Glass Performance Days 2025

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GLASS PERFORMANCE DAYS 2025

GRADING VISIBILITY OF DISTORTION AND ANISOTROPY IN HEAT-TREATED COATED GLASS

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Grading Visibility of Distortion and Anisotropy in Heat-Treated Coated Glass

In this presentation we hope to provide an overview of state-of-the-art tools and techniques for measuring and grading the quality of heat-treated glass.

We will touch on many areas, but the emphasis will be on distortion and anisotropy as those are the two fundamental side effects of heat treatment that need to be controlled.

We have attempted to make this more technical than sales focused, but please contact us at GlassQuality.com and we can provide more specific product and solution options.

Topics

Tempering Process

Anisotropy

- How internal stress profile causes anisotropy
- Coatings make anisotropy more (or less) visible
- Quantify coating impact on visibility – **SigmaQM**

Distortion

- How optical distortion is measured
- Coatings make distortion more (or less) visible

Grading

- Quantifying objectionability of patterns – **Global Score**

Implementation

- Equipment and measurement techniques

Why Tempered (Safety) Glass?

- **STENGTH**

4 to 5 times stronger

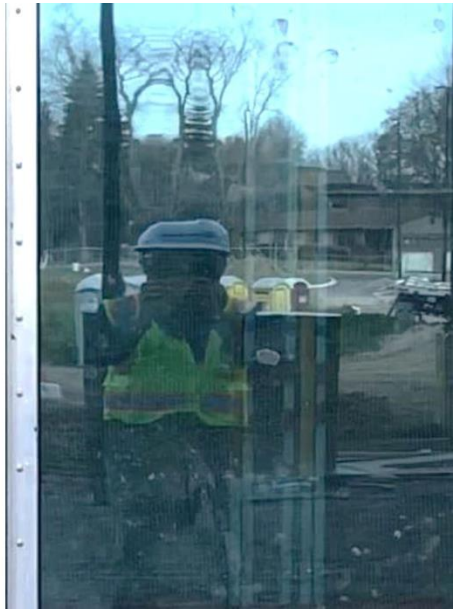
- **SAFETY**

shatters into small dull fragments rather than large sharp shards

- **THERMAL SHOCK**

far superior ability to withstand rapid temperature changes

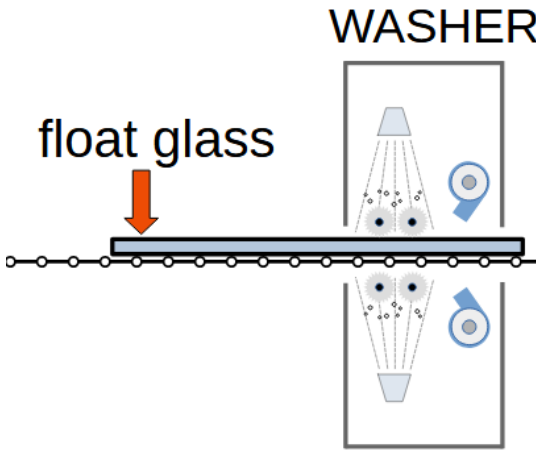
Heat-treatment of glass can adversely affect two largely **independent** properties:



Optical Distortion

Anisotropy

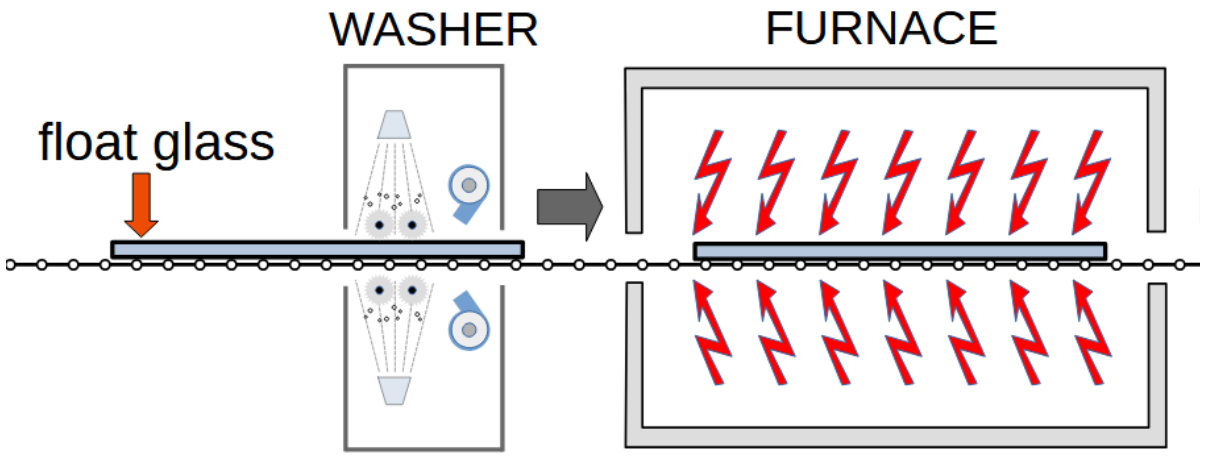
Step 1: **Washing**



Raw annealed glass enters from the left and is cleaned and dried.
It is important for any foreign matter to be removed from the glass to avoid staining.

HEAT TREATMENT PROCESS

Step 2: **Heating**



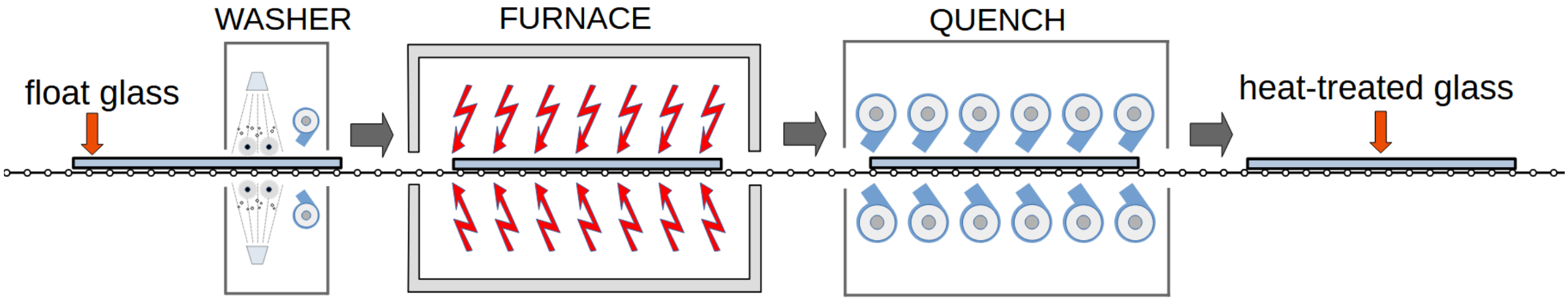
Heated above transition temperature (~550 C) but below softening point (~750 C)

Competing Goals:

- Hot enough to relieve all the internal stress
- Not too hot or too long to minimize physical distortion

HEAT TREATMENT PROCESS

Step 3: **Cooling / Quench**



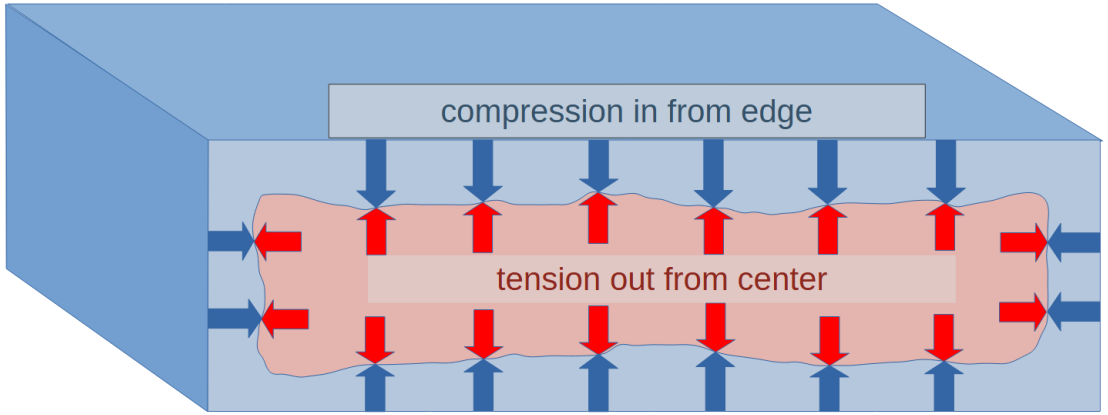
The glass then moves into the air-cooling or quench phase where, in the case of tempering, it is cooled rapidly by forced air (cooled more slowly in the case of heat-strengthening).

HEAT TREATMENT PROCESS

Fully Tempered Glass

- During rapid cooling, the outer surfaces of the glass cool first, forming a solid outer shell that 'locks in' the slower-cooling interior. The interior now cannot contract as it cools so it is forced into tension. This creates **Anisotropy.**

- The cooling of the quench also locks in any physical deformation that has occurred while the glass was above transition temperature. This creates **Optical Distortion.**



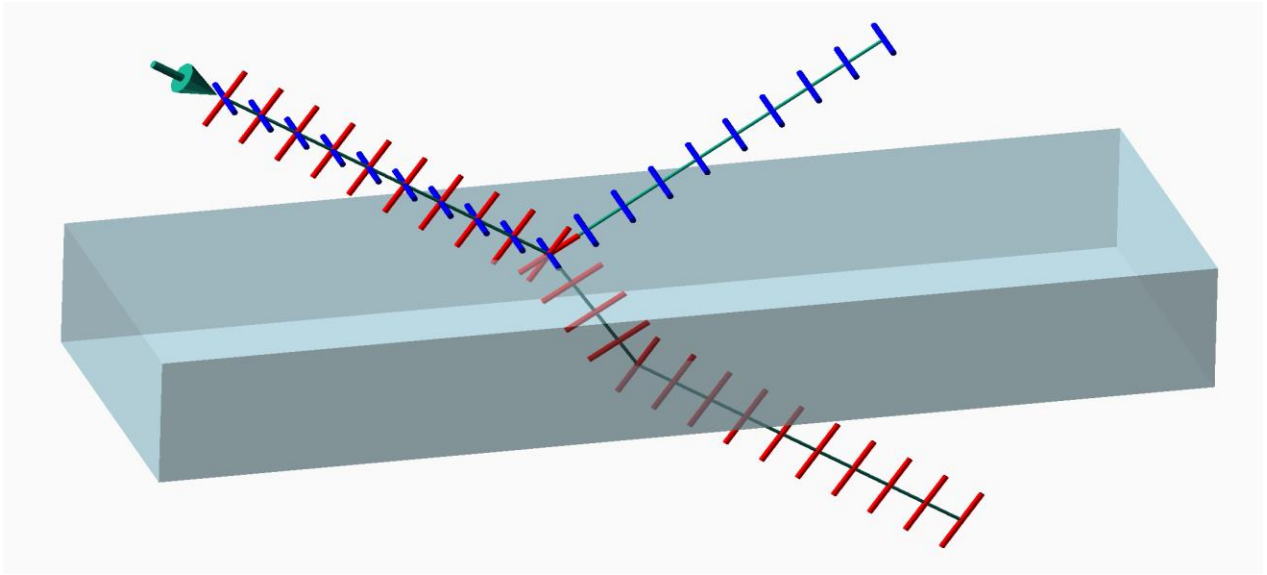
Polarized Light

All light is comprised of 2 polarization states:

P (**red**) is oscillating in the plane of the page
S (**blue**) oscillates out of the page.

A non-metallic surface (such as glass or water) it reflects P but allows S to pass.

Polarized sunglasses filter S polarization which is the reflection of the top surface of the water.

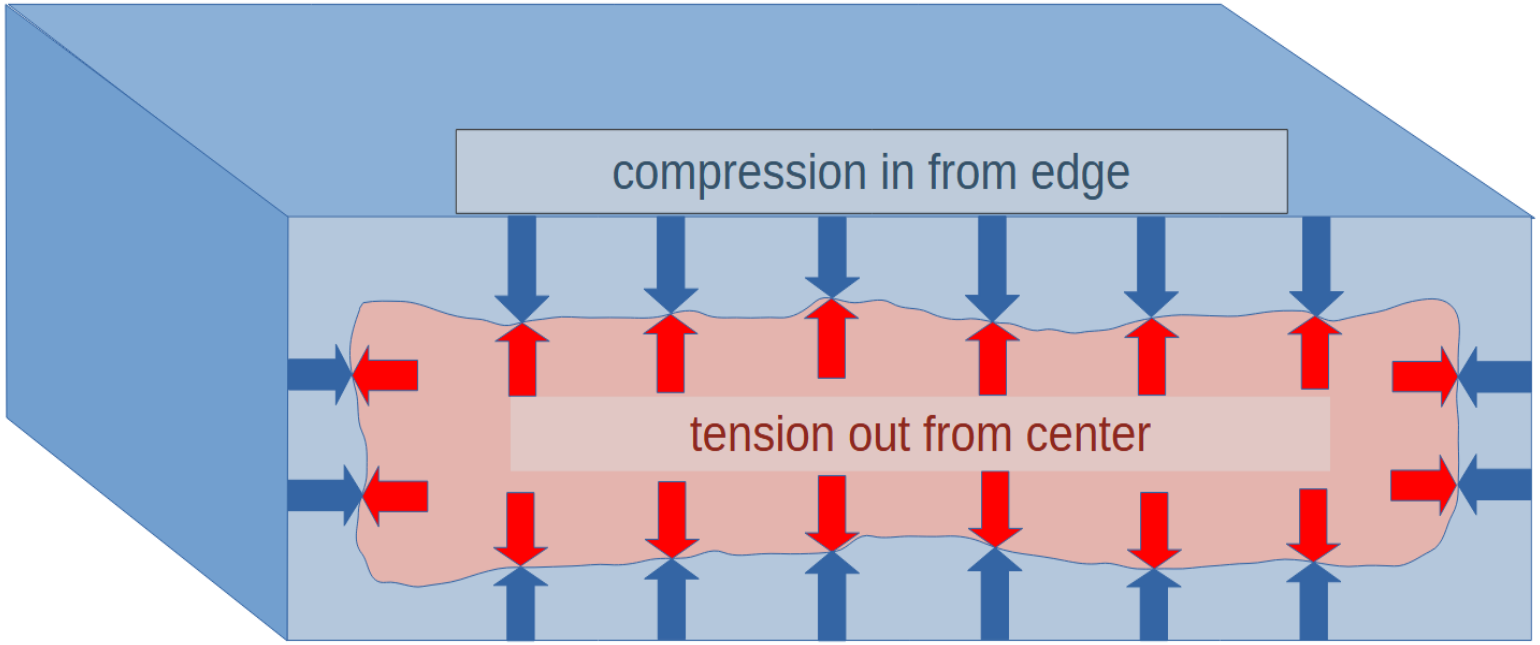


Anisotropy is caused by stress imbalances

Always variation in cooling rates across the glass

The boundary between the tension and compression is uneven.

