Development and testing of an unique telescope enclosure design, optimized for seeing and telescope thermal control

Robert Brunswick
EOS Space Systems Pty Limited, 55A Monaro St, Queanbeyan, NSW 2620, Australia

ABSTRACT

To realize the full performance potential of the new generation of ground based telescopes, whether optical or IR, enclosure seeing control and telescope temperature control must be optimized. While the techniques for optimizing seeing are well known, EOS' IceStorm Enclosures, specifically developed for interferometric applications, introduced a number of novel physical implementations of these known techniques.

A 9.5m prototype IceStorm enclosure was assembled and extensively tested in 2002, including independent testing of thermal performance. Four enclosures have since been completed, one of which was installed at the EOS Space Center on Mt Stromlo, Australia in 2003. Design principles for the IceStorm enclosure and thermal test results are described, and the application of these principles to larger enclosures is discussed.

Keywords: Enclosure, co rotation, dome, seeing, athermalization, flushing, insulation, seals

1. DESIGN PRINCIPLES

There are two fundamental operation modes for an astronomical observatory:

Observing, where the slit is open and the observing space is open to the atmosphere, and

Shut Down, where the observatory is closed (sealed) from the outside environment

Some design principles, such as the isolation of "hot" equipment from the observing space, apply to both modes, but others are mode specific. In general, to optimize telescope performance, during the **shut down** period (daytime) the telescope should be at close to, or just below, the predicted night time local temperature. During **observing** periods, enclosure seeing must be minimized and the telescope must be protected from wind shake.

These basic design principles are well known and have been widely employed by many enclosure designers, both for new designs and for upgrades of existing enclosures. See (amongst numerous other publications) references 1 to 5.

For best seeing, the mirror should be at or up to a maximum of 2.5°C below the temperature of the surrounding air [2,3,6], and the air temperature differentials throughout the enclosure and to the outside air should be minimized. A useful target is to keep the difference between the inside and outside air below 0.4°C [1]. To make best use of observing time, these conditions should be established at the start of the observing period.

These requirements for optimizing seeing lead to designs in which

- Active cooling is used to control the temperature of the mirrors (especially the primary mirror, which typically has a long time constant) and to athermalize the enclosure internal surfaces and the telescope and enclosure structure when the dome is **shut down**,
- Passive ventilation is used to flush the dome with outside air once the enclosure is opened for **observing**,
- Heat sources (motors, instrument controllers, electronics and electrical control equipment etc.) are all isolated as far as possible from the observing space in both modes, and

Astronomical Structures and Mechanisms Technology, edited by
Joseph Antebi, Dietrich Lemke, Proceedings of SPIE Vol. 5495
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.551637

- Waste heat is exhausted remotely from the observatory (the "rule of thumb" is to exhaust waste heat at least three dome diameters away, down wind from the slit).

Effective flushing requires air movement through the enclosure during observations. If air speeds are too high, wind shake, due to the effect of wind on the telescope structure or mirrors, will produce image degradation which can easily negate seeing improvements obtained from the isothermal environment. For Reynolds numbers appropriate to air flow through telescope enclosures, the flow is in the fully turbulent region. Turbulence per se is not a source of image degradation if the flow is fully isothermal and incompressible. [7] However, if the wind flow is favorable from the seeing standpoint, wind load may affect the performance of a large telescope in two areas:

1. The tracking performance of the telescope, which may be degraded by drag fluctuations on the exposed telescope structure.

2. The effect of wind buffeting on the figure of the primary mirror.[8]

Zago[8] describes an "open enclosure" concept for the VLT, in which active control, using a servo-controlled tilting secondary, is used to compensate for high frequency oscillations which cannot be reduced by the main tracking control loop acting on the main telescope drives. This design relies on active mirror supports but it was found that the active mirror support system on such a large mirror would not be capable of dynamic figuring corrections to the required frequency (> 1 Hz). In his assessment of the issues for the final selection of the VLT enclosure design, the sensitivity of the 8m VLT primary mirror to wind buffeting, and the need to protect it, was the key issue which led to the choice of the cylindrical enclosure with flexible ventilation possibilities over an open enclosure.

