TEMPERED GLASS – The Risks and How to Avoid Them

AG-0003 / 05

AGNORA

WHO WE ARE

AGNORA is an award-winning glass fabricator providing the largest, high-quality architectural glass in North America.

Known as an industry leading, team-based customer service company, AGNORA employs innovative production processes and invests in leading-edge machinery to push the boundaries of what is possible in architectural glass fabrication and meet challenging design objectives brought by their customers.

Louis Moreau
Head of Technology and Innovation, AGNORA

Louis brings a unique mix of international experiences in float manufacturing, high-performance vacuum coatings, large building glazing, and high-end glass fabrication.

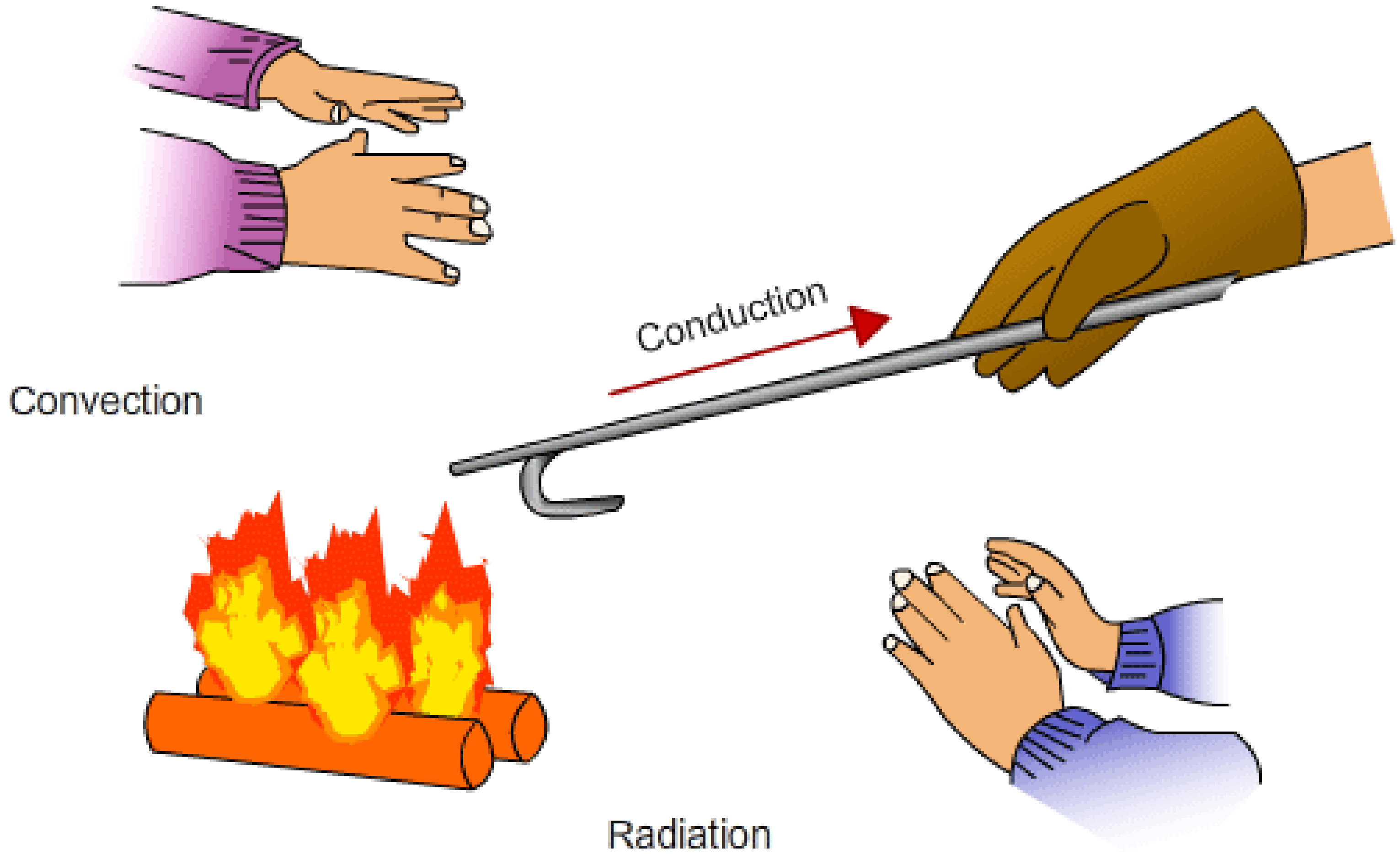
Louis considers architecture as the purest form of art and loves glass. He explores the limits of materials and processes to create innovative solutions that can be easily built.

Adam Mitchell
Marketing Manager, AGNORA

Adam is a marketing professional focused on the manufacturing sector for over 10 years. He has a strong focus on building relationships and delivering value added content that support evolving partnerships.

Optical Distortion

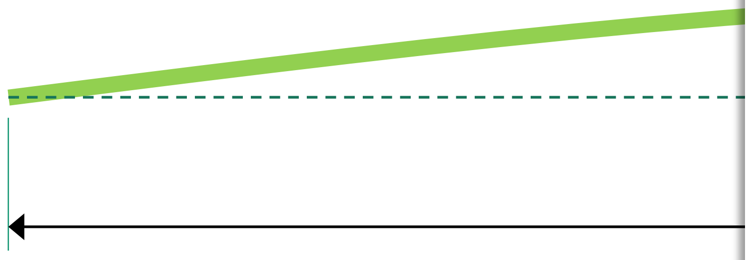
Convection, Conduction and Radiation



- Heat Distribution
  - Left ⇔ Right
  - Front ⇔ Back
  - Top ⇳ Bottom
- Also in Cooling!
- Amount of material
- Speed

- Good craftmanship avoids
  - Distortion
  - Edge Lift
  - Anisotropy
  - Overall bow
  - Pitting

Overall Bow



C1048 – 18

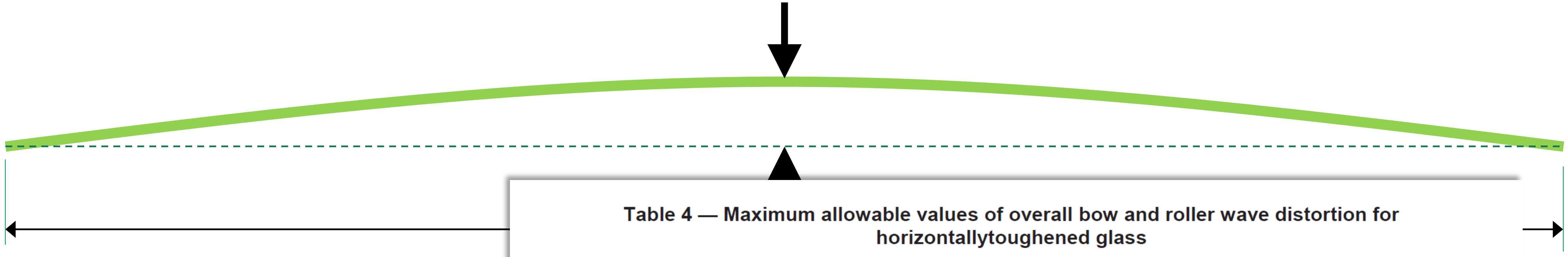
TABLE 2 Overall Bow, Maximum

Nominal Thickness Desig., mm (in.)	Edge Dimension, cm (in.)											
	0–50 (0–20)	>50–90 (>20–35)	>90–120 (>35–47)	>120–150 (>47–59)	>150–180 (>59–71)	>180–210 (>71–83)	>210–240 (>83–94)	>240–270 (>94–106)	>270–300 (>106–118)	>300–330 (>118–130)	>330–370 (>130–146)	>370–400 (>146–158)
	Maximum Bow, mm (in.)											
3 (1⁄8)	3.0 (0.12)	4.0 (0.16)	5.0 (0.20)	7.0 (0.28)	9.0 (0.35)	12.0 (0.47)	14.0 (0.55)	17.0 (0.67)	19.0 (0.75)	. . .	. . .	. . .
3 (1⁄8) Alternate Method[A]	2.0 (0.08)	2.0 (0.08)	2.0 (0.08)	3.0 (0.12)	5.0 (0.20)	6.0 (0.24)	7.0 (0.28)	8.0 (0.31)	10.0 (0.39)	. . .	. . .	. . .
4 (5⁄32)	3.0 (0.12)	4.0 (0.16)	5.0 (0.20)	7.0 (0.28)	9.0 (0.35)	12.0 (0.47)	14.0 (0.55)	17.0 (0.67)	19.0 (0.75)	. . .	. . .	. . .
5 (3⁄16)	3.0 (0.12)	4.0 (0.16)	5.0 (0.20)	7.0 (0.28)	9.0 (0.35)	12.0 (0.47)	14.0 (0.55)	17.0 (0.67)	19.0 (0.75)	. . .	. . .	. . .
6 (1⁄4)	2.0 (0.08)	3.0 (0.12)	4.0 (0.16)	5.0 (0.20)	7.0 (0.28)	9.0 (0.35)	12.0 (0.47)	14.0 (0.55)	17.0 (0.67)	19.0 (0.75)	21.0 (0.83)	24.0 (0.94)
8 (5⁄16)	2.0 (0.08)	2.0 (0.08)	3.0 (0.12)	4.0 (0.16)	5.0 (0.20)	6.0 (0.24)	8.0 (0.31)	10.0 (0.39)	13.0 (0.51)	15.0 (0.59)	18.0 (0.71)	20.0 (0.79)
10 (3⁄8)	2.0 (0.08)	2.0 (0.08)	2.0 (0.08)	4.0 (0.16)	5.0 (0.20)	6.0 (0.24)	7.0 (0.28)	9.0 (0.35)	12.0 (0.47)	14.0 (0.55)	17.0 (0.67)	19.0 (0.75)
12–22 (1⁄2 –7⁄8)	1.0 (0.04)	2.0 (0.08)	2.0 (0.08)	2.0 (0.08)	4.0 (0.16)	5.0 (0.20)	5.0 (0.20)	7.0 (0.28)	10.0 (0.39)	12.0 (0.47)	14.0 (0.55)	17.0 (0.67)

[A] Values apply to 3 mm (1⁄8 in.) thickness only when the alternative checking procedure in 10.7.2 is used.

