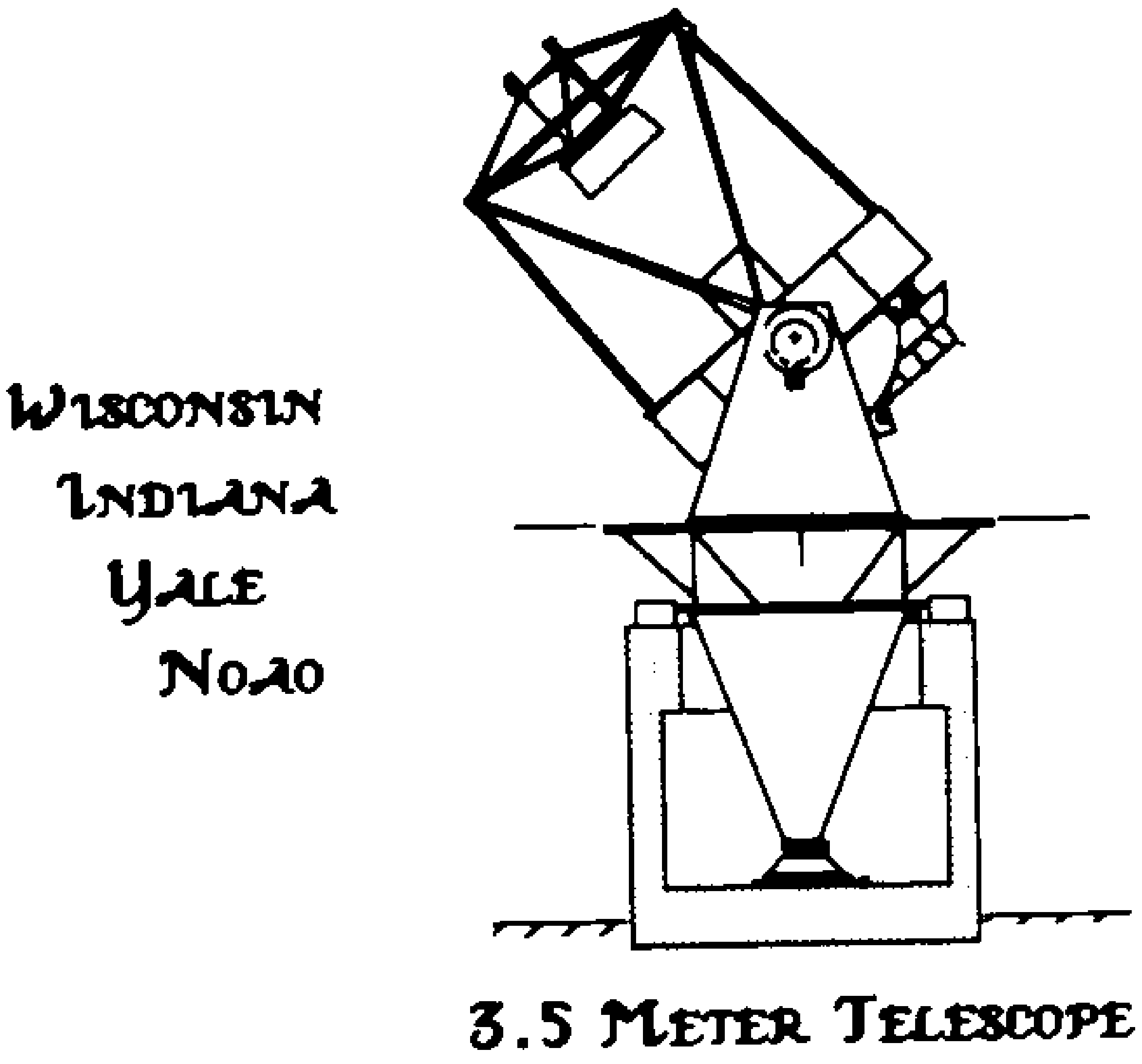

Enclosure Thermal Design for the WIYN 3.5 Meter Telescope

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1. Purpose and Scope

This document describes the thermal design of the WIYN 3.5-M enclosure.

2. General Description

The WIYN Observatory consists of two connected buildings: the telescope enclosure and control building.

The telescope enclosure houses the 3.5 m telescope and provides space for activities directly associated with the telescope operation. The building concept has three stories with the telescope imbedded in the center of the building and spanning the three floors. The rotating roof (hereafter referred to as "the dome") opens up to allow the telescope to view all parts of the sky.

