Proc. of SPIE Vol. 2199, Advanced Technology Optical Telescopes V, ed. L M Stepp (Jun 1994) Copyright SPIE

The Gemini Primary Mirror Thermal Management System

RJS Greenhalgh

Building R65, Rutherford Appleton Laboratory, Chilton, Didcot,
Oxon OX11 OQX, United Kingdom

L Stepp, E Hansen

Gemini Project, National Optical Astronomy Observatories,
950 N. Cherry Avenue, Tucson, Az 85719, USA

1. Abstract

This paper describes work done on the design of the thermal management system for the primary mirrors of the Gemini Telescopes. The concept developed has a set of radiating plates behind the mirror, which can be used to heat or cool the mirror. In addition, there is a provision for heating the front surface of the mirror by passing a current through the reflective coating. It is shown that the heating and cooling together can be used to raise or lower the temperature of the surface of the mirror by about 1 degree per hour. Experiments and calculations are reported which show that the system can meet the target temperature range up to 90% of the time. The temperature gradients induced in the mirror have little effect on the optical performance. Experiments have shown that no degradation to the surface is caused by the current passing process. This approach potentially will allow thick mirrors of low thermal expansivity to follow rapid ambient air temperature changes, thereby avoiding mirror seeing.

2. Introduction

At one time many astronomers believed that atmospheric seeing limited the resolution of large telescopes to about one arc second, but over the last two or three decades it has become apparent that local seeing, produced by pavement, domes, and even the telescope itself, can be as significant as the effects of the rest of the atmosphere. One type of local seeing that is receiving particular attention is mirror seeing caused by the primary mirror. When the mirror is at a different temperature than the air, heat transfer between the mirror and air results in refractive index differences in the air that produce wavefront aberrations. In some cases these refractive index patterns are relatively stationary, and can be corrected by active optics, but in general they change and move over time periods of a few seconds.

Most telescopes with thick glass mirrors suffer from noticeable amounts of mirror seeing. As the air cools at sunset, the thick mirror cannot cool as rapidly. After sunset the air cools more slowly, but if the mirror is already significantly warmer than the air, it will remain so throughout the night unless its temperature is actively controlled in some way. The temperature of the mirror surface is cooled by contact with the air (it is this heat transfer, after all, that produces the mirror seeing) but the core of the mirror substrate continues to conduct heat to the surface, maintaining its temperature at an intermediate point between the temperature of the air and that of the mirror core.

The image quality of the Gemini Telescopes is such that it demands control of mirror seeing. The error budget for the telescopes1 requires that the contribution due to this effect be less than 0.04 arc seconds beam width at 50% encircled energy. After a study of the literature[2,3,4,5,6] we have concluded that the specification can be achieved if we can keep the mirror temperature within a band between 0.6°C below ambient to 0.2°C above ambient. This is a very narrow range. However, it should be borne in mind in all that follows, that we are trying to make the mirror match the ambient air temperature - not reach some fixed offset from it. Any errors will tend to be self-correcting by natural convection, and so the task is less severe than one might at first suppose.

A key realisation of this work has been that it is the temperature of the front of the mirror rather than the temperature of the bulk of the mirror that is significant for mirror seeing. In many telescopes, of course, it is essential that the whole of the