- Important for two-side s
- Will likely be flatten on f
- Limits established in bot

Overall Bow

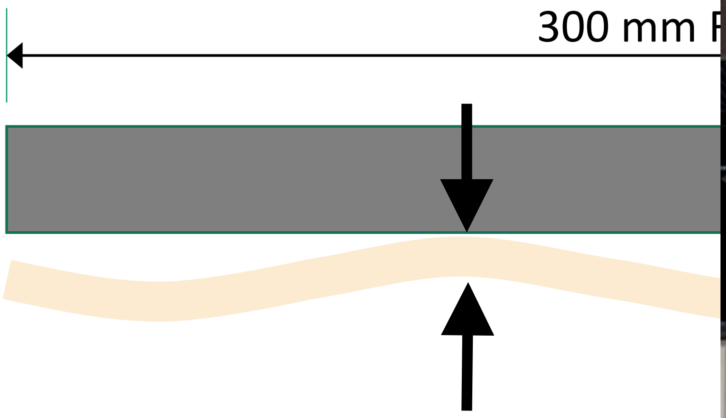


- Important for two-side sup
- Will likely be flatten on fou
- Limits established in both

Table 4 — Maximum allowable values of overall bow and roller wave distortion for horizontallytoughened glass

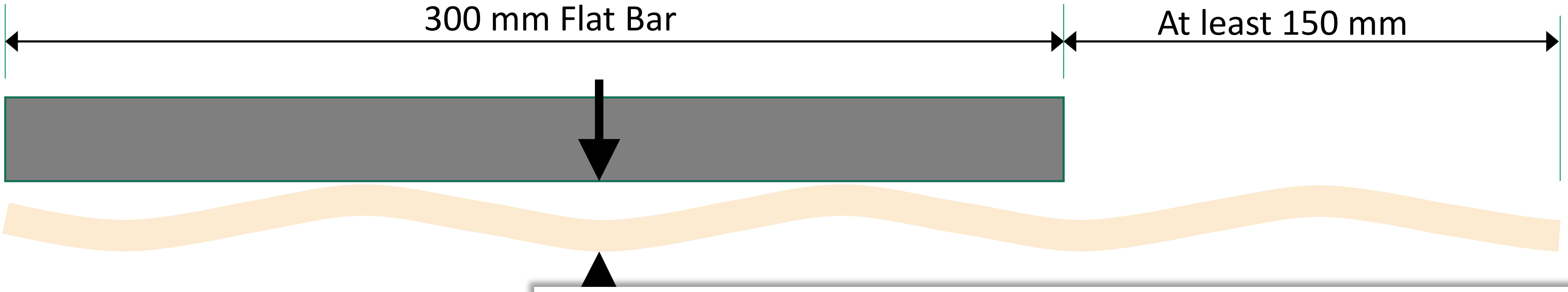
Glass Type	**Maximum allowable value for distortion**	
	Overall bow mm / m	**Roller Wave** mm
Uncoated float glass in accordance with EN 572-1 and EN 572-2	3,0	0,3
Others [a]	4,0	0,5
[a] For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.		
NOTE Dependant upon the wave length of the roller wave an appropriate length of gauge has to be used		

Roller wave



- External reflection is not pleasant
  - To minimize keep horizontal

Roller wave

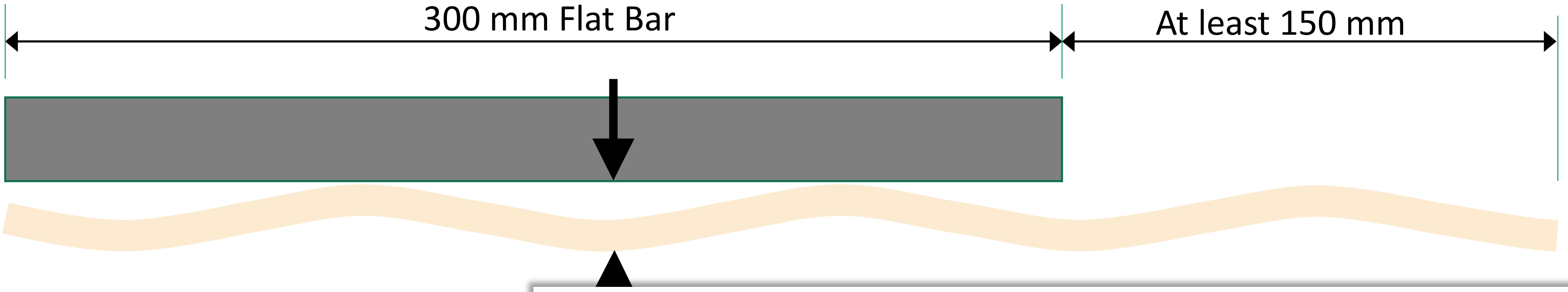


- External reflection is not pleasant
  - To minimize keep horizontal
- If vertical will be noticeable also fr
- Limits established only in EN stand

Table 4 — Maximum allowable values of overall bow and roller wave distortion for horizontallytoughened glass

Glass Type	Maximum allowable value for distortion	
	Overall bow mm / m	Roller Wave mm
Uncoated float glass in accordance with EN 572-1 and EN 572-2	3,0	0,3
Others [a]	4,0	0,5
[a] For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.		
NOTE Dependant upon the wave length of the roller wave an appropriate length of gauge has to be used		

Roller wave



- External reflection is not pleasant
  - To minimize keep horizontal
- If vertical will be noticeable also fr
- Limits established only in EN stand

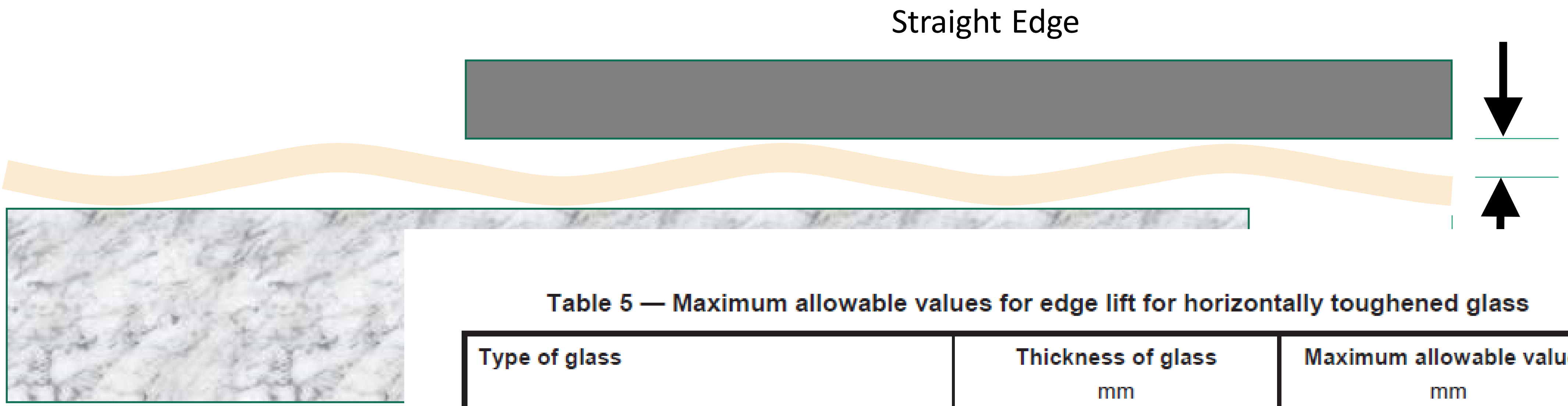
Table 4 — Maximum allowable values of overall bow and roller wave distortion for horizontallytoughened glass

Glass Type	Maximum allowable value for distortion	
	Overall bow mm / m	Roller Wave mm
Uncoated float glass in accordance with EN 572-1 and EN 572-2	3,0	0,3
Others [a]	4,0	0,5

[a] For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.

NOTE Dependant upon the wave length of the roller wave an appropriate length of gauge has to be used

Edge Kink / Lift

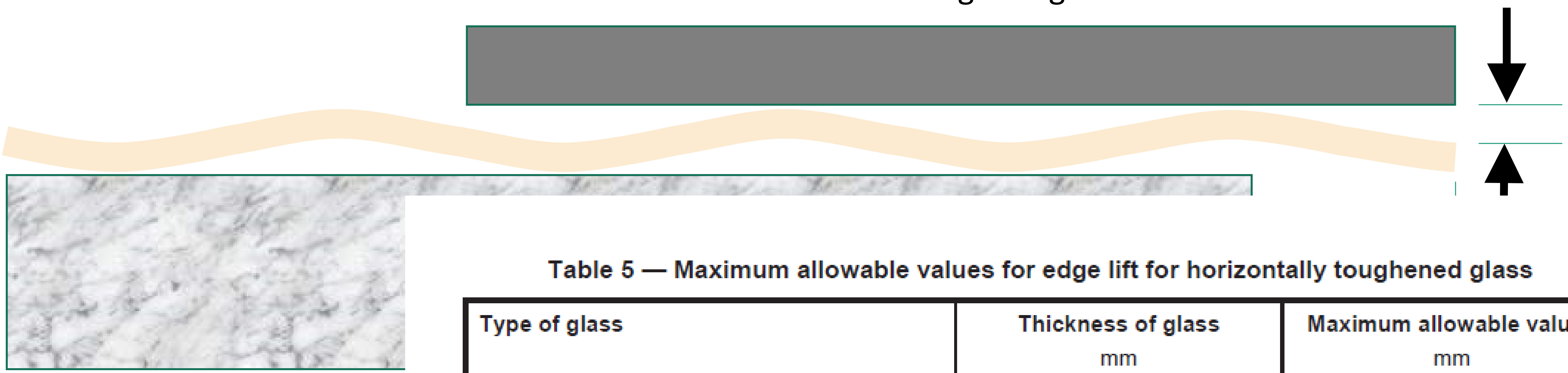


- First and last wave on the l
- Usually larger value than ro
- Because it is stronger, ofte
- In heat treated laminate ca
- Limits established only in E

