INFLATABLE GLAZING

Prototyping of a dynamic thin glass unit
with a switchable thermal insulation

Building Technology Graduation Project
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Marcel Bilow

Research Framework | Background | Design | Prototyping | Simulations | Conclusion

Problem statement

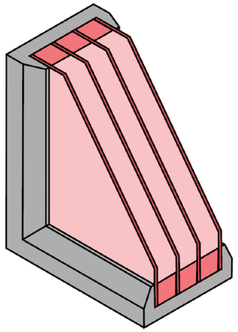
Two contrasting problems

MIXED CLIMATE ZONES

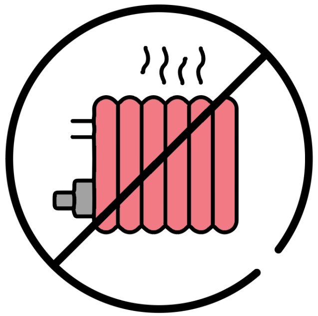
Designing for high insualation

Bambou House, (Karawitz)

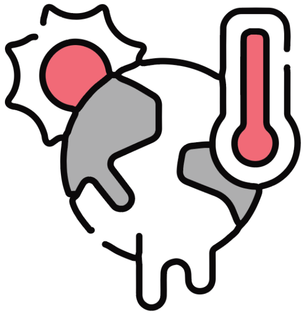
MIXED CLIMATE ZONES
Increasing difficulty to select appropriate glazing



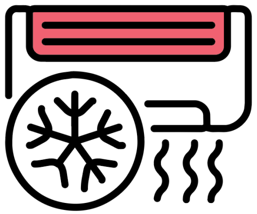
Building energy regulations advocating for **better insulated facades**



Improved insulation substantially **reduces heating energy demand**



Over past decades significant **rise in surface temperatures**



Well-insulated buildings are soon at the **risk of overheating** resulting in an increased **cooling demand**

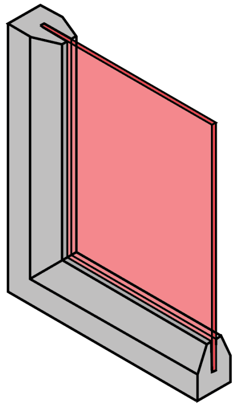
MILD CLIMATE ZONES

Desgining for low insulation

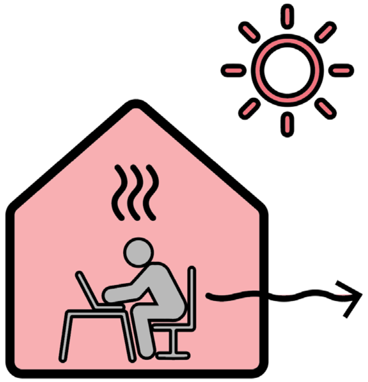
Apple Park, (WSJ. Magazine)

ON THE OTHER HAND...

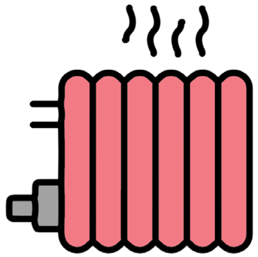
...California as an example



Mostly comfortable temperatures. Buildings are equipped with **single glazing**



Very **effective for heat dissipation**, cheap and aesthetic. Works well for most of the year.



However, in winter, single glazing is a poor choice resulting in **high heating demand**

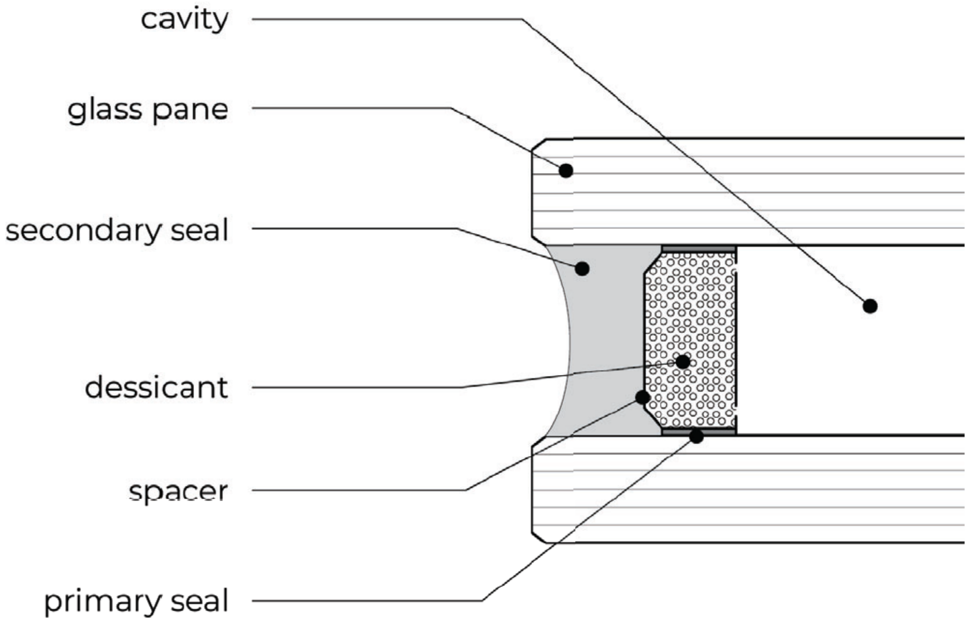
PROBLEM STATEMENT

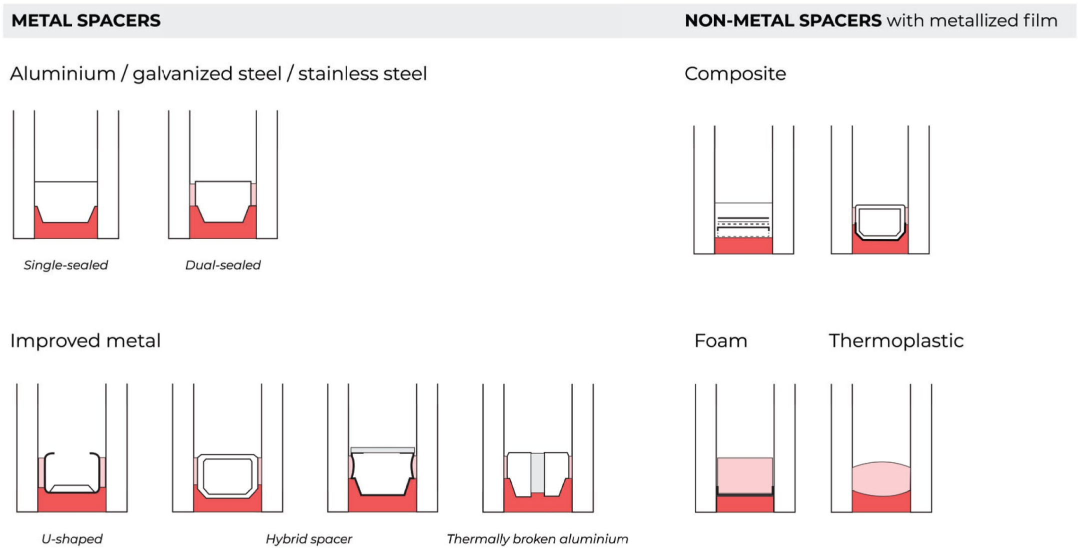
Selecting an appropriate U-value for glazing in mixed and mild climate zones poses a challenge due to the difficulty to balance conflicting thermal insulation requirements.

IGUs, THERMAL INSULATION AND SOLAR CONTROL

Fundamental knowledge

COMPOSITION OF AN INSULATED GLASS UNIT
...and its components

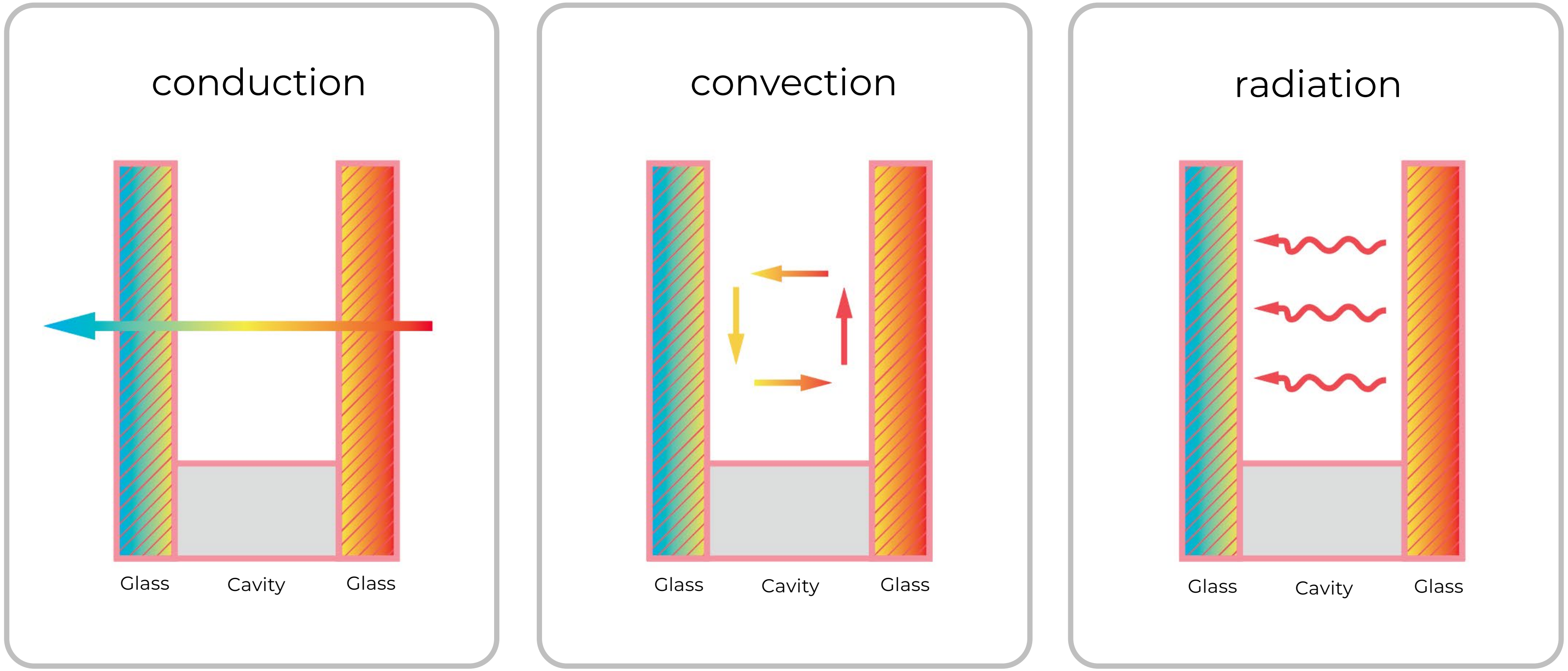




WHAT IS THERMAL INSULATION

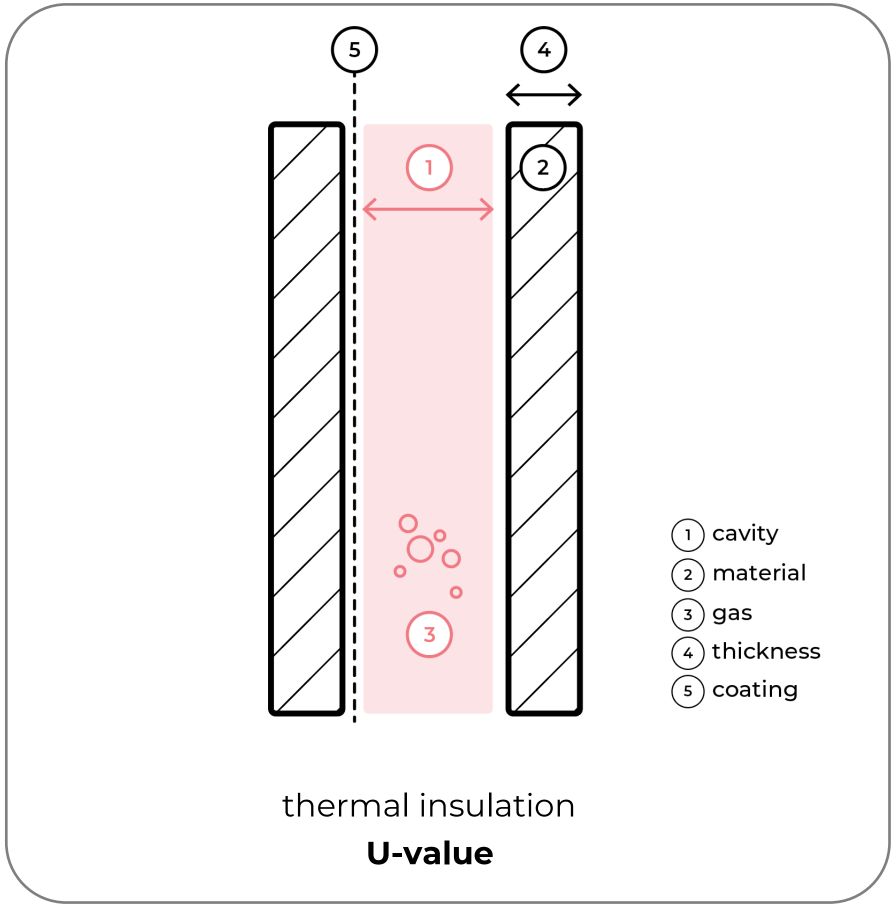
...in glazing

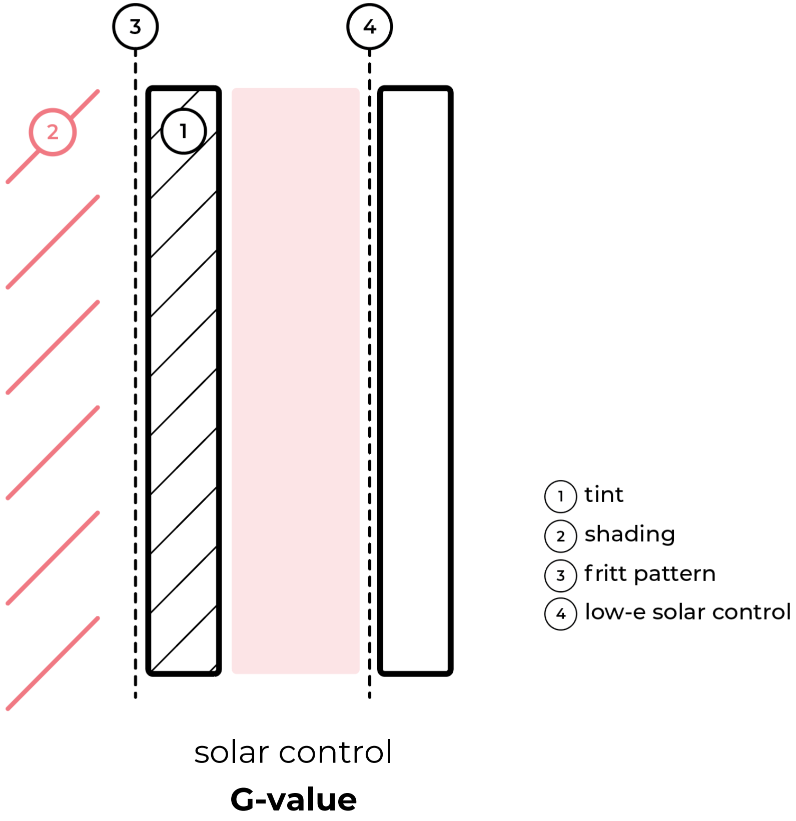
EXT.



INT.

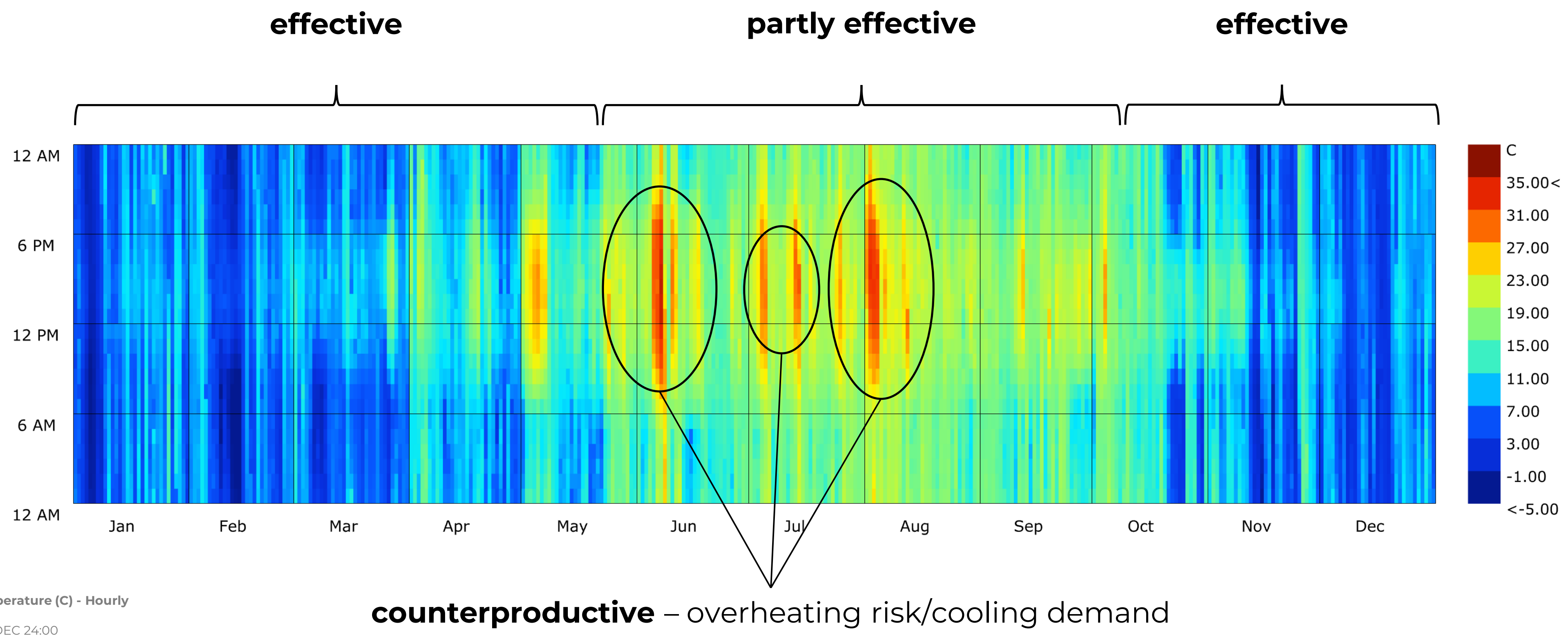
THERMAL INSULATION & SOLAR CONTROL
...what is the difference?





WHEN IS THERMAL INSULATION USEFUL

...and is it counterproductive?



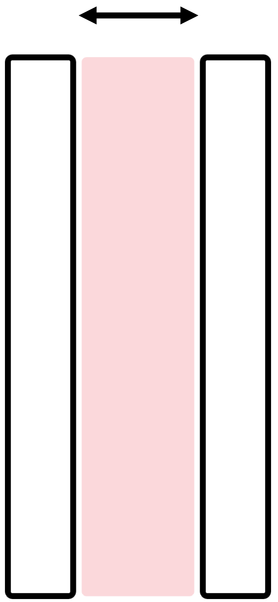
Dry Bulb Temperature (C) - Hourly
Amsterdam
1 JAN 1:00 – 31 DEC 24:00

DYNAMIC INSULATION

Working principle

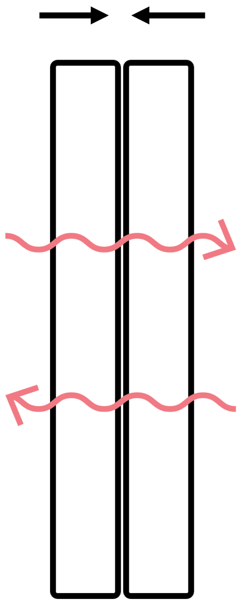
THE CONCEPT OF DYNAMIC INSULATION
Opening and closing a cavity

What if the glazing could **adapt to different climatic scenarios**?



insulating

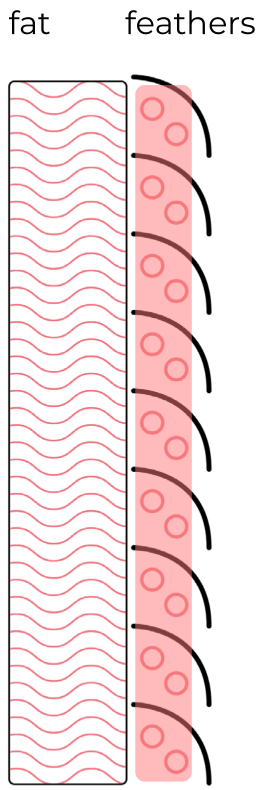
slow heat transmission



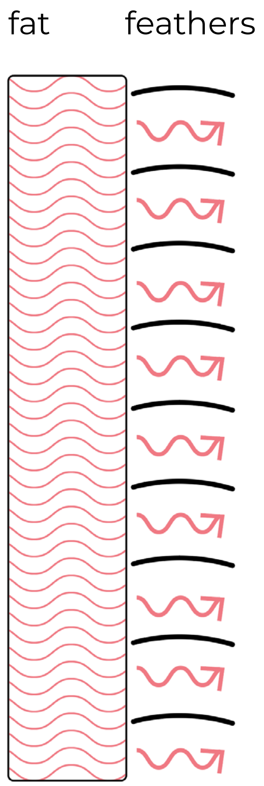
conducting

fast heat transmission

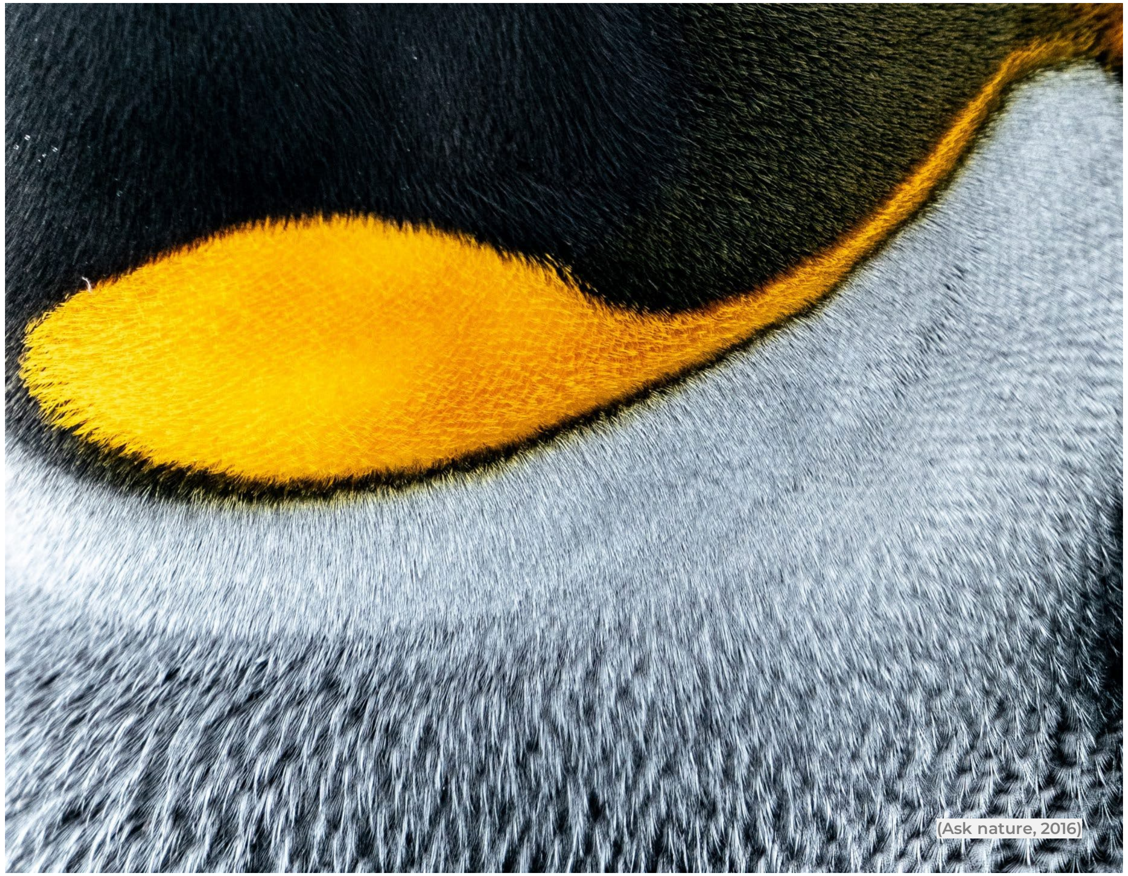
PENGUINS HAVE AN EXCELLENT DYNAMIC INSULATION
...opening and closing an air cavity



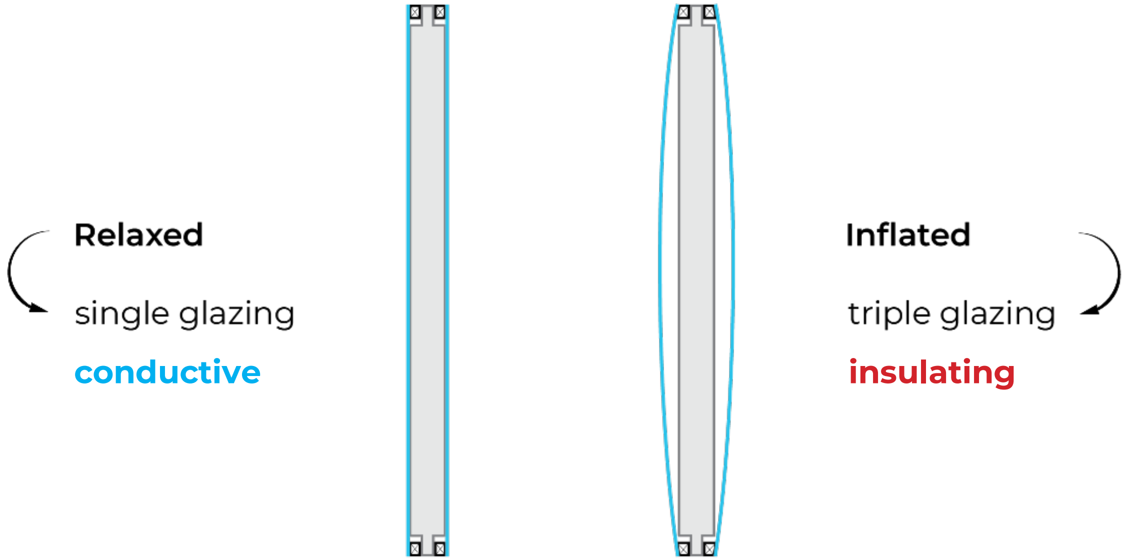
Trapping air

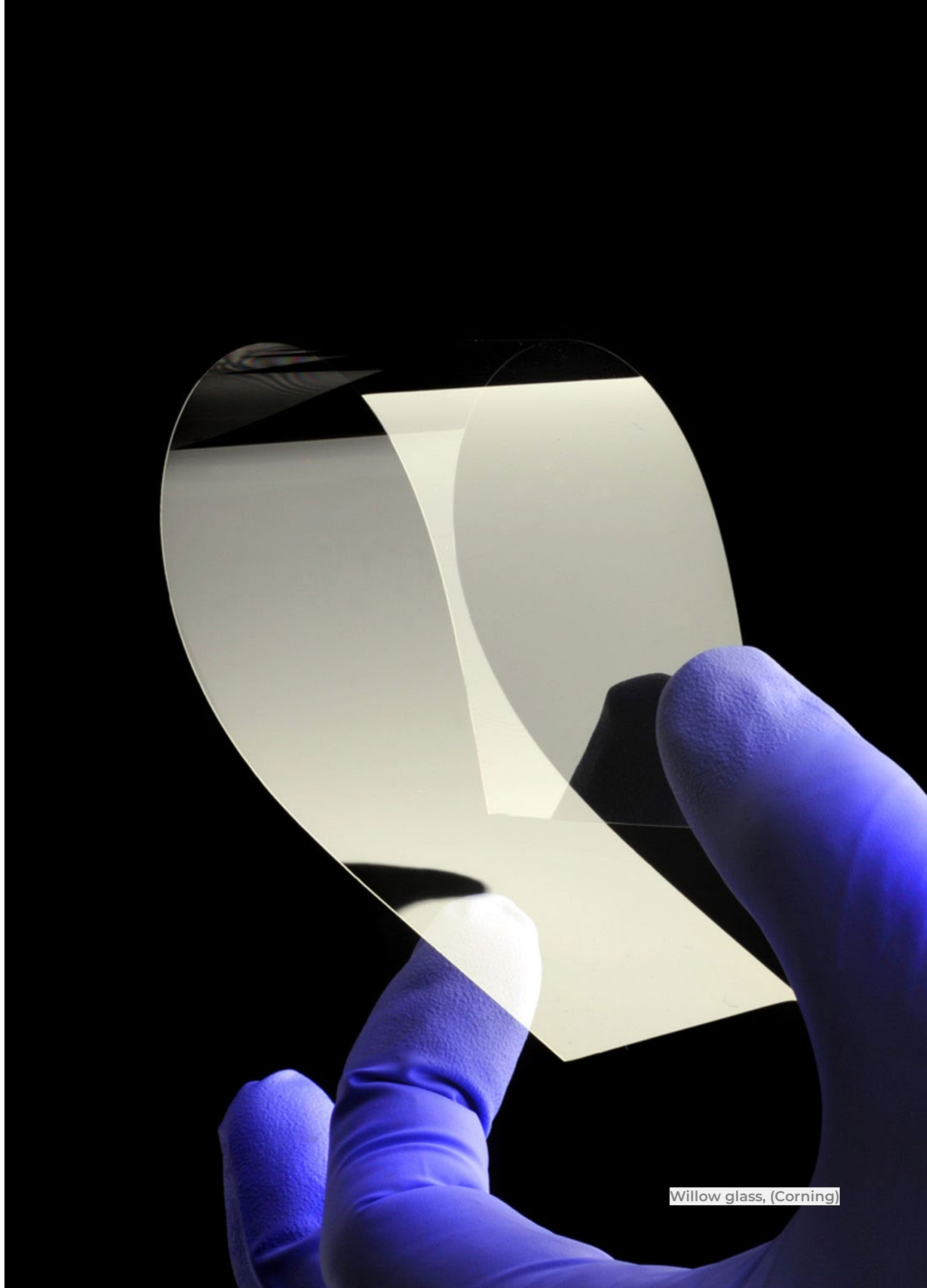


Heat dissipation



RELATION BETWEEN CONCEPT & STUDIO
Transparent Structures and Glass Design



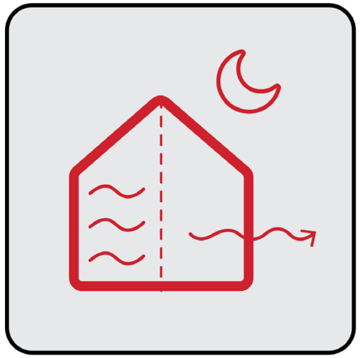


Willow glass, (Corning)