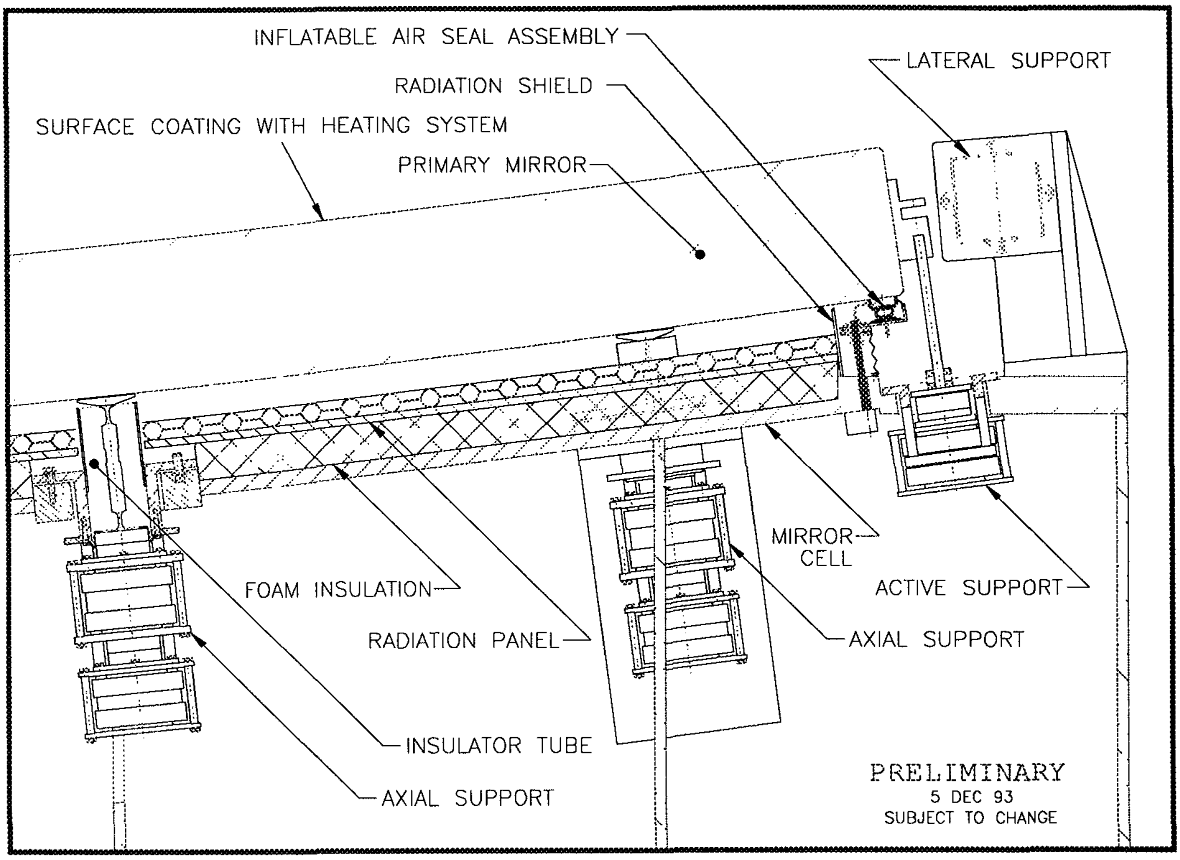


Figure 1. The layout of the principal components

mirror is kept at a uniform temperature in order to avoid warping. The Gemini telescopes, however, will have a primary mirror made of ULE^{TM}, and whose thickness is the same near the centre as it is near the edge. Also, the telescopes will be equipped with active optics and autofocus. The homogenous material and uniform thickness mean that any temperature gradients we may generate in our attempts to control mirror temperature are essentially uniform across the mirror. Autofocus and active optics ensure that any change in shape of the mirror so caused (principally change in radius) has a negligible effect on imaging performance. And the very low thermal expansivity of the ULE^{TM} material means that small gradients, or small differences in gradient, also have a negligible effect. All of this has been carefully numerically modelled, and the result is that we can allow temperature gradients (within limits) through the thickness of the Gemini primary mirror. Allowing ourselves to generate such gradients, we have found it is feasible to achieve far better control of the surface temperature than would be the case were we required to control the bulk mirror temperature. In fact as we shall show, we can achieve the required level of control under most conditions.

Another scientific requirement on the primary mirror is the control of dewing. The performance of the telescopes in the infra-red requires an extremely low coating emissivity (around 2%); any occurrences of dewing will degrade the performance.

Our concept features a system of radiating plates behind the mirror, similar to those proposed by the ESO project7 as shown in figure 1. The maximum heat transfer rate (heating or cooling) is about 3kW, with the plates about 15°C hotter (or cooler) than the mirror. These allow slow control of the temperature of the front of the mirror. With the radiating plates at full power, it takes about two hours for the temperature change to reach the front of the mirror. The second part of the concept is the use of an air-conditioning system which will control the air temperature in the dome during the day. It will be set to the temperature expected at the start of the following night's viewing and will help to precondition the mirror. The third part of the concept, which we believe to be unique in a telescope, is the passing of a current through the surface coating to allow fast control of the surface temperature. The maximum heating rate is 2kW. A one degree change takes 18 minutes; by arranging for a negative temperature gradient through the mirror the temperature can be made to fall at about the same rate when the heaters are switched off. The surface heating system can also be used to control dewing. We have run a series of tests to demonstrate that the required rates of temperature change can be achieved and that no damage to the coating occurs.

In this study we have demonstrated that the proposed system will work, and will allow the telescopes to achieve the required imaging performance up to 95% of the time.

3. Scientific specification

Allowable limits on the effects of mirror seeing are established by the Gemini error budget, which allows mirror seeing to add 0.04 arc second to the 50% encircled energy diameter of the image (assumed to add in quadrature) at the design wavelength of 2.2 microns. It is not easy, however, to determine the level of mirror temperature control required to meet this specification. There is little quantitative data at even the 4m scale to associate mirror surface temperature differentials with image quality degradation at the 0.04 arc second level, and we know of no measurements of mirror seeing in large telescopes at infrared wavelengths. The current Gemini specifications are based on seeing measurements made at visible wavelengths by a number of authors[2,3,4,5,6]. Their results have been adjusted to reflect the effects of moderate wind flushing rates using the curve developed by Zago8, and they have been scaled to near infrared wavelengths using the Kolmogorov 5/3 power law assuming the mirror turbulence is homogeneous and isotropic. In addition, several studies have shown that the effects of mirror seeing are not as pronounced for a mirror cooler than the air as for a mirror that is warmer. Taking all this into account, we believe that with a moderate amount of ventilation by the wind, mirror seeing will be within the levels set by the Gemini error budget if the mirror temperature is no more than 0.2°C warmer than the air, and no more than 0.6°C cooler. The Gemini Science Working Group has accepted these limits as being conservative, and there is evidence that under certain conditions the mirror could be somewhat cooler without exceeding the error budget. Recent measurements taken on the 4.2-m William Herschel Telescope appear to support this view -- mirror seeing values of 0.006 to 0.012 arcseconds were calculated from the measured structure function when the mirror was 2°C cooler with moderate wind flushing (Jenkins, et al., in preparation). It is our understanding that ESO has adopted the same temperature specification for the VLT Project.

The requirement can thus be expressed:

$$-0.6 < \Delta T < +0.2$$

The Gemini Primary Mirror Preliminary Design Review resulted in a strong recommendation that the mirror be protected from dewing, because of the degradation in emissivity that might result. A system which could guarantee to prevent dewing would enable the telescope to be used in conditions in which it might otherwise be necessary to close down for fear of damage to the mirror coating. In his survey of conditions on Mauna Kea, Merrill9 reports that 7% of nights otherwise suitable for astronomy had a dewpoint within 1°C of the ambient air temperature.

