

Advanced Manufacture of Second-Surface, Silvered Glass Reflectors for High-Performance, Low-Cost CSP Collector Systems

The University of Arizona

Award # DE-EE0005796



Principal Investigator: Roger Angel

Project Manager: Steve Warner

Project Objectives and Novelty

Objectives

- Develop new methods for rapidly shaping self-supporting glass mirrors
- Allows for production of point-focus as well as line-focus (trough) mirrors
- Performance objectives include:
 - Optical accuracy of 2 mrad RMS (slope error 1 mrad RMS)
 - 95% reflectivity by novel coating for high reflectivity and soil resistance.
 - Potential for reduced cost ($\sim \$20/\text{m}^2$ vs. present cost of $\sim \$35/\text{m}^2$)
 - Reduce the shaping step down to 200 sec. using a new fast furnace.

Novelty

- High accuracy surface achieved by slumping the glass onto a precision mold
- Glass chilled and frozen in shape before removal from mold
- fast rate of manufacture by rapid thermal cycling of the mold

Matching Partners



CSP in Arizona:

Rioglass Solar and Tucson Electric Power



RioGlass in Surprise, Az makes the trough reflectors for Solana 300 MW CSP – one every 20s, 24/7



Tucson Electric Power is installing linear Fresnel glass reflectors for Ariva CSP steam boost plant

UA glass test mirrors will duplicate those being made for Solana

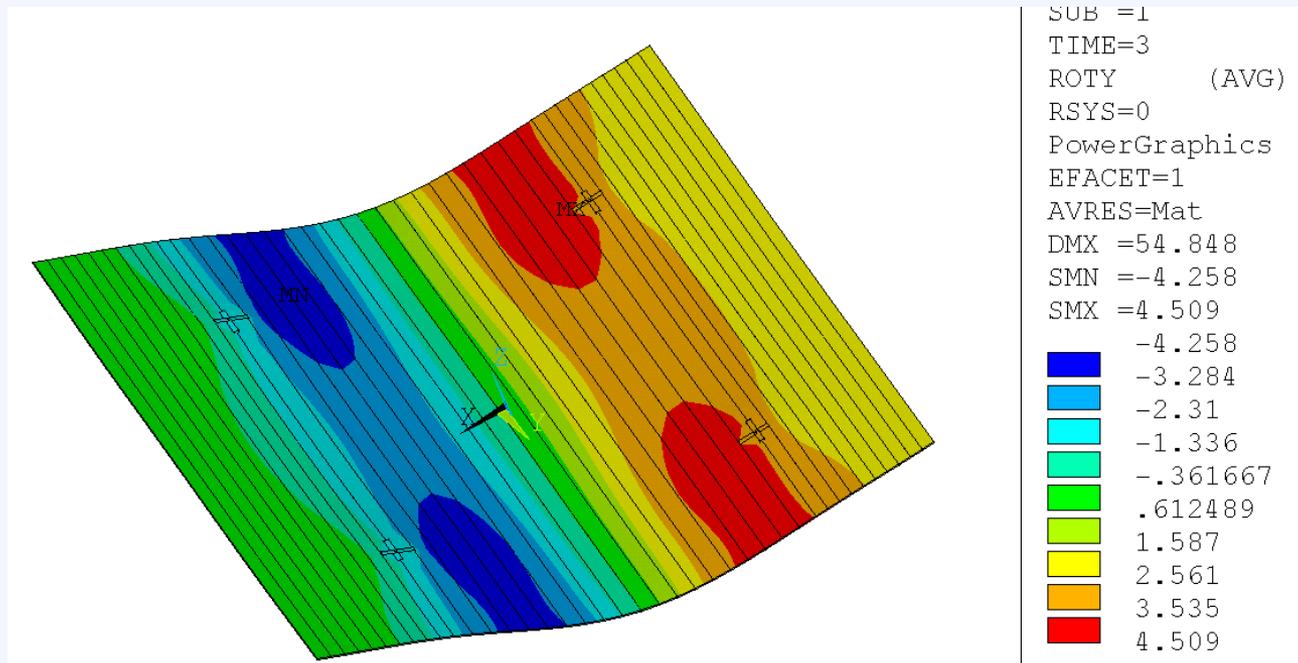
- UA will make reflectors that match units currently in production at RioGlass Solar for the Solana trough plant
 - 1.7m parabolic cylinder with 1.71m focal length.
- Rioglass will measure UA sample reflectors along with the Solana production
 - Detailed map surface slope by Q-Dec Optical deflectometry
 - Spectral reflectivity across the full solar spectrum



Solana trough reflector at RioGlass factory. UA will make identically sized reflectors, to higher quality. Jordi Villanueva of RioGlass (left) and PI Roger Angel (right)

Mold shape

- optimum is not parabolic
- Solana design droops ± 4 mR under gravity at 45° el
 - Exceeds total error of 1 mR rms surface slope
- Final mold shape will compensate for average (45°) gravity deflection.