USEFUL SCENARIOS OF DYNAMIC INSULATION

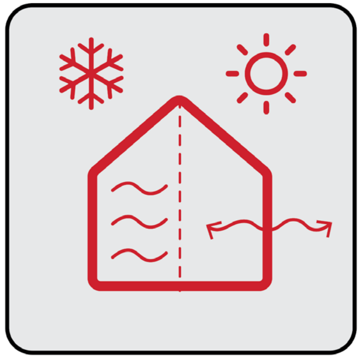
Switching from insulating to conducting state

Controlled by internal & external sensors + weather forecast + adjusted HVAC



Nocturnal cooling/heat storage

Rapid temperature changes



Seasonal changes

Occupants, Pcs, servers

THE MATERIAL: THIN GLASS

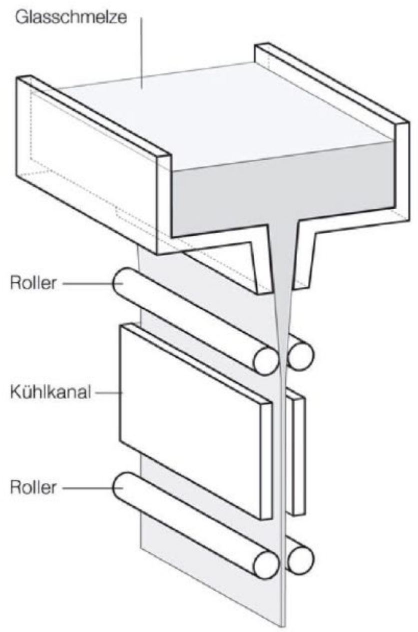
Transparent Structures and Glass Design

Alumino-silicate glass

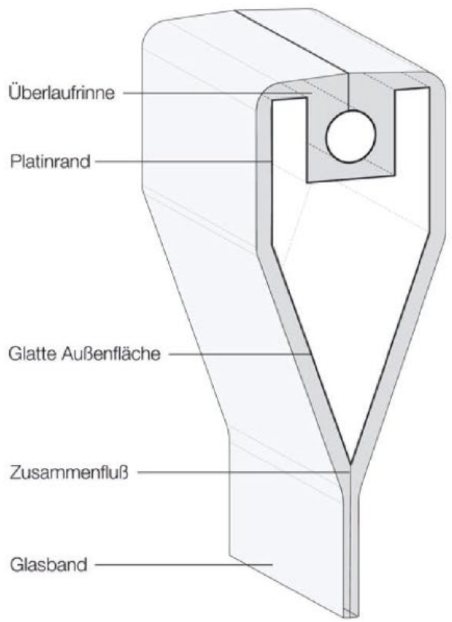
Composition		
Silica sand	SiO_2	62%
Soda	Na_2O	1%
Lime	CaO	8%
Magnesia	MgO	7%
Alumina	Al_2O_3	17%
Boron-oxide	B_2O_3	5%

(Schlösser, 2018)

Down-draw



Overflow-fusion

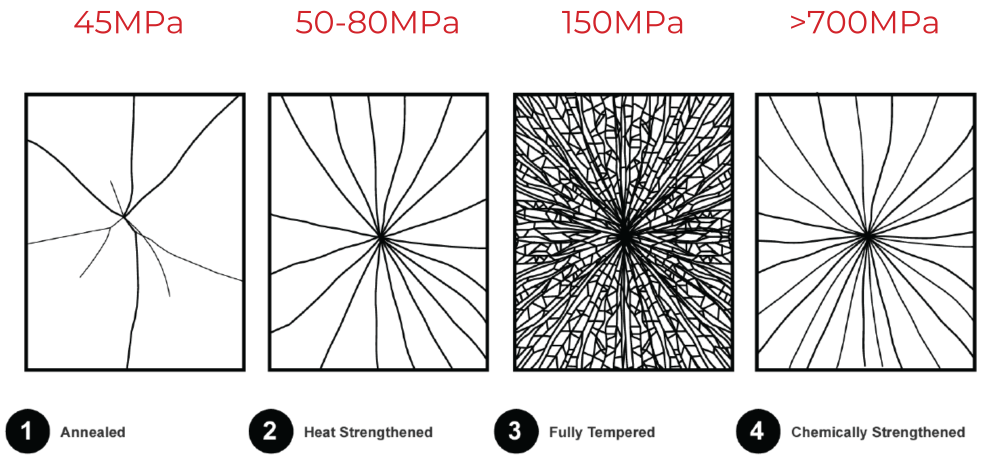


(Albus & Robanus, 2014)

THE MATERIAL: THIN GLASS

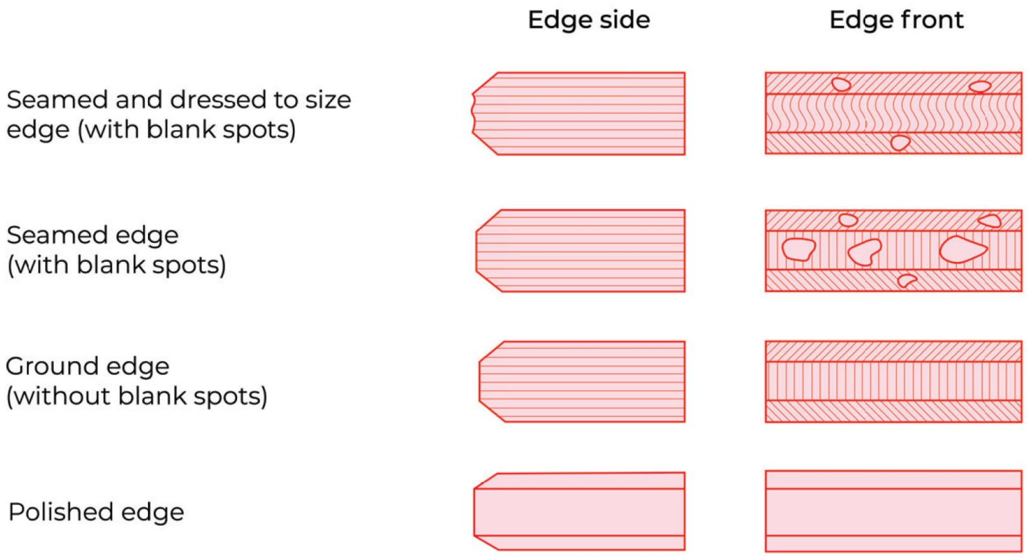
Transparent Structures and Glass Design

Tempering



(Rammig, 2022)

Glass edge



(Feldmann et al, 2014)

MAIN RESEARCH QUESTION

Transparent Structures and Glass Design

How can thin glass be utilized as a dynamic component to enable a switchable U-value in a glass unit?

SUB-QUESTIONS

Transparent Structures and Glass Design

1. *What are the **resulting U-values** when the unit's cavity is either open or collapsed?*

2. *What is the **effect on energy efficiency** of a building with Inflatable Glazing equipped and **where is it the most effective**?*

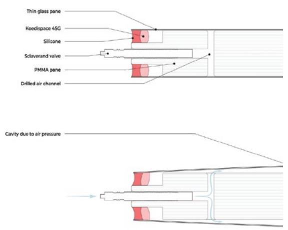
3. *What are the main **challenges in manufacturing** a dynamic thin glass unit and how could the process be improved?*

4. *What are the **desired cavity widths to achieve the best thermal results** and which pressures and stresses can be expected?*

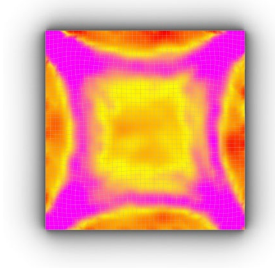
5. *What is the **resulting inflation geometry** and curvature of the inflated thin glass unit?*

RESEARCH AND DESIGN

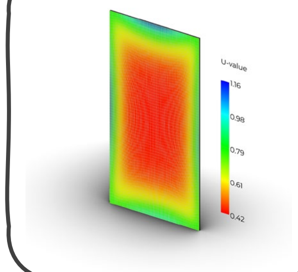
The process towards the end product



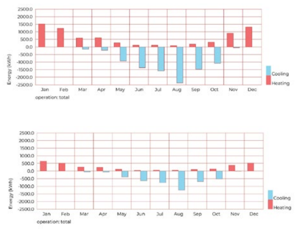
Design Development



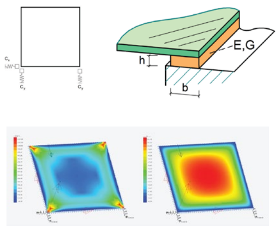
Prototyping + 3D scan



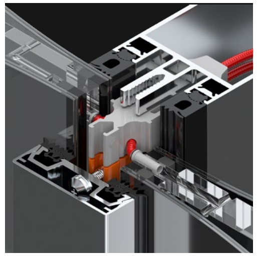
Thermal Performance



Energy Efficiency



Structural Performance



Final Product + Impressions

PRESENTATION STRUCTURE

DESIGN DEVELOPMENT

From sketch design to final prototyping design

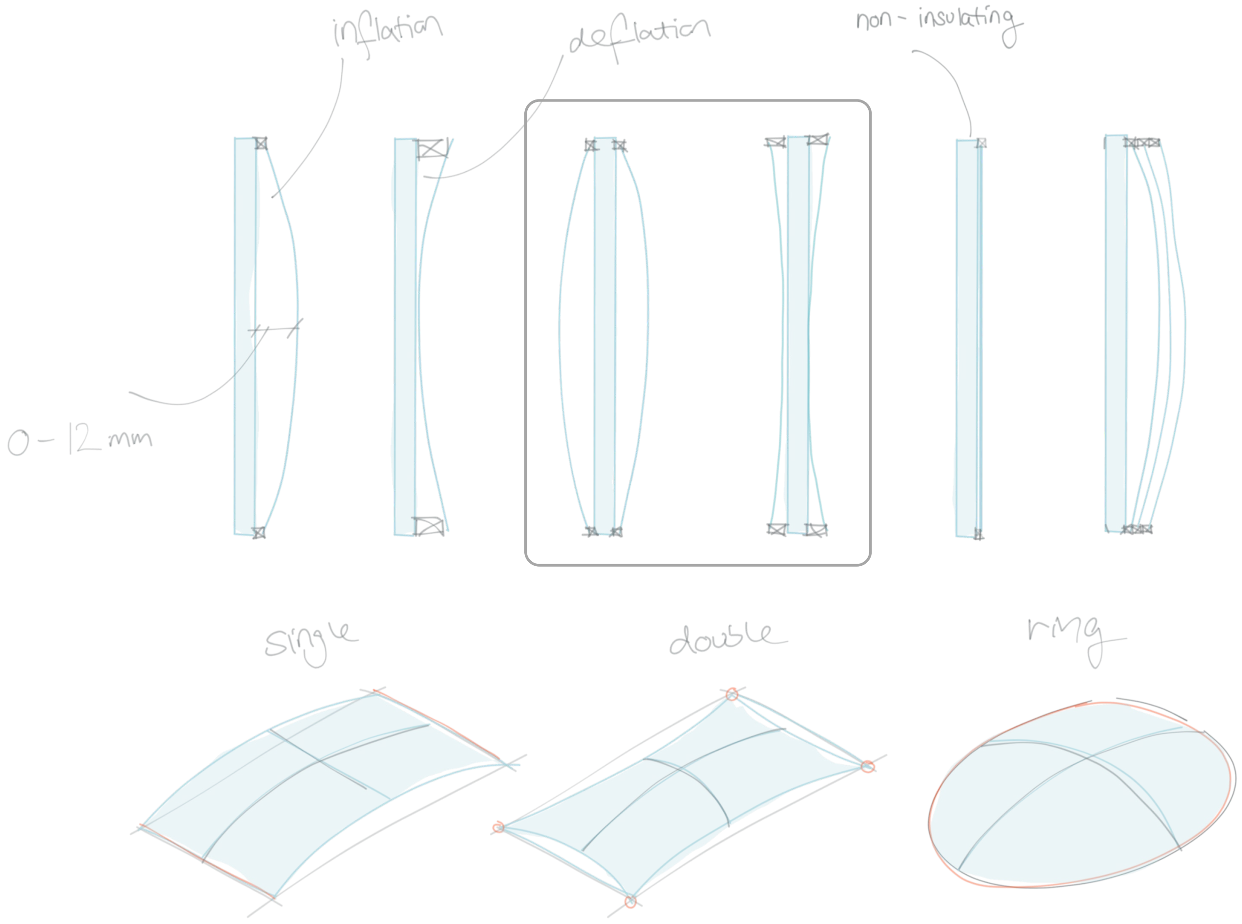
DESIGN CRITERIA

Hard and soft criteria

- **Full transparency** in all insulation states
- Adjusting the U-value from **single to triple glazing properties**
- Manufacturing and assembly similar to **current practices and materials**
- Maintaining **uniform deformation/curvature** of inflated glass
- Ensuring **compatibility with standard façade frames** and aiming for a slim design to use in **renovation projects**

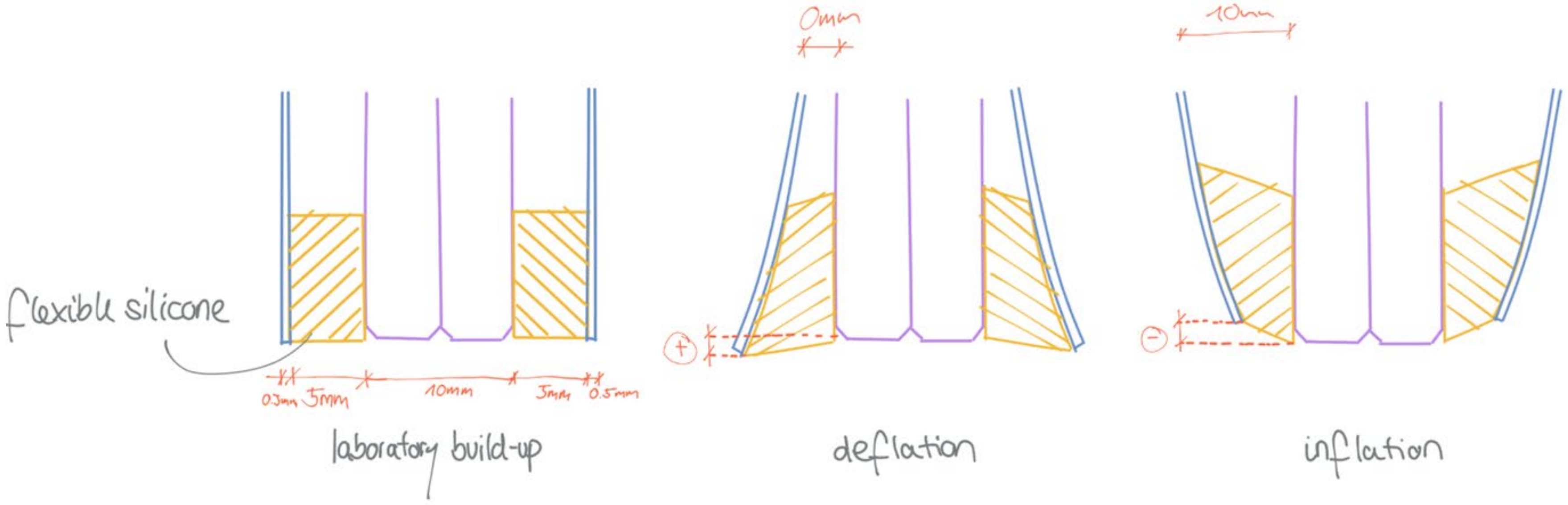
CONCEPT OF INFLATION

Initial sketches



CONCEPT OF INFLATION

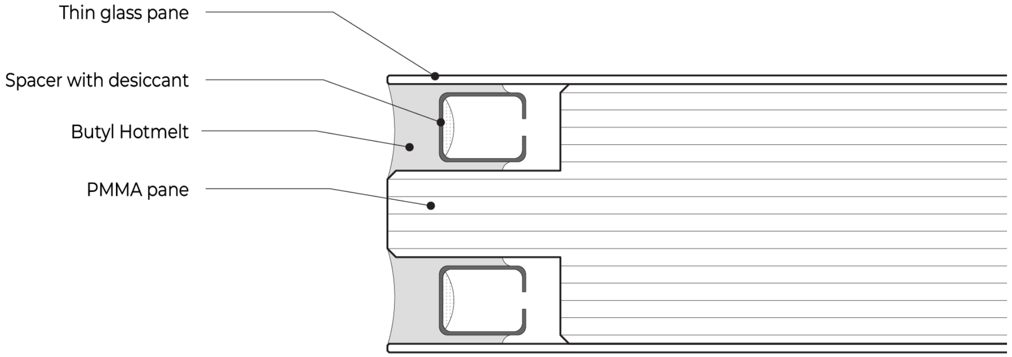
Initial sketches

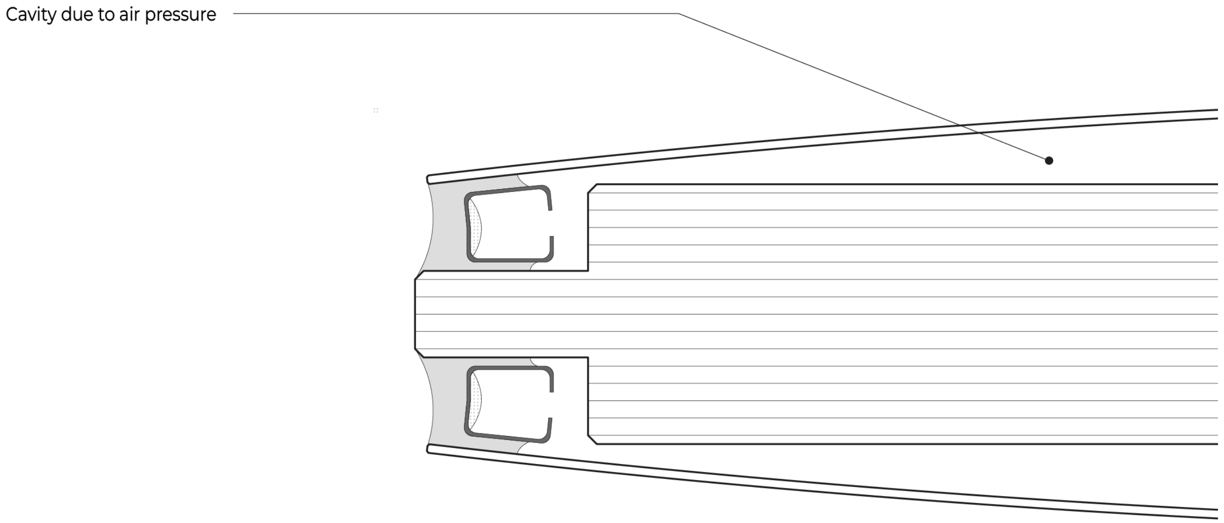


CONCEPT OF INFLATION

Initial sketches

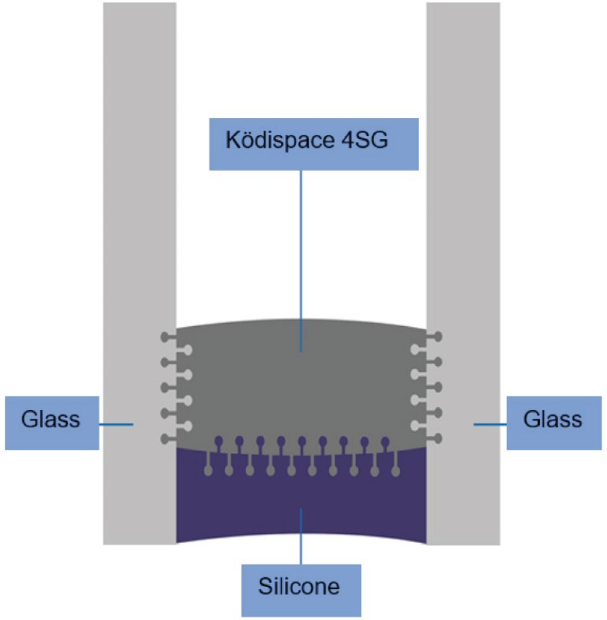
Option 2: C-shaped intercept spacer **acts like a hinge**



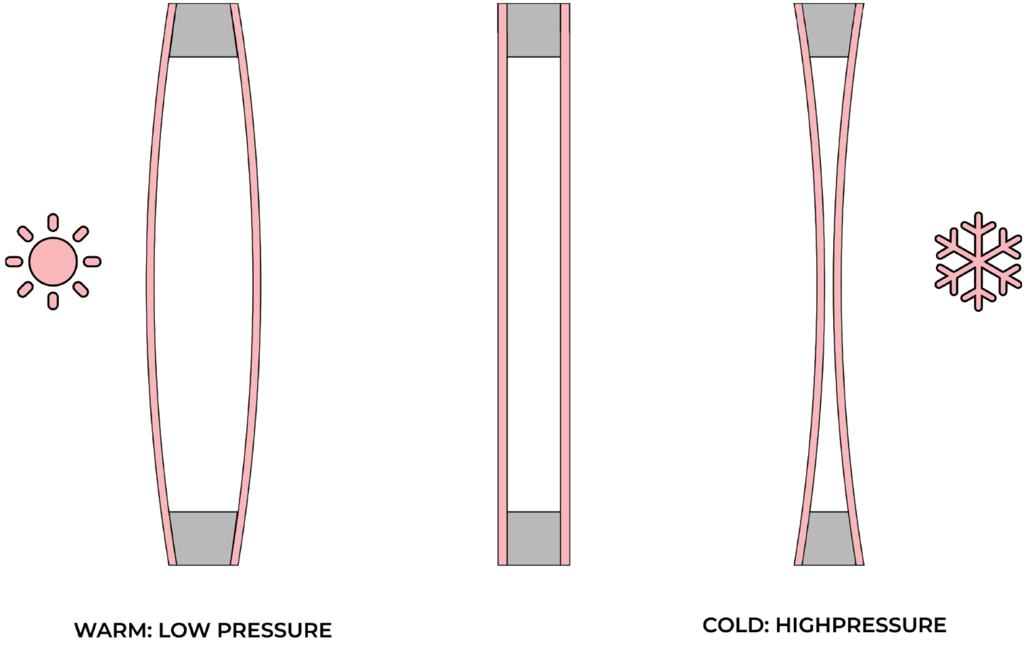


CONCEPT OF INFLATION
Spacer selection

Thermoplastic spacer optimal for resisting shear forces



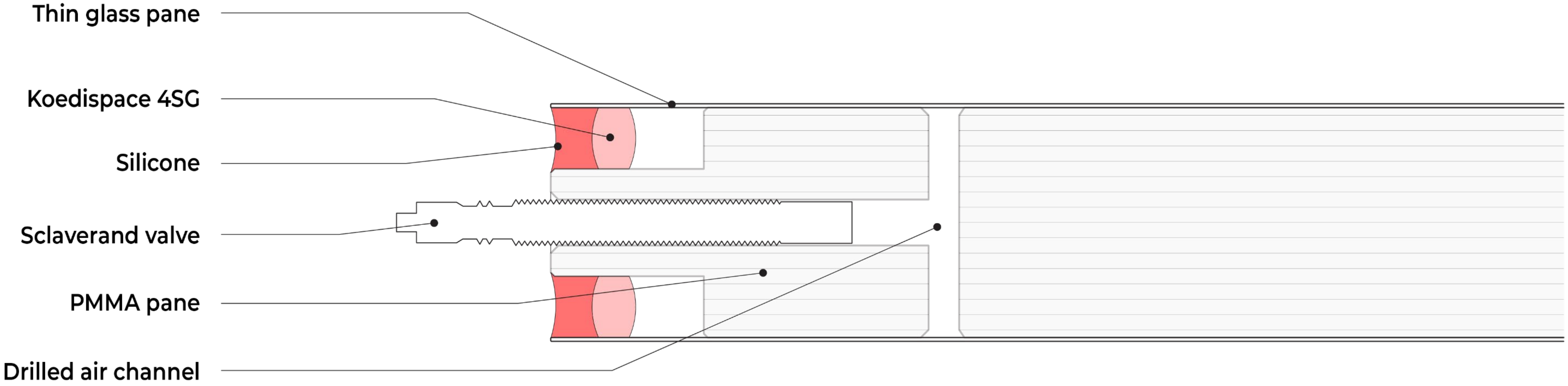
Deformation of IGUs due to **thermal pressure**



