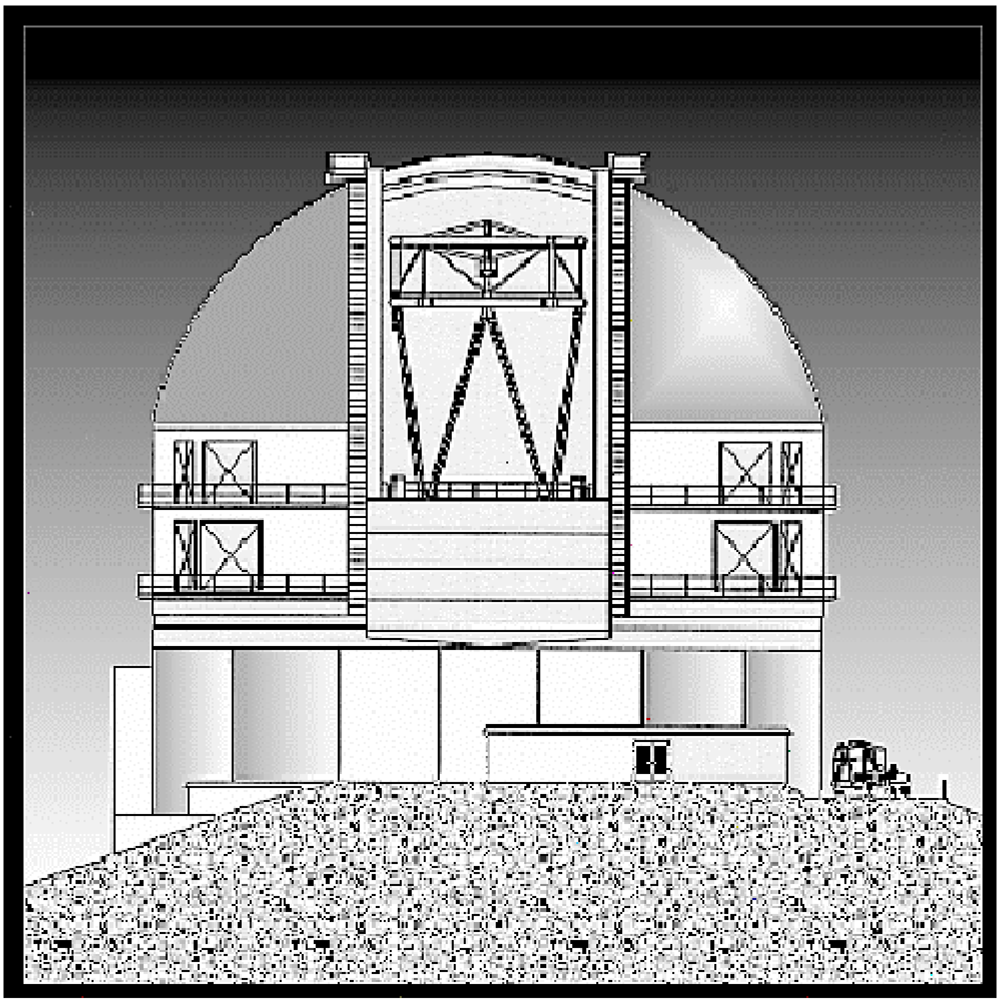
GEMINI
8-M Telescopes
Project

RPT-TE-G0033

# The Effect of Insulation on the Thermal Response Of the Floor and Basement Walls of the Gemini Enclosure

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# TABLE OF CONTENTS

## List of Figures



## List of Tables

# 1. Introduction

Thermal modeling was used to investigate how insulation installed in the basement walls and floor of the Gemini enclosure would affect:

- The formation of convective plumes on the outside of the basement walls;
- The ambient air water content (relative humidity) for which condensation would occur on the bottom of the enclosure chamber floor;
- The enclosure chamber air conditioning load;
- The chamber seeing.

