# *- Astronomical telescopes -*
# *Modern solutions for large telescopes*

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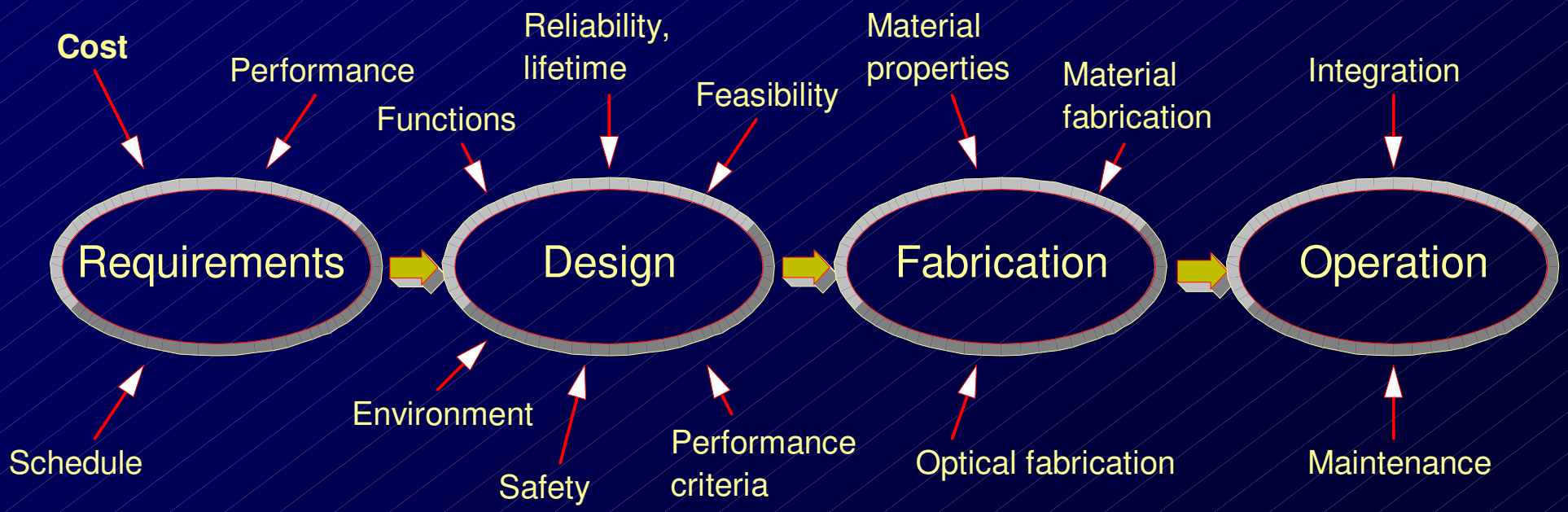
# ***Big is beautiful***

- Larger ⇨ higher S/N ratio & sensitivity, shorter exposure times
- Key issues – not only a matter of mirrors … !
  - Maximize throughput ⇨ large diameter
    ⇨ minimum number of surfaces
    ⇨ high reflectivity, low emissivity
  - Maximize resolution ⇨ optical quality (design, construction, operation)
    ⇨ site (atmospheric turbulence)
    ⇨ large diameter (with adaptive optics)
    ⇨ accurate guiding
  - Maximize efficiency ⇨ reliability, durability
    ⇨ operations scheme
  - Minimize cost ⇨ compact design (⇨ structure, enclosure, …)
    ⇨ affordable solutions
  - Minimize schedule ⇨ project management / risk management

# Modern solutions

- Start with requirements, not with design !!!




- Engineers may do
  - A good job if you tell them what you want (keep checking them, though)
  - A good but potentially useless job if you let them do what they want
  - An awful job if you tell them how to do what you want

# *Setting down a few driving parameters*

- Telescope diameter ?
- Specialized or multi-purpose ?
  - Specialized: high performance / cost ratio, but not flexible
    Examples: survey telescopes, dedicated to IR, spectroscopic telescopes
  - Multi-purpose: be prepared for compromises
- Fixed elevation or fully steerable ?
- Funding ?
- Timescale ?
  - Possible complementarity with other projects
  - Window of opportunity
  - Time for R&D ?
- Operations
  - your own telescope or service-oriented ?
  - Lifetime ?