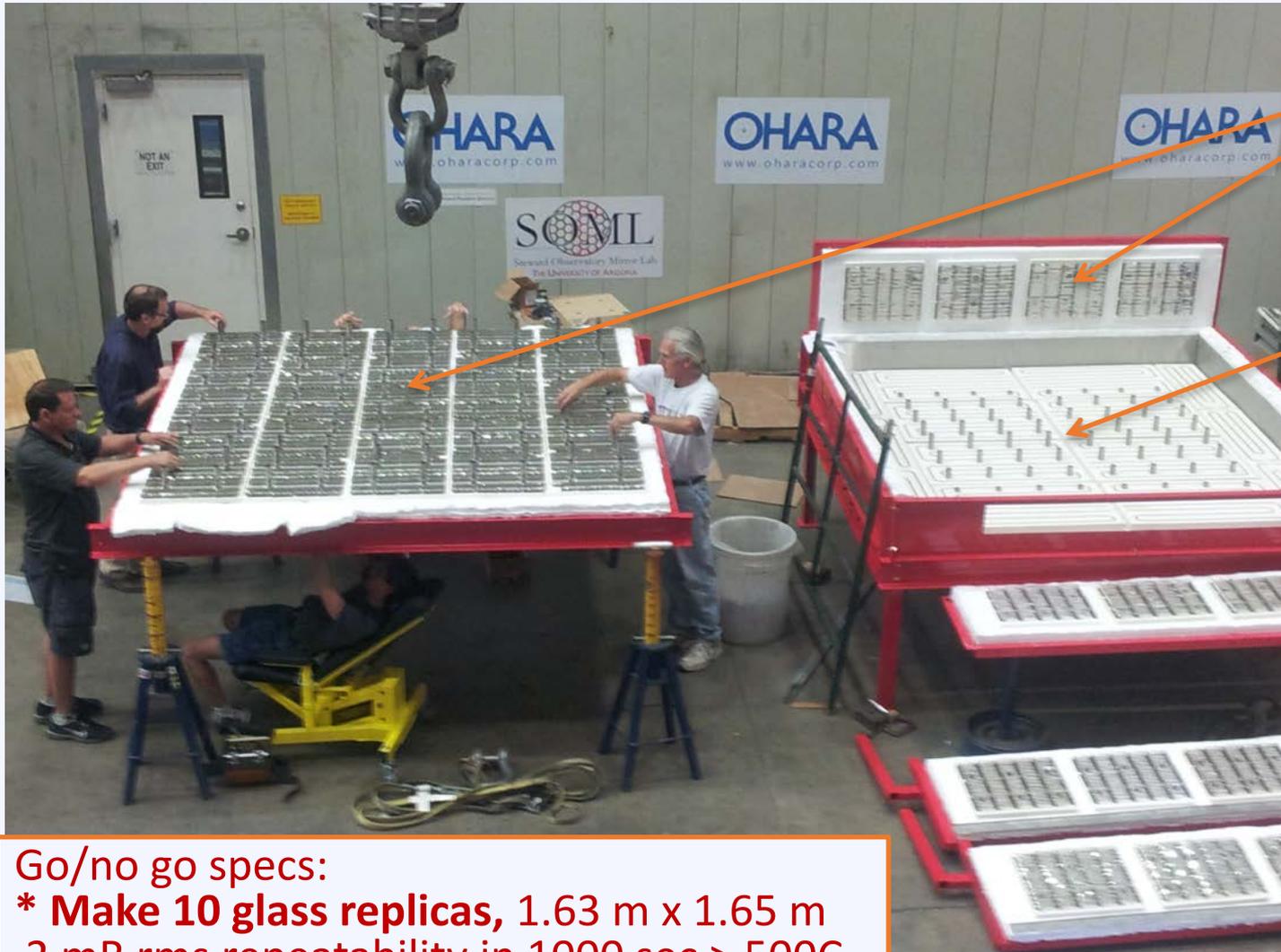


Trough mold faceplate rolled from stainless steel



- Accuracy of rolled mold surface being checked against template.
- Will be machined to <1 mrad slope accuracy

new “giant toaster” glass furnace under construction



Nichrome heater panels being installed into lid and side wall

Mold cooled rapidly by air jets from below

Being made in U of Arizona Mirror Lab, where world's largest telescope mirrors (28 foot) are cast from glass and polished

Go/no go specs:

* **Make 10 glass replicas, 1.63 m x 1.65 m**
2 mR rms repeatability in 1000 sec > 500C

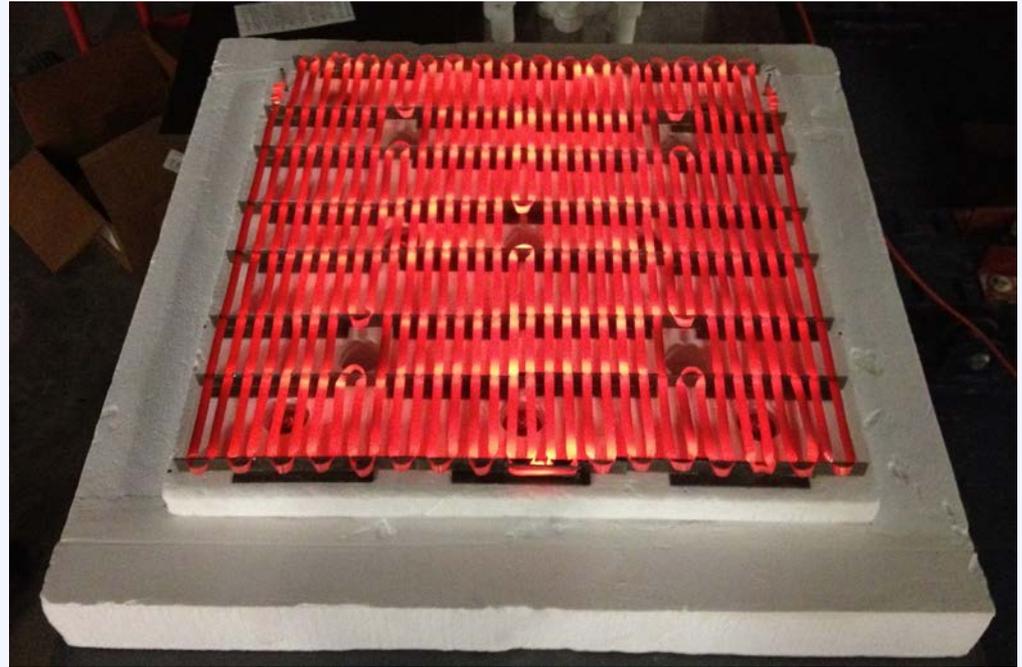
Lid heater prototyped with one of the 25 nichrome panels, each rated at 10 kW