The operational experience of the few "open" enclosures which have been implemented to date, e.g. the AEOS retractable enclosure at the Maui Space Surveillance Centre, indicates that, once wind speeds exceed a certain value, telescope performance is invariably compromised by wind shake.

Additional performance requirements therefore include:

- Minimization of wind shake, due to wind loads on the telescope structure and / or mirrors

As well as performance requirements, the design must also meet economic requirements, such as

- Minimization of cooling loads for the active cooling system

- Minimization of construction and operation (maintenance) costs

2. ICESTORM ENCLOSURE: OVERVIEW

The IceStorm design was driven by the above design requirements. This enclosure series was originally developed for the NASA 1.8m Outrigger Telescopes, and has subsequently been further developed for larger telescopes such as the PanSTARRS prototype PS1 and the Lick 2.4m APF. These 9.5m diameter, spherical enclosures offer a cost effective design solution for telescopes to 2.4m in which telescope performance is optimised at a cost comparable with conventional enclosure designs (comparing the installed cost of both dome and building).

In particular, the co-rotation concept, introduced in the early 1970's for the MMT on Mount Hopkins[5], in which the enclosure azimuth movements closely match telescope movements, allows for safe and unparalleled access to the telescope and instrumentation and also allows the design requirements for optimizing seeing to be met economically. The Alt over Az mount telescope configuration is particularly suited to this design. In combination with a spherical outer form, co-rotation facilitates the design of enclosures with the smallest enclosed volume and surface area.