CONCEPT OF INFLATION

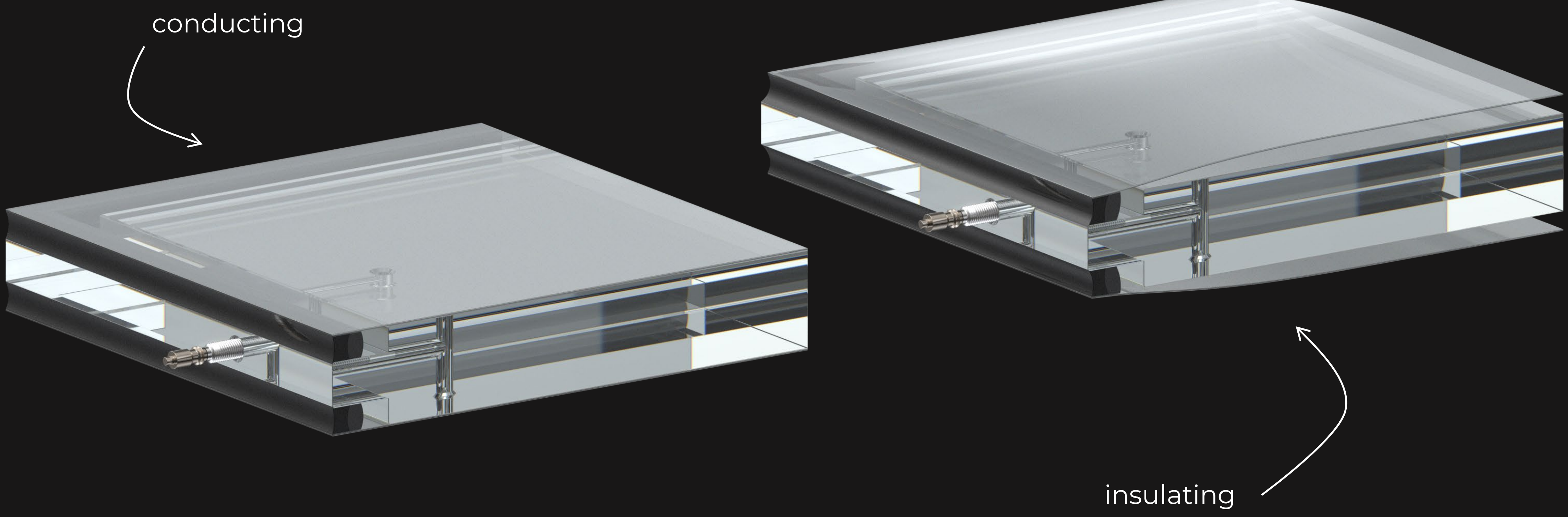
Initial sketches

Final build-up



PROTOTYPE CORNER FRAGMENT

Relaxed vs inflated state

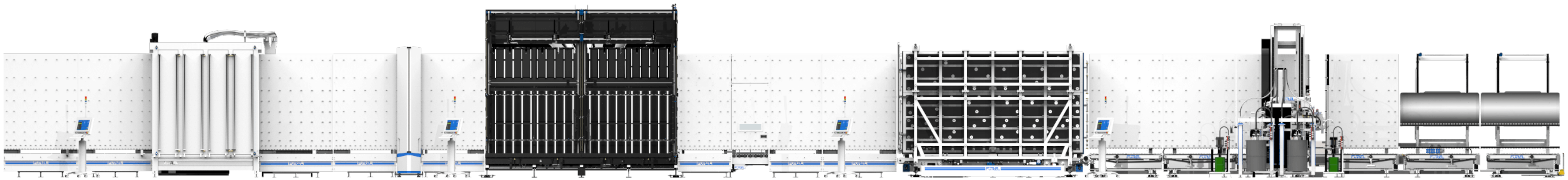


MANUFACTURING

Ideal manufacturing process in an automated facility

THERMOPLASTIC HIGH-TECH LINE

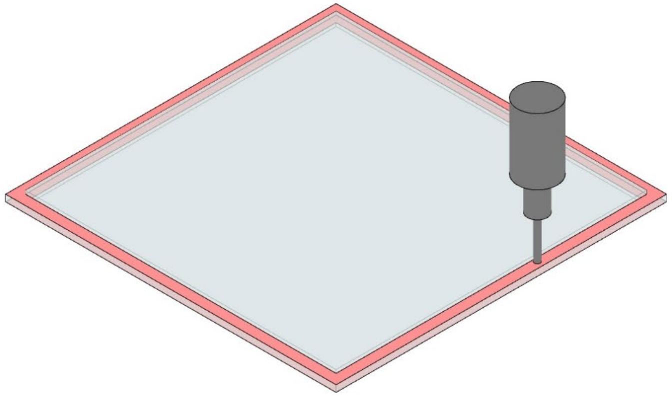
Fully automatic IGU assembly line



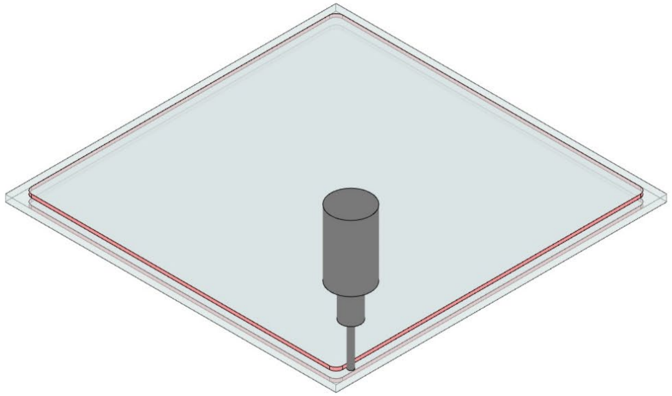
(Forel Spa, 2023)

PMMA PANE PREPARATION

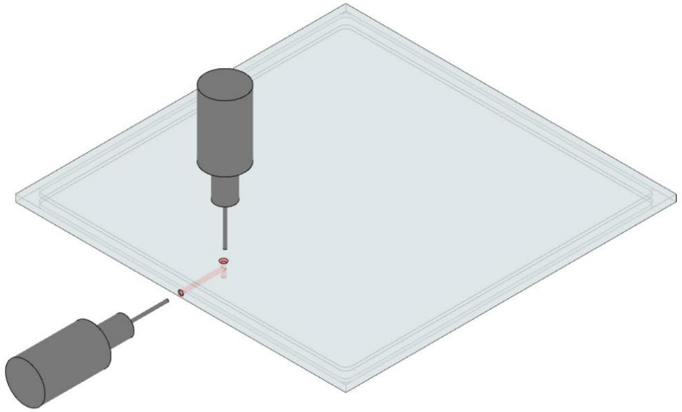
Step 1



Edge groove milling

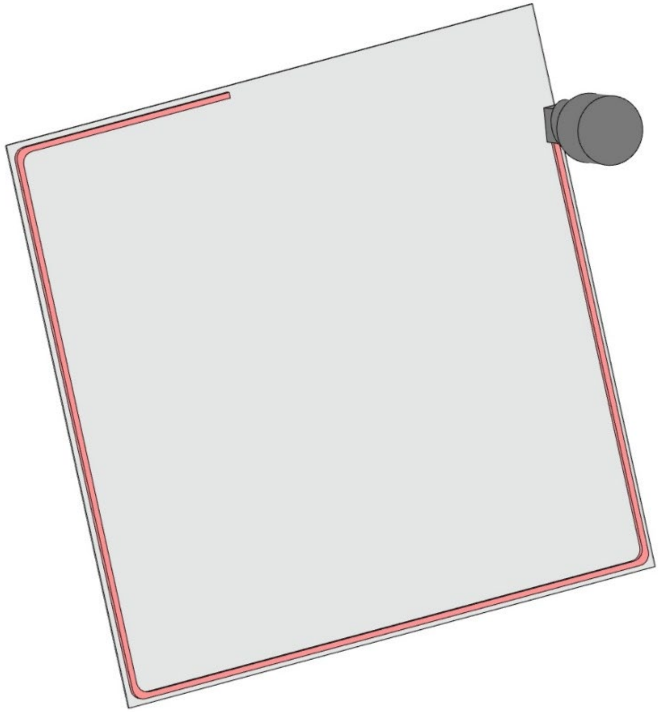


Beveling corners



Drilling T-channel

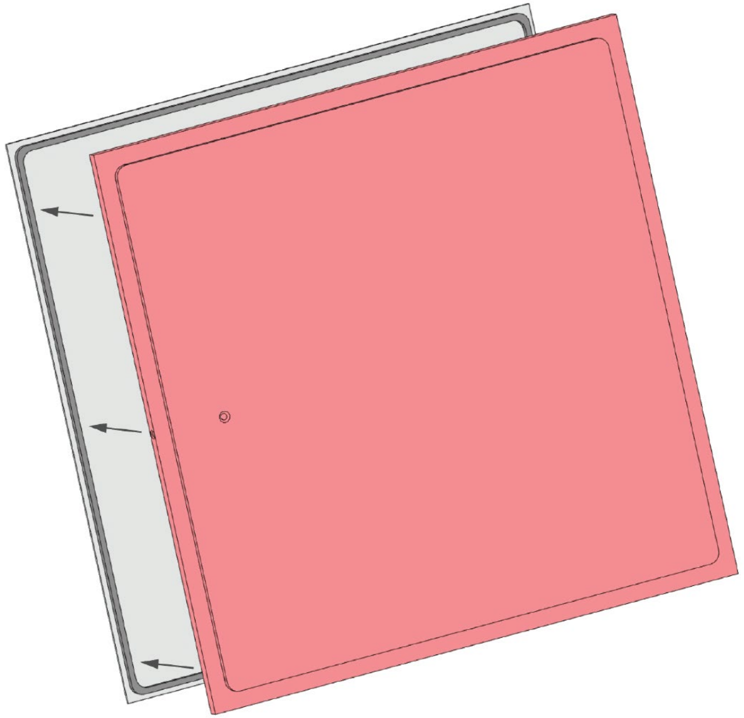
CNC OPERATED SPACER APPLICATION
Step 2



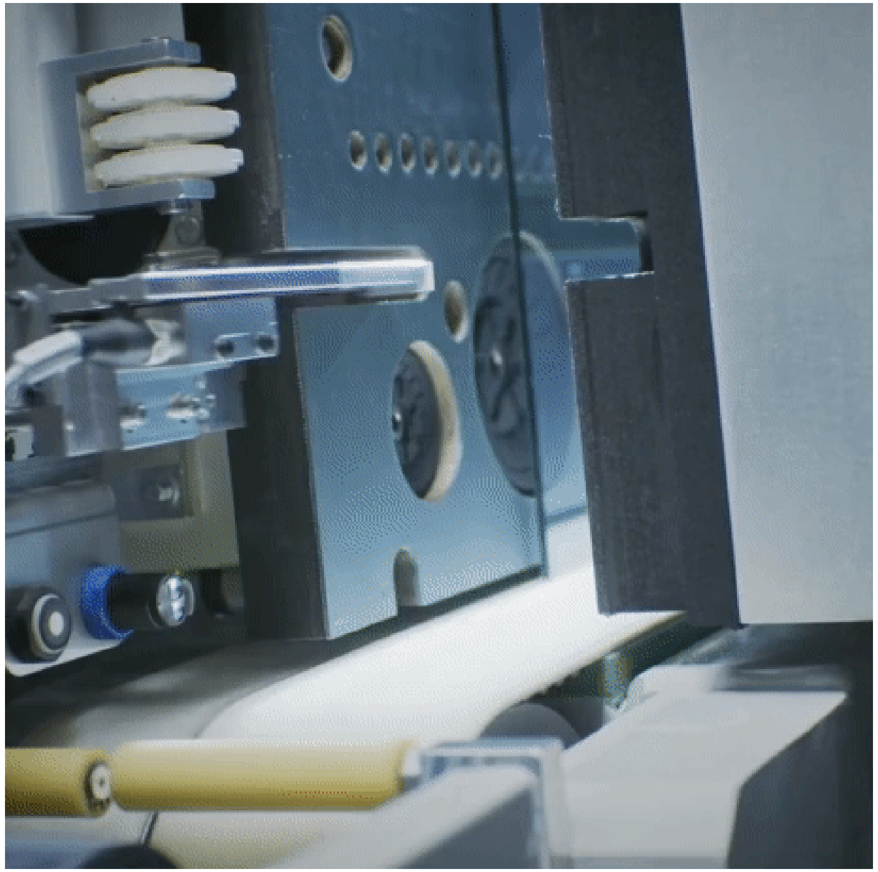
4SG thermoplastic spacer application

(Forel Spa, 2023)

COUPLING PRESS
Step 3



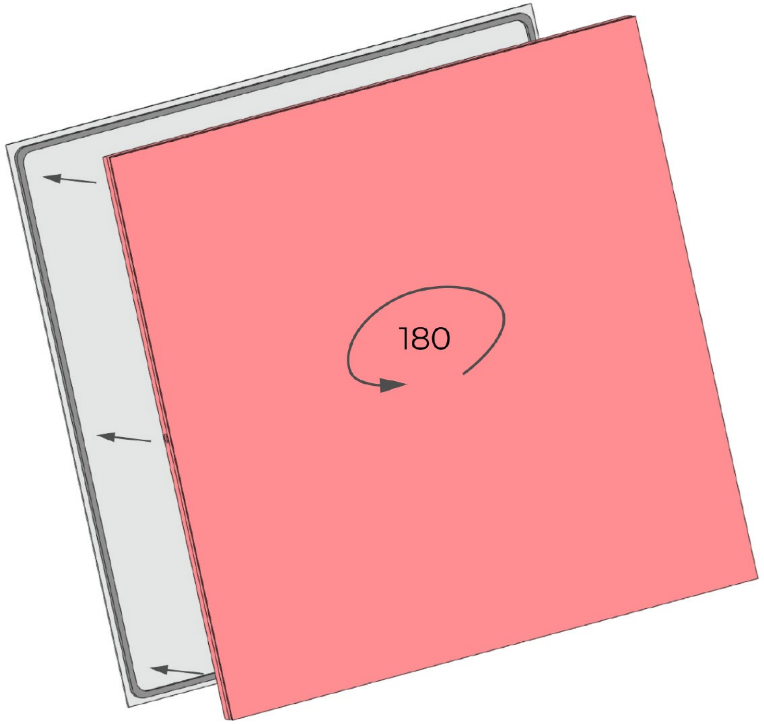
Coupling press, bonding glass with PMMA



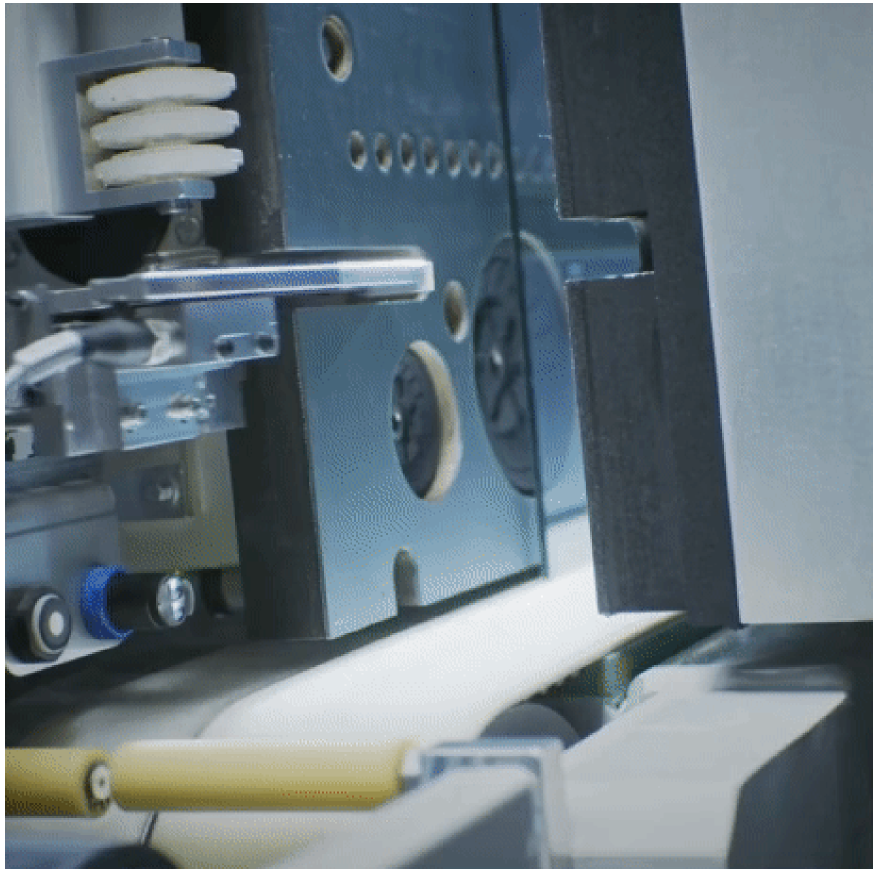
(Forel Spa, 2023)

COUPLING PRESS

Step 4



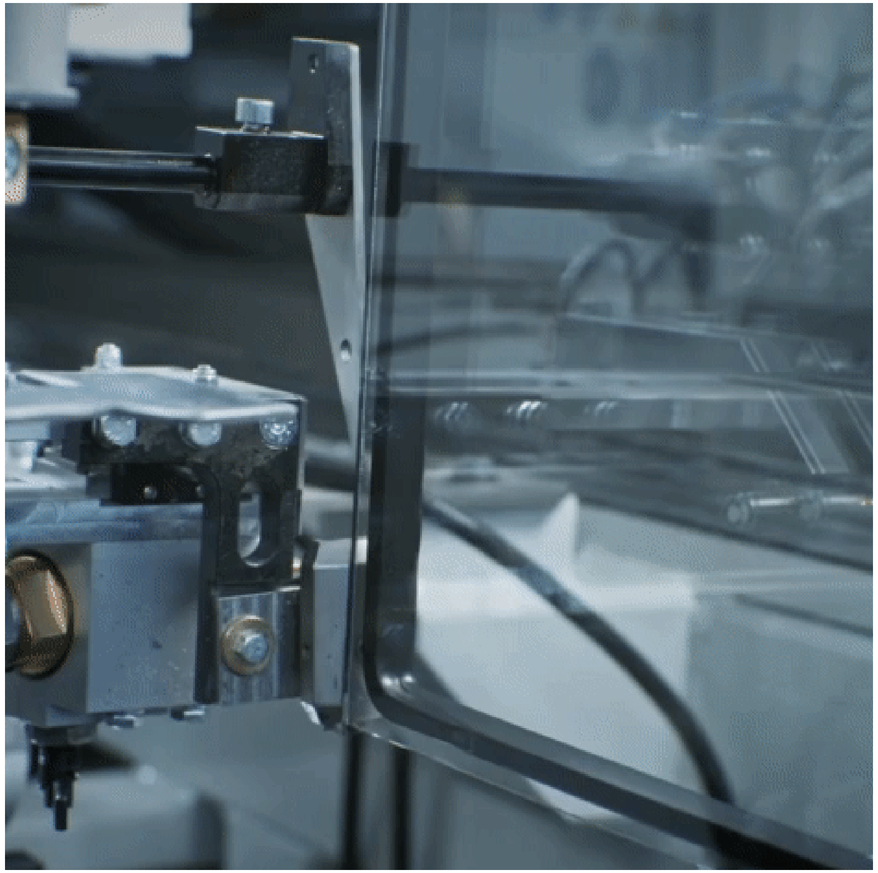
Coupling press, bonding unit to second glass pane



(Forel Spa, 2023)

SECONDARY SEAL APPLICATION
Step 5

Silicone (secondary) seal application

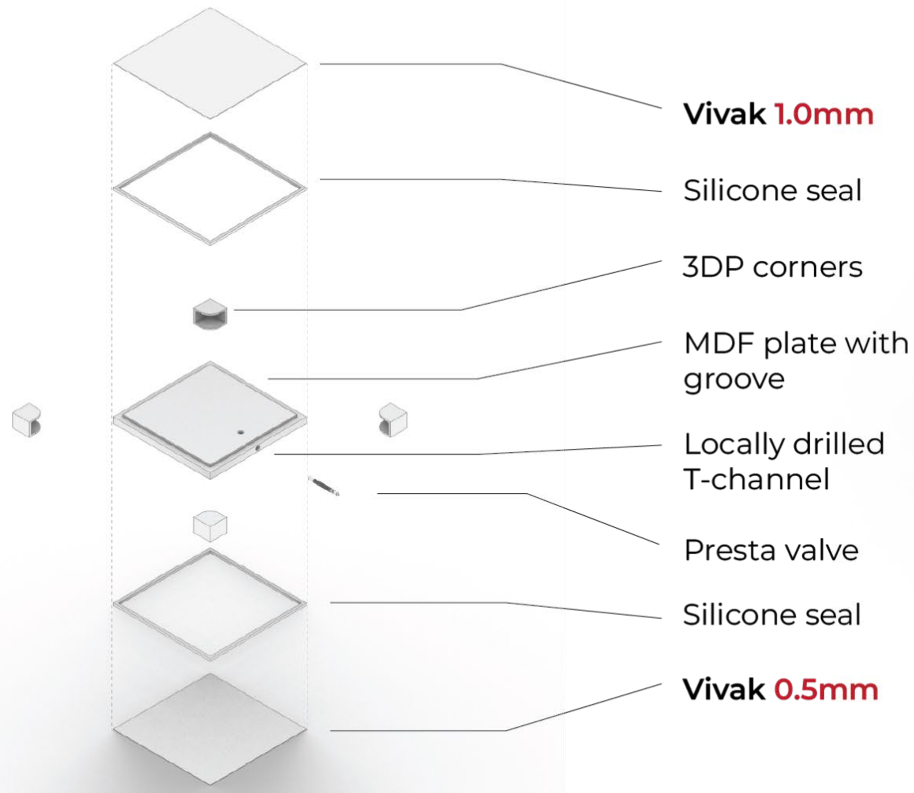


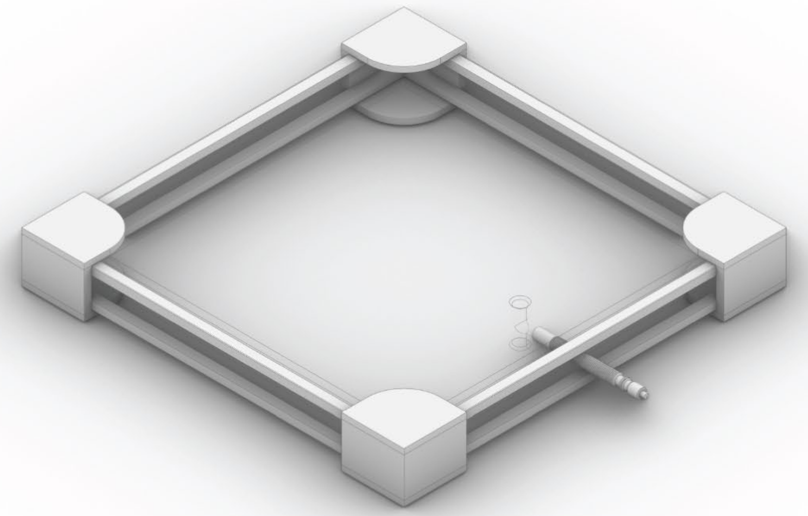
(Forel Spa, 2023)