# ***Quite likely …***

## *Assumption: you want it*

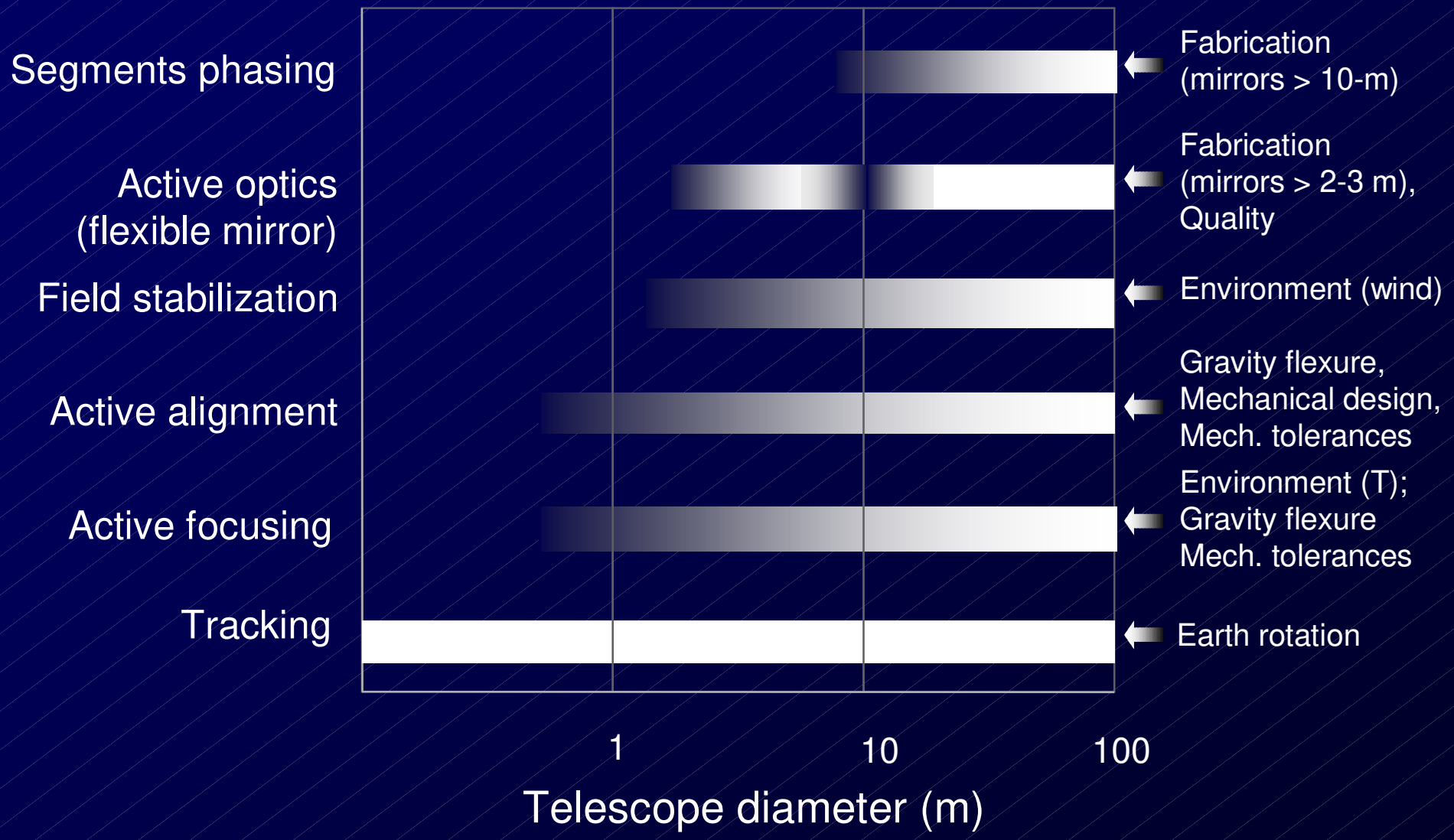
- Big (> 4-m)
- Multi-purpose
  (with possible optimization, e.g. infrared)
- Fully steerable
- Funding not hopeless
- Fast enough to compete
- For yourself only, but for some money you'd allow strangers to touch it
- To last until you retire

# A common design for modern telescopes

*Assumption: size not much larger than 10-m*

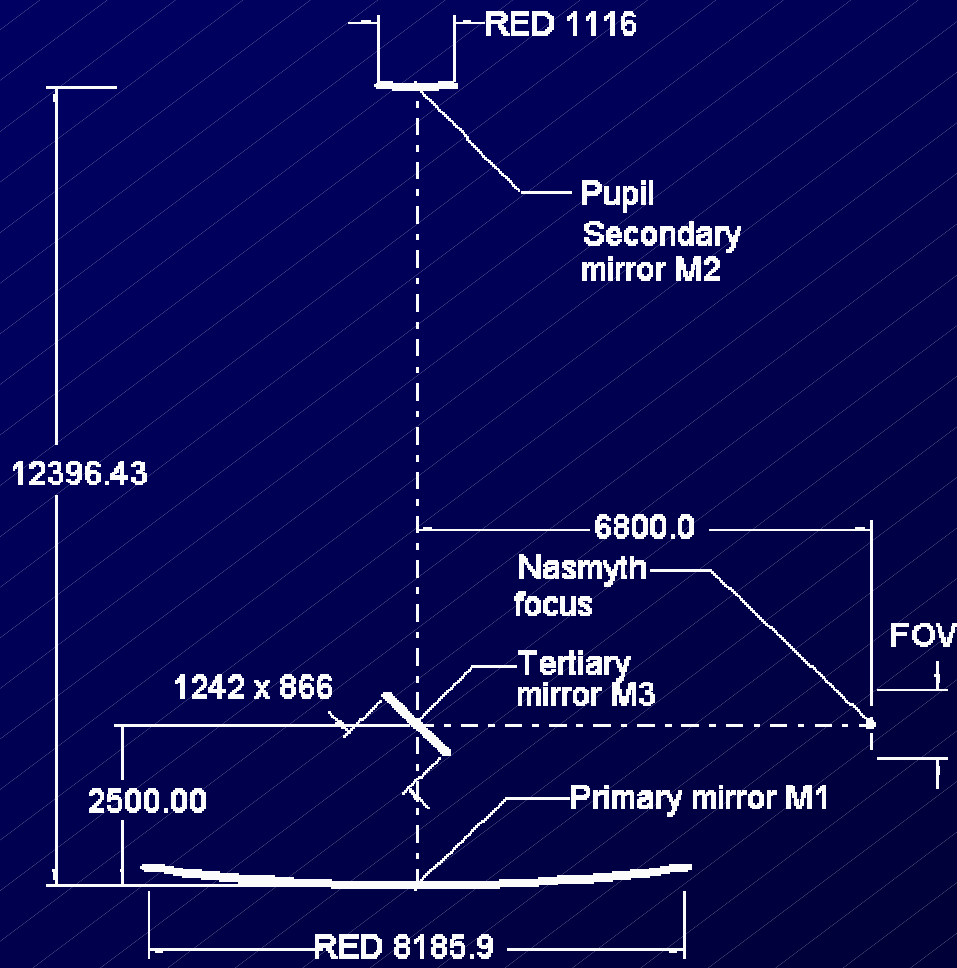
| Design solution | Comments (incomplete) |
|---|---|
| Ritchey-Chrétien | Best image quality (FOV) with 2 mirrors, high throughput |
| ~ F/1.5 primary mirror | Compact design (structure, enclosure) |
| ~ F/8-F/15 telescope | Obscuration, M2 max. size, plate scale, instrumentation |
| Nasmyth & Cassegrain foci | Several foci; NB: better without Cassegrain (higher fork) |
| Backfocal distance | Design volume for sensors, instruments |
| Primary mirror (M1) | |
| Glass / Glass-ceramics | Proven technology |
| Segmented or active | Segmented if D > 9-m, otherwise monolithic, active |
| Fixed secondary mirror unit | Alternative: exchangeable units; prime focus |
| Active focusing & alignment | thermal & gravity loads |
| Fast steering (~10-50 Hz) / chopping | vibrations, wind load / Infrared |
| Lightweight | fast steering; lower mass / inertia |
| Telescope pupil | Infrared |
| Alt-az telescope mount | Compact structure, small enclosure, low air volume |
| Co-rotating enclosure | Alternative: open air (sliding shelter, inflatable dome) |
| Air conditioned | Keep temperature to night one |
| Openings | for wind flushing |