Figure 1. IceStorm Series I Enclosure: Test Installation at Mt Stromlo

Figure 2. Vent and Shutter Opening

Figure 3. EOS Space Research Center, Mt Stromlo

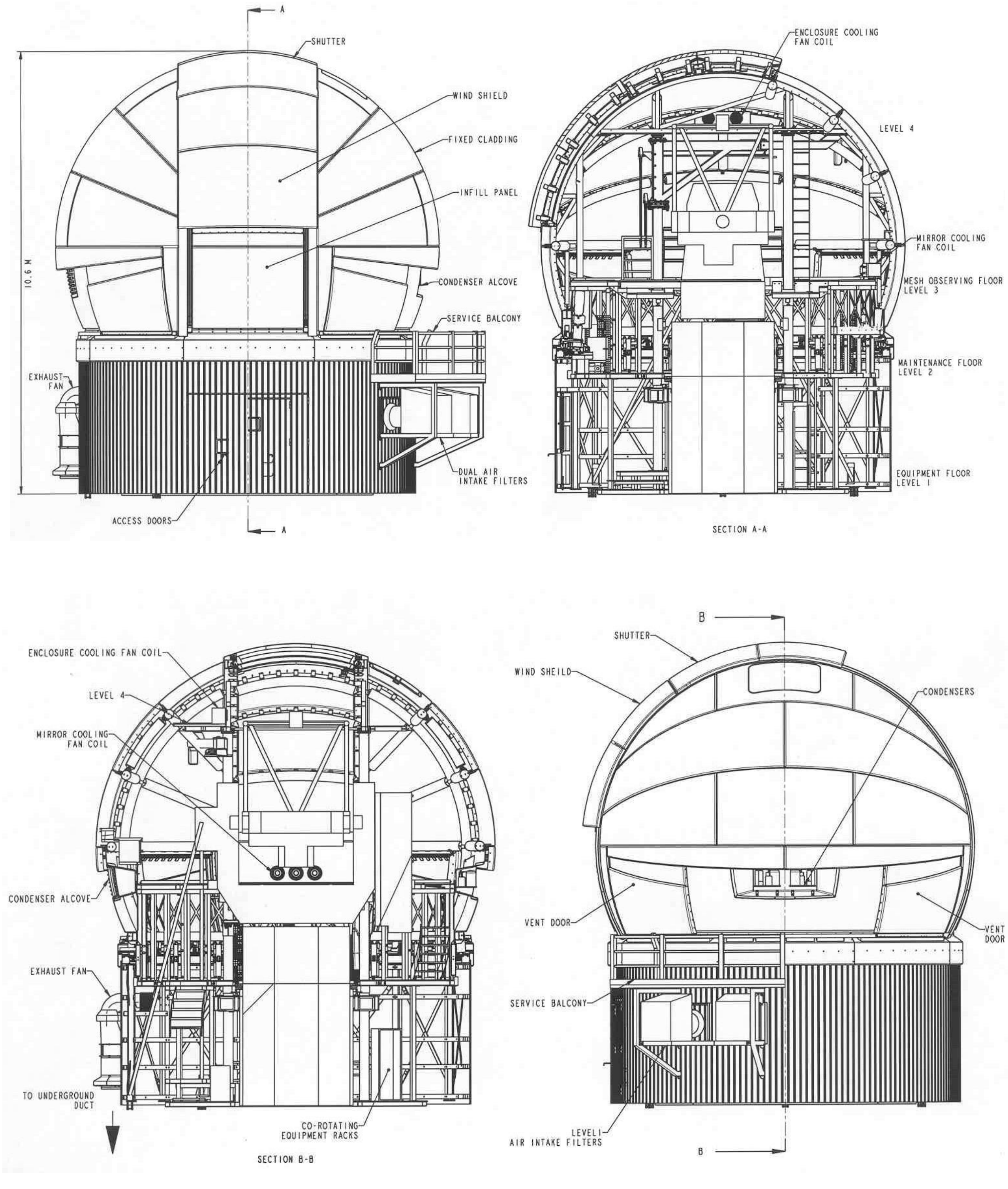

Figure 4. Section Views of the IceStorm Series I Enclosure

It is useful to consider the requirements and design implementation for each mode separately, as follows:

3. DESIGN IMPLEMENTATION: SHUT DOWN MODE

During daytime, or in bad weather, the enclosure is shut down i.e. effectively sealed from the external environment. From the above requirements, it is obvious that active cooling of the observing space is required to condition the telescope and enclosure interior during the day. Since in this design there is no significant equipment load within the observing space, the cooling plant must be capable of removing building “skin” heat gains, plus gains resulting from air infiltration via the azimuth, shutter and vent seals.

Active Cooling: The IceStorm enclosure has provision for multiple, active cooling systems, according to site requirements. Series I enclosures were designed to accommodate packaged commercial “freezer” condensers, mounted on slides in the insulated alcoves located on the enclosure exterior, feeding individual, direct expansion fan coil units inside the observing space. To reduce the differential temperature of the cooling air entering the enclosure, IceStorm Series II enclosures use an external glycol chiller, mounted at least 20m from the dome, feeding fan coil units with proportional controls. A low temperature differential is essential to avoid condensing conditions in the enclosure, so having control over the “air off” temperature allows cooling under conditions which would not be possible with the fixed differential of a direct expansion coil. The 3 way proportional flow valves are independently controlled and thermostat setting and monitoring is over the CAN network.

One fan coil unit is mounted on a fixed platform (See fig. 4, Level 4) in the top of the dome and directs air across the slit and over the top of the telescope, setting up a circulation pattern transverse to the slit. The cold air, falling on the telescope structure, circulates though the observing space, conditioning the internal structure and surfaces of the enclosure as well as the telescope structure. The open gratings of the observatory floor and service platform allow free air circulation throughout the observing space.