Table 5 — Maximum allowable values for edge lift for horizontally toughened glass

Type of glass	Thickness of glass mm	Maximum allowable values mm
Uncoated float glass in accordance with EN 572-1 and EN 572-2	3	0,5
	4 to 5	0,4
	6 to 25	0,3
Others [a]	all	0,5
[a] For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.		
NOTE Dependant upon the wave length of the roller wave an appropriate length of gauge has to be used		

Edge Kink / Lift



- First and last wave on the l
- Usually larger value than ro
- Because it is stronger, ofte
- In heat treated laminate ca
- Limits established only in E

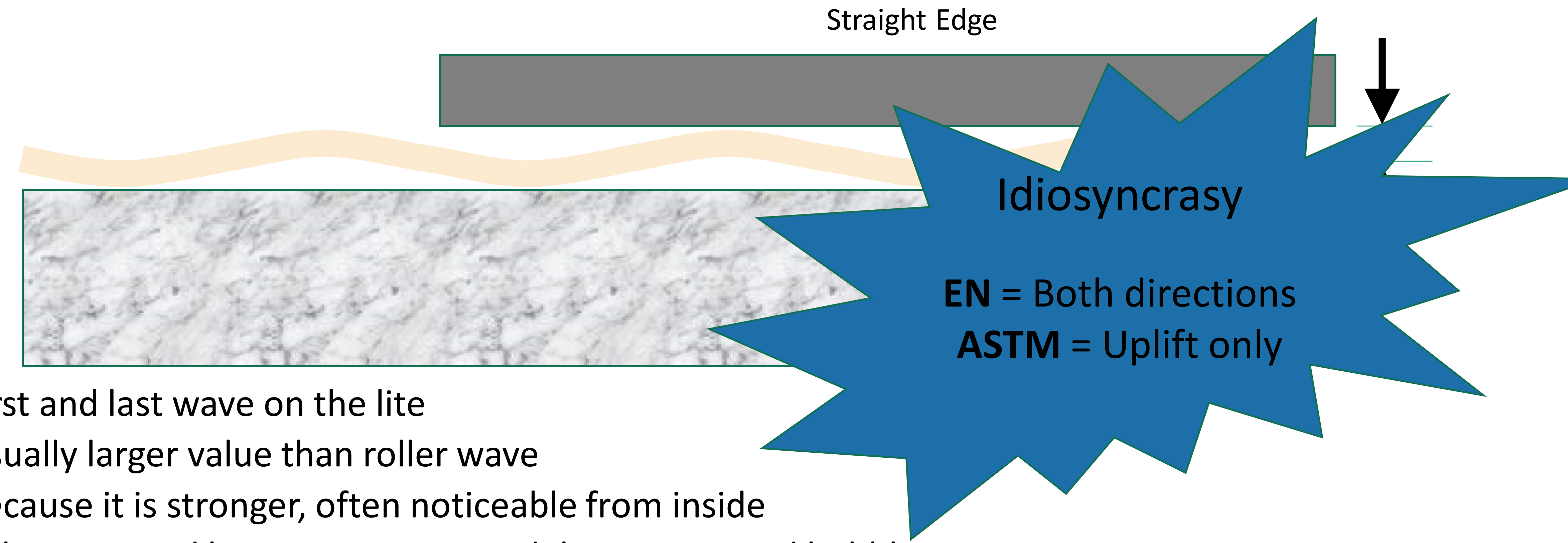
Table 5 — Maximum allowable values for edge lift for horizontally toughened glass

Type of glass	Thickness of glass mm	Maximum allowable values mm
Uncoated float glass in accordance with EN 572-1 and EN 572-2	3	0,5
	4 to 5	0,4
	6 to 25	0,3
Others [a]	all	0,5

[a] For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.

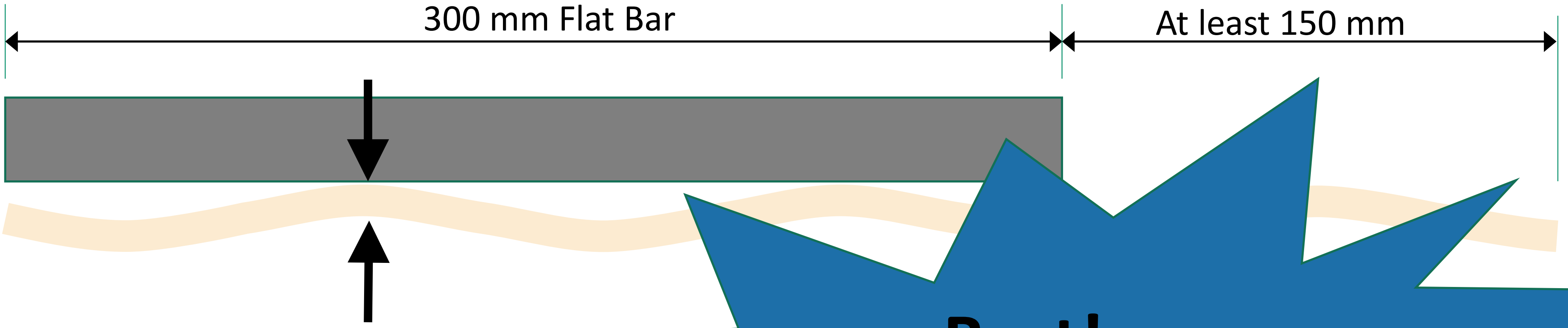
NOTE Dependant upon the wave length of the roller wave an appropriate length of gauge has to be used

Edge Kink / Lift



- First and last wave on the lite
- Usually larger value than roller wave
- Because it is stronger, often noticeable from inside
- In heat treated laminate can cause delamination and bubbles
- Limits established only in EN standards

Roller wave



- External reflection is not pleasant
  - To minimize keep horizontal
- If vertical will be noticeable al...
- Limits established only in EN standa...

Best!

Specify Optical Power

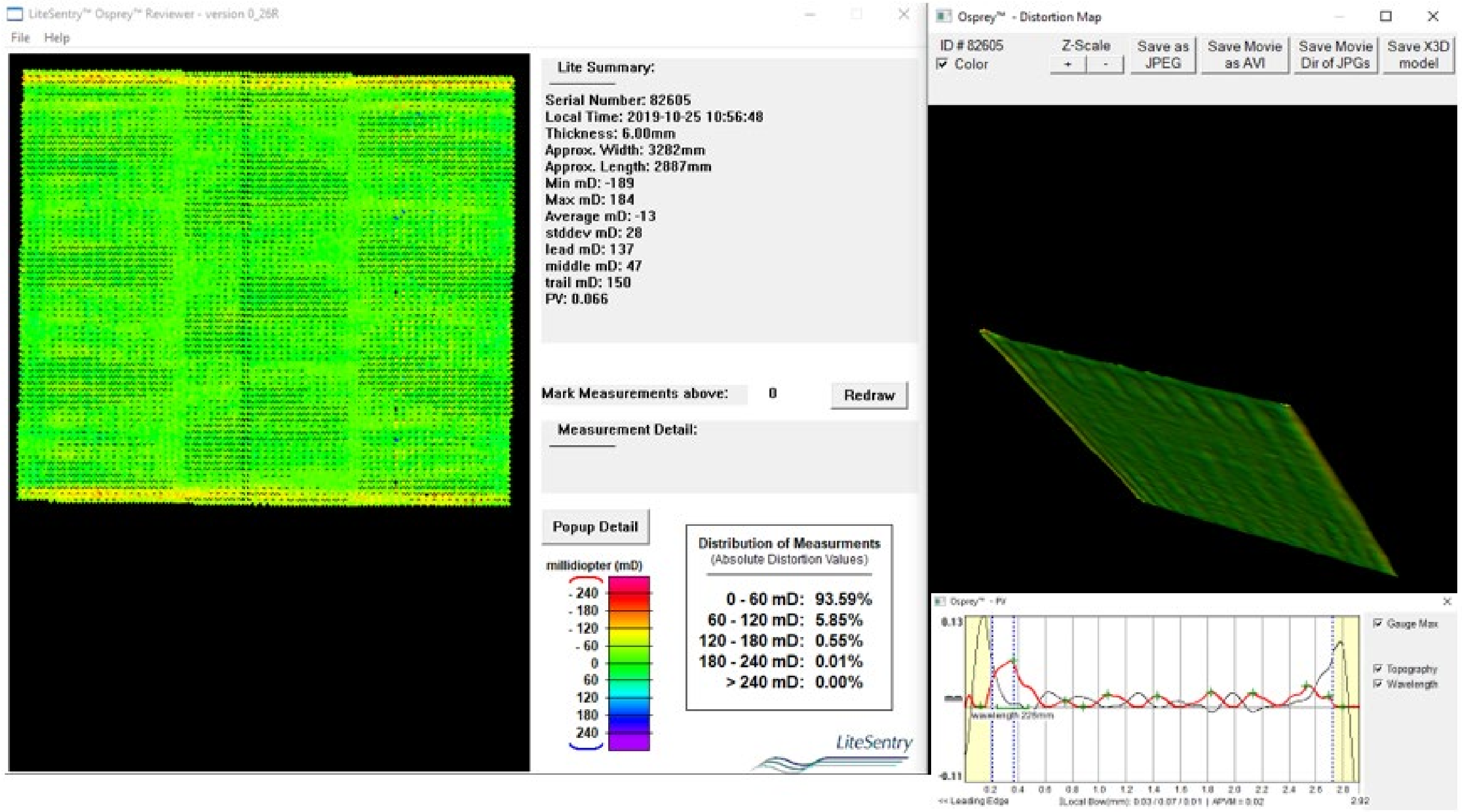
In millidiopter (mD)

- Original
  - 1/4" Annealed 112" x 112"
  - 15 PSF -76 MPH
- Now
  - 1/4" Ultra-flat FT+ HST
  - 46 PSF – 134 MPH

- Original
  - 1/4" Anneale
  - 15 PSF -76 M
- Now
  - 1/4" Ultra-fla
  - 46 PSF – 134

Order 30921

Line 1



- 126-3/8" X 112-9/16"
- PV = 0.066mm – 0.0026" Maximum Peak to Valley measurement.