# Functions


Segments phasing
Active optics (flexible mirror)
Field stabilization
Active alignment
Active focusing
Tracking
Fabrication (mirrors > 10-m)
Fabrication (mirrors > 2-3 m), Quality
Environment (wind)
Gravity flexure, Mechanical design, Mech. tolerances
Environment (T); Gravity flexure Mech. tolerances
Earth rotation
1
10
100
Telescope diameter (m)

# VLT optical design

| Surface | Conic constant | Radius of curvature | Axial distance to next surface | Diameter [mm] | |
|---|---|---|---|---|---|
| $M_1$ | -1.004690 | 28800 | 12396.429 | RED | 8185.9 |
| $M_2$ | -1.669260 | 4553.571 | 0 | RAD | 1116 |
| Exit pupil | - | - | 9896.429 | EXP | 1113.1 |
| $M_3$ | - | flat 45° | 6800 | RED | ≥ 866 × 1242 |
| IMG | - | 2089.6 | - | RFD | 1048.0 |

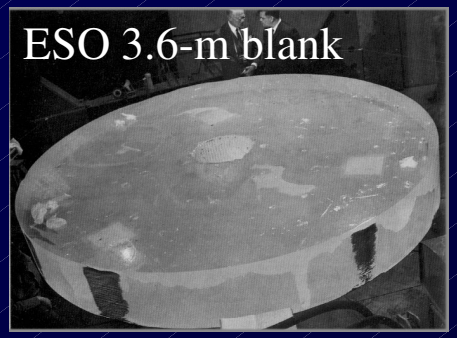


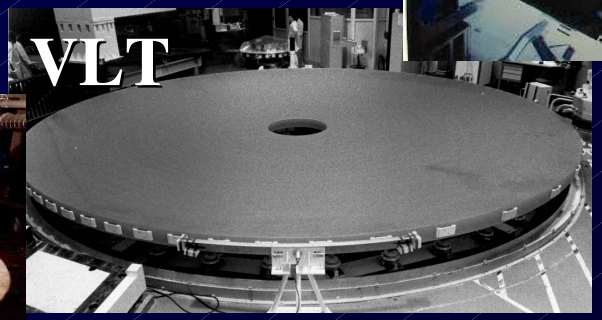

| Field radius [arc min] | Astigmatism coef. [nm] | Wavefront RMS [nm] | RMS radius geom. image [arcsec] |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 3 | 173 | 71 | 0.013 |
| 6 | 691 | 285 | 0.050 |
| 9 | 1555 | 642 | 0.113 |
| 12 | 2769 | 1143 | 0.201 |
| 15 | 4333 | 1777 | 0.314 |

- Ritchey-Chrétien
- 8.2-m active f/1.8 primary mirror
- Secondary mirror
  - Pupil
  - Focusing
  - Tip-tilt (field stabilisation, chopping)
  - Centring (rotation about centre of curvature)
  - Ultra-lightweight (Beryllium)

# Primary mirror technologies

- Classical approach (pre-1980):
  - Thick mirror blank, aspect ratio ~1/8, high mass
  - Passive support system (whiffle-tree or astatic levers)
  - Low expansion glass, but huge thermal inertia
  - Casting a serious issue (inhomogeneities, residual stresses)
- Modern options
  - Segmentation (Keck, HET) for D>9-m
  - Thin active meniscus for D < 8.4-m (NTT, VLT, Gemini, Subaru)
  - Semi-rigid, active structured mirror (Boro-silicate; also requires thermal control)





# *Primary mirror characteristics*

## 4-m < D < ~8.4-m
## Active mirrors

### PRO

- Relaxation of fabrication specs
- Very high quality for the money
- Will do more than correct its own shape
- Very fast focal ratio achievable (~f/1)

### CON

- Investment in production facilities
- Fragile; handling, & transport more cumbersome
- Requires large coating tank
- Unrealistic beyond ~8.4-m