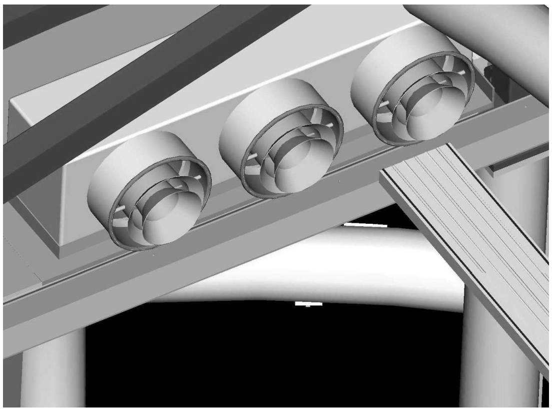

Figure 5. Level 4 Fan Coil: Enclosure Cooling

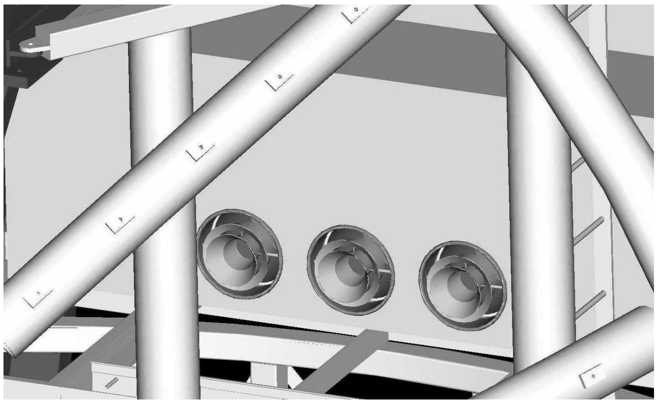

Figure 6. Level 2 Fan Coil and Jet Diffusers: Mirror Cooling

The second fan coil is mounted directly opposite the mirror cell on the observing floor (Level 3). This unit is fitted with a variable speed fan and multiple, variable throw jet diffusers (adjustable from 3m to 8m), which direct the air flow across the Level 3 floor and onto the mirror cell.

Seal System: The main determinant of active cooling capacity is the air infiltration rate. This depends on both the external wind speed and the integrity of the seals. For previous enclosure designs, a wide range of infiltration rates have been used, from less than one to over four air changes per hour, reflecting different seal efficiencies, enclosure geometries and site conditions.

IceStorm uses dual flap seals for all external seals. The dual flap seal is a passive sealing system, energized by both positive and negative pressure, to provide optimum sealing against air infiltration with minimum complexity. The same seal system is used on other EOS enclosures (e.g. Typhoon 4.5m and SkyMapper 6.5m) and on the K1 and K2 shutters at W. M. Keck observatory.

In the IceStorm enclosure, sliding dual flap seals are used for longitudinal motion (e.g. azimuth, shutter and vent door rails) and pocket seals are used for transverse sealing of openings (e.g. shutter and vent door leading and trailing edges). Single flap seals are used where seals are not subjected to wind pressure or suction (pier and ring wall seals). The flexible seal flaps are clamped between steel plates and run on polished stainless steel blades.

Seal materials were initially based on 3mm canvas reinforced rubber strip with UHMWPE anti friction tape on contact surfaces, but typically these seals require maintenance after a year or so. After extensive testing of unreinforced, UV stabilized silicone rubber extrusions on the IceStorm and Typhoon enclosures at the EOS Space Research Center, Mt. Stromlo (see Figure 3), EOS has standardized on this material for flap seals. Although running friction is higher than UHMWPE, these seals are extremely durable, even at speeds of over 30 ^{o}/sec, and the effect of the increased friction is negligible compared to other loads.