The enclosure uses steel construction for the walls and supporting structure keeping the building weight and thermal inertia low for good thermal performance.

The concept for the WIYN dome was adapted from the enclosure design for the proposed Magellan 8 m telescope[1]. The design provides a lightweight, thermally optimized structure by using space frame techniques. The shape approximates the traditional hemispherical dome but uses flat panels for ease of fabrication and low cost.

The dome has an uninsulated internal frame of square structural tubing to support the skin and shutters. Additional girts and bracing are included as necessary. The skin is be fabricated from commercially available insulated panels with a maximum U-value of 0.05. The estimated rotating weight of the dome is 70,000 lbs. The outer surface is covered with a low emissivity tape to eliminate nighttime over-cooling of the surface as a result of radiation to the sky. The frame and inner surface of the skins are painted.

A pair of laterally parting shutters open up during observing to provide a 14' wide slot for viewing. Each shutter is made up of three joined panels

Seven large remotely operated motorized windows are incorporated into the vertical side walls of the dome to provide openings for air to flush the telescope chamber.

The dome design incorporates seals in the following areas to prevent the infiltration of rain and snow:

- Brush seal at the interface of the stationary building and the dome.
- Inflatable or P-seals between the shutter panels.
- Inflatable or sliding seals around the shutter panels.
- As required for the windows.

The top floor of the building, the observing floor, provides access to the telescope OSS and instrument area. It is reached by an enclosed stairway

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[1] L&F Industries, "Octagonal an Dome Enclosures", Magellan Report No. 4, 1989.

from the intermediate level. A door at the bottom of the stairway prevents air exchange with the lower levels. The area above the floor, the telescope chamber, is exposed to the outside environment when the shutters are open and is unconditioned. The observing floor is plywood over corrugated metal decking which provides low thermal mass and conductivity. The floor is covered with sheet vinyl. Rigid insulation is attached to the under side of the floor.

The lower, stationary, portion of the enclosure surrounds the telescope and pier and provides a base for the dome. The steel structure of the base is uninsulated and exposed to the inside air. The exterior walls are constructed from sandwich panels insulated at a minimum to the same U-value as the dome. The exterior surface is painted.

The ground floor has space for equipment storage and a well insulated, unheated, spectrograph room. Except for the spectrograph room, the two lower floors will be maintained close to the outside temperature at night. The spectrograph room is allowed to find its own temperature without active controls.

The second floor is constructed with the same materials as the observing floor but is uninsulated. A large opening in the first floor allows a free flow of air between the lower levels. The concrete floor and telescope pier are uninsulated.

Air is drawn through the enclosure base to force the inside temperature to follow the air temperature in the telescope chamber. The air pressure in the base is maintained slightly below the pressure in the telescope chamber to insure a downward flow of air and prevent warm air from escaping upward into the telescope chamber.

Make-up air enters at the mezzanine level through vents in the observing floor and through a wall vent at ground level.

The control building contains all the heated spaces of the observatory. Conditioned areas are provided for an instrument lab, computer room, and telescope control room. Waste heat produced by the control building is released away from the enclosure. The steps taken to ensure this are:

- The control building walls and roof are heavily insulated.
- Potential air leaks are sealed.
- Waste heat from air conditioning and cooling equipment is collected and vented away from the enclosure.
- A thermal buffer space is provided between the control building and enclosure.

The parking lot will be paved with a chip and seal layer over asphalt base.

3. Ventilation

The telescope enclosure is provided with three ventilation systems for controlling the temperature in the building. One is passive and relies on the natural action of the wind to force air through the telescope chamber. The other two systems use blowers to draw air through the telescope and lower floors of the enclosure. The air is exhausted approximately 35 m to the northeast at a fan house downwind from the enclosure in the prevailing wind direction.

3.1 Dome Vents

Seven large vents are provided in the vertical walls of the rotating dome. Each has a clear area of about 10 m^2 when fully opened. The shutter gives an additional 75 m^2 opening for ventilation. All combined they represent about 24% of the surface area of the dome.

The shutter and vents will normally be open for observing. During times of high wind, the vents may be individually closed to reduce the flow. With all the vents closed, ventilation is provided primarily through the shutter with additional air being drawn through the telescope chamber to provide make-up air for the fan-forced systems described below.

Water tunnel tests using an acrylic scale model of the WIYN enclosure were conducted at the University of Washington Department of Aeronautics (Siegmund[1],) to test the flushing of the telescope chamber. Dye was injected into the telescope chamber of the transparent model and the time for the dye to completely clear was recorded. Tests were run with a flow velocity corresponding to 5.3 m/s when scaled up to the actual building. The model was rotated about its vertical axis to change its orientation with respect to the flow.