## D > 9-m
## Segmented mirrors

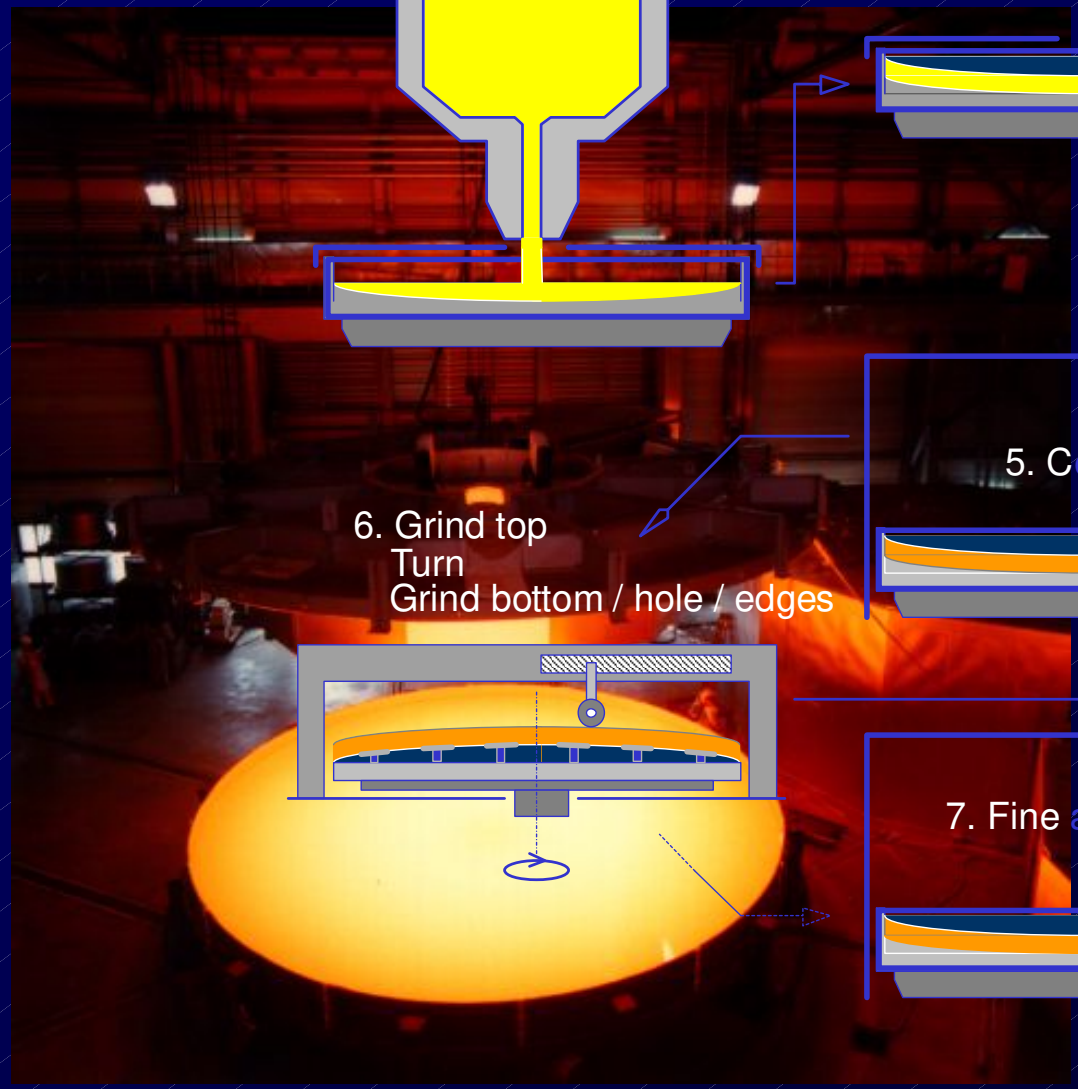
### PRO

- Blanks fabrication (up to ~2-m segment)
- Light, cost effective (thin blanks)
- Easy handling & transport
- Accident not catastrophic
- Scalable !!!

### CON

- Discontinuous aperture (uncritical if properly phased)
- Frequent handling
- Polishing & testing more difficult (off-axis aspheric segments, curvature)
- Longer focal ratio