4. How the system works - Theoretical performance

The environment in which the required small temperature difference must be maintained is that at the summit of Mauna Kea (MK) or Cerro Pachon (CP)[9,10,11]. The telescope enclosure is designed so that the telescope is exposed directly to the outside ambient air temperature. We are still gathering data for CP, but we can present data for MK. In figure 2, some typical night-time temperature profiles are shown. These were taken at UKIRT during 1992. What can be seen is that the temperature typically falls by a up to few degrees during the night, but superimposed on that are fluctuations of up to about a degree over an hour.

In this section we will consider how the system behaves under very simple conditions, in order to give an understanding of its behaviour under real conditions as reported in the section that follows.

The mirror has a diameter of 8m and is 0.2m thick, weighs about 22 tonnes, and has a heat capacity of about 17MJ/K. This can be more usefully expressed as 4.7kWh per degree; to change the average temperature of the mirror by one degree using 1 kW takes about 4.7 hours. We are only transferring heat at the surface of the ULE^{TM}, and so there will be transient effects to consider. To explore these, consider the effect of cooling of the rear surface at maximum power (3kW) with the radiating plates. The effect is shown in figure 3. As can be seen, it takes about two hours before the temperature of the front of the mirror starts to change, thereafter it falls by about 4 degrees during 12 hours. This would be fast enough to track the slow component of the night-time temperature shown in the figure above, provided it could be reasonably well predicted. Now

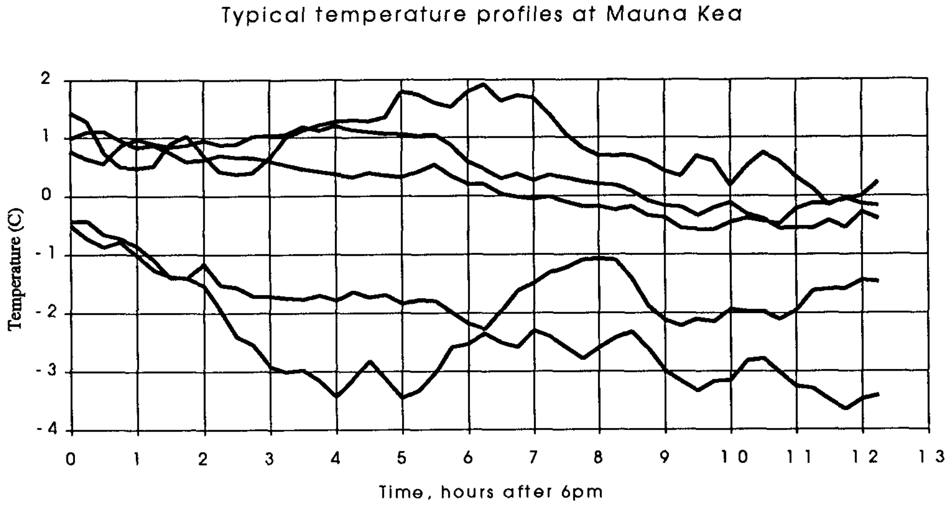
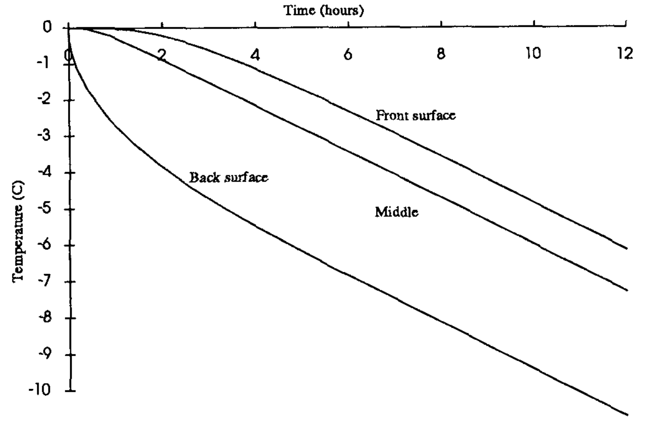


Figure 2. Typical night-time temperatures at Mauna Kea. Data from UKIRT, taken outside the dome at 15 minute intervals. A few nights selected at random from early 1992 are shown.

consider the effect that use of the heaters can have. If the radiating plates are used to establish a temperature gradient through the mirror, then the temperature of the front of the glass can be made to fall with no heating or to rise with heating. This is shown in figure 4, in which a 1kW cooling at the back is added to a 2kW heating at the front switched on and off on a two-hour cycle. It is possible to change the temperature by about a degree in an hour, which roughly matches the rapid fluctuations we need to track.

Thus the system with radiating plates alone should be able to track the night-time temperature on a long timescale, and the addition of the heating system should improve things on shorter timescales. We have also seen that there are large temperature gradients through the mirror - the effect of these on the optics turns out to be small, as is discussed in section 6 below. In the next section, we describe predictions of the system's performance modelled using actual night-time temperature profiles over about a year.