The criteria above were evaluated at two different wind velocities (Mauna Kea):

- The 5th percentile value of the wind speed (0 m/s);
- The 70th percentile value of the wind speed (11 m/s).

Installed cost (labor and materials) for the insulation was estimated at US \$100/m$^2$.

# 2. Recommendations and Summary

## *2.1 Recommendations*

Option 4 (no insulation installed in floor or basement walls) should be selected. The consequences of selecting this option are:

- \$234,000 will be saved by not insulating the floor and the basement walls;
- The relative humidity of the ambient air can be as high as 80 % before condensation will form on the bottom of the chamber floor (the ceiling of the enclosure basement);
- Convective plumes will form on the basement walls the first 2 to 4 hours of the night depending on the windspeed: adding insulation in the basement walls will not completely alleviate plumes;
- The highest differential in average daytime air conditioning load is at the 5th percentile wind: here the average load (17.5 kW for the recommended option No. 4) will increase by 4 kW compared to option No. 3: enclosure with wall and floor insulation). The power cost for this additional load will amount to only several dollars per day;
- At the 5th percentile of the windspeed, the chamber seeing will increase an average of 5 to 8 milli-arcsecs over the first half of the night;
- At the 70th percentile of the windspeed the chamber seeing will not be affected.

### *2.2 Summary*

The two tables below summarize the results.

Table 1- Summary of Results for Model Run at the 5th Percentile of the Wind Speed

| Criteria | Option 1 Insul. basement walls only | Option 2 Insul. chamber floor only | Option 3 Insul. Basement walls and chamber floor | Option 4 No Insul. in basement walls chamber floor |
|---|---|---|---|---|
| *Prevent Free Convective Plumes* | Plumes first hour of night | Plumes first 4 hours of night | Plumes first hour of night | Plumes first 4 hours of night |
| *Max. rel. hum. of ambient air to cause condensation* | 70% | 77% | 88% | 88% |
| *Air Conditioning Load* | Peak=18.8 kW Ave.=15 kW | Peak = 18.3 kW Ave. = 14.2 kW | Peak = 17.5 kW Ave. = 13.8 kW | Peak = 23.3 kW Ave. = 17.5 kW |
| *Chamber Seeing (First half night)* | Peak = .045 " Ave. = .015" | Peak = .045" Ave. =.015” | Peak = .040" Ave. = .012" | Peak =.060" Ave. =.020” |
| *Installed Cost* | $144,000 | $90,000 | $234,000 | $0 |

Table 2- Summary of Results for Model Run at the 70th Percentile of the Wind Speed

| Criteria | Option 1 Insul. basement walls only | Option 2 Insul. chamber floor only | Option 3 Insul. Basement walls and chamber floor | Option 4 No Insul. in basement walls chamber floor |
|---|---|---|---|---|
| *Prevent Free Convective Plumes* | Plumes first hour of night | Plumes first 2 hours of night | Plumes first hour of night | Plumes first 2 hours of night |
| *Max. rel. hum. of ambient air to cause condensation* | 70% | 89% | 75% | 80% |
| *Air Conditioning Load* | Peak=32.5 kW | Peak = 31.0 kW | Peak = 31.0 kW | Peak = 35.0 kW |
| *Chamber Seeing (First half night)* | sub 0.005” | sub 0.005” | sub 0.005” | sub 0.005” |
| *Installed Cost* | $144,000 | $90,000 | $234,000 | $0 |

# 3. Why the temperatures of the basement wall and chamber floor are important

## *3.1 Convective plumes*

To minimize convective heat flow into the telescope lightpath, the temperature of structural surfaces near the lightpath must be as close as possible to the temperature of the ambient air. if the temperature of the basement wall of the enclosure is greater than the ambient air temperature at night, then convective plumes can rise up and be carried through the lightpath of the telescope, particularly during periods of very low ambient windspeed. Higher windspeeds will help to blow any plumes rising from the walls sideways and downstream well before they have a chance to enter the lightpath; the basement walls are below the height of the boundary layer.