# SCHOTT Zerodur (spin-casting)



1. Casting

2. Spinning / cooling to 800 deg. C

3. Annealing / cooling

4. Unmold
Turn
Grind bottom / edges
Turn
Grind top

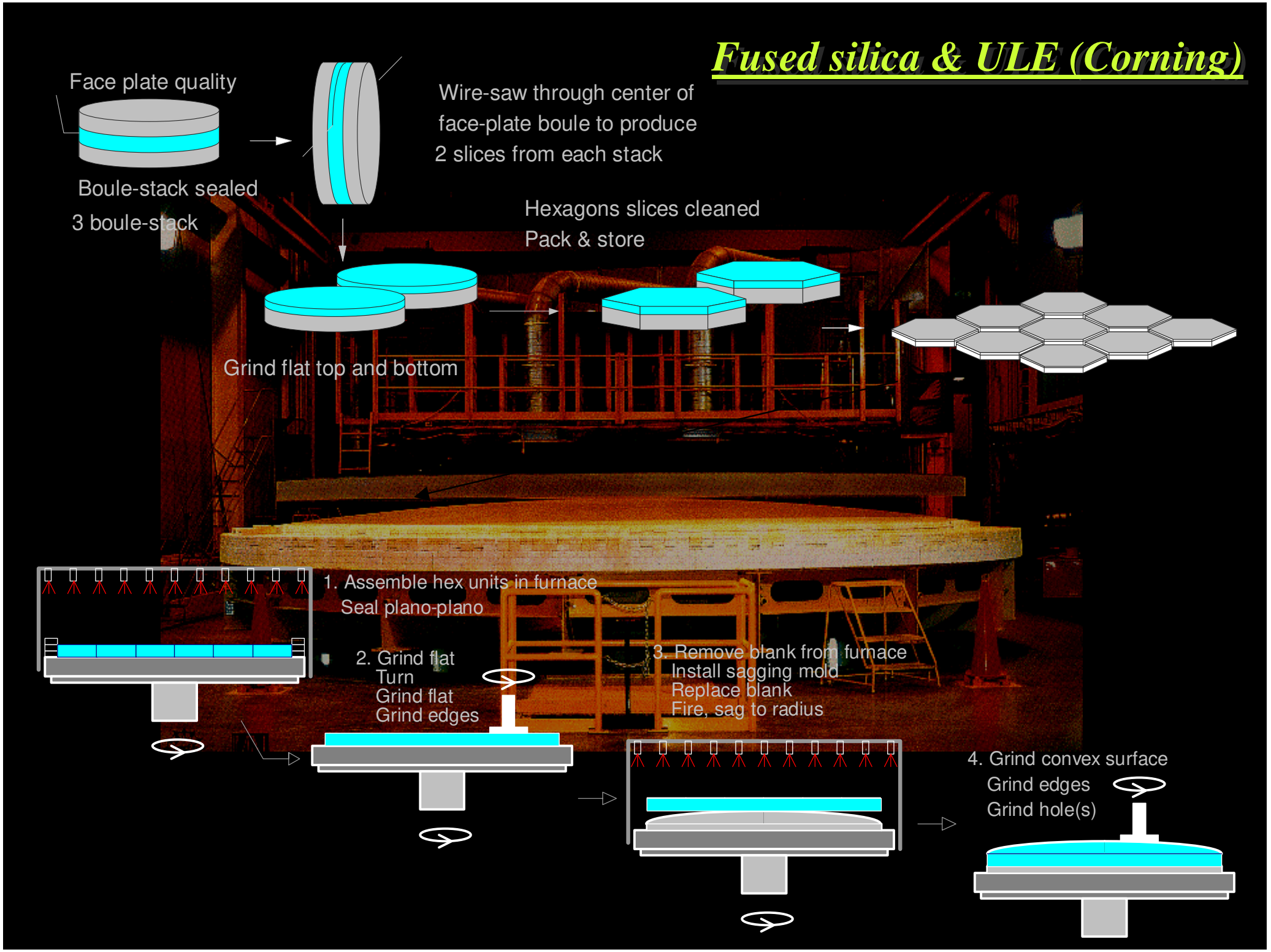
5. Ceramize

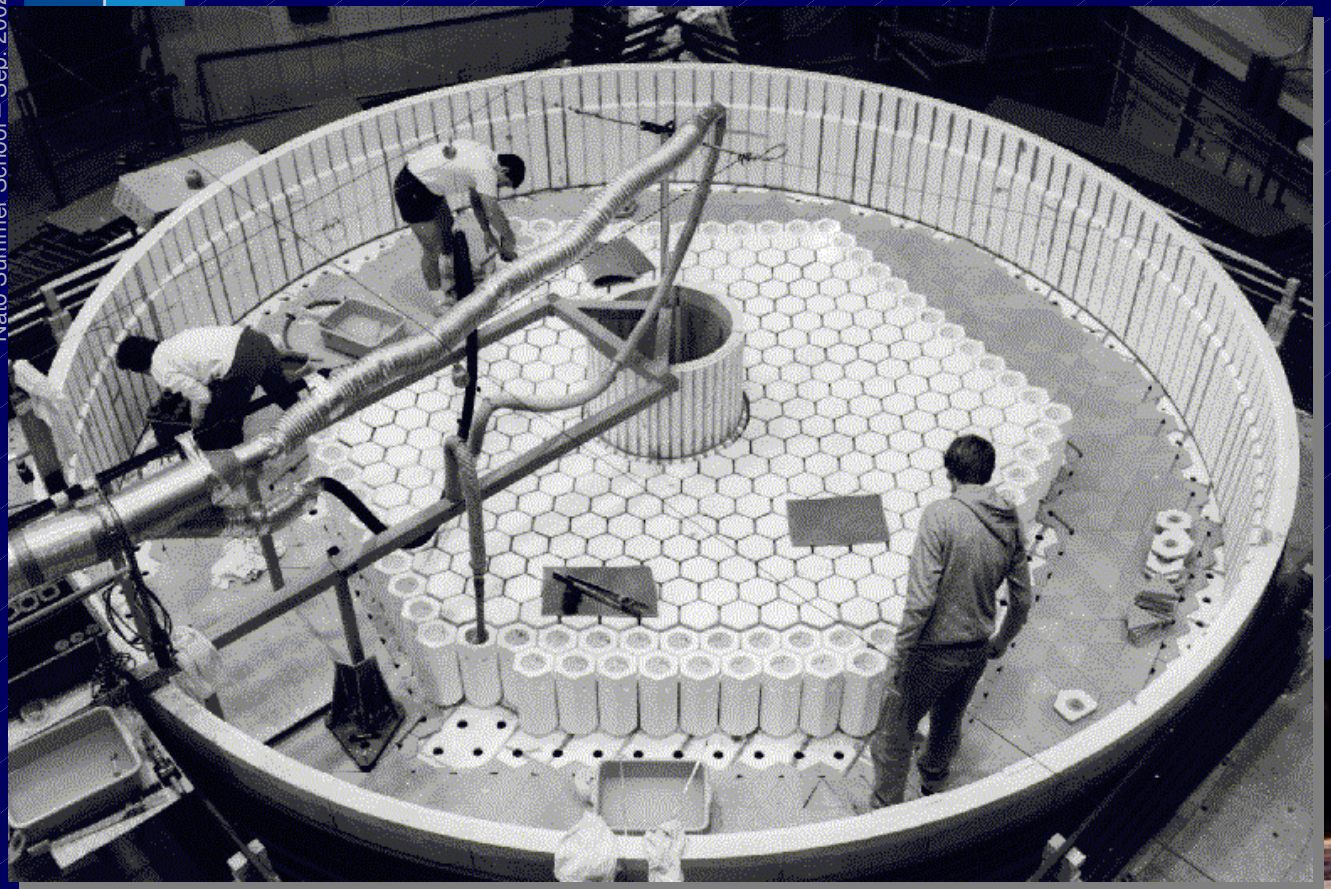
6. Grind top
Turn
Grind bottom / hole / edges

