Replicated Nickel Optics for the Hard-X-Ray Region

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1. Approach
2. Application … HERO balloon paload
3. Application … Constellation-X
4. Further Developments
5. Other Applications
6. Conclusion

Approaches

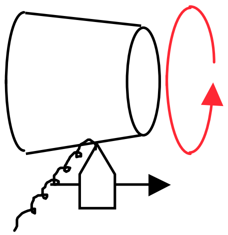
Different approaches to hard-x-ray optics:

- *Full shell optics (e.g. Electroform nickel replicated [XMM])*
  - *Advantage – Good angular resolution (= sensitivity), easy to fabricate multiple copies.*
  - *Disadvantage – nickel is heavy, mandrel fabrication can be expensive.*
- *Segmented optics (aluminum foil [ASCA], glass[NuSTAR], plastic)*
- *Others (e.g. Microchannel plate, Laue and Bragg)*

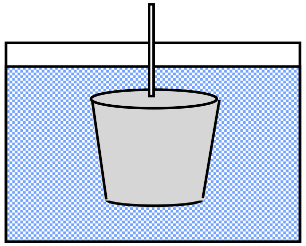
Electroformed nickel replication

Mandrel Preparation

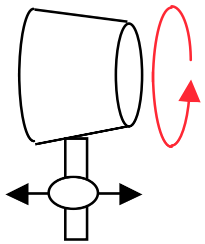
1. CNC Machine, Mandrel Formation From Al Bar



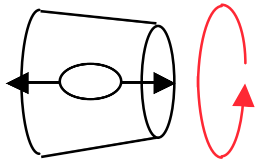
2. Chemical clean and activation & Electroless Nickel (EN) plate



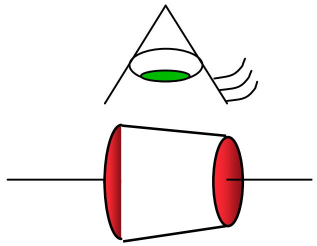
3. Precision machine to sub-micron figure accuracy



4. Polish and Superpolish to 3 - 4Å rms finish

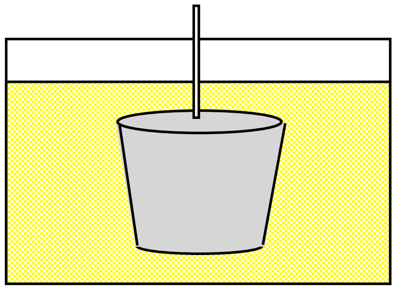


5. Metrology On Mandrel

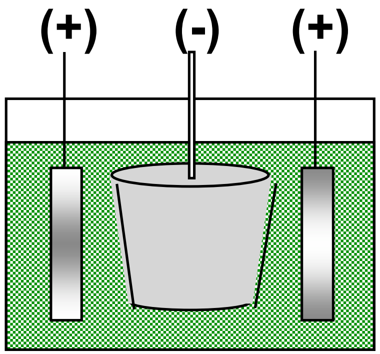


Shell Fabrication

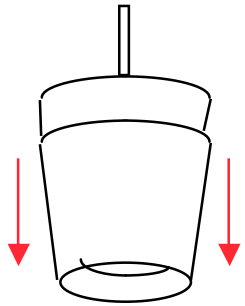
6. Ultrasonic clean and Passivation to Remove Surface Contaminants



7. Electroform Ni Shell onto Mandrel



8. Separate Optic From Mandrel in Cold Water Bath



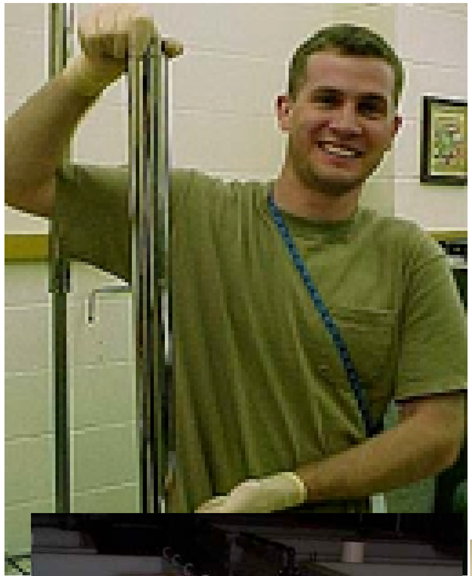
Application : HERO Program

- ***HERO, for High Energy Replicated Optics, is a balloon program designed to demonstrate MSFC optics and perform science.***

- ***Utilizes in-house-fabricated hard-x-ray mirrors plus supporting x-ray detectors, gondola and pointing system.***

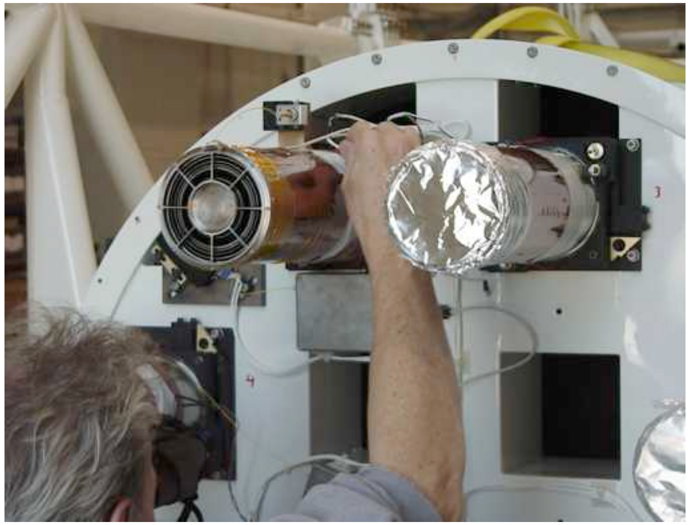
- ***Optic design philosophy :***
  - *Utilize a large number of shallow-graze-angle, iridium-coated full-shell mirrors*
  - *Obtain significant collecting area by using narrow-aspect ratio mirror shells (ie large length to diameter ratio), by nesting many thin shells and by using multiple mirror modules.*
- ***Cost Factor (big concern):***
  - *Use conic approximation to Wolter-1 geometry*
  - *Keep costs down by utilizing inexpensive grinding for mandrel figuring*
  - *Develop simple polishing machines*
  - *Electroform multiple shells simultaneously*