Glass to be heated by radiation absorbed at $\lambda > 4\mu\text{m}$

high power required at low radiation temperature

Heater panel developed with $\frac{1}{4}$ " wide nichrome ribbon

furnace lid will use 25 panels in 5 x 5 array



Panel test - here operating in the open at 10 kW

480V variable power controller

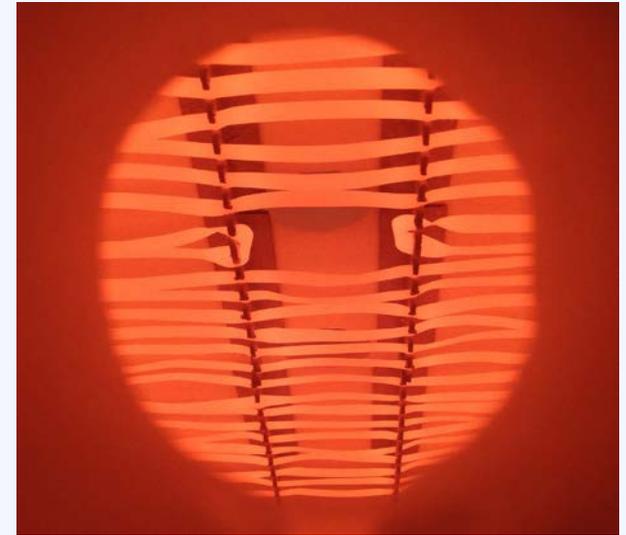
18" square test furnace built with single 10 kW panel



Temperature data logger

Test furnace with open ventilation holes

Programmable controller, 480V variable power



Heater panel seen through sapphire window

life tested through 120 fast cycles, 500C – 900C

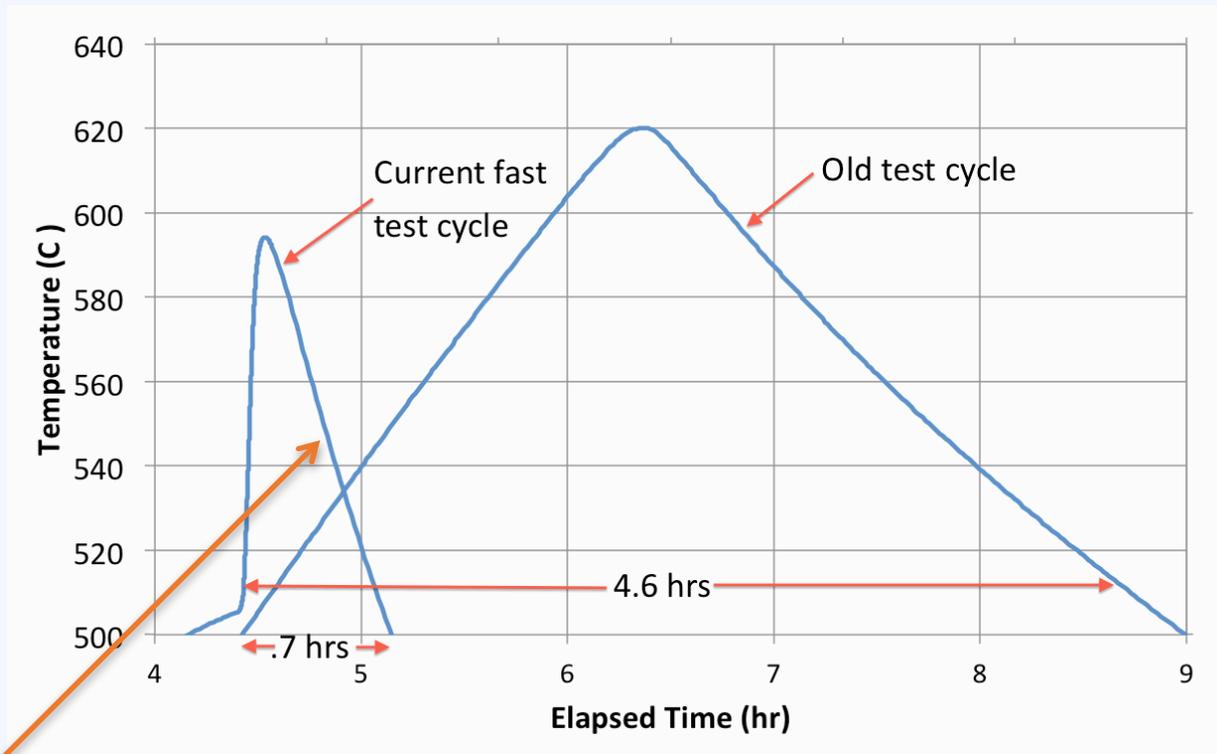
first look at 12” glass test replica made with test furnace using just one heater panel

In the a sunny parking lot outside the U Az Mirror Lab



This pickup truck makes a handy screen to check solar image quality. A perfect solar image would be for the 1.7 m focal length would be 0.56” diameter.

