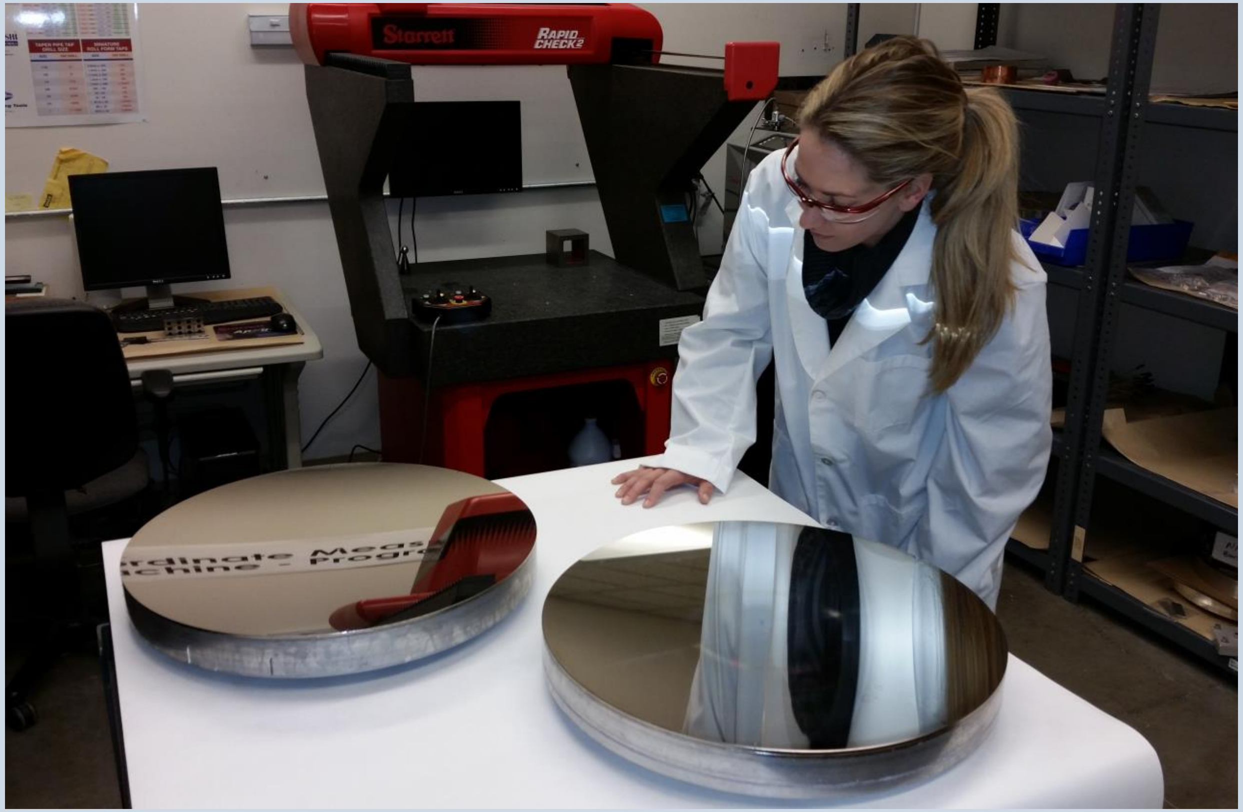


Advanced Mirror Material System

The Peregrine Falcon Corporation

Mirror Technology Days

SBIR/STTR Workshop 2017

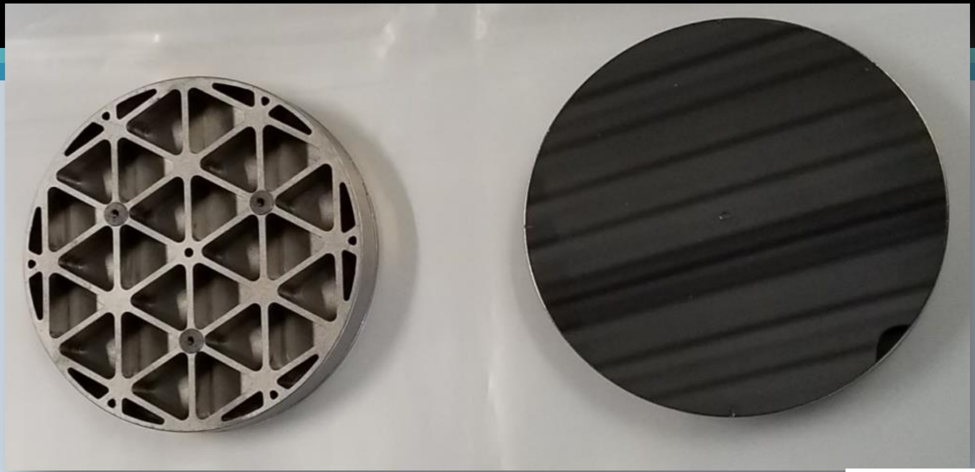
Advanced Mirror Material System

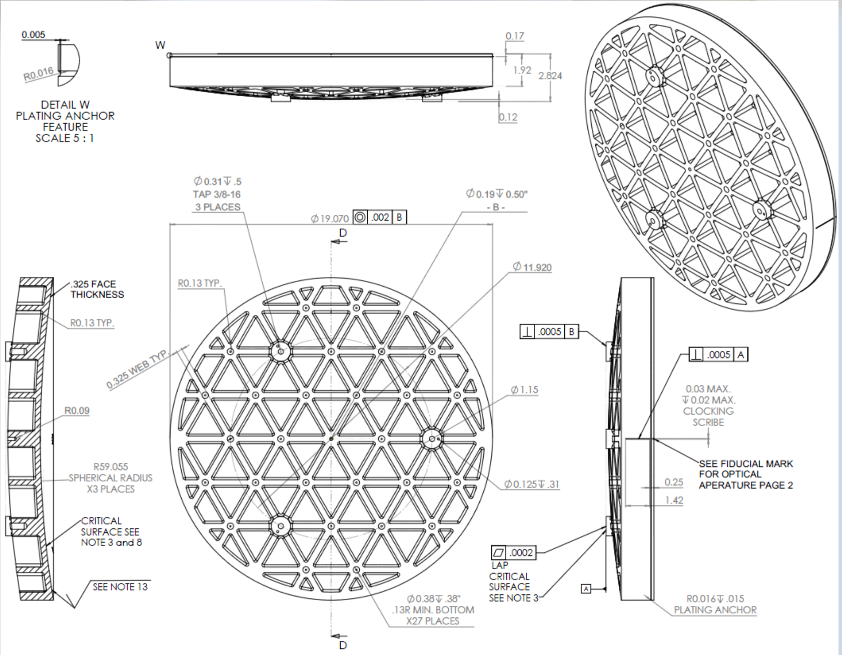
<u>Phase II Objectives</u>

Develop a material system that can…

- Reduce the cost of mirrors by a factor of 4 from current state of the art \$6.5 M/m^2, while minimizing production time in half.
- Maintain stiffness, low density, stability, and performance.
- Produce mirrors > 4 m in size.
- Match CTE of electroless nickel to Be-38Al substrate by controlling phosphorous content.
- Operate across wide temperature ranges down to low temperature.

Hardware

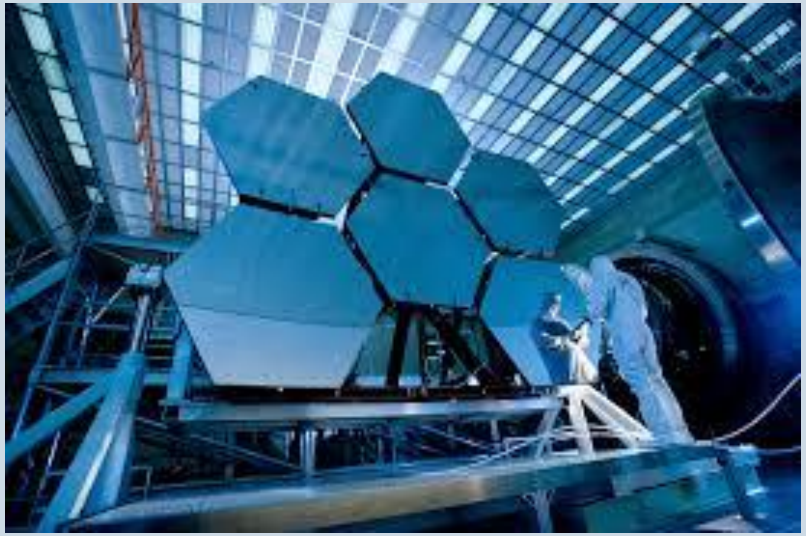




0.005
R0.016
W
0.17
1.92
2.824
0.12
DETAIL W
PLATING ANCHOR
FEATURE
SCALE 5 : 1
Ø0.31 ↧ .5
TAP 3/8-16
3 PLACES
Ø0.19 ↧ 0.50"
- B -
Ø19.070 .002 B
D
Ø11.920
.325 FACE
THICKNESS
R0.13 TYP.
R0.13 TYP.
0.325 WEB TYP.
⊥ .0005 B
⊥ .0005 A
0.03 MAX.
↧ 0.02 MAX.
CLOCKING
SCRIBE
Ø1.15
R0.09
SEE FIDUCIAL MARK
FOR OPTICAL
APERATURE PAGE 2
R59.055
SPHERICAL RADIUS
X3 PLACES
Ø0.125 ↧ .31
0.25
1.42
CRITICAL
SURFACE SEE
NOTE 3 and 8
.0002
LAP
CRITICAL
SURFACE
SEE NOTE 3
A
SEE NOTE 13
Ø0.38 ↧ .38"
.13R MIN. BOTTOM
X27 PLACES
D
R0.016 ↧ .015
PLATING ANCHOR

Phase II Effort

- Motivation = Make mirrors more cost effective.
  - ¼ cost of James Webb Space Telescope which was $6.5 million/m^2$
- When NASA sent men to the moon, no one heard anything about budgets… now everything has to fit into a budget.

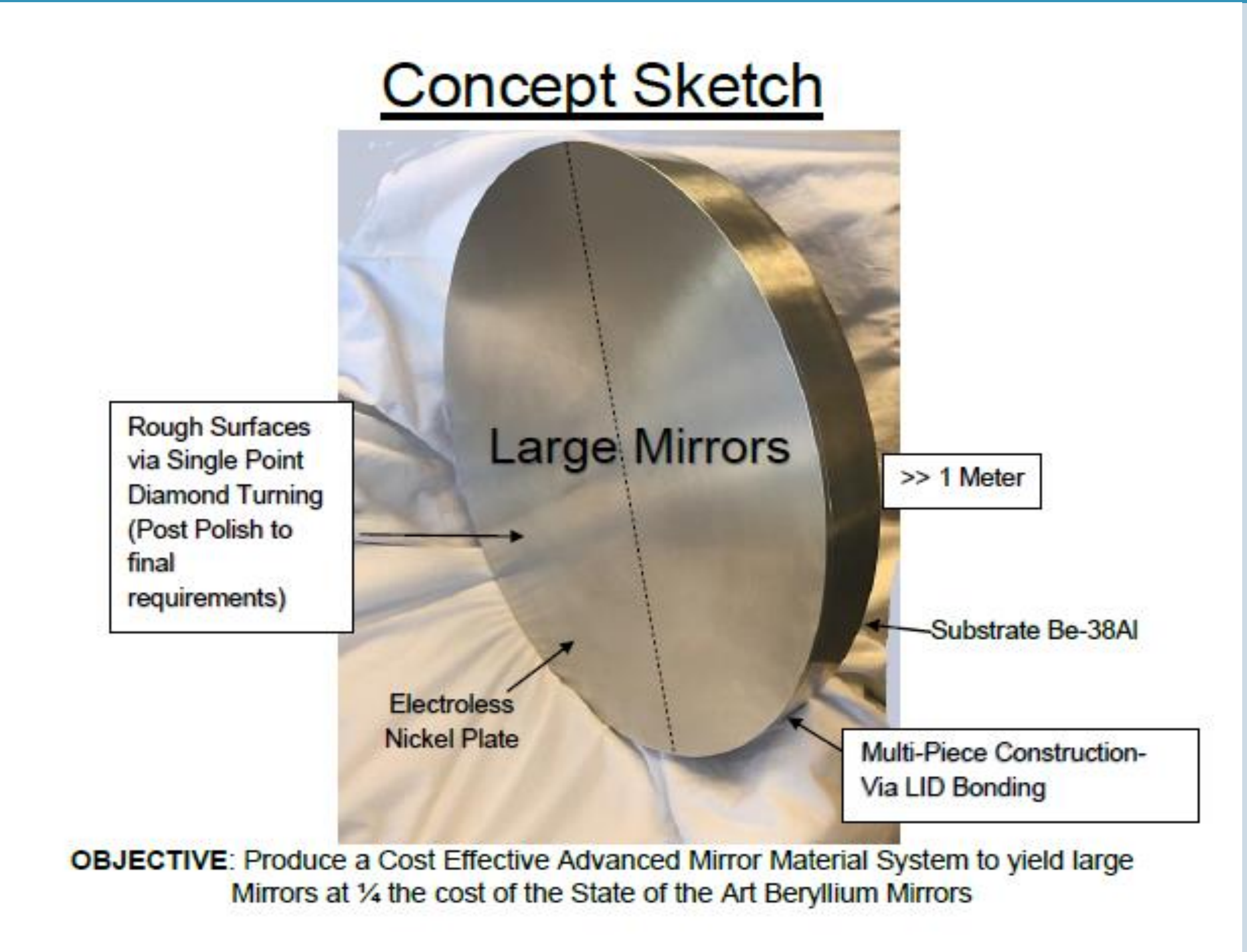


Mirrors are Getting Bigger and Bigger

Future Larger Observatories…

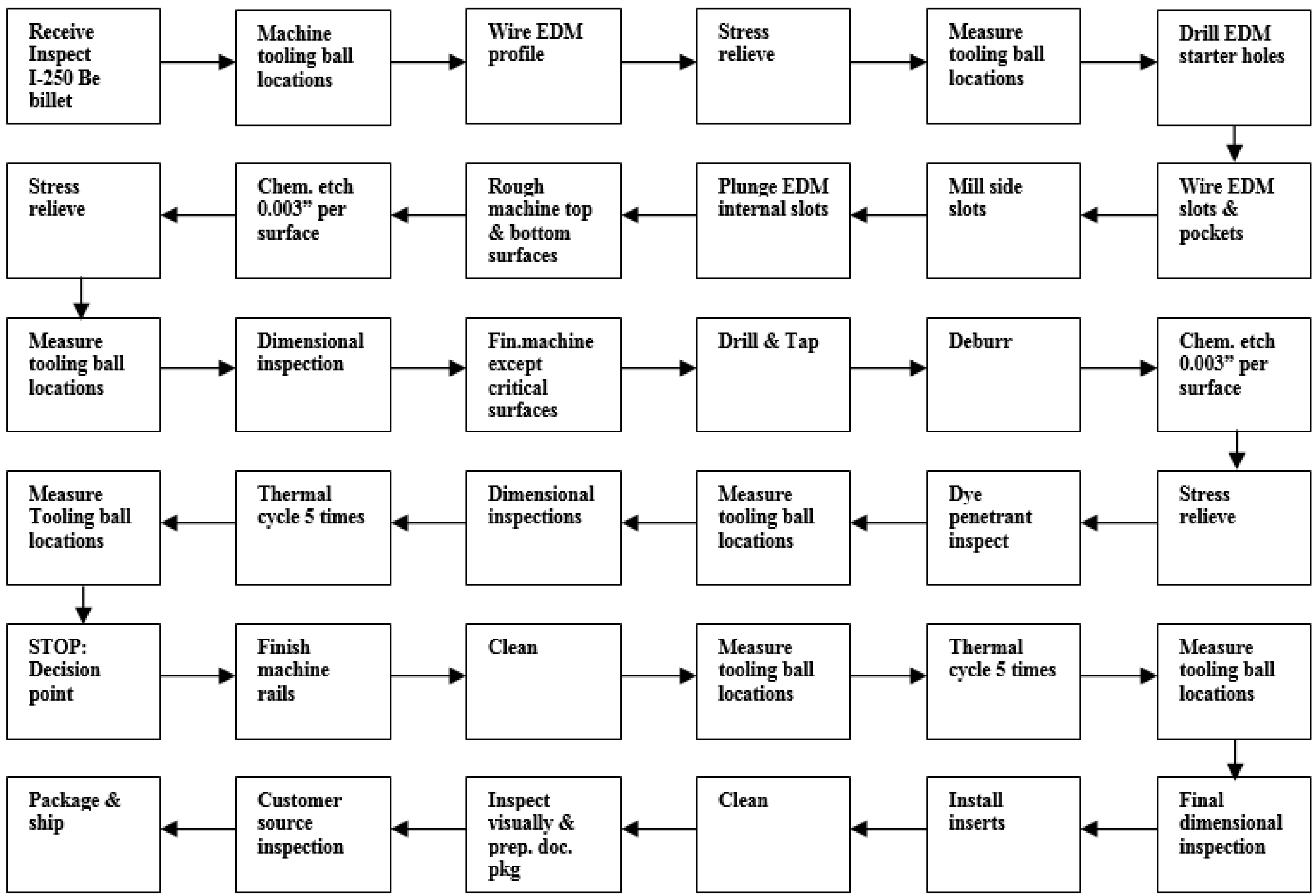
Goal to Make Very Large Mirrors

The bigger the optic, the higher the cost.