HERO Mirror Shell Production

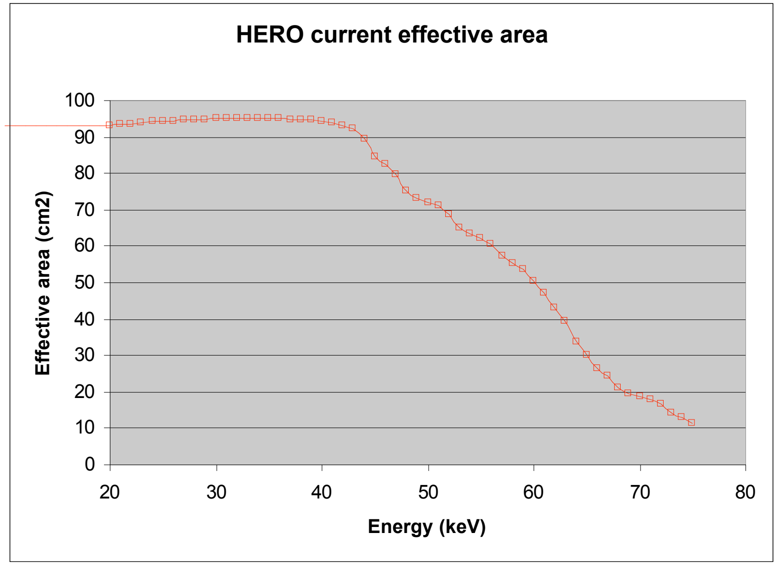





HERO Current Status



Number of modules	8
Number of shells	14
Inner, outer diameters	50, 94 mm
Shell thickness	0.25 mm
Focal length	6 m
Angular resolution	~ 13-15 arcsec HPD shells 20 arcsec modules
Field of view	9 arcmin at 40 kev

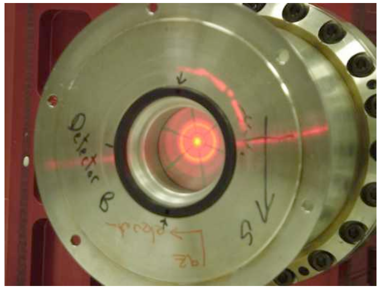


HERO Current Status

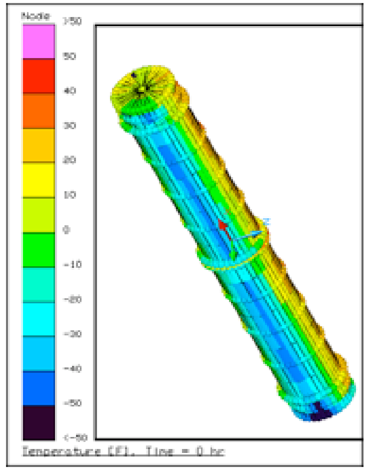
HERO payload awaiting launch in New Mexico (Spring 05)

HERO Current Status

- ***Some challenges flying 15 arcsec optics on a balloon***
  - *Alignment*
    - > *Laser alignment system to co-align mirror modules to star camera*



  - *Stability*
    - > *Extensive thermal modeling necessary (+20 → -70 ºC environment) for optical bench to optimize composite weave*



  - *Pointing / aspect*
    - > *Normal sun sensors / magnetometers not good enough*
      - *Developed day/night aspect camera (9-10 th mag during day / < 8 arcsec)*