Local imbalance alters the way light propagates through the material

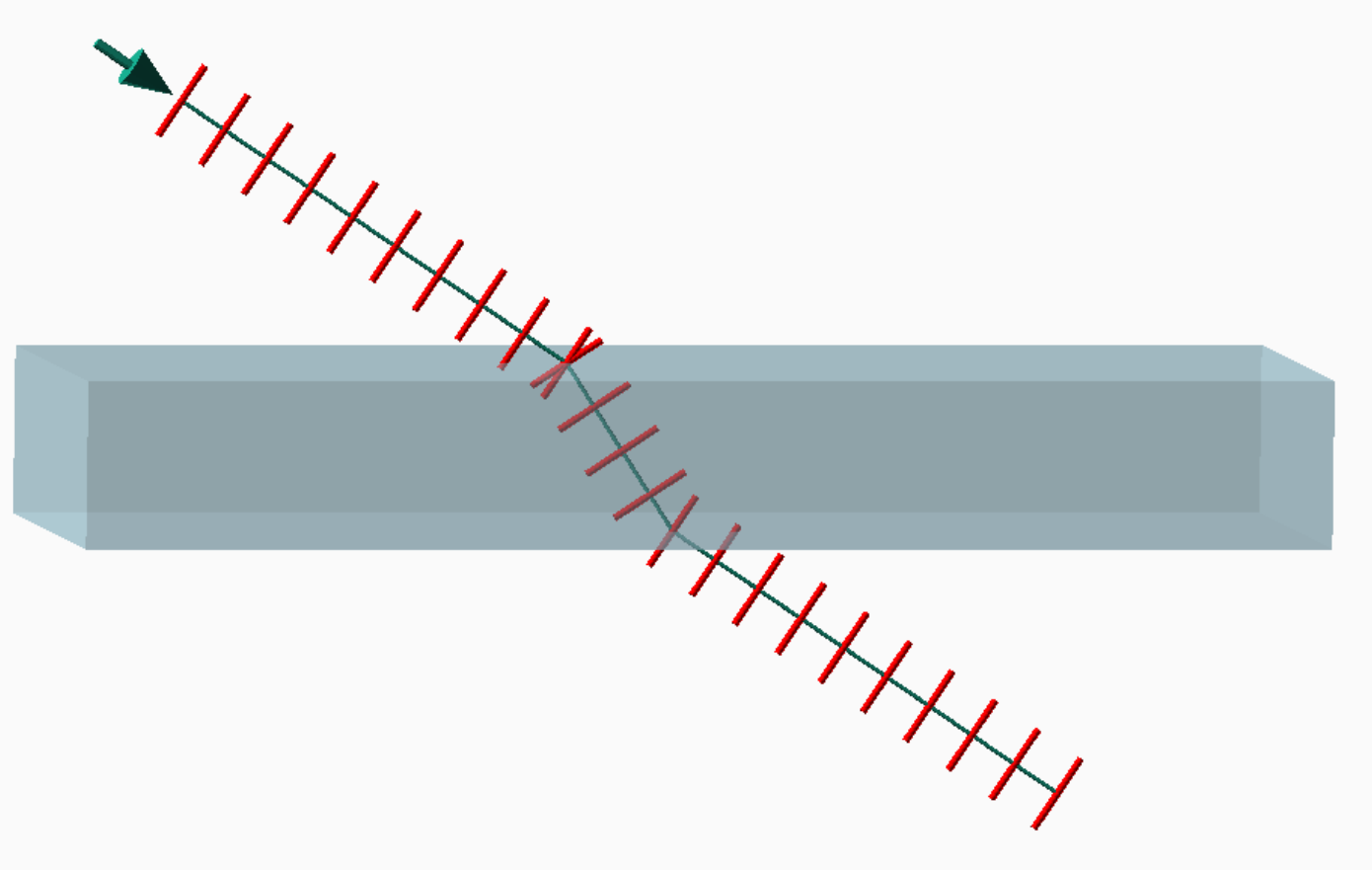


No Stress = No Anisotropy

Annealed Float Glass
(stress relieved)

All P polarization light will pass through the glass.

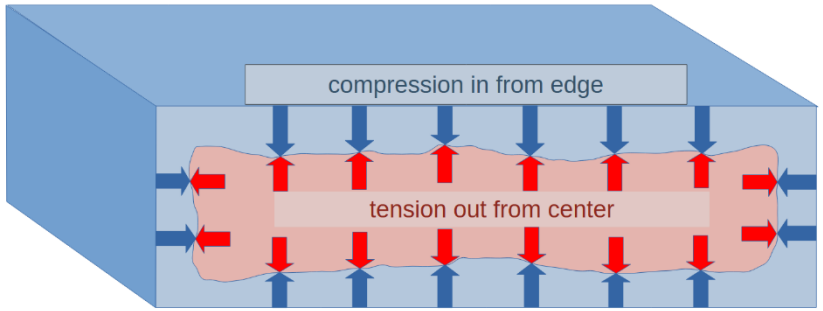
No visible anisotropy will be present.



We will focus on the P polarization component – as we will see later it is the component that interacts with the body of the glass

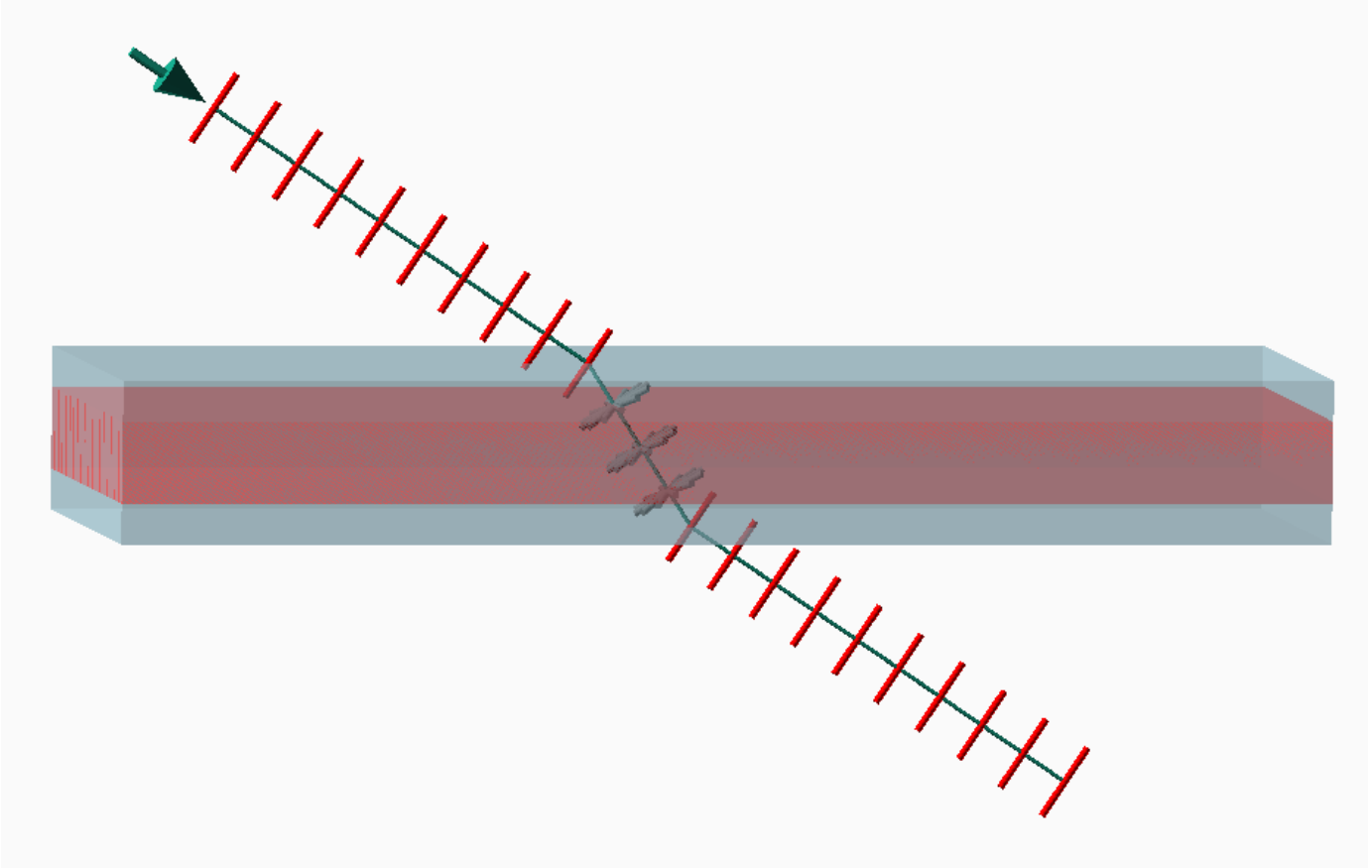
Light is affected by the Molecular Arrangement and Density

- Anisotropic (direction-dependent) deformation in the molecular level of glass structure.
- These localized anisotropic deformation of the density and arrangement of glass molecules cause the polarization to rotate as the light traverses the thickness of the glass.



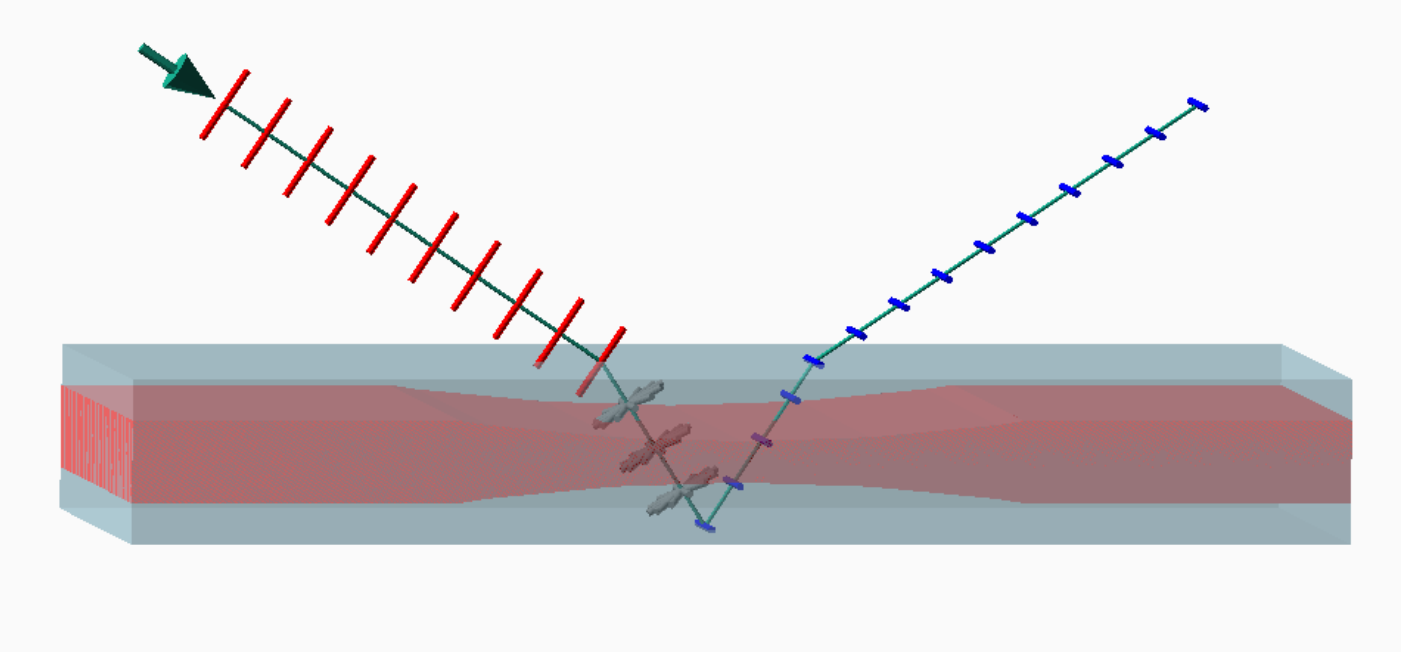
Theoretical Perfect Stress Balance = No Anisotropy

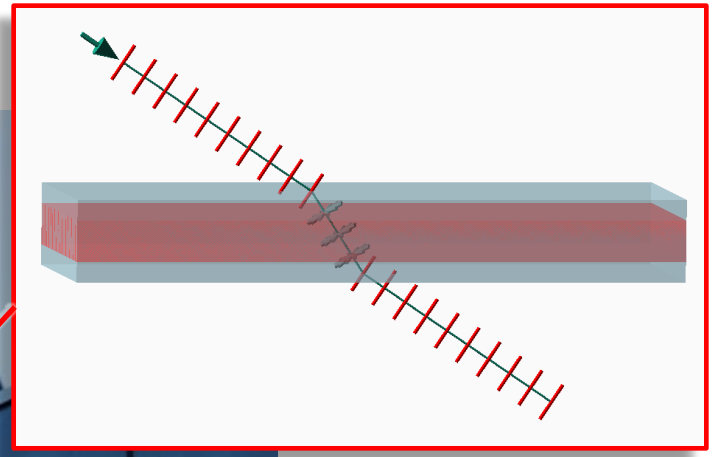
Where tensile and compressive stresses are exactly balanced, all P polarization light will pass through the glass like in this figure (the red central area of the glass represents inner tensile zone), and no anisotropy will be present.



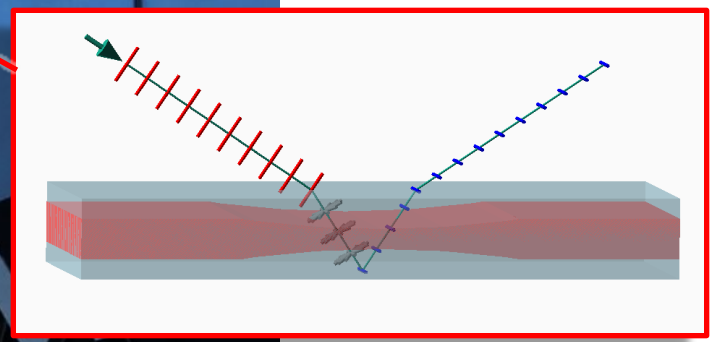
Real Stress Profiles with Imbalances = Anisotropy

Areas of imbalance cause the polarization to have a net rotation as it reaches the far surface of the glass and some of the light that would otherwise pass through the second surface now reflects off the 2nd surface.