This paper does not attempt to quantify the magnitude of seeing that would result from plumes rising up off the walls of the basement during low wind speeds.

The only way to prevent the formation of convective plumes of the basement wall during the nighttime hours is to force the wall to operate at a temperature lower than that of the ambient air. Previous modeling has shown that this may be accomplished by coating the walls with a high emissivity coating. The current modeling investigates how insulation installed on the inner surface of the walls affects the nighttime thermal performance of the wall.

## *3.2 Condensation*

If the temperature of the bottom surface of the chamber floor (basement ceiling) falls below the dewpoint temperature of the ambient air, then water will condense on the bottom of the floor.

The overall effects of this condensation are undesirable, as the water will:

- corrode structural elements composing the floor;
- increase the rate of heat transmission through any insulation placed on the bottom of the floor;
- drip into the basement.

The thermal model predicts the temperature of the bottom surface of the basement floor. The dewpoint temperature of the ambient air can be determined for different levels of moisture content (relative humidity) in the ambient air. Condensation on the floor bottom is predicted to occur when the dewpoint temperature equals the floor bottom temperature.

## 3.3 *Air conditioning load*

If the floor and basement walls of the enclosure are not insulated, the daytime air conditioning load will increase because more heat will be conducted into the chamber from the basement. The thermal model can find the amount of heat transmitted into the enclosure air during the daytime hours for different insulation configurations on the walls and floor.

### *3.4 Chamber Seeing*

The initial nighttime temperature of the chamber floor will be warmer for an enclosure without insulation installed in the basement walls and floor. The chamber floor is one of the surfaces convectively coupled to the chamber air. A warmer floor will transfer more energy into the chamber air, and the chamber seeing will be greater than that for an enclosure utilizing floor and basement wall insulation. The thermal model will show how chamber seeing is affected by installing insulation in the basement walls and enclosure floor.

The formula used for the determination of chamber seeing is: [Reference 1]

$$S_C=C_R(\Delta T)^{6/5} \tag{1-1}$$

where:
- $S_C$ chamber seeing, expressed as 50% encircled energy in arcsec (");
- $C_R$ seeing coefficient (0.15”/°C$^{6/5}$);
- $\Delta T$ temperature difference between the air inside the enclosure and the ambient air (°C)

## 4. Parameters used in the modeling

### *4.1 Ambient wind speed*

Model runs were performed at both the 5th and 70th percentile values of the wind velocity distribution (0 m/s and 11 m/s, respectively). The 70th percentile has been defined in the Gemini Science Requirements as the wind velocity up to which the enclosure seeing error budget of 0.030" must be met. [Reference 2]

At the 70th percentile value of the wind velocity, forced convection thermal linkages are defined the outer surface areas of the basement walls and the ambient air. At the 5th percentile value of the wind velocity, free convection linkages are defined between the basement walls of the enclosure and the ambient air. The free and forced convection correlations suggested by Woolf [Reference 3] were used in the modeling:

$$h_{FORCED} = 4\sqrt{v} \quad (\mathrm{W/m^2\,°C}) \tag{1-2}$$

$$h_{FREE} = 2(\Delta T)^{.25} \quad (\mathrm{W/m^2\,°C}) \tag{1-3}$$

where:
- $\sqrt{v}$ air velocity (m/s);
- $\Delta T$ temperature difference between the wall and the ambient air.

### *4.2 Ambient Air Temperature Profile*

To model the temperature of the ambient air, the modeling utilized a profile derived from data obtained from the UKIRT observatory weather tower. The temperature profile represents an average for the month of August. The profile is displayed on all of the temperature plots in the results (Section 6) of this report.