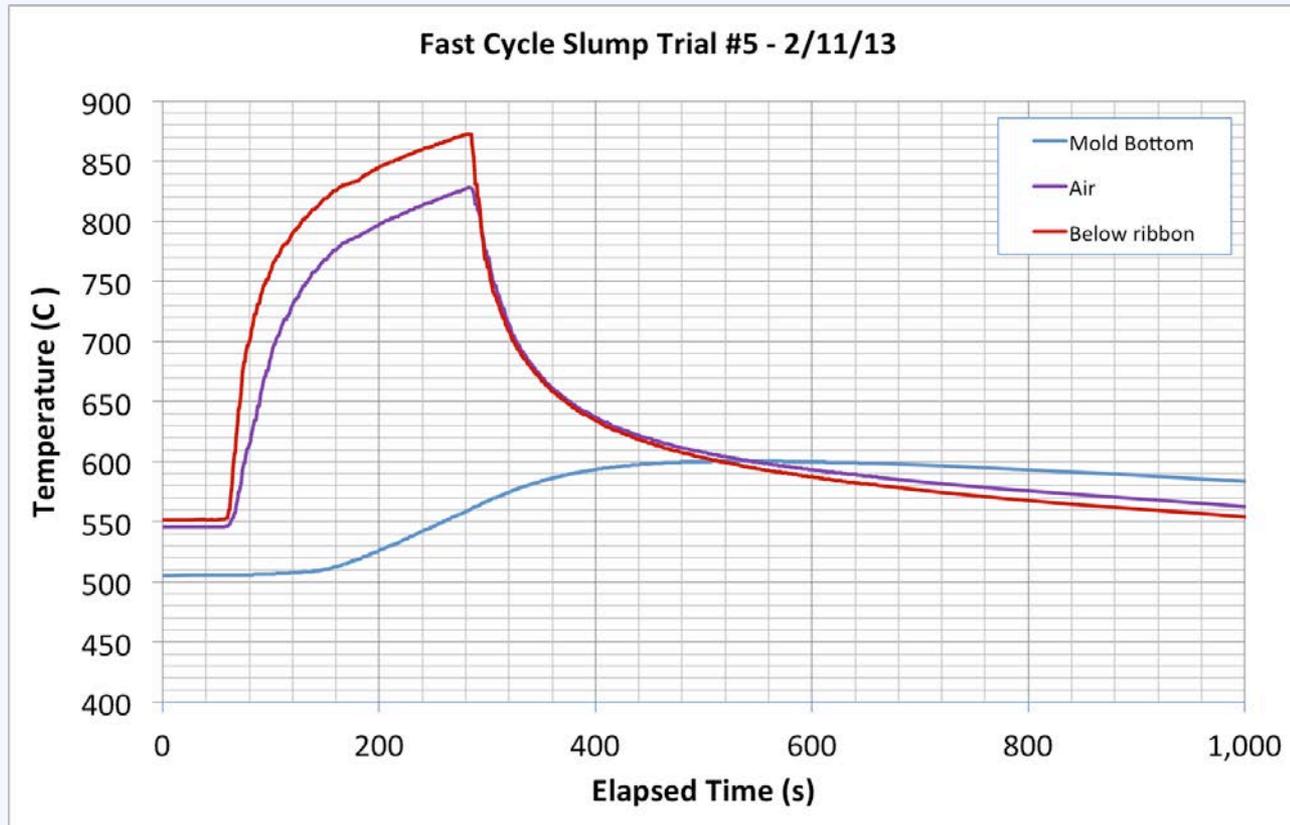
Thermal cycle used for the test replica (1/5 scale)



Slow natural convection cooling dominates the current test cycle

Fast radiative heating, but rapid convective cooling not yet implemented

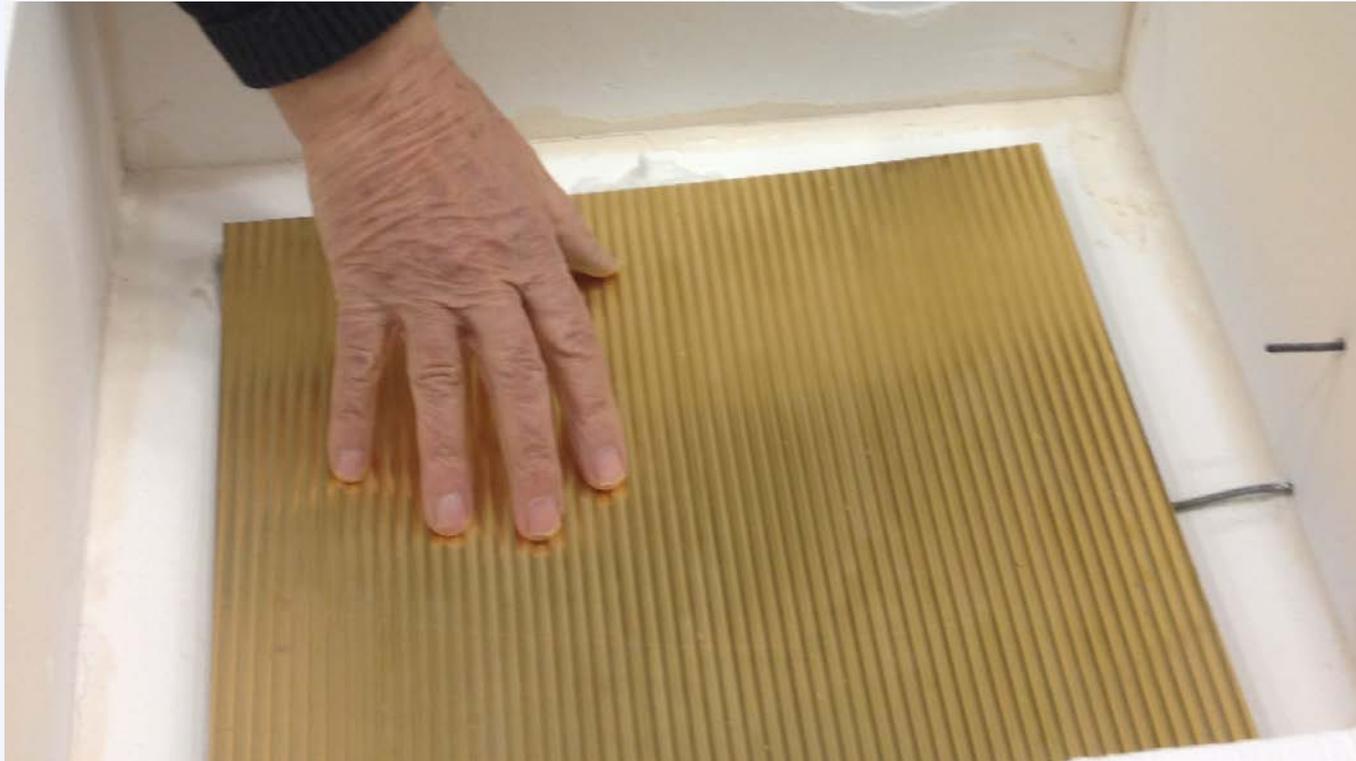
Detail of heating step



- 1) Flat 12" glass square set on concave gold mold with 1.7 m focal length
- 2) Mold temperature brought to initial 500C, glass to 550C
- 3) Heater panel powered at 7.5 kW for 210 sec
- 4) natural convection cooling – back to 500C after 2500 sec