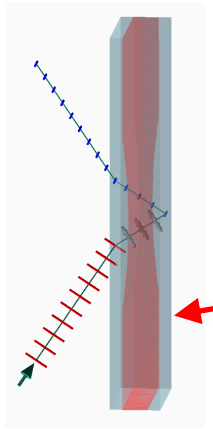
Balanced
all P polarization light will pass through

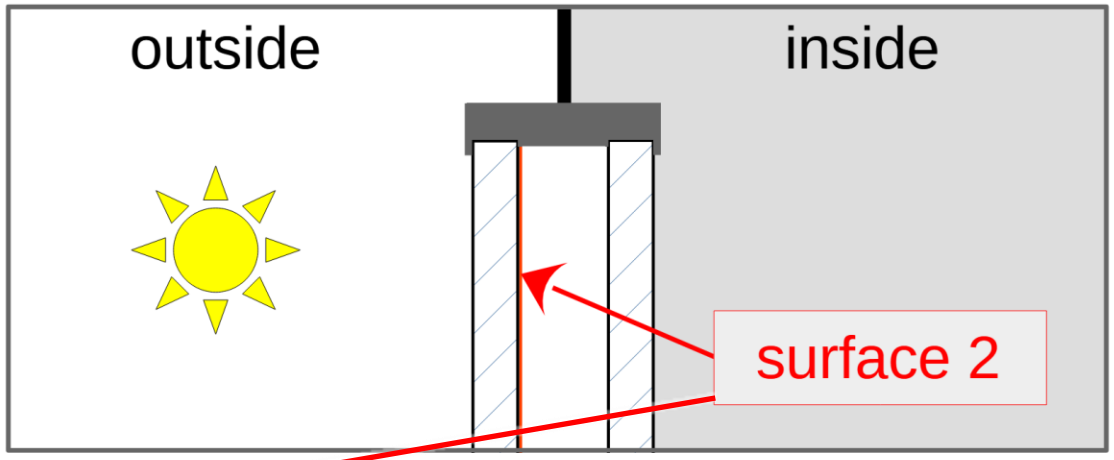


Unbalanced
Some P polarization light rotated to S and therefore reflects off the 2nd surface causing brighter areas

Anisotropy and Coatings

The largest contributor to anisotropy is typically reflection from surface 2.

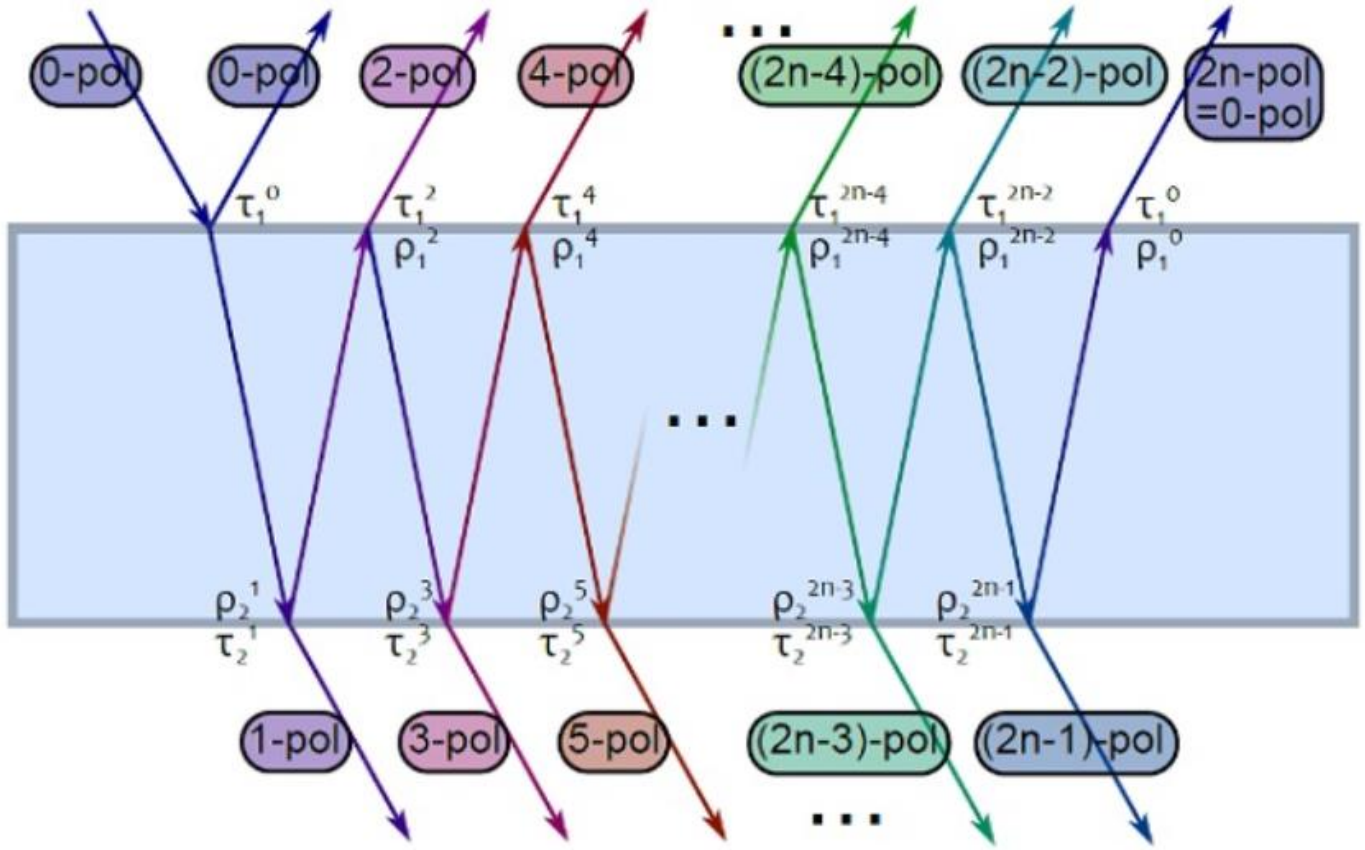




- The stress imbalance causes rotation of polarization.
- The reflection from coating influences anisotropy visibility.
- Q: *Can we quantify the effect of the coating?*

Computing Sensitivity to Quench Marks - SigmaQM

A mathematical series computation of the effects of the multiple internal reflections, the range of visual influence was converted into a well-established perceptual color model (CIEDE2000). From this a well quantified perceptual separation could be computed. This figure shows a ray diagram of the internal reflections and how they contribute to the visibility of the level of anisotropy



Transmission and internal reflection used for computing SigmaQM – Maccariello (2022)

Verifying Sensitivity to Quench Marks - SigmaQM

Perceptual color difference or “apparent anisotropy” level

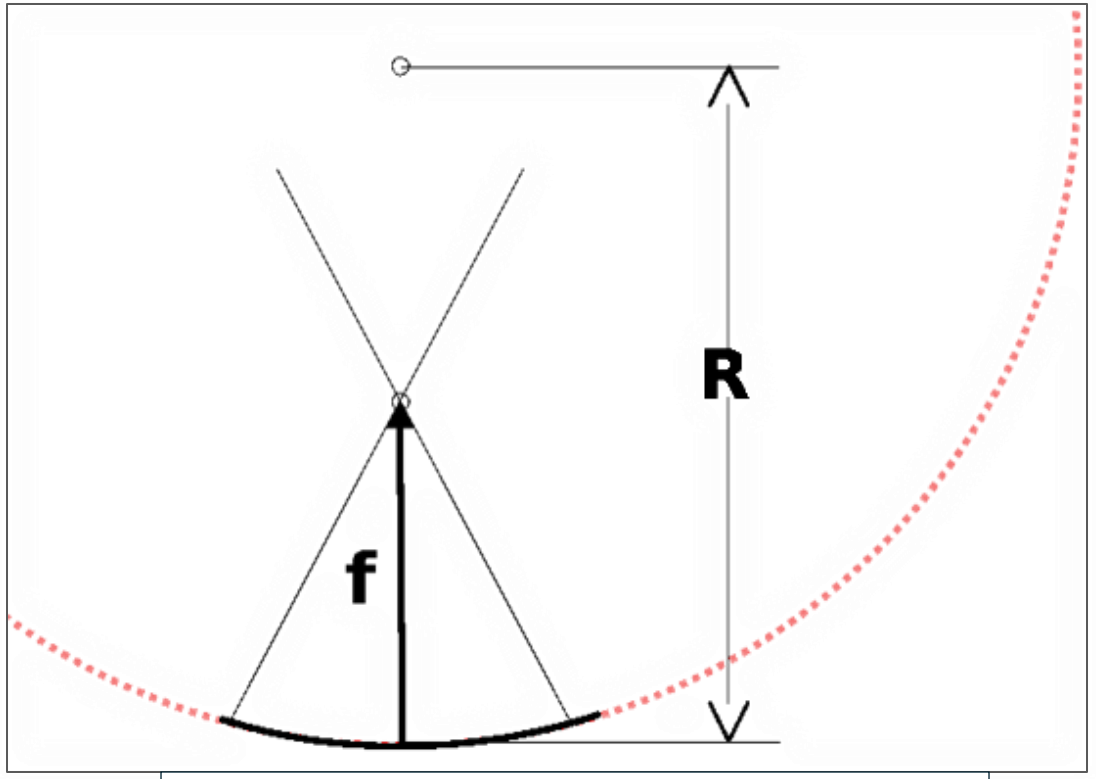
Psychophysical testing

- human studies on perception and objectionability support the objective calculations of SigmaQM.
- 40 glass samples was produced
  - 5 different total temper strengths
  - 8 different coatings
- 30 observers rated these samples.

…"for a given product, the visibility increases with the tempering strength… [T]he global tendency of detection of the defects from the observers matches with a good level of accuracy the trend of the σQM. So, the global trend suggests a good reliability of the estimated quench mark sensitivity factors” Maccariello (2022).

Optical Distortion - Review

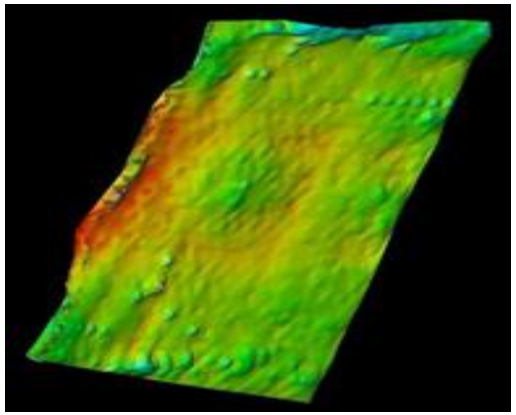
- Optical distortion is caused by the physical warping of the glass
- Reflected images become magnified or de-magnified based on the local curvature of the surface.
- lens power or curvature of a glass mirror is measured in diopters (**D**)
- See GPD 2023 Presentation Goes into more Detail



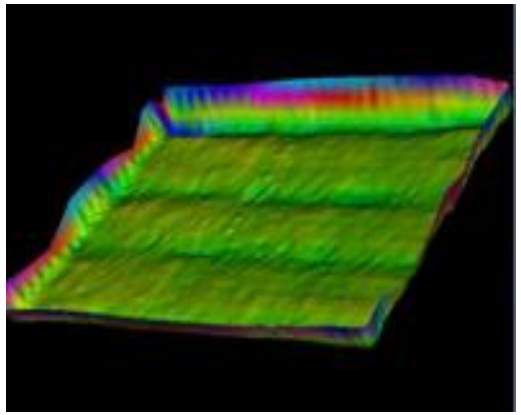
$$D = \frac{1}{f} = \frac{2}{R}$$

D is power in Diopter
f is focal length in meters
R is radius of curvature

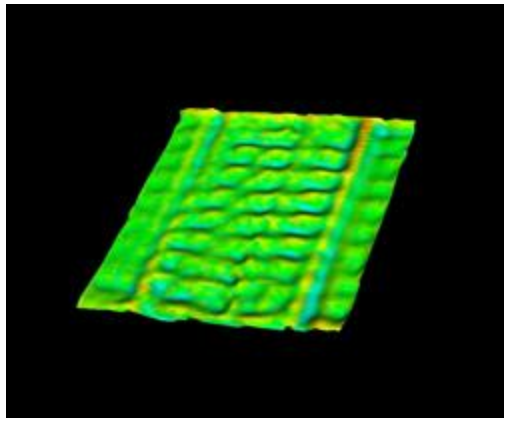
Optical Distortion – Comes in Many Flavors



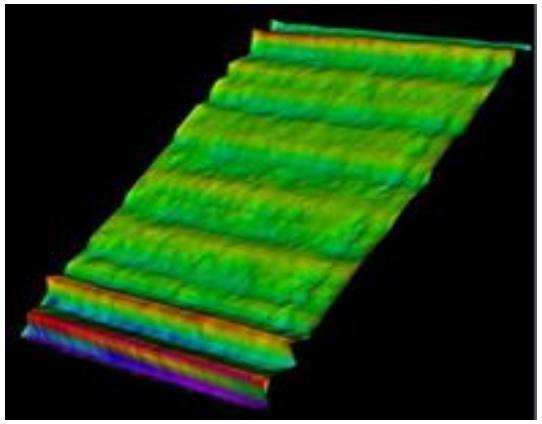
Possible Cold Center Bistability



Picture Framing



Cross Conveyor (w/Light Pocket)



Classic Rollerwave & Edge-Lift

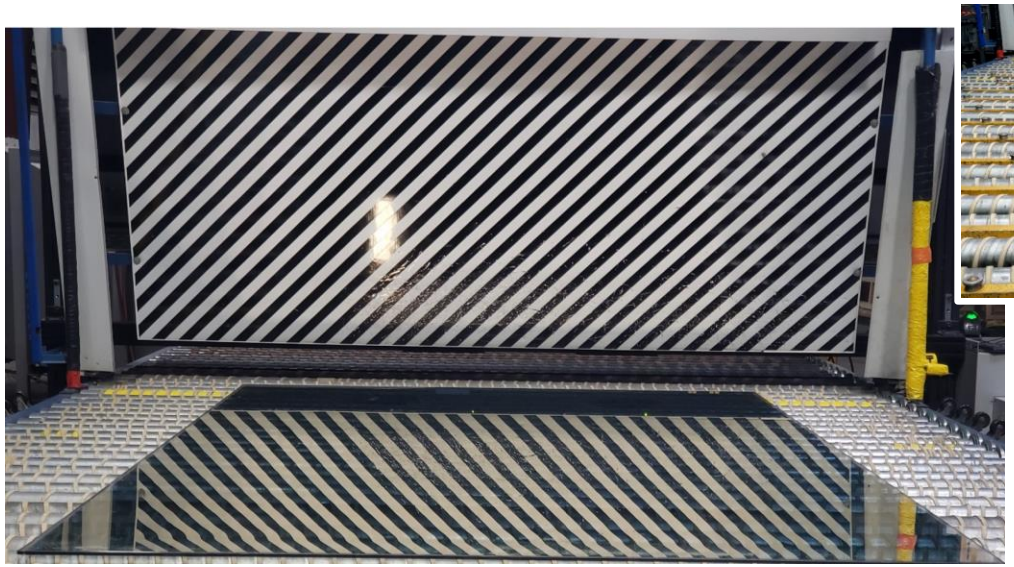
Specific shapes of distortion include roller wave (sag between rollers in the furnace), edge lift, center kink, and pocket distortion. These are covered in greater detail in our earlier presentation (Hegstrom 2023).

