glass
- Minimal chemical reactivity with glass
- Glass doesn’t “wet” it
- Boiling point well above 2000 °F
- Melting point below 1100 °F
- Low vapor pressure
- Manageable metal chemistry
- Affordable

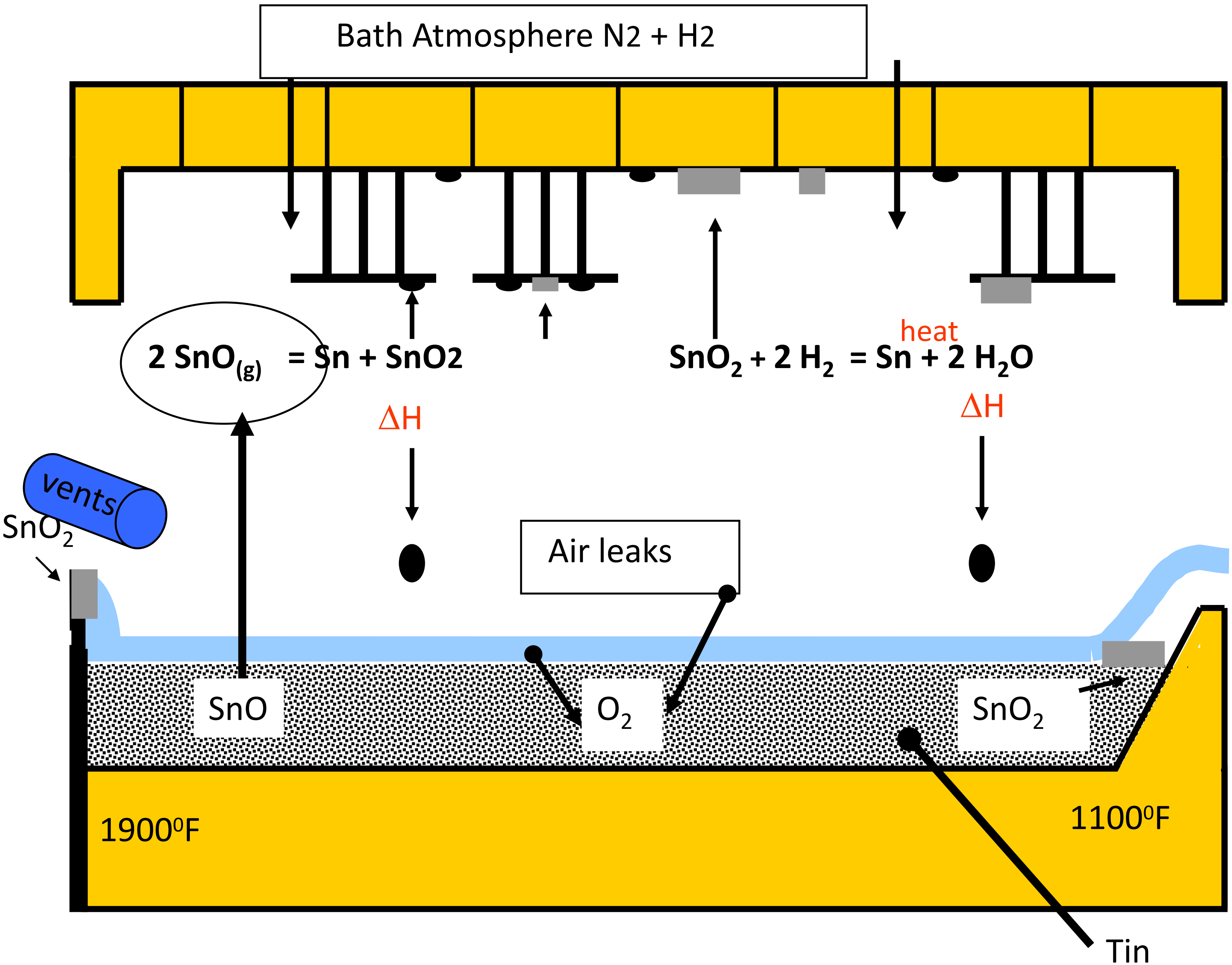
Properties of Various Metals

	METAL	MELTING POINT °F	BOILING POINT °F	VAPOR PRESSURE @2000°F mmHg	REMARKS
	TIN	450	4120	.002	
INCREASING	GALLIUM	86	3600	.023	WETS GLASS
	INDIUM	313	3630	.11	
VAPOR	ALUMINUM	1220	3733	.45	WETS GLASS FORMS NITRIDE
PRESSURE	BISMUTH	520	2588	4.1	
	LEAD	621	3270	4.3	
	BARIUM	1340	2980	15	FORMS NITRIDE
	ANTIMONY	1168	2625	22	
	CALCIUM	1553	2710	32	FORMS NITRIDE
	THALLIUM	576	2637	35	
	STRONTIUM	1420	2523	82	
	CERIUM	1480	2550	-	
HIGH	GERMANIUM	1720	4900	.00003	
MELTING	SILVER	1762	3540	.027	COULD USE OXIDIZING ATM.
	GOLD	1945	4710	.00001	COULD USE OXIDIZING ATM.
POINT	COPPER	1980	4237	.0003	