Mold has cusped grooves with low-e coating

- Gold applied to machined cusped grooves (patent)
- low radiative coupling measured in furnace tests
- No evidence of degradation over multiple slumping cycles

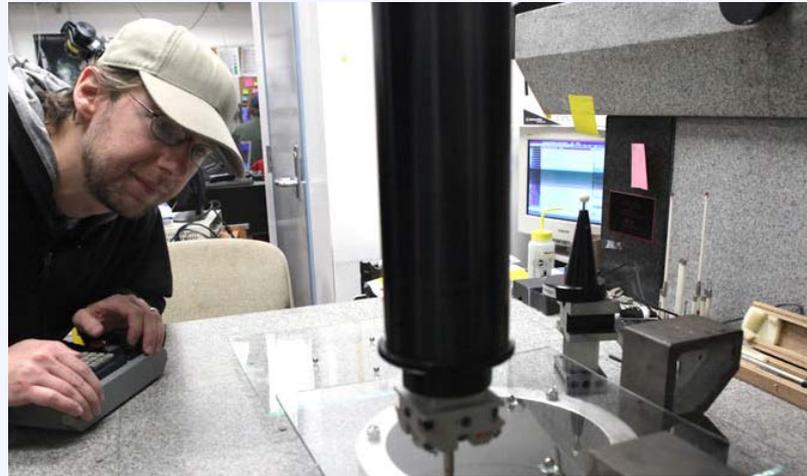


Patent protection for this molding process (in collaboration with REhnu Inc.)

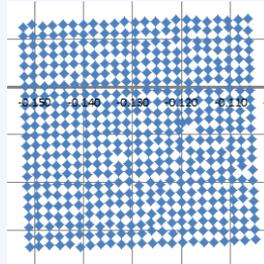
- patent already issued in the US in 2011
- since the August 2012 start of this award, a patent was issued in Australia, # 2009246639
- patent applications are being pursued also in:
 - EPO
 - Germany
 - Israel
 - Mexico
 - UK
 - China
 - India

replica metrology with coordinate measuring machine

- two 12" glass replicas measured with xyz coordinate measuring machine (CMM)

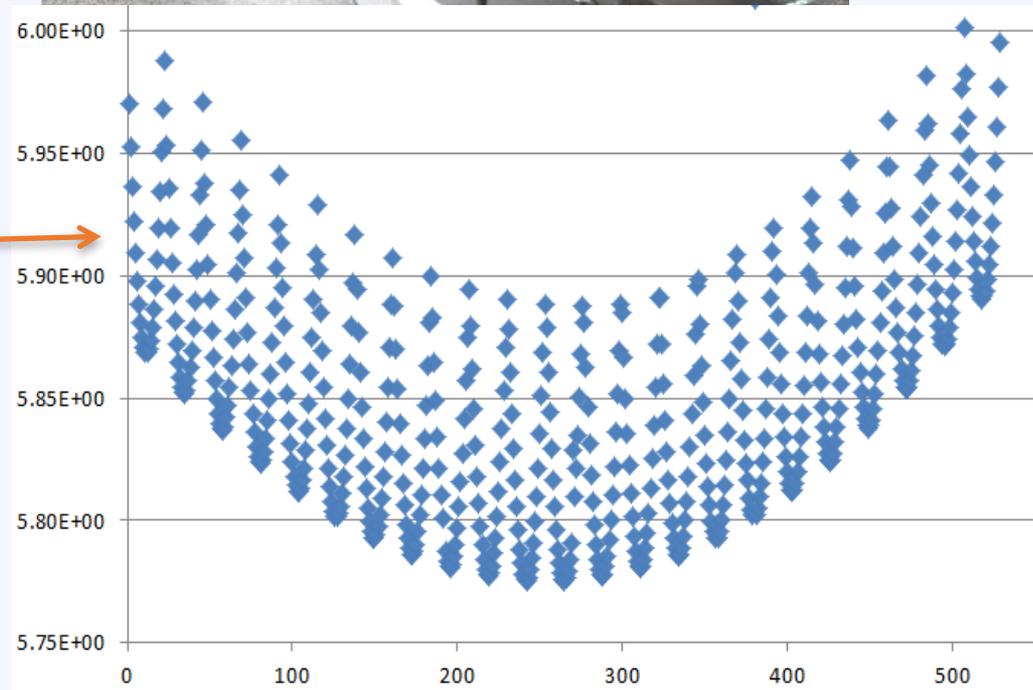


- 500 (x,y) points on 1/2" grid



- z values for all grid points.

- Glass shaped with sagittal depth of 5.8 mm (corner to corner), focal length of 1.7 m.