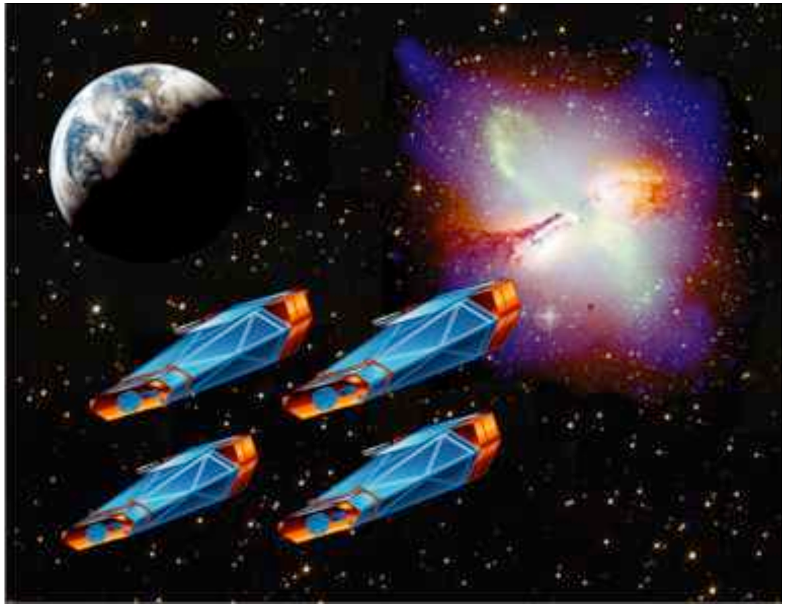
HERO Current Status

Flight planned for Spring 06, from Fort Sumner, New Mexico

Application - Constellation-X

<u>Baseline Mission Characteristics</u>

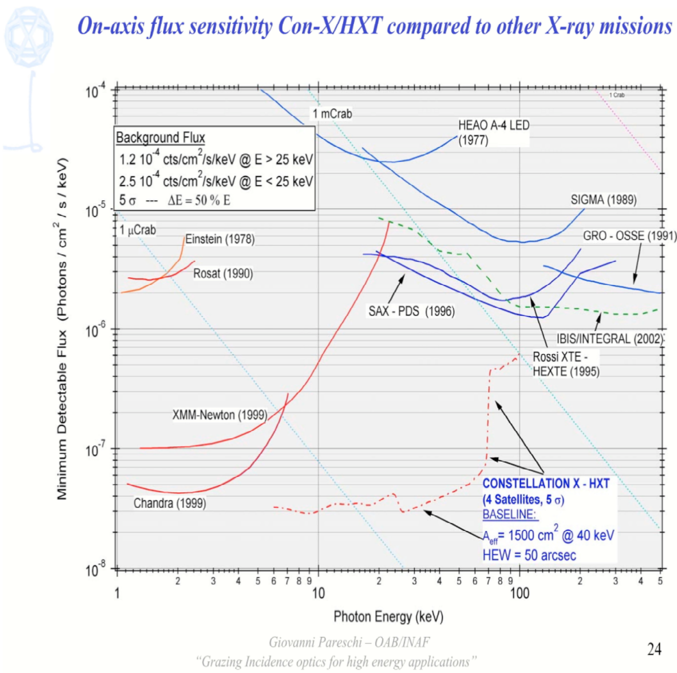
Minimum effective area:	1,000 cm^2 from 0.25 keV to 10 keV 15,000 cm^2 at 1.25 keV 6,000 cm^2 at 6.0 keV 1,500 cm^2 from 10 keV to 40 keV
Minimum telescope angular resolution:	15 arcsec HPD from 0.25 to 10 keV 1 arcmin HPD from 10 keV to 40 keV
Spectral resolving power: (E/ΔE)	>~ 300 from 0.25 keV to 6.0 keV 1,500 from 6.0 keV to 10 keV > 10 from 10 keV to 40 keV
Band Pass:	0.25 to > 40 keV
Diameter Field of View:	SXT > 2.5 arc min > 30 x 30 array (5'' pixels) HXT > 8 arc min
Mission Life:	> 4 years (full capability)
Redundancy/Reliability:	No one on-orbit failure to result in loss of more than 25% of the mission science



http://constellation.gsfc.nasa.gov/docs/science/staudience.html

Constellation-X

To meet HXT baseline requirements need the following optics configuration:



- *3 mirror modules per satellite*
- *~ 85 nested shells per module*
- *Inner shell ~ 100 mm diameter*
- *Outer shell ~ 330 mm diameter*
- *Total shell length ~ 70 cm*
- *Focal length = 10 m*

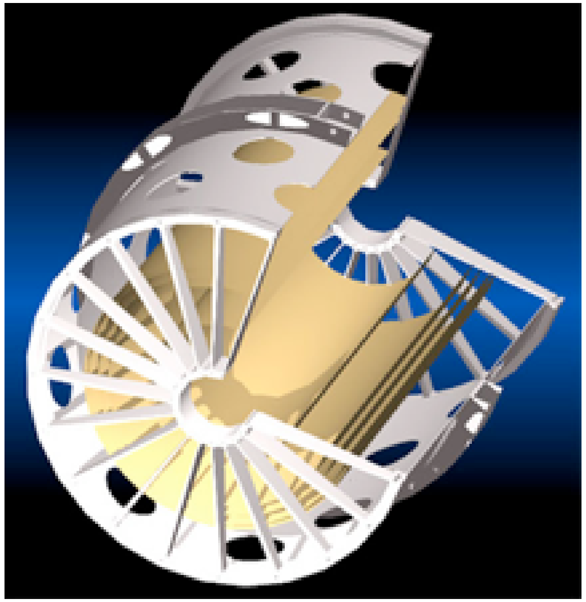
~ Depends on technology used (both glass and nickel being considered……only nickel discussed here)

Constellation-X

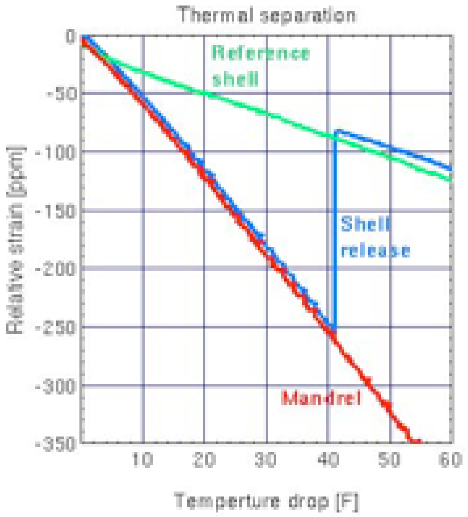
- **A prototype HXT optic will be made using each technology**

- **MSFC is collaborating (with Brera Observatory, Italy and SAO) on the nickel full shell version**

  - *MSFC will produce two shells*
    - *426-mm-long, 230-mm diameter shell to be coated with multilayers (SAO)*
    - *426-mm-long, 150-mm diameter shell to be coated with Ir*
  - *Both shells need to be 100 micron thick to meet HXT weight budget*
  - *Larger shell must have very good surface finish for multilayer coatings (< 5Å RMS)*



ENR Development



Thin shells can experience large strain stresses under separation from a mandrel

Stress =(CTE $_{al}$-CTE$_{ni}$).Δ T.Youngs mod

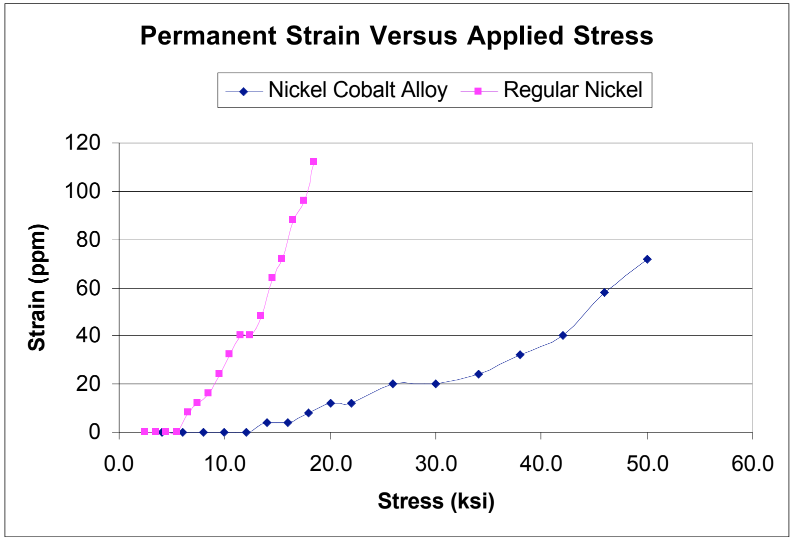
Example at right, show 0.25-mm-thick shell released from treated mandrel .. Stress ~ 35 MPa (5 ksi)