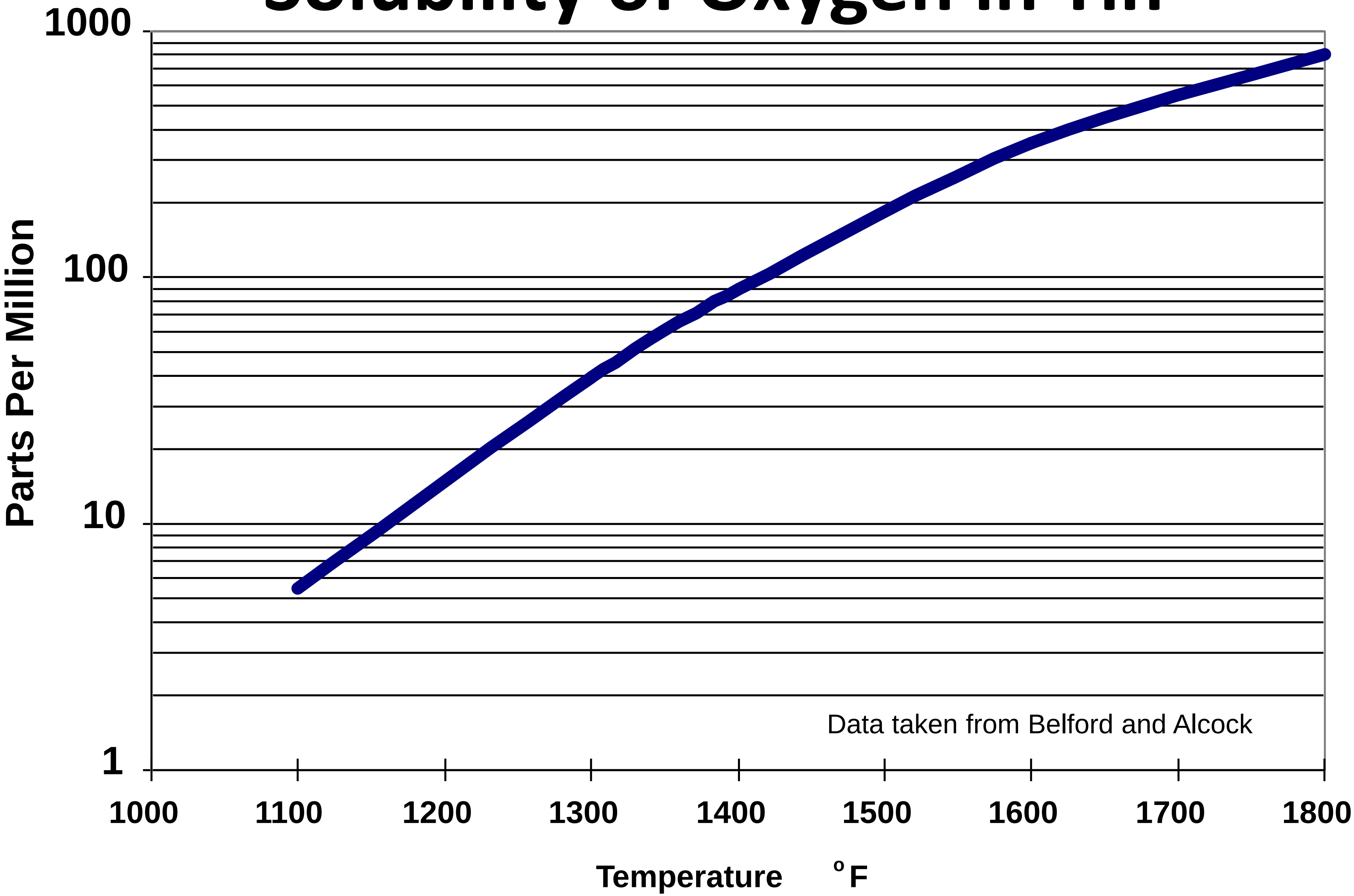
Properties of Tin

- Melting Point = 232 °C
- Boiling Point = 2271 °C
- Vapor Pressure = 0.002 mm Hg @ 1100 °C
- Density = 6.5 g/cc
- Low viscosity at bath temperatures (0.01 p)
- Low reactivity/solubility with H_2 and N_2
- High reactivity with O_2
- Does not wet the glass