7. Fine annealing

8. Fine machining all surfaces
Pack & deliver

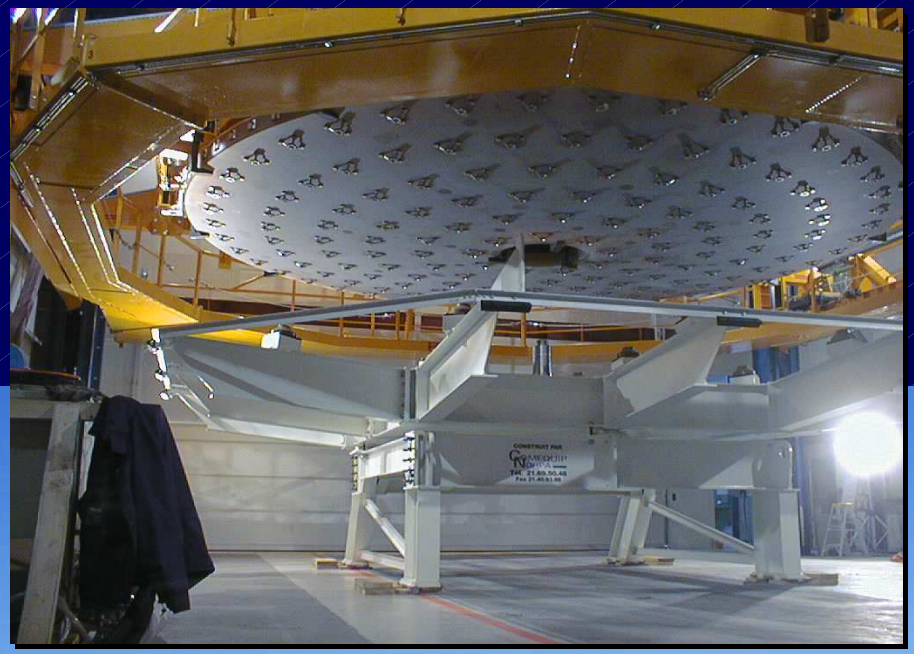
# Fused silica & ULE (Corning)