Standards

- **ASTM C1048-18**
- Standard Specification for Heat-Strengthened and Fully Tempered Flat Glass

- **ASTM C1651-11**
- Standard Test Method for Measurement of Roll Wave Optical Distortion in Heat-Treated Flat Glass

- **ASTM C1652**
- Standard Test Method for Measuring Optical Distortion in Flat Glass Products Using Digital Photography of Grids

- **EN 14179-1**
- Glass in building — Heat soaked thermally toughened soda lime silicate safety glass

- **EN 1863-1**
- Glass in building - Heat strengthened soda lime silicate glass

- **ISO 20657**
- Glass in building — Heat soaked tempered soda lime silicate safety glass

Anisotropy

Milwaukee, WI   USA

Apple Store Yorkdale   Toronto, ON Canada

Apple Store Legacy   Boston, MA USA

With polarizing filter

Apple Store Glendale, AZ

The Word…

Anisotropy

What does it mean?

- ≠ Isotropy
    - Water
    - Vacuum
    - Annealed glass

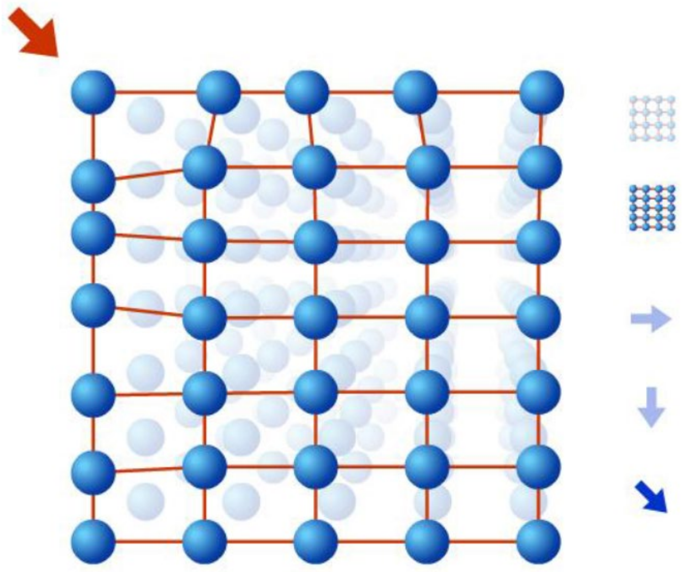
- Wood is anisotropic

The Word...

Birefringence

What does it mean?

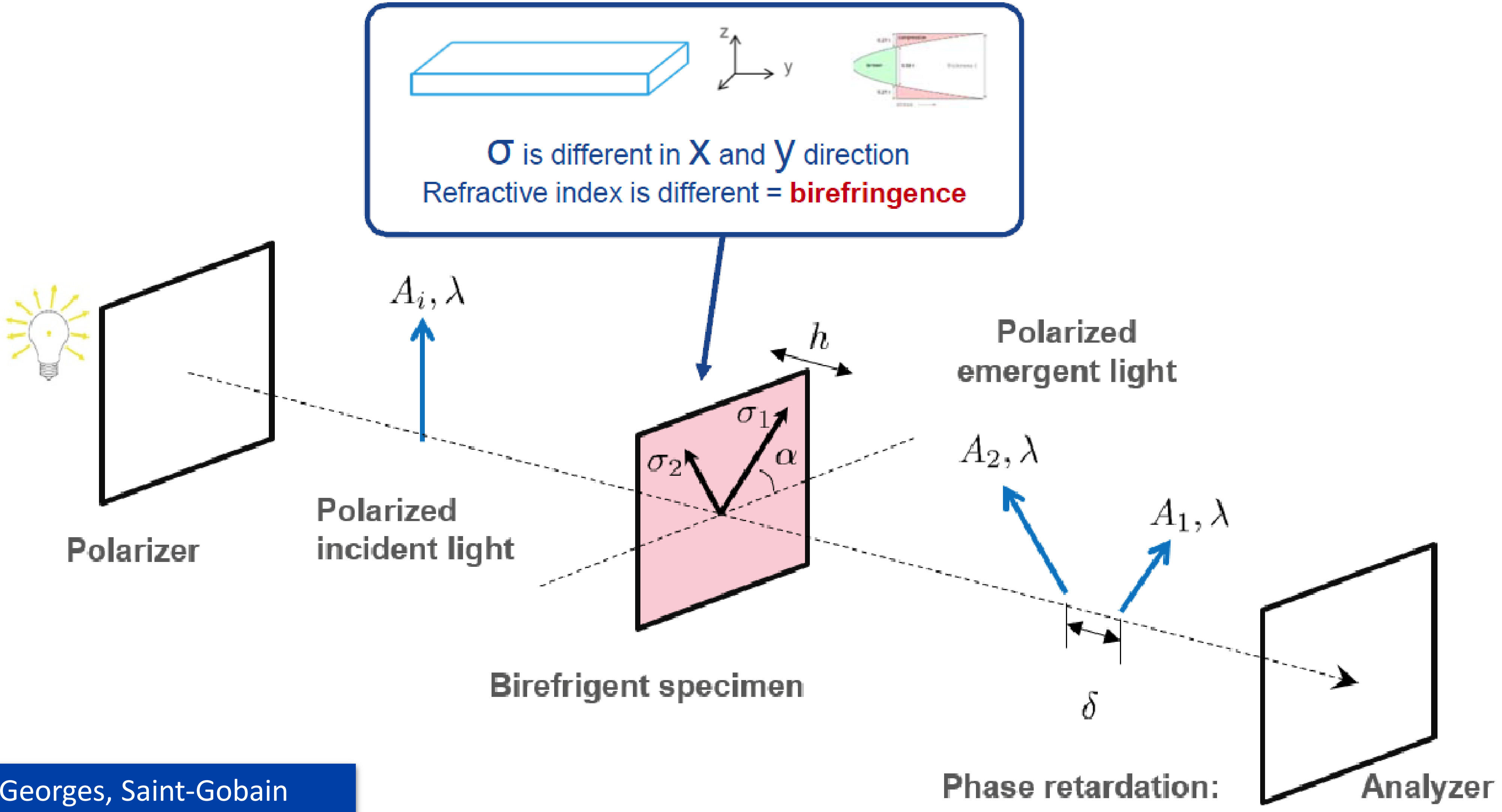
- Mechanical stress leads to deformation of the material structure and therefore changes the particle density and the velocity of light



- Refracts a single incoming ray in two directions
- Corresponds to the two different polarizations
- Noticeable under polarized light

BIREFRINGENT PROPERTIES OF HEAT TREATED GLASS

- POLARIZED LIGHT + STRESS-INDUCED BIREFRINGENCE = PHOTOELASTICITY



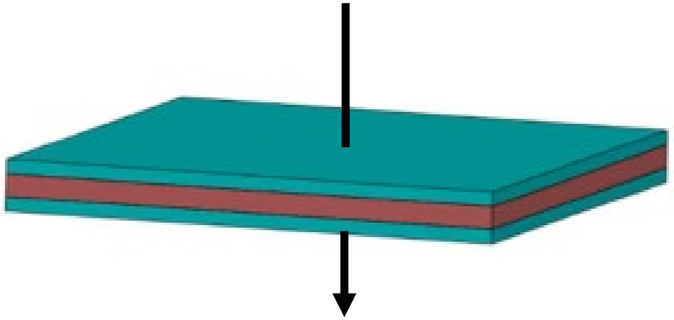
The Word…

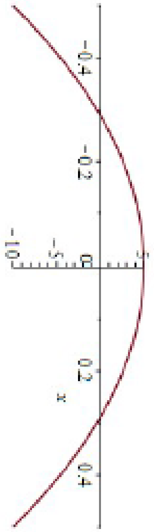
Birefringence

What does it mean?

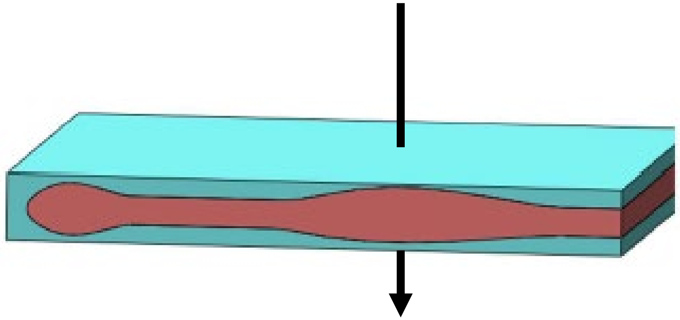
- Optically anisotropic material
  - Having differences of index of refraction
- Heterogenous stresses
  - Caused by not perfectly homogeneous heating and cooling in the tempering furnace
  - Or, for plastic, in the autoclave

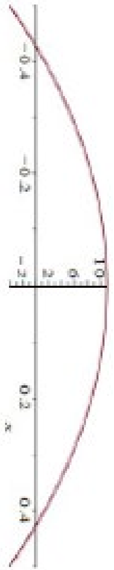
Area Stresses



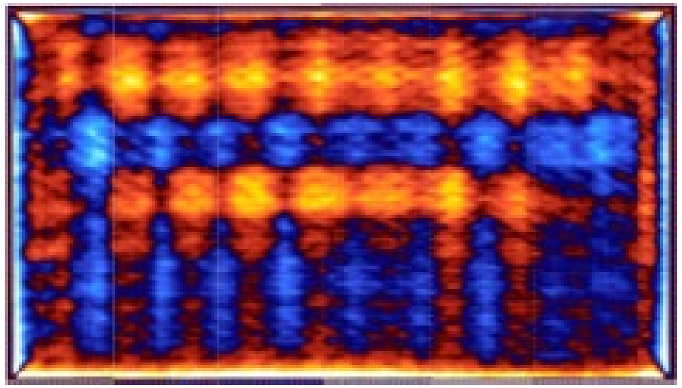


Even though there are intentionally high surface and center stresses in tempered glass, the average stress is 0. So, it has no net effect on the P polarized light and does not reflect it.





Areas that have an imbalanced parabolic stress profile have a non-zero average stress through the thickness and are able to rotate the P polarized light for reflection.



Eric Hegstrom, LiteSentry

The Word...