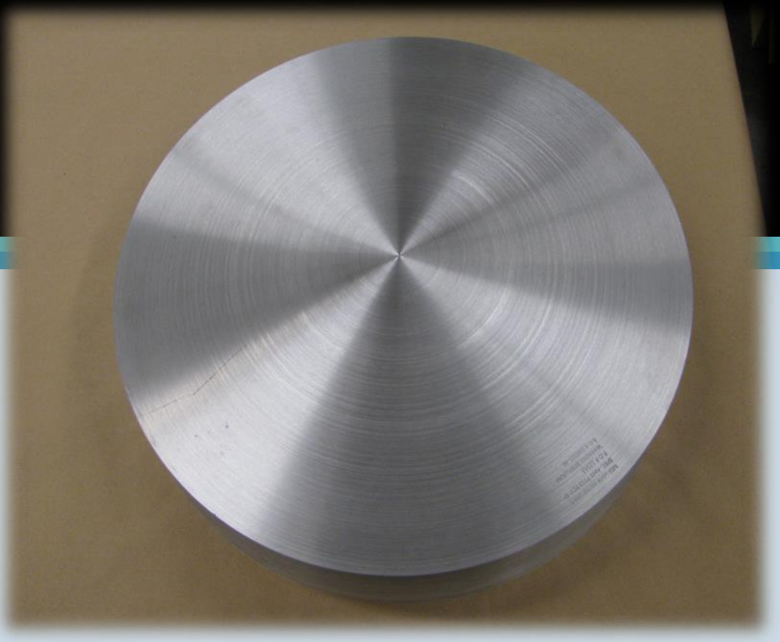
Beryllium Significant Substrate Processing

Flowchart I: Beryllium RGA Integrating Structure, Machining Flow Chart



XMM

The Process



"The New"

Process Be-38Al Substrate (AMS 7911) with Stress Relieving

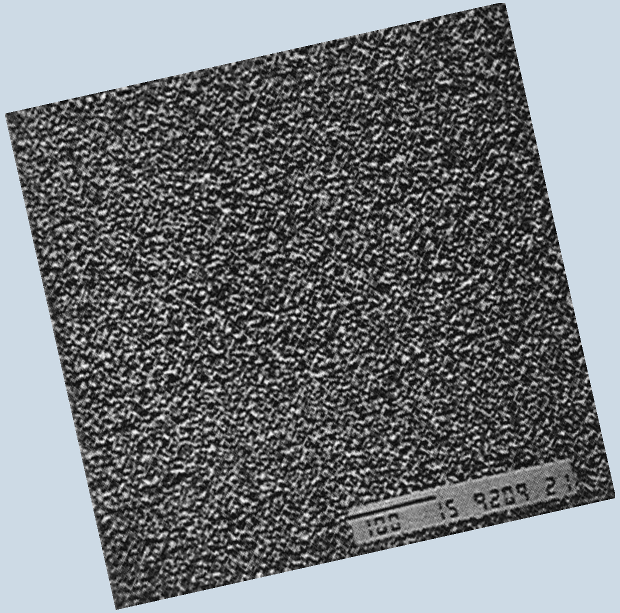
Apply Electroless Nickel (AMS 2404)

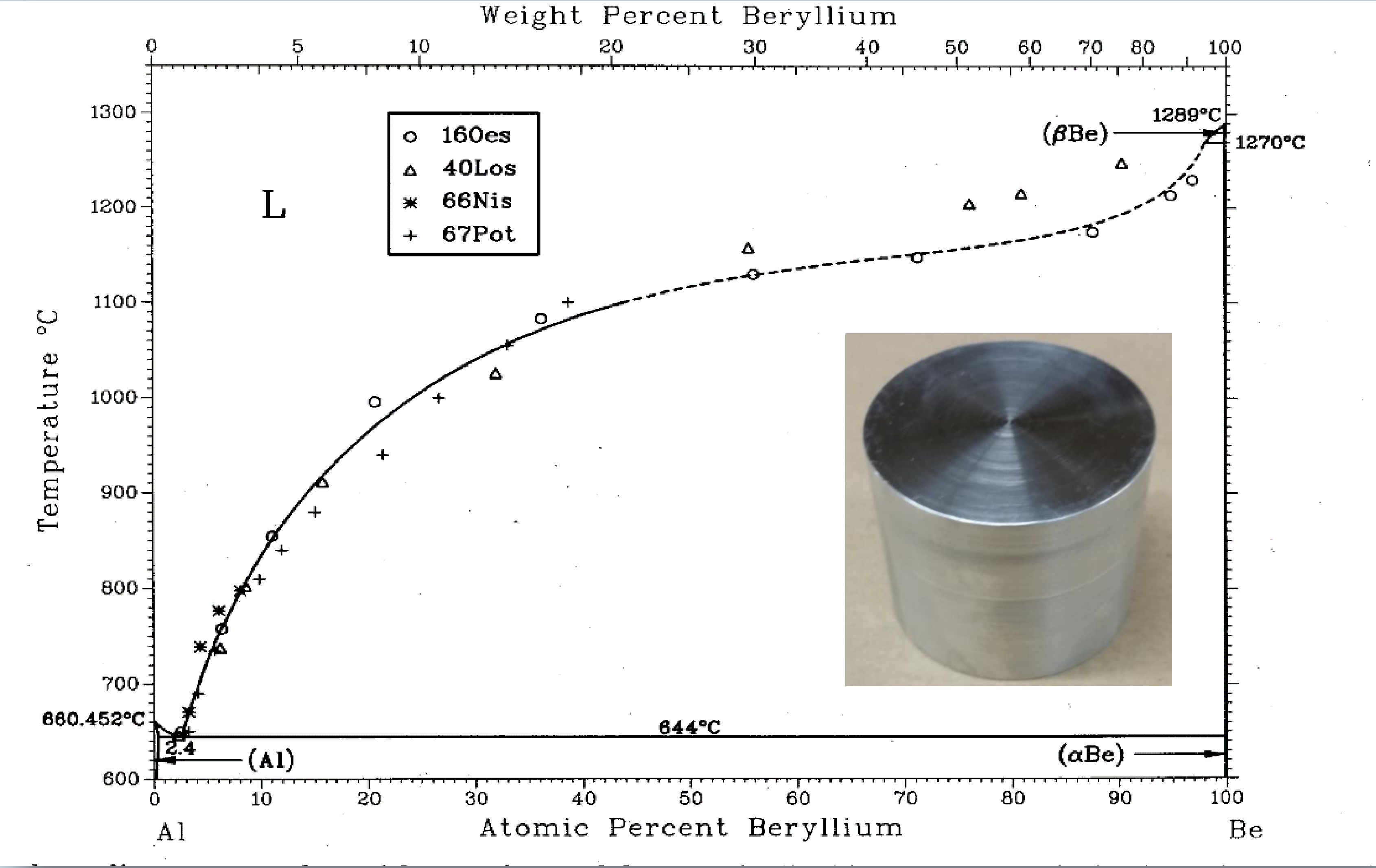
Liquid Interface Diffusion Bond

Single Point Diamond Turn

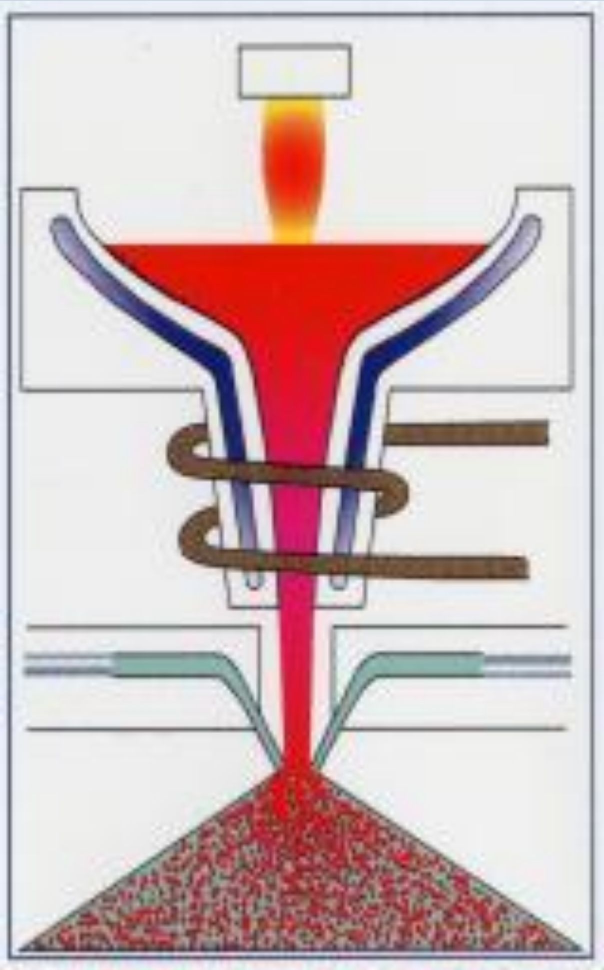
Results in a large reduction in the number of processing steps compared to Be.

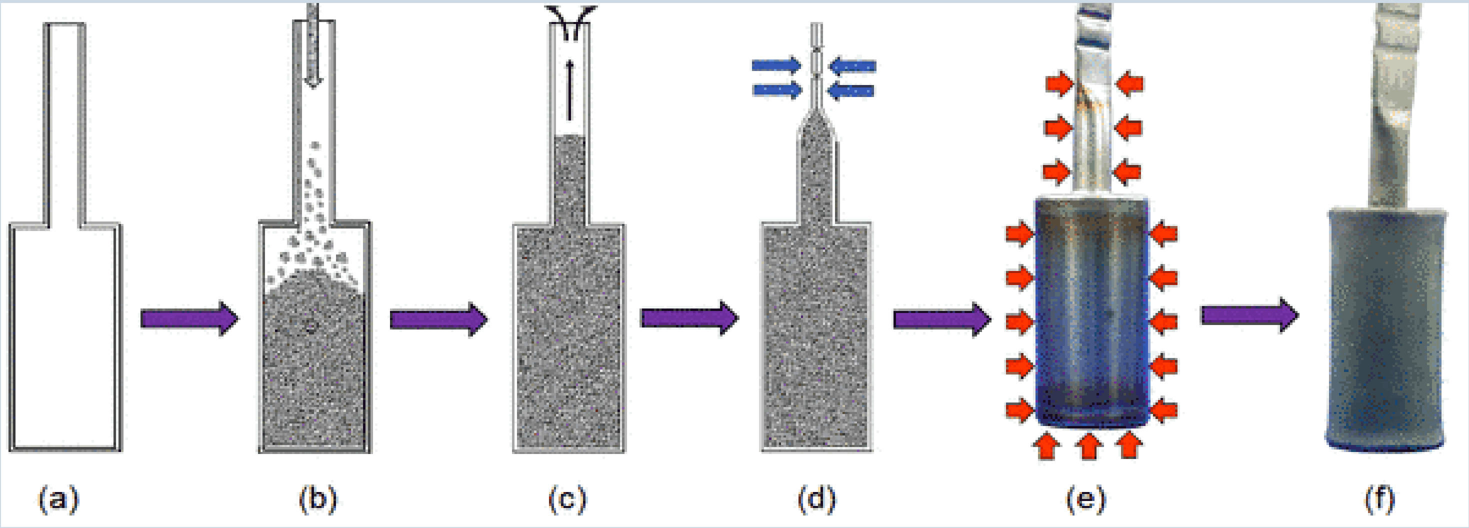
Mirror Substrate: Be-38Al (LockAlloy)





Be-38Al

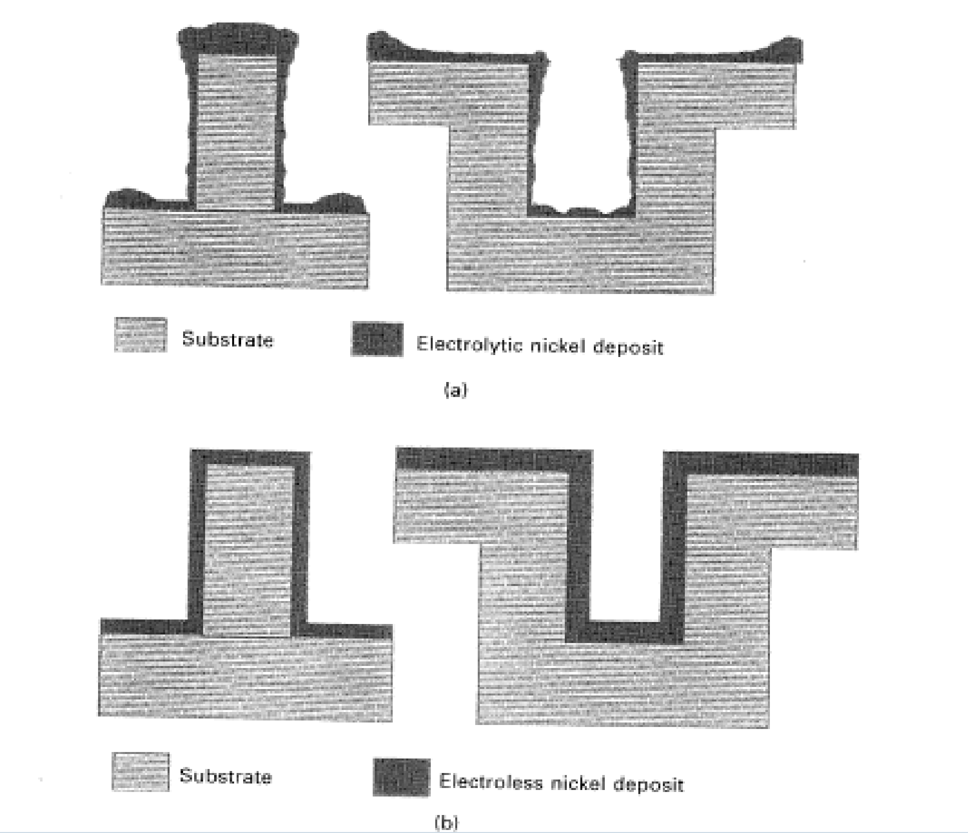


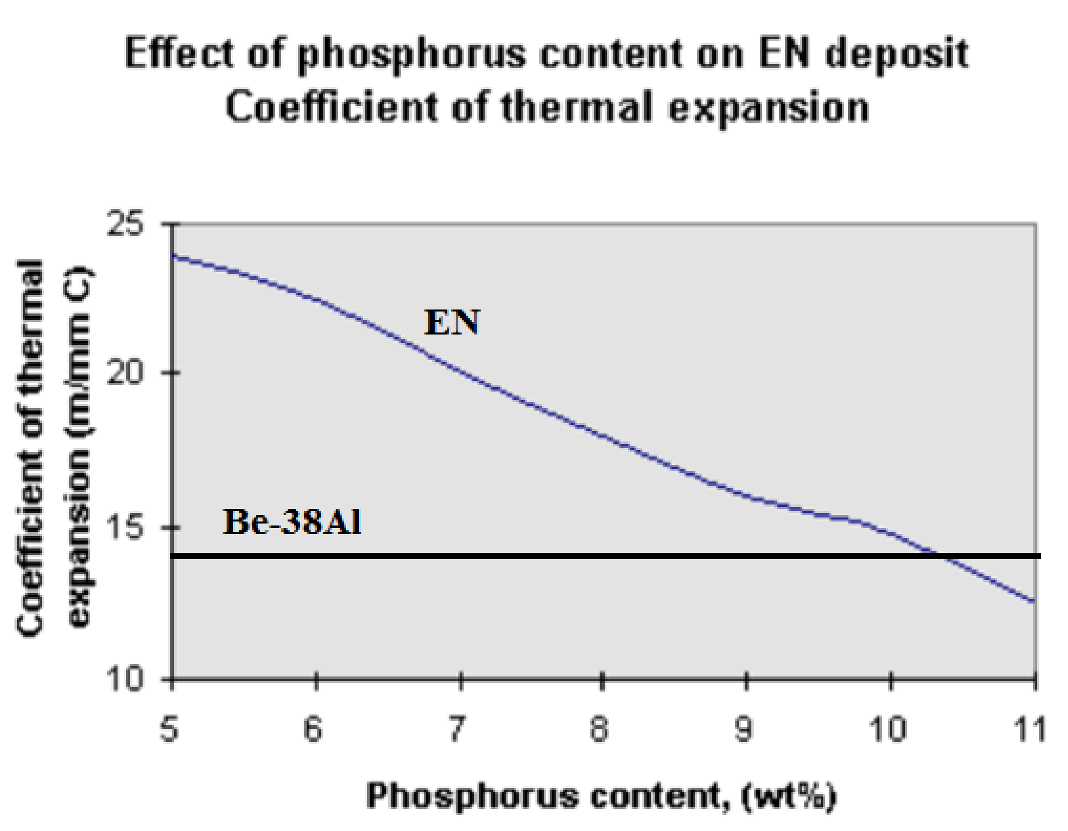


Material Comparison Chart of Metals
(Ambient Temperature Properties)

Property	Be AMS 7908	Be-38Al AMS 7911	Aluminum 6061 T6	Titanium Ti-6Al4V	Magnesium AZ91D-F
Density (g/cc)	1.85	2.10	2.70	4.43	1.81
Thermal Conductivity (W/mK)	216	210	167	7.8	72.7
CTE (ppm/°C)	11.4	13.9	22.9	9.0	26
Modulus of Elasticity (GPA)	303	192	69	110	45
Ductility (%)	2	2	8	10	3
Yield Strength (MPA)	241	192	255	1034	150
PEL (MPa)	>30	17.3	<6.5	N/A	NA
Specific Heat (J/kg°K)	1925	1506	896	597	NA
Electrical Conductivity (% IACS)	41	45	43	N/A	<40
Melting Point (°C)	1285	1082	652	1660	650
Specific Stiffness	164	91	26	25	25

Mirror Surface: Electroless Nickel



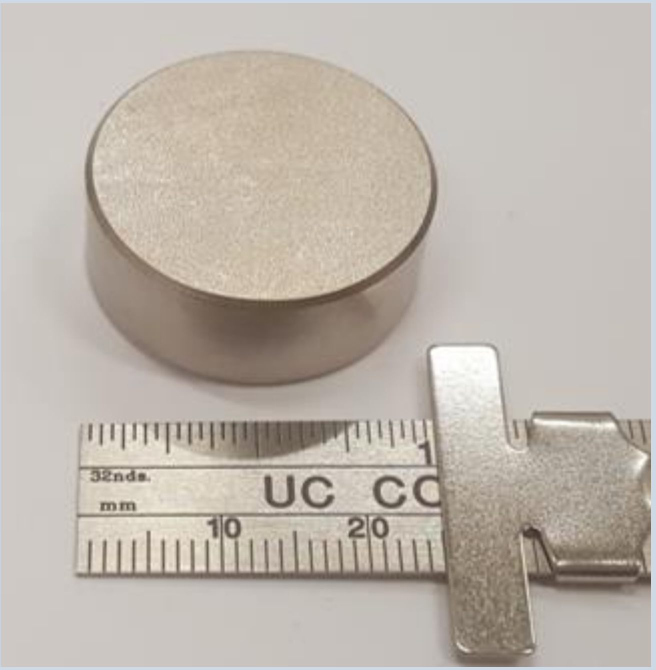


In Phase I, we demonstrated a phosphorous match.