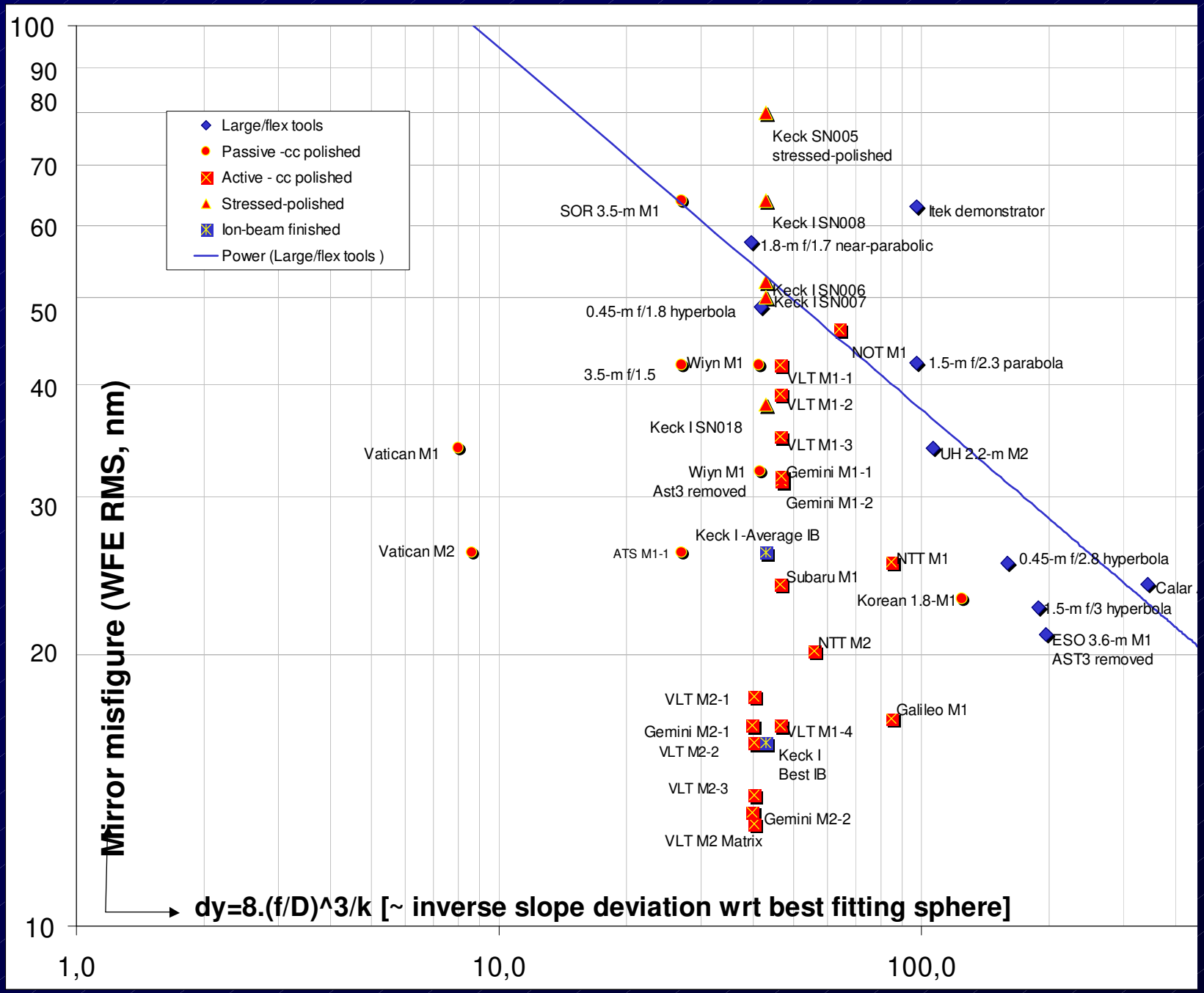


***Borosilicate Spin-casting, structured (Mirror Lab, UZ)***

# Transport & handling



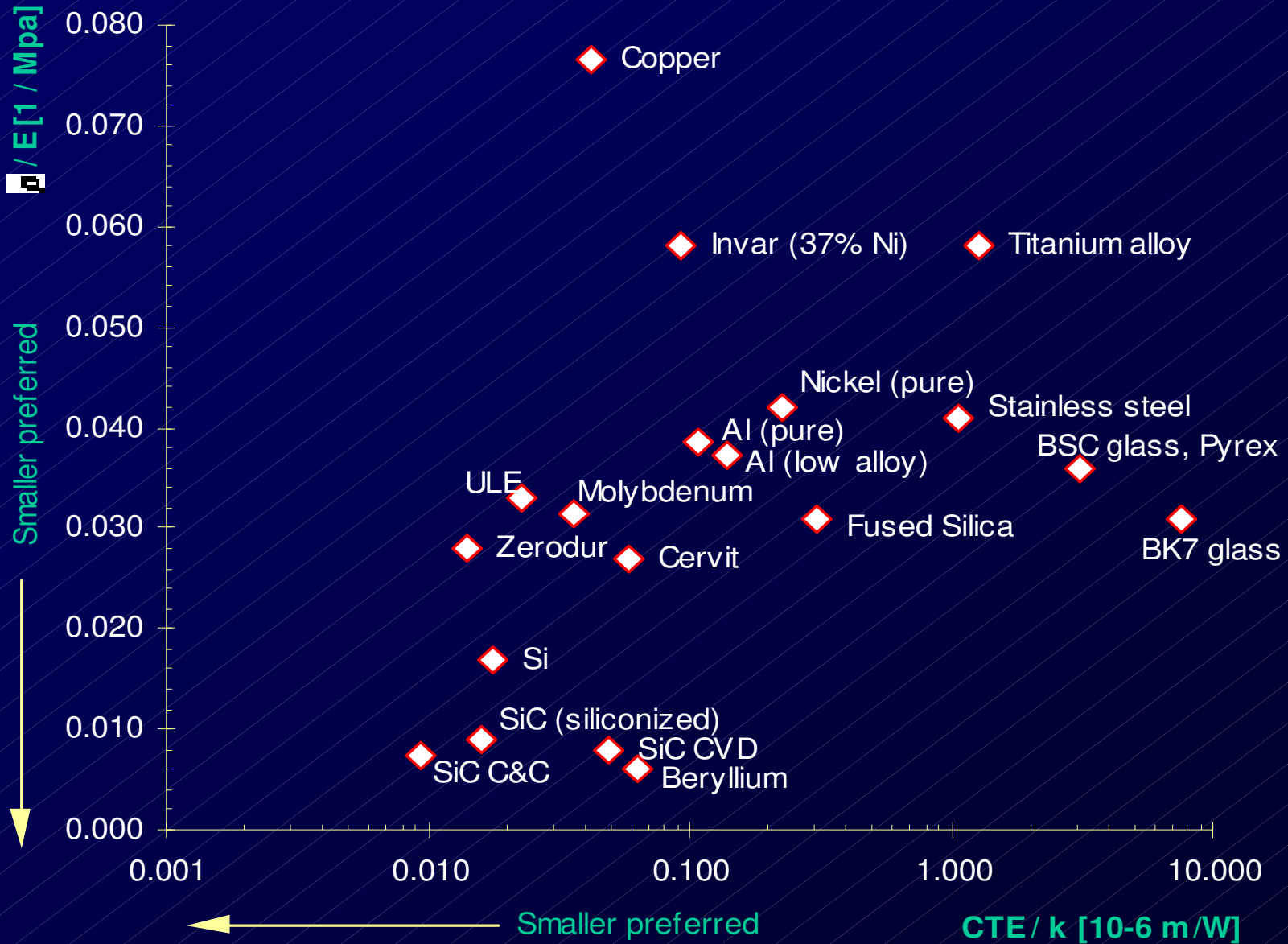
# Focal ratio


Large/flex tools
Passive -cc polished
Active - cc polished
Stressed-polished
Ion-beam finished
Power (Large/flex tools )
Mirror misfigure (WFE RMS, nm)
dy=8.(f/D)^3/k [~ inverse slope deviation wrt best fitting sphere]
100
90
80
70
60
50
40
30
20
10
1,0
10,0
100,0
Keck SN005 stressed-polished
SOR 3.5-m M1
Keck I SN008
Itek demonstrator
1.8-m f/1.7 near-parabolic
Keck I SN006
Keck I SN007
0.45-m f/1.8 hyperbola
NOT M1
1.5-m f/2.3 parabola
Wiyn M1
3.5-m f/1.5
VLT M1-1
VLT M1-2
Keck I SN018
VLT M1-3
Vatican M1
UH 2.2-m M2
Wiyn M1
Ast3 removed
Gemini M1-1
Gemini M1-2
Keck I -Average IB
Vatican M2
ATS M1-1
NTT M1
0.45-m f/2.8 hyperbola
Subaru M1
Korean 1.8-M1
1.5-m f/3 hyperbola
NTT M2
ESO 3.6-m M1
AST3 removed
VLT M2-1
Galileo M1
Gemini M2-1
VLT M1-4
VLT M2-2
Keck I
Best IB
VLT M2-3
Gemini M2-2
VLT M2 Matrix

# *Want some R&D ? Mirror Materials*

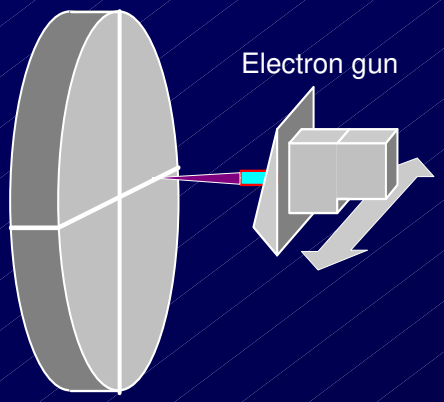
- Category I - thermally stable. Astro-Sitall, Zerodur, Silica, ULE, (aluminium)
  - Thin active meniscus up to ~8-m, 12-14-m probably feasible.
  - Lightweight machined/structured up to ~2-4 -m
- Category II - BSC glass.
  - Spin-cast structured up to ~8.5-m, moderately active, needs thermal control
  - Lower aerial density, higher stiffness
- Category III - “Super-materials”, Be, SiC
  - Very high specific stiffness, ultra-lightweight mirrors.
  - Max size ~1-m, ~2.5-m probably feasible.