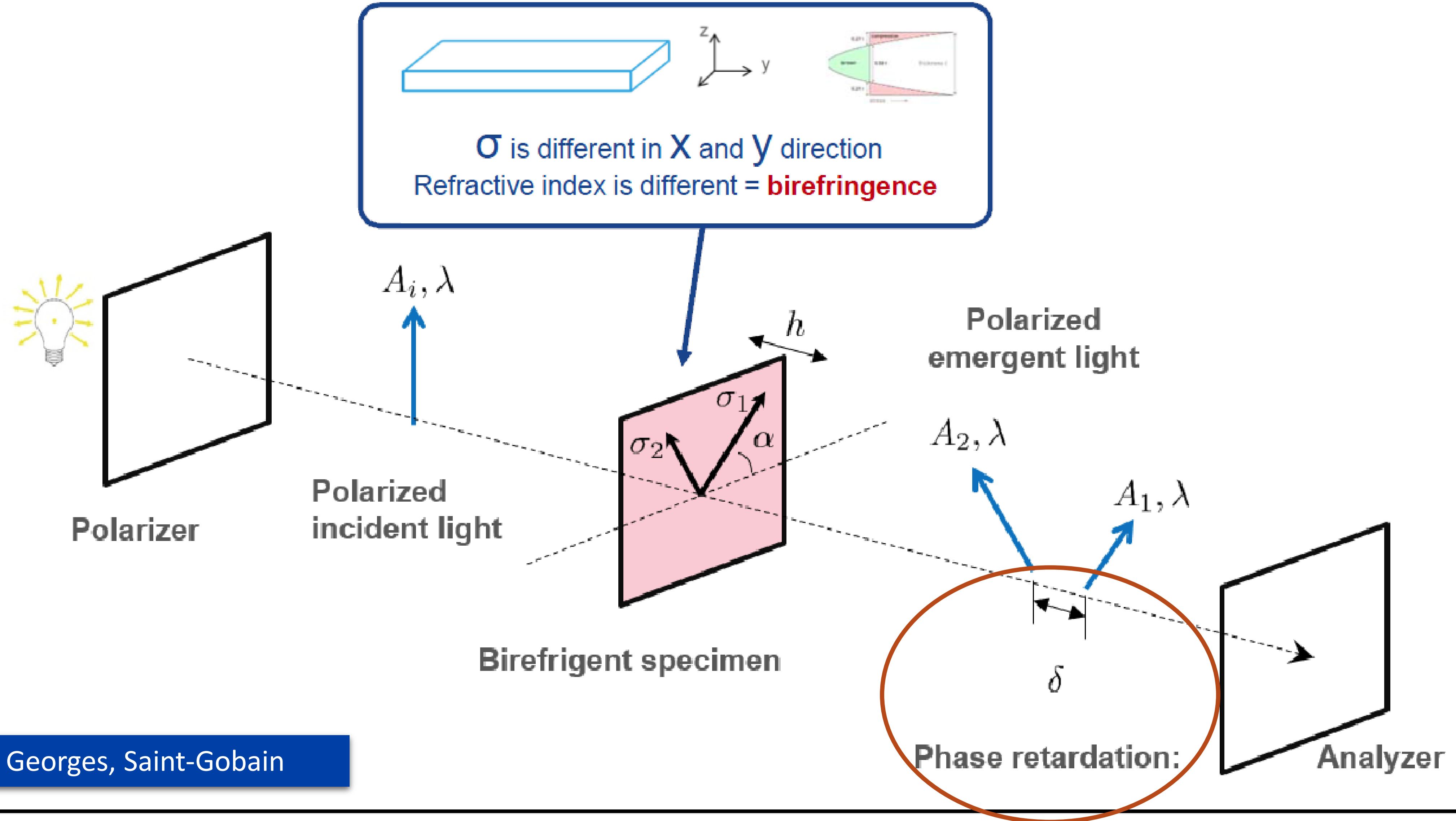
Retardation

What does it mean?

- In a birefringent material, the light waves propagate in the horizontal and vertical directions at different speeds, resulting in an optical path difference or optical retardation
- Measure of birefringence
  - Expressed in nanometer - nm