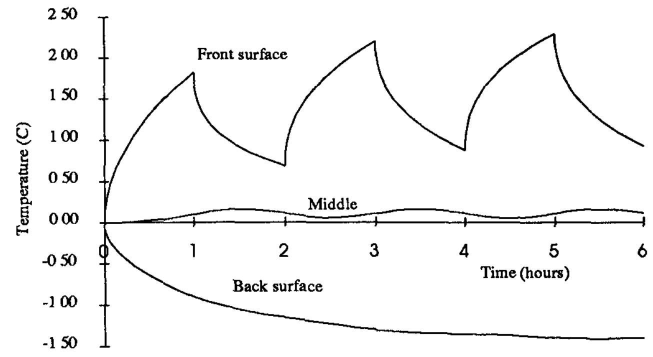


Figure 3. The effect of cooling the rear surface of the mirror with 3kW cooling power.

Figure 4. The combined effect of the radiating plates (1kW cooling) and the surface heaters (2kW, switched every hour)

5. Simulated performance under real conditions

To predict the overall performance of the thermal control system, we have modelled the operation of the thermal control system under observatory conditions12. The transient heat transfer to, from and through the primary mirror was modelled using finite difference methods. Both the radiation plate and surface heating produce uniform heat transfer across the front and rear surfaces of the mirror. This, along with the uniform mirror cross section allows the use of a one dimensional model. Temperatures through the thickness of the glass are found assuming uniformity along any plane parallel to the front surface of the mirror. This simple modelling approach was confirmed by modelling possible edge effects; three dimensional models showed the edge effects to be small.

Closed loop control of the radiation plate temperature was used within the model to minimise the mirror front surface to ambient air temperature difference. In addition to closed loop control algorithms, many other parameters are available to improve the mirror's ability to track the ambient temperature. These parameters include mirror surface heating algorithms, start-of-night temperature prediction algorithms, daytime preconditioning and exterior-to-interior wind speed reduction factors. To gain a realistic assessment, control parameters were adjusted to optimise performance for one data set and then tested on a second data set from another year. Using this approach, a one year time history of mirror temperature was evaluated using actual temperature and wind data taken on Mauna Kea. The performance assessment of the system was based on the percentage of time the mirror-air temperature difference is between +0.6°C to -0.2°C during potential observing times.

The results show that the system performance is most sensitive to two factors, temperature prediction accuracy and temperature data source. Because of the large thermal inertia of the mirror, correction of an error at the start of the night requires substantial time and impacts performance. In order to bound this effect, two cases were tested for each data set. The first assumed perfect prediction of the start of night temperature, yielding an upper bound on performance. The lower bound resulted from assuming that the next night's starting temperature would be the same as the last night's. In fact, results from Murtagh et al[11] show that temperature prediction much better than this can be achieved for astronomical sites.

The source of the temperature data also had a large effect on resulting performance. Again, the large thermal inertia of the mirror limits its ability to track short term temperature fluctuations without the use of surface heating, and data with high levels of fluctuation produced reduced performance figures. Outside temperature data from UKIRT, CFHT and an NOAO site survey were all evaluated. The data were taken in different locations using different equipment and different sampling rates. This made selection of which would best represent the temperature inside the Gemini enclosure difficult. We therefore attempted to bound the uncertainty by looking at the "best and worst case" data sets.

The results, based on data supplied by CFHT, with highest temperature fluctuations, and from the NOAO site survey, with lowest fluctuations, indicate that without implementation of surface heating the mirror surface temperature can be expected to be within +0.2 to -0.6 degrees Celsius of the ambient temperature for approximately 50 to 85 percent of potential observing times, depending on the data set and prediction algorithm used. With resistive optical surface heating this increases to approximately 75 to 95 percent.

6. Effect of temperature gradients on mirror

As was mentioned earlier, this method of controlling the mirror front surface temperature will produce temperature gradients within the primary mirror. In order to predict the optical surface errors caused by these gradients as well as more general thermal errors, we modelled possible temperature distributions and CTE variations within the mirror using finite element methods13. The errors analysed fall into two broad categories. The first deals with errors caused by non-uniform temperature distributions such as those produced by the proposed thermal management system. Because ULE™ has a low but non-zero coefficient of thermal expansion at the operating temperature of 0°C, gradients through the thickness of the blank can produce localised bending, leading to wavefront aberrations.

The second category deals with the surface errors that are caused by non-uniform CTE. The CTE of individual boules that make up the primary mirror vary slightly from one to another. Because of these variations, a change in temperature, such as between the optics shop and observatory or under the influence of the thermal management system, can cause bending of the mirror.

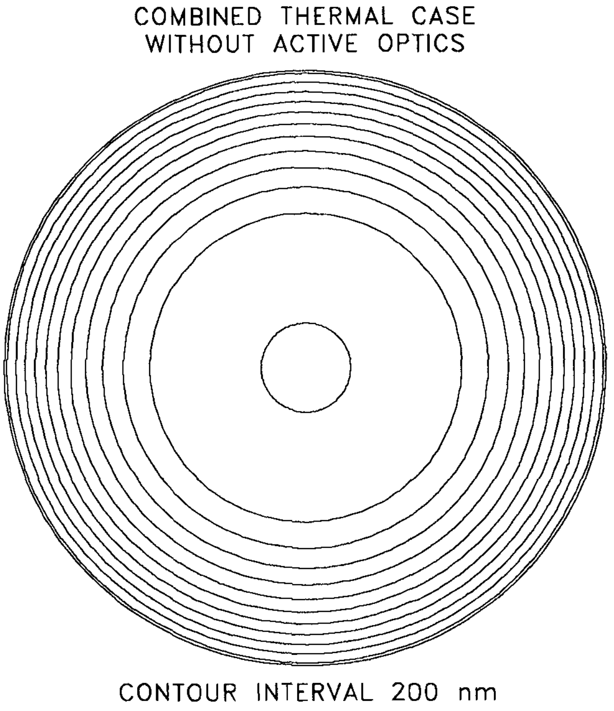


Figure 5. Worst-case residual errors caused by thermal distortions before focus and active optics correction.