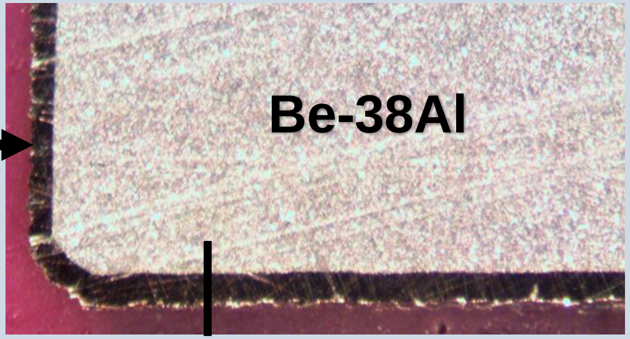
Influences on the As-Plated Nickel Deposition Residual Stress

- Bath Chemistry (Including P%)
- pH
- Temperature
- Agitation
- ***MTO (Metal Turn Over; small amount of solution drained of (~1%); solutions added)***
  - The bath age
    - Fresh Bath; deposition layer tends to have residual stresses that are in compression (~5,000 psi).
    - Baths with 3 MTO; depositions tend to be stress free (use in line controller to maintain MTO 3 bath).
    - Baths with over 3 MTO; depositions tend to have residual stresses that are in tension (~3,500 psi).

Electroless Nickel



Cross Section of Electroless Nickel



EN layer

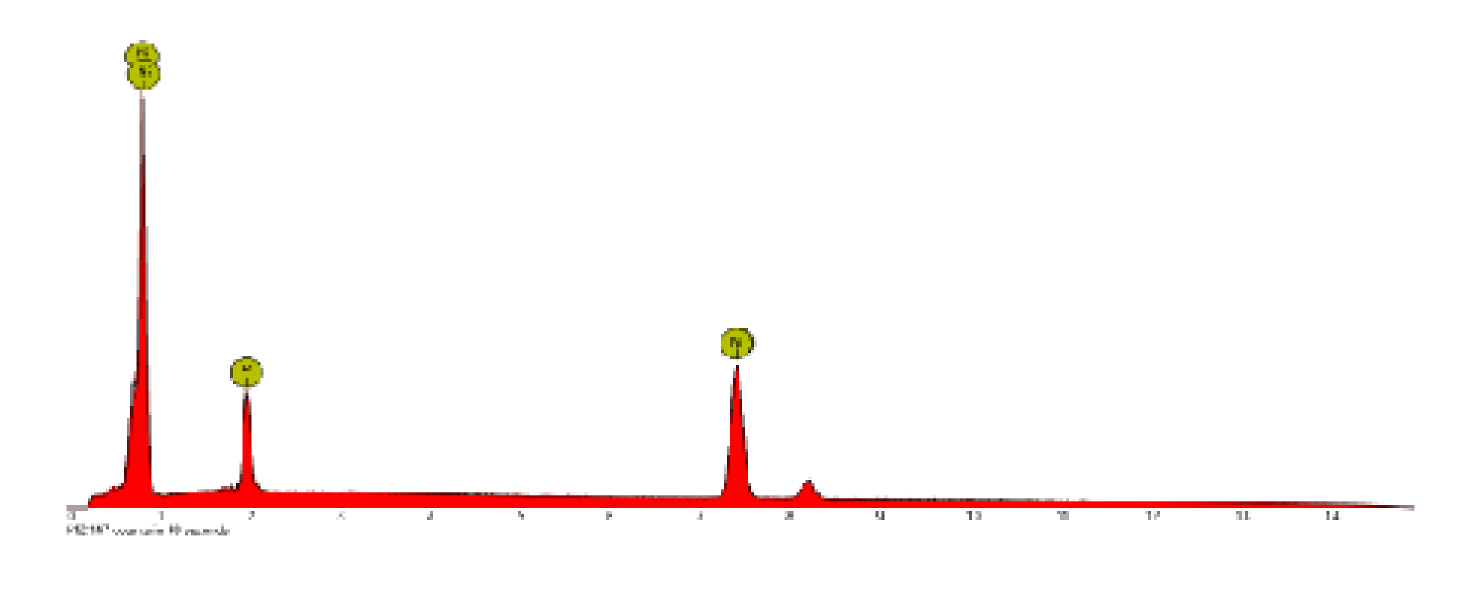
~.004"

Nickel Layer

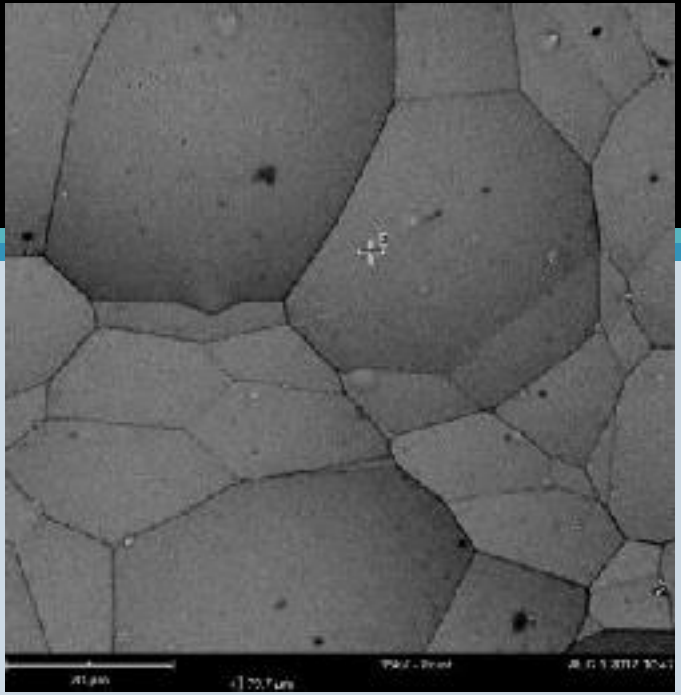
Scan path through plating
Via X-Ray Fluorescent
Microscopy

The sample to the left is cut in half and the cross section polished. The view to the right shows the cross-section and the X-ray beam scan line

Electroless Nickel



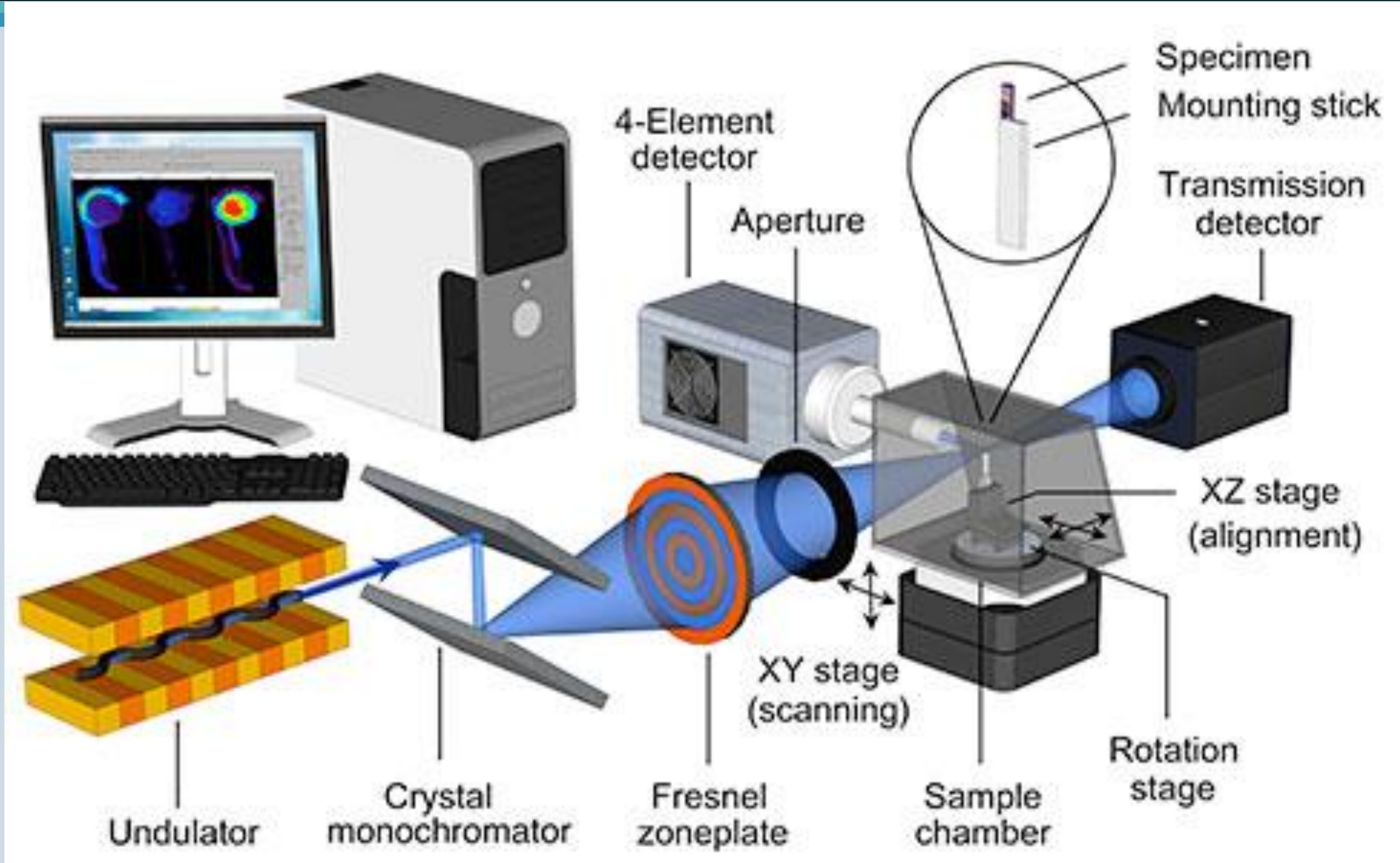
X-Ray Analysis of Spot 2 on Sample A-1



X-Ray Analysis of the Cross Section of EN Plating

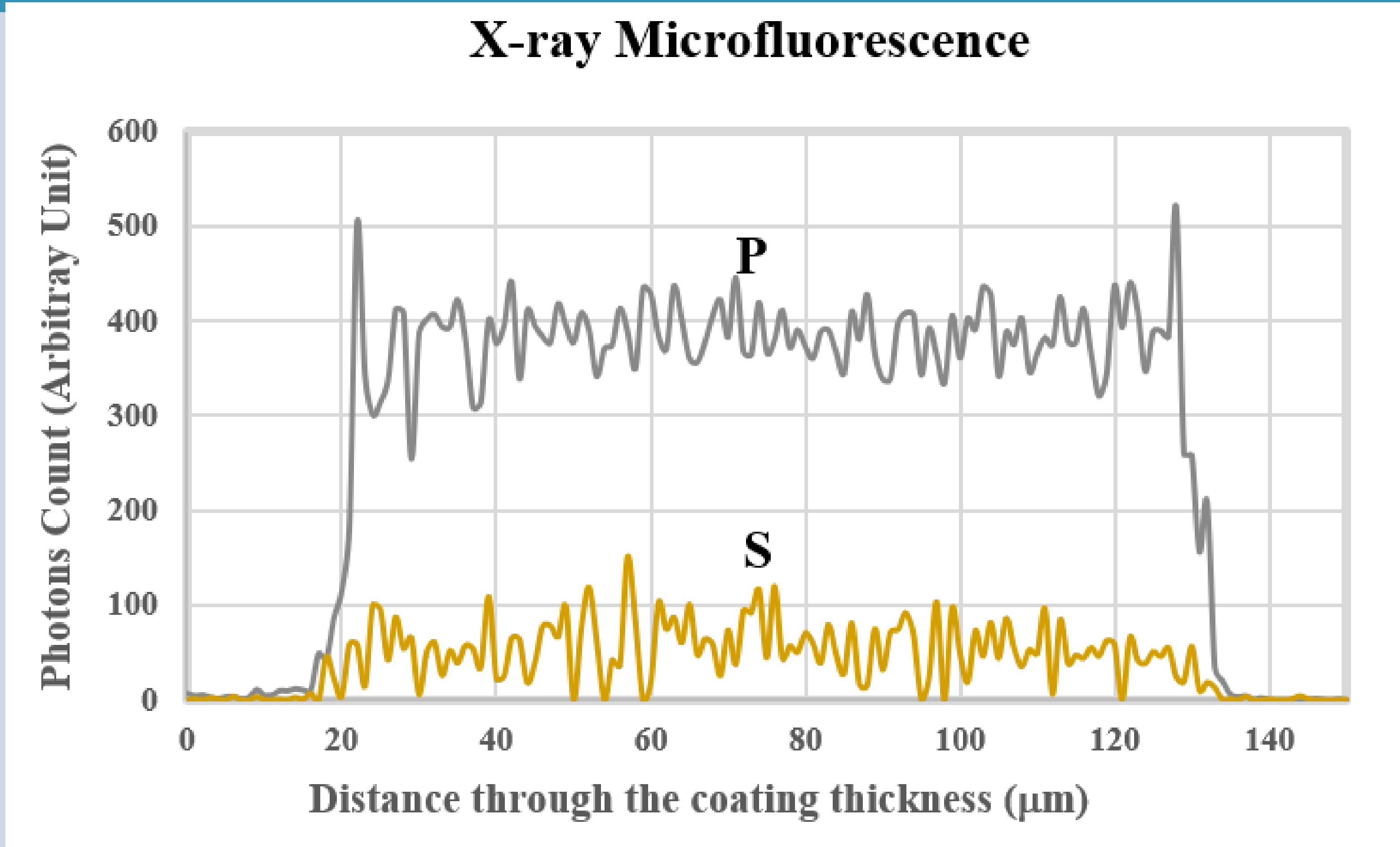
Qualitative Elemental Analysis (Preliminary)				
Element Number	Element Symbol	Element Name	Weight Concentration	Error
28	Ni	Nickel	88.6	0.0
15	P	Phosphorous	11.4	0.0

X-Ray Fluorescent Microscopy



Curtesy [Georgia Tech]()

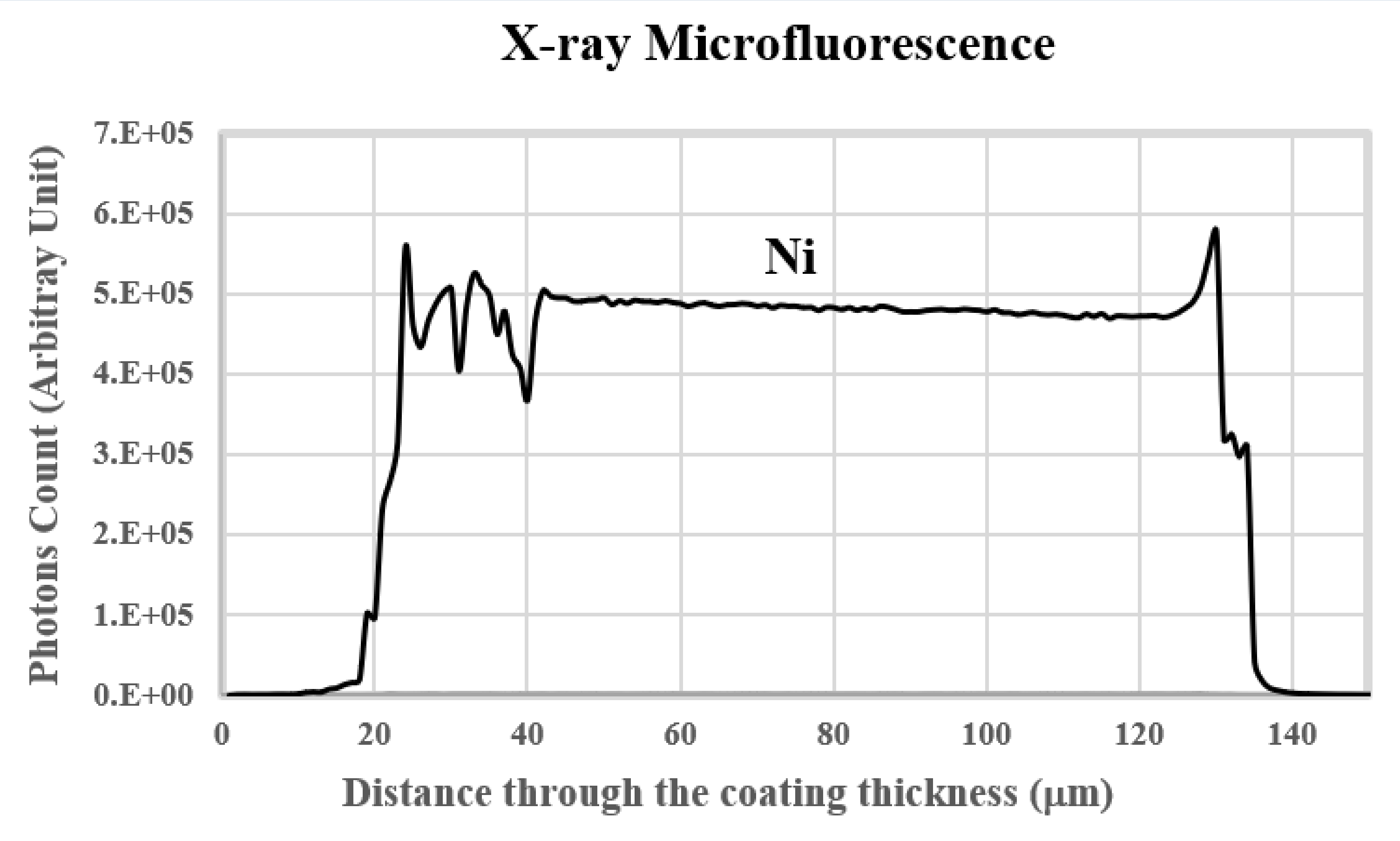
Through the Thickness Elemental Composition of a Peregrine Sample (10 keV Beam, 300 nm Size)