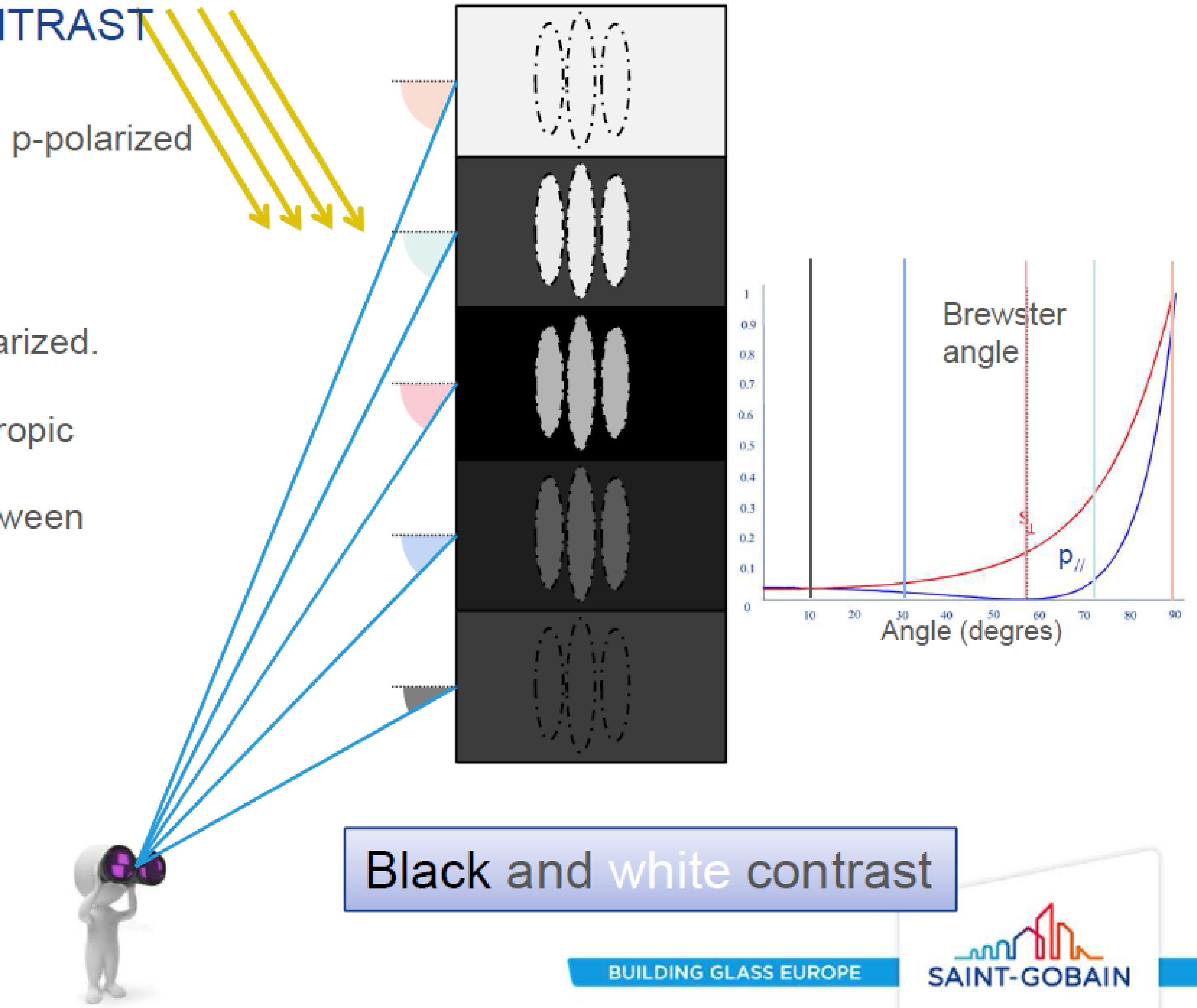
BIREFRINGENT PROPERTIES OF HEAT TREATED GLASS

- **POLARIZED LIGHT + STRESS-INDUCED BIREFRINGENCE = PHOTOELASTICITY**



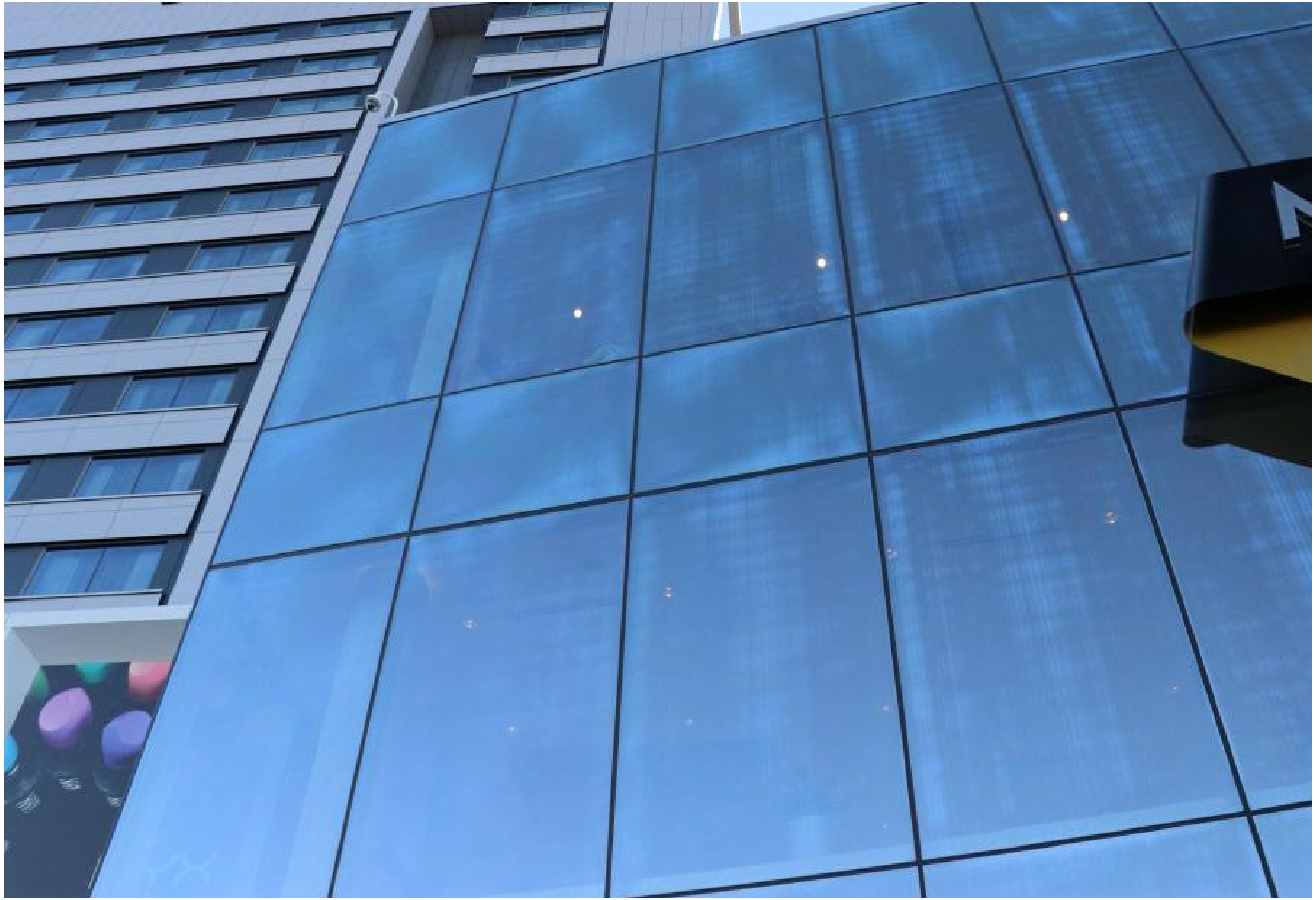
Benoît Georges, Saint-Gobain

PERCEPTION = CONTRAST



Let us consider the illumination p-polarized.

When observing a facade with anisotropic glass, the observed pattern is directly linked to the reflectivity difference between s and p polarizations.



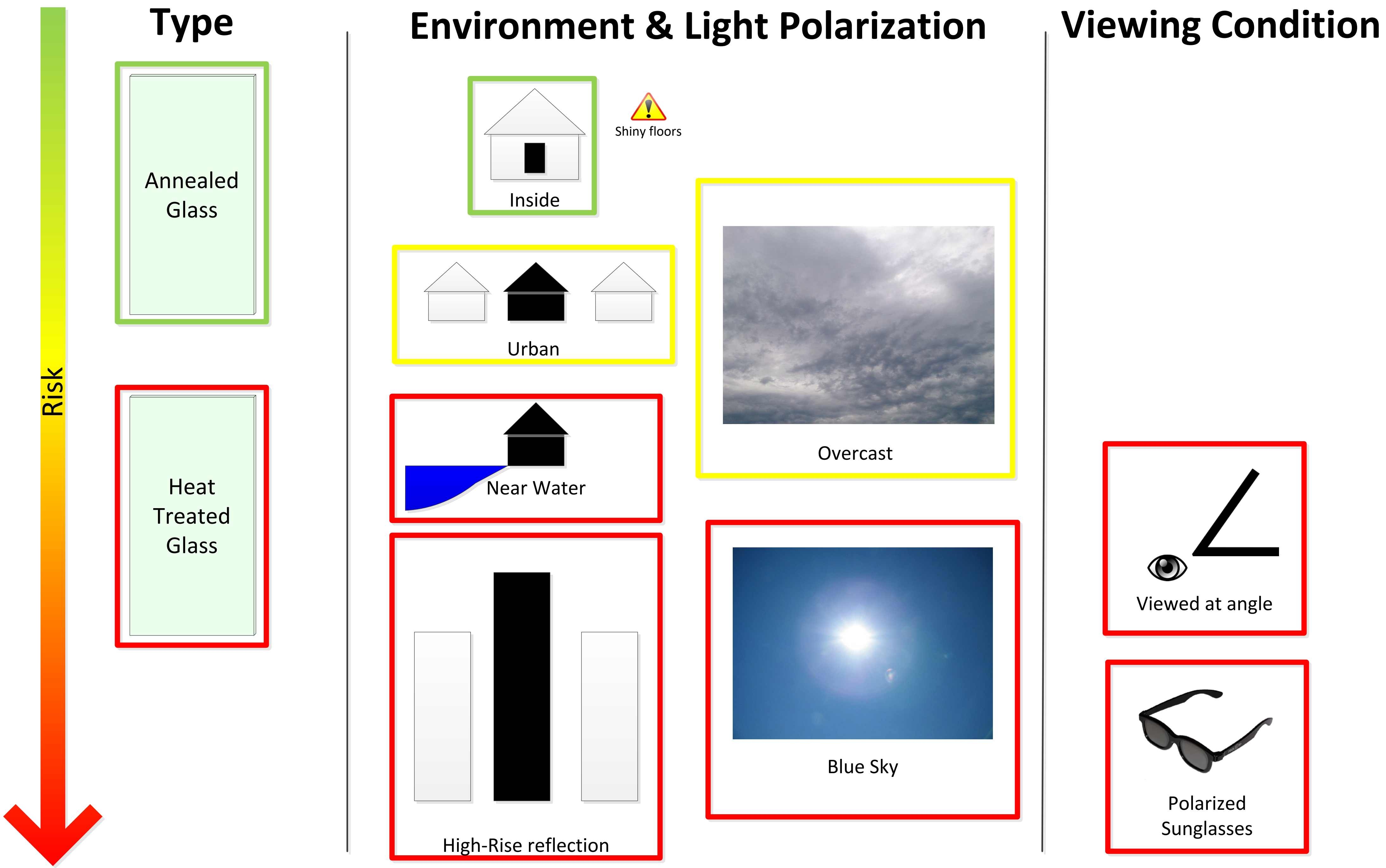
A typical example of iridescence

Eric Hegstrom, LiteSentry

Stress Photonics

LiteSentry

Setting the Standard in Glass Inspection



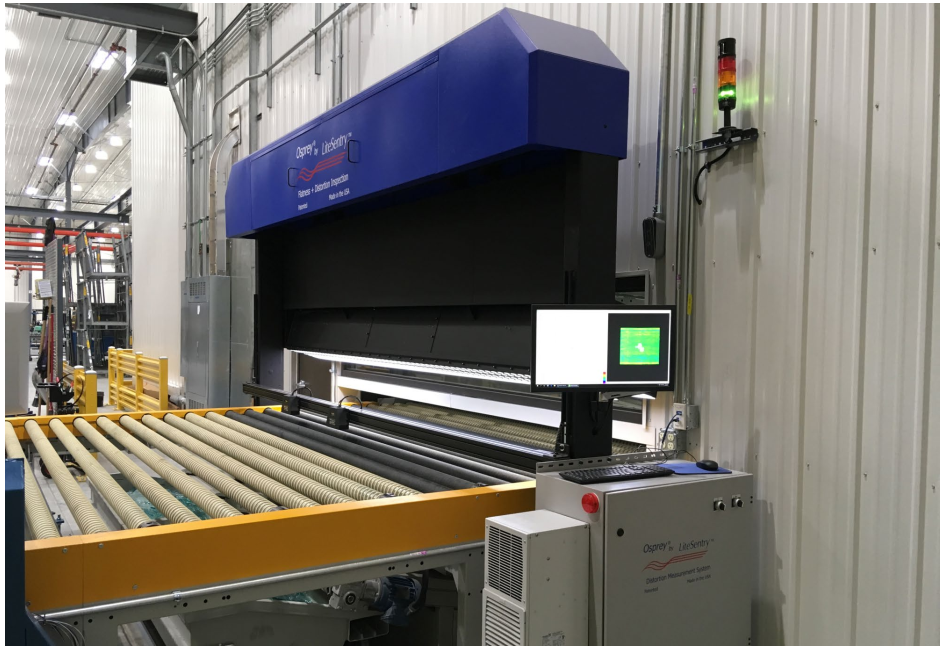
Risk
Type
Annealed Glass
Heat Treated Glass
Environment & Light Polarization
Inside
Shiny floors
Urban
Near Water
High-Rise reflection
Overcast
Blue Sky
Viewing Condition
Viewed at angle
Polarized Sunglasses

C1901-21

Standard Test Method for Measuring Optical Retardation in Flat Architectural Glass

- S**tandard test method** for measuring optical anisotropy
- Heat treated flat monolithic glass
- Educate stakeholders on the phenomenon and on technology available
- Establish a language, a methodology
- Confirm that numerical values are expressed in a fundamental physic unit
- Certify that measurements are consistent, repeatable and traceable
- Building block that allows you to create a **specification**