PROTOTYPING & EXPERIMENTS

Various prototypes and surface evaluation

PETG/MDF PROTOTYPE
First inflation test





PETG/MDF PROTOTYPE
First inflation test




1.0mm Vivak

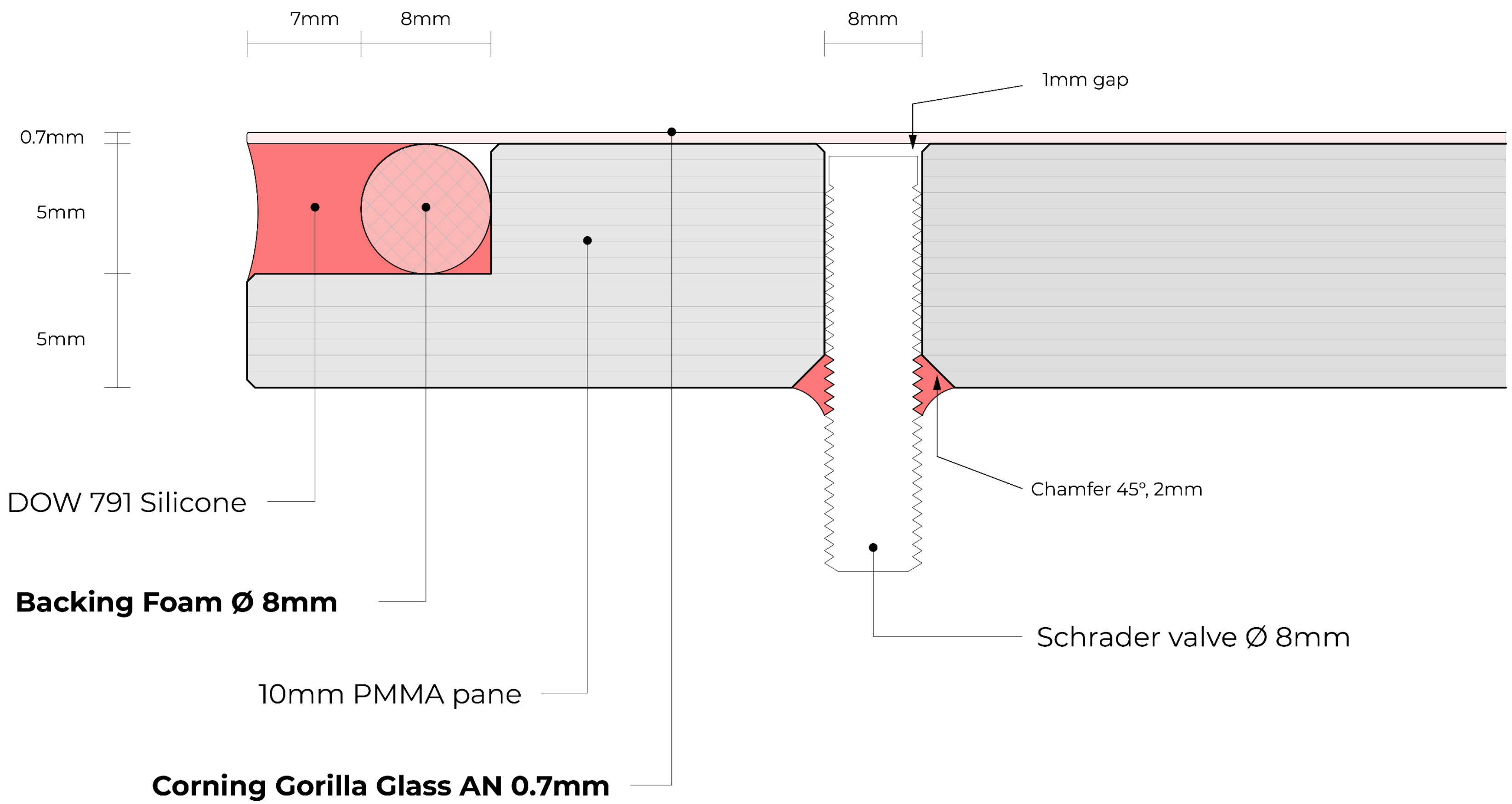
8mm deformation

0.5mm Vivak

12mm deformation

ANNEALED THIN GLASS PROTOTYPE

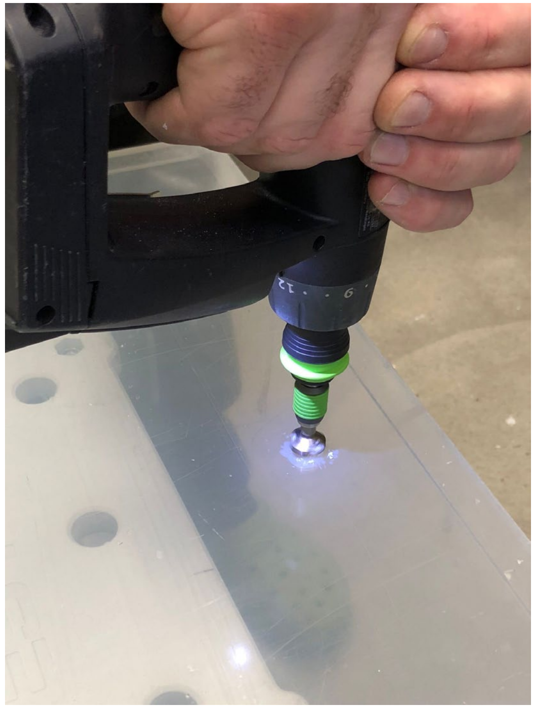
Composition



ANNEALED THIN GLASS PROTOTYPE
Manufacturing

Sawing groove

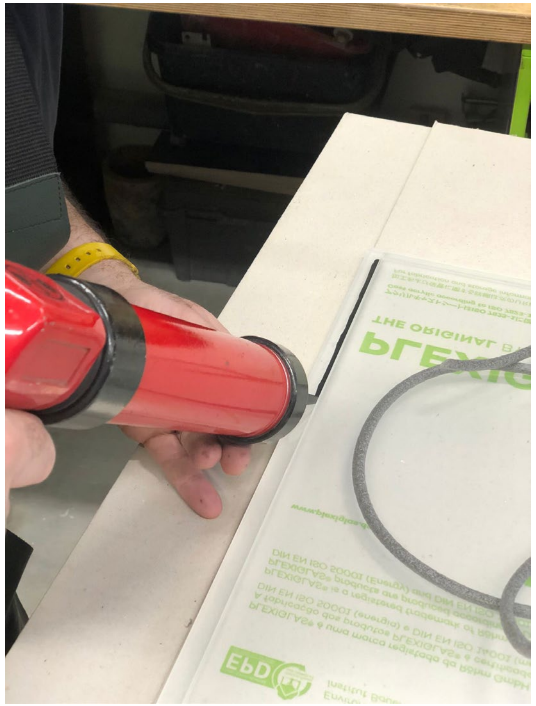

Edge groove


Drilling & chamfering

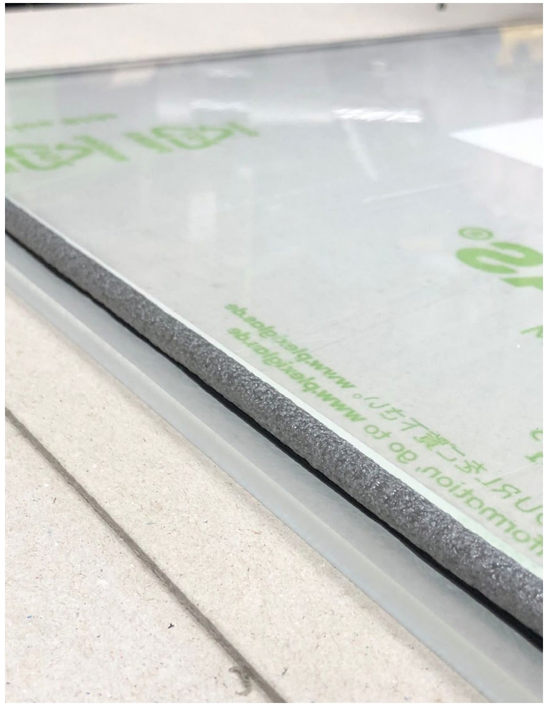
Cone drilling

ANNEALED THIN GLASS PROTOTYPE

Assembly



Silicone for foam bead

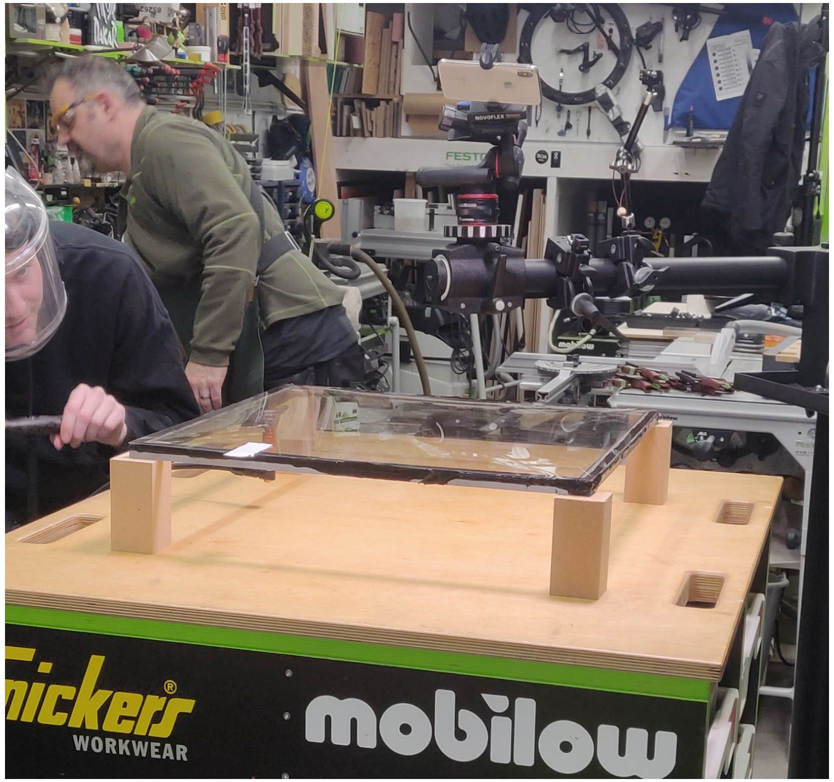


Foam bead application

Sealed valve

Edge sealant & clamping

ANNEALED THIN GLASS PROTOTYPE
Inflation

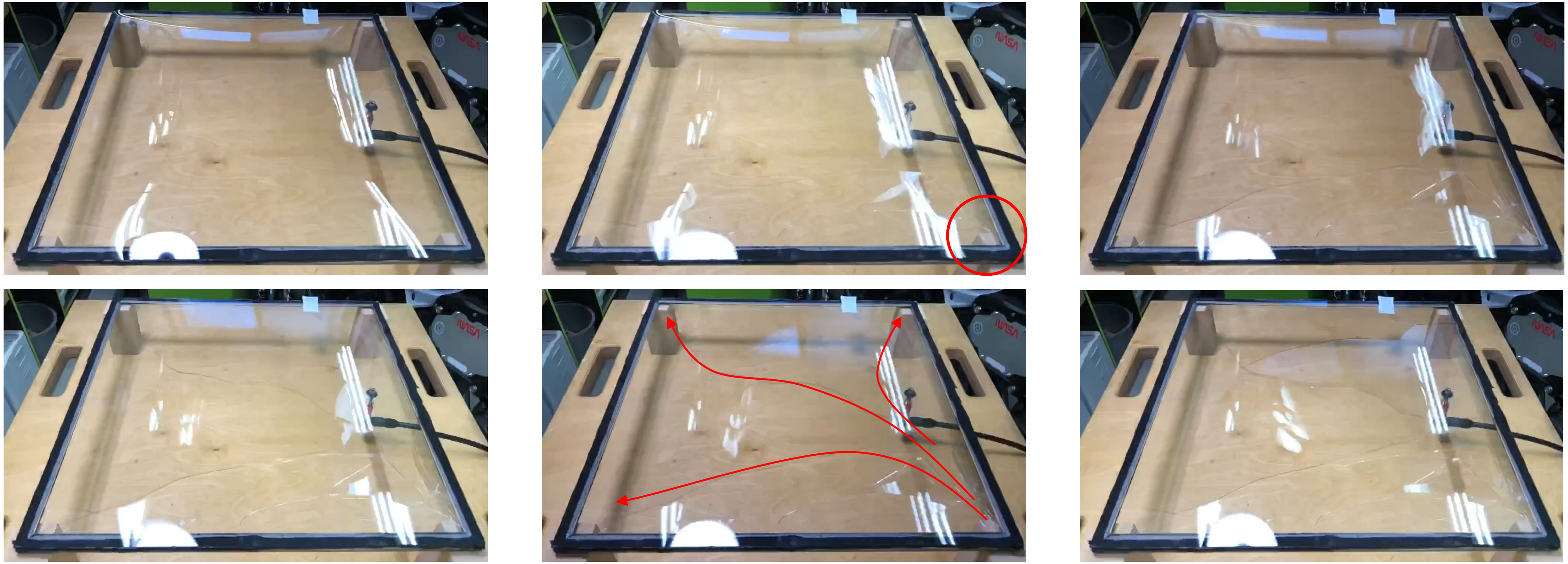


Setup: Unit on 4 wooden blocks with bicycle pump attached

Inflation: Minimal pressure was needed to achieve a 10-15mm cavity

ANNEALED THIN GLASS PROTOTYPE

Breakage

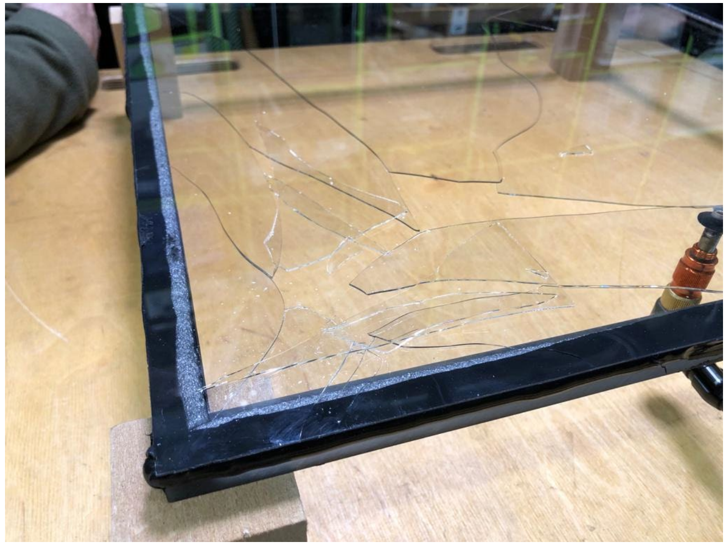


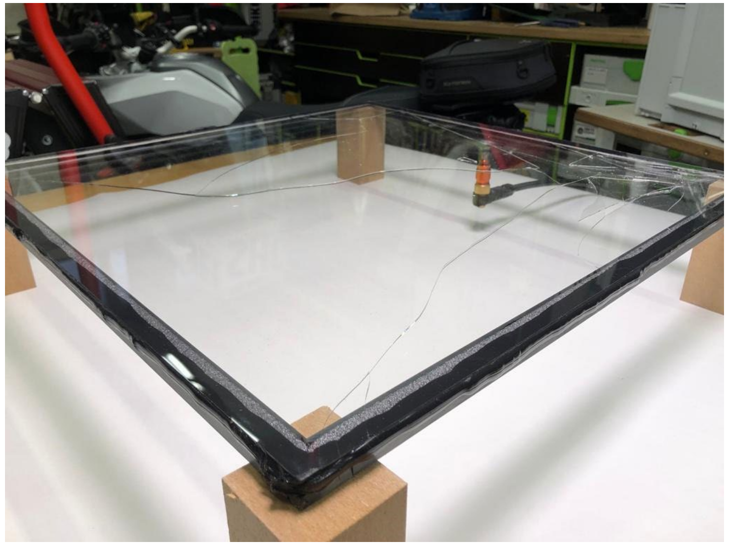
Breakage Frames: cracks emerged from corner bottom right