Variations of P & S elements concentration through the thickness of a sample 100 µm coating

Demonstrates the "Power of Technique"

Through the Thickness Elemental Composition of a Peregrine Sample



Variations of Ni concentration through the thickness of a sample 100 μm coating

Allowable Stress

Achieving a “stress free” substrate then:

Max allowable range of stress in the system (compressive or tensile) σ_{max}

Thermal expansion and Youngs modulus of substrate $\alpha_s(T)$, $E_s(T)$

Thermal expansion and Youngs modulus of plating $\alpha_p(T)$, $E_p(T)$,

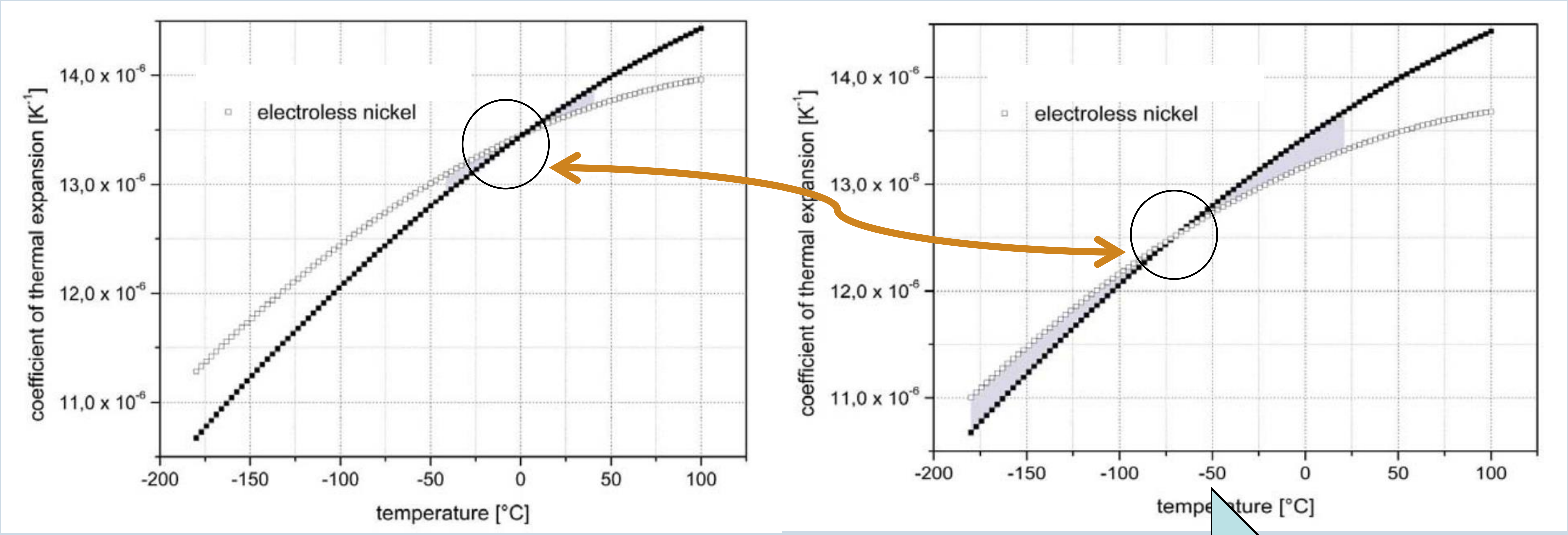
Temperature of the bath T_{bath}

Lets define residual stress σ_r

$$\sigma_r = \int_{T_{bath}}^{T} [E_s\alpha_s(T') - E_p\alpha_p(T')]dT'\}$$

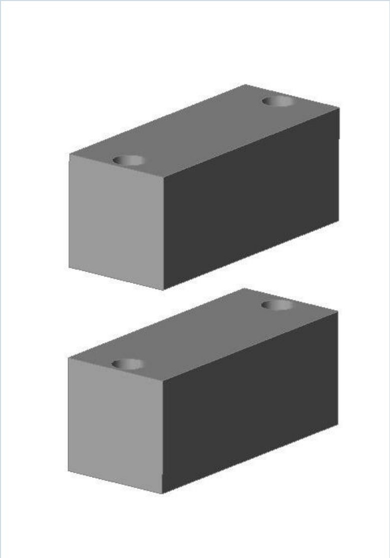
where the integration limit T is any temperature in the operating range at which σ_r has a maximum (tensile) or minimum (compression)

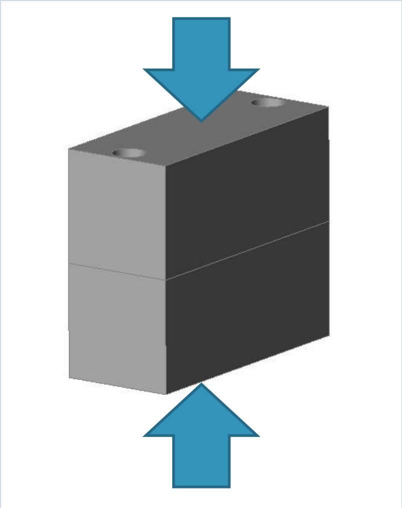
Manage the Bath to Minimize Residual Stress



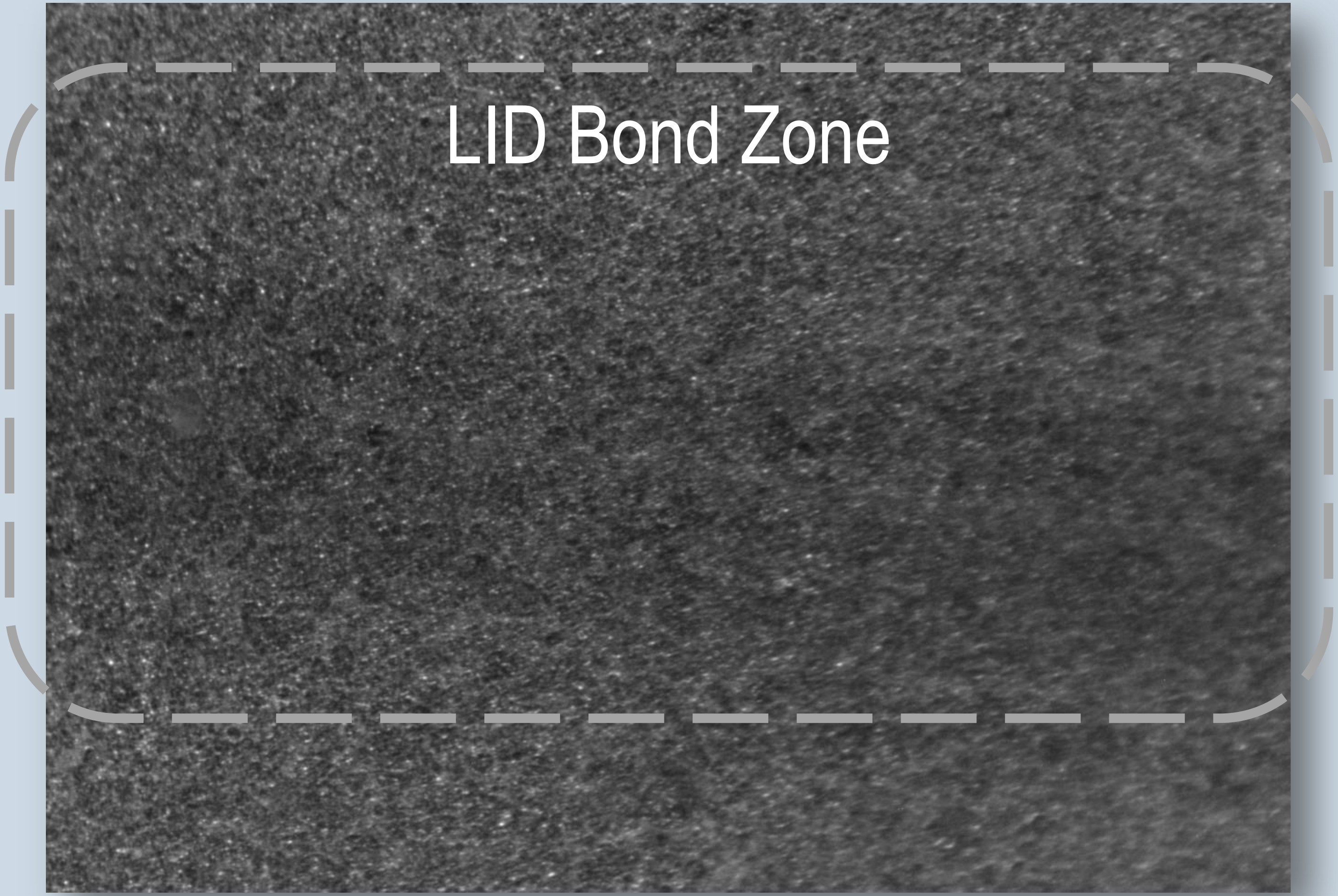
Minimizing residual stress is a function of controlling chemistry, pH, temperature, & "age" of bath .

Joining: Liquid Interface Diffusion Bonding



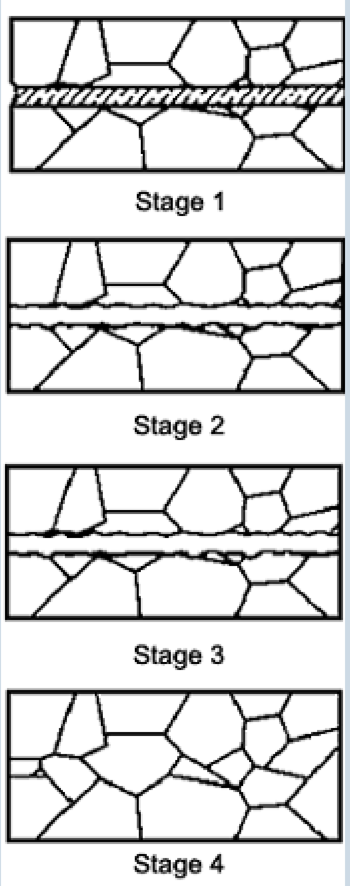


Parts Joined Together under Temperature and Pressure



Liquid Interface Diffusion Bonding

Enables large mirror production.

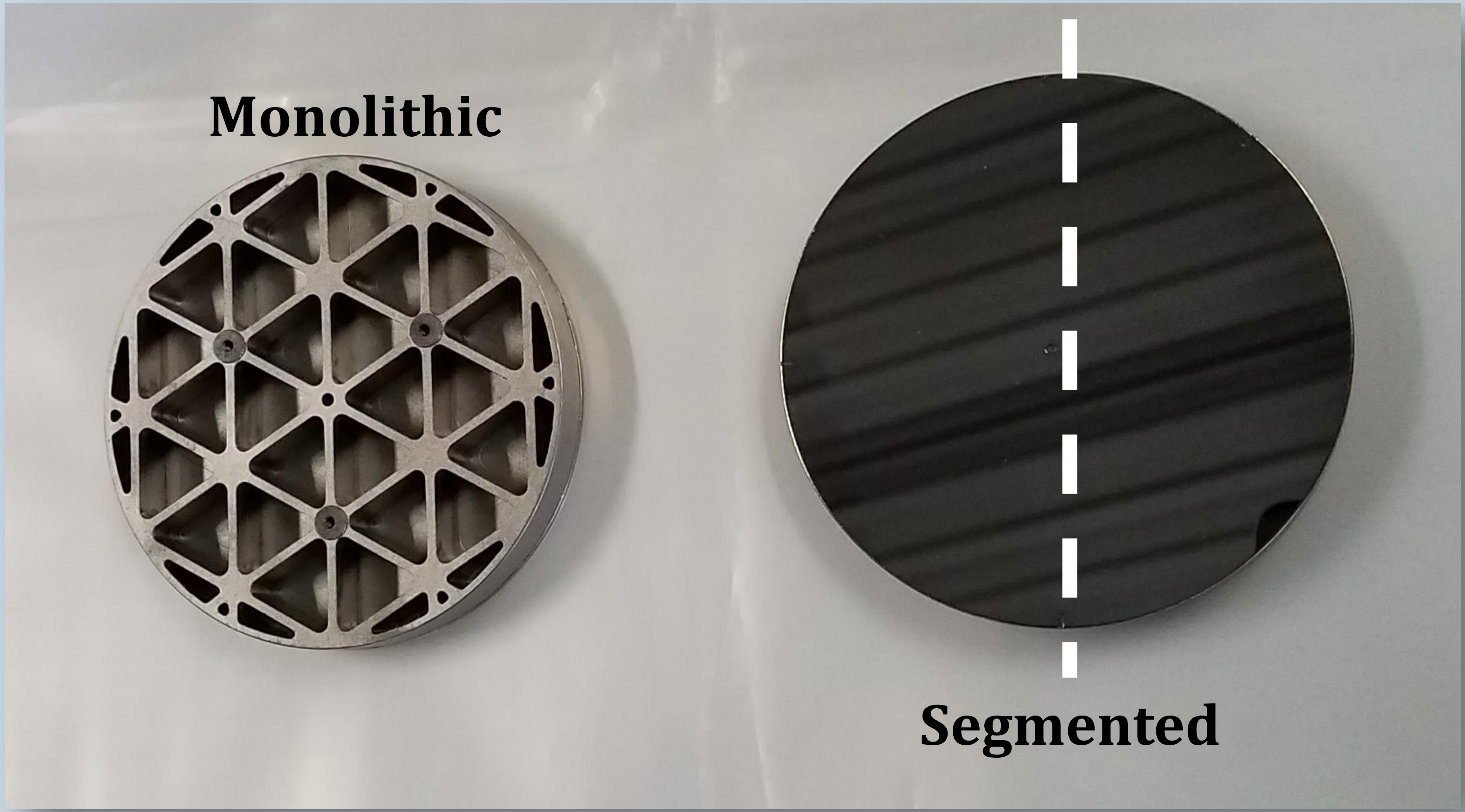


The major stages in LID Bonding…

1. **Preplacement and fixturing of parts**
2. **A liquid front smooths the interfaces**
3. **The intermediate layer diffuses into the base metal**
4. **Diffusion occurs to create a homogeneous joint**

Mirror Surface: Single Point Diamond Turning

Integrated Test: 90 mm Mirrors

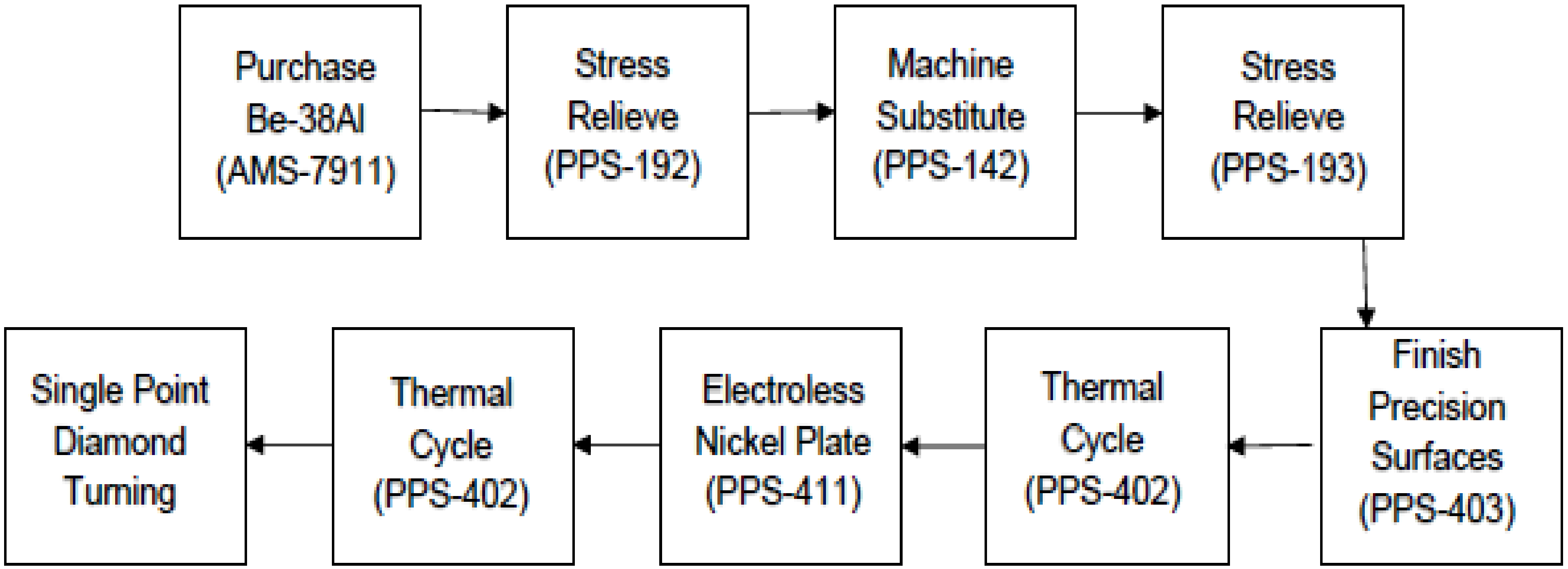


Both the monolithic and segmented mirrors were processed through electroless nickel side by side. Only thing that is different in the second one is that it was liquid interface diffusion bonded together.