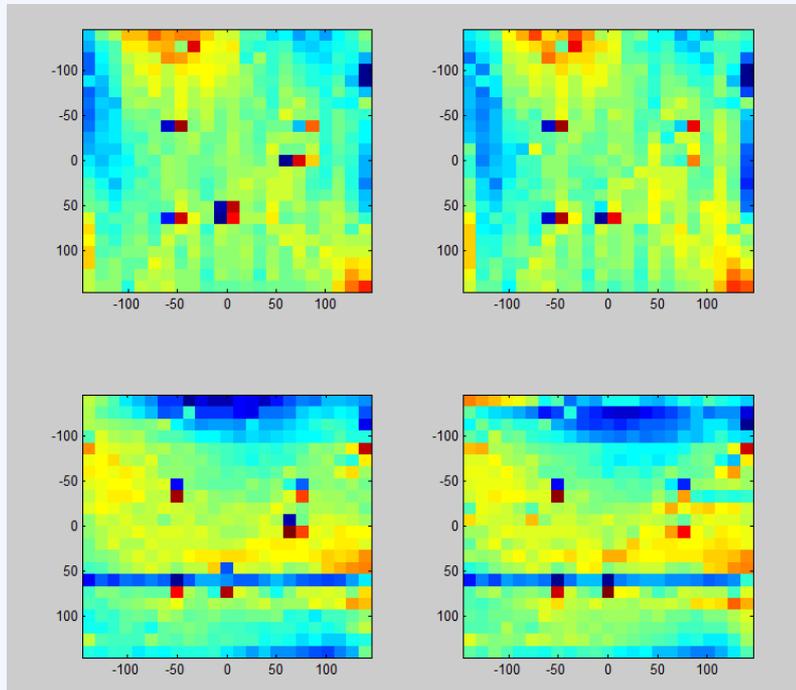


Measurements reduced to slope accuracy

Replica 1

x-slope error
(0.48 mR rms)

y-slope error
(0.61 mR rms)



Replica 2

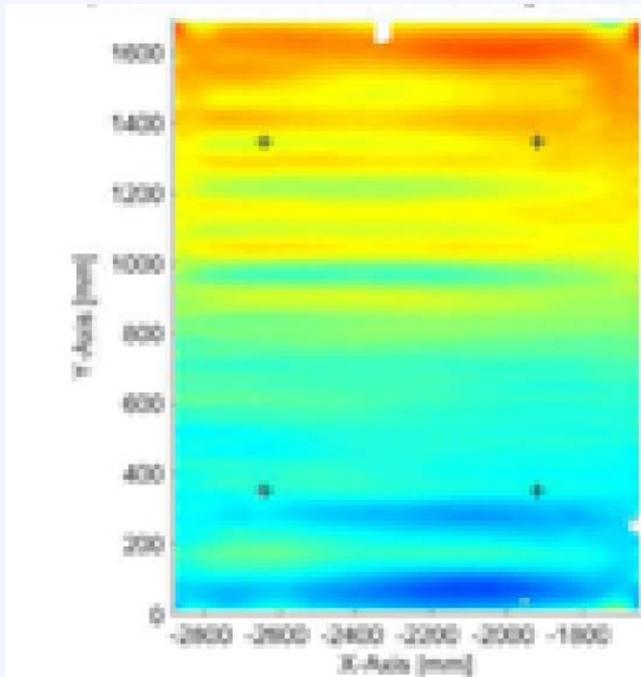
x-slope error
(0.50 mR rms)

y-slope error
(0.60 mR rms)

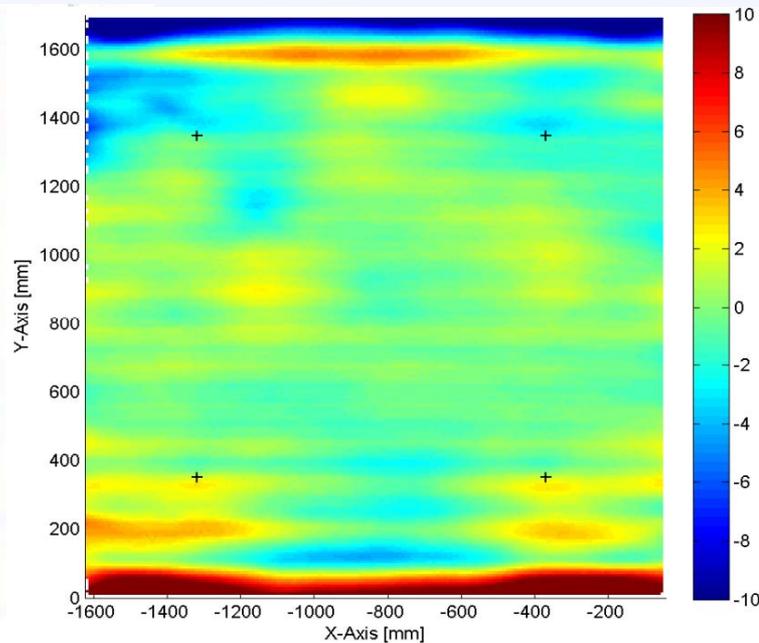
- x and y slope maps given for successive replicas
- rms values are the average slope error compared to the best fit targeted mold shape, an off-axis paraboloid segment
- The errors are dominated by errors in mold shape
- The accuracy of replication is measured by the *difference* in slope between the replicas, 0.22 mR (S_x) and 0.31 mR (S_y)

test replica vs commercial trough mirror production

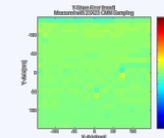
Comparison of slope errors and size, both to same scale