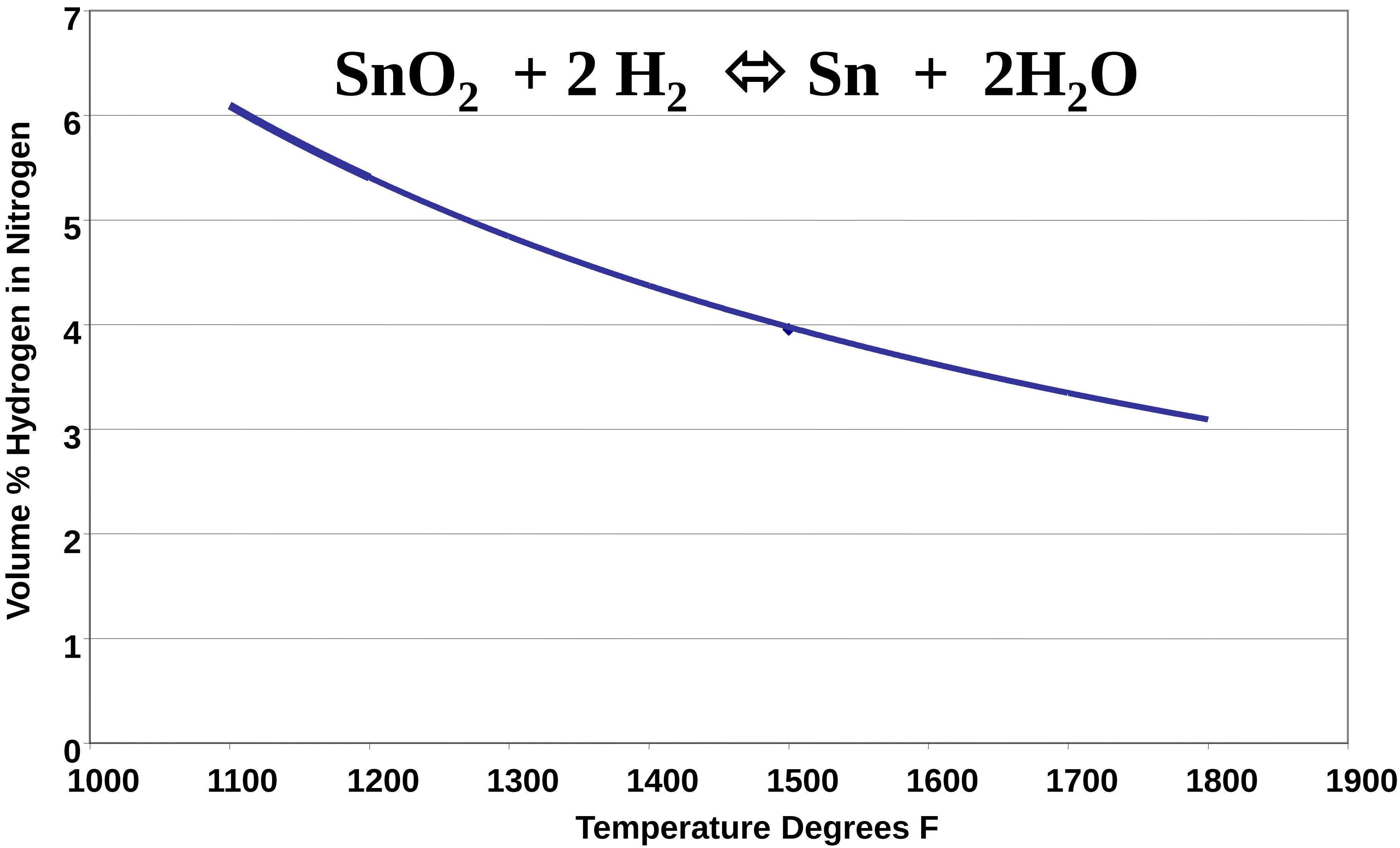
Oxygen Cycle



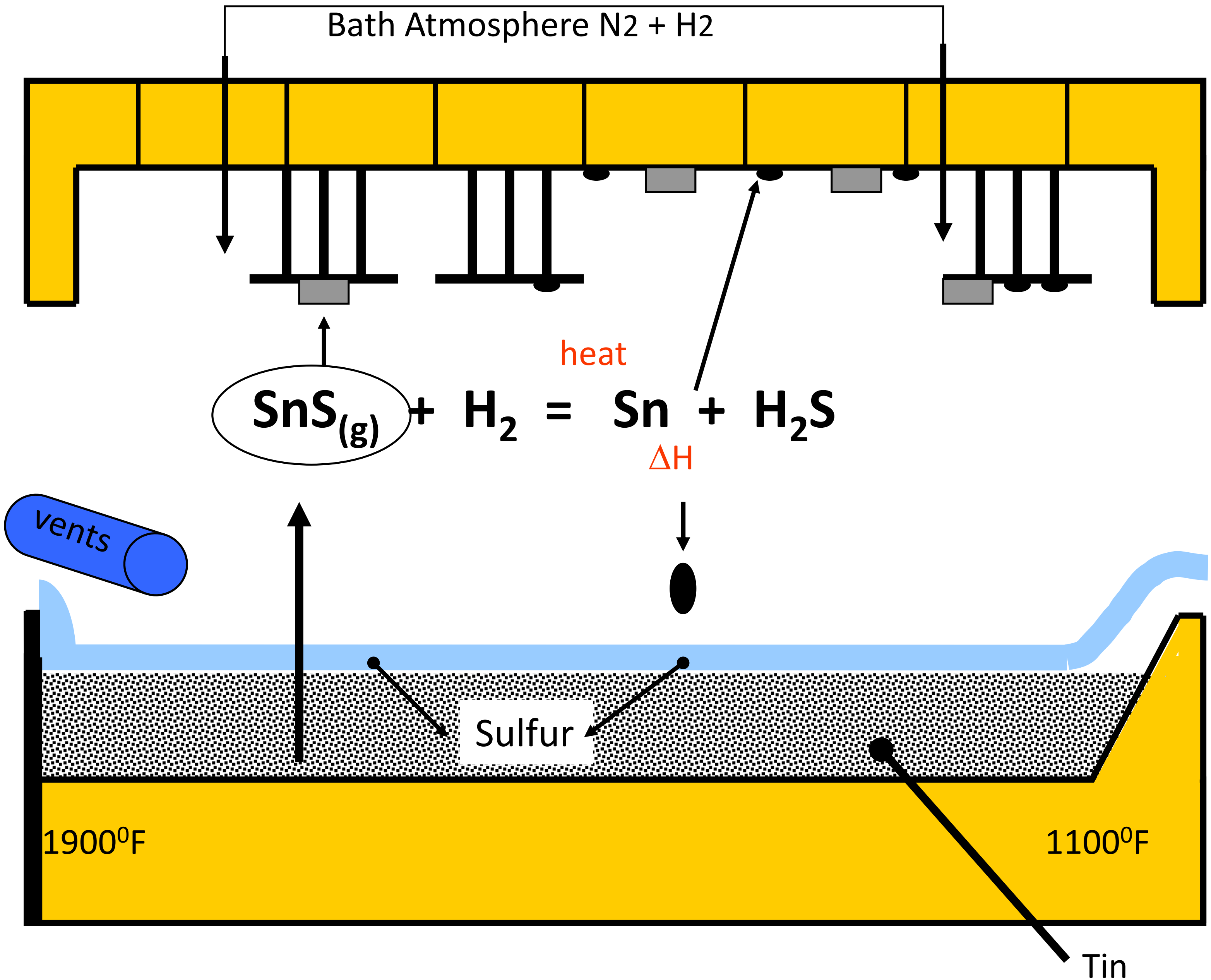