Two series of tests were conducted: One series of the model with vents representative of the proposed WIYN design and the second with additional vents provided in the sloping upper panels of the dome. The lower vents were represented by four small openings with a combined scale area slightly less than than is actually planned. Only the results from the first series are described here.

No attempt was made to measure the optical density looking through the dye to get the 1/e time to clear. In general the dye appeared well mixed with the incoming flow and so it is likely that more than one volume change occurs during the time it takes to clear.

A venturi action causes the flow to speed up coming in through the upstream vents.

There were clear differences in the effectiveness of the flushing for different orientations of the enclosure with respect to the flow. The ventilation is most effective with the dome pointing into the wind. The time to completely clear in this configuration averaged 0.4 minutes. With the dome pointed away from the flow, the time increased to 0.9 minutes.

In the worst case orientation with the shutter pointed downwind, air enters only through the three vents on the upwind walls. The combined effective area of these vents is $(2.4 \times 10) = 24$ m^2. Assuming a wind velocity of 5.3 m/s, the volume of air flowing into the enclosure (not assuming speed-up) is 127 m^3/s (267,000 cfm). Since the volume of the telescope chamber is approximately 1300 m^3, this produces a volume change every 10 seconds or 360 changes per hour! Some reduction in the flow may be expected if louvers are installed in the vents for directing the air into the corners of the octagon.

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[1] W. A. Siegmund, "Report on Flow Visualization of the WIYN Telescope Enclosure Design", 1990

The rate of heat extraction from the air exchange is given by:

$$P_V = C_a \, \Delta T \, \frac{dV}{dt}$$

where Ca = 1.0×10^3 Jm^{-3} is the volume heat capacity of air, V is the volume of air exchanged, and ΔT is the temperature difference between the incoming and exiting air. With an air flow of 127 m^3/s, heat is extracted at 127 kW/°C . The average temperature rise in the air is 0.008°C per kilowatt of dissipated heat.

While this airflow might seem like overkill from the standpoint of heat transport, keeping the flow rates high through the structure will lower the thermal relaxation time of the telescope and dome for the reason that (1) the temperature of the air in contact with the surfaces will be closer to the outside temperature and (2) the heat transfer coefficients at the surface will be greater with more air moving over the surface. High flow rates will also rapidly sweep hot air bubbles out of the telescope beam.

3.2 Enclosure Base Ventilation System

The stationary enclosure base is ventilated with a blower that draws air through the lower two floors. Make-up air enters through registers in the observing floor, upper stairway and around the base near ground level. The louvers around the ground floor are operable to control the air intake at this level. Additional air is drawn down through gaps around the hatches and other equipment that penetrate the floor including the telescope. The system will perform the following functions:

- Extract waste heat from structure and equipment located on the lower floors.
- Extract heat from the around the dome ring beam.
- Remove heat from the dome rotation motors.
- Extract heat stored in the lower building structure.
- Prevent hot air bubbles from rising into the telescope chamber.

The system will have a capacity of 6000 cfm at 1/8" SP. Excluding the pier and spectrograph lab, the ventilated volume is 734 m^3 for a rate of air exchange of 13.8 building volumes per hour. This flow of air will extract 2.7 kW per 1°C temperature rise.

The exhaust air is carried away from the telescope enclosure in a duct that terminates at the fan house, approximately 120' from the center of the enclosure.

Since most of the make-up air comes through registers in the observing floor, the base ventilation system provides additional ventilation for the telescope chamber during rare times of dead calm wind.

3.3 Telescope & Equipment Ventilation System

A high pressure ventilation system is provided for the telescope and attached instrumentation. Air is drawn through the telescope structure into a plenum formed by the telescope pier. From there it is ducted away from the building. A rotating seal is provided between the telescope and pier just below the azimuth drive disk to prevent air intake from the lower levels of the enclosure.

Make-up air will enter the mount structure through vent holes distributed over the surface of the telescope. Ducting is provided to connect instruments to the system. The system will perform the following functions:

- Remove heat stored in the telescope structure & promote cooling.
- Extract waste heat from instrumentation & electrical equipment.
- Prevent hot air from rising up inside the fork assembly.

The system will have a capacity of 5000 cfm at 1" SP and extract 2.2 kW per 1°C temperature rise. The air will be daylighted at the fan house. Like the Enclosure Base Ventilation system, this system will provide additional ventilation for the telescope chamber.