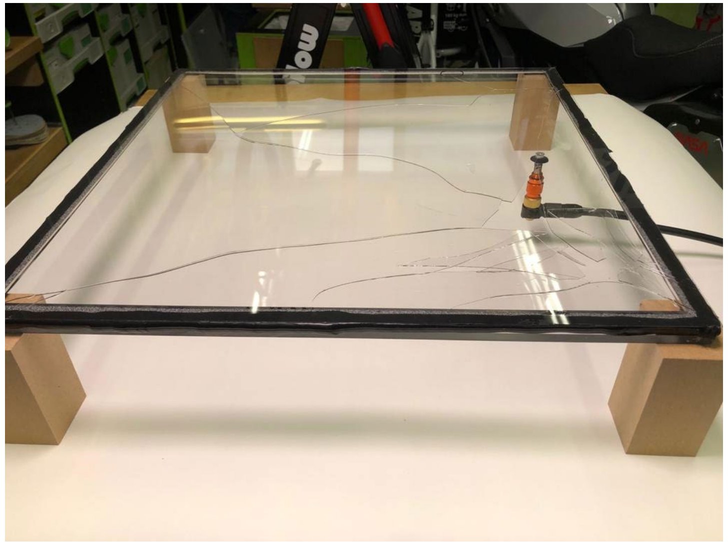
PROTOTYPING

ANNEALED THIN GLASS PROTOTYPE

Breakage







Main issue: Silicone did **not cure**

3D SCANNING PROTOTYPES

2 different glass manufacturers with different edge details

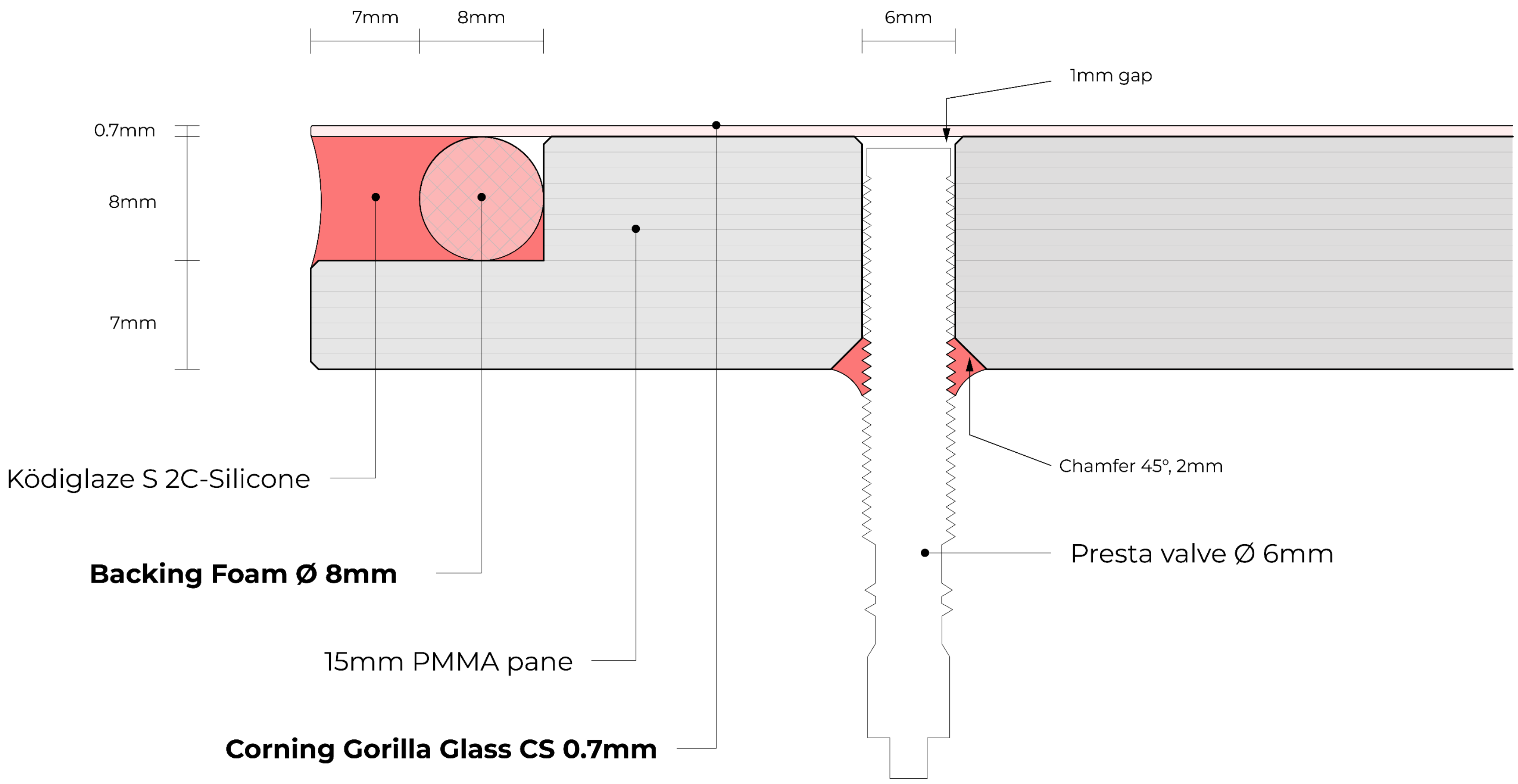
2-COMPONENT SILICONE GUN

With Kömmerlings Ködiglaze S

PROTOTYPING

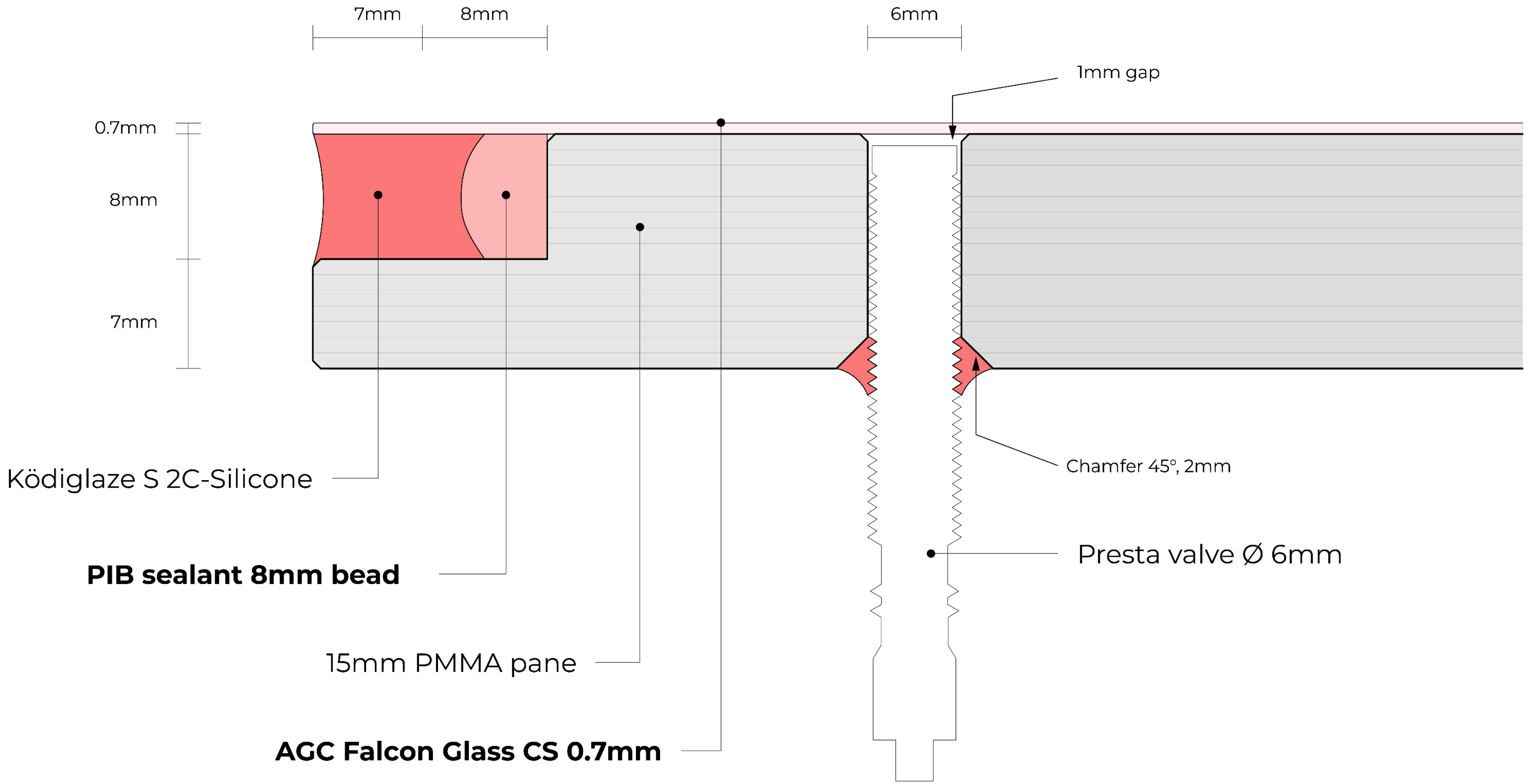
CORNING GORILLA GLASS PROTOTYPE

Edge detail



AGC FALCON GLASS PROTOTYPE

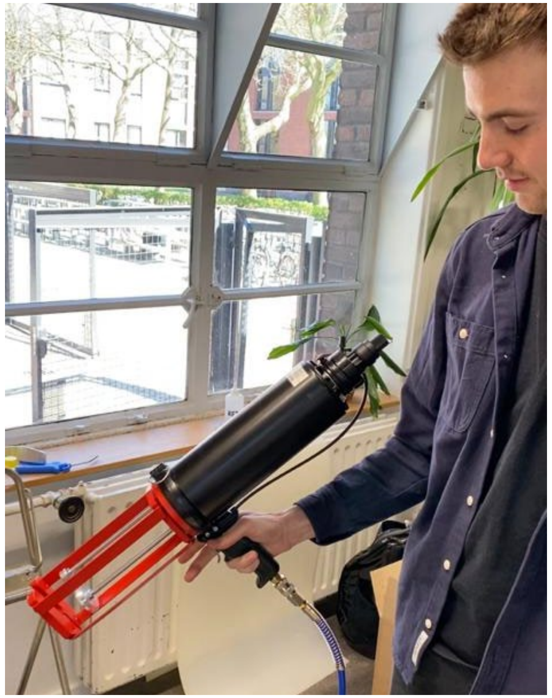
Edge detail



PROTOTYPING

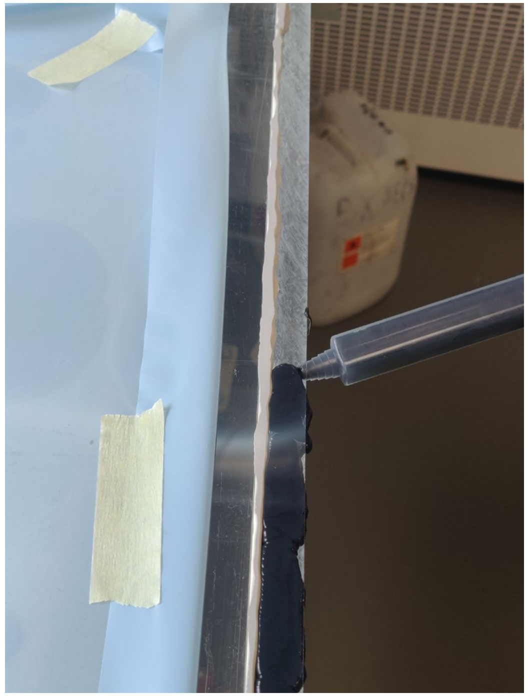
CHEMICALLY STRENGTHENED PROTOTYPES

Assembly



Silicone gun

Self-mixing extruder



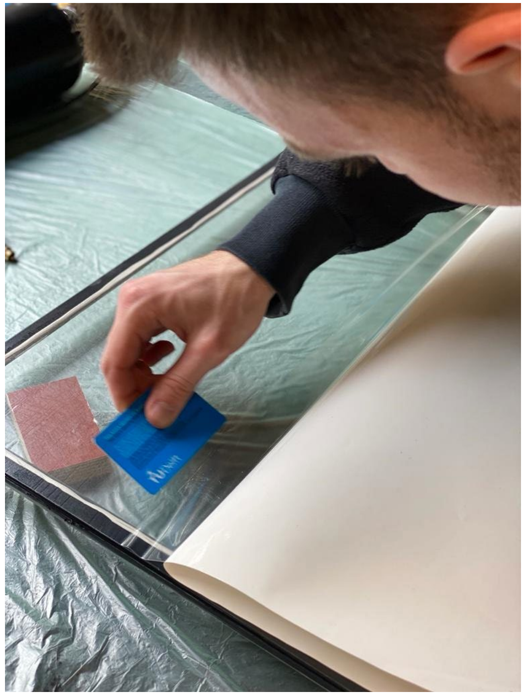
Silicone application

Finished edge seal

CHEMICALLY STRENGTHENED PROTOTYPES
Assembly

Taping edges

Valve insertion from below



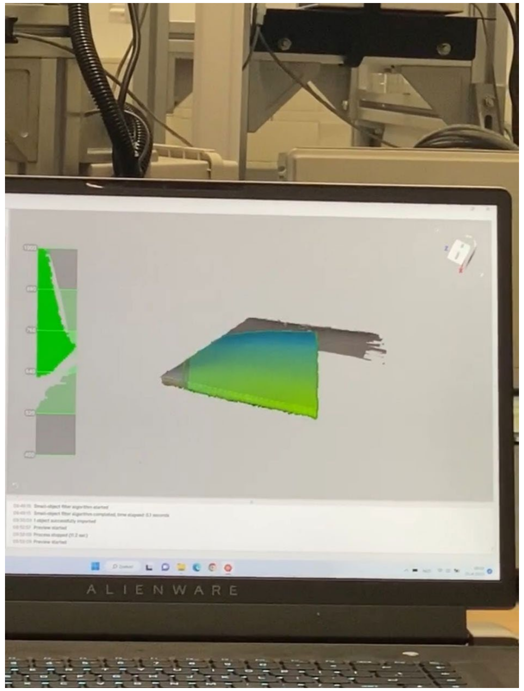
PVC foil application

Spray painting

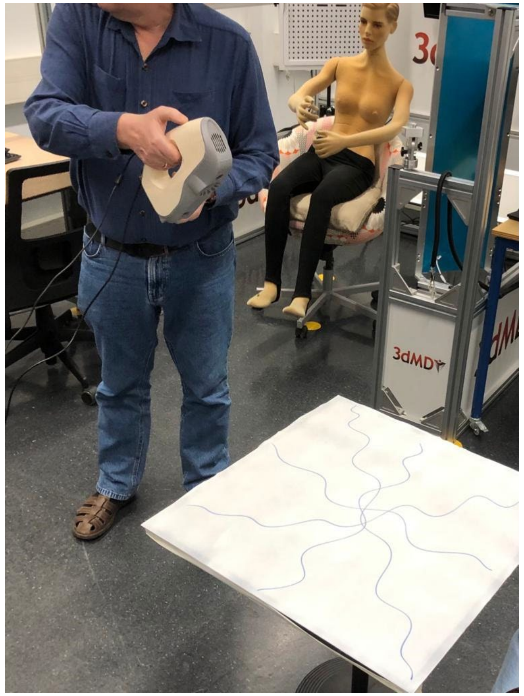
3D SCANNING AT CDAM

Faculty of Industrial Design

Drawing random lines



Real time results



Rotating table

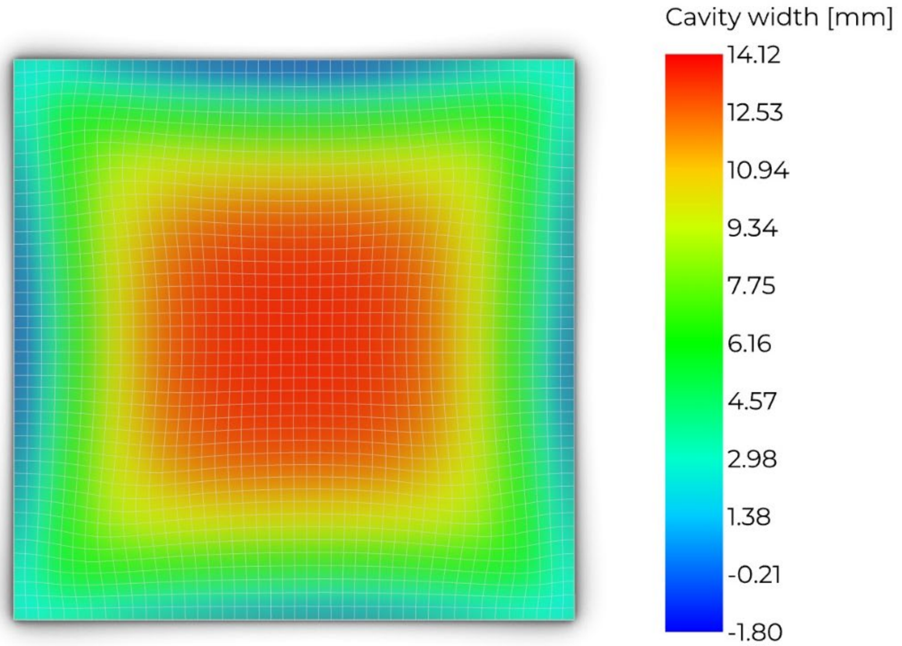
Corning unit with flaw

CORNING THIN GLASS UNIT WITH EDGE DEFORMATION
4 steps of inflation

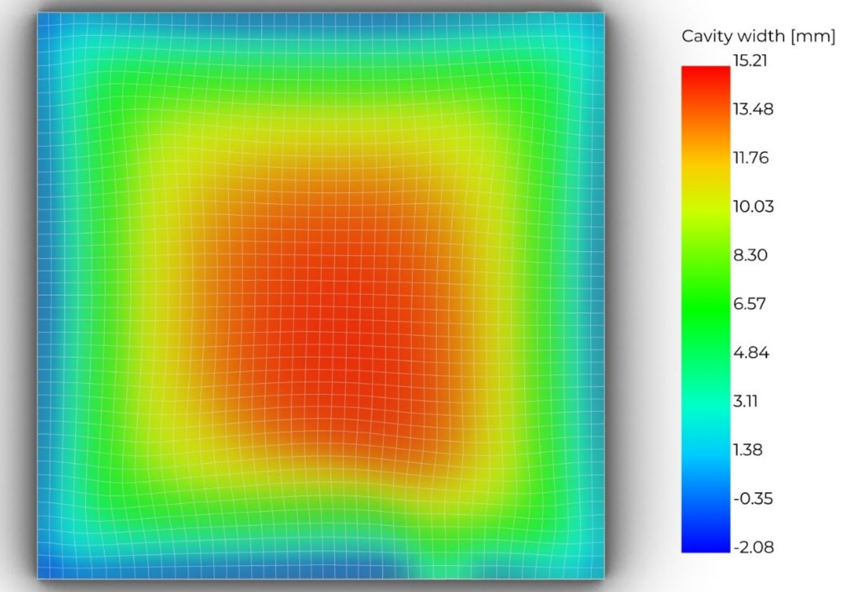
relaxed | 1 | 2 | 3 | 4

3D SCAN DEFORMATION EVALUATION

15mm cavity before edge bond failed



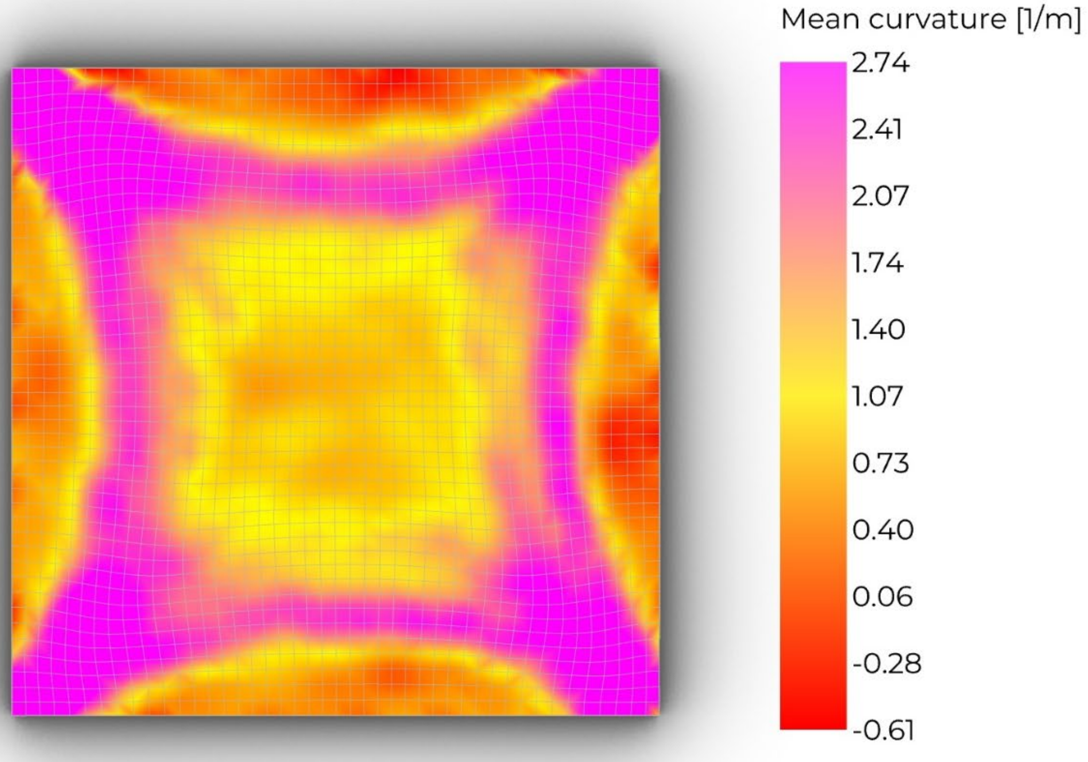
AGC Falcon Glass

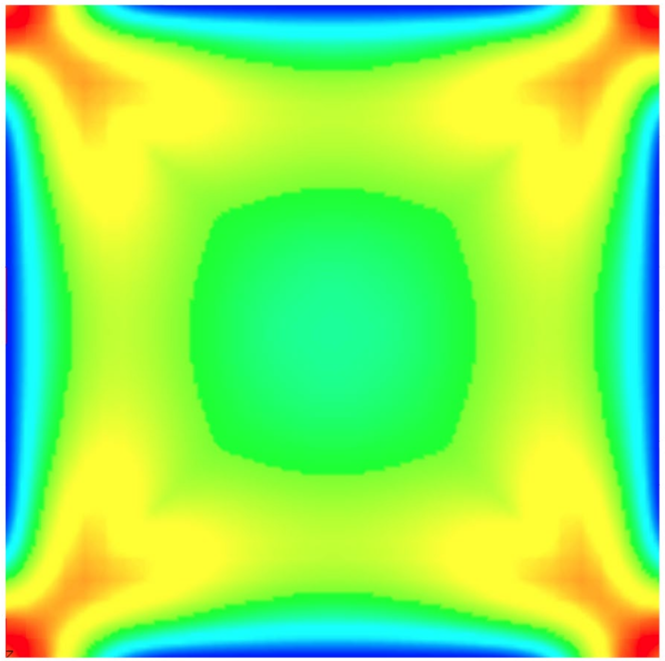


Corning Gorilla Glass

3D SCAN CURVATURE EVALUATION

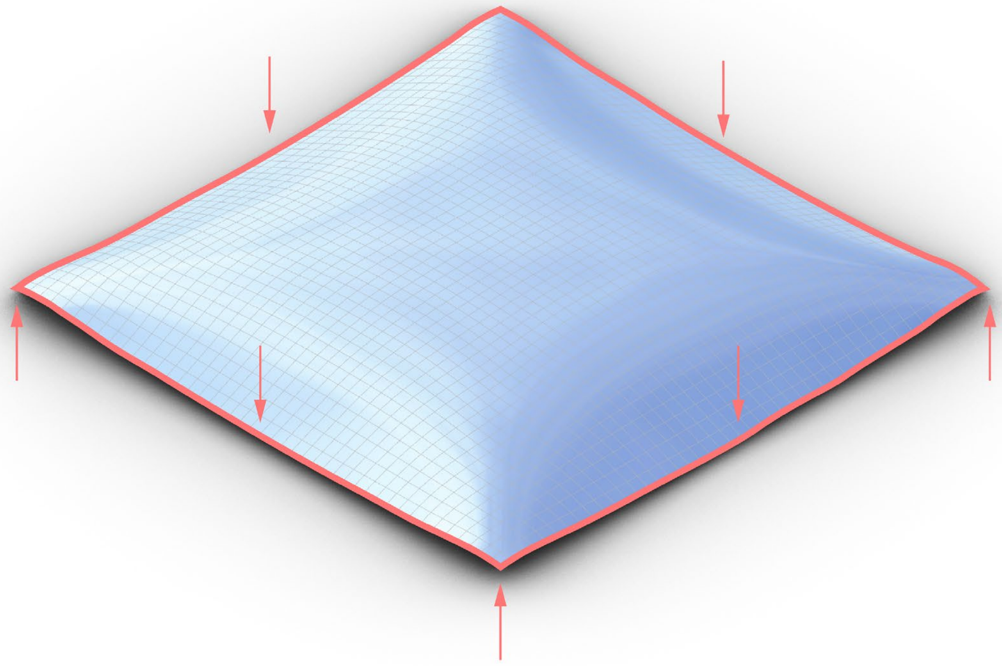
Highest curvatures similar to FEA principal stress pattern

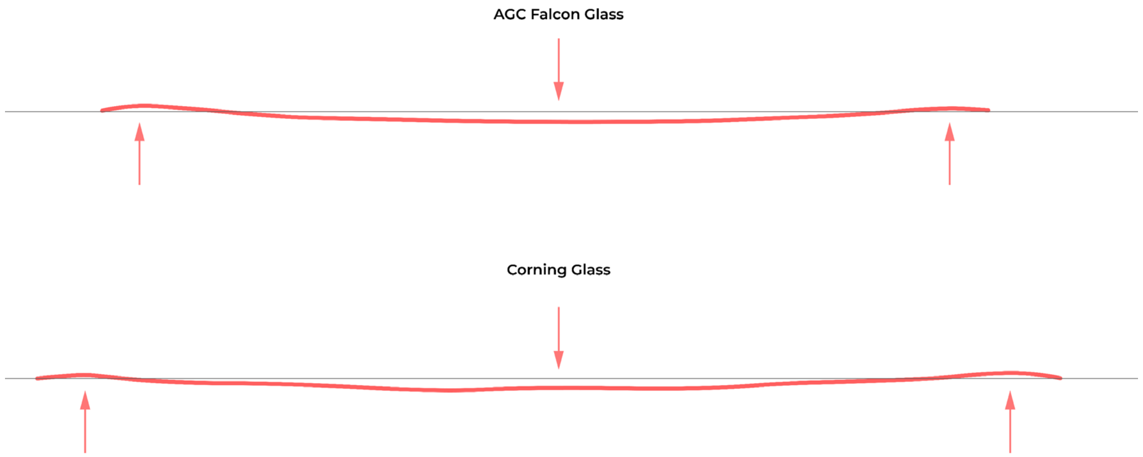




3D SCAN CURVATURE EVALUATION

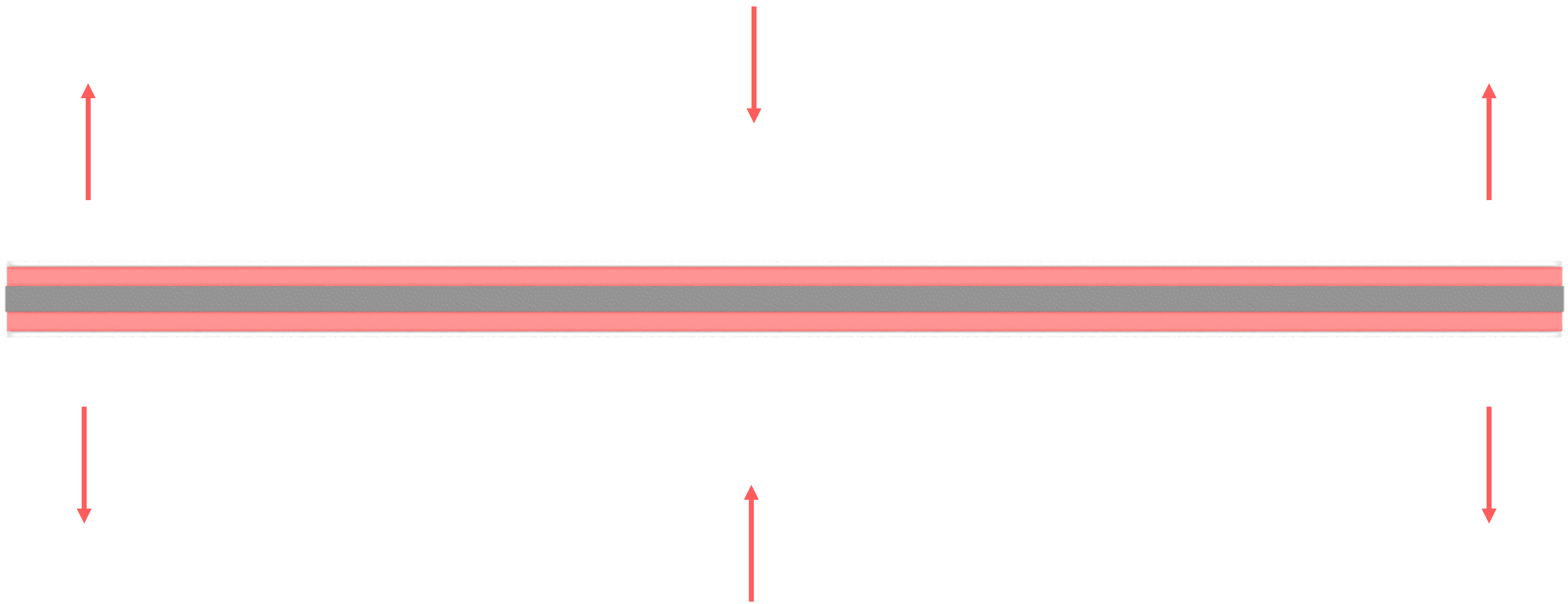
Edge and corner deformation





3D SCAN CURVATURE EVALUATION

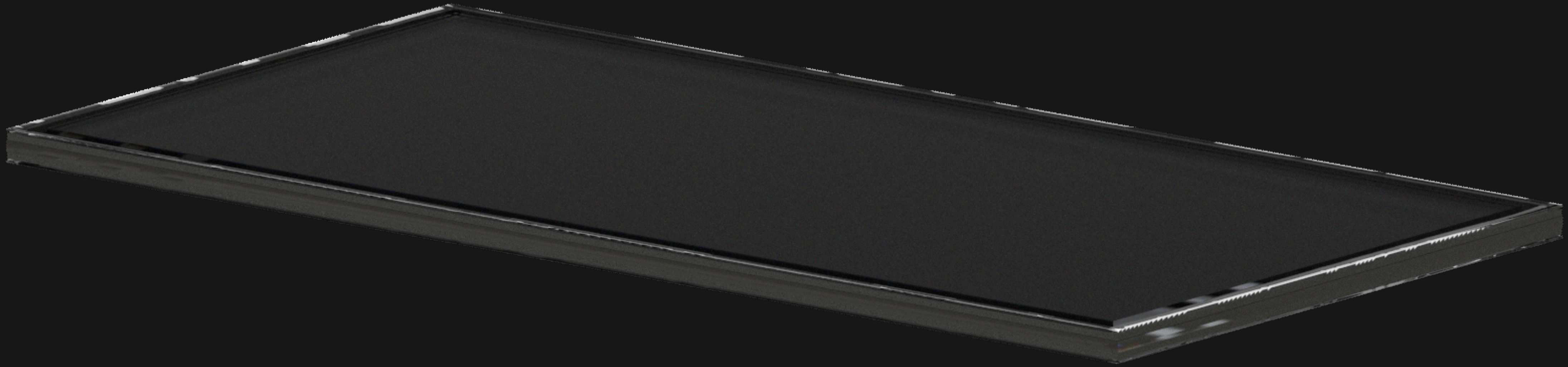
Edge and corner deformation, scaled x3



Elevation – edge seal deformation

REFLECTIONS OF INFLATED UNIT

Scaled by x3 for a 1500x3000mm panel



THERMAL PERFORMANCE

U-value calculation and ideal cavity widths

SIMULATION WORKFLOW

According to EN-673:2011

$$\frac{1}{U} = \frac{1}{h_e} + \frac{1}{h_t} + \frac{1}{h_i}$$ (Formula 1)

$$\frac{1}{h_t} = \sum_{1}^{N} \frac{1}{h_s} + \sum_{1}^{M} d_j \cdot r_j$$ (Formula 2)

$$h_{s,k} = h_{r,k} + h_{g,k}$$ (Formula 3)

U-value

Material Thickness

$$h_r = 4\sigma \left(\frac{1}{\varepsilon_{1,k}} + \frac{1}{\varepsilon_{2,k}} - 1 \right)^{-1} T_{m,k}^{3}$$ (Formula 4)

Radiation conductance

Low-e coating

$$h_{g,k} = Nu \frac{\lambda_k}{s_k}$$ (Formula 5)

$$Nu = A \cdot (Gr \cdot Pr)^n$$ (Formula 6)

Nusselt number

Cavity width

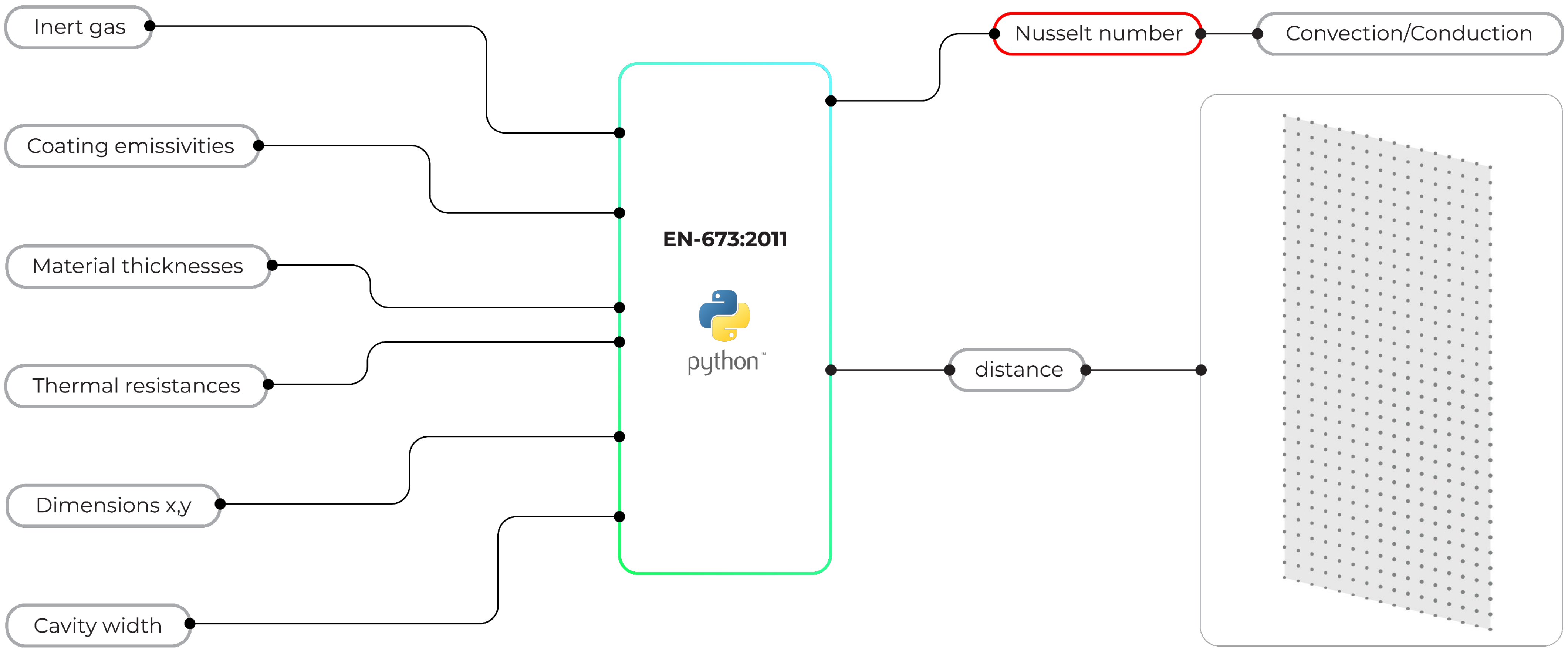
$$Gr = \frac{9{,}81\, s^3 \Delta T \cdot \rho^2}{T_m \mu^2}$$ (Formula 7)

$$Pr = \frac{\mu c}{\lambda}$$ (Formula 8)

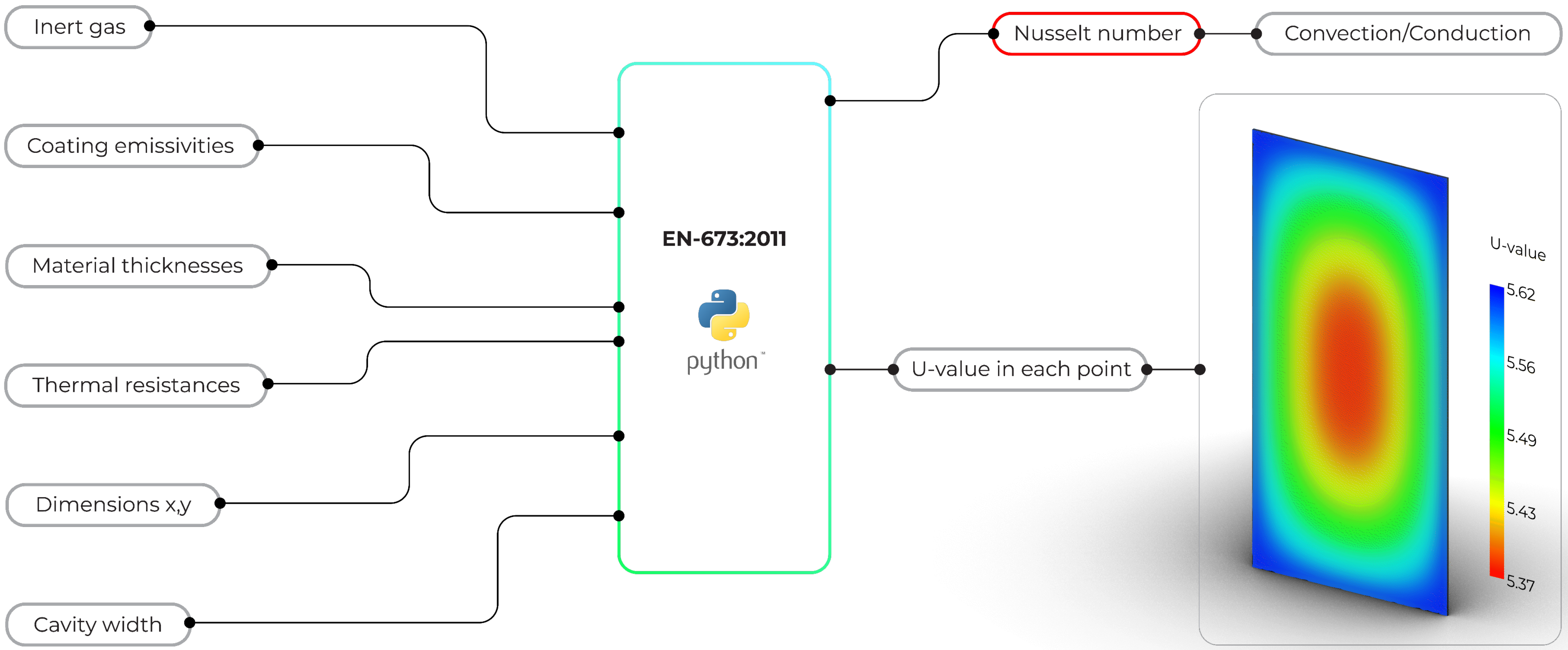
Gas conductance

Gas infill

SIMULATION WORKFLOW
According to EN-673:2011

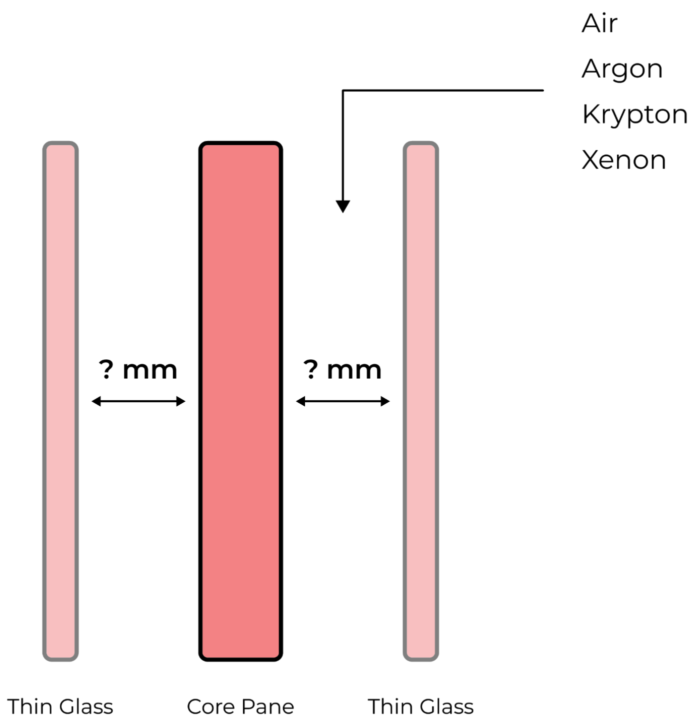


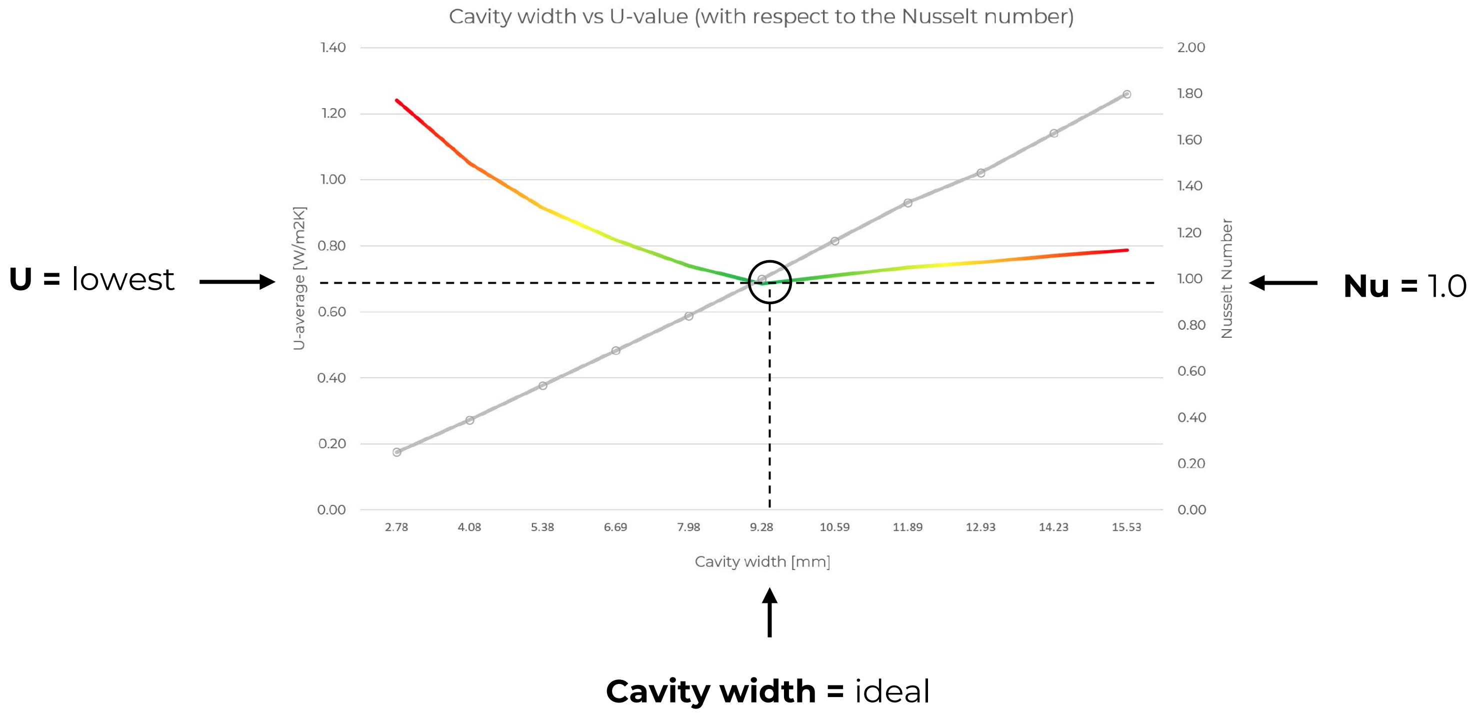
SIMULATION WORKFLOW
According to EN-673:2011