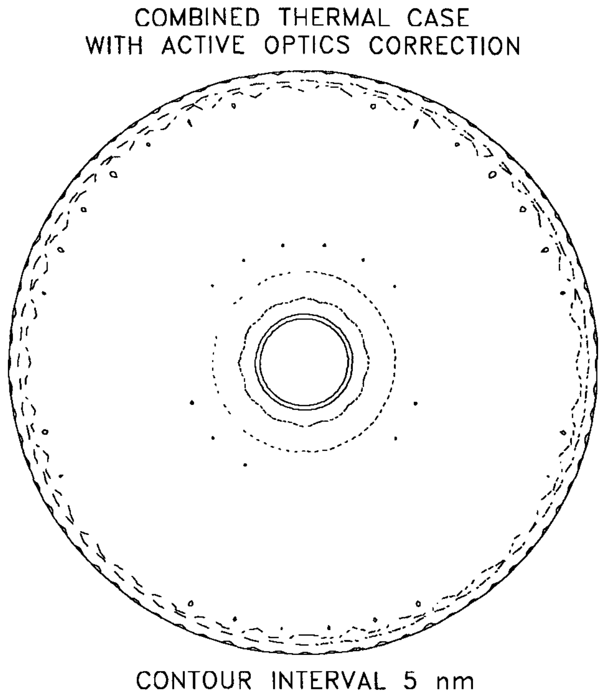


Figure 6. The same errors but with focus correction (15ppm plate scale) and active optics correction applied.

To evaluate the effect of temperature gradients within the mirror, a variety of distributions were analysed to find their effect on mirror figure and image quality both before and after active correction. These cases included radial and axial gradients as well as localised heating and a random surface temperature distribution. In order to model a realistic temperature distribution, we reviewed the most severe temperature distributions produced by the thermal management system under real conditions. We then combined a 3.2°C axial gradient with a 0.3°C random surface pattern and a 0.3°C increase in temperature at the mirror outer edge from surface heating non-uniformities. Figures 5 and 6 show the mirror surface figure change from this distribution both before and after active correction. This shows the magnitudes of thermally induced deformations are low even with substantial temperature gradients due to the low CTE of the ULE^{TM} primary mirror. The slow rate of change and smooth shape of thermal deformations allows them to be well corrected using active optics. With correction, this temperature distribution results in only a 3.8 nm RMS surface deformation and an increase in 50% encircled energy which is a factor of four below the error budget allowance *(.00125 as @ 50% Encircled Energy & 2.2um)*. The associated plate scale change of 15 PPM is well within the allowable budget of 100 PPM.

Another concern is the effect of differences in CTE between hexagonal sections, or boules, within the primary mirror. Each boule is produced individually, and is characterised by measurement of CTE at the fabricator in both radial and axial directions. By distributing the boules in the primary mirror with regard to their CTE, the effects of their variations can be minimised. The Japanese National Large Telescope (JNLT) has developed one method to optimise boule distributions14. As fabrication of Gemini boules is not complete, analysis of CTE effects were done using CTE data from the JNLT mirror boules, which we believe will be very similar to the boules for the Gemini mirrors. This analysis shows that the effect of moving the mirror from optics shop to the mountain top, a uniform change of approximately 25°C, has a larger effect than gradients induced by the thermal management system. By optimising the placement of the boules within the mirror, the surface figure change from a 25°C temperature drop after correction would be only 3.3 nm RMS with a resulting plate scale change of 25 PPM.

Due to the low CTE of the ULE^{TM} primary mirror, the magnitude of thermally induced deformations are low even with large temperature changes or gradients. Thermal gradients or changes in ambient temperature could be substantially larger that those that will be experienced in operation and still be within the error budget. This is due in part to the smooth shape and slow change rate typical of thermally induced errors, allowing these already small deformations to be further reduced using active optics. Based on the results of this study to date, we expect that primary mirror thermal distortion will not limit telescope performance.

7. Detail of mechanisms - radiating plates

The radiating plate array is designed to allow heat to be made to flow into or out of the back of the mirror. It does this by radiation from a set of temperature controlled panels behind the mirror. The panels (figure 7) are hollow and their temperature is set by a fluid circulating inside them. The fluid is fed through a heat exchanger mounted in the basement of the building. Heat flow of up to about 60 W/m^2 (3kW total) can be achieved in this way.