Some of the subtler optical distortions, such as center kink, which may be overlooked in an uncoated product, become quite prominent in coated products, as found in this forensic study presented at IIBEC International Institute of Building Envelope Consultants Conference (Rosen, A., Hegstrom, E. 2024).

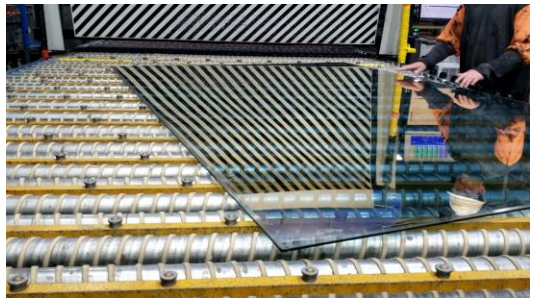
Optical Distortion – How Coatings Affect Visibility

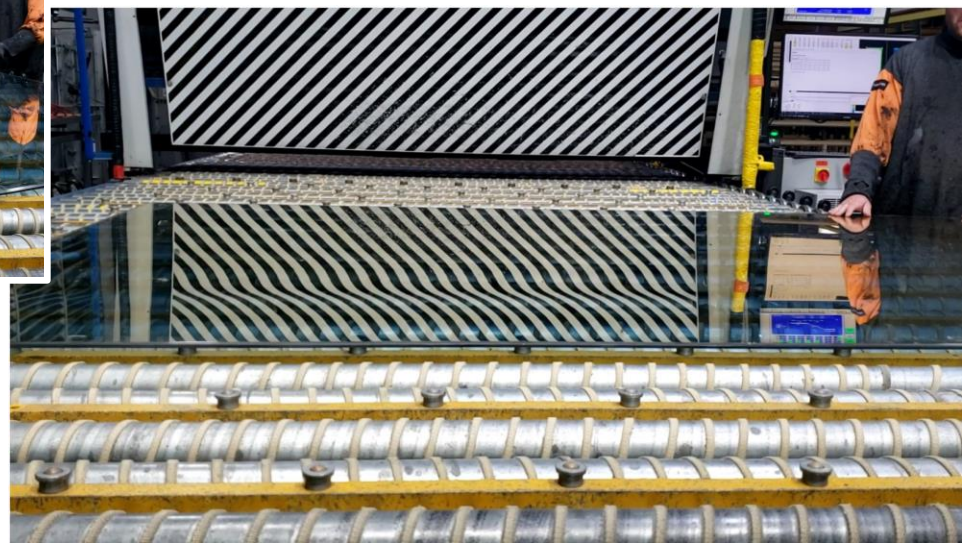
The visibility of reflected distortion image is impacted proportional to the reflectivity of the coating.

The following shows an actual photograph of center kink optical distortion not visible during the standard zebra board visual check conducted after heat treatment. This part passed all tests related to roller wave, edge lift, and pocket distortion yet was still objectionable as installed.



Center kink not visible with standard zebra board

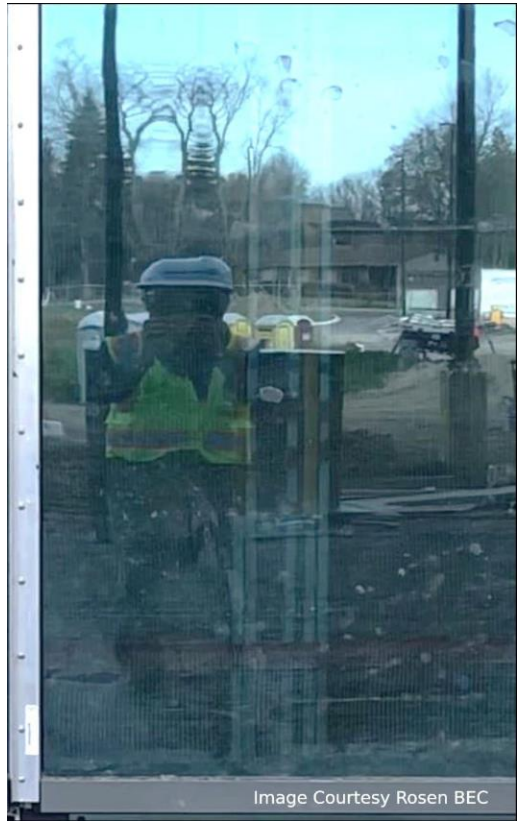


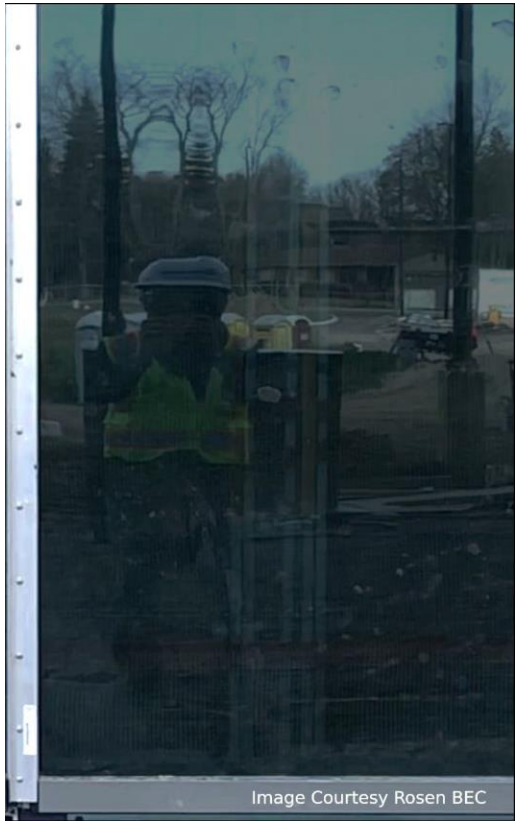


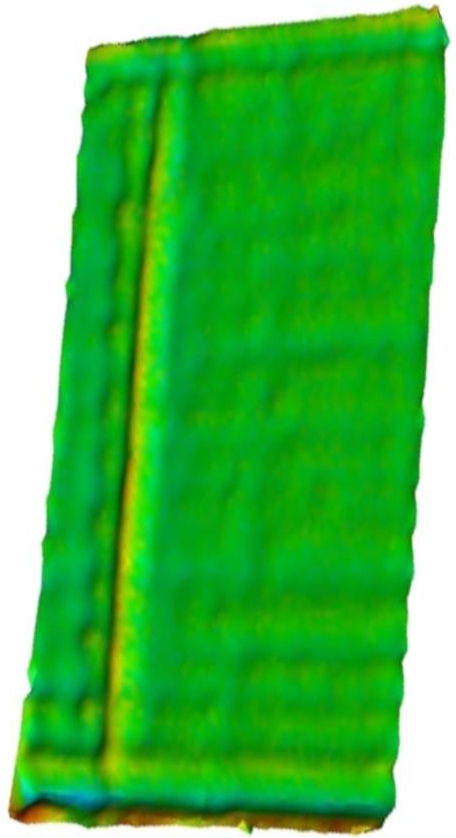
Only visible after part is rotated 90°

Images Courtesy Rosen BEC

Optical Distortion – How Coatings Affect Visibility







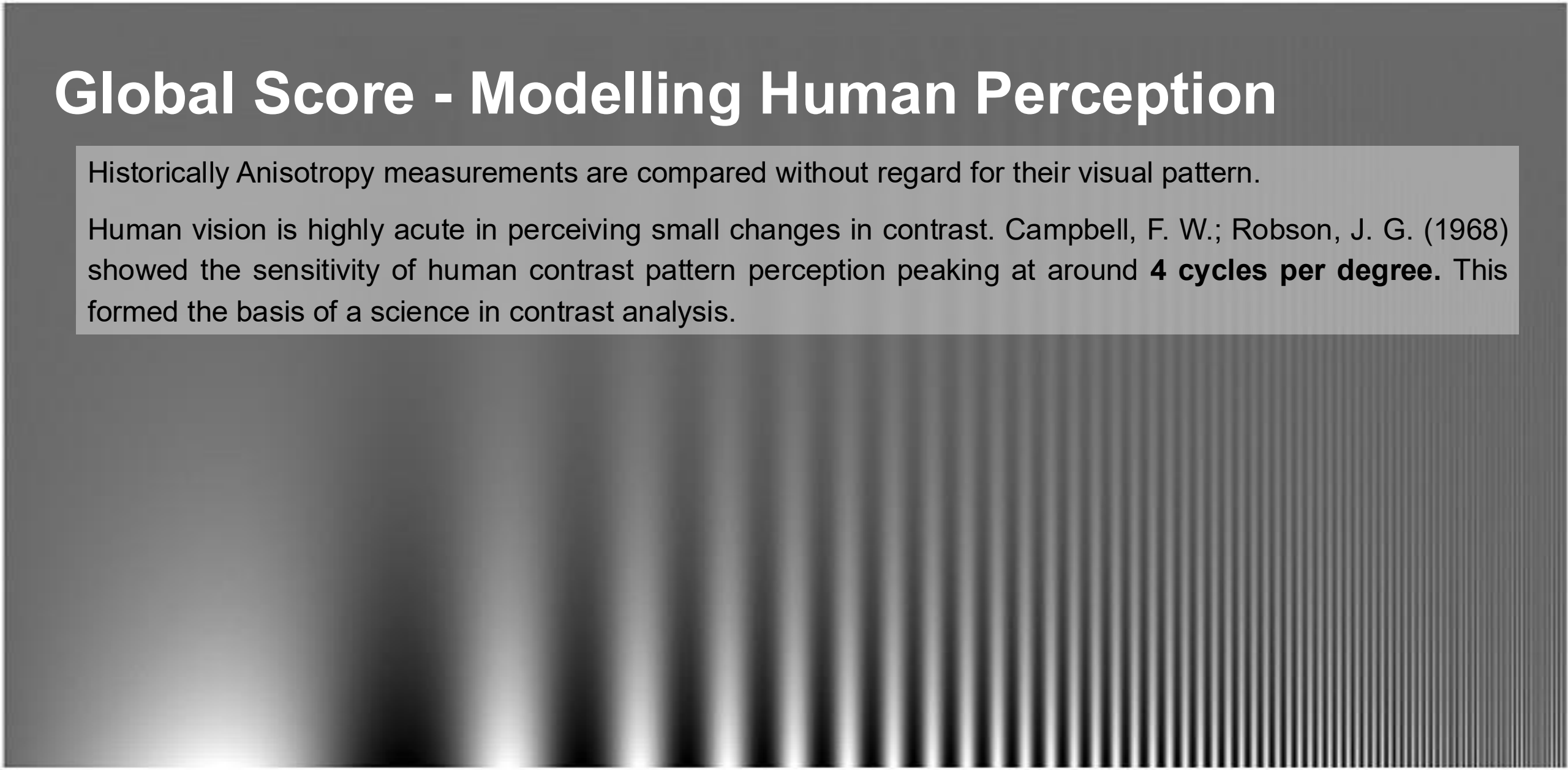
A simulation of how a less reflective coating makes the entire reflected image darker therefore minimizing, but not eliminating, the objectionable visual impact.

Center kink – actual photograph, simulated less reflective coating, and measured part

Global Score - Modelling Human Perception

Historically Anisotropy measurements are compared without regard for their visual pattern.

Human vision is highly acute in perceiving small changes in contrast. Campbell, F. W.; Robson, J. G. (1968) showed the sensitivity of human contrast pattern perception peaking at around **4 cycles per degree.** This formed the basis of a science in contrast analysis.



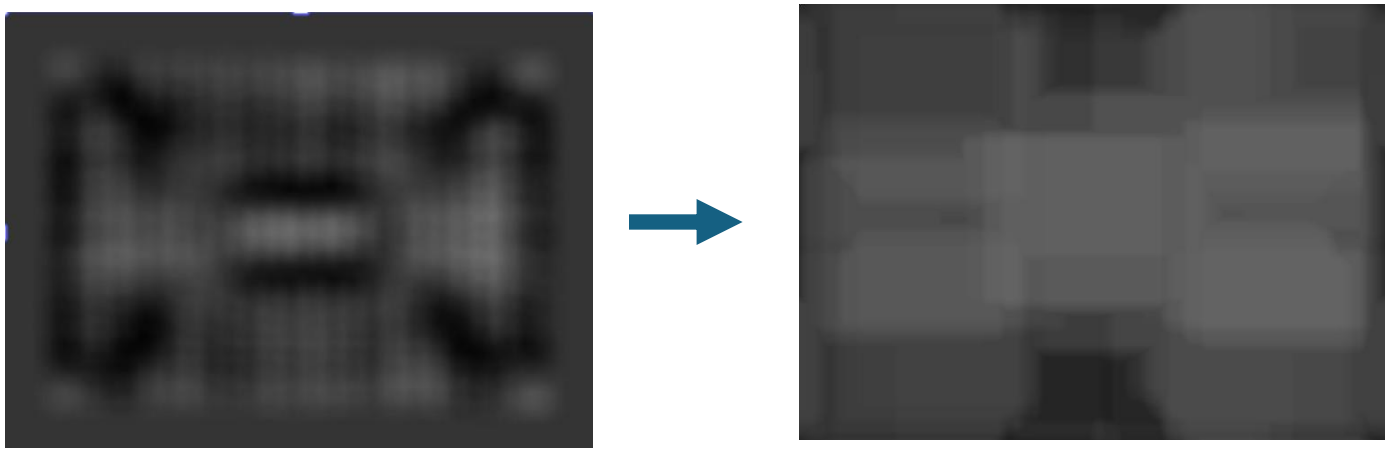
The Campbell–Robson illustration of the spatial frequence/contrast function of the visual system. Sinusoidal density with increasing frequency from left to right and contrast from top to bottom.