A shell 0.12-mm thick would experience twice this stress

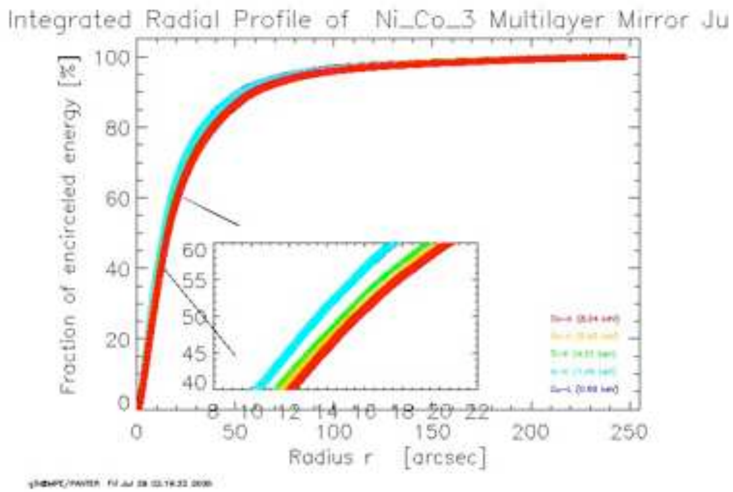
Small stresses, well below the yield stress of a material can cause microyielding, of importance to high-resolution optics

We have developed alloys with higher yield strengths than pure nickel

Have made shells from this alloy, just 0.075-mm-thick (0.003")



Constellation-X



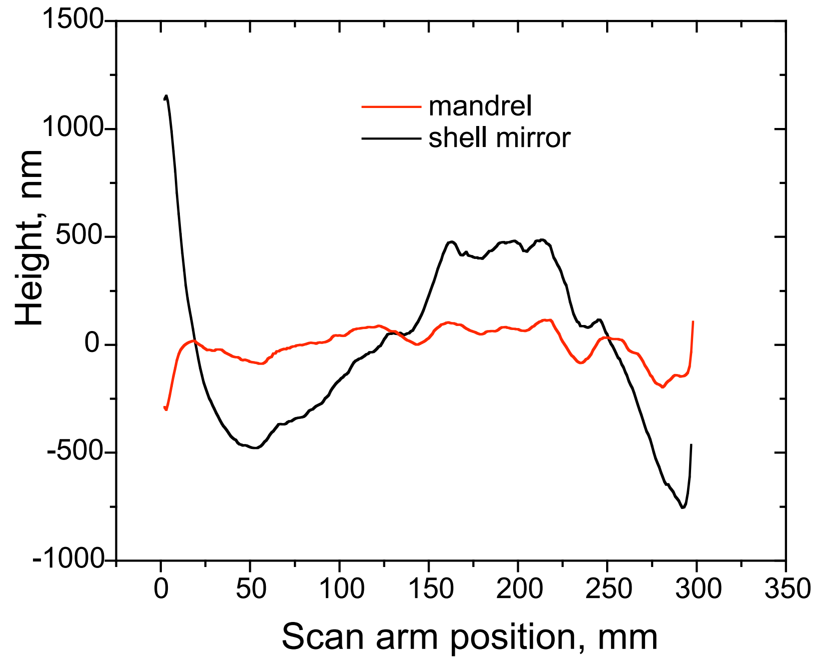
ENR Development

- *Most mirror shells fabricated to date are at ~ 15 arcsec level*
- *Is it possible to improve much beyond this with thin shells ?*

Surface Error Type	***Image RMS Diameter Sensitivity***	***Allocation per Shell***	***Image RMS Diameter Arcsec***
Delta-Delta Radius	5.4 arcsec / micron rms	0.3 micron rms	1.7
Average Radius P	0.04 arcsec / micron	2 micron	0.08
Average Radius H	0.11 arcsec / micron	2 micron	0.22
Average Axial Sag	12.5 arcsec / micron	0.3 micron	3.5
Axial Slope (mid freq)	8 arcsec / arcsec rms	1.0 arcsec	8.0
Roundness	0.15 arcsec / micron rms	3 micron rms	0.5
Circumferential slope	$8.3.10^{-3}$ arcsec / arsec rms	6 arcsec rms	0.05
P-H tilt	2 arcsec / arcsec	0.5 arsec*	1.0
P-H Decenter	$3.4.10^{-2}$ arcsec / micron	0.5 micron	0.02
Total			9.0

ENR Development

- *For a 'perfect' Wolter-1 mandrel, the principal source of errors in the replicated optics is in the axial figure*

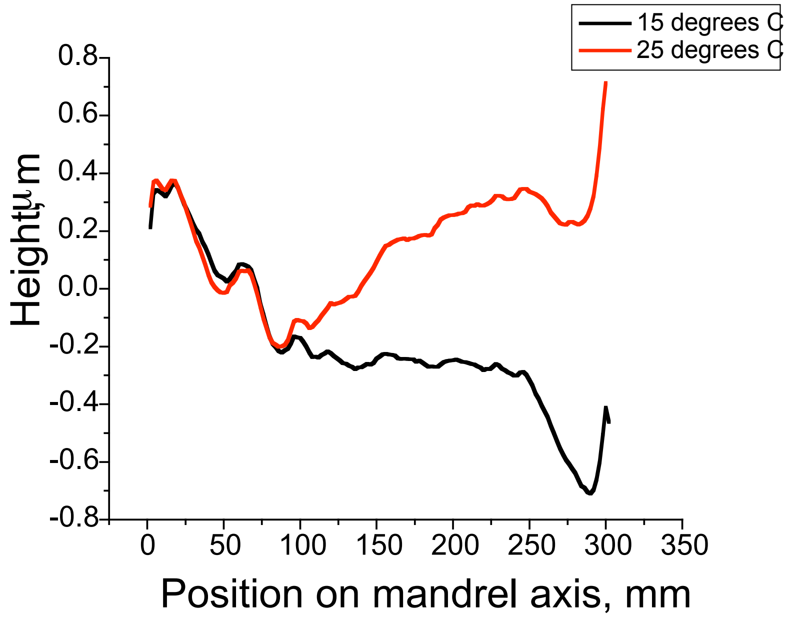


We identify two contributors :