CAVITY WIDTH AND NUSSELT NUMBER

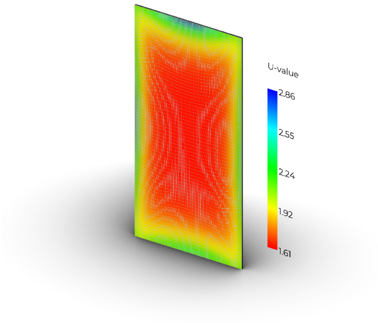
According to EN-673:2011

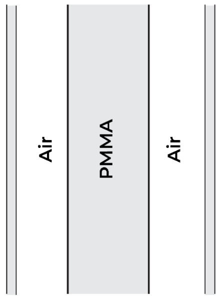




THERMAL PERFORMANCE RESULTS

Different specifications resulting in different cavity widths





U_{av}= 1.82-3.90

Change: 214%

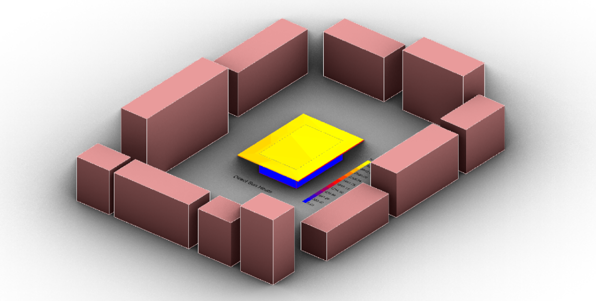
Ideal cavity: 16mm

ENERGY EFFICIENCY

Energy model evaluating location, passive and active performance

ENERGY MODEL
Building, model and analyses

Building + context



fully glazed
12x6m
office function
overhang shading
context

Energy model

python

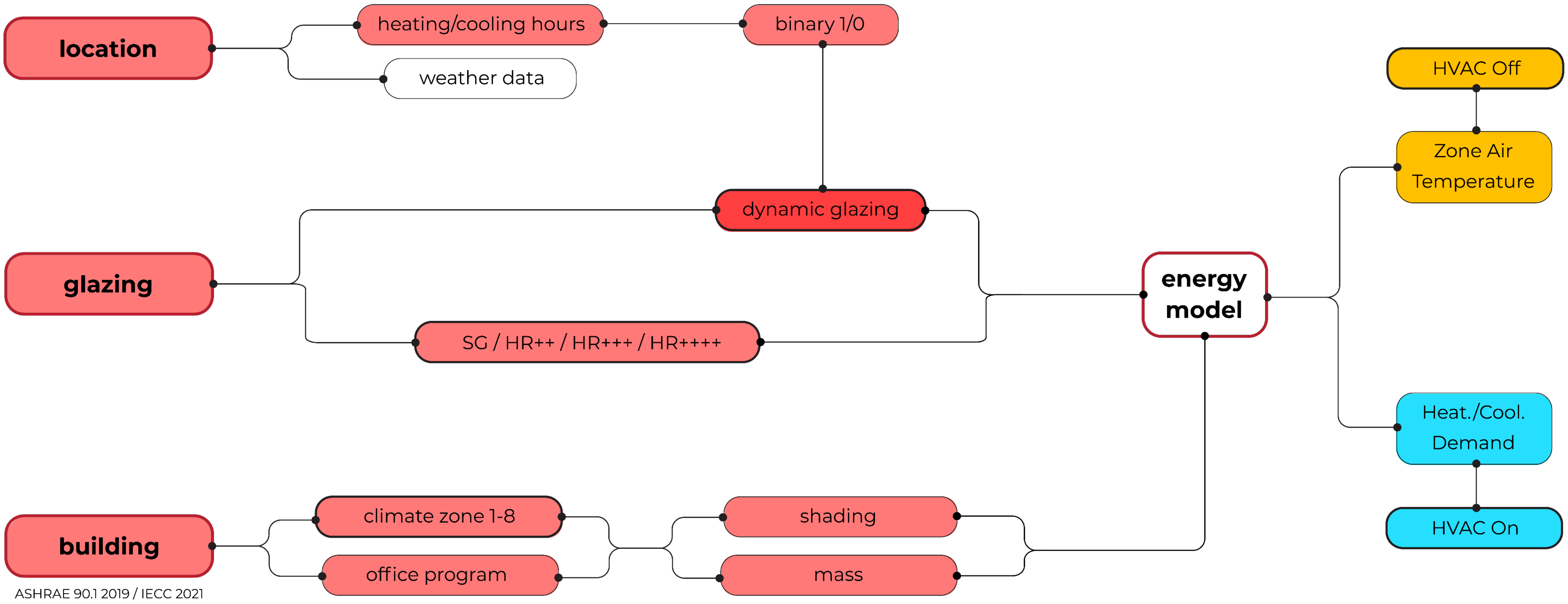
Simulations

1 Optimal location

2 Zone air temperature

3 Energy demand

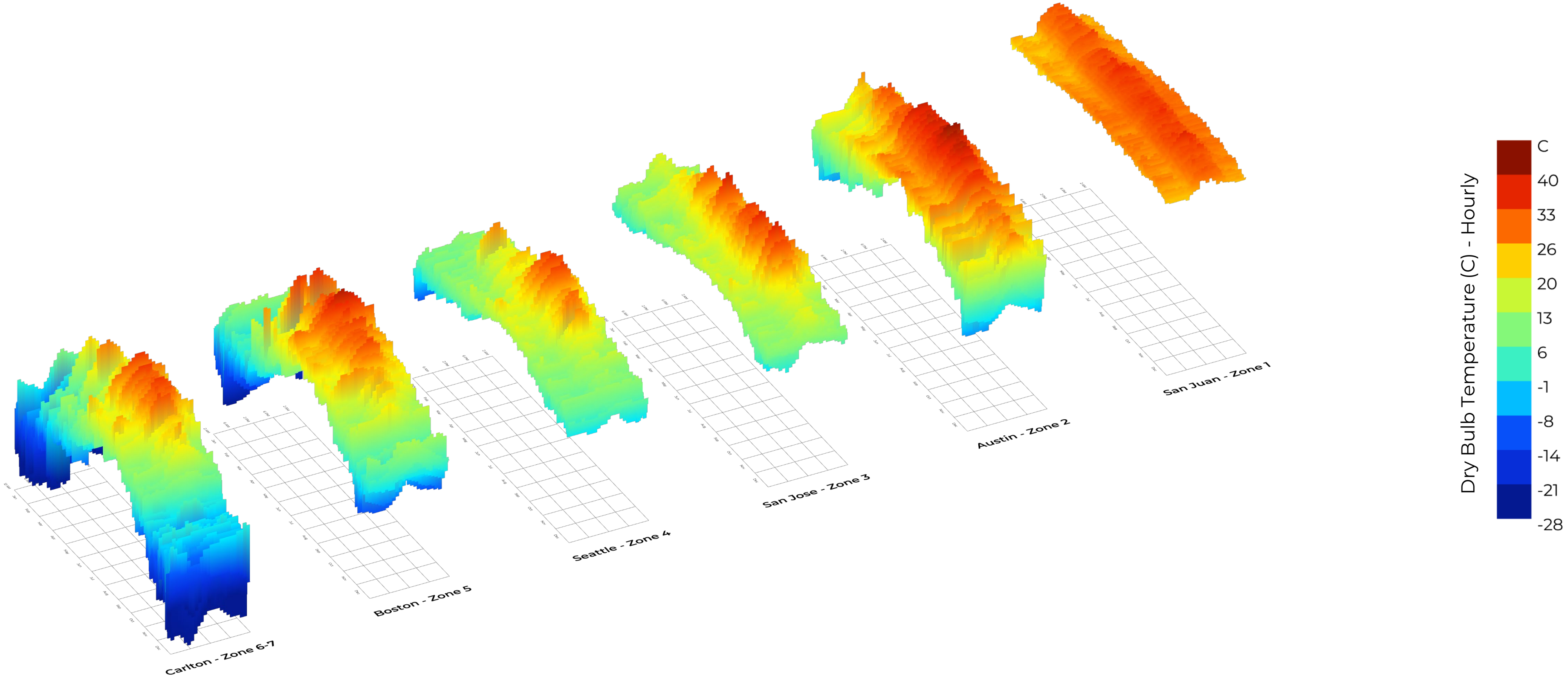
WORKFLOW
H+C days schedule for inflation states



ENERGY EFFICIENCY

ENERGY MODEL

Building, model and analyses

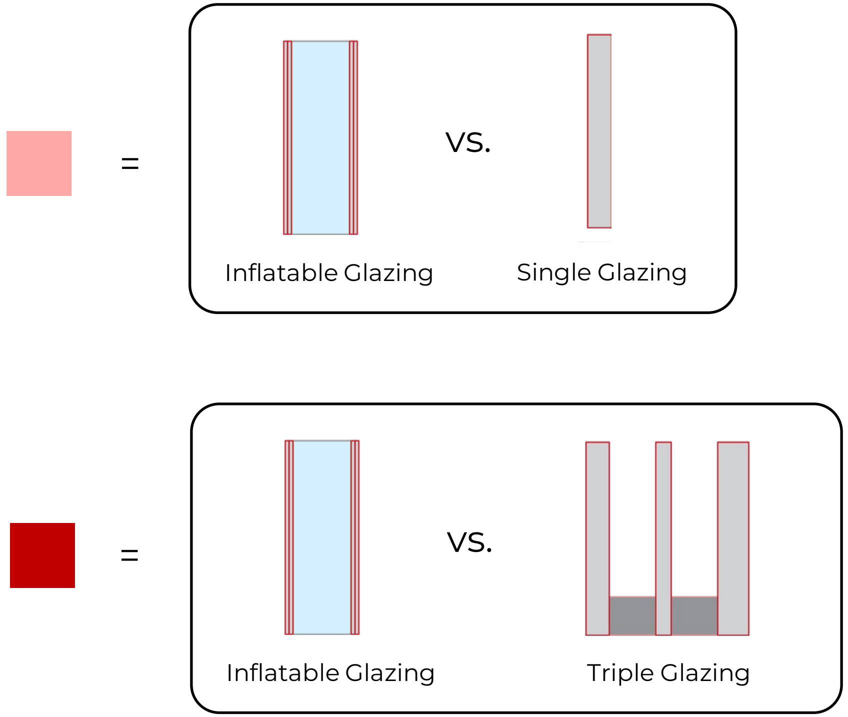


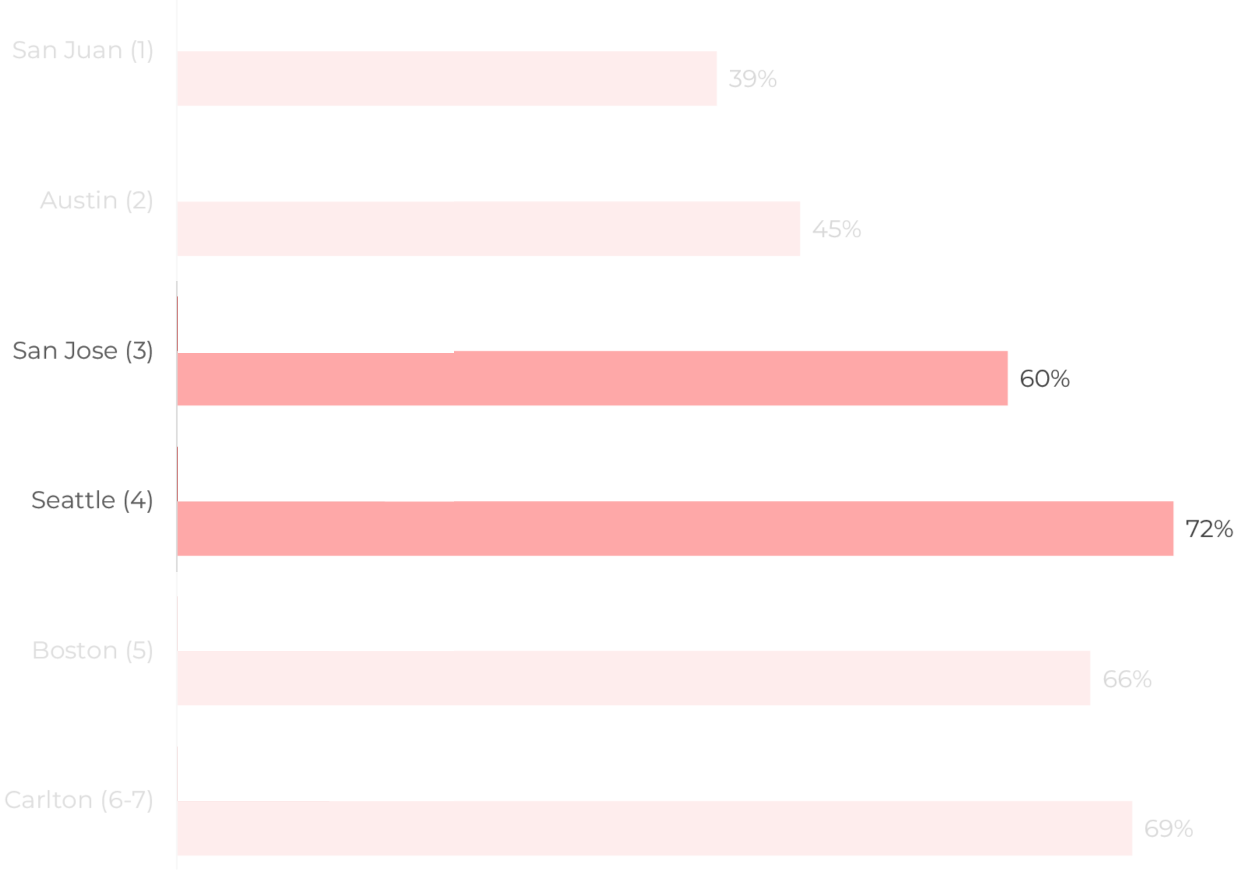
LOCATION PERFORMANCE COMPARISON

SG AND TGU vs. Inflatable Glazing

Glazing	Ug-value	g-value	Coating
Single Glazing	**5.8**	0.87	No
Double Glazing	**1.1**	0.3	Yes
Triple Glazing	**0.6**	0.3	Yes
Quadruple Glazing	**0.33**	0.3	Yes
Inflatable Glazing (Xenon)	**0.6 - 5.46**	0.3	Yes

LOCATION: PERFORMANCE COMPARISON
Energy Demand Reduction in %

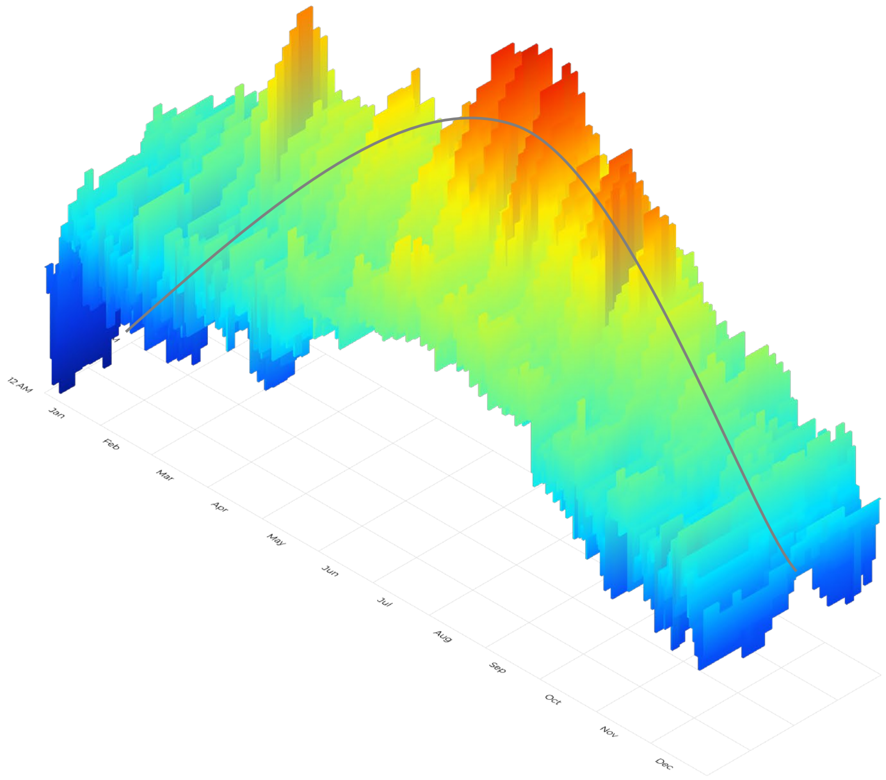




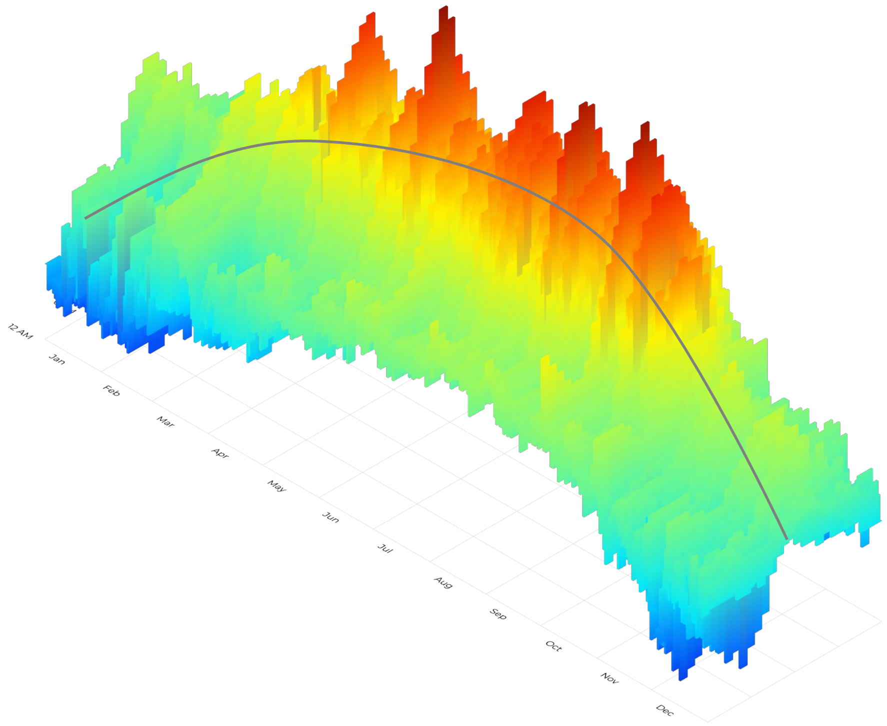
ENERGY EFFICIENCY

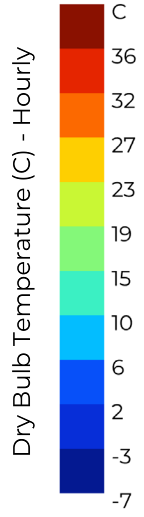
ENERGY MODEL
Building, model and analyses

Seattle (4) – mixed climate high fluctuations



San Jose (3) – warm climate with mild winter



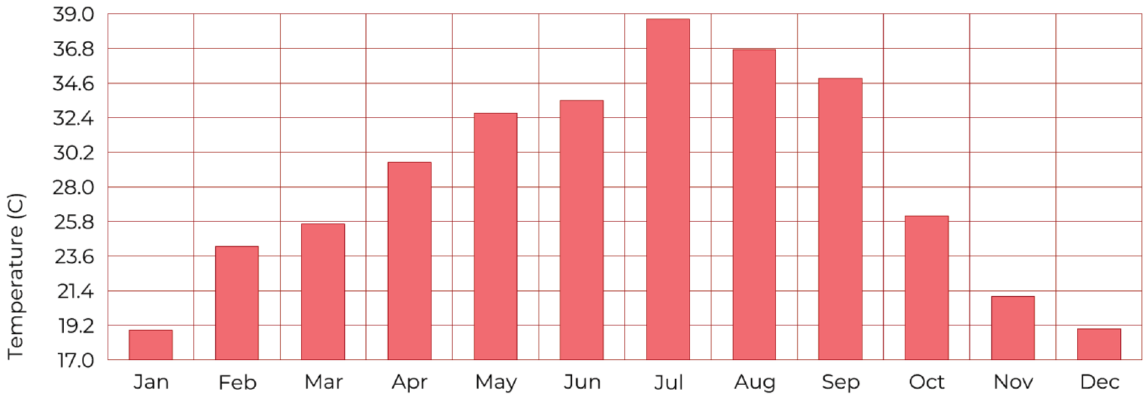


ZONE AIR TEMPERATURE

Triple glazing vs Inflatable Glazing (Krypton) in Seattle

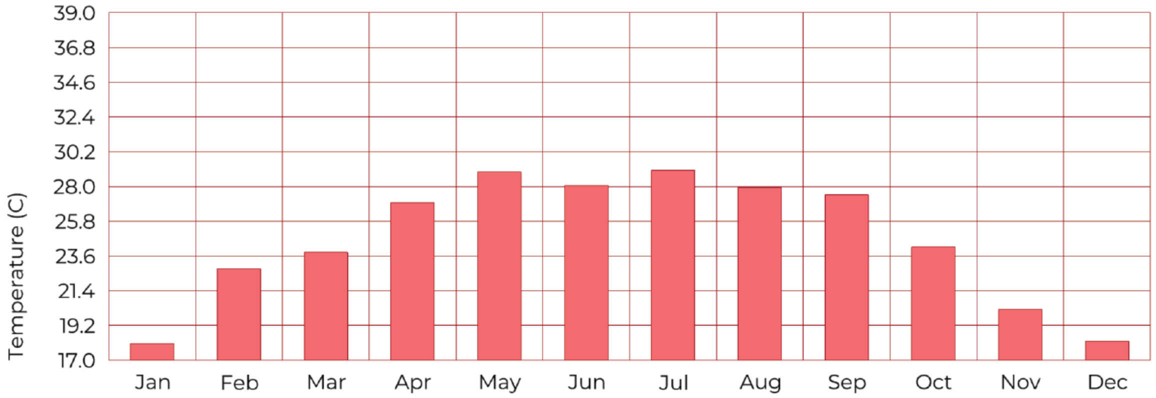
Triple Glazing

Maximum Temperature:
52.6°C



Inflatable Glazing (Krypton)

Maximum Temperature:
37.6°C



operation: average

ENERGY DEMAND

Energy demand reduction – glazing comparison

Seattle	IG (Xenon)	IG (Krypton)	IG (Air)
HR++++	22%	17%	-11%
HR+++	18%	12%	-16%
HR++	33%	29%	5%
SG	73%	71%	61%

18-33% improvement to current building practices

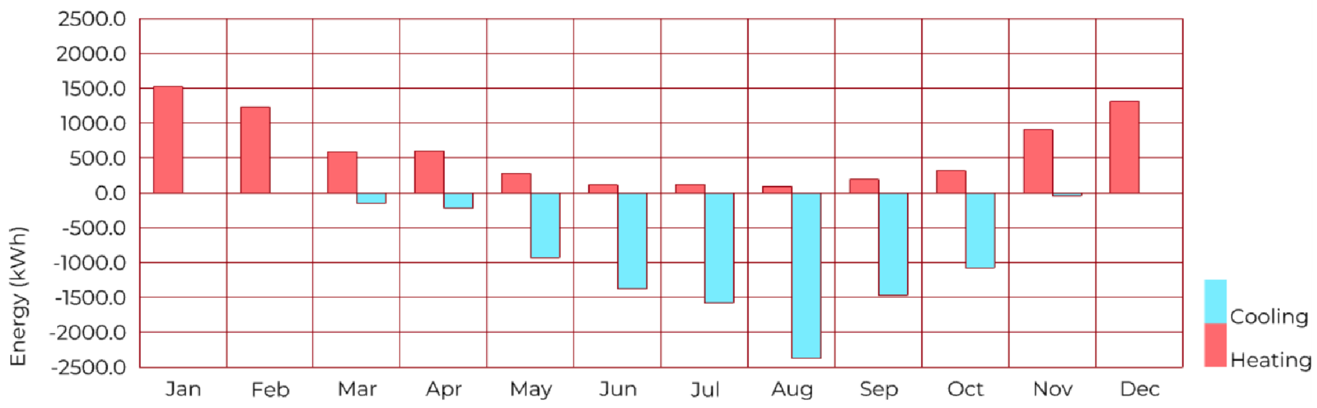
San Jose	IG (Xenon)	IG (Krypton)	IG (Air)
HR++++	18%	16%	5%
HR+++	20%	18%	7%
HR++	24%	22%	11%
SG	62%	61%	56%

24% improvement to current building practices

ENERGY DEMAND
Single glazing vs Inflatable Glazing (Air) in San Jose

Single Glazing

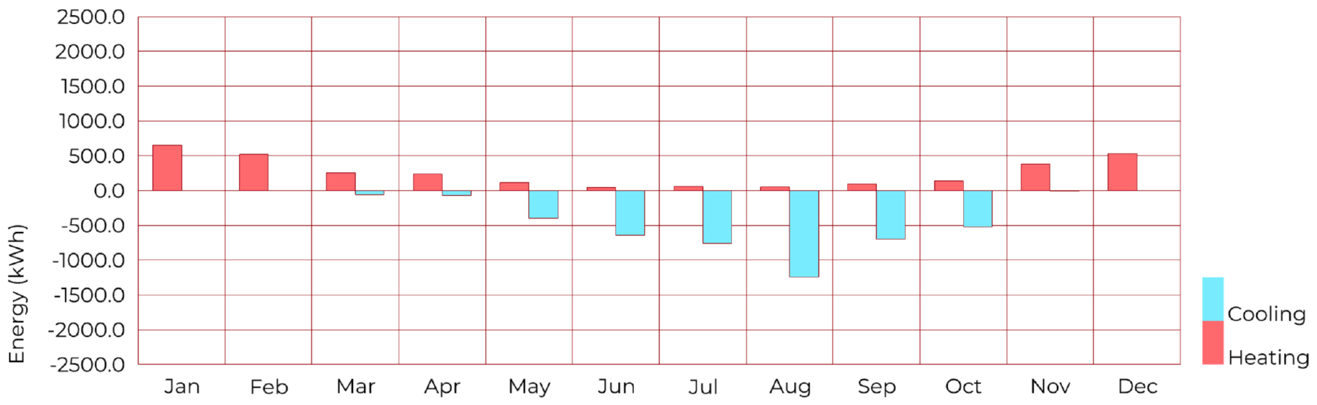
Annual energy demand:
16500 kWh



Inflatable Glazing (Air + Low-E)

Annual energy demand:
6970 kWh

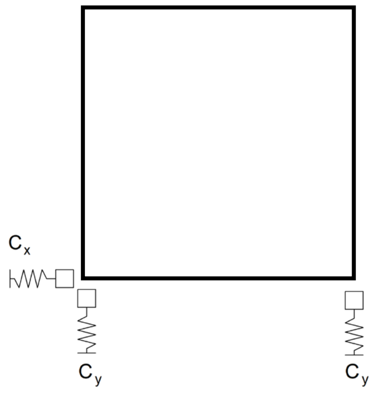
Energy reduction: **-57%**



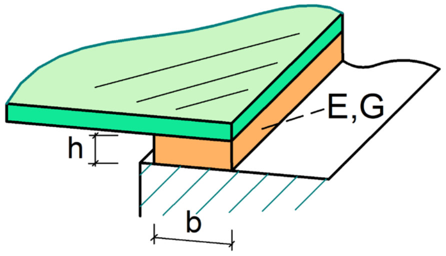
STRUCTURAL ANALYSIS

Thicknesses, stresses and weight

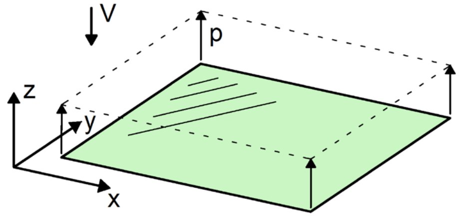
Finite Element Analysis
SJ MEPLA



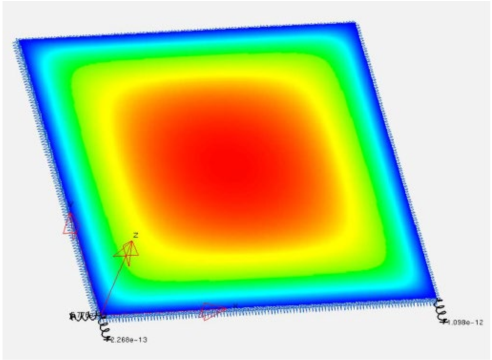
Spring supports



Elastic edge support



Uniformly distr. load + Self-weight



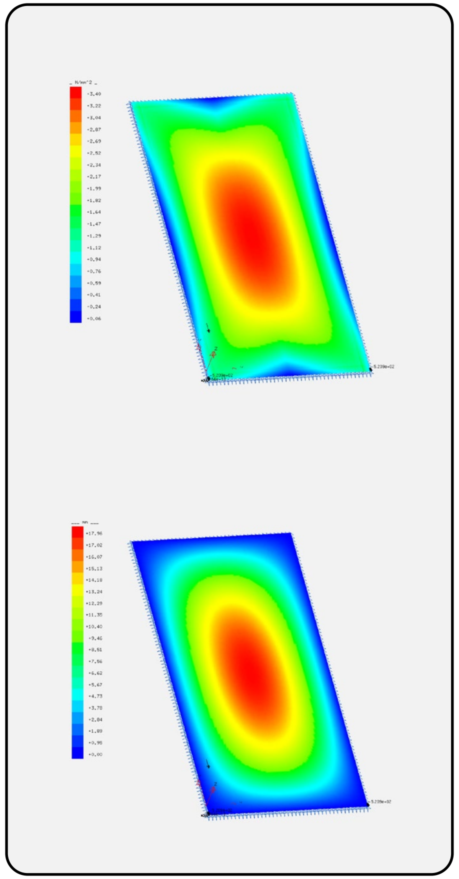
Non-linear geometric calculation

Finite Element Analysis
Office window dimensions 1500x3000mm

Core pane

Wind load
(1.5kN) - 5 steps

Self load



Principal stresses

PMMA: 3.4MPa

Glass: 23.6MPa

Deformation
(1/100 – 1/250)