Global Score - Modelling Human Perception

Maccariello (2020) presented a method for computing a Global Score of a contrast pattern by analyzing the mean local contrast in anisotropy images. 3 key parameters are used:

- Contrast, linked with the luminance and background
- Size or the spatial frequency of the periodical stimulus
- Observation distance

This is further refined by subsequent local filtering to remove area that are not discernable beyond a defined distance. A high frequency blur shown here.



From: Classification method for quench pattern visibility - Maccariello (2020)

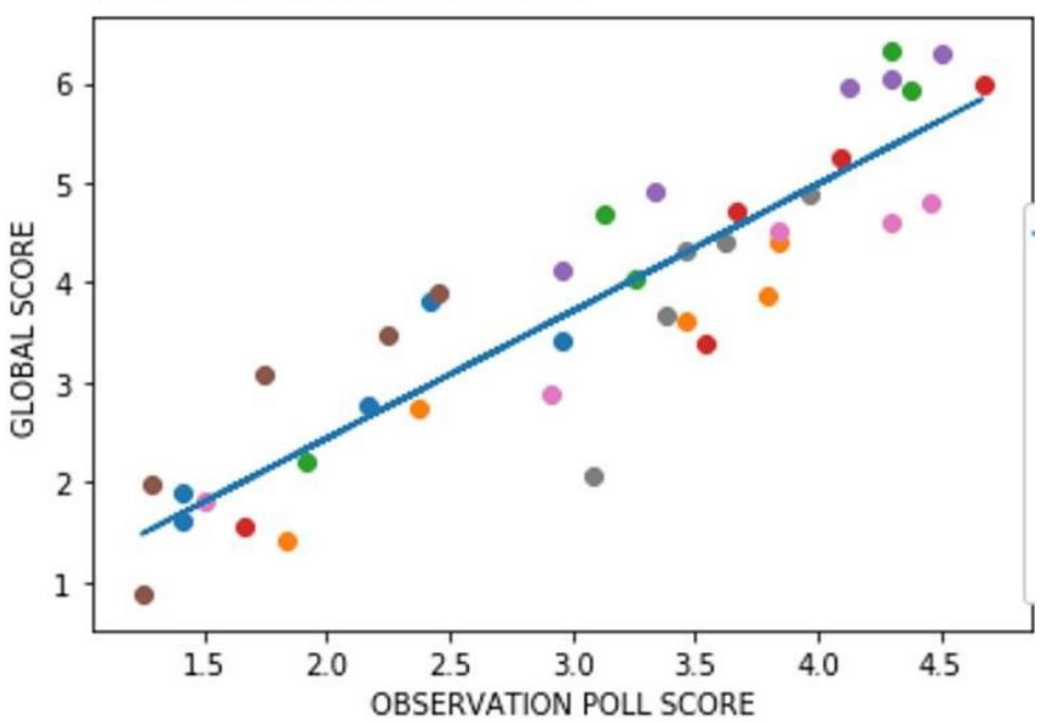
Global Score - Modelling Human Perception

Further psychophysical testing, including multiple human studies with refined protocols showed how subjective analysis supports the objective calculations to an even higher degree.

This figure shows a high positive correlation between a computed Global Score and a human observational score:

Global score parameters: updates from a novel observation poll

E_s	A_s	C_s	α	k_L	k_H	k_C
50	6	170	4	1	2	1



Correlation between a computed and human score – Maccariello (2021)

QC Measurements for Grading Visual Quality

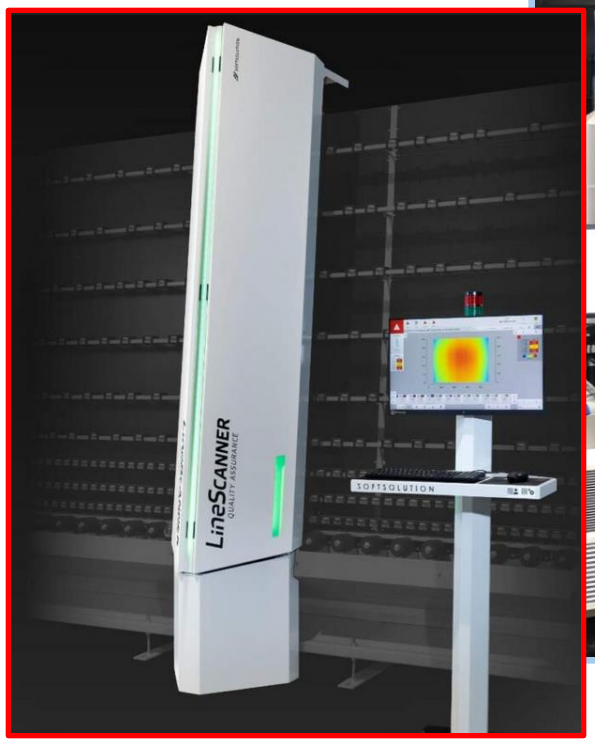
We now have everything necessary for a complete product agnostic grading system using a Global Score.

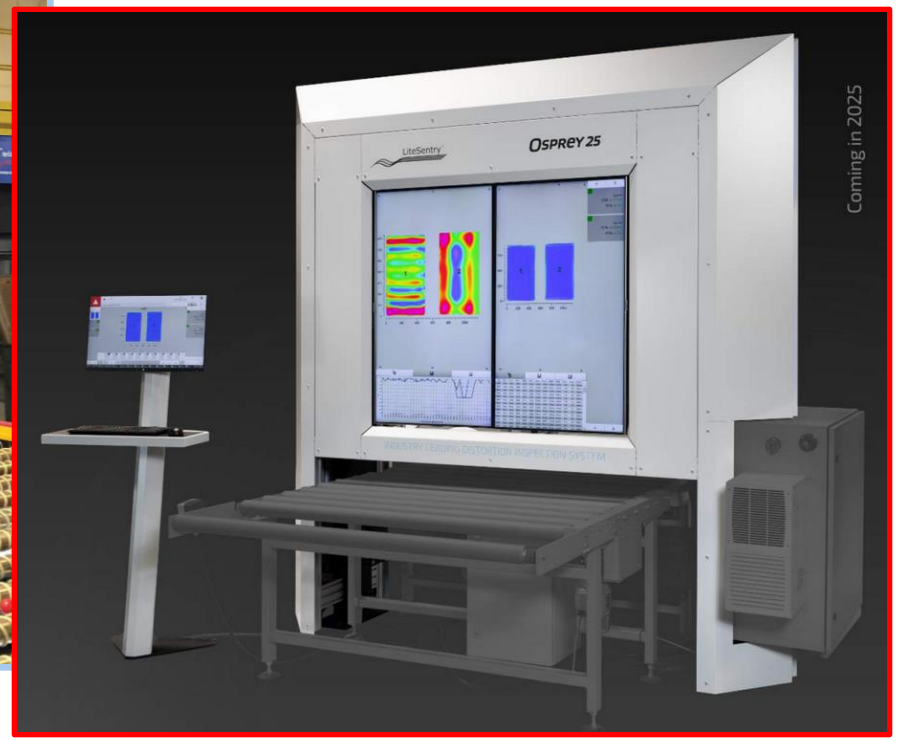
Soon it will be possible for everyone in the process, builders, owners, architects, fabricators, building envelope consultants, etc., to communicate the expectations on the visual quality of their heat-treated coated glass.

The machines to make all the necessary QC measurements are available today..

Implementation Requirements

- Accurate proven real-time 100% measurement with online coating detection.
- Tracking, QC, and reporting tools identify trends in these measurements.
- Tune the process before rejectable products are produced.





Examples of provide ASTM C1901 compliant equipment
LiteSentry Osprey and the Softsolution LineScanner

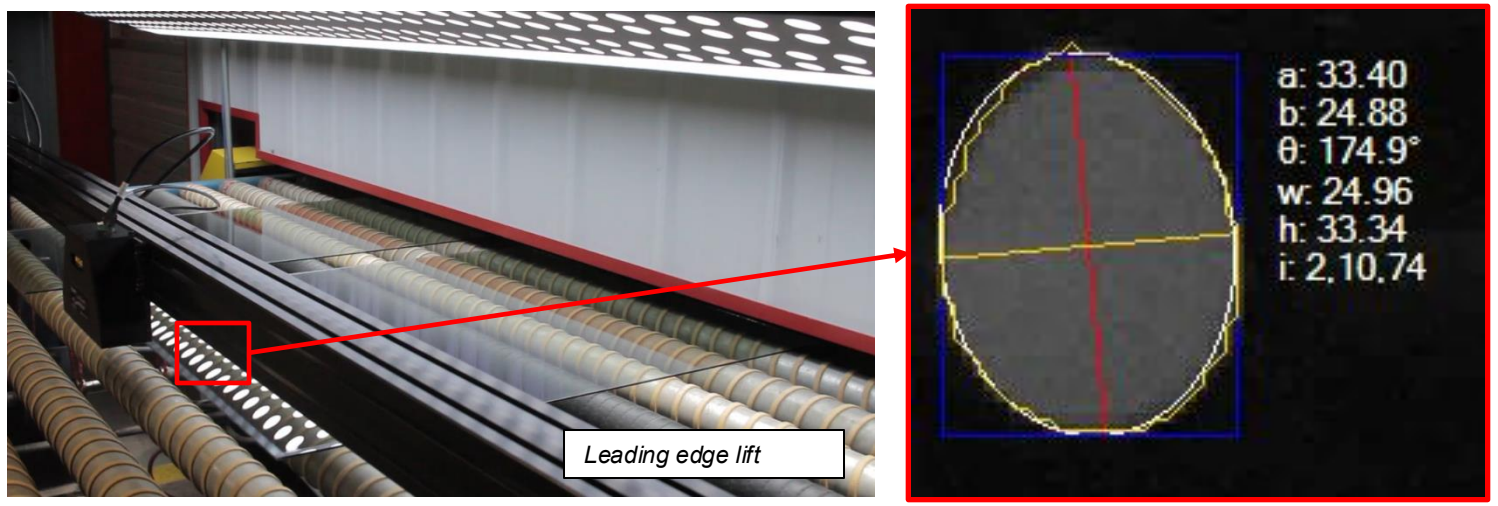
Distortion360™

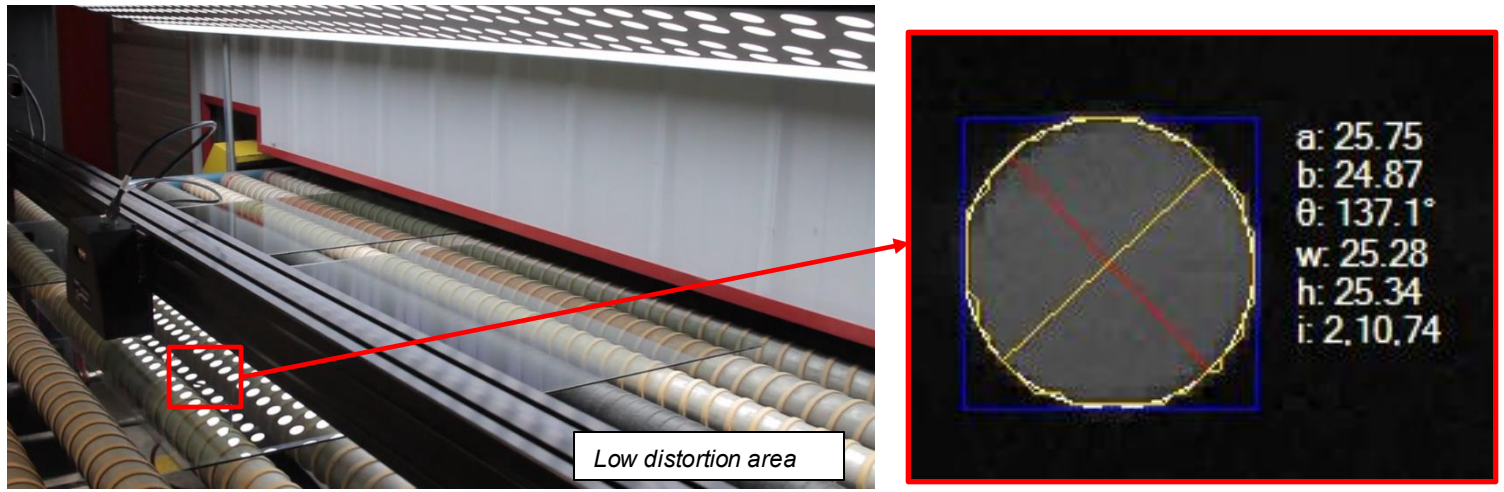
Omnidirectional Optical Power Measurement

Distortion measured in all directions simultaneously.

Intensity and geometry-based analysis provides sub-pixel resolution in multiple dimension.

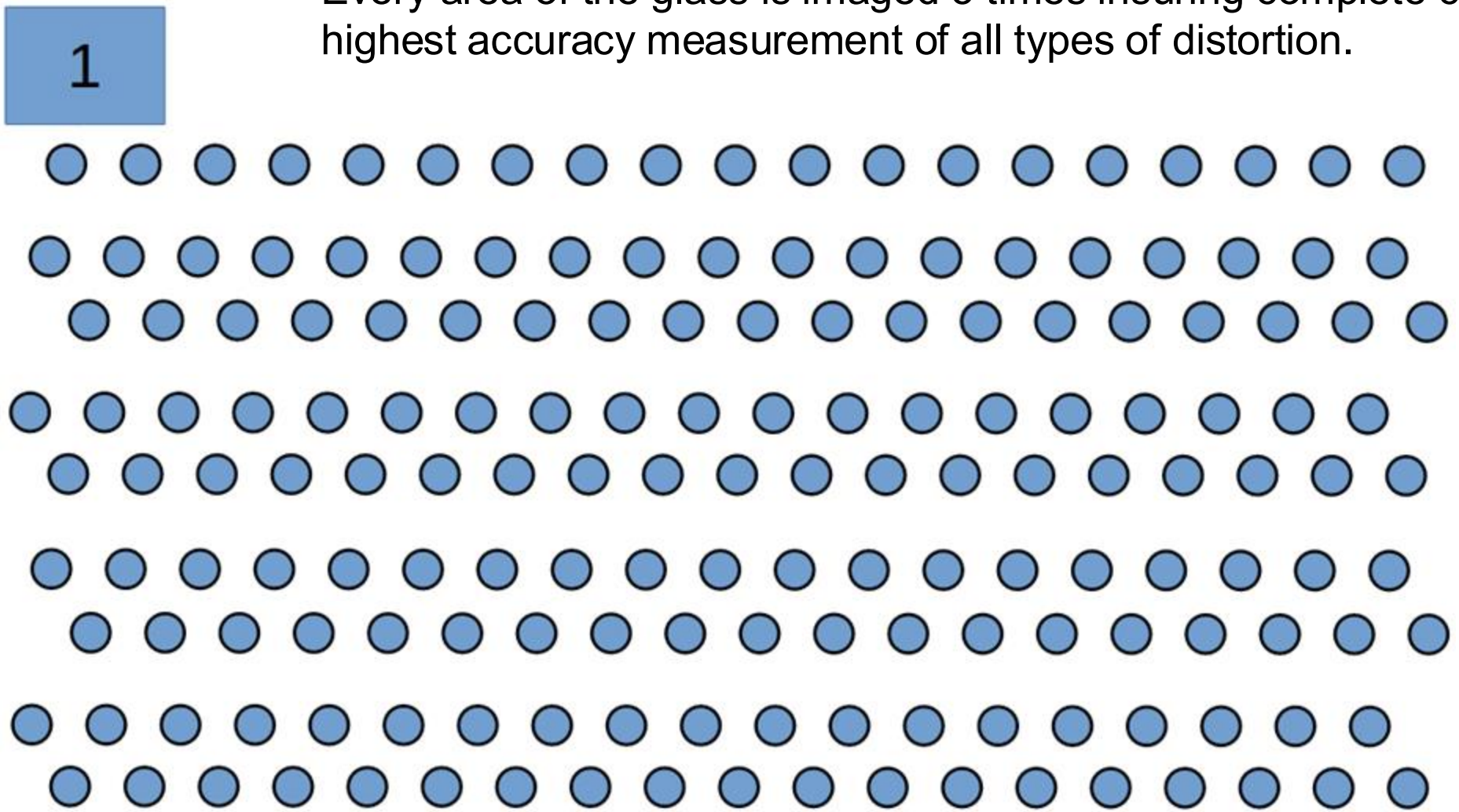
Measurement to all edges.