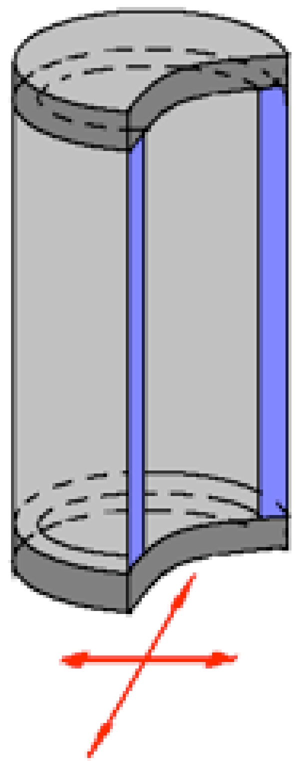
- *Mandrel stability --- small deviations in mandrel shape with temperature (electroformed at 45 C, but metrology at 25C*
- *Stress in electroforming --- small amounts of non-uniform stress in the deposit has a large effect on very thin free-standing shells*

ENR Development

Temperature dependence



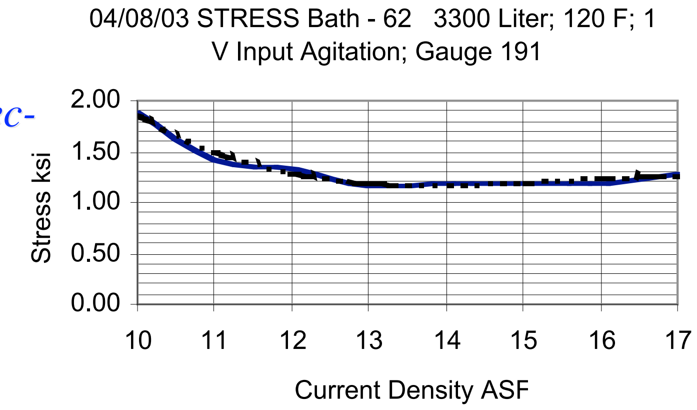
88 mm diameter mandrel



- *the mandrel ends and the middle of the mandrel are expanding at different rates with temperature*
- *the amount of axial displacement was radially dependant.*

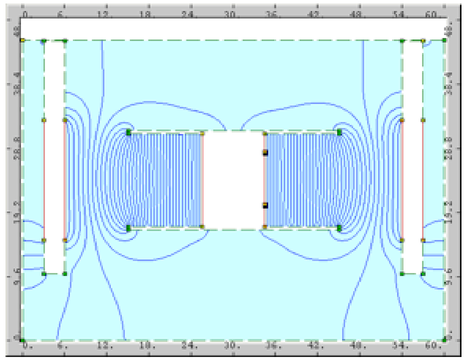
ENR Development

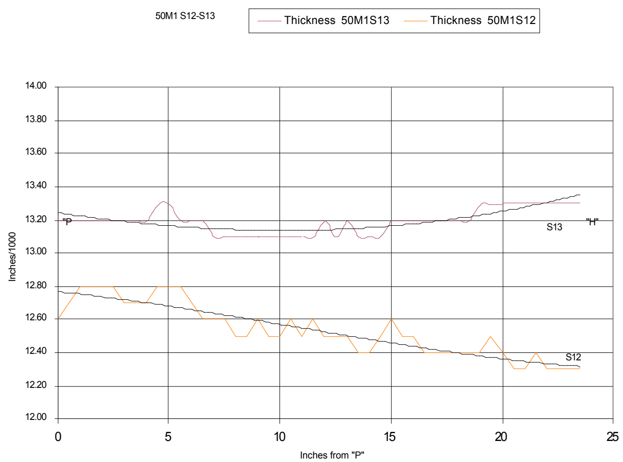
Plating stress control



Need to control the stress to ~ 10's psi to maintain 10-arcsec-level figure …adjust chemistry of bath to give flat uniform stress

Stress still varies with plating current density, so in turn need to control field … use models of plating bath to fine-tune layout of shields which modify field ⇒