commercial, annealed



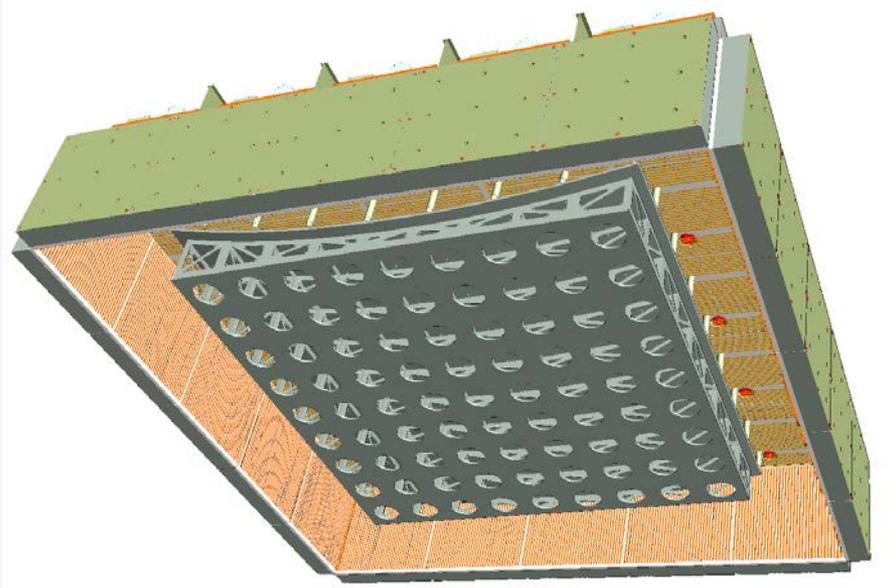
commercial, tempered



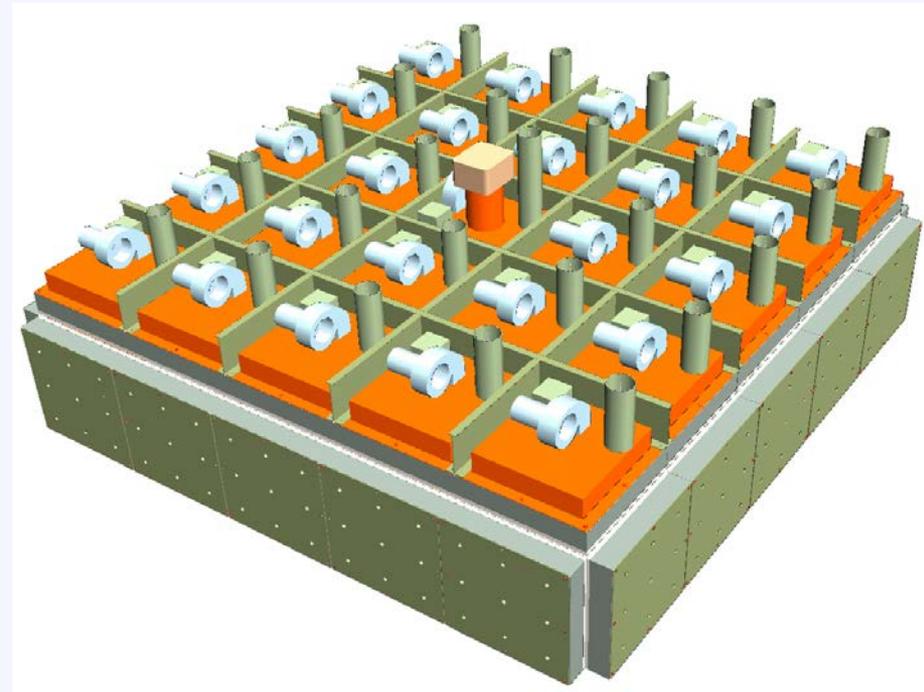
UA test replica

The UA slump-molded test replica shows smaller errors at the edges, where the commercial reflectors show slope errors inherent in their being bent by rollers.

Model views with initial (point focus) test mold (in collaboration with REhnu Inc)



view from below, with mold in place



View from above
5x5 panel array with blowers and chimneys

Test of uniformity of cooling by air jets

- air jets to cool the shaped glass from 700C to 500C
- 100 sec. goal requires 250 sec. cooling time constant
- Modelling and lab tests to determine optimum jet grid
- Initial tests near room temperature show 200 sec. time constant

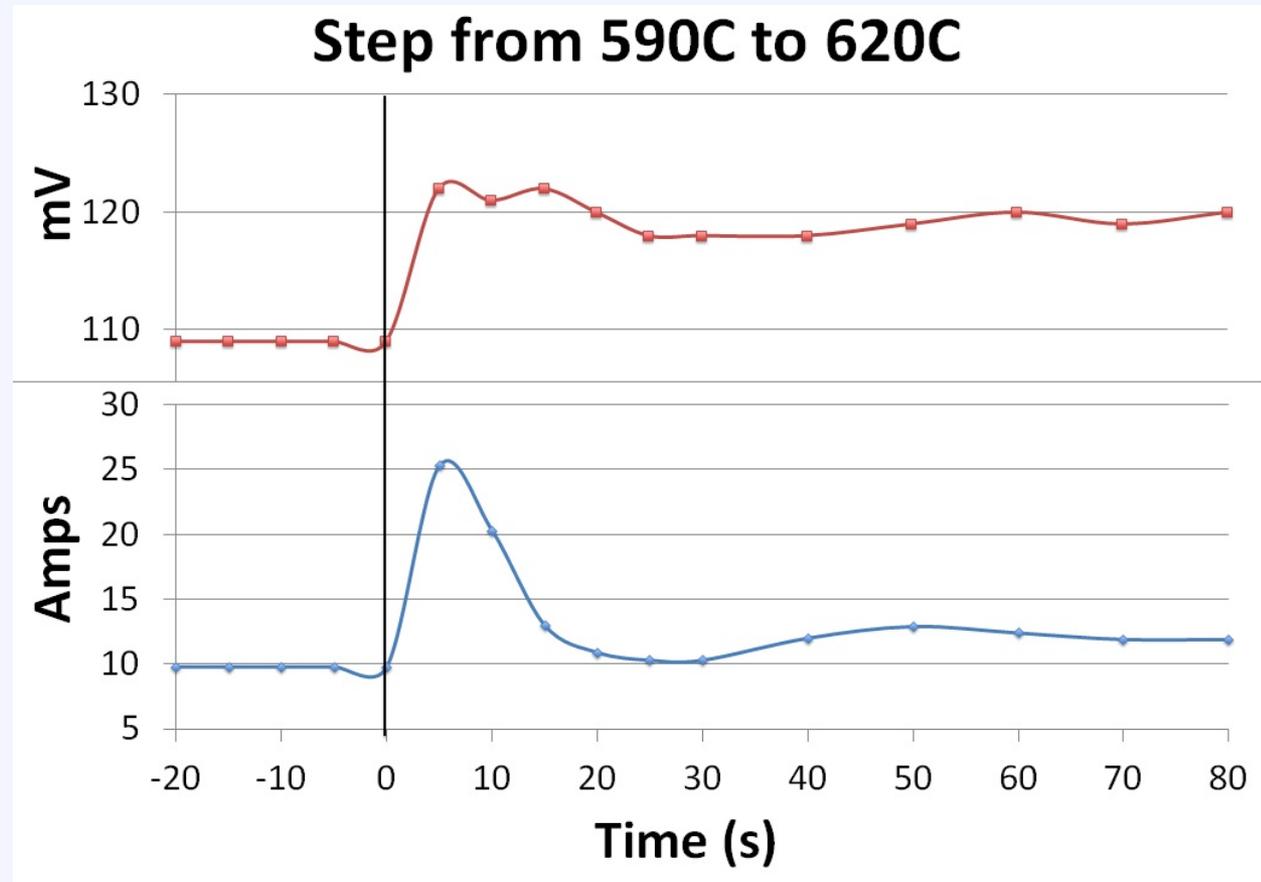


Thermal camera view of hot glass sheet cooled from behind by jet nozzles in a square grid