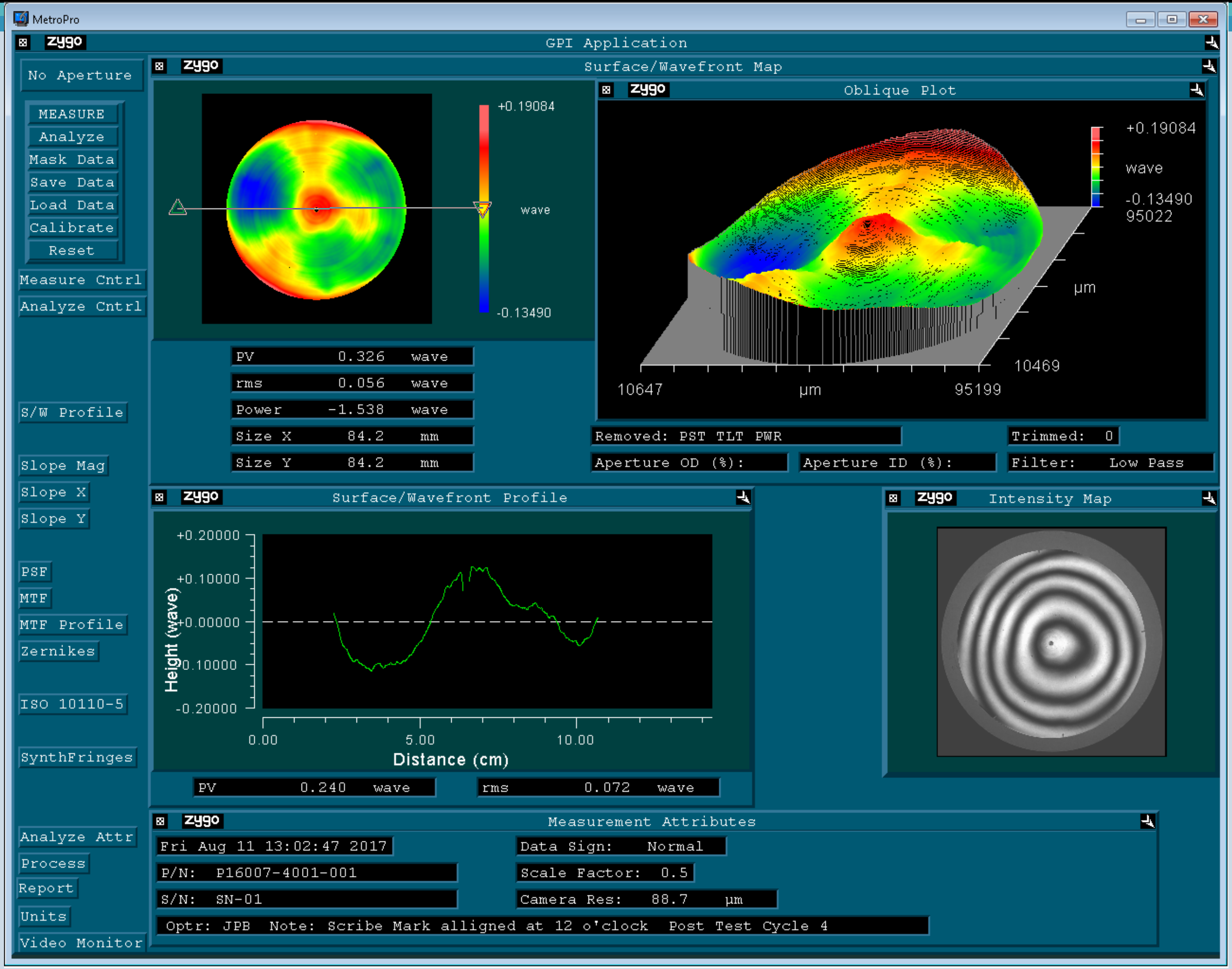
Monolithic Mirrors

Manufacturing Flow Chart

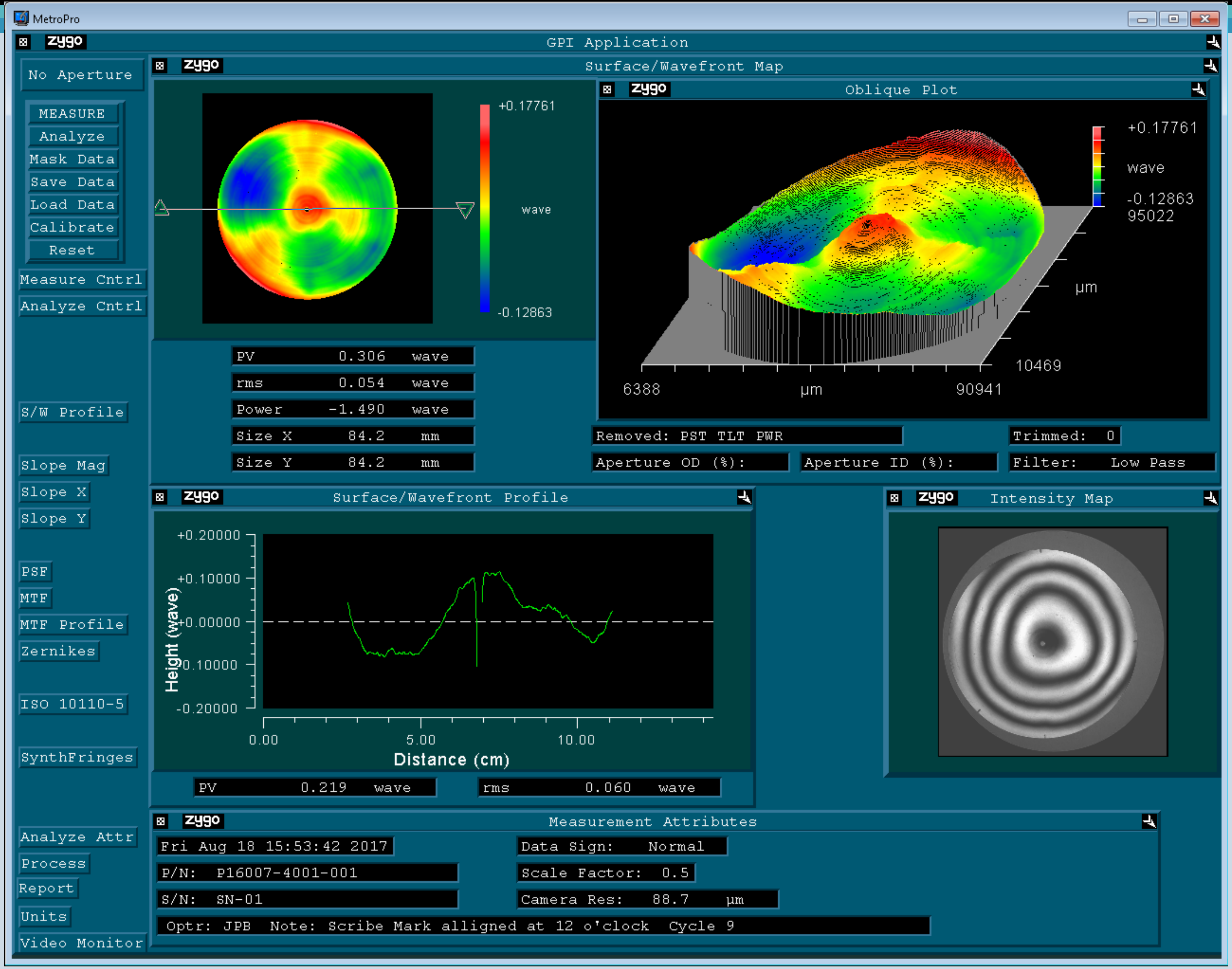
(Major Steps for the Monolithic Mirrors)



Monolithic Mirrors – Baseline



Monolithic Mirrors – After Thermal Cycling

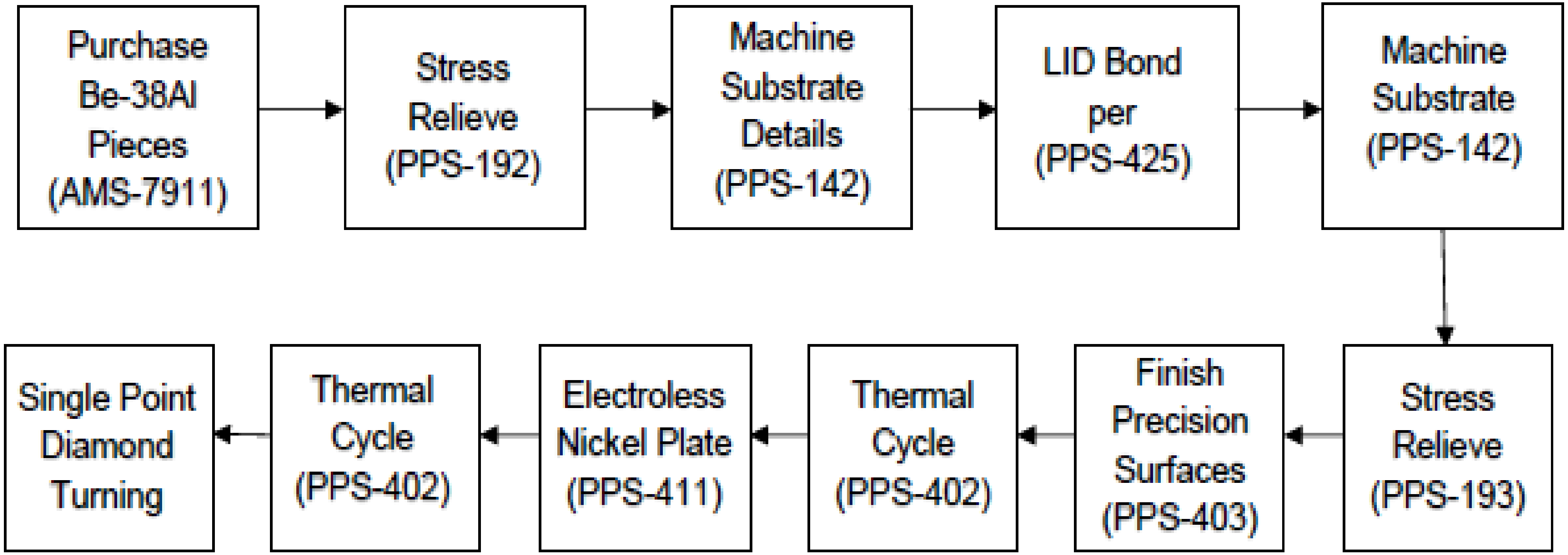


- Showed little movement from baseline to thermally cycled mirrors.
- These mirrors are very stable over long periods of time.
- Everything is somewhat unstable; it degrades at some level over time.
- Goal would be to have the system operate over a wide temperature range.
- We want a usable system that is cost effective.

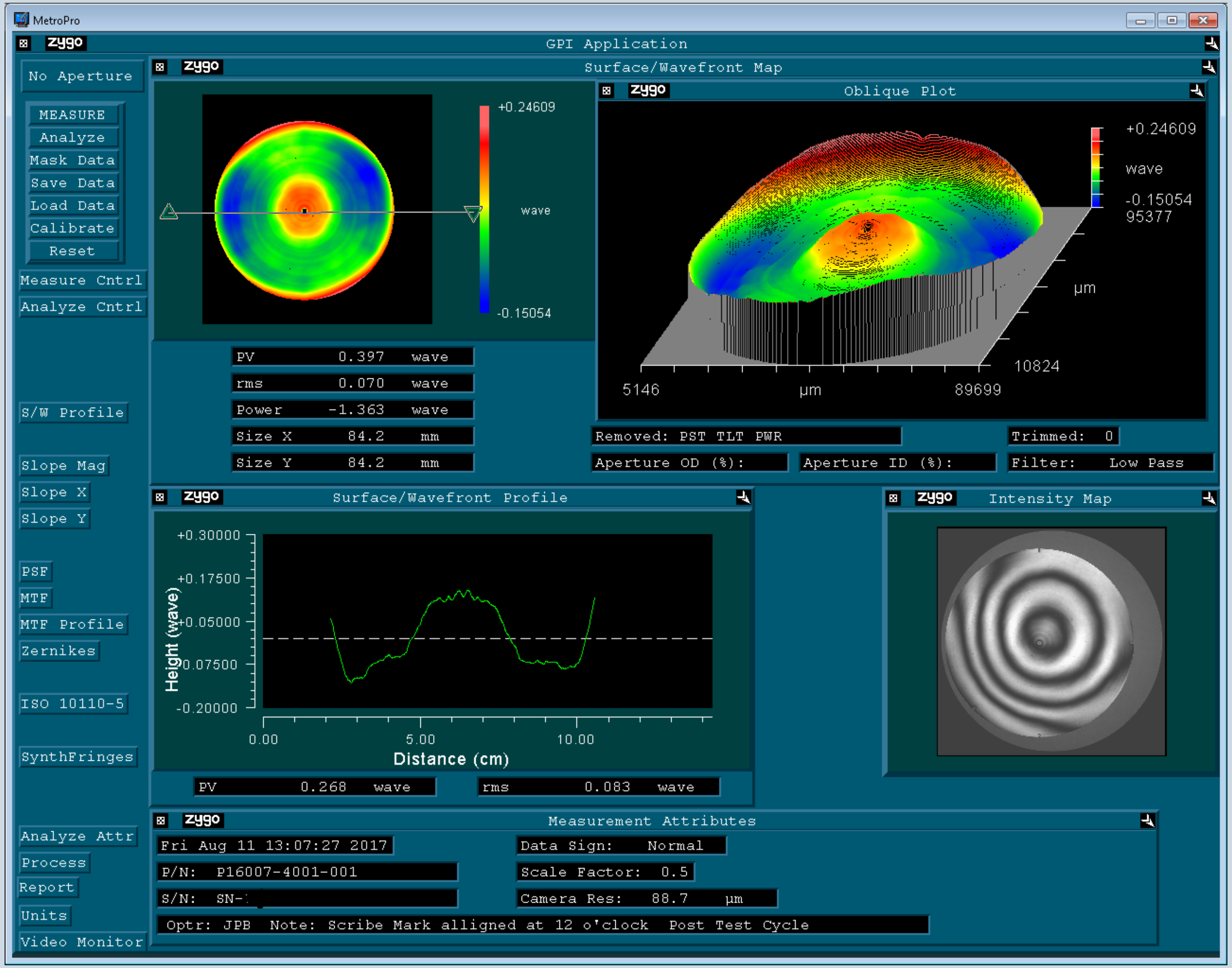
Segmented Mirrors

Manufacturing Flow Chart

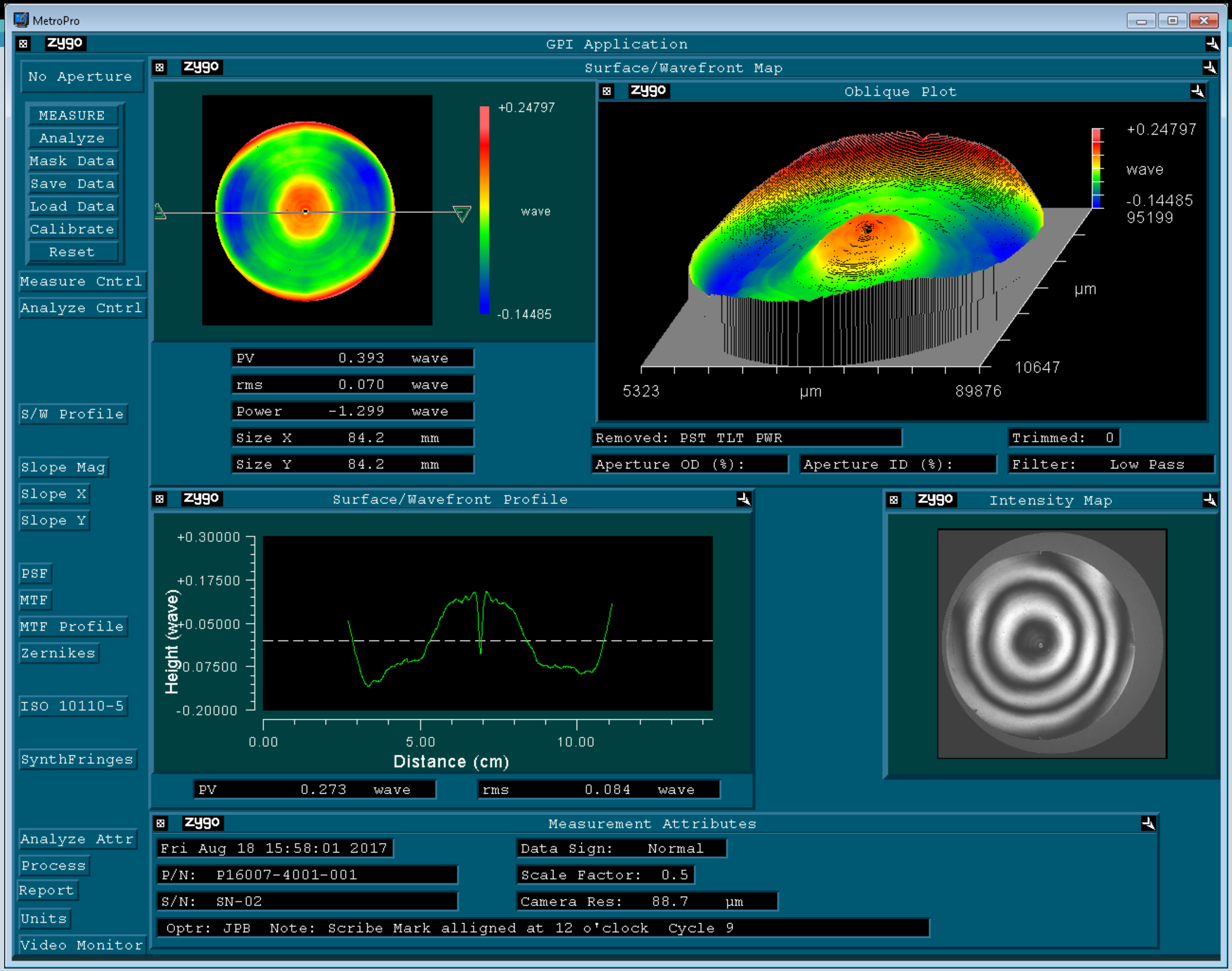
(Major Steps for LID Bonded Mirrors)