Other features of the system are:

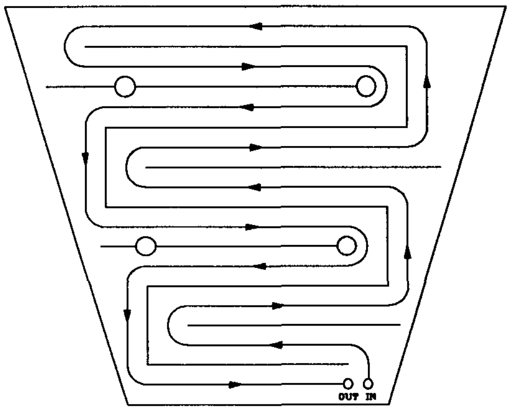


Figure 7. Schematic layout of radiating plate

- The fluid is a water/glycol mix, with corrosion inhibitors. The materials of the plates and the pipes will be chosen to minimise corrosion.
- The temperature limits we have chosen are +/- 15°C which, together with the high emissivity of the surface finish of the plates, sets the maximum heat transfer rate. The flow rate is set at 1kg/sec for the entire system, which gives a temperature change in the fluid of about 1 degree at maximum power. In order to further guarantee uniform heat transfer rates, the flow path to each plate will be about the same length, the flow path within each plate will be 'double serpentine' (see figure), and finally there will be a heater tape on the inlet of each plate to allow the temperatures to be individually adjusted if required.
- The system will be carefully designed to allow air bleeding; vacuum bleeding can be used if need be. All demountable joints will use high-quality self-sealing fittings. All joints inside the air pressure mirror support system15 are welded. There is insulation behind the plates to minimise heat transfer to the cell. Because the plates are inside the air pressure support system which will be filled with dry gas, there will be no condensation problems.
- The pump, mounted in the basement, will be selected to minimise transmission of vibration along the pipes. There will in any case be flexible pipes in the run which will tend to absorb any residual effects. The plates will have anti-vibration mounts to minimise transmission of turbulence-induced vibrations to the mirror cell structure.

8. Detail of mechanisms - heaters

The resistive heating system is designed to allow the temperature of the surface of the mirror to be changed rapidly, thus following rapid or unpredicted temperature fluctuations. The concept of the heating system is very simple. There is a metallic film on the surface of the mirror, and if a current is passed through that film then resistive heating will take place. The expected performance of the system was described in sections 4 and 5.

In the next three subsections, we deal with the three design challenges: Can suitable electrodes be designed? Will the system give uniform heating? Will the system damage the coating?

8.1 Design of the electrodes

The scope of the present study did not allow us to arrive at a definitive design. However, several lessons were learnt, from which we have arrived at the preliminary design shown in figure 8. The electrodes would be permanently bonded to the edge of the mirror. Use is made of the chamfer to allow the electrode surface to be flush with that of the mirror. If we cannot find a material that is of a low enough thermal expansivity to be bonded successfully to ULE™ and which also has enough corrosion resistance to allow for coating removal, we may consider using a plated metal for the electrodes.

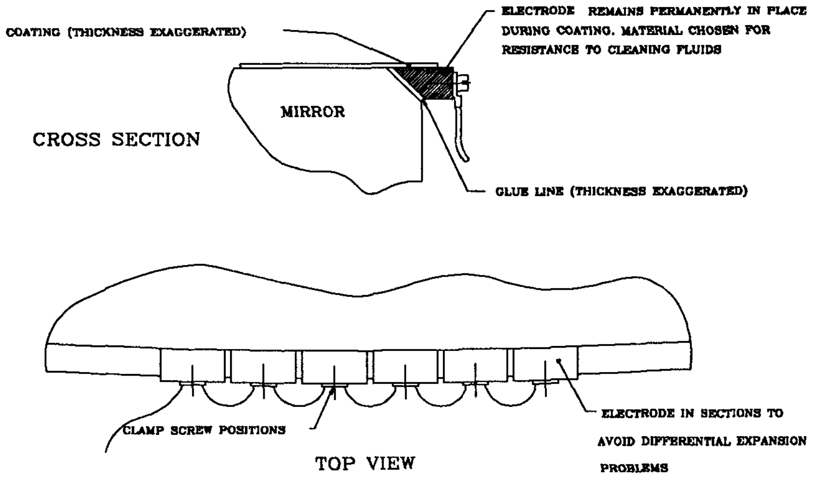


Figure 8. A possible design of the electrode, exploiting the chamfer at the edge of the mirror to save space and to allow a flush coating surface.

8.2 Uniformity of heating

We were concerned that non-uniformities in the thickness of the coating might cause non-uniformities (perhaps disproportionately large) in the heating level.

Various regimes can be imagined for non-uniformities in the thickness of the coating. For example, a zone of thin material running parallel to the current flow would have minimal effect on the heating. On the other hand, a scratch perpendicular to the current flow would stop the flow completely. It is felt that the most likely form of non-uniformity is a patch of coating of some small deviation from nominal thickness.

A simple FE model was made of a square area of coating, having a zone within it of 10% reduced thickness. The finding was that this zone did not have much effect on the voltage distribution, so that the increased resistivity caused the current to fall by about 10% in the zone. This caused a decrease in heating density of about 10%. The conclusion is that for typical variations in coating thickness, the power density varies with the first power of the thickness. The target for coating uniformity is +/- 2.5%, so we would expect power density uniformity of the same level.

We carried out an experiment to see, as far as practicable, that the required level of heating uniformity could be achieved over a large area. A slab of optical quality glass, approximately 1000mm by 700mm by 75mm thick, was coated on one face and had electrodes attached along the 700mm edges. It was found that when current was passed, a temperature rise of 1.2°C could be obtained, uniform to +/-0.05°C. Elaborate steps had to be taken to insulate the slab from heat transfer from the environment in order to obtain this result, because it involved making the slab temperature different from the ambient air temperature.