Solubility of Oxygen in Tin



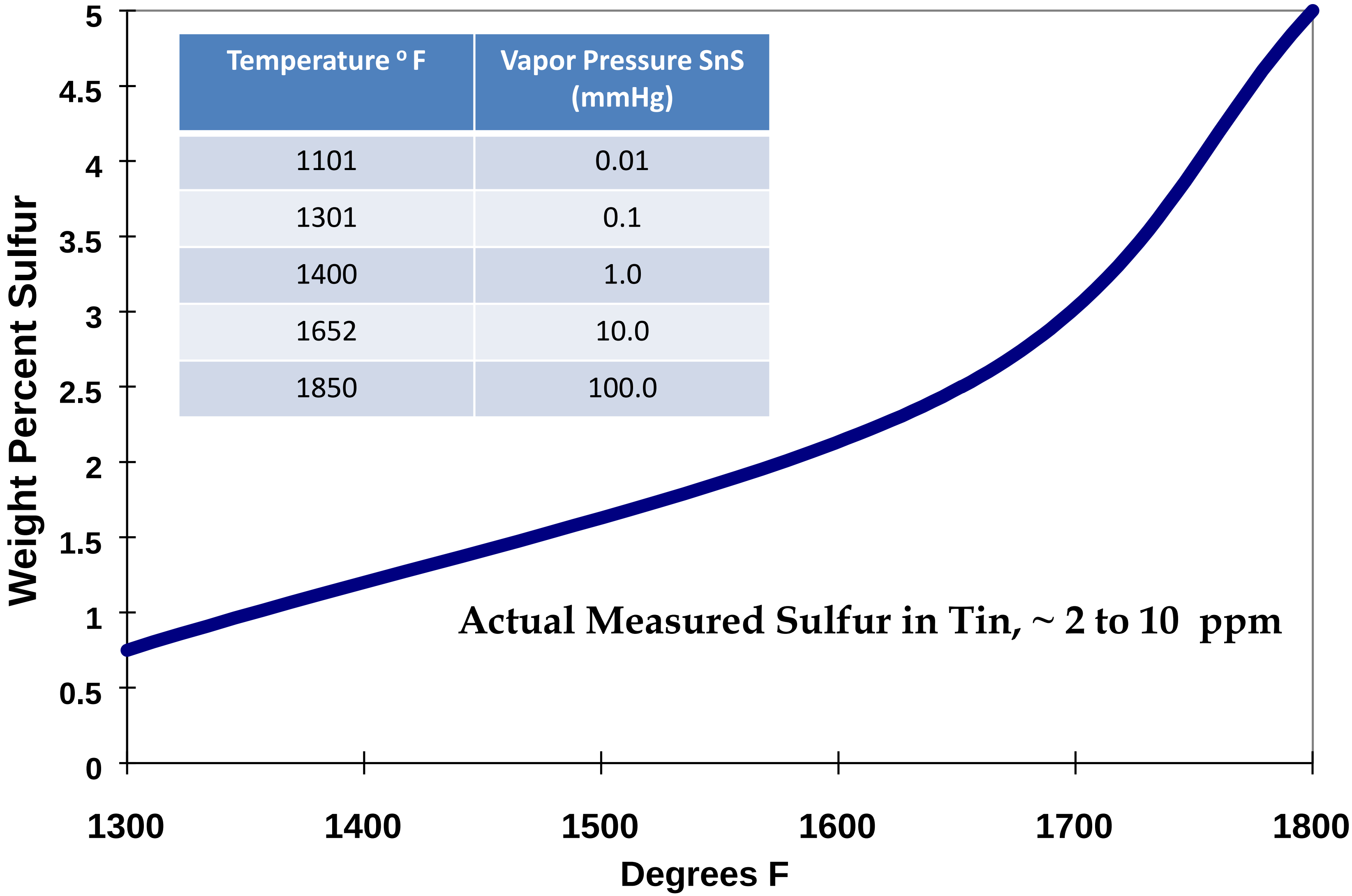
SnO_2 Reduction by H_2



Sulfur Cycle



Solubility of Sulfur in Tin



Temperature ° F	Vapor Pressure SnS (mmHg)
1101	0.01
1301	0.1
1400	1.0
1652	10.0
1850	100.0