Segmented Mirrors – Baseline

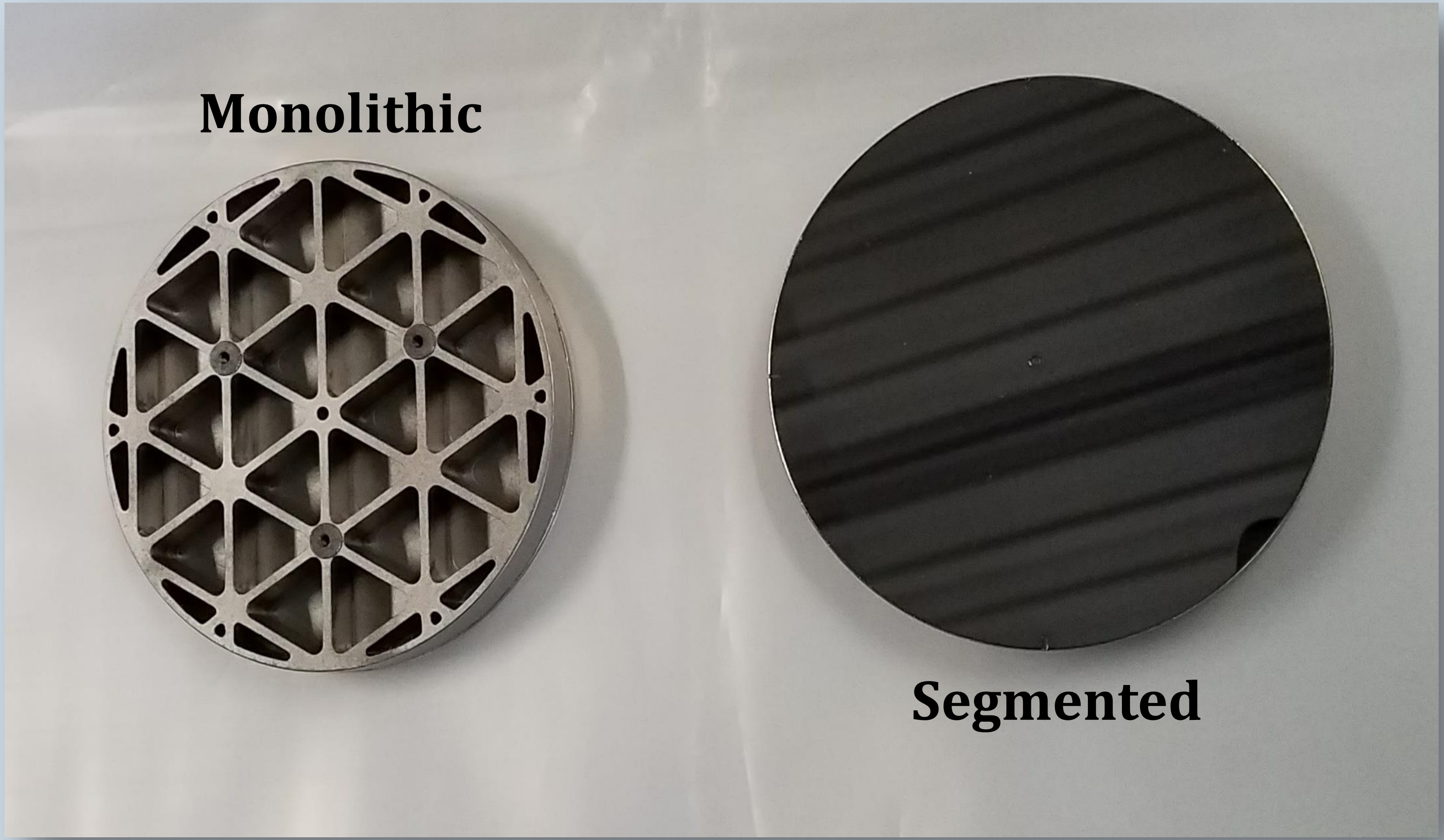


Segmented Mirrors – After Thermal Cycling



The LID bonded, segmented mirror produced more stability than the monolithic mirror. It was able to withstand higher temperatures over longer periods of time.

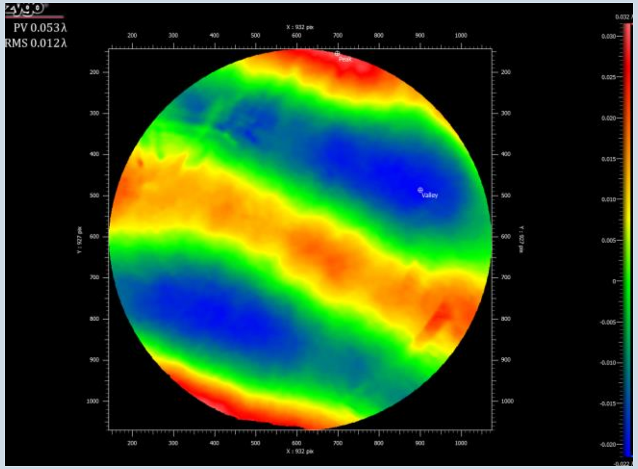
Integrated Polish



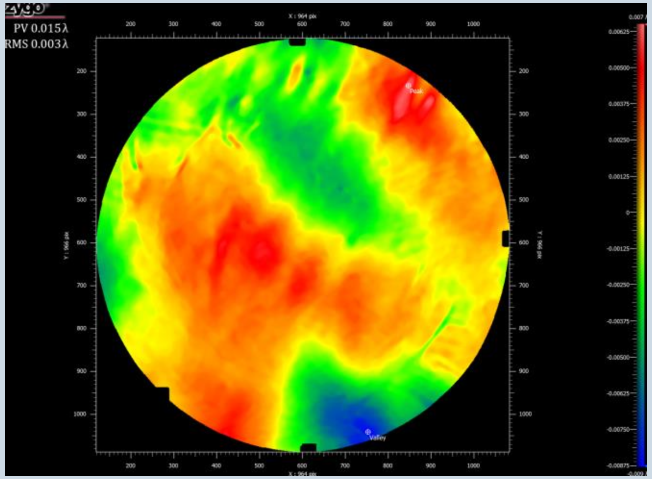
Because of its success, we want better resolution on movements through the use of re-polishing the optics to get to an even finer finish before we retest them.

This should yield even better results.

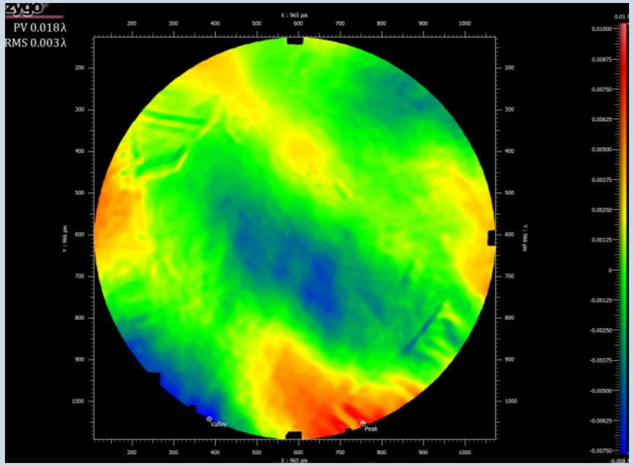
Test Data – 90 mm Polished Monolithic Mirrors



Cycled to 0°C

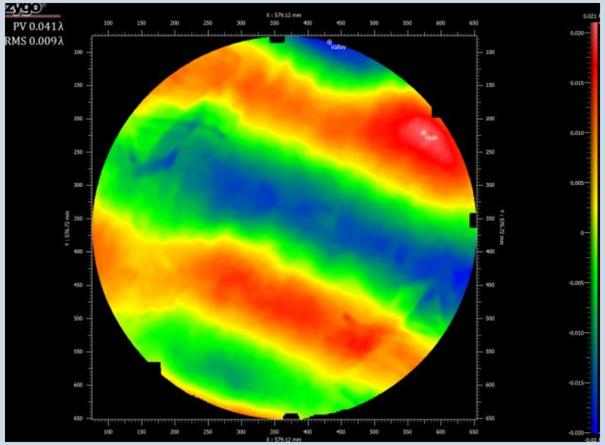


Cycled to -20°C

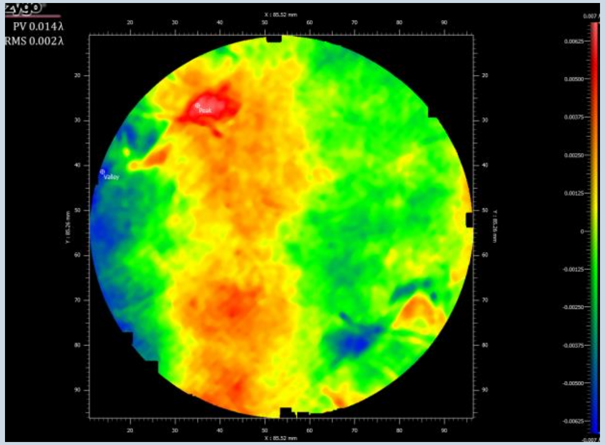


Cycled to -40°C

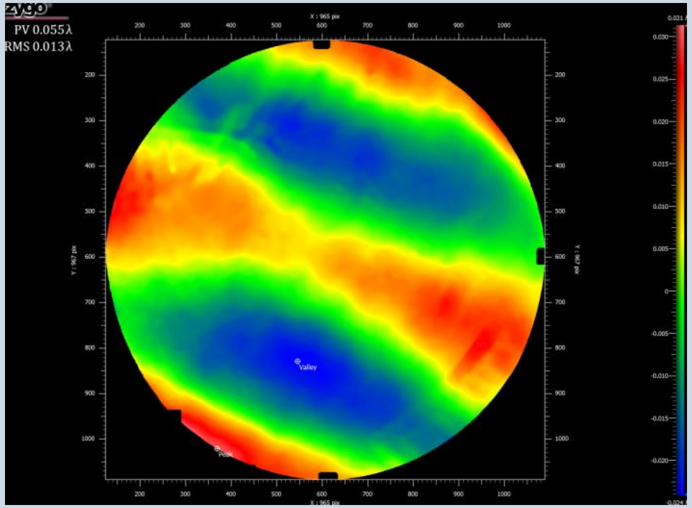
Cycled to -60°C



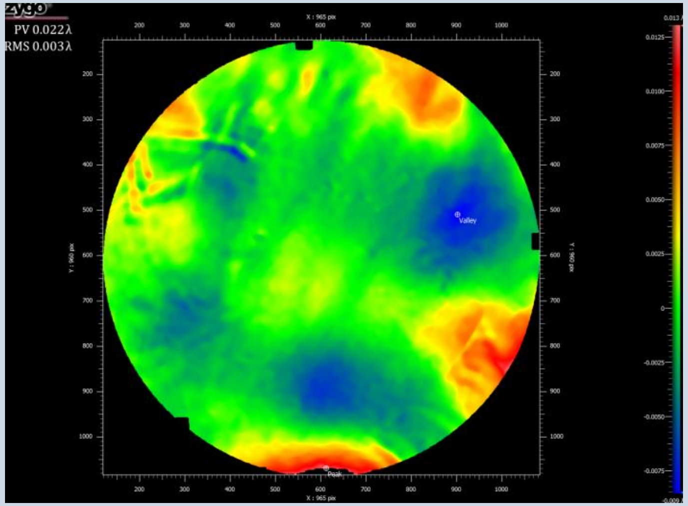
Cycled to -72°C



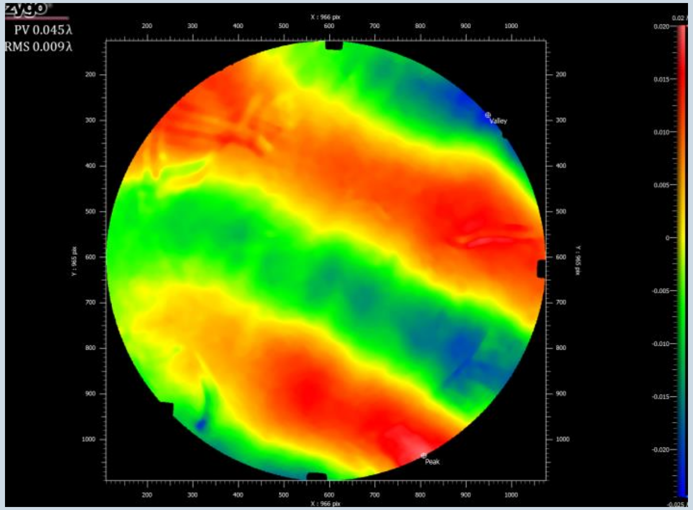
Test Data – 90 mm Polished Segmented Mirrors