### *4.3 Insulation type and installed thickness*

Where insulation is utilized (walls or floor) in the modeling, it is assumed to be 75 mm of spray applied cellular urethane (R= 3.0 $m^2$-°C/W). Model runs utilizing basement insulation assume the insulation is applied only to the inside surface of the basement wall membranes, and does not cover the structural steel which supports the wall. When a model run utilizes insulation applied the chamber floor, the insulation is assumed to be spray applied to the bottom surface of the circular annulus that forms the lower membrane of the (ventilated) floor.

### *4.4 Air Condition*

All results assume that the chamber air of the enclosure is conditioned during the daytime hours such that the chamber air is I degree warmer than the minimum nighttime ambient air temperature.

### 4.5 *Flow links between the basement and floor*

To help remove heat from the basement, the model uses a flow link between the basement air and the air volume constrained in the flushing floor of the enclosure.

During the nighttime hours, one basement air volume per hour is drawn into the floor. The make up air source for this flow link is ambient air moving into a single louver located in the lower portion basement wall. The basement air enters the flushing floor of the enclosure at two louvers located in the bottom surface of the floor. The flow then proceeds into the ring plenum surrounding the floor, where it then proceeds to move out of the enclosure via the exhaust tunnel.

During the day, this ambient air to basement air to floor air flow link path is not defined. This is because a flow control damper in the riser plenum connecting the exhaust tunnel to the ring plenum surrounding the flushing floor is closed, and thus no basement air can be drawn up into the floor.

### *4.6 Radiative links from the basement walls to the sky and to the surface of the earth*

The basement walls will radiate energy to the sky and to the surface of the earth. The thermal model utilizes radiative thermal links to simulate this radiant energy exchange.

A value of 243 °K is used in the model for the effective sky temperature at Mauna Kea. There is no recorded data relating the variation of earth surface temperature with time at the locale of the summit ridge of Mauna Kea. The thermal model was used to determine this temperature variation.

Geophysical reconnaissance has shown that the wind has scoured all fine ash from the top layers of the cinder formations in the locale of the summit ridge [Reference 4]. The bulk thermophysical properties listed in Table 3 assume that the upper soil region at the site has a porosity of 50%, and that air fills all free voids. The thermal properties of red clay firebrick were used to model the solid soil particles representing the cinders.

Table 3- Bulk Thermophysical Properties Used to Model the Soil at Mauna Kea

| Density (kg/m$^2$) | Specific Heat (J/kg °C) | Thermal Conductivity (W/m °C) | Solar Absorp. (dimensionless) | Thermal Emiss. (dimensionless) |
|---|---|---|---|---|
| 1,162 | 960 | 0.3 | 0.63 | 0.9 |

To be consistent with the August average ambient air temperature profile used in the modeling, the solar flux applied to the top of the group of elements used to model the soil was for the same time period. The soil top element also has a radiative link to the sky with a view factor of unity. The magnitude of the convective link between the soil and the ambient air depends on the wind velocity.

Figure 1 shows the simulated soil top temperature at the 5th percentile (0 m/s) of the windspeed and Figure 2 shows the same information at the 70th percentile (11 m/s) of the windspeed.

- At the 5th percentile of the wind velocity, the model predicts that the top surface of the soil will be 40 degrees warmer than the ambient air at solar noon, and that the soil top temperature will drop 10 degrees below ambient at night;
- At the 70th percentile of the wind velocity, the model predicts that the top surface of the soil will equal the ambient air at solar noon, and that the soil top temperature will subcool 5 degrees below ambient at night.

To form the earth element used in the modeling, a very large planar element is formed at the base of the enclosure. Depending on what percentile value of the ambient windspeed is used for a model run, the temperature profile of either Figure 1 or 2 is assigned to this element. The element is assigned the radiative properties of the soil. Radiative links are then defined between this earth element and elements representing the basement walls of the enclosure.

### *4.7 Coatings used on the exterior of the basement walls*

All model runs utilize a high emissivity basement wall coating (enamel paint; e=0.90). To minimize daytime solar beating, the paint has a white pigment (solar absorptivity = 0.25).