Dense Coverage Oversampling

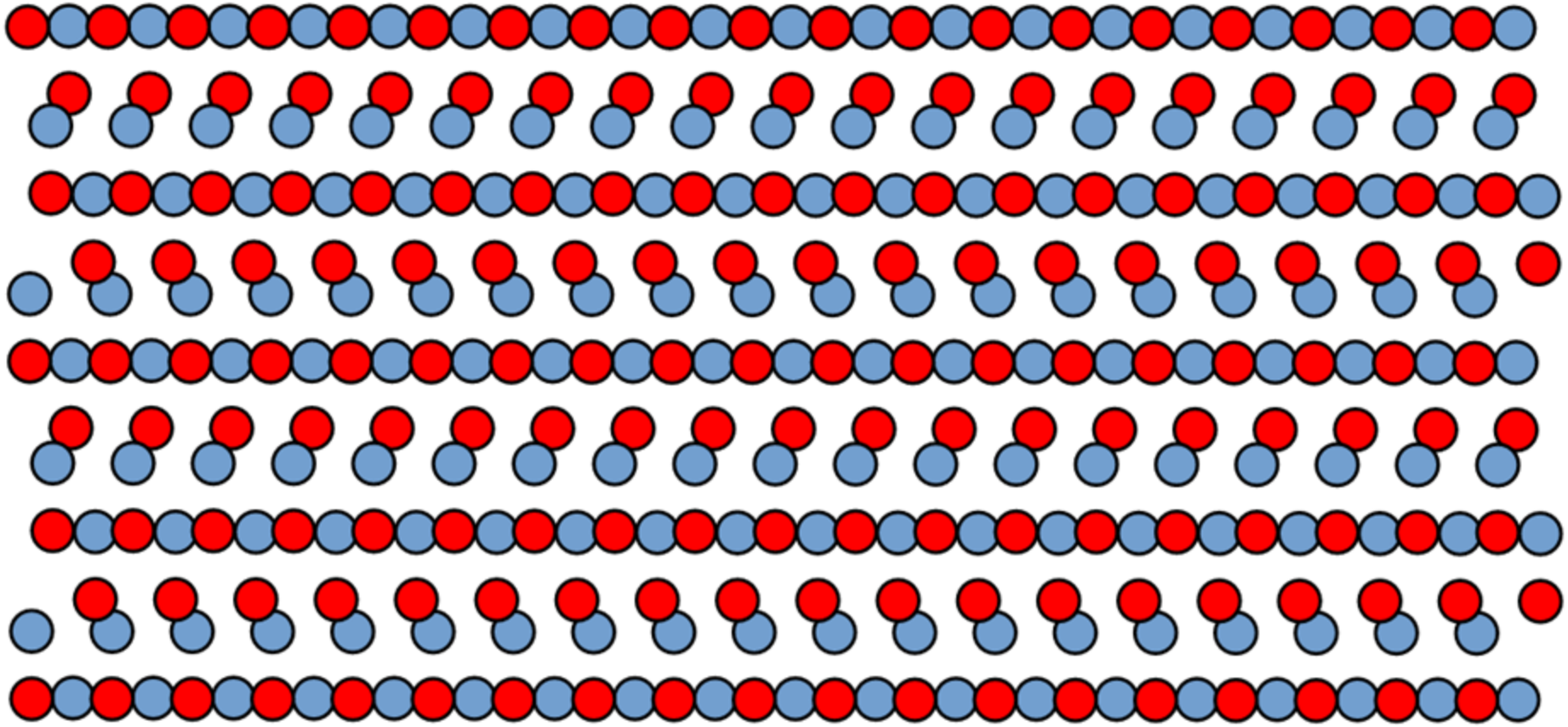
Every area of the glass is imaged 5 times insuring complete coverage and the highest accuracy measurement of all types of distortion.



Dense Coverage Oversampling

2

Every area of the glass is imaged 5 times insuring complete coverage and the highest accuracy measurement of all types of distortion.



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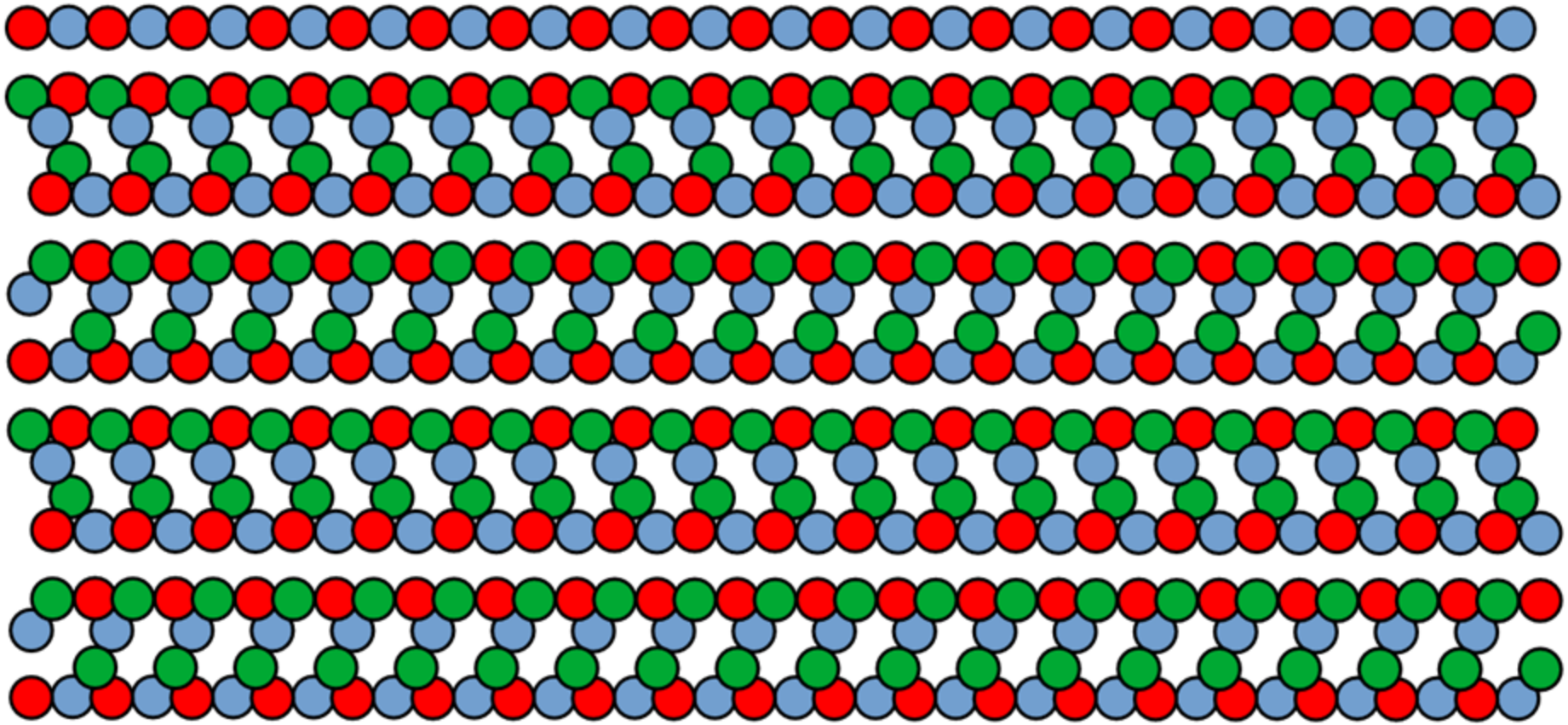
3



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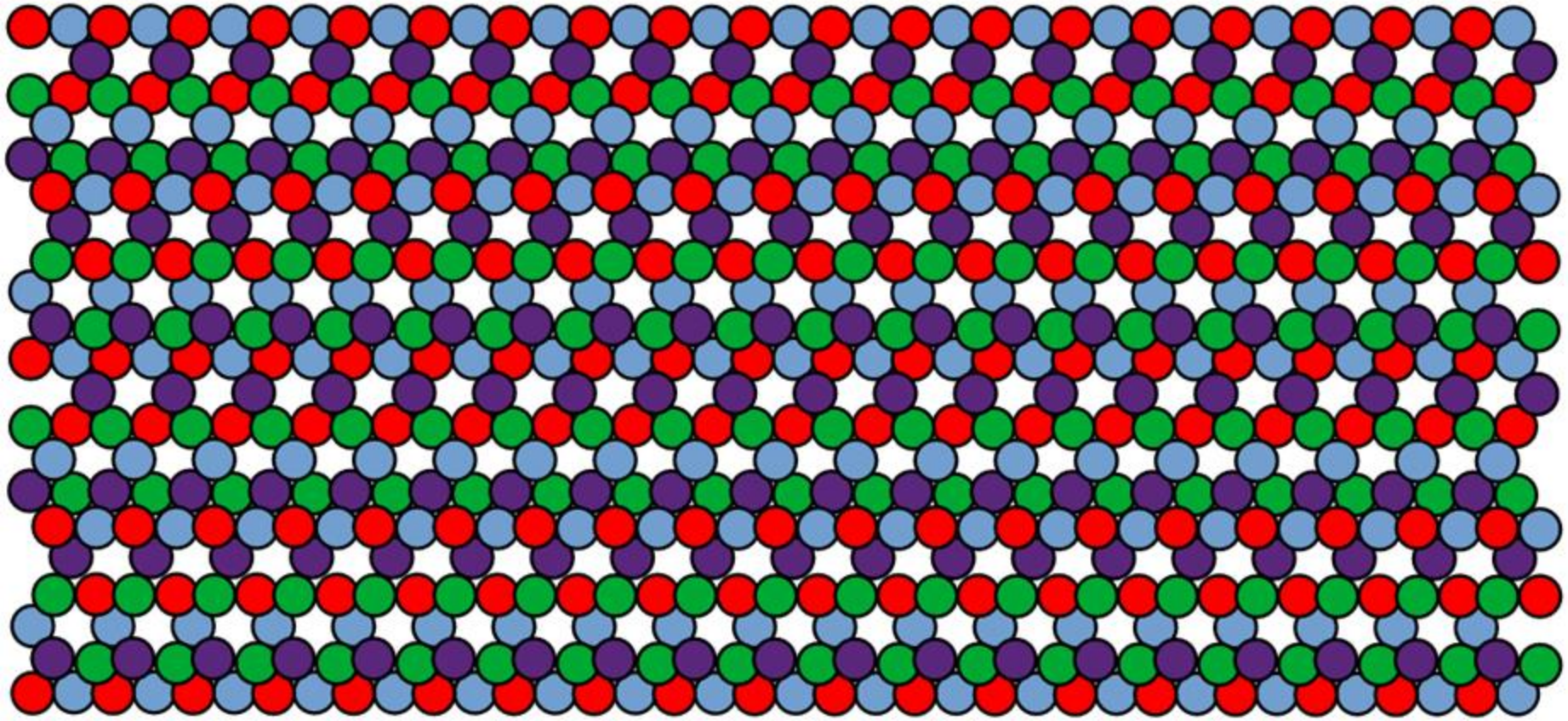
4