Cycled to 0°C

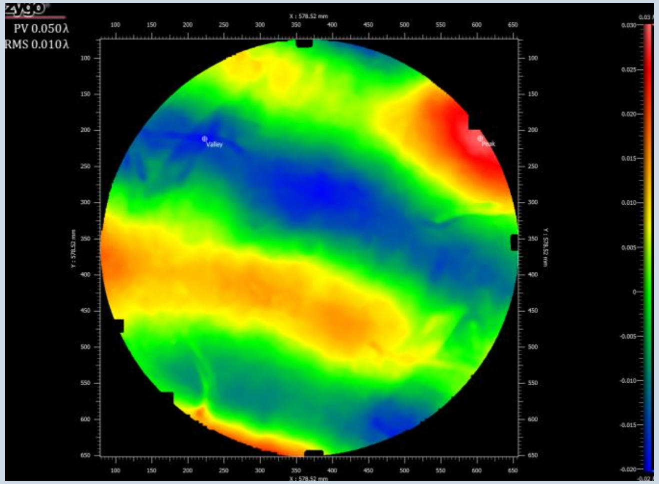


Cycled to -20°C

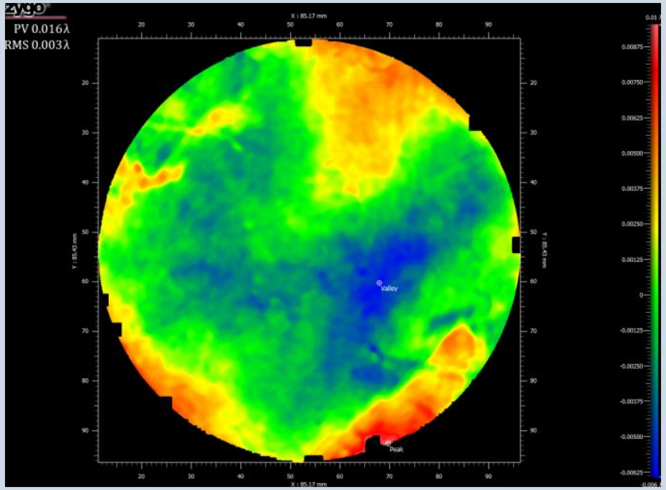


Cycled to -40°C

Cycled to -60°C



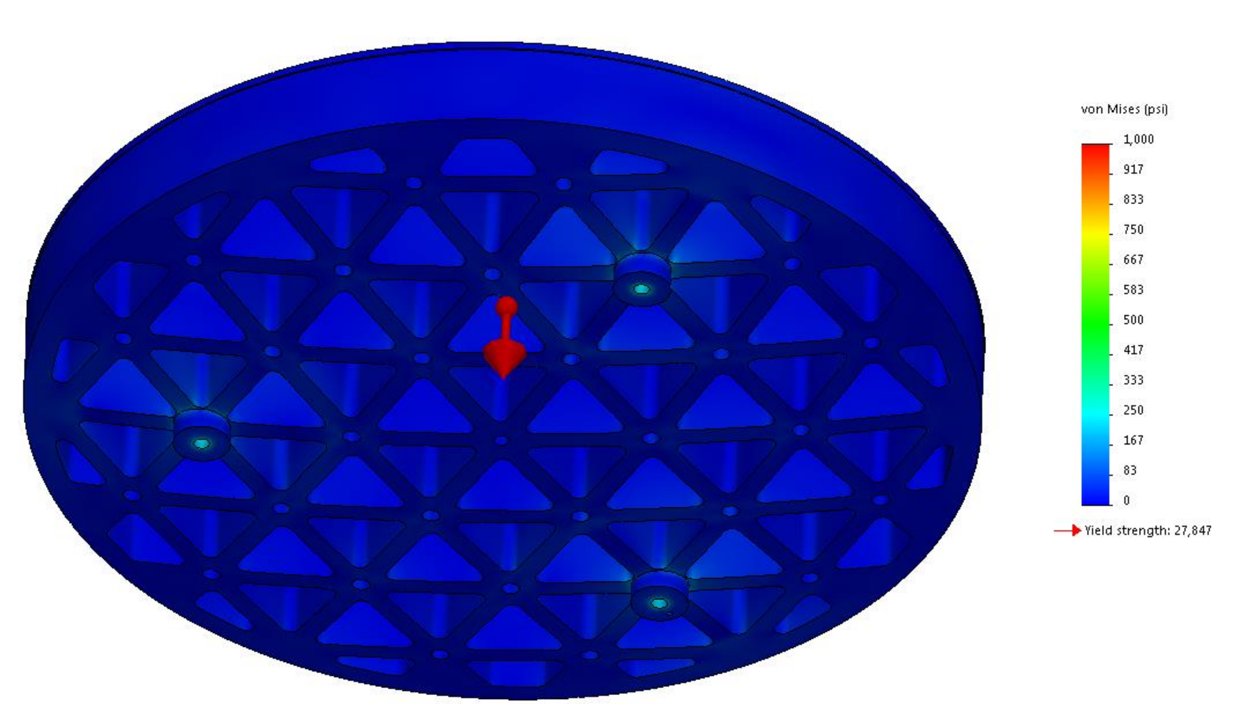
Cycled to -72°C



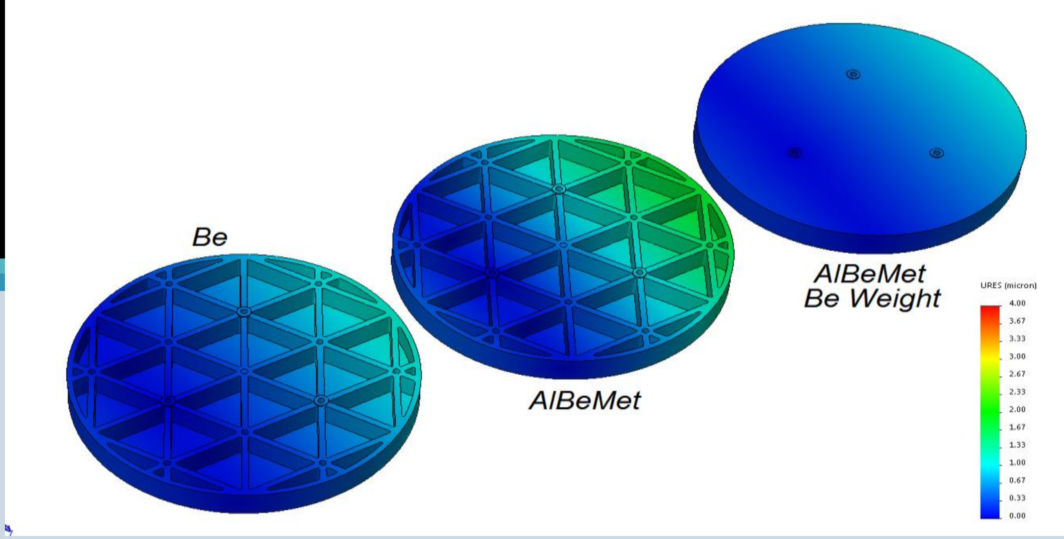
½ m Sized Optics

Initial Monolithic ½ m Design based on JWST Mirrors

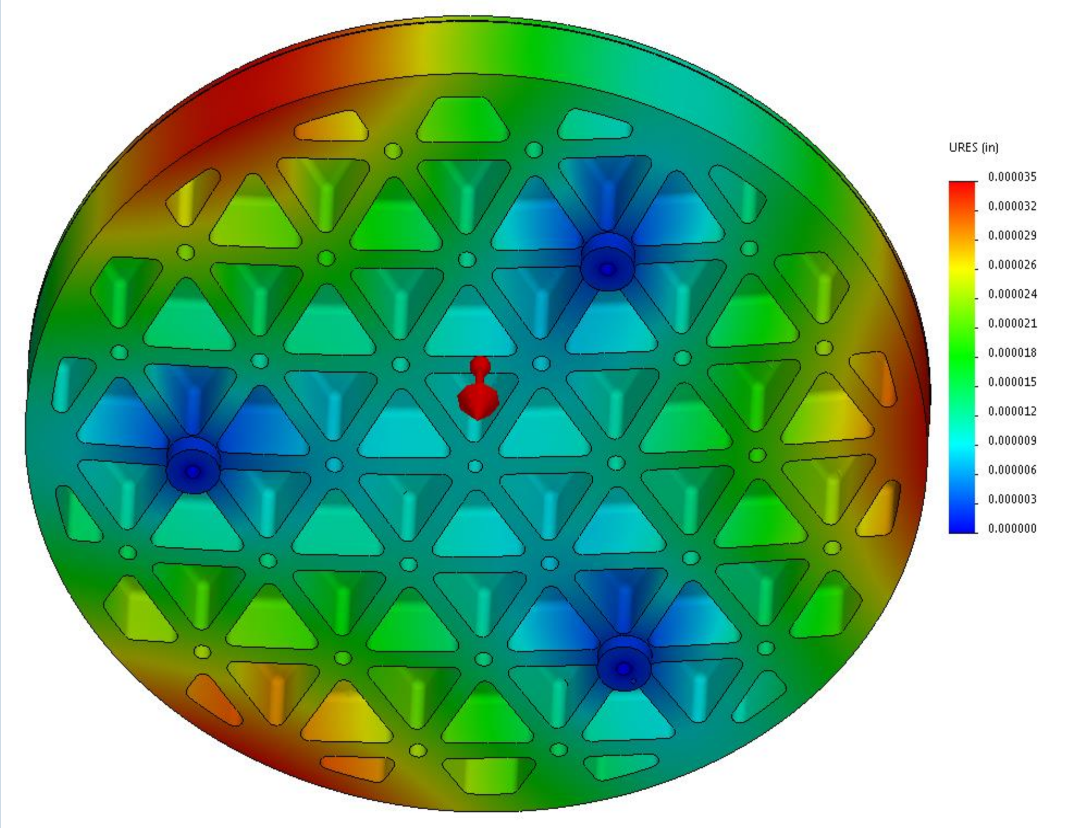
Stress at 10g Loading



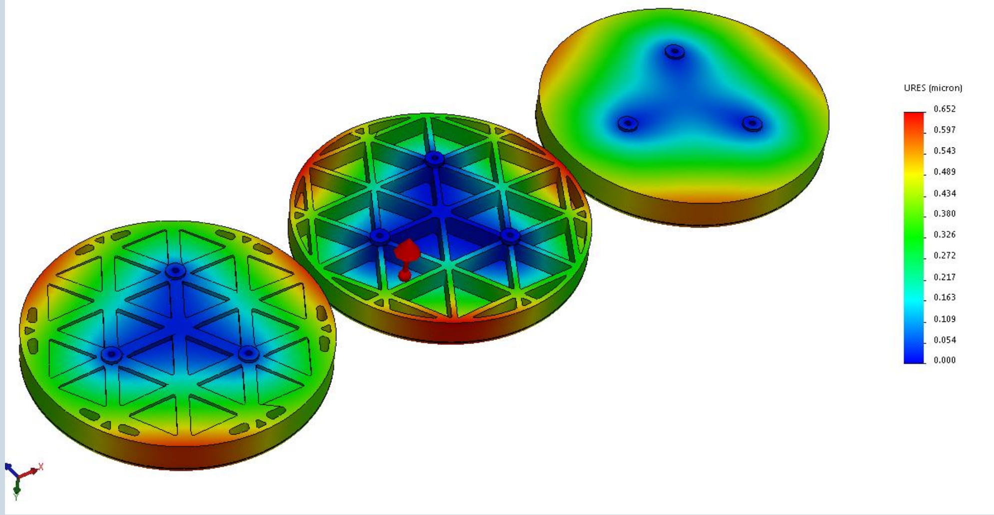
½ m Sized Optics



Equivalent Weight Designs, The Closed Back Be-38Al Design is Equal to Weight and Stiffness to the Beryllium Design on the Left



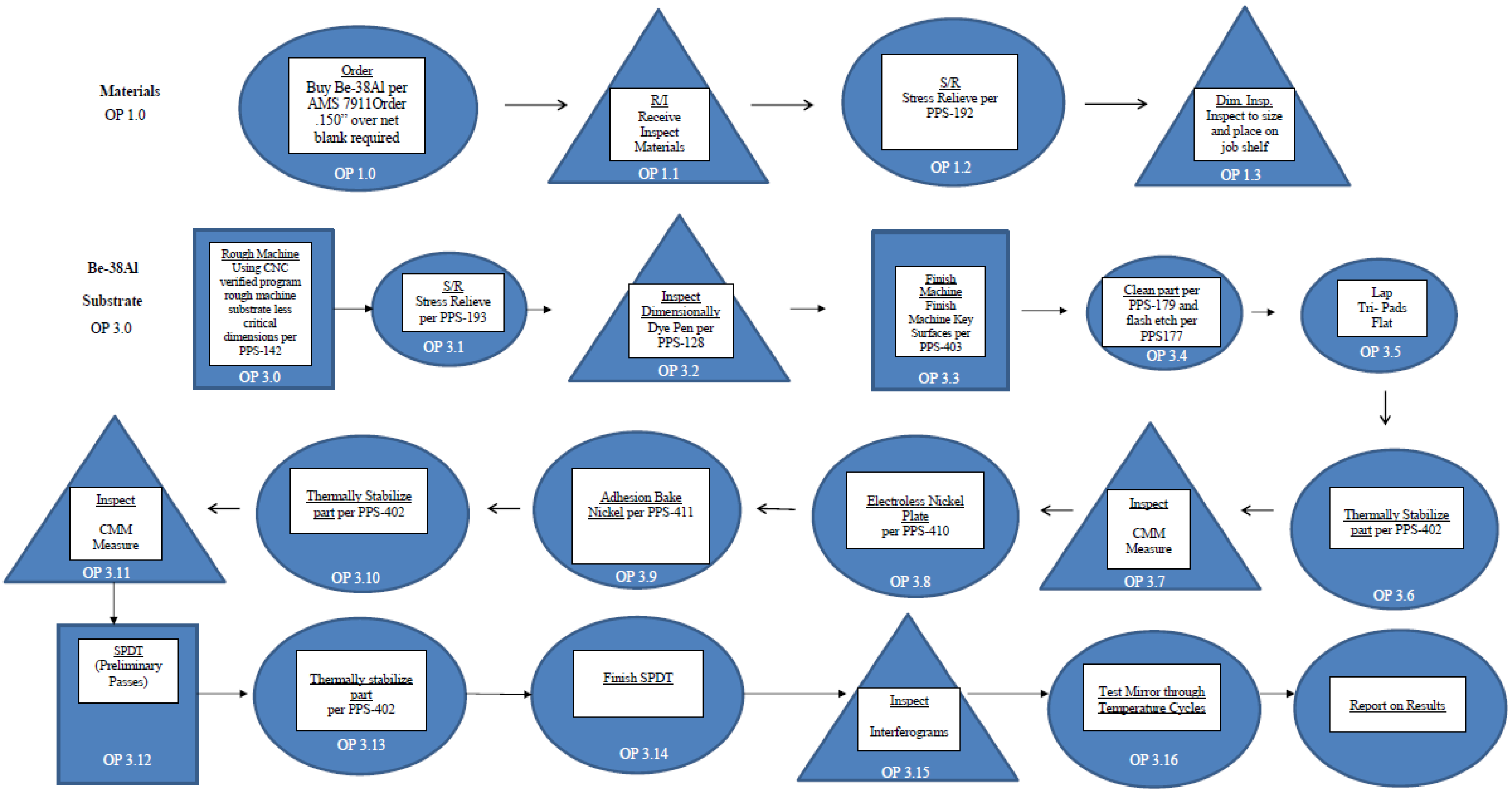
Deflection at 10g Loading



Various Design Scenarios were Explored

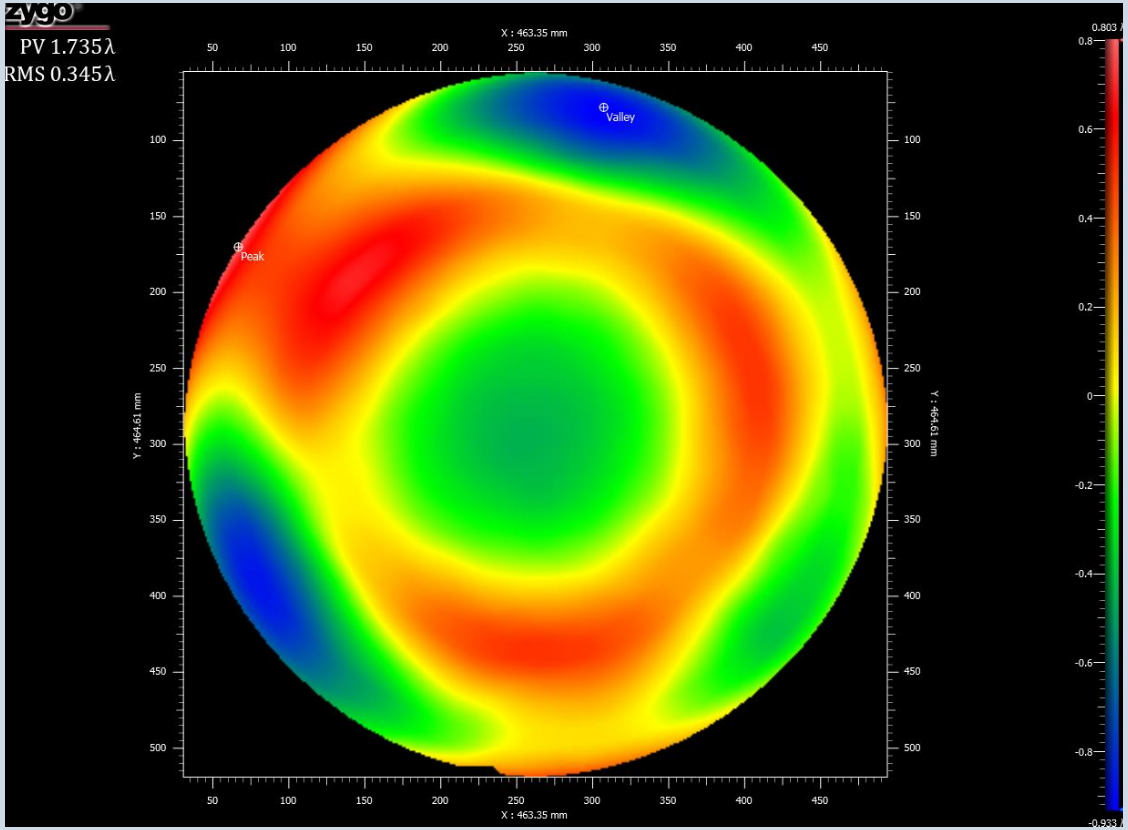
Monolithic Mirrors

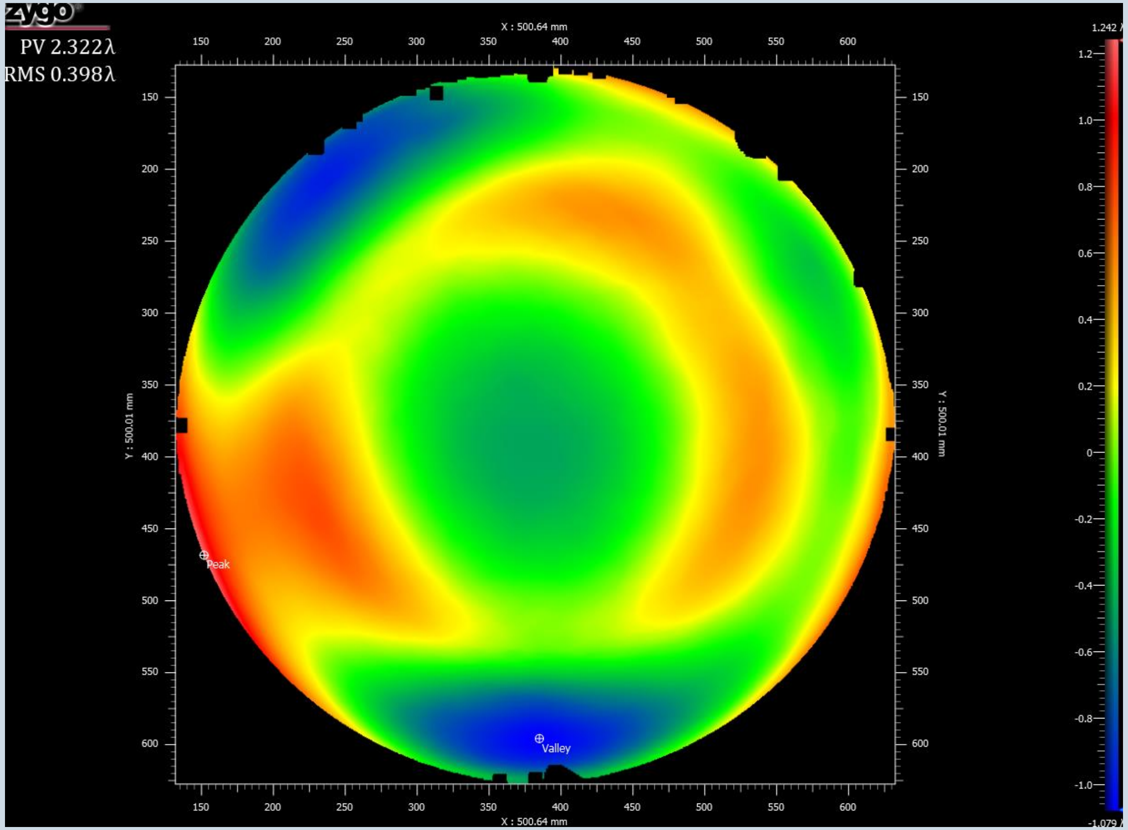
Substrate Fabrication for Monolithic Be-38Al Mirrors