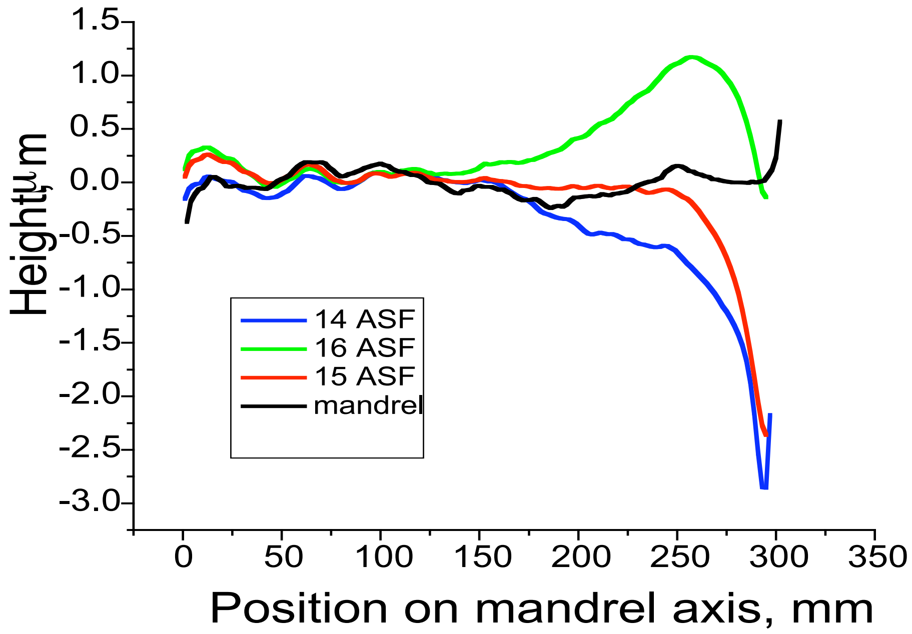


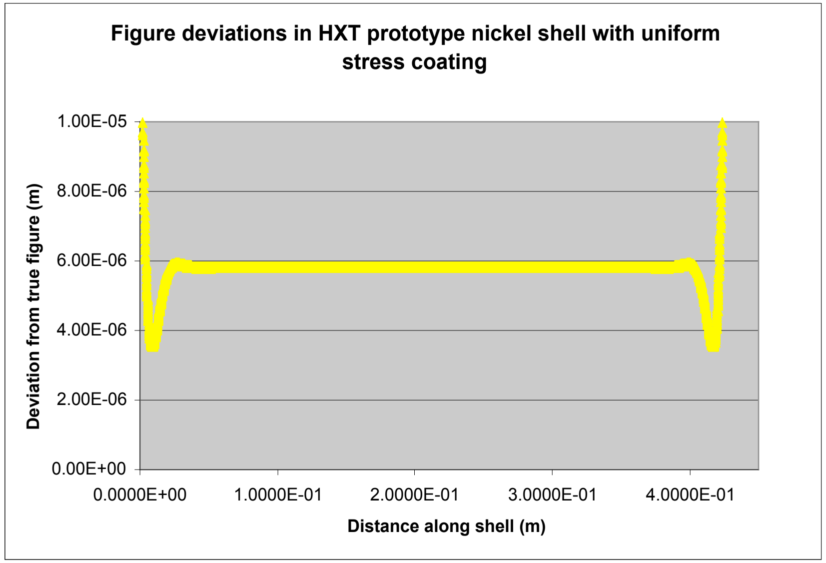
Resulting deposit is very uniform,

⇐

so stress variations are very low

ENR Development

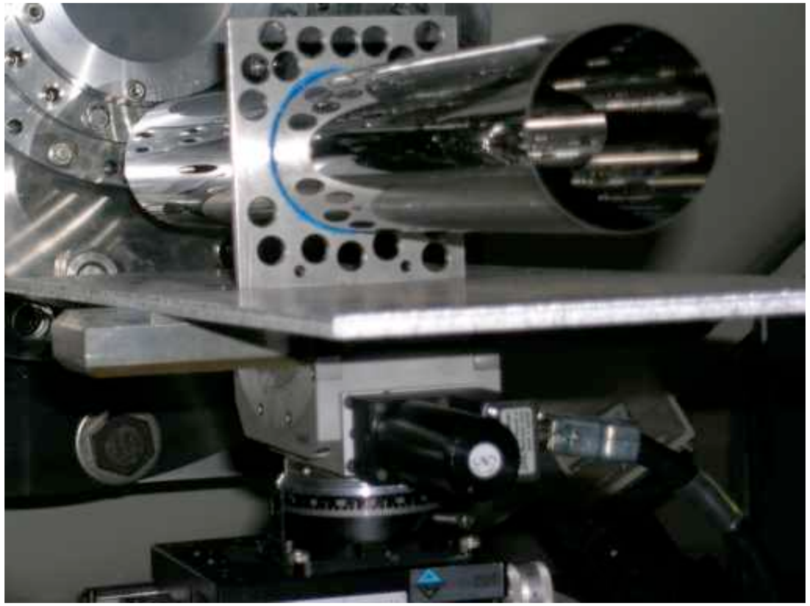




Effect of uniform stress (170 MPa, 25 ksi)

- *Uniform low stress can be achieved, if plating is performed at current densities within narrow range. Standard monitoring equipment does not have enough accuracy to determine the optimal current density*
- *The axial profile of the shell optics matches the one of the mandrel for ~ 85% of the length.*
- *The “hook” effect can be minimized by further optimizing the plating parameters.*
- *Some tensile stress is needed to prevent plating solution from leaking in during fabrication.*

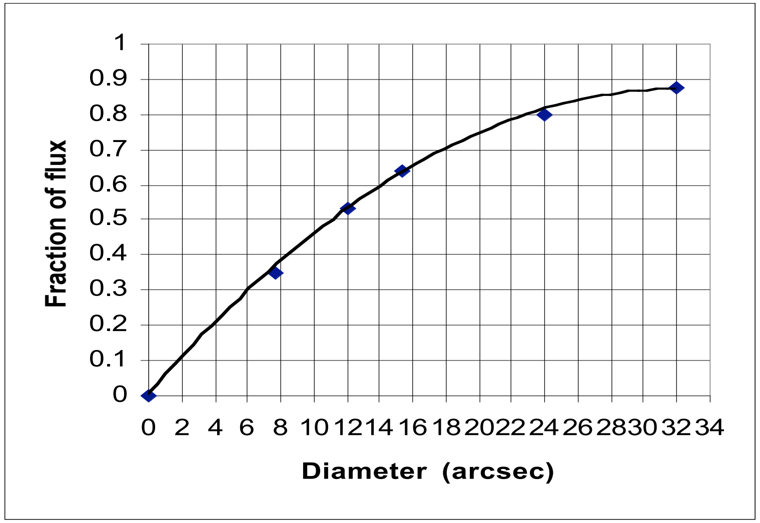
ENR Development



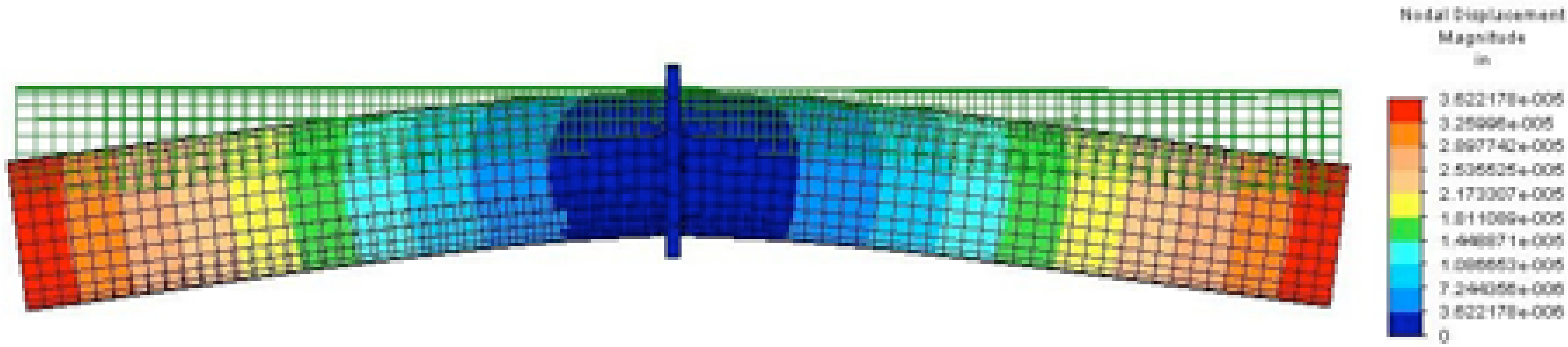
Performance predictions for the 68-mm-diameter *solid* conical mandrel