FeneVision LineScanner



Osprey 9 by LiteSentry

Ilis - Arcon

Commercial Anisotropy Scanners

SoftSolution

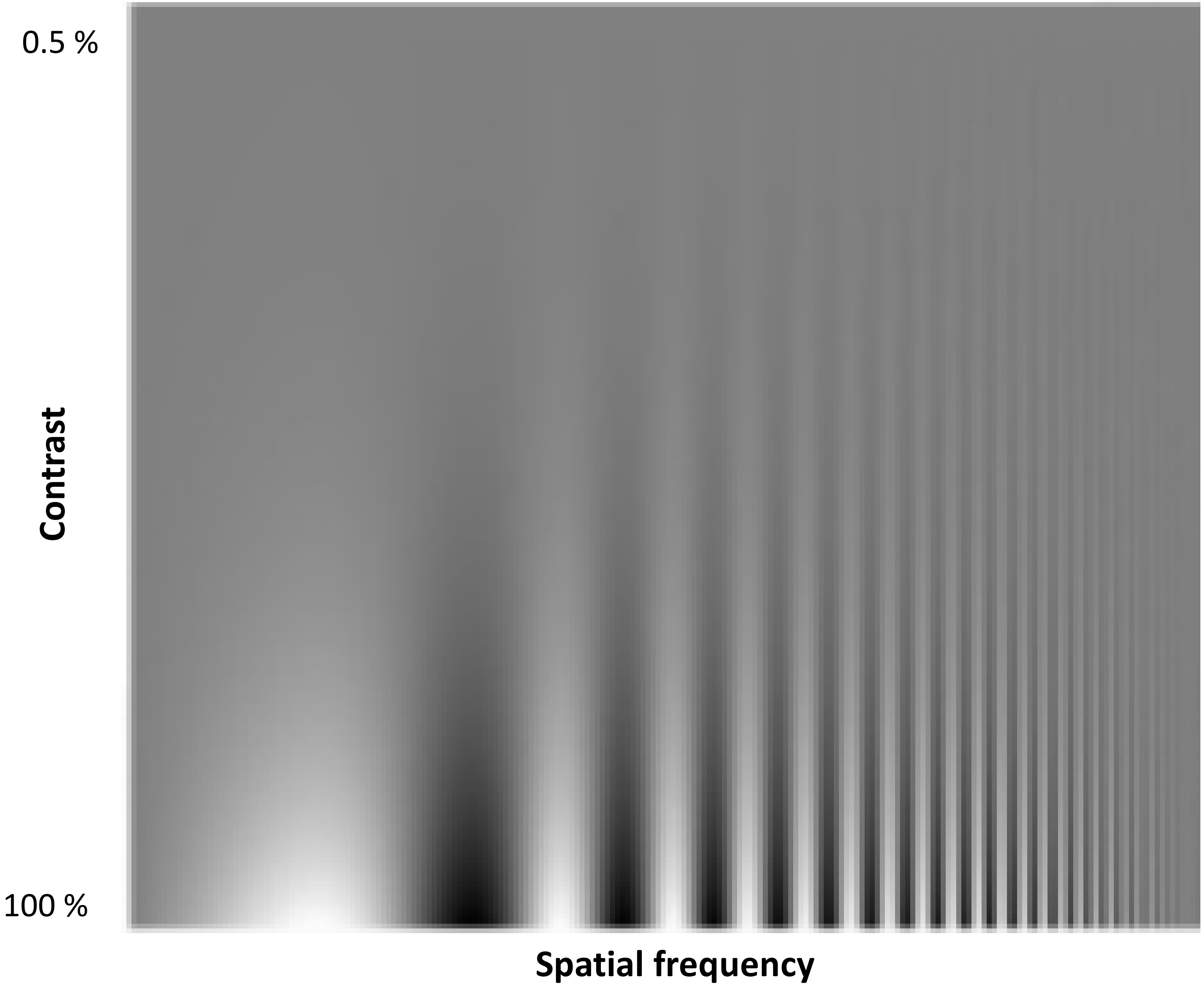
Viprotron

Quick comparison

Manufacturer	Light source	Type	Polarization	Captor	Extra function
Arcon *ilis*	LED Panels	Polarimeter	Circular	StrainCam cameras	
Glaston	LED Panels	Polariscope	Linear	High Resolution Cameras	Direct feedback to furnace operator
Lite-sentry *Stress Photonics*	Colour balanced	Polarimeter	?	Multiple Grey Field Polariscopes	Distortion Inspection
SoftSolution	Multi-colour telecentric	Polariscope	Circular	Linear sensor	Blemishes, Dimensioning, Edge stress
Viproton	Red stabilized LED	Polariscope	Circular	High Resolution Cameras	Bottom Haze

Next steps in our journey

- R&D Watch
  - How to evaluate the retardation map
  - How to describe the light environment
  - Create realistic glass renderings
- How can we measure and describe the light polarisation environment of the building and catch the environments more susceptible to anisotropy?
- Better understand human eye perception
  - Contrast sensitivity


0.5 %
Contrast
100 %
Spatial frequency

Next steps in our journey

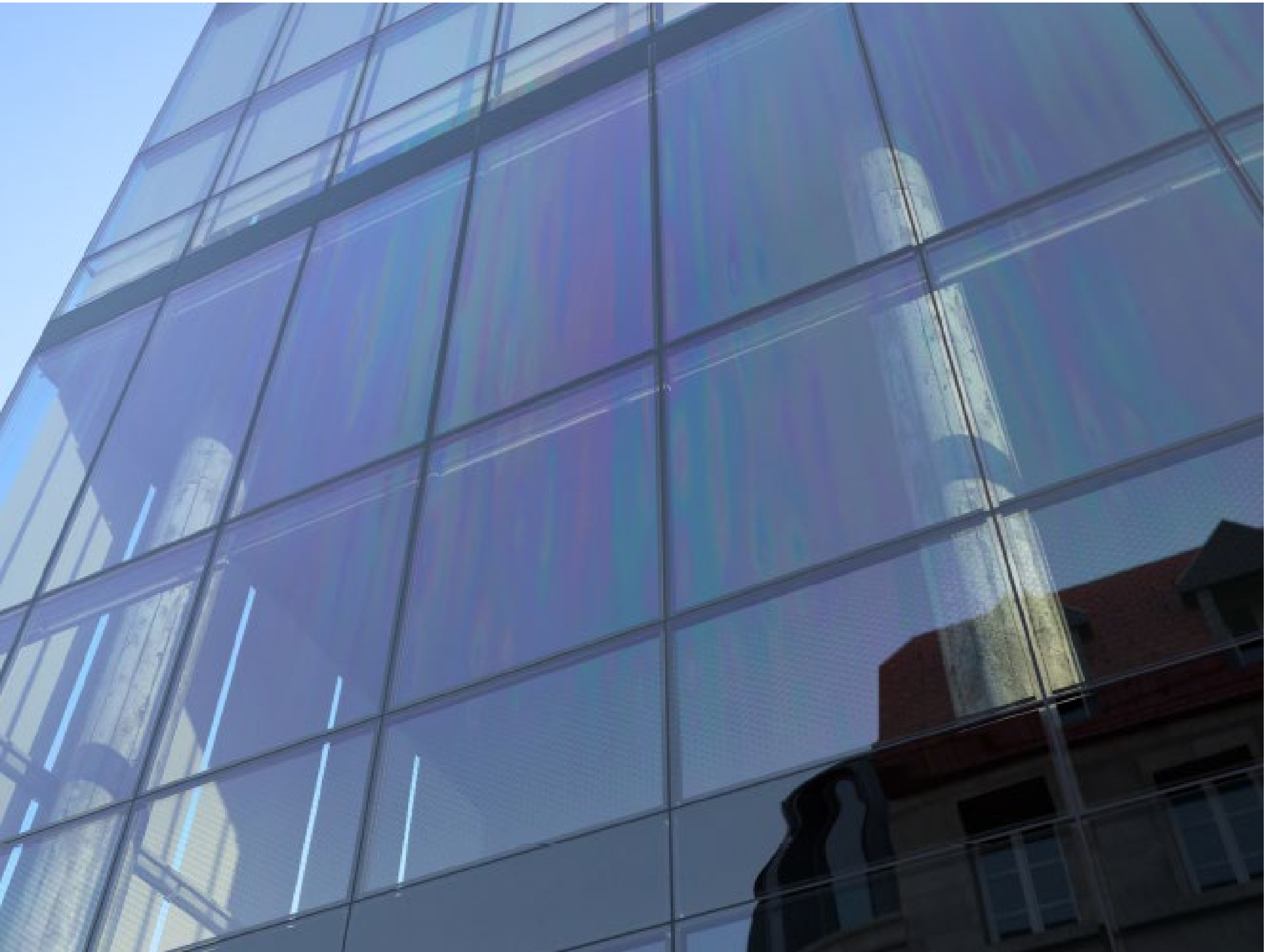
- Use human perception studies to see what is the most important data
  - Mathematical average
  - Island of high retardation
  - How to treat the edges, holes, notches
  - Geometry
- Define a mathematical method to work with the large array of retardation data
- Come up with guidelines per application

Next steps in our journey

Virtual prototyping and aspect prediction with OCEAN ™

Preetham-Wilkie (Polarized) Sky
Sun position
Altitude = 0° Azimut = 0°

Next steps in our journey



Virtual prototyping and aspect prediction with OCEAN ™

Preetham-Wilkie (Polarized) Sky
Sun position
Altitude = 15° Azimut = 292°

Takeaways for anisotropy

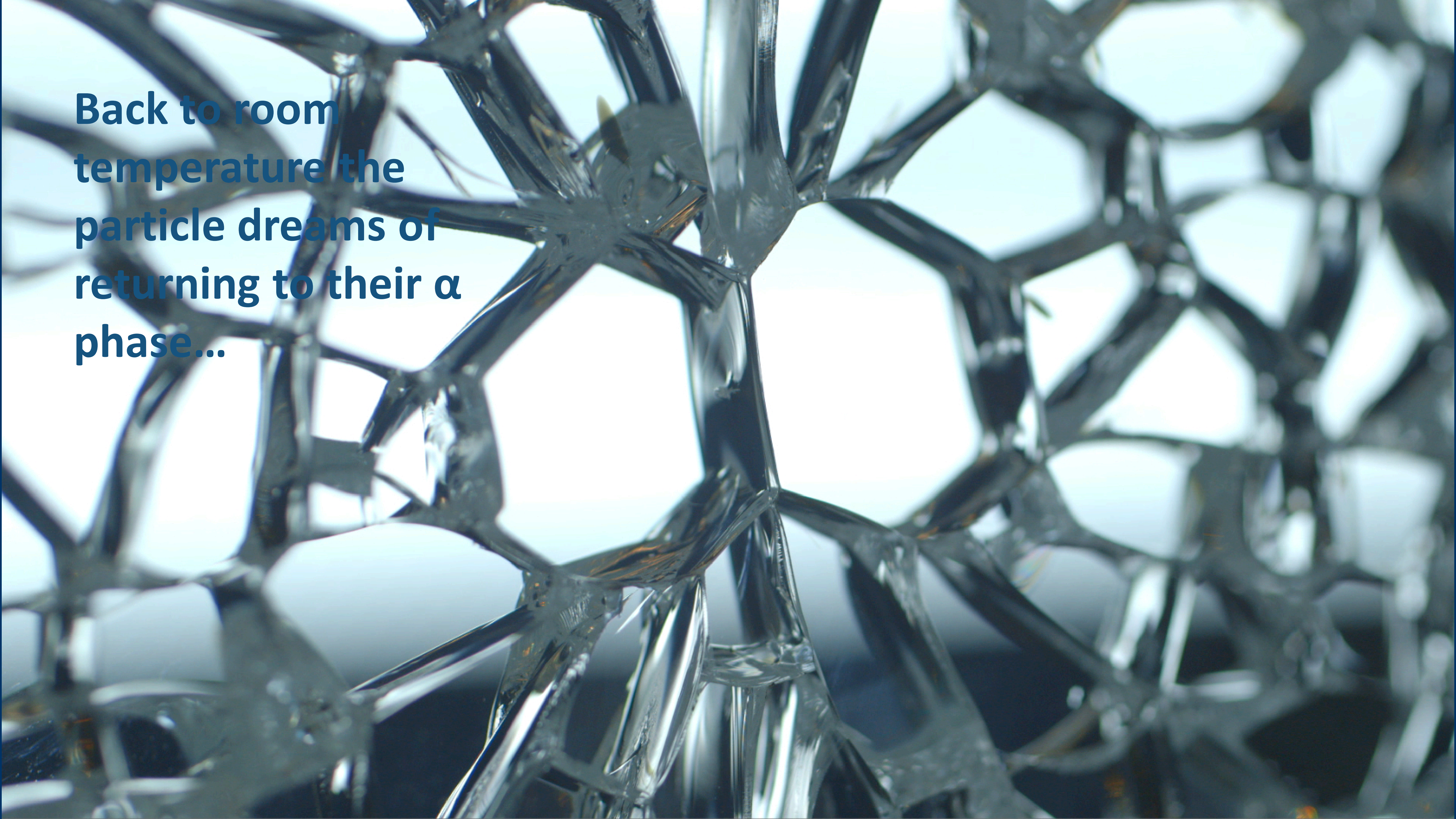
- *It takes two to tango*
  - Glass with anisotropy
  - Polarized light environment
- Computing power and optical technology paved the way to online scanners
- Optical retardation mapping at zero degree is exact to quantify the tempering quality
- Now possible to have accurate and repeatable measurements
  - Objectively improve process
  - Quantify anisotropy between parties