In all of the above, we have assumed that a uniform voltage gradient exists across the mirror. If the mirror were rectangular, that would be easy to achieve. With a round mirror, one could arrange for a uniform gradient across the mirror (from side to side) by providing a graded voltage around the edge, provided by a large number of discrete electrodes. The central hole could be catered for in a similar manner. However, we would like to use as small a number of electrodes as will yield the desired level of heating uniformity. Initial studies by David Hagelbarger16 have been extended as part of this study. The result so far is that electrodes are required around the inside and the outside edges of the mirror, and that a uniformity of 2%

over 66% of the mirror, and 50% over 90% of the surface, can be obtained using 48 electrodes in total. We stress that this is only a preliminary result; several possible methods could be used to improve it. For example, the number of electrodes could be increased (guaranteed to solve the problem but at a cost), or their spacing or shaping could be altered.

8.3 Experiments verifying that no damage to the coating will occur

In discussions with various experts, we have been able to identify only ion migration as a possible source of damage to the coatings. When glass is subject to large voltage gradients, the sodium can ionise and migrate to the surface, reacting with the electrode and eventually destroying it. This only happens with large DC voltages; we plan to use small levels of AC. In order to satisfy ourselves that no other damage mechanisms exist, we performed tests on a set of samples.

Several sets of test specimens were made, as follows:

- evaporated aluminum on plain window glass,
- evaporated silver with a quartz overcoat on plain window glass, and
- sputtered aluminum on ULE™.

For every specimen the emissivity, surface adhesion, and surface roughness (for scatter) were measured. The samples were then subjected to current passing designed to simulate six month's use, and the properties were remeasured. The power levels were based on early design work with a maximum power level of 1kW over the mirror. Since then the requirement has increased to 2 kW and we are in process of making new tests at higher power levels. To date, the most severe current passing gave a heating density of 20 w/m^2 (equivalent to 1kW over the whole mirror), for 1 hour per 'night', for about 200 'nights'. We hope to report more recent results, with higher power levels, at the Conference.

We have tried a variety of coatings, substrates, and power levels, and detected no degradation of any optical property in any sample.

9. Test on 200mm thick sample of ULE™

We have conducted an experiment to verify that the proposed combination of resistive heating and radiative cooling can be used to control the temperature of the surface of a 200mm thick piece of ULE™.

A piece of ULE™, 200mm thick, coated with aluminum on the front, was subjected to surface heating by current passing through the coating on the front surface and to heat exchange with a radiative plate at the back surface. The results were predicted using a finite element model. The temperatures observed both under surface heating and when using the radiating plate both agreed with the predictions within about 10%. The differences were probably due to convection from the surface of the test-piece, which was not well controlled in the experiment. Importantly, the results confirmed that the emissive link

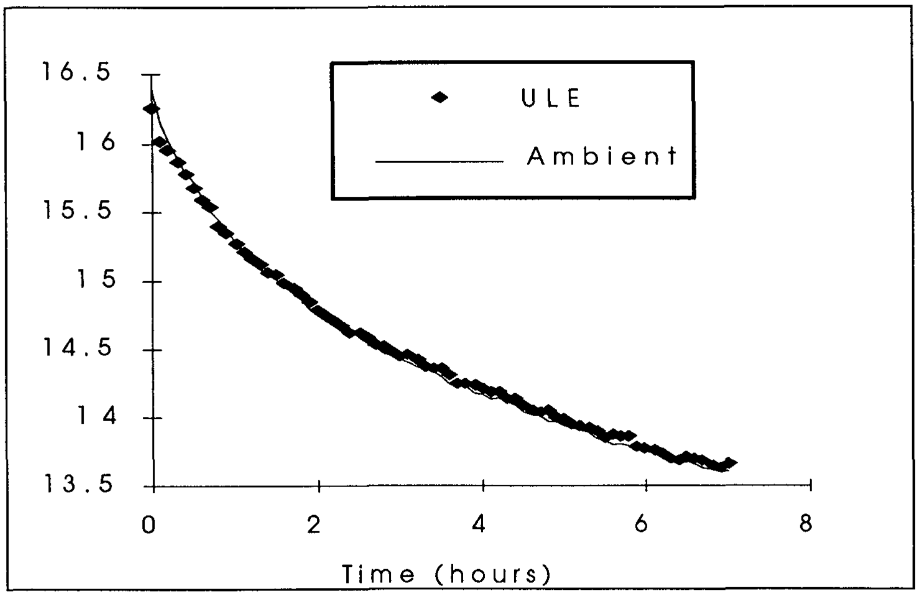


Figure 9. The results of our first attempt to control the temperature of a 200mm thick block of ULE using the techniques described here - radiating plates behind and current passing through a coating. Over a period of 7 hours, the mirror temperature matched the air temperature within about 0.05 degrees.

between the radiating panels and the ULE^{TM} is at least as good as we need (combined emissivity about 90%). When a simple control system was implemented with the aim of tracking the air temperature, it was able to match the temperature in a non-air-conditioned laboratory well within +/- 0.1 degrees over a 10 hour period (see figure 9)

10. Other areas considered

The study also considered several areas of importance to the realisation of a complete control system.

A set of temperature sensors are required. We propose to use platinum resistance thermometers (PRTs). High grade PRTs will give the required levels of differential and absolute accuracy without the need for special calibration.

There will be several sets of temperature monitors:

1. A set of monitors to detect the difference in temperature between the surface of the mirror and the air. It is expected that 12 pairs of sensors will be used.
2. A set of monitors to detect the temperature of the back of the mirror and of the radiating panels.
3. Some monitoring of the temperature of the material of the mirror cell, to verify the performance of the cooling systems for components inside the cell.

A dewpoint monitor will also be required.

A control system will be needed to drive the various components described above.