PMMA: 18mm

Glass: 18mm

Thickness

PMMA: 20mm

Glass: 8mm

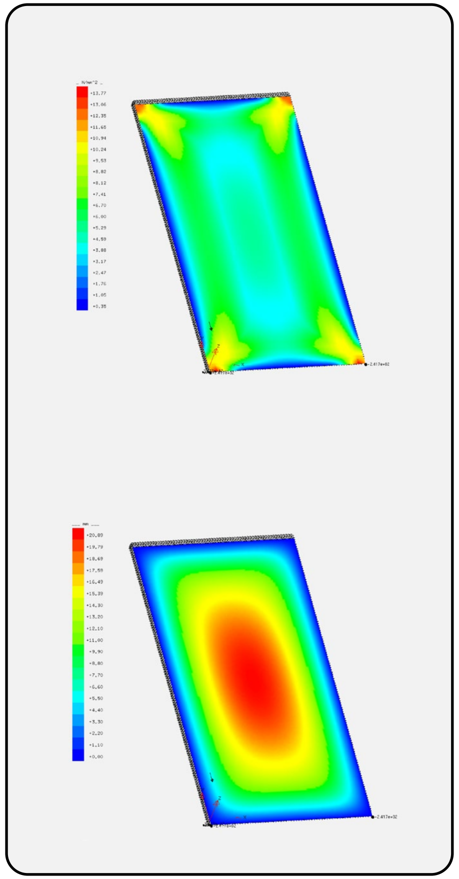
Finite Element Analysis

Office window dimensions 1500x3000mm

Thin glass

Cavity pressure
2000-3000 Pa

Self load



Principal stresses

Thin glass: 13.8 MPa

Deformation

Thin glass:
Up to 20mm

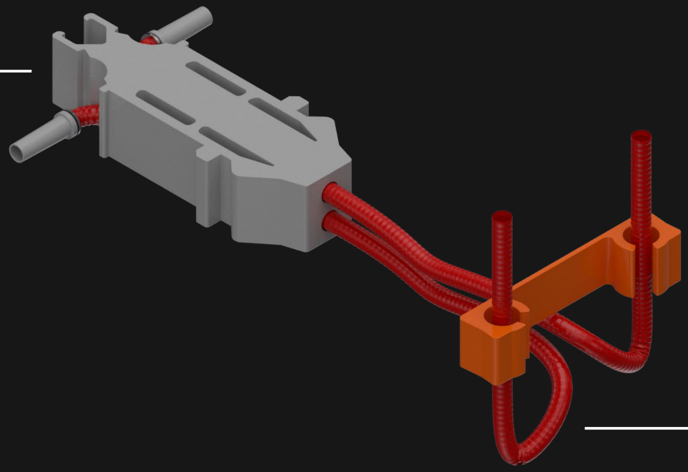
Thickness

Thin glass:
2.1mm – 0.38mm PVB – 2.1mm

FINAL PRODUCT

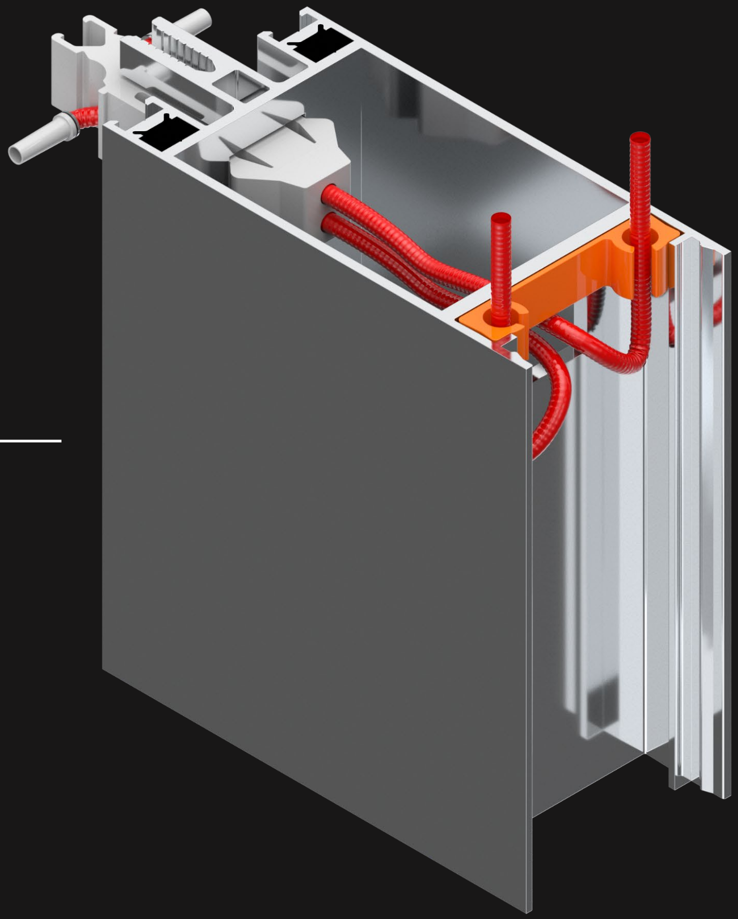
Glass Edge Design, Mullion Design and Impressions