A Bath Atmosphere Management System

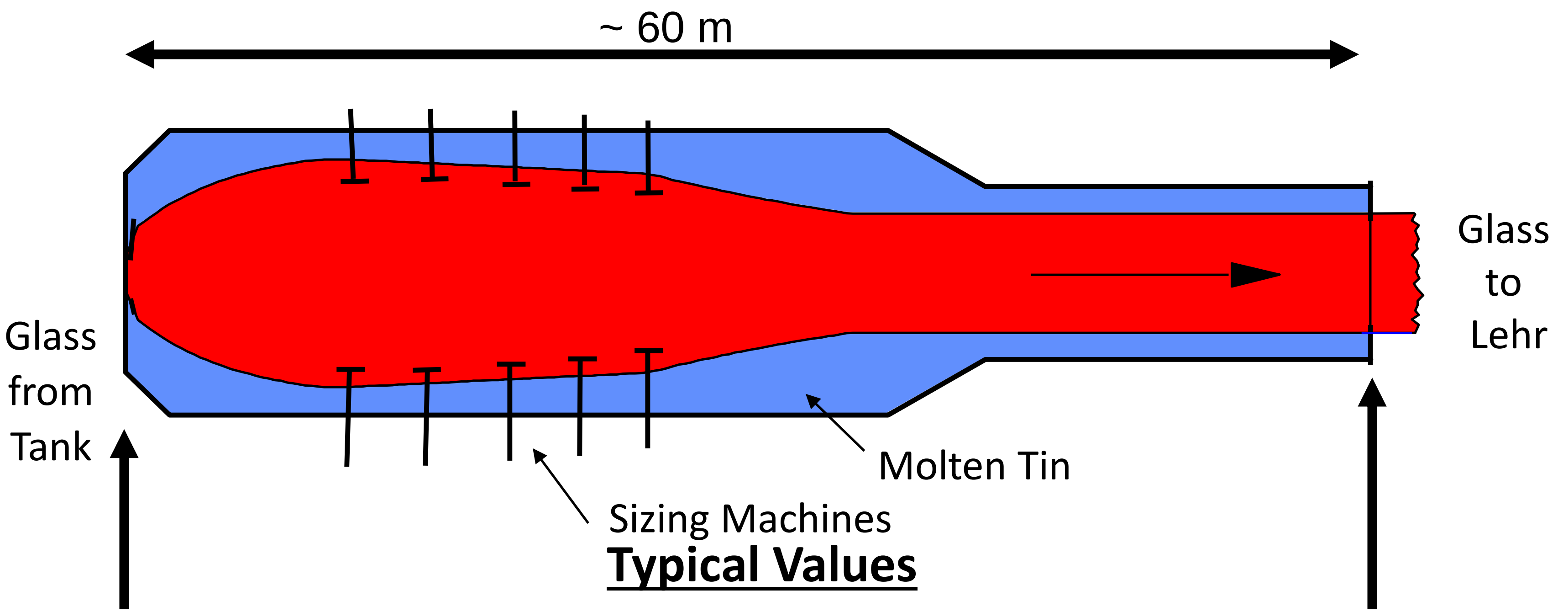
- **H_2 usage:** 1% - 5% throughout the bath
- **N_2 usage:** 50,000 – 100,000 scfh (size dependent)
- **Bath pressure:** 0.20” H_2O or higher
- **Hot end venting:** vent 15-20% of the total atmosphere flow

Bath Modeling

Modeling Float Bath

- Three major computation fluid dynamics areas
  - Bath atmosphere flow
    - Effects bath defects like top tin
  - Glass flow
    - Need to make glass in needed thickness and width
  - Liquid tin flow
    - Influences glass temperature since tin is a liquid metal