3.4 Control Building

All heated space in the observatory is located in the control building. A buffer space (the "vestibule" and mechanical rooms) between the control building and the telescope enclosure is unheated and actively ventilated. The exhaust air is ducted away from the enclosure and released at the remote fan house. Building heating and air conditioning systems that operate at night will use the same duct for their exhaust.

The walls and roof of the control building are heavily insulated.

4. Thermal Balance of the Telescope Chamber

Heat loads in the telescope chamber may arise from (1) stored heat in structures, (2) conduction from outside the chamber, (3) radiation, and (4) active sources such as electrical equipment. For the present we neglect convective processes.

The thermal environment of the telescope is continually changing in response to random changes in the many external variables that affect the system. To investigate the thermal balance between sources of heating and cooling, we assume an idealized steady model of the telescope chamber where the rate of temperature change is held constant and we look at the heat flow on time scales longer than the thermal relaxation times of the telescope and dome.

4.1 Passive cooling.

The steady state heat load into the telescope chamber from parts of the telescope and enclosure cooling at a uniform rate is given by:

$$P_T = \alpha \, C_T \, M \frac{dT}{dt}$$

where C_T is the heat capacity, M the mass and T the temperature. α is the fraction of the structure mass that couples into the telescope chamber.

The total rotating mass of the telescope is 36,400 kg. Approximately 11,500 kg of that is below the floor level and is ventilated by the telescope and enclosure ventilation systems. The primary mirror and cell weldment, with a combined mass of 5,700 kg, have their own thermal control system that will extract approximately half of the heat given off by them. The mass that will release heat at the observing floor level is (36,400 - 11,500 - 5,700/2) = 22,000 kg.

The rotating dome extends down to the level of the observing floor. The total mass of the dome is 32,000 kg. Insulated sandwich panels weighing 4,800 kg make up the skin of the dome. The panels have steel sheet metal faces separated by 50 mm of insulating foam. The mass is evenly distributed between the inner and outer surfaces. The outer surface contributes a negligible amount to the telescope chamber heat load.

The observing floor is constructed of 31 mm thick plywood with rigid insulation on the bottom side. The floor releases all of its stored heat to the telescope chamber.

Table 1. Heat released from passive cooling @ 1.0°C/hr.

Structure	Material	Mass (kg)	α	Heat (kW)
Telescope	Steel	36,400	0.6	2.7
Dome	Steel	32,000	0.9	3.4
Floor	Plywood	3,000	1.0	2.0
Total:				8.1

Table 1 lists the amount of stored heat released into the telescope chamber per 1°C of temperature change per hour. α is the fraction of the mass that releases its heat directly into the chamber.

4.2 Heat conduction

Heat is conducted into the telescope chamber through (1) the dome skin, (2) the observing floor, and (3) by equipment that pierces the observing floor including the telescope. The amount of heat is given by:

$$P_C = \frac{A \, k_C}{l} \Delta T$$

where A is the cross sectional area, k_C the thermal conductivity, l the plate thickness, and ΔT the temperature difference across it. We assume, for the purpose of this discussion, that the temperature inside the dome closely matches the outside air temperature.

The dome is covered with a sandwich panel of steel skins separated by 50 mm of insulating foam with a conductivity of 0.04 W/m°C. The skin has a surface area of 613 m^2. It is covered with a self-adhesive, mylarized aluminum tape made by 3M[1]. The total heat conducted is 490W/°C or 0.8 W/m^2-°C. The amount of heat conducted to the dome air is reduced by the thermal resistance between the inside surface of the skin and the air. We get $P_c = 423$ W/°C assuming a heat transfer coefficient to air of 5 W/m^2-°C where ΔT is now the difference between the outer skin temperature and air temperature in the dome.

Measurements of the temperature difference that develops between the exterior surface and the ambient air have been made at the MMT[2] using panels similar to those planned for WIYN. The panels were covered with 3M tape and mounted outdoors face upwards exposed to the sky. At night with a 10 mph wind the panels cooled 0.28°C below the nighttime air temperature from radiation to the cold sky. Solar heating warmed the panel top to 11°C above the air temperature at noon with the same 10 mph wind.

When open, the shutters part laterally and block approximately 78 m^2 from seeing the sky. In addition the sloping and vertical panels of the dome have only a partial view of the sky and their cooling is less. Even if the entire surface were cooler than the inside by 0.28°C, the nighttime heat loss through the skin would be only 137W. We conclude that conduction through the skin may be ignored at night.