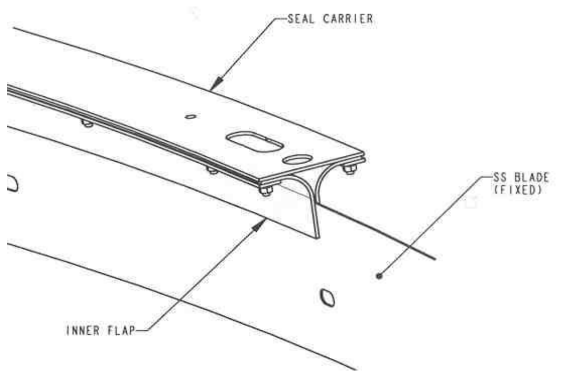

Figure 7. Azimuth Dual Flap Seal

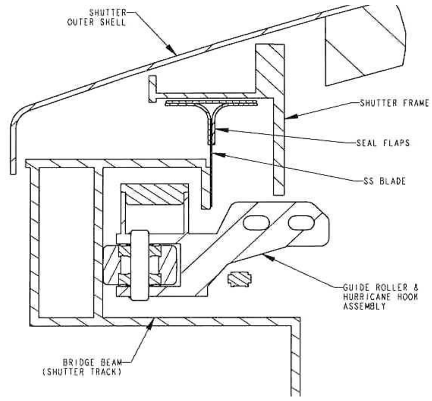

Figure 8. Series I Shutter Longitudinal Seal

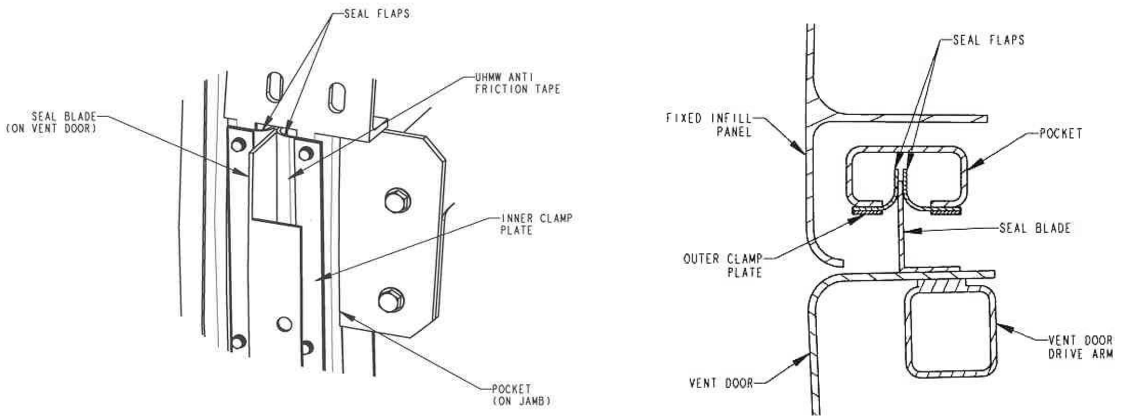

Figure 9. Vent Door Pocket Seal

Cooling capacity is primarily determined by the rate of air infiltration, which is dependent on wind speed and seal efficiency. The internal volume of the IceStorm enclosure (conditioned space) is 275 m^3 and the total seal length (azimuth, shutter, wind shield and vent doors) is approximately 75m. Leakage is notoriously difficult to estimate and historically, infiltration estimates have been found to be incorrect by factor of 2 or more, so most enclosure cooling systems are under designed and are not able to maintain temperatures in humid and / or high wind conditions.

At low wind speeds, a leakage rate of less than 40 l/s, equivalent to ½ an air change per hour can be achieved, so that heat gain from infiltration (both sensible and latent) will be roughly equivalent to the heat gain through the cladding. At high wind speeds, leakage rates could rise to over 230 l/s, which is equivalent to 3 changes per hour. The Series II IceStorm active cooling system therefore has a minimum cooling capacity of 12 kW with a glycol supply temperature of –8^{o}C to cope with these uncertainties. Because standard industrial chillers are used, Additional capacity, to accommodate large customer equipment loads e.g. on site data reduction by parallel processing on multiple PC's, can be easily and economically added.

Note that a commonly used design guide, the Carrier System Design Manual [9] discusses formulae for the calculation of infiltration rate (see Chapter 6 “Infiltration and Ventilation”), then discards these in favor of a “pragmatic solution” in Table 44 – INFILTRATION DUE TO WIND FORCES. This table sets out air changes / hour in a plus or minus format. These factors are added or subtracted to a base infiltration rate. Assuming the IceStorm enclosure is a “building”, the table produces a maximum infiltration rate of 2 ½ air changes / hour (190 l/s).

Insolation: The IceStorm Enclosure external cladding is molded from an advanced composite, with low thermal mass and very low conductivity. The same system is used for the fixed cladding (dome shell and infil panels) as well as the cladding of exterior moving elements (shutter, wind shield and vent doors).

To reduce solar gain during the day, the external surface is a reflective, high gloss, white polyester resin (gelcoat) with a very high titanium oxide content (> 22%). The anisotropic FRP skin is backed by fire retardant, extruded polystyrene foam insulation (thickness can be tailored to site conditions), protected by a fire retardant, glass fiber reinforced membrane lining. Note that no polyurethane insulation materials are used in these enclosures because of fire / toxic smoke hazard considerations.

Figure 10. Ring Wall Insulation Detail

The steel clad / steel lined ring wall is insulated with a dual layer of conventional glass fiber insulation blanket, with the external cladding spaced and insulated from the support columns to reduce thermal “print through” into the equipment space (Level 1). This cladding system reduces heat gain from thermal insolation to a minimum.