# *5.* Economic Parameters

## *5.1 Installation options*

We estimate that the material and labor cost of installing the insulation on site is US $100.00/m^2$. This cost value includes the application of a fire retardant coating. There exist four options for installing the insulation. The following table summarizes the information.

Table 4 - Cost of Insulation Installation Options

| **Insulation Installation option** | **Where Insulation Installed** | **Installation Surface Area ($m^2$)** | **Total Installation Cost ($ US.)** |
|---|---|---|---|
| 1 | basement walls only | 1,440 | 144,000. |
| 2 | chamber floor only | 900 | 90,000. |
| 3 | basement walls & chamber floor | 2,340 | 234,000. |
| 4 | no insulation installed | 0 | 0 |

# 6. Results

## *6.1 The effect of insulation on the enclosure basement wall temperature and the enclosure basement air temperature.*

Results for the model run at the 5th percentile wind velocity are shown on Figures 3, 4, and 5. Figure 3 shows the basement wall temperature profiles for an enclosure with insulation installed against the inside of the basement wall surfaces (Option 1 & Option 3). Figure 4 shows the same information for an enclosure without basement wall insulation (Option 2 & Option 4). Both figures include the ambient air temperature profile. Basement air temperature profiles are included on the plots to help explain the results. Figure 5 shows the temperature differential between the west basement wall (the side last exposed to the sun) and the ambient air for an enclosure with insulation installed against the inside of the basement wall surfaces (Option 1 & Option 3), and for an enclosure without basement wall insulation (Option 2 & Option 4). Convective plumes will occur for positive temperature differentials. The information on Figures 3, 4, and 5 is summarized in Table 5.

Results for the model run at the 70th percentile wind velocity are shown on Figures 6, 7, and 8, and present information analogous to that previously presented on Figures 3, 4, and 5; the information is summarized in Table 6.

Table 5 --Results Table (5th Percentile wind) for Enclosure Basements; Walls With and Without Insulation. (H.S.T. = Hours Solar Time)

| Criteria | Enclosure w/ basement wall insulation (Option 1 & Option 3) | Enclosure w/o basement wall insulation (Option 2 & Option 4) |
|---|---|---|
| Basement air temperature maxima relative to ambient air temperature | Peaks at value equal to ambient air temp. 17:00 H.S.T. | Peaks at value 10 degrees above ambient air temp. at 15:00 H.S.T. |
| Basement air temperature minima relative to ambient air temperature | Equal to ambient air temp at 06:00 H.S.T. | 1.5 degrees below ambient air at 06:00 H.S.T. |
| Eastern basement wall temperature relative to ambient air temperature | Peaks at 20 degrees above ambient at 10:00 H.S.T. | Peaks at 12 degrees above ambient at 12:00 H.S.T. |
| Western basement wall temperature relative to ambient air temperature | Peaks at 21 degrees above ambient at 15:00 H.S.T. | Peaks at 16 degrees above ambient at 15:00 H.S.T. |
| Total time period west wall is cooler than the ambient air | 11 nighttime hours | 8 nighttime hours |

Table 6 --Results Table (70th Percentile wind) for Enclosure Basements; Walls With and Without Insulation. (H.S.T. = Hours Solar Time)

| Criteria | Enclosure w/ basement wall insulation (Option 1 & Option 3) | Enclosure w/o basement wall insulation (Option 2 & Option 4) |
|---|---|---|
| Basement air temperature maxima relative to ambient air temperature | Peaks at value equal to ambient air temp. 17:00 H.S.T. | Peaks at value 1 degree above ambient air temp. at 17:00 H.S.T. |
| Basement air temperature minima relative to ambient air temperature | Equal to ambient air temp at 06:00 H.S.T. | Equal to ambient air temp at 06:00 H.S.T. |
| Eastern basement wall temperature relative to ambient air temperature | Peaks at 4 degrees above ambient at 10:00 H.S.T. | Peaks at 2.5 degrees above ambient at 10:00 H.S.T. |
| Western basement wall temperature relative to ambient air temperature | Peaks at 6 degrees above ambient at 16:00 H.S.T. | Peaks at 4.5 degrees above ambient at 16:00 H.S.T. |
| Total time period west wall is cooler than the ambient | 11 nighttime hours | 10 nighttime hours |

| | | |
|---|---|---|
| air | | |

Conclusions:

- basement wall insulation decreases basement air temperature;
- insulated walls are cooler at night because the insulation decreases the amount of power convected into the walls from the basement air at night;
- at the 5th percentile of the windspeed, the West basement wall of an enclosure with uninsulated walls will subcool below the nighttime ambient air temperature two hours later than the West basement wall of an enclosure with insulated basement walls;
- at the 70th percentile of the windspeed, the West basement wall of an enclosure with uninsulated walls will subcool one hour later than the West basement wall of an enclosure with insulated basement walls.

### *6.2 The effect of insulation on the temperature of the chamber floor.*

Model runs were performed to investigate the thermal behavior of the chamber floor for the four different insulation installation options at the two different windspeeds.

All of the subsequent temperature plots include the dewpoint temperature of the ambient air. For these plots, the relative humidity of the ambient air was increased in the model post processing software until the dewpoint temperature of the air became equal to the bottom surface of the chamber floor.

Regardless of whether insulation is used in the basement walls and floor of the enclosure, the following results (together with the results of the previous section) show that the basement air temperature can be warmer than the ambient air temperature at night. However, it is not possible for this warm air to rise up into the enclosure chamber, *because it will be interrupted by the flushing floor and drawn away into the exhaust tunnel.* Thus the flushing floor serves as an infiltration barrier, and the basement air temperature is not considered a selection criterion for the installation of insulation in the walls or floor of the enclosure.

Figures 9, 10, 11 and 12 show the results of model runs at the 5th percentile wind for insulation installation options 1, 2, 3 and 4, respectively. The results are summarized in Table 7. Figures 13, 14, 15 and 16 show the results of model runs at the 70th percentile wind for insulation installation options 1, 2, 3 and 4, respectively; these results are summarized in Table 8.

Table 7 – Results Table (5th percentile wind) Enclosure Floors (With and Without Insulation) in enclosure with and without basement wall insulation

| Criteria | Option 1 Insul. in basement walls only | Option 2 Insul. in chamber floor only | Option 3 Insul. in basement walls and chamber floor | Option 4 No insul. in basement walls or chamber floor |
|---|---|---|---|---|
| Floor top temperature relative to ambient air temp. | Below ambient last 5 hours of night | Below ambient last 8 hours of the night | Below ambient last 7 hours of the night | Below ambient last 6 hours of the night |
| Max rel. hum. of ambient air to cause condensation on floor bottom | 70% | 77% | 88% | 88% |

Table 8 – Results Table (70th percentile wind) Enclosure Floors (With and Without Insulation) in enclosure with and without basement wall insulation

| Criteria | Option 1 Insul. in basement walls only | Option 2 Insul. in chamber floor only | Option 3 Insul. in basement walls and chamber floor | Option 4 No insul. in basement walls or chamber floor |
|---|---|---|---|---|
| Floor top temperature relative to ambient air temp. | Below ambient last 8 hours of night | Below ambient last 9 hours of the night | Below ambient last 9 hours of the night | Below ambient last 7 hours of the night |
| Max rel. hum. of ambient air to cause condensation on floor bottom | 70% | 89% | 75% | 80% |

Conclusions:

- insulation applied to the bottom of the chamber floor (option 2 or option 3) results in a lower daytime floor top temperature, which results in the floor subcooling sooner during the nighttime hours;
- regardless of the windspeed, the lowest observed value for maximum relative humidity (70%) occurs when insulation is applied to the basement walls (option 1);

- at the 5th percentile of the windspeed, the highest value (88%) for maximum relative humidity occurs when the walls and floor are both insulated (option 3) or both uninsulated (option 4),
- at the 70th percentile wind, the highest value for maximum relative humidity (89 %) occurs when only the floor is insulated (option 2). Removing the floor insulation (option 4) reduces the maximum relative humidity level by only 9%.