Plan View of A Float Glass Tin Bath



Typical Values

1100	Temperature (C)	600
10^2	Viscosity (Pa-s)	10^9
10	Glass Thickness (mm)	3

Massive glass viscosity variation 1:10^7

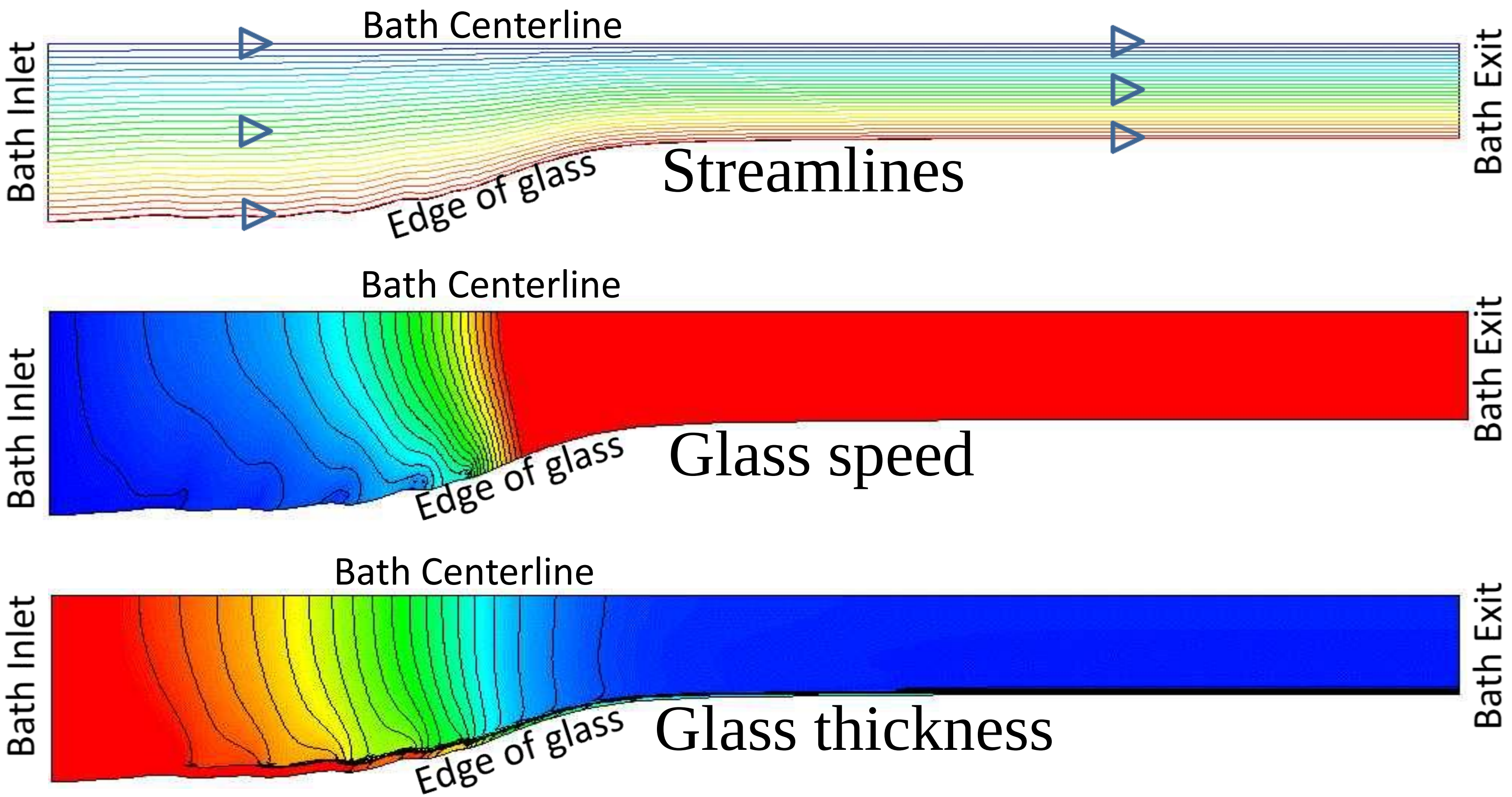
Glass aspect ratios are large - Length:Width:Thickness = 10,000:1,000:1