X-ray energy, keV	Angular resolution, arcsec
Geometric	5.0
0.277	5.25
40.0	8.3
60.0	8.9

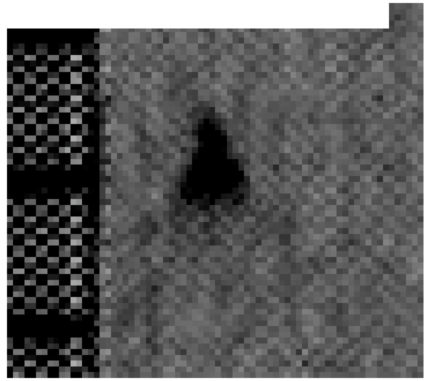
11.5 arc second resolution (~ 40 keV) →



ENR Development



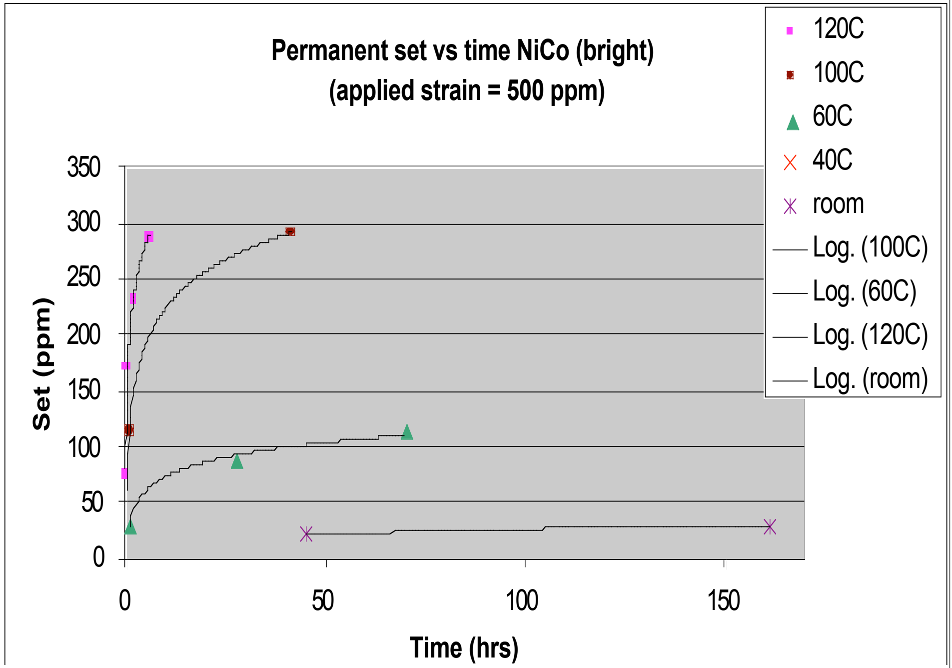
- *shell optics angular resolution of 10.5 ± 0.5 arcsec, if gravitational sag is taken into account*
- *Thus shell figure contribution is ~ 6.5 arcsec and conical mandrel ~ 8.3*
- *Wolter-1 mandrels of ~ 4-5 arcsec HPD have been fabricated -- thus we could expect ~ 8 arcsec shells from these under the same circumstances*

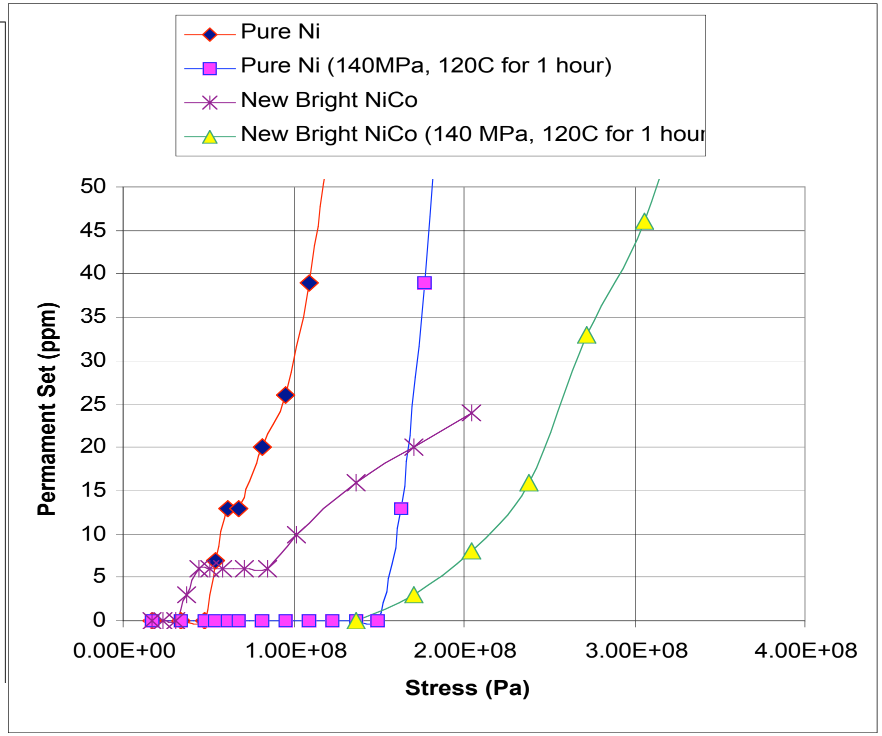


- *BEYOND THIS ??????*

ENR Development

- **Thermal Setting**
  - *Noticed that some plated material that we had crammed into a (too small) oven took on the shape of the interior at a surprisingly low temperature (120 ºC.)*
  - *Performed series of tests on samples to examine this effect :*





Future Developments

- **Thermal Setting**
  - Large amount of ‘stretch’ possible offers the possibility of forcing the shell to accurately conform to the mandrel
    - > Stretching also makes the material stronger (strain hardening)

What about plating stresses ?