### *6.3 The effect of insulation on the magnitude of the da3iime air conditioning load.*

Figure 17 shows the variation in air conditioning load for the four insulation options for the 5th percentile wind. Figure 18 shows the a.c. loads for the option at the 70th percentile wind. The air conditioning load is defined as the power removed from the chamber air by the enclosure air conditioning system. The chamber wall, chamber floor, telescope mount, top end, and truss are all connected to the chamber air element with convective linkages. An active source power level is set at 8.5 kW to represent the heat being dissipated by electronics packages, lights, etc. In addition, at the 70th percentile wind, an infiltration load is defined for the air conditioning system; one enclosure volume per hour of ambient air is being forced into the enclosure air volume over the daytime hours. For the model run at the 5th percentile of the wind (0 m/s), the infiltration load is zero. The total air conditioning system capacity is 100 kW, similar to the Keck enclosures.

<u>Conclusions:</u>

- the peak load observed (35 kW) is at the 70th percentile wind velocity;
- the 70th percentile loads are higher (by an average of 15 kW) than the 5th percentile loads because of the infiltration load;
- the 100 kW capacity air conditioning system has excess capacity;
- this excess capacity can be used to condition the chamber air to even lower daytime temperatures should this be necessary;
- at the 70th percentile wind, the air conditioning load does not vary appreciably, regardless of the insulation option: the peak load for the options occurs two hours after solar noon and averages about 32.5 kW;
- at the 5th percentile wind, the air conditioning load profiles for options 1, 2, and 3 are very similar: the loads ramp up in linear fashion from about 6 kW at 07:00 to peak at 17.5 kW at 17:00;
- at the 5th percentile wind, option 4 will result in the highest peak load (23.3 kW) and the highest average load;
- the cost of this additional load can be computed as follows:

At Mauna Kea, the cost of electrical energy is $0.12/kW-hr. Assuming a 12 hour daytime air conditioning period, and a coefficient of performance for the air conditioning system of 3.0, then the daily cost of an additional 4 kW a.c. load is only several dollars.

### *6.4 The effect of insulation on the magnitude of the nighttime chamber seeing.*

Figure 19 presents chamber seeing values for the four options at the 5th percentile value of the wind velocity. Figure 20 presents the same information for the 70th percentile value of the wind. Model runs for the 5th percentile wind speed utilize a nighttime enclosure chamber ventilation rate (fan forced) of 10 chamber volumes per hour. For model runs at the 70th percentile of the ambient windspeed, the model uses a larger infiltration flow link (equal to 60 enclosure volumes of ambient air per hour) between the ambient air and the chamber air. (The magnitude of this flow link was derived from water tunnel test data, [Reference 5] and represents the passive flushing volumetric flow rate we would expect while the telescope is in the observing mode and the flushing vent doors are fully open.)

Conclusions:

- at the 5th percentile wind, seeing values for the options differ only slightly during the first half of the night and average 0.01 5 arcsecs: the last half of the night the seeing for all options is indistinguishable and averages 0.005 arcsecs.
- at the 70th percentile wind, the seeing is always below 0.005 arsecs over the nighttime hours because of the amount of air being forced into the chamber;

## 7. References


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2. Osmer, P.S., "Gemini Science Requirements", Gemini Project Document SPE-PS-G0001, November 1992.
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5. R. Ford, P. Gillett, S. Hardash, G. Pentland, K. Raybould, "Gemini 8M Enclosure, Support Facility and Site Plan Preliminary Design Review", Gemini Project Document No. RPT-TE-G0015, May 1993.

# FIGURES

(Figures can be found in the hard copy.)