# *Thermal & mechanical figure of merit*

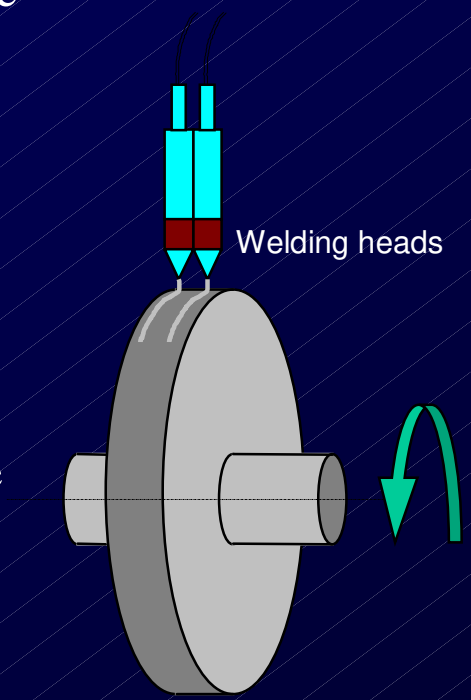


# *Aluminium*

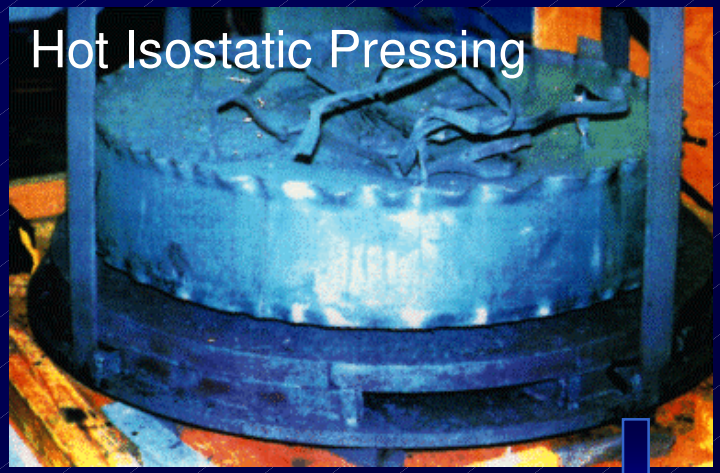
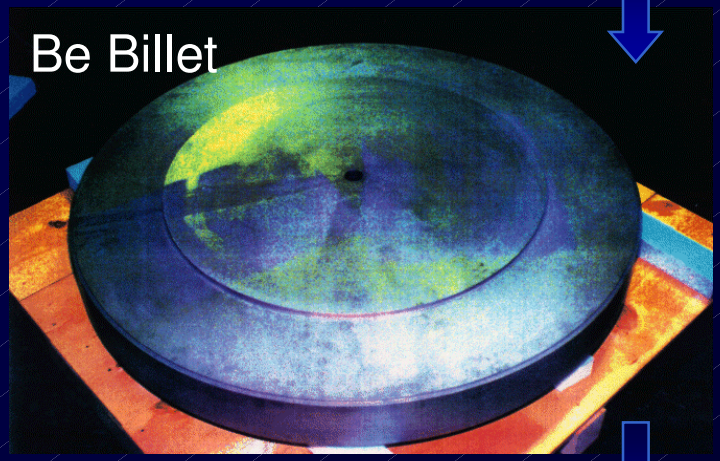
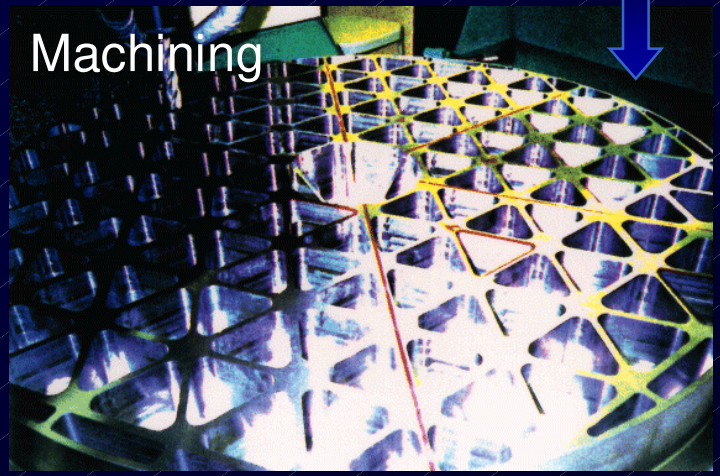
- 1.8-m mirrors, 2 technologies (backup VLT M1):
  - Electron-beam welding
  - Build-up welding
- Thermally cycled, found stable within ~1 fringe, suitable for active mirrors
- Ni overcoating a source of risk
- Room for improvement: residual stresses, canigen coating.
- A cost-effective alternative above 1-2m
- CTE homogeneity still needs to be demonstrated.




Electron-beam weldi




Build-up welding

# *Ultra-lightweight optics*

- Aerial density ~ 40 Kg / $m^2$
- Glass-ceramics (Gemini), Beryllium (VLT)
  - 1-m class demonstrated to diffraction-limited quality
  - very high cost (risk, process complexity)
- Silicon Carbide
  - history of "problems" -above all commercial!
  - Not all technologies suitable -CVD unsuccessful
  - Potentially the most attractive: best material, fully elastic, fast processes
  - Ultra-lightweight ~20-30 Kg/$m^2$ OK up to ~ 1-m.
  - ~50 Kg/m2 cost effective within 3-5 years?