During the day, the outside skin temperature will peak at around 15°C ±4°C above the nighttime value due to the diurnal variation and solar heating the of the dome. This will impose a heat load in the telescope chamber which will have to be removed at the time or later in the afternoon and early evening in the form of stored heat in the telescope and enclosure structure.

Conduction through the observing floor depends on the relative temperatures above and below. The structural steel, concrete pier and concrete floor in the enclosure base provide large uninsulated masses that will tend to stabilize the temperature. The perimeter wall is insulated with 50 mm of polystyrene and there are no heated spaces during normal operation. Sources of heating will include conduction through the walls and observing floor, air infiltration through doors, etc., and electrical equipment. At night the enclosure base is ventilated. In addition there are night to night variations in the outside temperature that are reflected in the temperature difference between the telescope chamber and second floor. Heating from electrical equipment including lighting will average around 3 kW. As a result, the temperature is expected to stay relatively constant throughout the day.

It will usually be the case that the enclosure base will be warmer at night than the telescope chamber. We estimate that with the ventilation fans running the average air temperature difference will be 4°C ± 3°C RMS including night to night variations in the outside air temperature. The observing floor and skirt around the telescope is insulated to a similar degree and may be lumped together for calculating the conduction. The floor is constructed of 31 mm of plywood with a conductivity of 0.12 W/m°C over 50 mm of polystyrene with a conductivity of 0.04. Heat is conducted at

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[1] 3M Catalog No. 427 Aluminum tape.

[2] J. M. Beckers and B. L. Ulich, MMTO Technical Memorandum No. 81-1, 1981.

a rate of 0.5 W/m^2-°C including the effects of the two air-surface boundaries. The effective area is 175 m^2.

Table 2. Heat Conducted into Telescope Chamber at Night

Through	Area (m^2)	ΔT (°C)	HTC (W/m^2-°C)	Heat (W)
Dome	613	-0.28	0.8	-137
Floor	175	7.0	0.5	613
Total:				476

Table 2 lists the identified contributions to heat conducted into the observing chamber at night with the assumptions shown. Careful attention to the detailed design of the observing floor and telescope is necessary to eliminate thermal bridges from the enclosure base below conducting heat in parallel to the floor. This is particularly true around the telescope skirt and floor hatches.

4.3 Radiational cooling

At night, heat is removed from the telescope chamber by radiation through the shutter. The opening is 4.2 m wide and made up of three 6 m long sections that follow the contour of the octagon structure. The lower sections have partial views of both the sky and ground. The upper section only sees the sky. We estimate the effective area of the opening to be 55 m^2 and assume the radiation loss is 100W/m^2.

The top end of the telescope and the structure just inside the shutter will tend to cool more due to their greater exposure to the sky. The upper end of the Optical Support Assembly is covered with 3M tape to lower its emissivity.

4.4 Active heat sources

Active sources of heat include the telescope and dome electrical equipment, science instruments, and lighting. There are no heated spaces in the telescope enclosure.

Active heat sources around the telescope may be particularly troublesome if they produce localized hot spots that find their way into the telescope beam. Ducts connecting into the telescope ventilation system are provided for the elevation drive motors and electronics, the instrument rotators, other miscellaneous controllers, and science instruments.

4.5 Heat balance

The heat balance in the telescope chamber is dominated by passive cooling of the telescope and dome structure, radiation losses through the shutter opening, and wind forced ventilation through the shutter and vents. In this section we begin by looking at all sources of heat gain (or loss) except wind forced ventilation. We sum up the contributions and what is left is taken care of by the natural ventilation.

Table 3. Electrical heat sources.

	Peak (W)	Average Released (W)
Telescope chamber:		
Primary Mirror supports	200	125
Primary mirror thermal	1,000	100
Secondary Mirror axial	50	10
Secondary mirror vacuum	60	60
Elevation drives (n)	700	100
Instrument rotators (n)	100	100
Other controllers	200	200
Science instruments	500	500
Lighting (d)	1,200	600
Days:	3,210	1,595
Nights:	2,810	1,195
Enclosure base:		
Dome drives (n)	4,500	1,000
Azimuth drives (n)	700	100
Science Instruments	500	500
Lighting (d)	2,400	1,200
Totals:	8,100	2,800

(n): nighttime only (d): daytime only

To estimate the stored heat released by the telescope and dome, we assume the ambient air has been changing temperature at a steady rate long enough so that the internal temperatures of the structures have had time to adjust themselves and produce the same rate of temperature change in the structure. Once this is the case, the heat gained (or lost) is easily obtained from the results of section 4.1. The question of how long we must wait for this to be true is considered in section 5.