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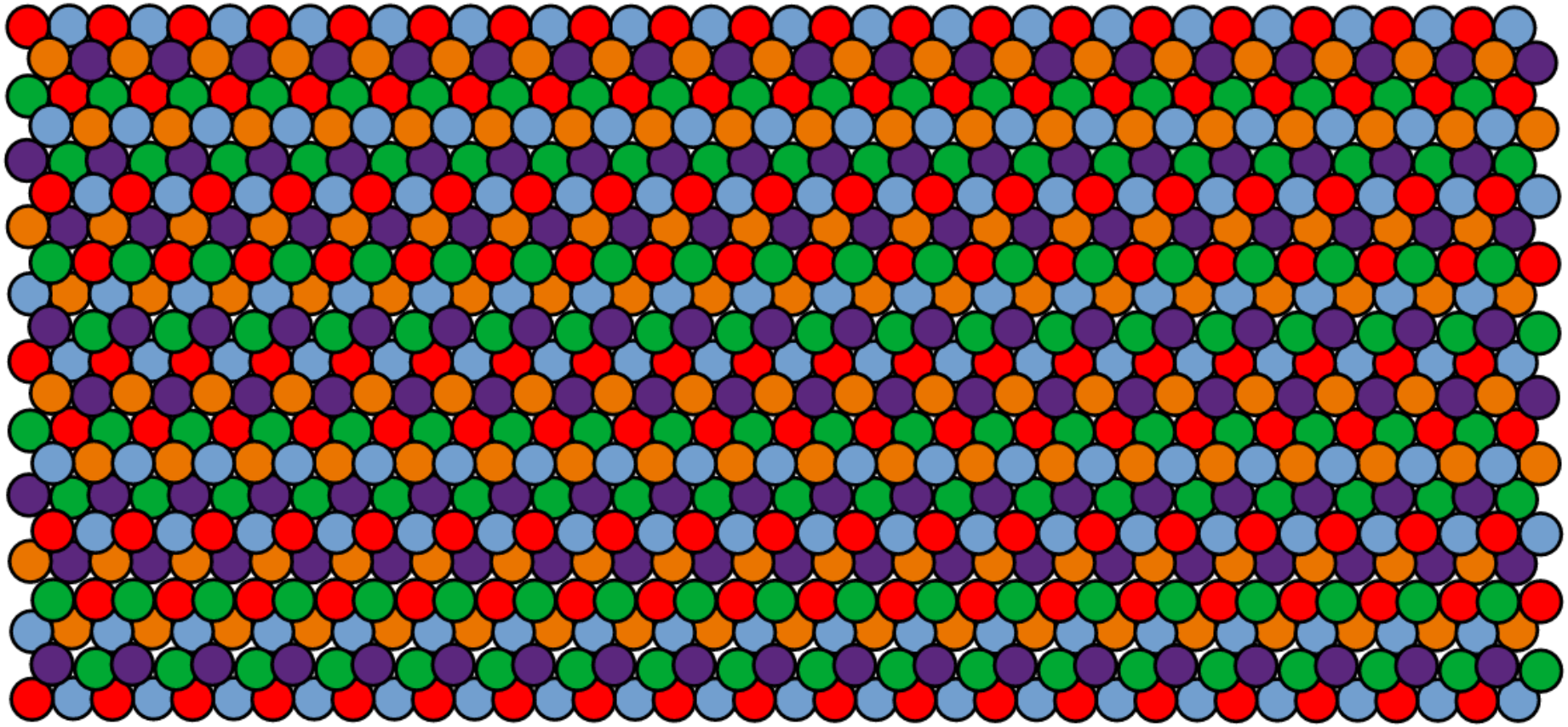
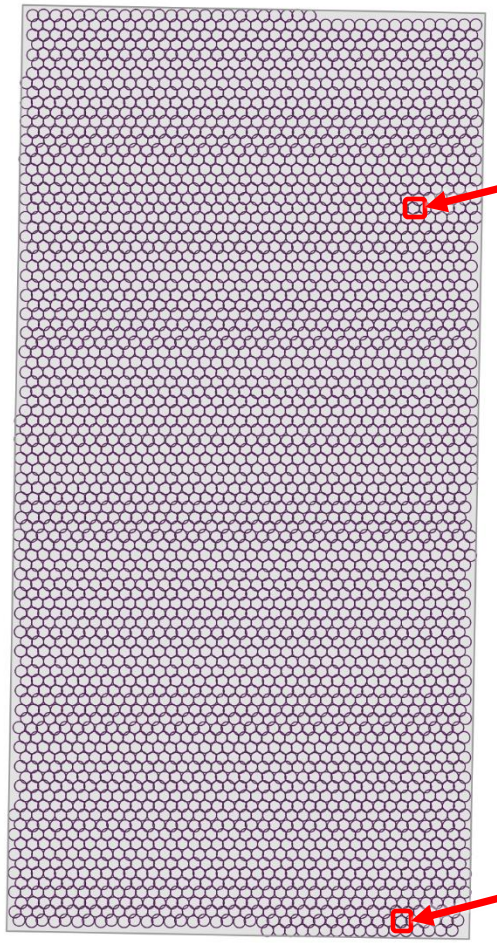
5

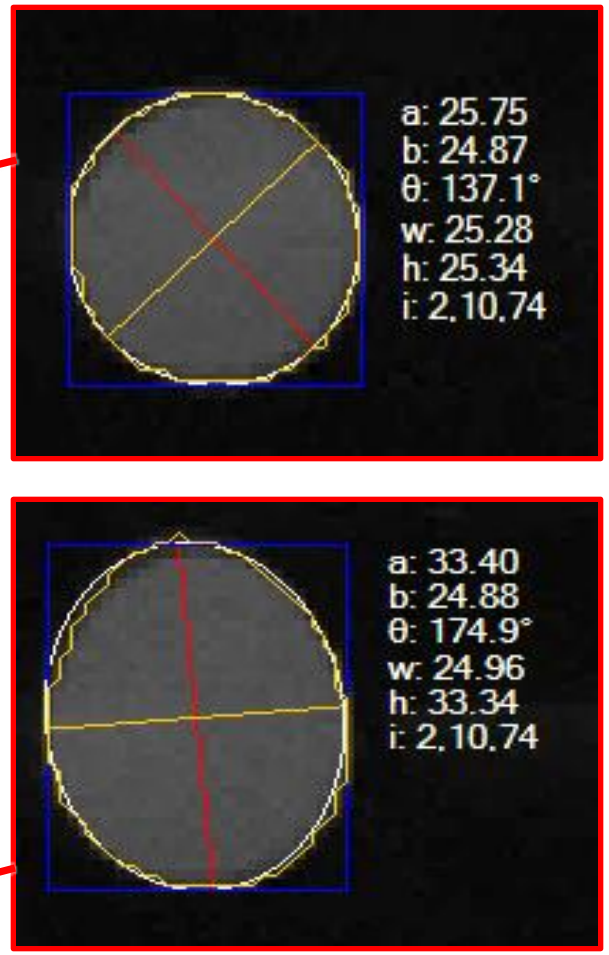


All Edge
(not just lead and trail)



Typical 1m x 2m part

Distortion360 (not limited to 1 dimension)



Actual Distortion360 Screenshots

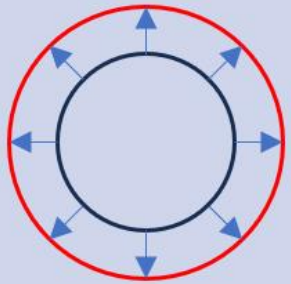
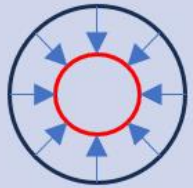
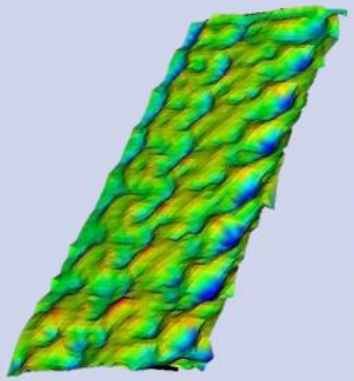
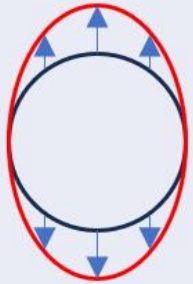
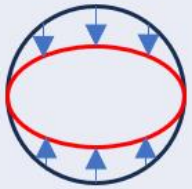
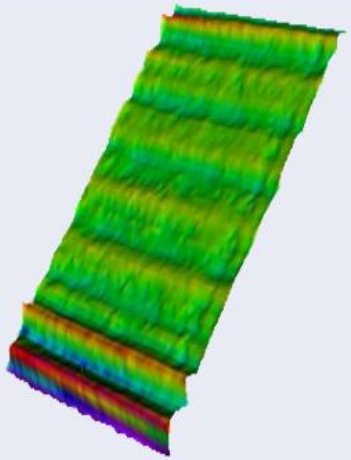
Each part has thousands of *Distortion360* measurements.

Each individual measurement employs intensity and geometry-based analysis to provide sub-pixel resolution distortion measurements in multiple dimension.

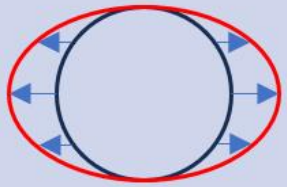
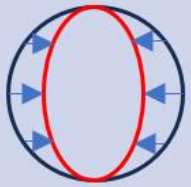
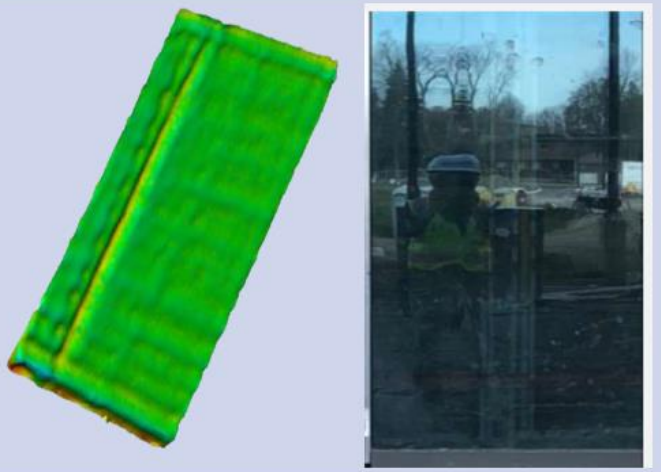
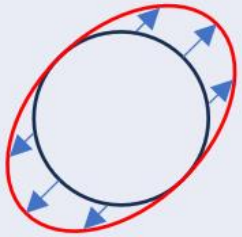
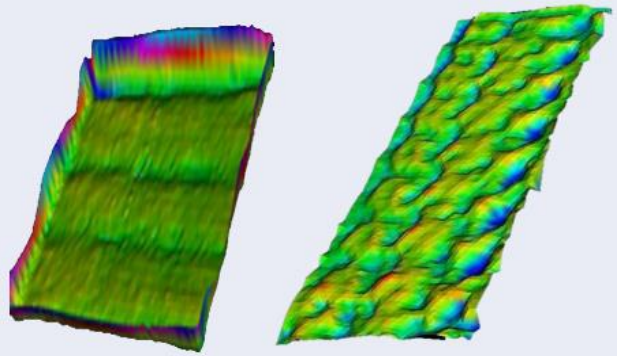
Many distortion types are not measured by classic 1D measurements:

- Center kink
- Corner kink
- Picture frame

Distortion360

Spherical Power is equivalent along all axes – often a component of pocket distortion				
Rollwave Historically measured with 1D flatbottom gauge along travel direction (sole RWE type)				

Distortion360

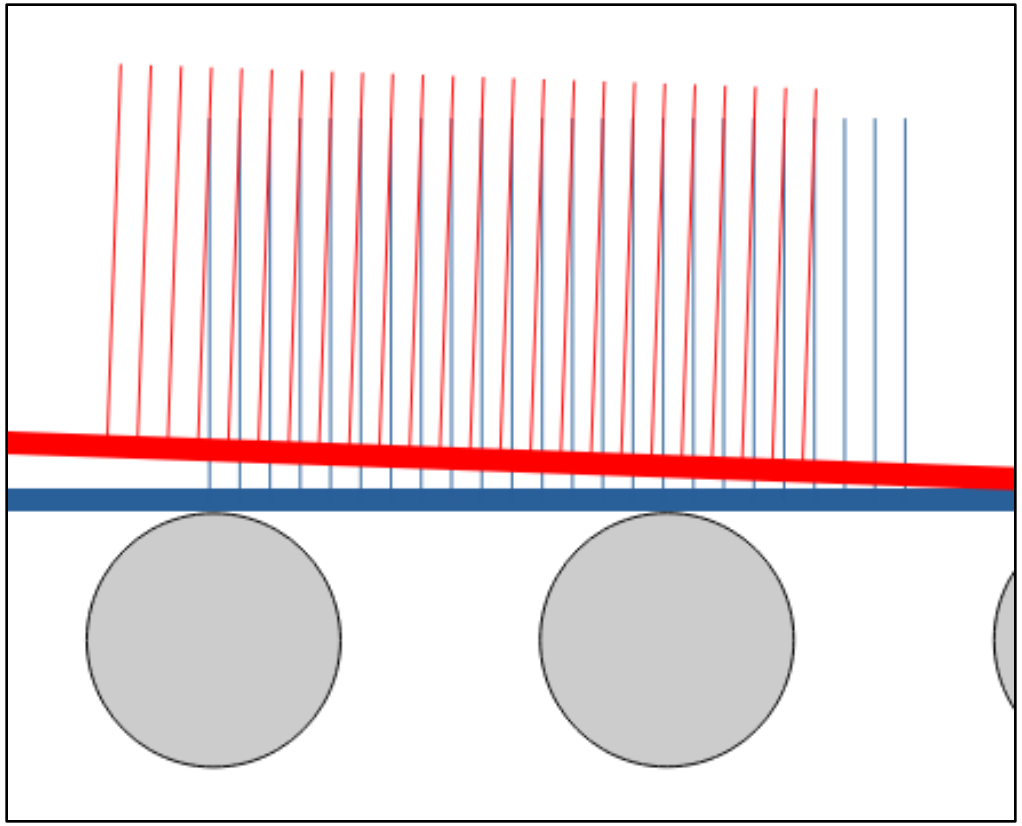
Centerkink aka Cross-conveyor or XmD distortion This is very hard to see with standard zebra board			
Mixed Power varies over all axes – often a component of pocket or picture framing distortion			

Unparalleled Vibration Insensitivity

Fundamental Distortion Measurements acquired in single high-speed 0.5 ms (1/2000 sec) exposure using

High-speed global shutter area scan cameras freeze the motion of the part before any measurements are made.

Linescan camera-based systems must stitch single pixel strips of data captured at different times so they are inherently more susceptible to many conveyor/transport issues including slippage between sections of conveyors (happens often when on separate motor controllers), out of round or out of level rollers, etc…



Online Thickness & Coating Measurement

Coating Information is either:

- Entered Manually
- Supplied from an ERP system
- Detected with online coating sensor

Measures thickness 1-25mm

Discerns coating type (including electrochromic, pyrolytic coatings and more) on front and most back surfaces.

Also discerns tinted glass.

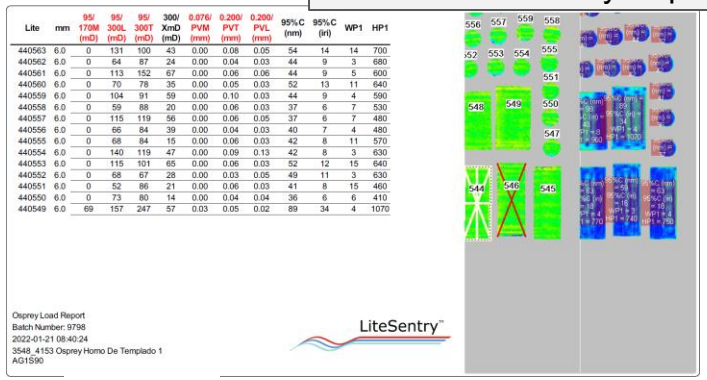
Nothing required below the glass.