Separate cooling will be provided for other items inside the cell structure, such as the electronic crates for the local components of the control system and the power supplies for the heating system.

11. Conclusions

We have elected to control mirror seeing by controlling the temperature of the primary mirror. A study has been undertaken to show that the required levels of temperature control can be achieved. The mirror is homogenous, of uniform thickness, and made of ULE^{TM}, and the telescope features autofocus and active optics. Because of these features, we can introduce temperature gradients through the thickness of the mirror with effects on optical performance entirely within our error budget. That has enabled us to devise a strategy of controlling just the surface temperature of the mirror, without having to make the bulk of the material track every perturbation in ambient air temperature.

The key results of this work are:

- A system can be designed to control the temperature of the Gemini Primary Mirror. No 'show stoppers' have been found in either the proposed heating method or the radiating plate system.
- Using the radiating plates alone, the system will achieve the target temperature differences up to 75% of the time under realistic operating conditions.
- With the addition of the surface heaters, the system will perform within specification up to 95% of the time.
- A further benefit of the heating system is that it will enable control to be exercised over dewing.

12. Acknowledgements

This work has been a truly international collaboration, and we are pleased to be able to acknowledge the help of many colleagues in carrying it out. Our first recognition must be of Earl Pearson of the Gemini Project who originated the concept of surface heating by passing a current through the optical coating. We thank Martin Cullum and others in the ESO project for showing us their early theoretical results on radiating plates. We also thank the following for jointly carrying out the considerable amount of work required:

David Hagelbarger, for his early work on distribution of the electrodes;

staff at Rutherford Appleton Laboratory, and in particular D Sole, J Mills and R Carter for carrying out the experiments, NH Cunliffe, SK Chanda, M Brown, and A Pilling for thermal and electric field modelling, GP Warner for advise on thermometry, B Shaw for design work, and E Bateman and R Wade for early input on the practicality of the scheme;

staff at the Royal Greenwich Observatory and in particular David Jackson, for giving the project the benefit of his considerable expertise in the field of optical coatings, for putting evaporated coatings on the samples and for measuring emissivity and adhesion of the coatings often on a very short turnaround;

Myung Cho of the Gemini Project Office, for much of the modelling work on temperature gradient effects;

AG Electro-Optics, for measuring the surface roughness of the samples;

Balzers AG, for putting sputtered coatings on the samples;

David Walker of Optical Sciences Limited (OSL), University College, London, for the loan of the large glass blank.

The Gemini 8m Telescopes Project is managed by the Association of Universities for Research in Astronomy, for the National Science Foundation, under an international partnership agreement.

13. References

1. Oschman, J. "Gemini system Error budget plan Version 2.0" Gemini project report SPE-S-G0041, 1993

2. Lowne, C.M. "An investigation of the effects of mirror temperature upon telescope seeing" *Mon. Not. R. astr. Soc. (1979)* 188, 249-259

3. R. Racine, D. Salmon, D. Cowley and J. Sovka,"Mirror, dome, and natural seeing at CFHT" *Publications of the Astronomical Society of the Pacific* 103:1020-1032 September 1991

4. M. Iye, T. Noguchi, Y. Torii, Y. Mikami, Y. Yamashita, W. Tanaka, M. Tabata, and N. Itoh, "Active optics experiments with a 62cm thin mirror" *SPIE vol 1236 Advanced Technology Optical Telescopes IV (1990)* 929

5. L. D. Barr, J. Fox, G. A. Poczulp, and C. A. Roddier, "Seeing studies on a 1.8m mirror" *SPIE vol 1236 Advanced Technology Optical Telescopes IV (1990)* 492

6. M. Iye, T. Noguchi, Y. Torii, Y. Mikami, and H. Ando, "Evaluation of seeing on a 62-cm mirror," *Publications of the Astronomical Society of the Pacific* , vol. 103, pp. 712-722, 1991.

7. M Cullum "Primary mirror cooling simulations" VLT Technical report in preparation.

8. L. Zago, "The design of telescope enclosures for the VLT," Progress in Telescope and Instrumentation Technologies, ed. M.-H. Ulrich, ESO Conf. and Workshop Proc. No. 42, pp. 235-246, Garching, 1992.

9. Merrill, M. NOAO site survey. Draft of 86/12/08 page 6.1-19, table 6.1#11

10. Bely, P-Y. "Weather and seeing on Mauna Kea" *Publications of the Astronomical Society of the Pacific* 99:560-570 June 1987

11. F Murtagh et al. "Statistical Prediction of astronomical seeing and of telescope thermal environment." *Proceedings of ESO conference on progress in telescope instrumentation and technologies, April 1992*, page 37

12. RJS Greenhalgh, NH Cunliffe, J Mills, TB Shaw, D Sole, GP Warner, E Hansen, L Stepp "Design study and tests of a thermal management system for the primary mirrors of the Gemini Telescopes" Gemini project report RPT-RAL-G0036, 1993

13. M Cho, E Hansen, "Distortion of the Primary Mirror due to Temperature Nonuniformity" Gemini project report RPT-O-G0034, 1993

14. I Mikami, "Hexes pattern optimization method in ULE$^{\text{TM}}$ primary mirror blank" Subaru Telescope technical report number 19, October, 1992

15. LM Stepp, EW Huang, MK Cho "Gemini Primary Mirror support system" SPIE Vol 2199 *Advanced Technology Optical Telescopes* V (1994)

16. Hagelbarger, D. "A Proposed Modification to Pearson's Thermal Control Strategy." Gemini project memorandum.