GAS SUPPLY
Custom thermal break with gas hoses



GAS SUPPLY

Mullion with cutout and rear cap for fitting hoses

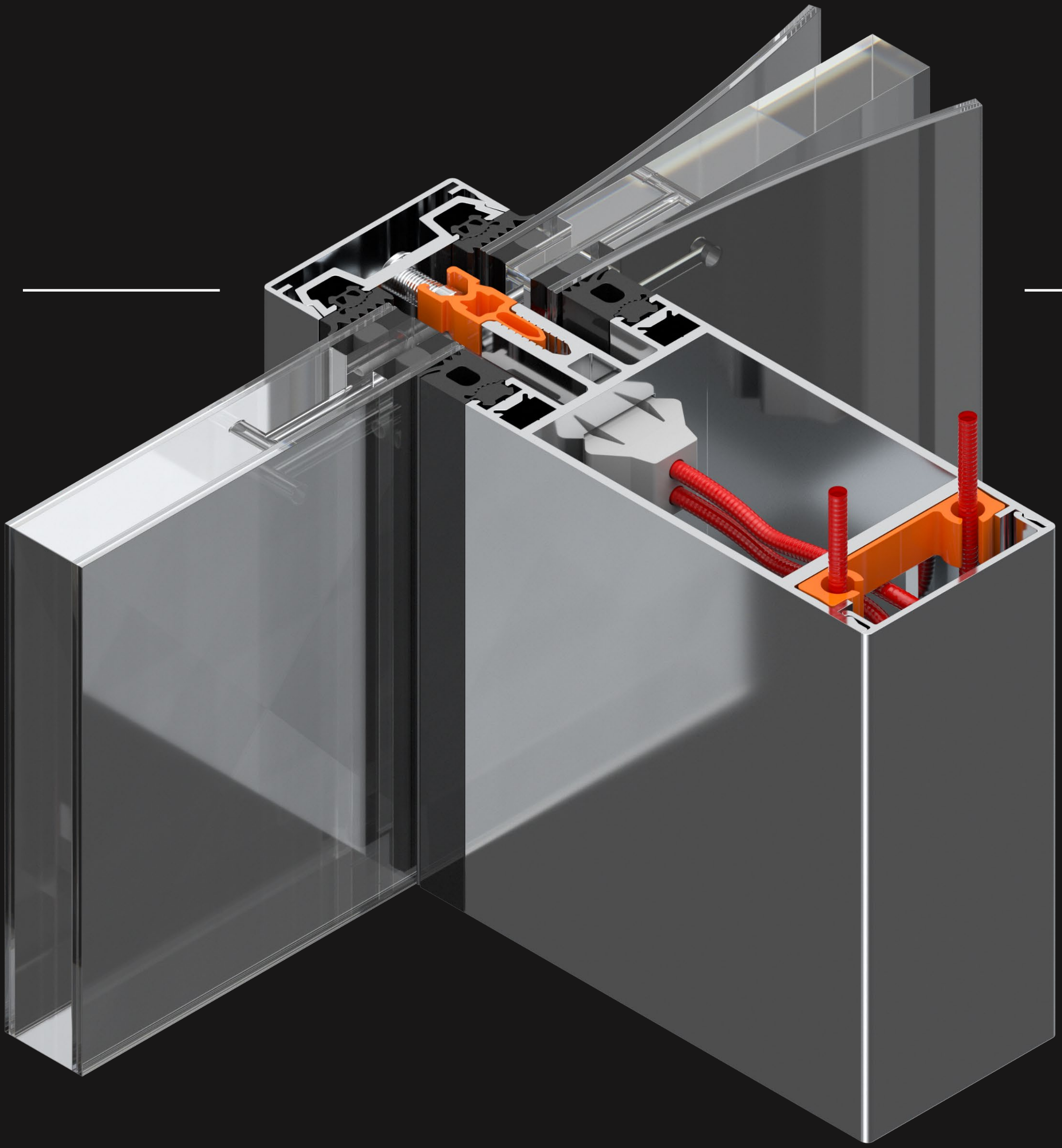


50mm aluminium mullion

Operable rear chamber

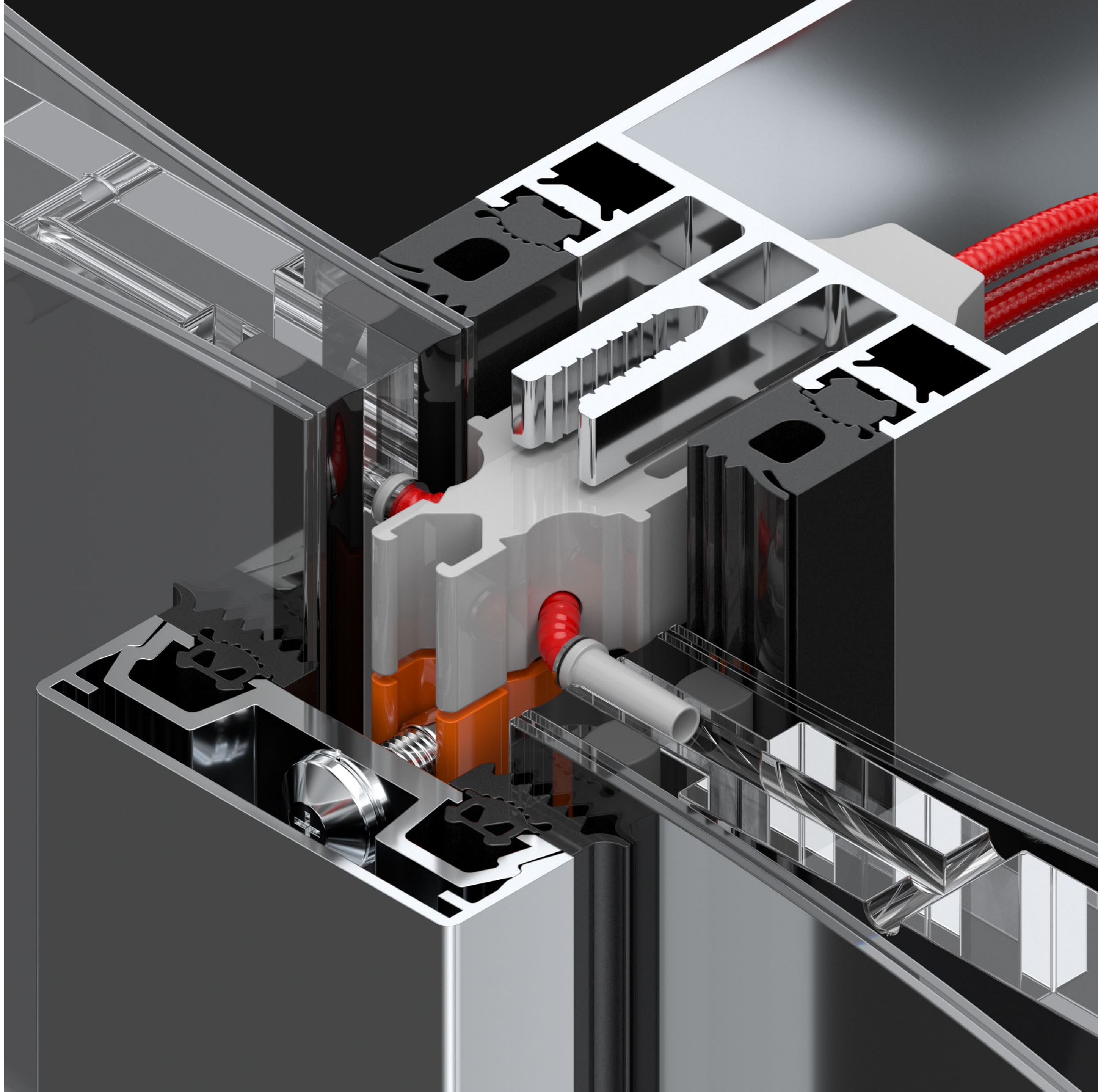
MULLION DESIGN

GAS SUPPLY
Final assembly



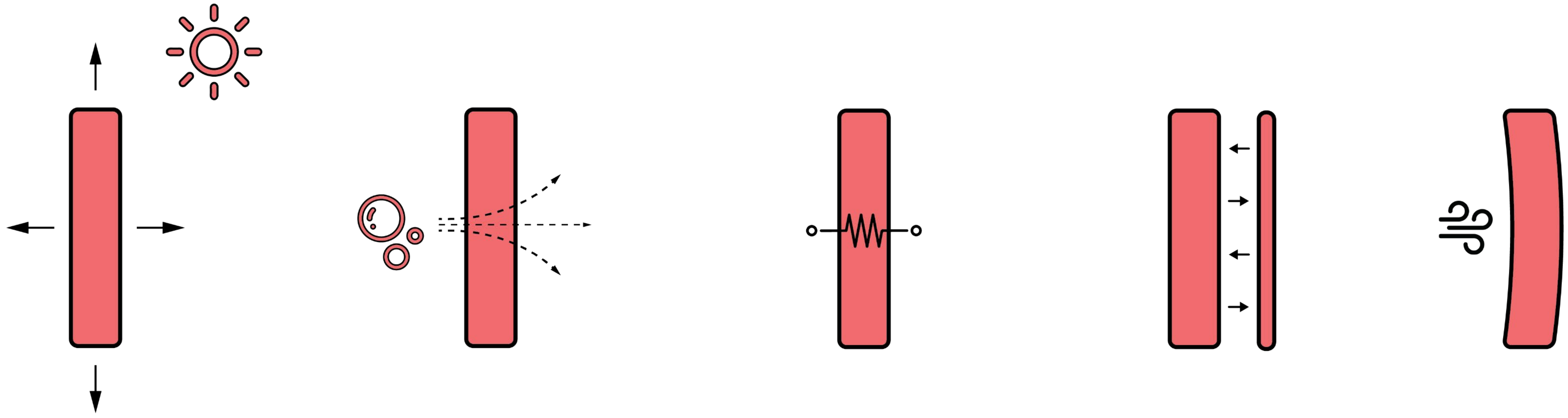
MULLION DESIGN

GAS SUPPLY
Section



CORE PANE: PMMA VS GLASS

Downsides of a PMMA core pane



Higher thermal expansion

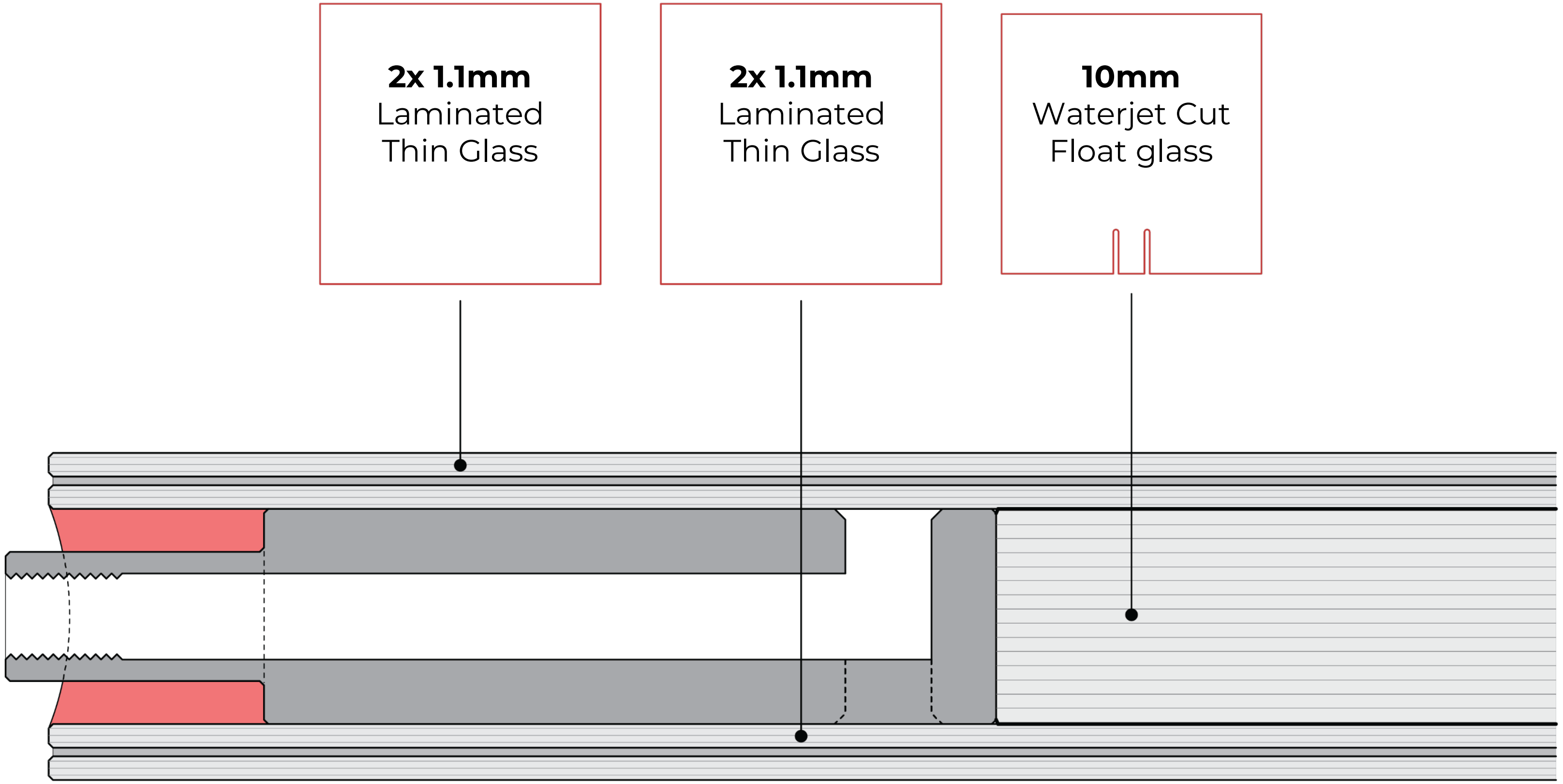
Higher gas permeability

Higher thermal resistance

Worse adhesion

Lower strength

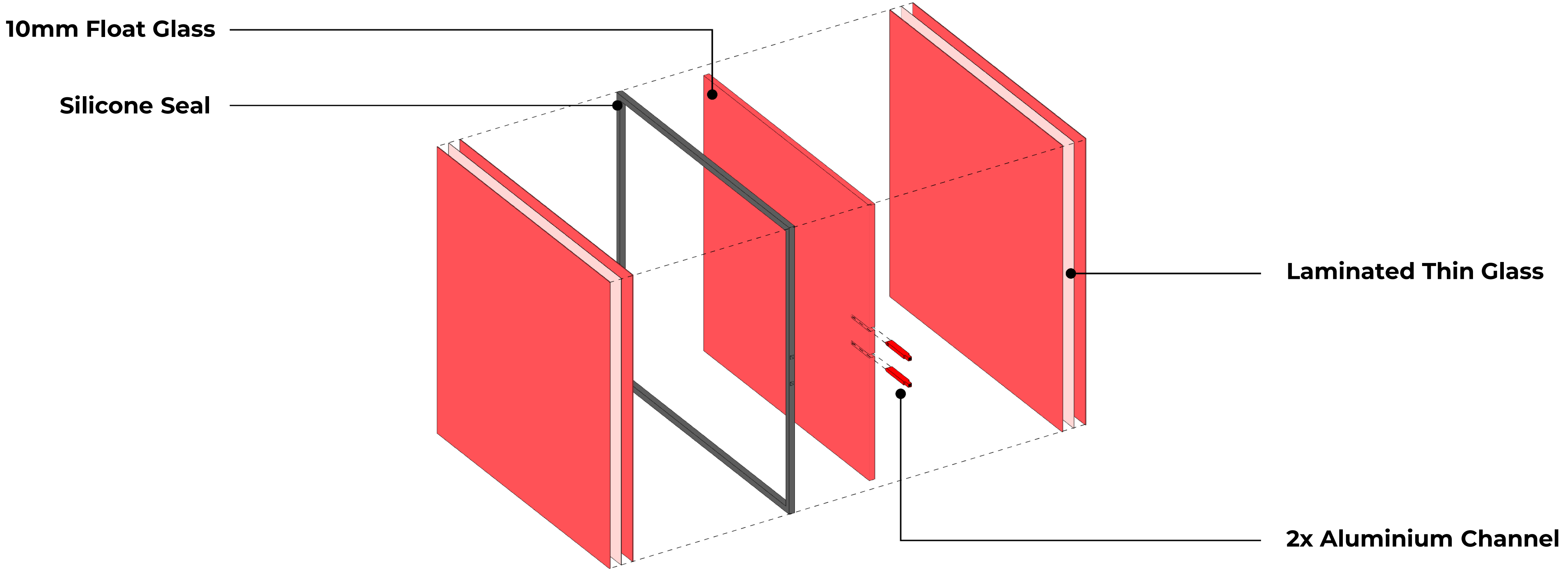
GLASS COMPOSITION 2
Edge detail



FINAL PRODUCT

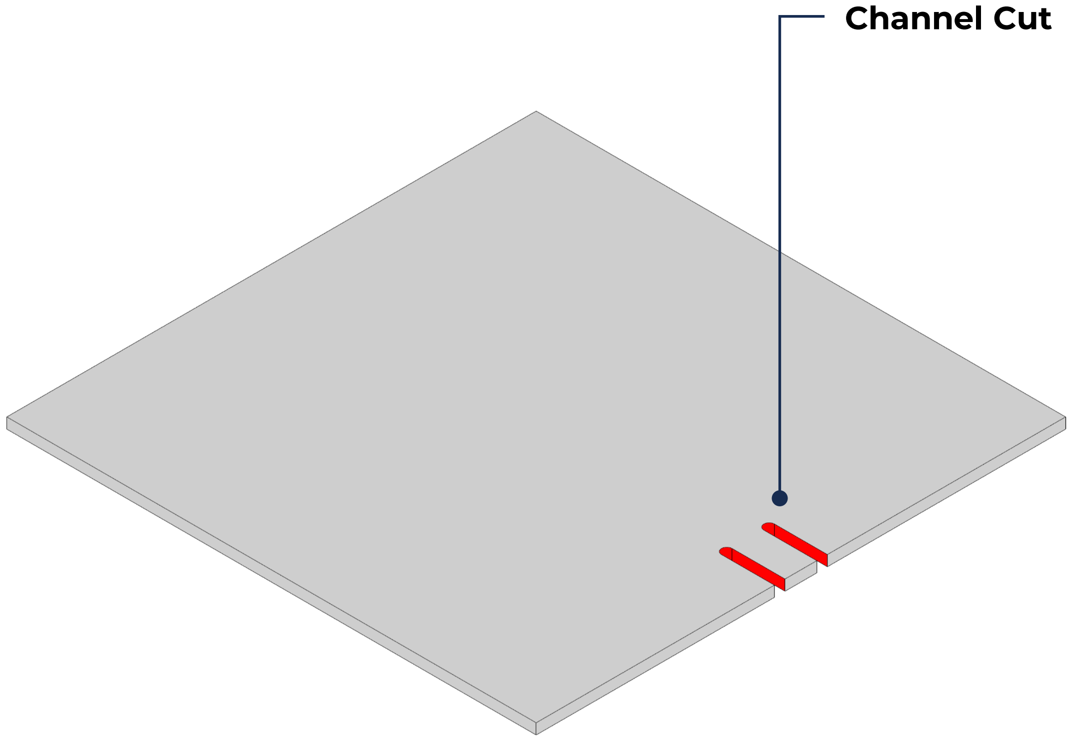
GLASS COMPOSITION 2

Assembly



FINAL PRODUCT

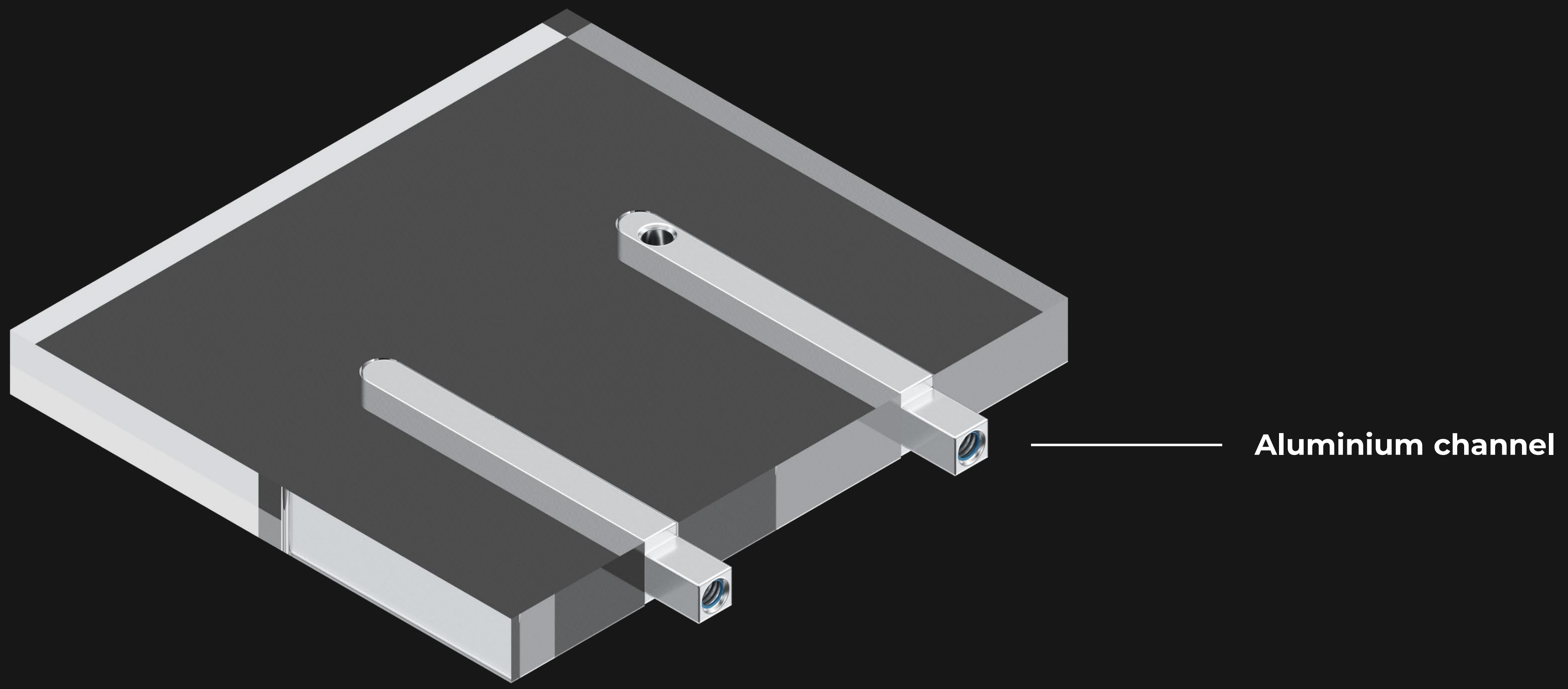
MANUFACTURING
Waterjet Cutter



FINAL PRODUCT

ASSEMBLY COMPOSITION 2

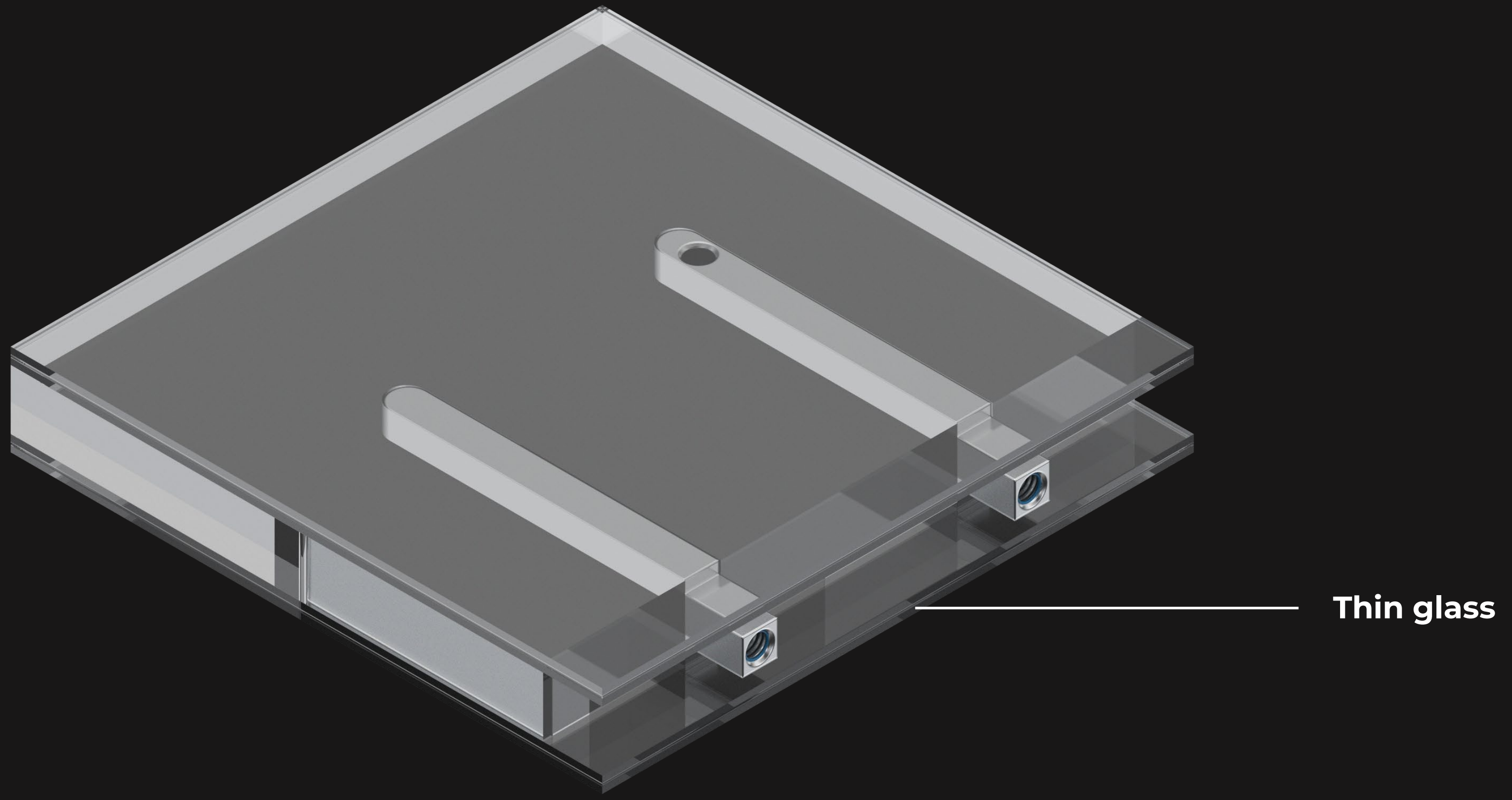
2x Channel insert



FINAL PRODUCT

ASSEMBLY COMPOSITION 2

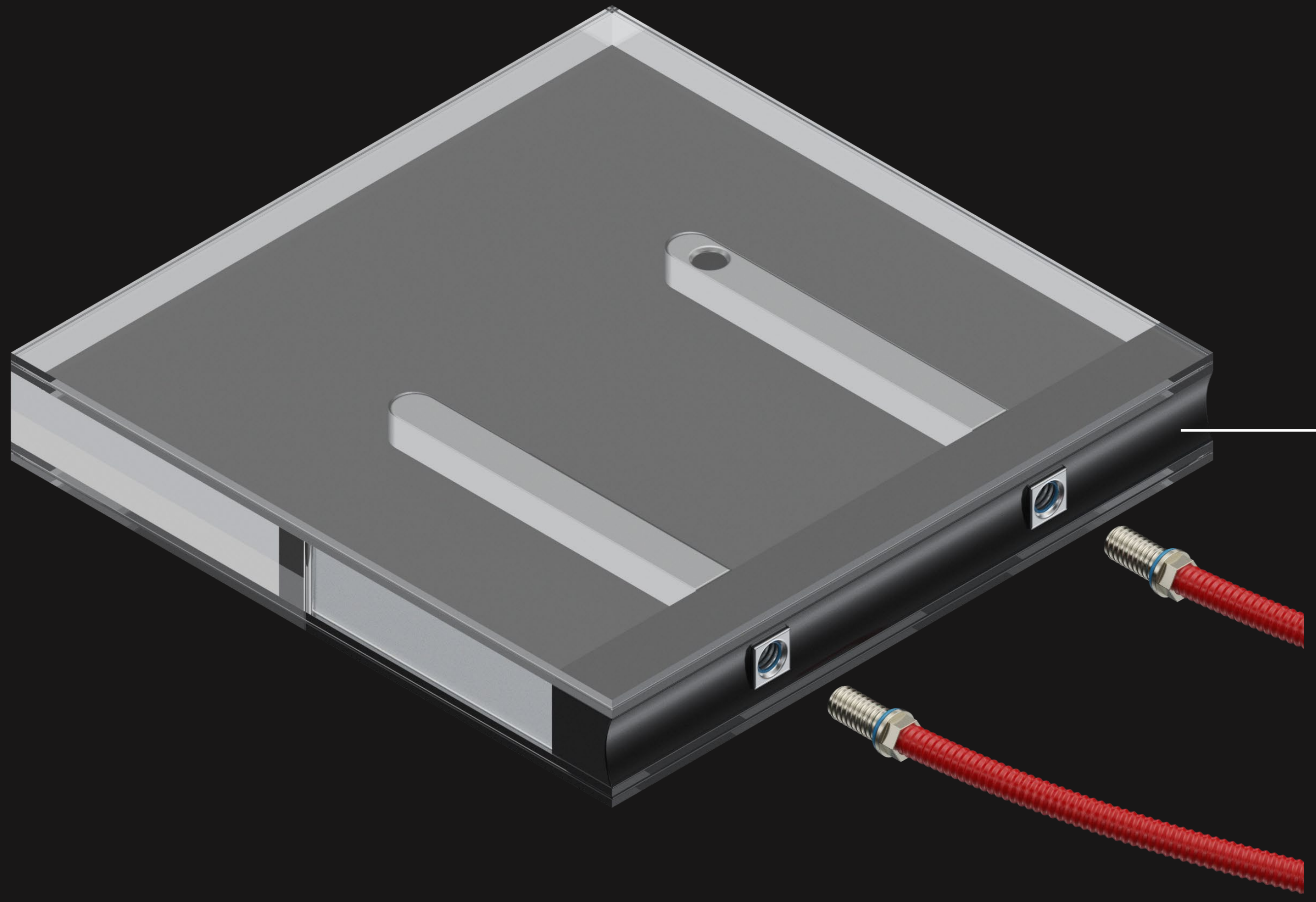
Laminated thin glass coupling



FINAL PRODUCT

ASSEMBLY COMPOSITION 2

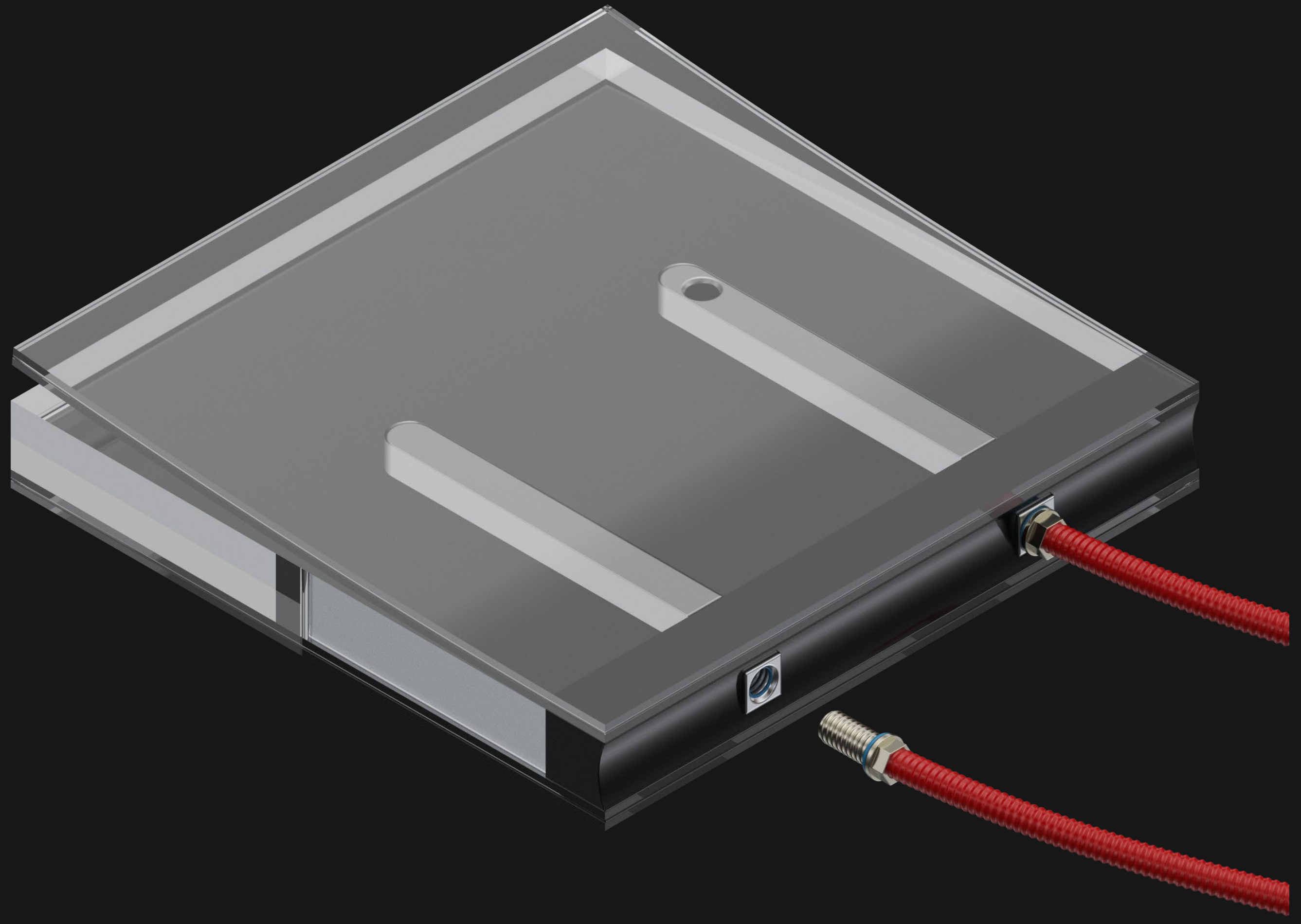
Secondary seal application



FINAL PRODUCT

ASSEMBLY COMPOSITION 2

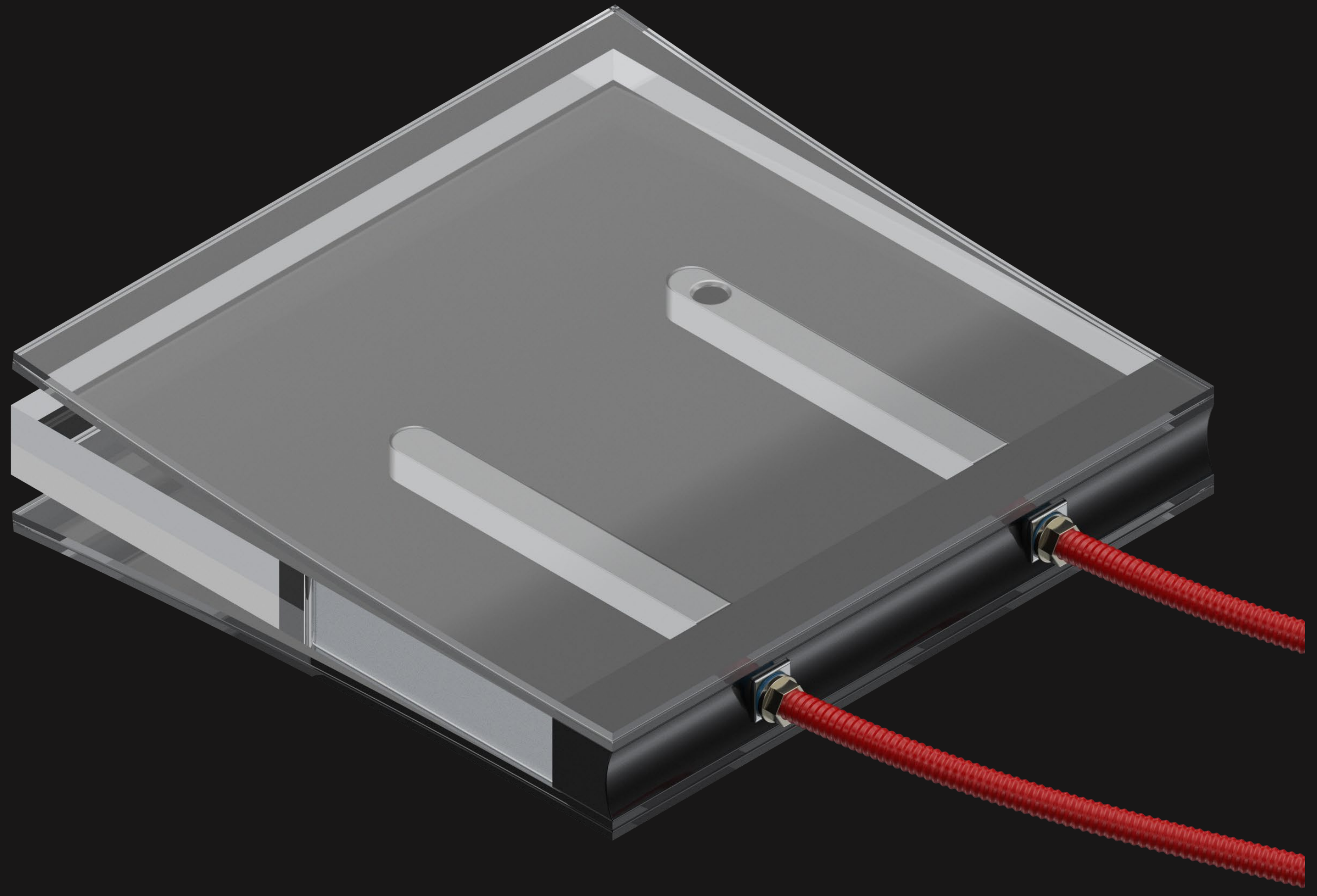
Separate cavity inflation possible



FINAL PRODUCT

ASSEMBLY COMPOSITION 2

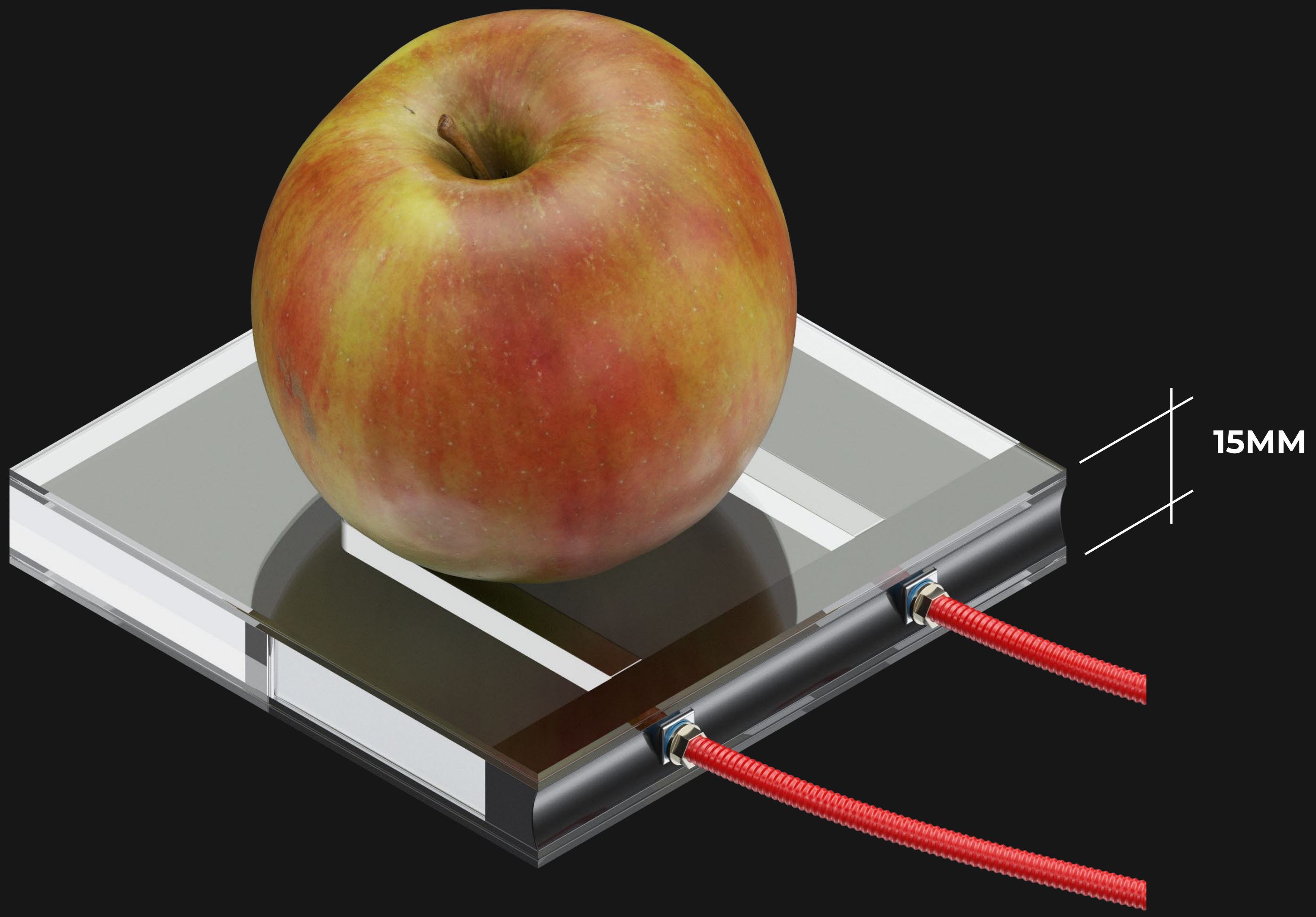
Separate cavity inflation possible



FINAL PRODUCT

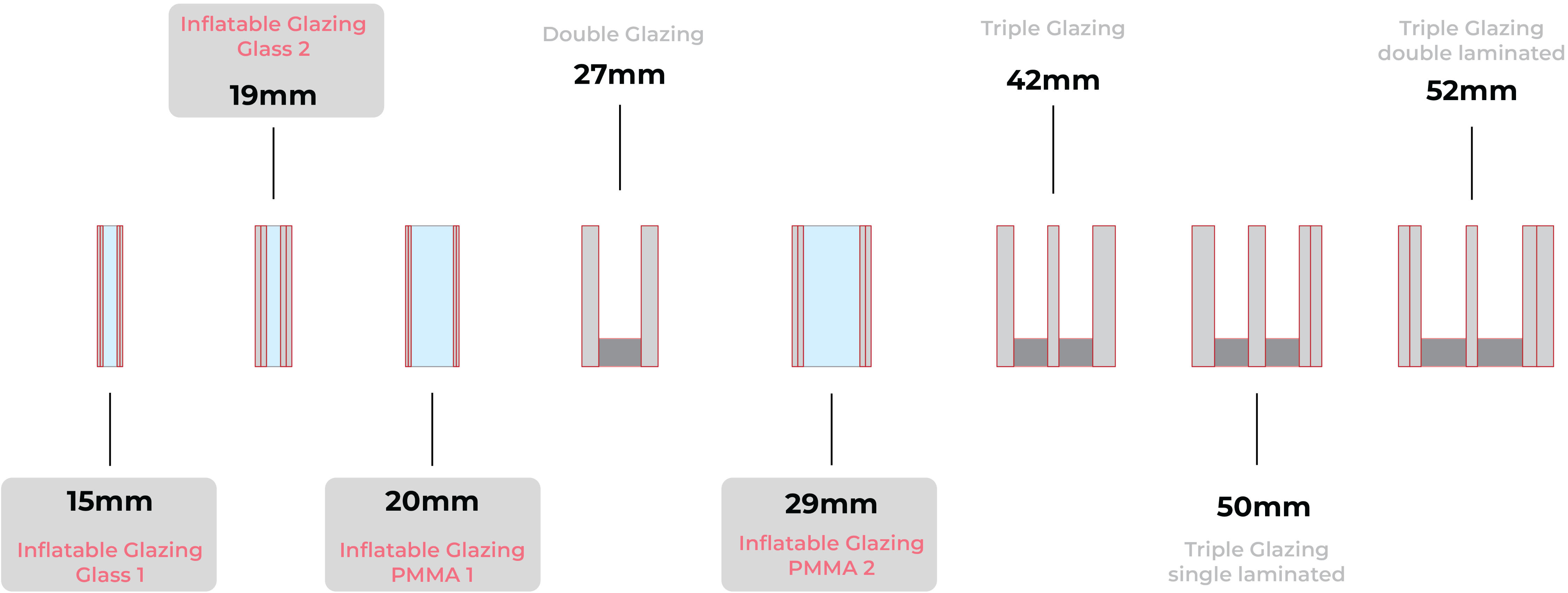
ASSEMBLY COMPOSITION 2

15mm unit – Apple for comparison



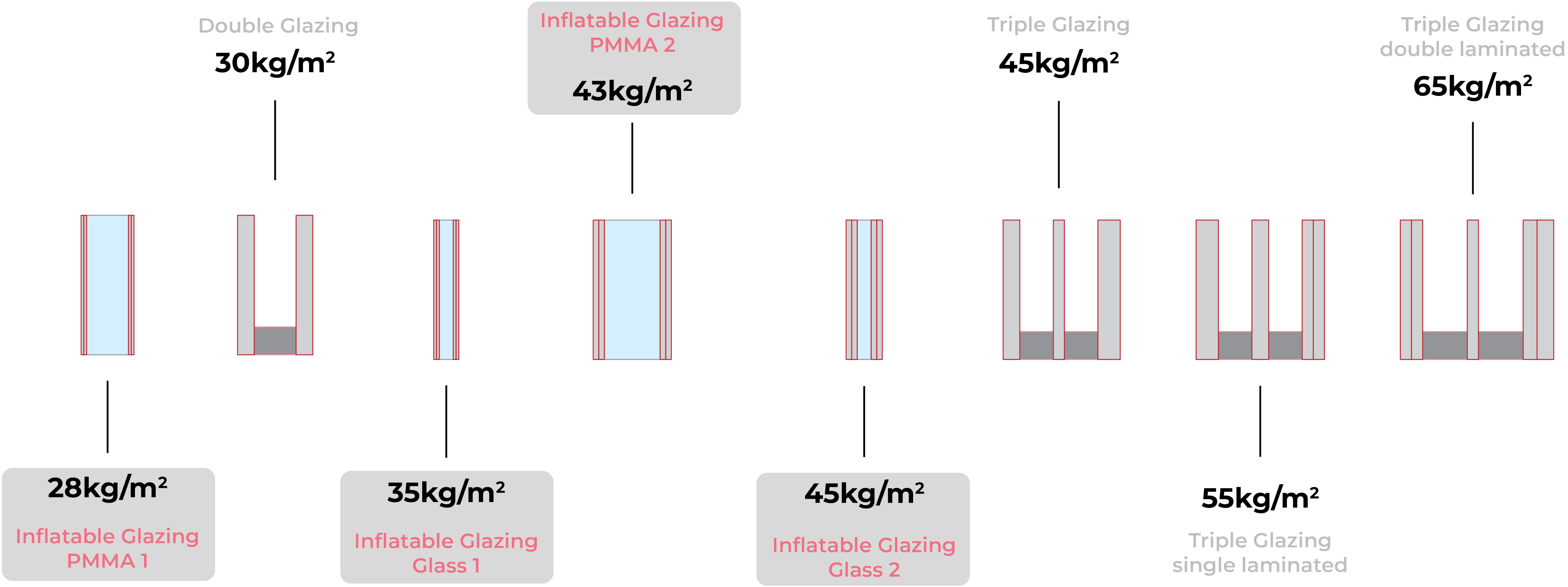
FINAL PRODUCT

THICKNESS
Comparison across IGUs

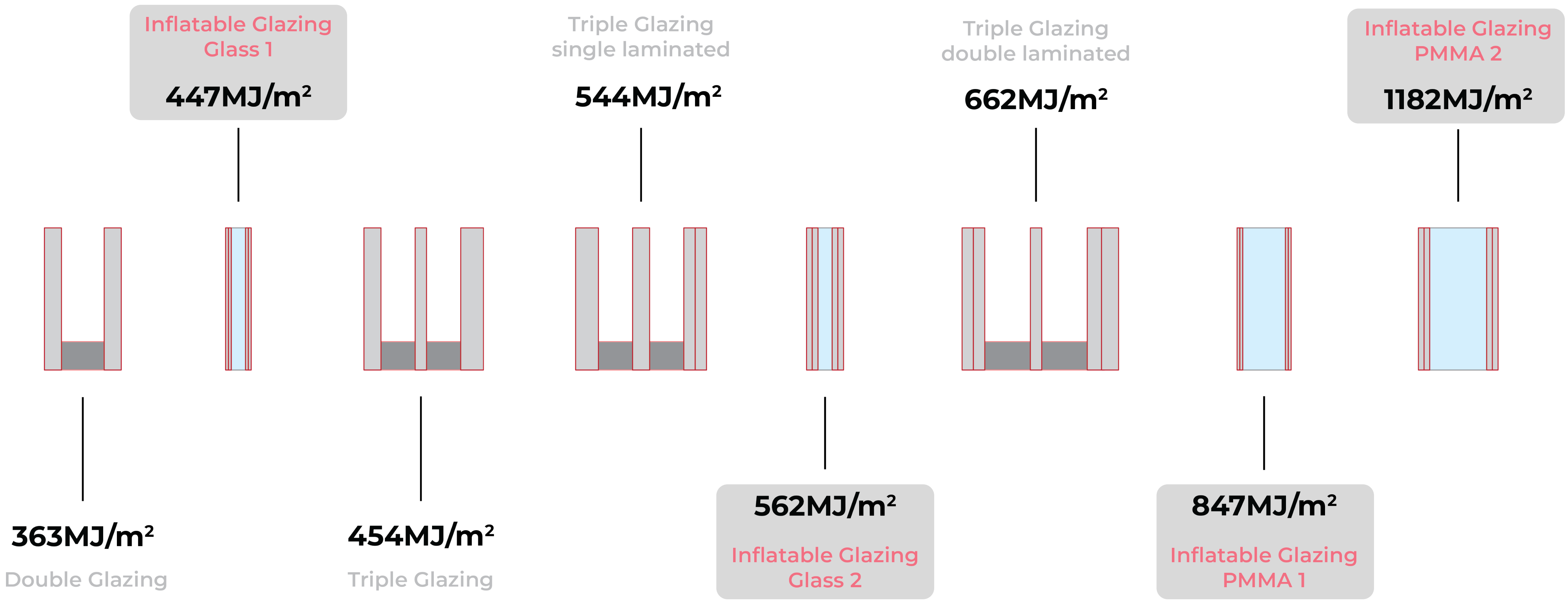


WEIGHT

Comparison across IGUs



EMBODIED ENERGY
Comparison across IGUs




STATIC TRIPLE GLAZING
Exterior reflections (RTX)
IMPRESSIONS


6MM CAVITY (XENON)
Exterior reflections (RTX)
IMPRESSIONS


10MM CAVITY (ARGON)
Exterior reflections (RTX)
IMPRESSIONS


16MM CAVITY (AIR)
Exterior reflections (RTX)
IMPRESSIONS

INFLATABLE GLAZING

Interior reflections (RTX)

IMPRESSIONS

CONCLUSION

Relevance and reflection

RELEVANCE
Societal relevance

Decreasing
energy demand

Enhancing
occupant comfort

Unobstructed
view

Renovation
possibilities

Reduced
weight

RELEVANCE

Scientific relevance

Manufacturing of novel glass unit

Thermal performance of dynamic insulation

Energy efficiency and optimal **locations**

Precise analysis of **curvature** and **deformations**

Behavior of **thin glass** and **edge sealants**

INFLATABLE GLAZING

Thank you!

TU Delft

Eckersley O'Callaghan

H.B. Fuller | KÖMMERLING

AGC

FRONTWISE FACADES

RÖHM