Spontaneous Breakage

Heat Soak test AGNORA video

- https://vimeo.com/185494434

During tempering, phase transformation of NiS from **α** to **β** decreases the volume by ~4%

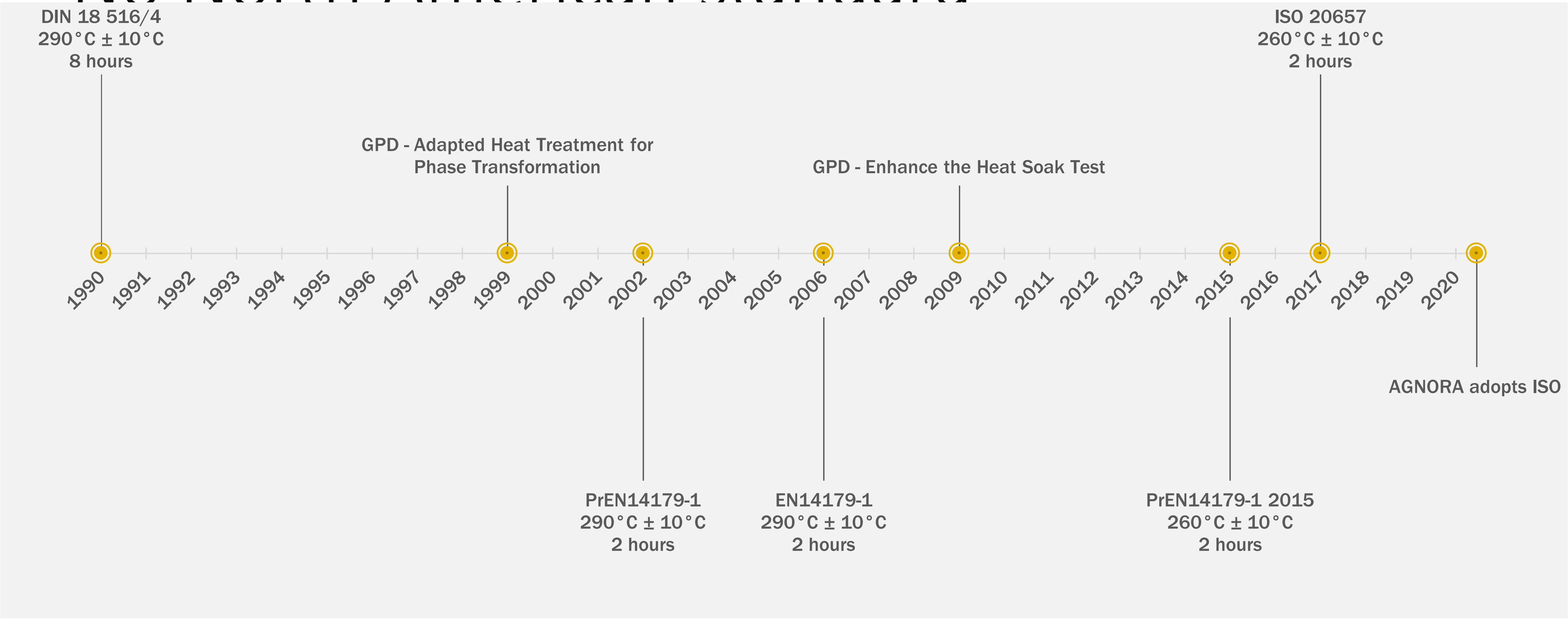


Back to room temperature the particle dreams of returning to their α phase…

Heat Soak Testing
make the dream come
true faster…

Heat Soak Test regulation a bit of history

No North American standard

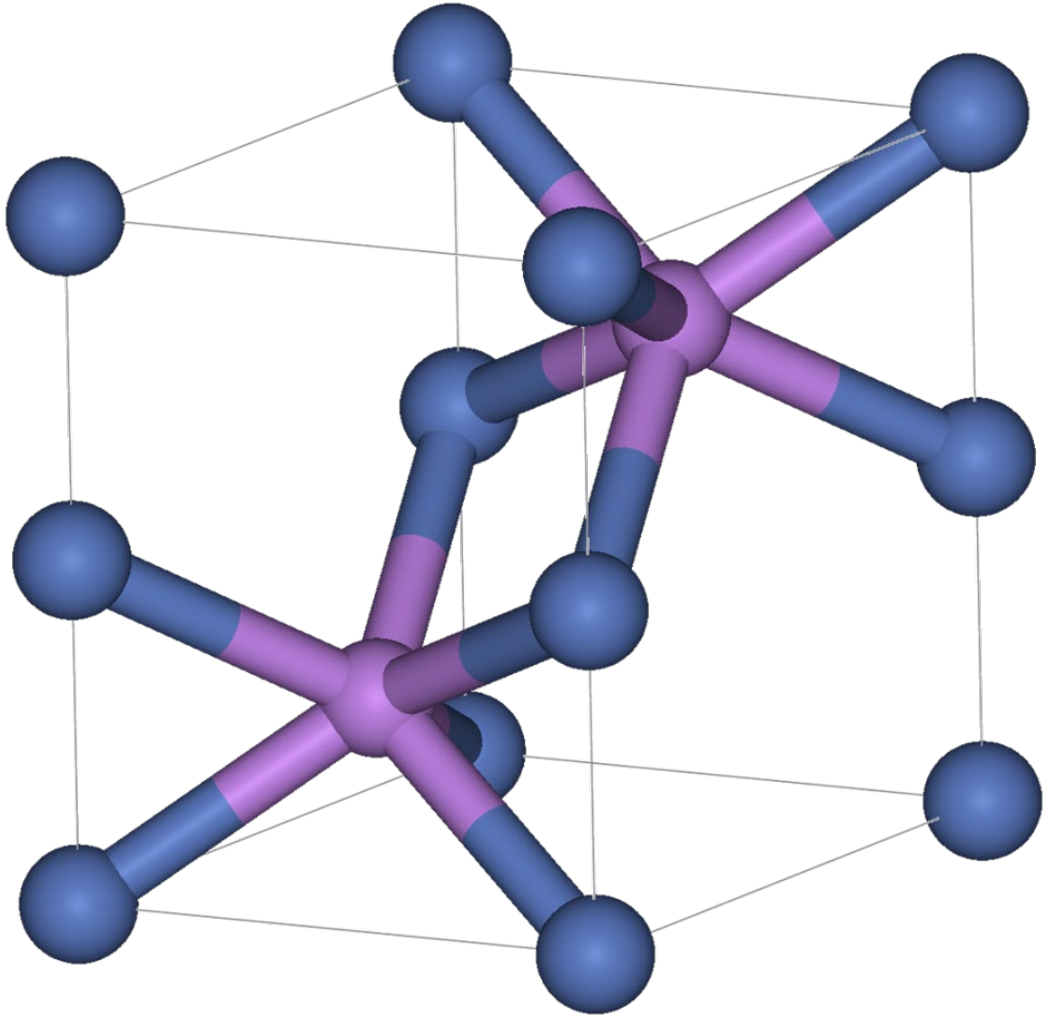


stoichiometry

- stoi·chi·om·e·try | \ ˌstȯi-kē-ˈä-mə-trē
- **Definition of *stoichiometry***
- 1 : a branch of chemistry that deals with the application of the laws of definite proportions and of the conservation of mass and energy to chemical activity
- 2a : the quantitative relationship between constituents in a chemical substance
- b : the quantitative relationship between two or more substances especially in processes involving physical or chemical change

The Physics

- NiS particles are not alike
  - Some are contaminated with iron
  - Some contain different proportions of Sulphur
    - NiS, Ni_7S_6 + NiS, $NiS_{1.01}$ + Ni_3S_4
  - This change the transformation's dynamic
  - Slowest transformation rate
    - High Sulphur %
    - Causes late NiS breakage
    - Might survive 290°C test



260°C ± 10°C

- Enhances safety
  - Eliminate more particles
- Reduce the soaking time
- Reduce the soaking cost
- Reduce environment impact due to reduced energy consumption
- Lessen the de-tempering effect
  - The surface compression level is slightly lower after HST

AGNORA

Thank you!