Auditability and Sharing Results

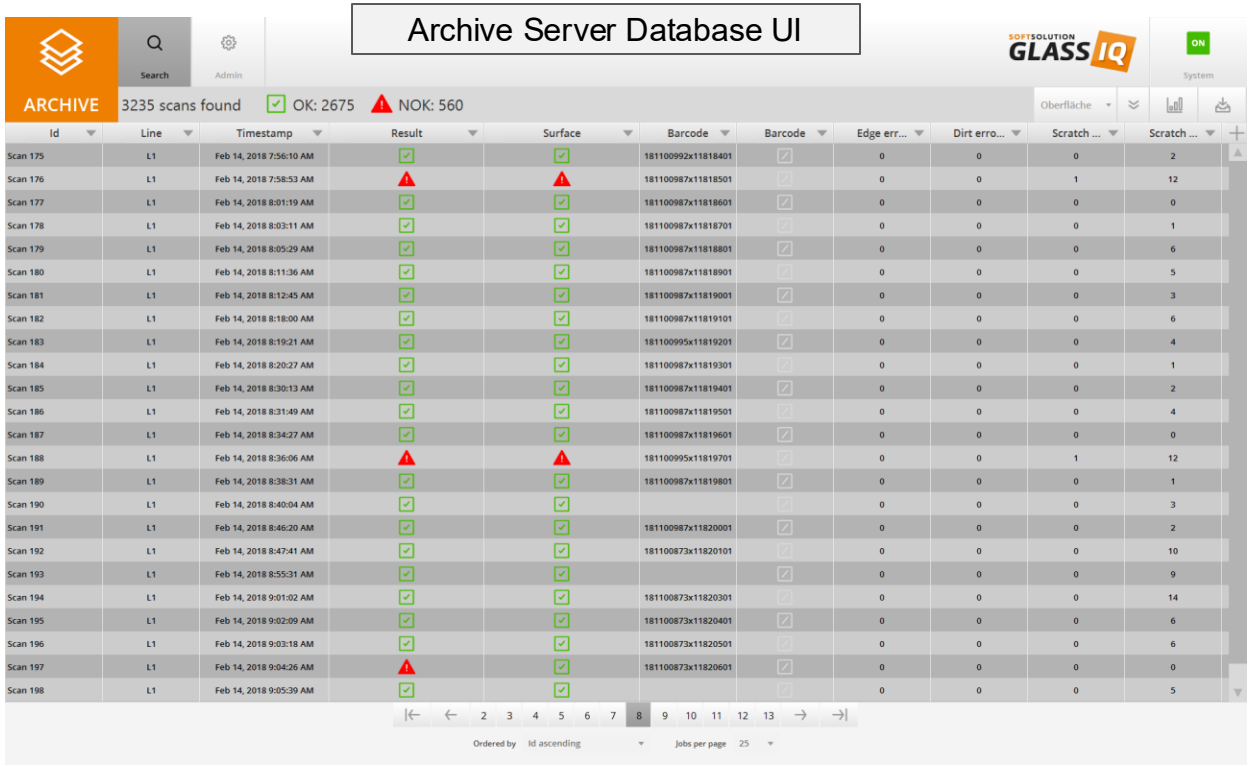
Data Can be shared with customers in a variety of ways:

- Archive relational databases with GUI frontend
- Flat databases (CSV or spreadsheets)
- Load summary reports
- Redistributable interactive viewers

PDF Load Summary Report

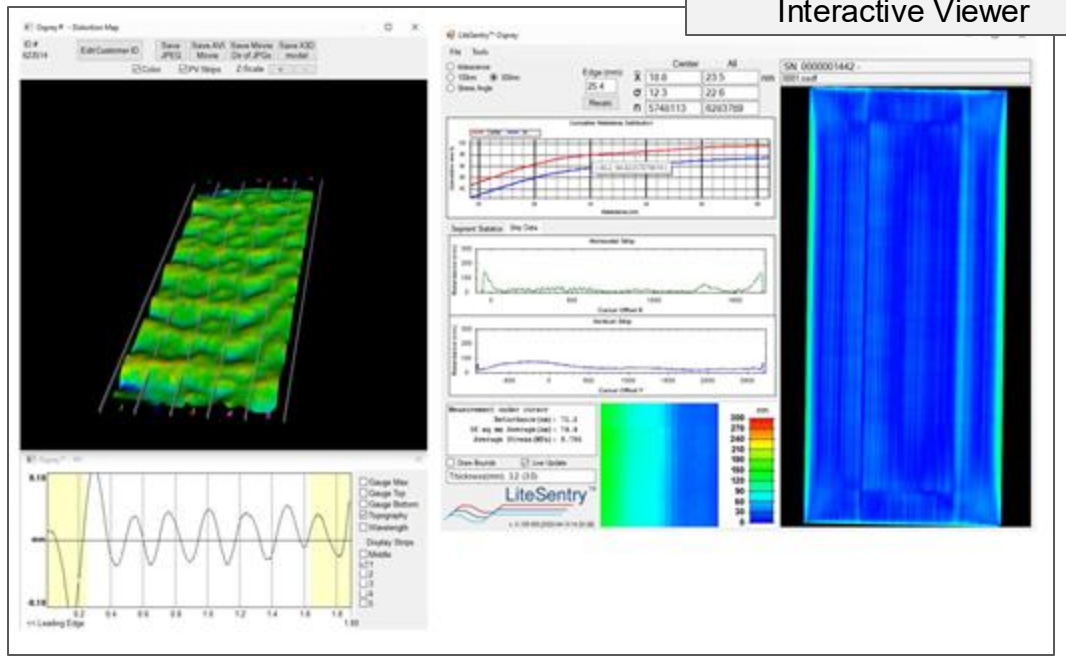


Archive Server Database UI



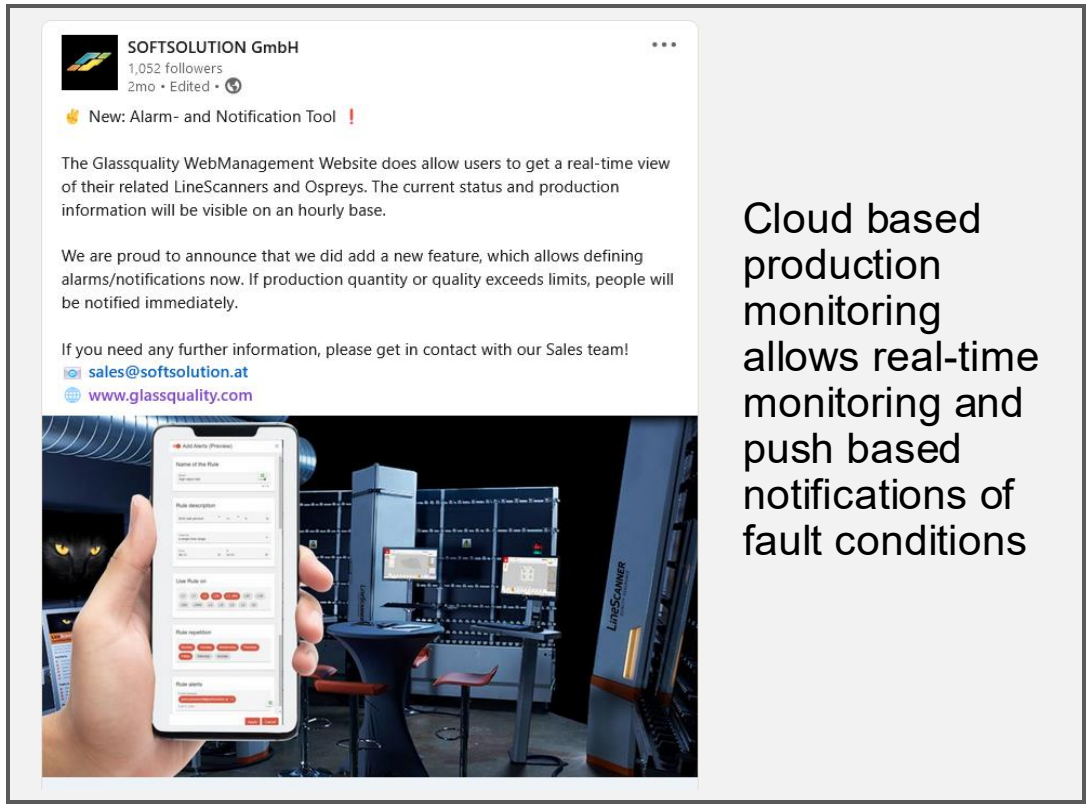
Id	Line	Timestamp	Result	Surface	Barcode	Barcode	Edge err...	Dirt erro...	Scratch ...	Scratch ...
Scan 175	L1	Feb 14, 2018 7:56:10 AM	✓	✓	181100992x11818401		0	0	0	2
Scan 176	L1	Feb 14, 2018 7:58:53 AM	!	!	181100987x11818501		0	0	1	12
Scan 177	L1	Feb 14, 2018 8:01:19 AM	✓	✓	181100987x11818601		0	0	0	0
Scan 178	L1	Feb 14, 2018 8:03:11 AM	✓	✓	181100987x11818701		0	0	0	1
Scan 179	L1	Feb 14, 2018 8:05:29 AM	✓	✓	181100987x11818801		0	0	0	6
Scan 180	L1	Feb 14, 2018 8:11:36 AM	✓	✓	181100987x11818901		0	0	0	5
Scan 181	L1	Feb 14, 2018 8:12:45 AM	✓	✓	181100987x11819001		0	0	0	3
Scan 182	L1	Feb 14, 2018 8:18:00 AM	✓	✓	181100987x11819101		0	0	0	6
Scan 183	L1	Feb 14, 2018 8:19:21 AM	✓	✓	181100995x11819201		0	0	0	4
Scan 184	L1	Feb 14, 2018 8:20:27 AM	✓	✓	181100987x11819301		0	0	0	1
Scan 185	L1	Feb 14, 2018 8:30:13 AM	✓	✓	181100987x11819401		0	0	0	2
Scan 186	L1	Feb 14, 2018 8:31:49 AM	✓	✓	181100987x11819501		0	0	0	4
Scan 187	L1	Feb 14, 2018 8:34:27 AM	✓	✓	181100987x11819601		0	0	0	0
Scan 188	L1	Feb 14, 2018 8:36:06 AM	!	!	181100995x11819701		0	0	1	12
Scan 189	L1	Feb 14, 2018 8:38:31 AM	✓	✓	181100987x11819801		0	0	0	1
Scan 190	L1	Feb 14, 2018 8:40:04 AM	✓	✓			0	0	0	3
Scan 191	L1	Feb 14, 2018 8:46:20 AM	✓	✓	181100987x11820001		0	0	0	2
Scan 192	L1	Feb 14, 2018 8:47:41 AM	✓	✓	181100873x11820101		0	0	0	10
Scan 193	L1	Feb 14, 2018 8:55:31 AM	✓	✓			0	0	0	9
Scan 194	L1	Feb 14, 2018 9:01:02 AM	✓	✓	181100873x11820301		0	0	0	14
Scan 195	L1	Feb 14, 2018 9:02:09 AM	✓	✓	181100873x11820401		0	0	0	6
Scan 196	L1	Feb 14, 2018 9:03:18 AM	✓	✓	181100873x11820501		0	0	0	6
Scan 197	L1	Feb 14, 2018 9:04:26 AM	!	✓	181100873x11820601		0	0	0	0
Scan 198	L1	Feb 14, 2018 9:05:39 AM	✓	✓			0	0	0	5

Interactive Viewer

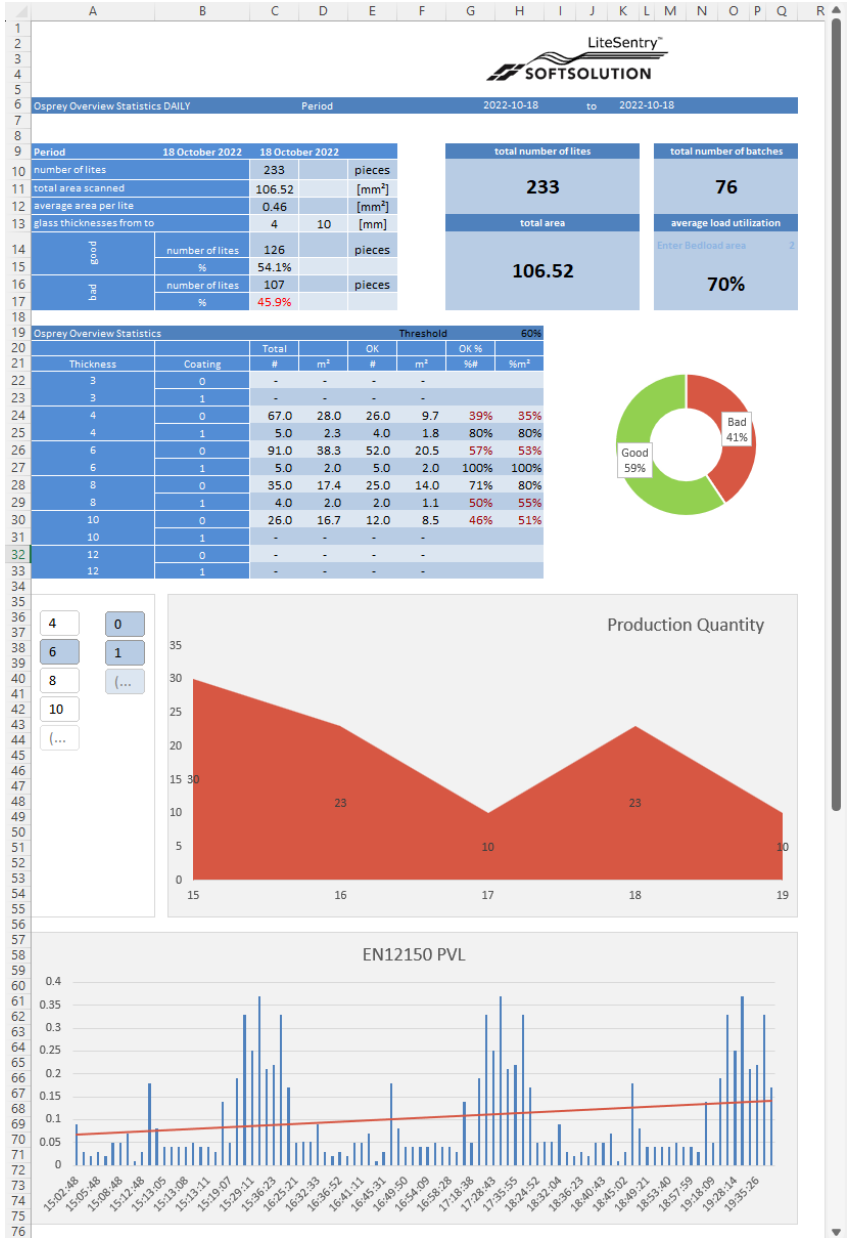


Automated Reports and Alarms

Smart production reports are automatically sent every shift / day / month -- show specific production, quality, bed utilization etc. The smart reports allow to quickly drill down to filter results based on specific coating and thickness to isolate and identify trends.



Cloud based production monitoring allows real-time monitoring and push based notifications of fault conditions



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Setting the Standard in Glass Inspection

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Strainoptics