1. Purpose and Scope

Several factors must be weighed in the choice of a mirror blank for the WIYN telescope. The blank must have sufficient rigidity to maintain an optical surface within a given error budget. It must resist deformation due to thermal transients in the telescope environment. The mirror and support cell package should not contribute unduly to telescope seeing. Finally, the mirror and its support cell must meet all these goals at a reasonable cost.

There are several choices of substrate that can meet the requirements for rigidity. This study addresses some of the thermal aspects of secondary blank selection. Some simple calculations regarding thermal bowing and seeing contributions may help in selecting among the possible purchase options.

2. Scaling

Surface distortions and seeing effects at each optical surface contribute to image aberrations at the focal plane. The effects at each surface scale (to the first order) with the effective distance from focus. For the secondary mirror the scaling distance is identical with the physical distance from focus, but the primary is effectively one system focal length - 22.05 m - from the focal plane.

The scaling factors for image aberrations due to support errors, thermal bowing, and mirror seeing for the primary and secondary are:

M1 22.05/22.05 = 1.0
M2 6.925/22.05 = .314

3. Thermal Bowing

Low cost makes borosilcate glass an attractive candidate for a secondary substrate, however it is susceptible to thermal bowing. Pearson and Stepp (1987) measured the image aberration due to thermal bowing in a 1.8 m borosilicate honeycomb mirror and developed scaling laws for larger mirrors. They found that image aberrations due to temperature gradients scale with the peak to peak temperature difference, the coefficient of thermal expansion, and the aspect ratio of the substrate. The predicted image aberration for the WIYN primary is .5 arcseconds per degree C.

For a secondary of aspect ratio 8 we include the distance scaling factor to find:

$$\frac{dI}{dT} = 0.5*(\frac{8}{9})*(0.314) = 0.14\ arcsec/C$$

In the case of the secondary mirror the thermal environment is dominated by the rear surface of the support cell exposed to the night sky. Andrew Cheng modeled the thermal performance of a secondary mirror in some detail and found that under normal observing conditions - that is with the ambient temperature changing at 0.25 C/hr, and a 2 m/s breeze - that the p-p temperatures in the substrate will be about 0.3 C, while under adverse conditions (0.5 C/hr, or low wind) temperature differences as high as 0.6 C can develop. For a borosilcate substrate the above scaling indicates the contribution from thermal bowing would be 0.04 arcseconds normally, and 0.08 under adverse conditions.

Since this is a large portion of the 0.07 arcsecond FWHM error budget allotted to thermal effects, borosilicate has a clear disadvantage for the WIYN secondary substrate.

4. Seeing Contributions

There are two ways in which the secondary mirror contributes to seeing in the telescope; first directly by mirror seeing due to a temperature difference between the glass and air at the reflective surface; second indirectly by air heated or cooled by contact with the secondary mirror and support package contributing to seeing in the primary beam. The first effect scales with the effective distance from the focal plane, the second does not. Both effects are reduced by lightweighting the mirror blank.

4a. Direct mirror seeing

The effects of direct mirror seeing have been addressed in recent studies some of which were summarized in WODC 02-05 (Tertiary Blank Selection Study). The temperature difference at the air to glass interface is driven by mirror's thermal time constant and by the ambient temperature slew rate. The thermal time constant can be determined by:

$$\tau = t\rho c/h$$

where t is the effective glass thickness
ρ is mass density
c is material specific heat.
h is the heat transfer coefficient

The effective thickness is determined by the lightweighting ratio. The air to glass temperature difference is dominated by convective coupling to the ambient air; a typical value for h under normal observing conditions is 6 $W/m^2/K$. For glass, the air to glass temperature difference is approximately the ambient temperature slew rate times the thermal time constant in hours.

Using these relations we can calculate the thermal time constant τ, and estimate the air to glass temperature difference at the secondary mirror surface. Using a model proposed by Racine et al (1991), we can estimate the direct contribution to seeing in arcseconds FWHM.

lw ratio (%)	**weight (Kg)**	**τ (hrs)**	**Seeing (FWHM)**
80	96	1.9	0.07
70	144	2.8	.12
60	192	3.8	.17
50	240	4.7	.22
40	288	5.7	.28
30	336	6.6	.33
20	384	7.6	.39
10	432	8.5	.45
(solid)	480	9.5	.51

Racine's model was based on statistical results of CCD frames taken at the prime focus of the 3.6 m CFHT. Extrapolating to a secondary mirror may not give good results, however the trend is intuitively correct; a lower mass mirror will track a changing ambient temperature with a lower ΔT and with a correspondingly lower mirror seeing contribution.