• Evidence is that they anneal out with temp / time

• A 75 arcsec 0.5-m-diameter shell was placed back on its mandrel and heated to 120 ºC for 12 hours. After cooling and removal it now had a 15 arcsec figure (mandrel was 13 arcsec HPD)

• Shell shown at left (0.5-m-diam, 0.15-mm-thick) improved from 38 arcsec to 19 arcsec over a period of 1 year at room temp !

Future Developments

- **Themal Setting**
  - Challenge is to understand and optimize this process
    > Early attempts placed shells back on mandrels after metrology. Difficult to do, can get them misaligned

    – Plan series of tests with well-mapped mandrel comparing shells thermally set before removal

      » Initially on low-quality mandrel to compare figures. Then on higher quality mandrels.

Con-X 15 cm mandrel should be ~ 5 arcsec (HPD). …possibly fabricated higher quality mandrel with Wolter-1 figure for demonstration ?

Other Optics Applications

PLANETARY

• *Io and Europa x-ray emission seen by Chandra*

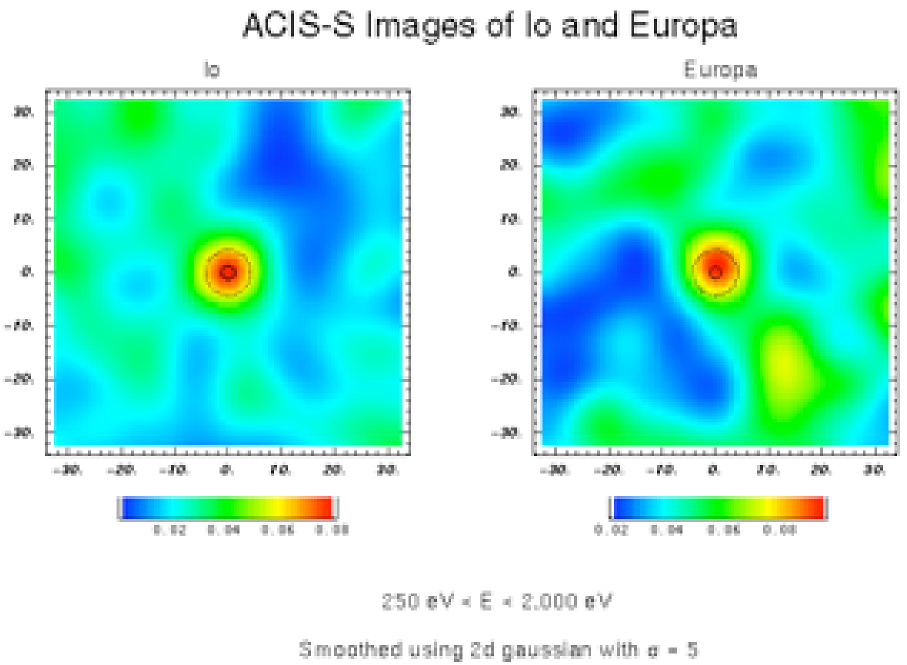
• *Intense charged particle flux from Jupiter excites surface elements*

• *Can use this flux to map out surface elements on these moons*

• *Propose high-speed silicon focal plane detector + x-ray optics*

• *Challenging aspect is detector 10^6 c / cm^2 s , _ Mrad radiation dose.*

• *MSFC working with Brookhaven National Lab on silicon drift detectors with custom ASICs*

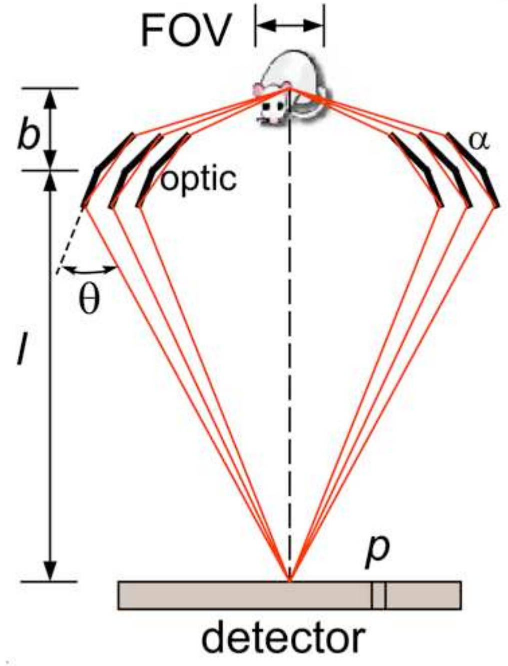


Other Optics Applications

MEDICAL IMAGING

• Animal imaging technology important for biomedical science
E.g., therapeutic development, disease study

• Non-invasive imaging plays a crucial role in anatomical studies
Ultrasound: ~200 _m resolution
CT & MRI: 25–50 _m resolution
Functional & Metabolic studies
SPECT & PET: ~1 mm resolution



Goal:

• *Develop radionuclide imaging with resolutions comparable to other techniques*
• *Fabricate a replicated optic with multilayers engineered to focus 27 keV photons from Iodine-125.*
• *Seek funding to build a 5_10 shell prototype to perform studies of phantoms or excised tissue labeled with either Iodine-125 or technetium (96Tc or 99mTc).*

Conclusion

- *MSFC has an ongoing development program in electroformed nickel replication for the hard-x-ray region*
- *The need for light-weight shells has necessitated the development of high-strength alloys and the control of stress in plating baths*
- *Over 150 shells total have been fabricated for the HERO balloon program and Constellation-X*
- *While ‘routine’ shells have 13-15 arcsec HPD, optics at the ~ 11 arcsec have been demonstrated and 8-9 arcsec should be possible with good stress control and stable high-quality mandrels*
- *Techniques to improve shells beyond this, by stress relieving and thermal ‘stretching’ are under investigation.*