Modeling Glass in Bath

- PPG has a detailed model
- Free surface model since glass thickness and width need to be calculated
- Inputs – Bath conditions (throughput, temperatures, machine speeds and angles, exit speed)
- Output
  - Glass thickness and width
  - Glass speed (residence time)
  - Glass stresses

Model Predictions

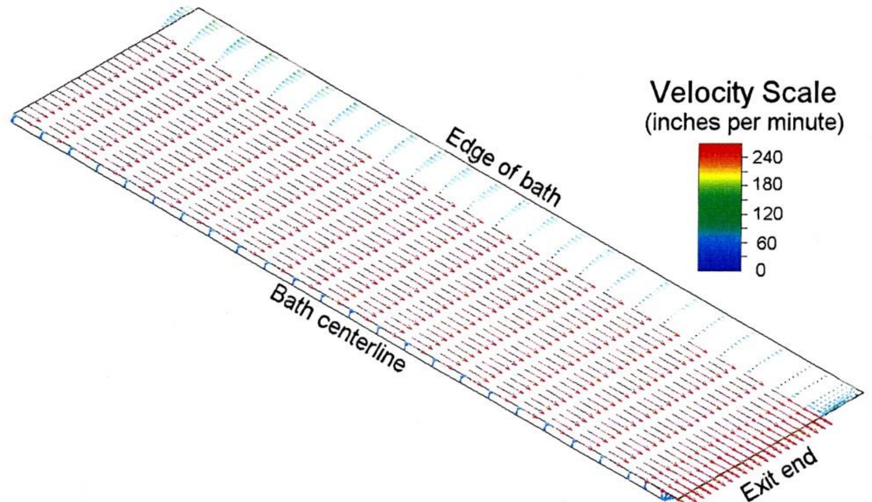
Top View of glass in float bath

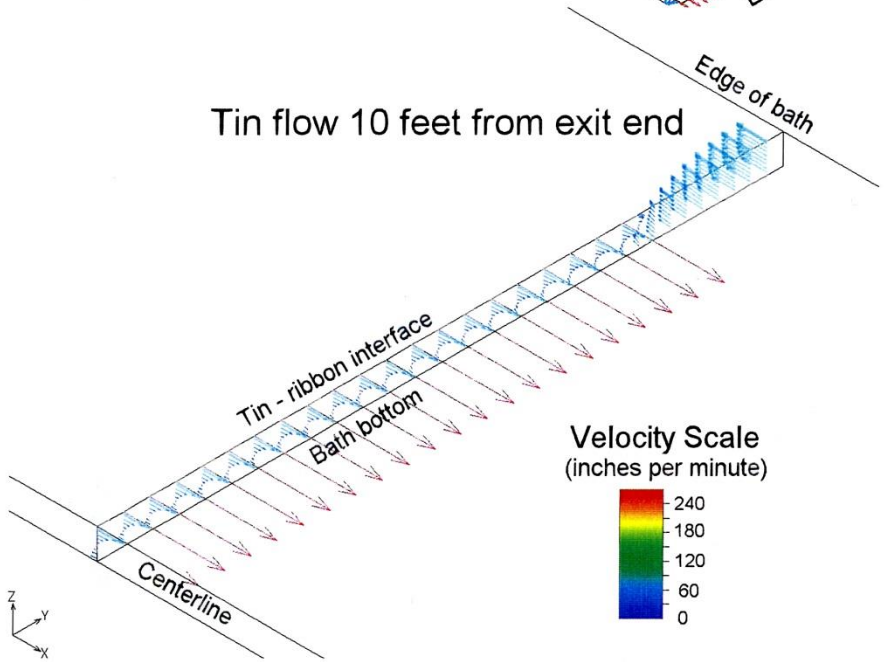


Tin Flow Modeling

- Liquid metal flow – high thermal conductivity
- Turbulent
- Moving glass drags thin boundary layer of tin
- Return flow along the sides
- Near bath entrance tin flow may laminarize

Typical Tin Flow Pattern at Exit End





Modeling Bath Atmosphere

- Composition generally 95% N_2 + 5% H_2
- Turbulent gas flow
- Buoyancy effects due to bath temperatures
- Lot of variation from bath to bath since baths conditions vary

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