These rough calculations are for glass substrates. One potential substrate, Silicon Carbide (SiC), is very different from glass in its thermal and structural properties. SiC has a very high elastic modulus - about five times that of glass. Substrates of SiC can be made very thin and light weight. A conservative design for WIYN would weigh about 63 kg. SiC has very high thermal conductivity - over a hundred times that of glass. This prevents temperature gradients from developing, eliminating thermal bowing despite its relatively high coefficient of thermal expansion.

For SiC we can expect a thermal time constant of about 0.25 hours, corresponding to about 0.02 arcseconds of mirror seeing under normal circumstances.

Despite its attractive properties, SiC has several drawbacks. It is a new material still under development, and is much more expensive than glass. As of this date, there is only one blank larger than 0.5 m, and none larger than one meter. It is an extremely hard material and requires special polishing techniques. Many opticians have no experience with this material.

4b. Indirect mirror seeing

Indirect seeing is driven by the entire mass of the secondary and support cell residing in the primary beam at some average temperature different from the ambient air. Unlike the local air to glass temperature difference at the mirror surface which is dominated by convective heat transfer, the temperature of the secondary package as a whole is dominated by radiative heat transfer to the night sky.

This can be controlled to a great extent by choosing the emissivity of the coating for the exposed surfaces of the secondary package. Some typical values for radiative heat transfer for a steel structure are 80 W/m^2 coated white paint, and 17 W/m^2 for a coating of aluminum foil tape. Beckers and Williams (1982) give an expression for the equilibrium temperature difference for a surface exposed to the night sky and ambient air:

$$dT_e = \frac{T_a - 50\varepsilon}{(9+v)}$$

where ε is emissivity
v is wind velocity in km/hr

A surface covered with aluminum tape ($\varepsilon \approx 0.1$) exposed to a 7.2 km/hr wind will reach equilibrium temperature about 0.3 degrees below ambient. For a typical paint painted surface of any color ($\varepsilon \approx 0.95$), the equilibrium temperature is about 3 degrees below ambient. The seeing contribution from this temperature difference should scale roughly by the ratio of the exposed surface area to the area of the primary. Using Racine's model and the appropriate scaling, the estimated contribution is about 0.07 FWHM for the painted steel surface, and less than 0.01 for the aluminum taped surface.

In principle this seeing source can be completely eliminated by adding heaters to the secondary package and actively driving the surface temperature towards ambient. For a borosilicate blank this introduces potential image aberration from hot spots.

This calculation is for equilibrium temperature, and applies to any kind of mirror. Even a massive solid glass mirror will reach equilibrium given enough time and a stable environment. Real observing conditions, however, are dynamic, with ambient temperatures changing typically 0.25 °C per hour.

Since mirror cells almost invariably weigh as much as the mirror, a reduction in weight of the glass results in a similar savings in the weight of the support cell. The lower mass and thermal inertia of a light weight secondary and support cell will reduce its thermal time constant, consequently reducing both the direct and indirect contribution to seeing.

5. Conclusions

While these calculations are only estimates, they do indicate some trends in the performance of various secondary substrates.

The secondary blank should be light weight to reduce mirror seeing. Intuitively, the lighter the weight the less the seeing. A blank lightweighted about 75% is estimated to contribute about 0.10 arcsecond mirror seeing under normal observing conditions, while a 50% lightweighted blank is estimated to contribute about 0.22 arcseconds.

It may not be possible to achieve thermal performance within error budget allowance of 0.07 FWHM using passive temperature control. Achieving performance within the allowance is even less likely with a borosilicate substrate which will have a further aberration contribution due to thermal bowing. Never the less, active control has not been considered here and is not being considered for the WIYN secondary.

Because of radiative coupling to the night sky, the secondary support cell will reach an equilibrium temperature cooler than ambient. This can contribute significantly to internal seeing. The effect can be reduced by coating exposed surfaces with aluminum foil tape.

The ideal material for a secondary substrate is clearly SiC, however uncertainty in producing a blank of sufficient size and the associated expense rule out this choice.

It would appear that the most cost effective choice for a secondary substrate is a zero expansion glass such as Corning ULE or Schott Zerodur, lightweighted by milling or drilling the core. In this way typically 50 to 75% of the mass of a solid blank can be removed. Based on quotes we have received there is a modest increment in cost going from 50% to 73% lightweight. Since the performance is significantly better for the lighter weight blank, the increase in price seems a good investment in the continuing performance of the telescope.

5. References

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