First tests of system response to radiant heater, glass temperature measured with 4.6 μm IR sensor (mV)

Temperature across glass sheet in furnace to be mapped with 25 thermal IR sensors looking down from the furnace lid

- filtered at 4.5 – 4.7 μm wavelength where glass is opaque
- view glass furnace through transparent sapphire window

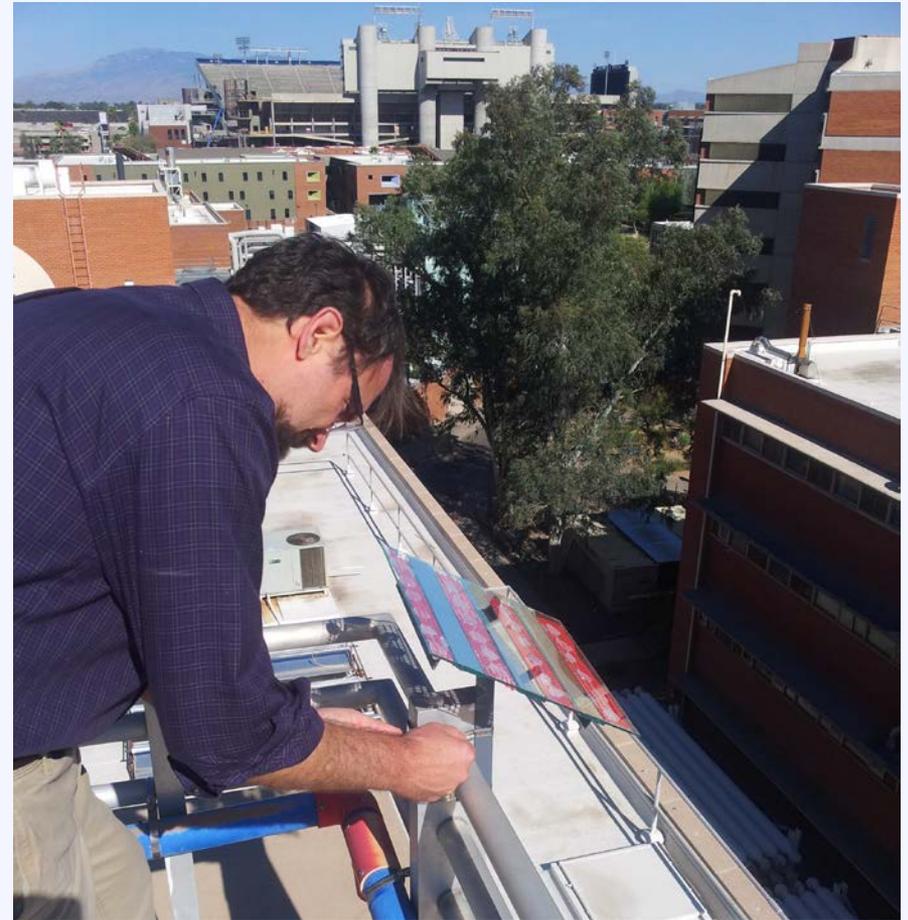


progress toward quantitative go/no go specs for fast molding

parameter	Go/no go spec	Current progress	notes
* Glass size:	1.63 m	0.3 m sample	glass size limited by size of test furnace
Surface accuracy	2 mR rms	0.8 rms, x and y combined	surface accuracy comfortably beats both go/no go and final specs, but needs to be demonstrated on larger scale
cycle time	1000 sec	2500 sec	Test cycle time dominated by slow natural convection cooling of mold. Forced convection in the big furnace will fix this
T_{start} & T_{finish}	500C	500C	

High reflectance and anti-soil mirror coatings (in collaboration with Tucson Electric Power)

- Field test of reflectivity degradation over time, between washings
- Specular reflectance comparison of:
 - Solana mirrors (no anti-soil)
 - UA mirrors (TiO_2 coating)
 - Ariva mirrors (3M coating)
- Measurements made with Devices and Services portable reflectometer
 - Resolution to 0.1%
 - Acceptance angles 7, 15 and 25 mrad



Initial test of single reflector with and without TiO_2 coating, at atmospheric particulate testing station on UA campus

In-process metrology to < 0.5 mrad accuracy bar of co-aligned lasers translated above mirror

- New Laser Hartmann system to measure replica slope directly
- will be validated against commercial RioGlass and laser tracker system
- 60 co-aligned lasers on bar project down to mirror under test
- bar translated to cover mirror with 2500 test points
- Spot positions along line focus recorded with high res. camera
- slope error for each test point



Key findings

- Key issues in fast slump molding from analysis:
 - For stability of mold shape, need to minimize thermal stresses
 - Glass takes thermally distorted shape of the mold as it freezes
 - Mold shape must be compensated
- Novel mold and furnace designed for fast thermal slewing with minimal thermal stresses
 - Incorporates radiative heating and air jet cooling
- Titania anti-soil coating preserves reflectivity, but:
 - May not be useful in SW climate
 - May not survive thermal shaping cycle - tbd
- Building a custom glass shaping mold and furnace at full scale (1.65 m square) is a big deal