The day-to-night temperature variations at the WIYN site are typically 11°C ± 4°C. Most of this occurs during the day with the greatest temperature swings occurring shortly after sunrise and shortly before sunset. The average rate of temperature change during the 10 hours from 8 pm to 6 am civil time measured on 61 randomly selected nights in 1986-1989 was 0.27°C/hr. On some nights fairly rapid ($t_{char} = 1$ hr.) temperature fluctuations (both positive and negative) were present. The characteristic rate of change of these fluctuations was approximately 0.5°C/hr. In the analysis that follows we adopt 0.25°C/hr for the nighttime rate of temperature decline to be consistent with the estimates of others. The air temperature rise in the forced ventilation systems from heat removed from the telescope chamber is assumed to be 0.5°C.

If we take the results of section 3.1 and ask what is the average temperature rise of the telescope chamber air with an exchange rate 127 m^2/sec under the conditions of Table 4, we get:

$$\Delta T = (0.008) \times (-3.6)$$

$$= -2.9\ \mathrm{e}{-2}\ ^\circ\mathrm{C}.$$

Table 4. Telescope Chamber Heat Budget

Sources:	Heat Gain (kW)	Conditions
Passive Cooling	2.0	$dT/dt = -0.25$°C/hr.
Active sources	1.2	Nighttime average.
Conduction	0.5	
Total gain:	3.7	
Cooling:	Heat Loss (kW)	
Radiation	5.5	
Telescope ventilation	1.1	6000 cfm, $\Delta T = 0.5$°C.
Enclosure ventilation	0.7	4000 cfm, $\Delta T = 0.5$°C.
Total loss:	7.3	
Balance:	-3.6	(Loss)

The degradation of the image size from "dome seeing" has variously been estimated[1,2,3] at 0.1 - 0.6 arcsecond per degree difference in the inside and outside air temperatures. The error budget for dome seeing is 0.15 arcsecond so we must maintain a temperature difference less than about 0.4°C. These results are well within that goal.

5. Cooling Times

We assumed above that we could investigate the thermal behavior of telescope chamber with a steady state model looking only at the heat balance for time scales longer than the thermal relaxation times. The thermal relaxation time for a structure in contact with the air is given by Cheng[4]:

$$\tau = \frac{l\ C\ \rho}{h_a}$$

where l is the characteristic length, C the heat capacity, ρ the density and h_a the heat transfer coefficient from the surface to air. Under the conditions in the dome, h_a should fall in the range 5-10 W/m-°C.

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[1] C. E. Coulman, J.-C. Andre, P. Lucamese, P. Gillingham, PASP 98, 1986.

[2] R. Le Poole, "Minimizing the Man-made Deterioration of the Seeing at the 3.6-m Telescope at La Silla", 1990.

[3] N. Woolf, "Dome Seeing",PASP 91, 1979.

[4] A. Cheng, Doctoral Thesis, U. of Arizona, .

Dome skin	0.9	0.09	0.17
Dome structure	7.9	0.75	1.51
Telescope	12.7	1.21	2.42
Floor			

Cheng also gives the steady state temperature difference of the surface in terms of the thermal time constant:

$$\Delta T = \tau \frac{dT}{dt}.$$

Table 5b gives surface temperatures relative to the air temperature for two sets of observing conditions at the observatory believed to represent "favorable" and "less favorable" conditions. The temperature differences include only the effects of convective cooling. In particular, radiation losses are important and need to be included in a more detailed model.

Table 5b. Surface temperatures (T_s - T_a), (°C).

h_a (W/m^2-°C) =	10.0	5.0
dT/dt (°C/hr) =	0.25	0.50
Dome skin	0.02	0.09
Dome structure	0.38	0.75
Telescope	0.61	1.21
Floor	0.61	1.21

6. Summary

The WIYN enclosure is a low mass, very well ventilated structure with well controlled heat sources in the telescope chamber. The dome will equilibrate rapidly and track the night temperature to within a degree through most of the night. Except under rare conditions where the wind is dead calm, the average air temperature in the telescope chamber will track the incoming air to better than 0.3°C, the goal set by the imaging error budget for dome seeing.

Possible improvements to the design include reducing heat build-up during the day, reducing the thermal time constant of the telescope and better control over radiation losses.