½ m Optic – Monolithic Mirror

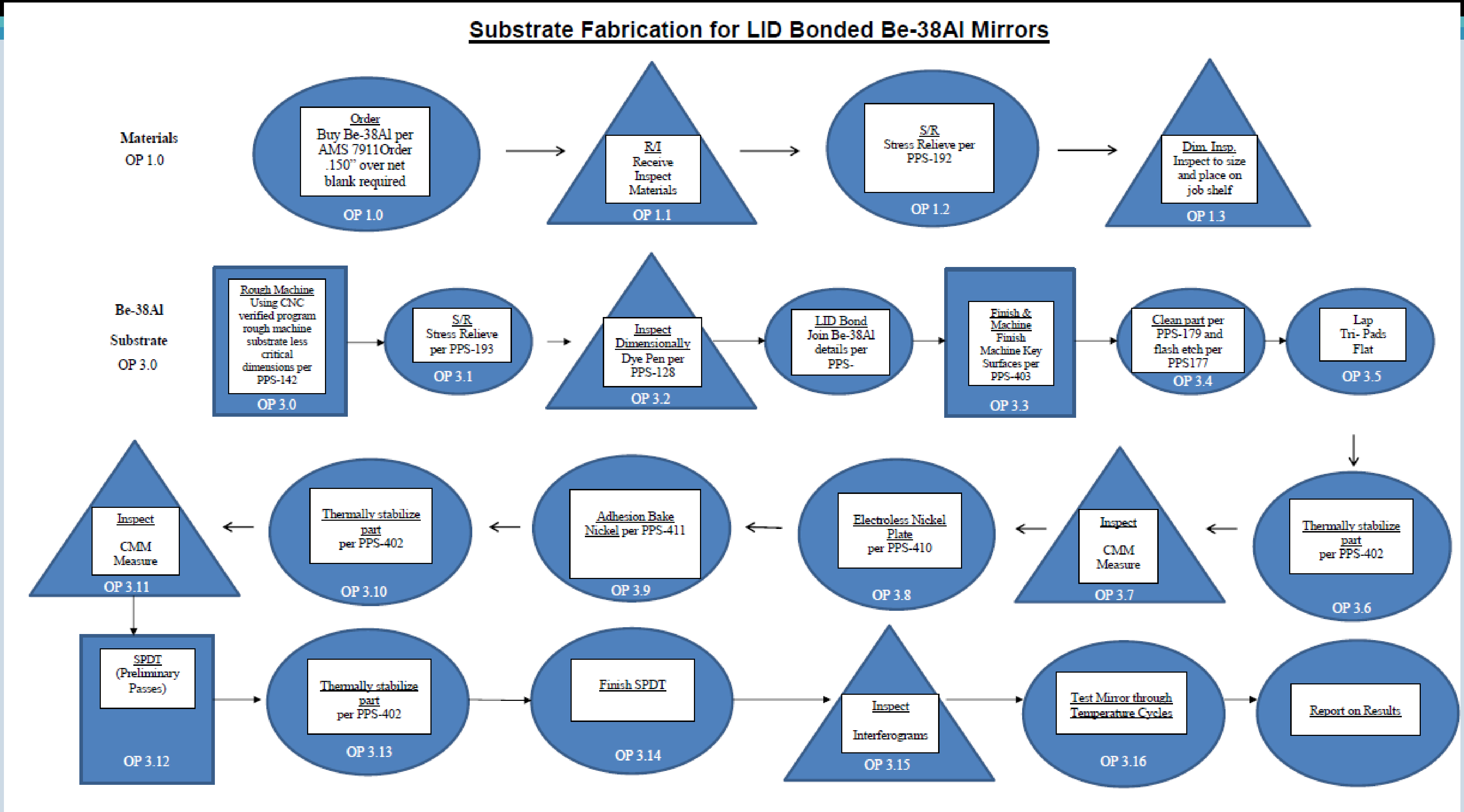
BASELINE



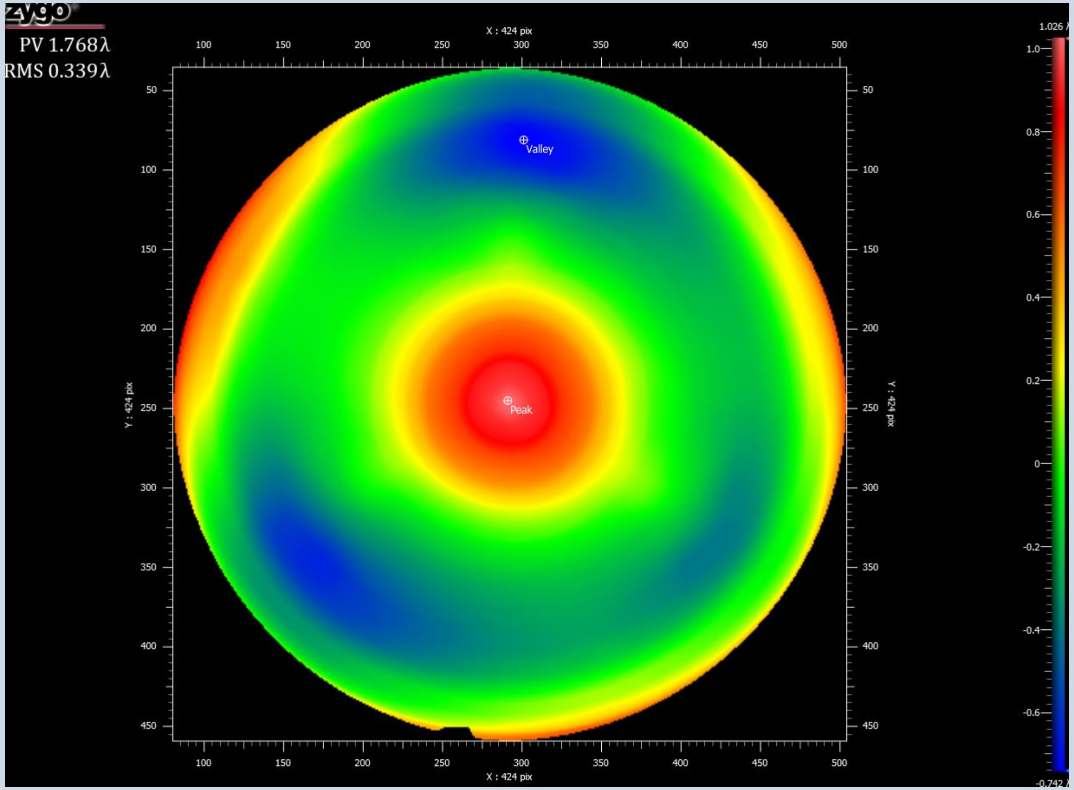


AFTER ALL THERMAL CYCLING

Segmented Mirrors

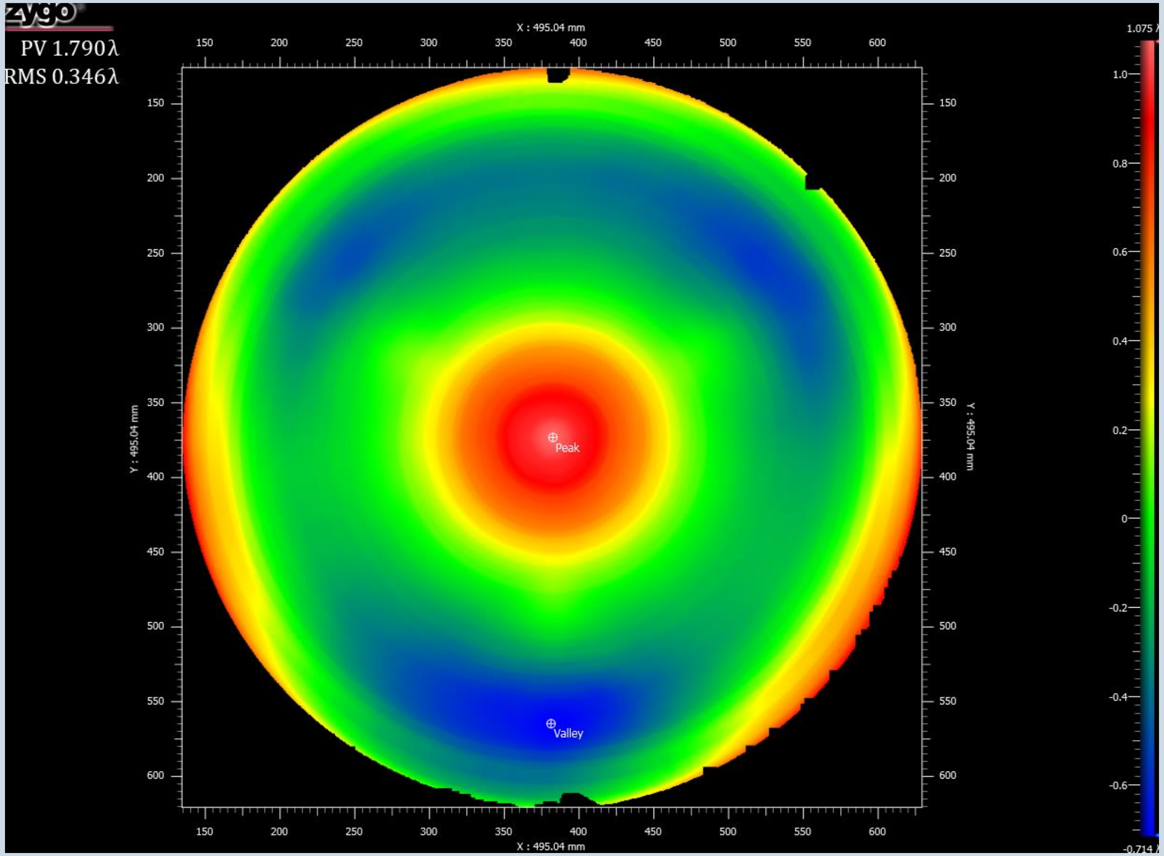


½ m Optic – Segmented Mirrors

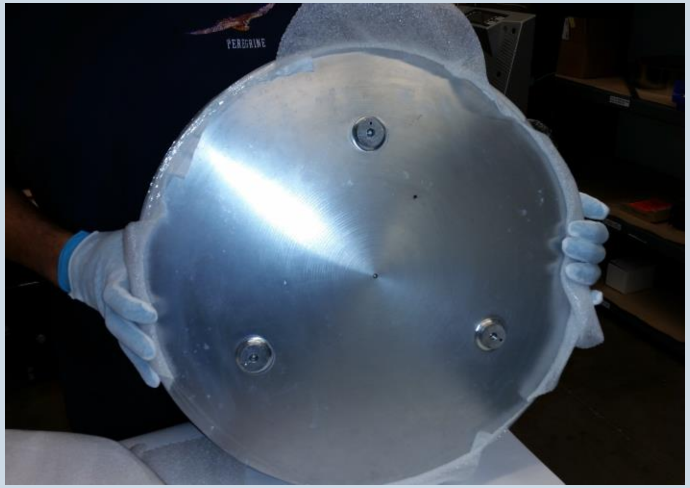


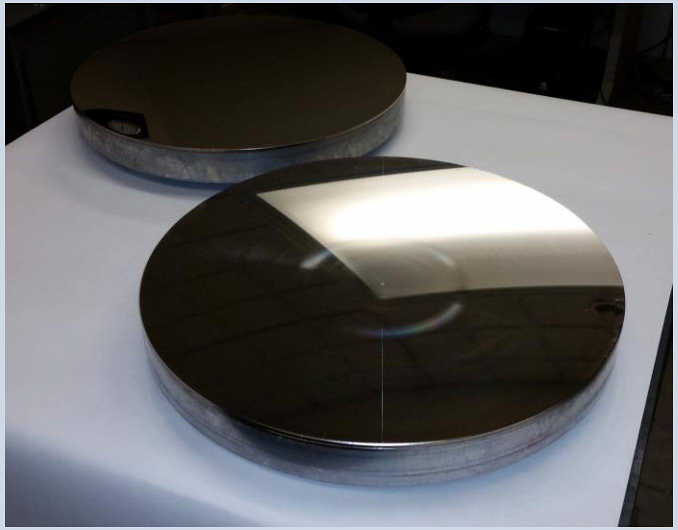
BASELINE

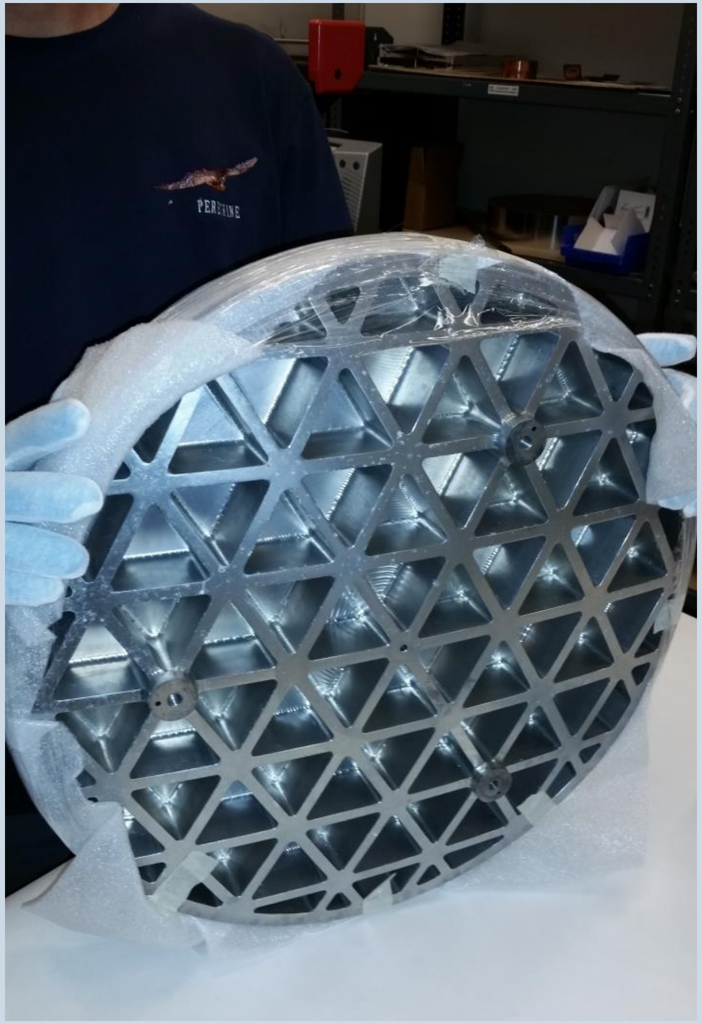
AFTER THERMAL CYCLING AT LOW TEMPS.

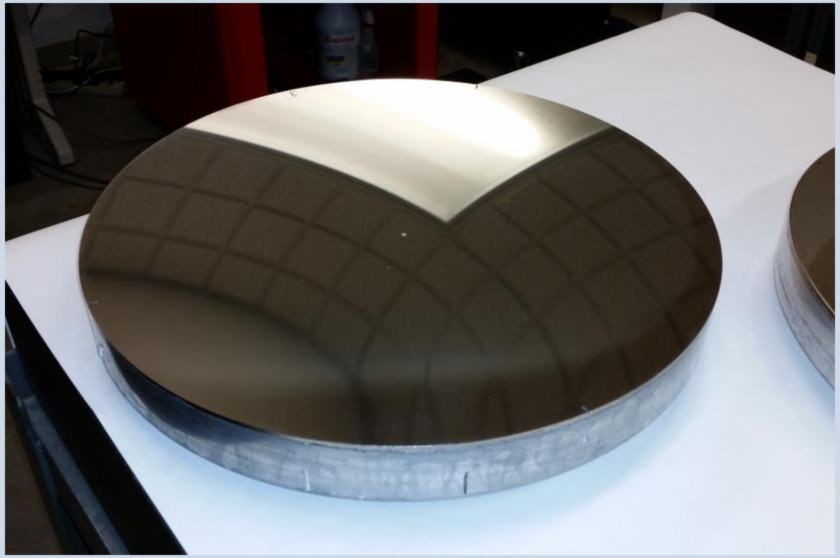


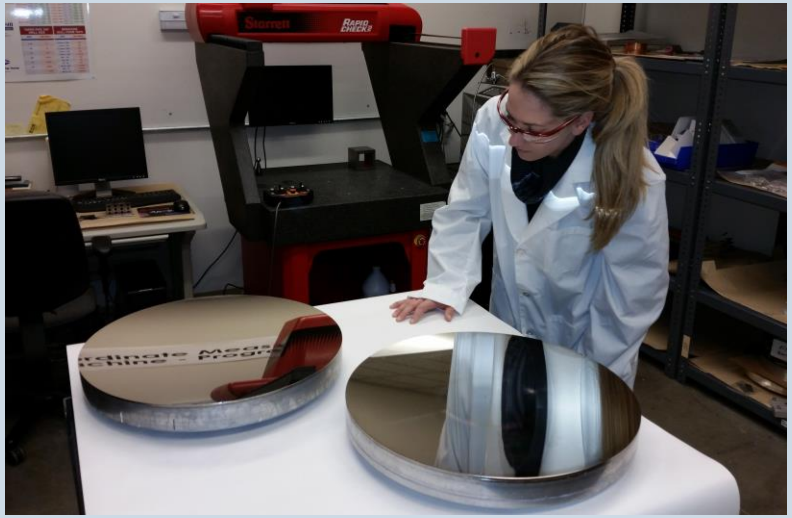
Hardware (½ m Mirrors)











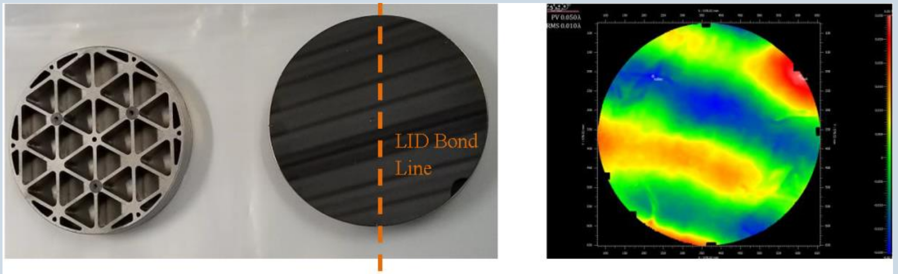
Advanced Mirror Material System

PI Robert Hardesty

Objectives

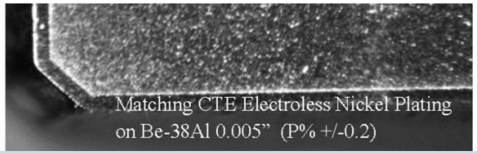
- Develop a Material System that can:
  - Reduce the cost of mirrors by a factor of 4 from $6.5M/m^2, while minimizing production time in half.
  - Maintain stiffness, low density, stability and performance.
  - Produce >4m in size.
  - Match CTE of Electroless Nickel to Be-38Al substrate by controlling Phosphorous content.
  - Operate across wide temperature ranges down to low temperature.

Advanced Mirror Material System



Be-38Al / LID Bonding / Electroless Nickel Plating (CTE Matching) / SPDT- Polished

Testing demonstrates stability to 1/50th λ



Future Planned Developments

<u>Planned Post Phase II Partners</u>

Peregrine has the ability to produce mirrors using this technology – however, we seek Partnerships on a program by program basis.

<u>Planned / Possible Mission Infusion</u>

1. CIBER-2 a Sounding Rocket Telescope application for 80K operation.
2. Visible to MWIR Imaging System for Military application.

<u>Planned / Possible Commercialization</u>

After initial key applications development, we plan to pursure scan mirrors and Earth Observation Athermal Systems.

Accomplishments

- Matched (WI +/- .2%P) Electroless Nickel (EN) Plating to Be-38Al to yield a stable substrate.
- Seamlessly joined Be-38Al together that can create large substrates for mirrors (no surface indication).
- Demonstrated stability to 1/50th λ.
- Successfully tested across large temperature ranges down to low temperatures.
- Delivered two half meter mirrors (Monolithic and LID bonded versions) using SPDT at an areal cost of <<$1M/m^2.

<u>Key Milestones Met:</u>

- Dialed in Electroless Nickel Plating process to +/- .2%P.
- Dialed in Liquid Interface Diffusion Bonding process for seamless joints.
- Integrated Be-38Al/LID Bond/EN/SPDT to create stable substrates.
- Tested Material System over wide temperature range to low temperatures.

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