Isolation of “Hot” equipment: All heat generating equipment is located on the ground floor (“Level 1”) of the enclosure, except for the azimuth and shutter drives, which do not operate during the day. In IceStorm Series I enclosures, this equipment area is cooled by outside air drawn into the enclosure through large dust filters by a large, variable speed fan and exhausted through an underground air pipe. In Series II enclosures, equipment cooling is provided by one or more fan coils with proportional controls, fed from the common external chiller.

The Level 1 equipment floor is thermally isolated from the maintenance floor (“Level 2”), the observing floor (“Level 3”) above and the telescope pier. The design requirement for Level 1 is that total transmitted heat from Level 1 to Level 2 is less than 150W from a 12 kW heat load in the equipment space. This is achieved by:

- Insulating the ceiling of the equipment area (Level 1). The ceiling is finished with melamine coated MDF on battens (to avoid a conduction path through the steel floor framing) and the Level 2 sub-floor is hardwood ply.

- Effective sealing of the rotating floor (Level 2) to the external ring wall and the pier top, using flap seals. As the equipment floor is held at negative pressure with respect to the observing floor, these seals are especially effective in preventing air flow into the observing space.

- Stair insulation. The complete stairwell enclosing the stair from Level 1 to Level 2 is insulated.

- Level 2 access door. This is a standard insulated cool room door, with magnetic seals and an hydraulic door closer

Summary: The design requirements for the **shut down mode** are met through the following techniques

- Active cooling of observing space to condition telescope (held at next night's temperature)
- Extremely effective sealing systems (pressure actuated), external insulation and reflective outer skin
- Thermal isolation of hot equipment from the observing space < 150W total transmission
- Continuous cooling of the equipment ("Hot") space

4. DESIGN IMPLEMENTATION: OBSERVING MODE

Passive ventilation: During observation, the slit and vent doors may be fully opened (low wind conditions) or, depending on wind speed and direction, the operator may deploy the tracking windshield and selectively open any or all of the four Vent Doors to obtain optimum flow through the enclosure. Optimum flow produces effective flushing without wind shake. The observing floor and even the upper equipment access floor (Level 4) are all open grid mesh, which allows unrestricted air flow though the observing space.

The two up–and–over shutters are essentially identical, steel framed composite panels. The transverse pocket seal between the shutters is not directly above the primary, but offset and incorporates an overlapping section to prevent snow or ice falling into the enclosure when the shutters are opened. Since the front shutter operates as a windshield, it has a high speed drive, which can position at 2 ^{o}/sec to match the telescope elevation slew speed. Shutter / wind shield absolute positioning accuracy is better than ±20mm, so the operator can place the windshield in the best position for protection against wind shake or it can automatically follow telescope elevation movements.

Figure 11. IceStorm Series I Vent Doors Open Front and Rear

Active cooling: At the start of the observing period the active cooling system, having maintained the telescope structure and primary mirror at or just below the expected night time temperature throughout the day, is switched off.

Supercooling: To reduce emissivity, the telescope tube is wrapped in highly reflective Mylar tape. The inside walls of the slit edges have stainless steel air dams to direct supercooled air from the exposed (painted steel) shutter arch down the shutter chain tracks. The open grid mesh observing floor is galvanized for low emissivity and all other surfaces are gloss white. These measures prevent seeing disturbance from supercooled air falling into the beam.

Should further protection against supercooling be required, aluminized Mylar tape can be applied to the upper steel structure. Initial testing of the WIYN 3.5m[1] indicated that the temperature difference between Mylar taped and painted surfaces are in the order of 1^{o}C on the telescope tube under radiative sub cooling conditions, so application of Mylar tape may be advantageous.

Isolation of Enclosure Drives: The enclosure controls, including power supplies, braking resistors, load inductors etc are located on Level 1 (Equipment floor) and so are effectively isolated from the observing space. In Series I enclosures, the principal source of heat from the azimuth and shutter (wind shield) drives are the motors themselves, the speed reducers and the electro magnetic disc brakes used for parking (energized when moving). The final stage gearing (helical bevel gears) operates at relatively low speeds, even during slew and do not generate significant heat. In Series II, the shutter motors are mounted to the shutters and therefore do not discharge heat into the observing space.

The drives are enclosed in insulated cabinets, fitted with filtered air intakes through which air is drawn from the observing space by a thermostatically controlled fans, and exhausted into the Level 1 space via insulated ducting.

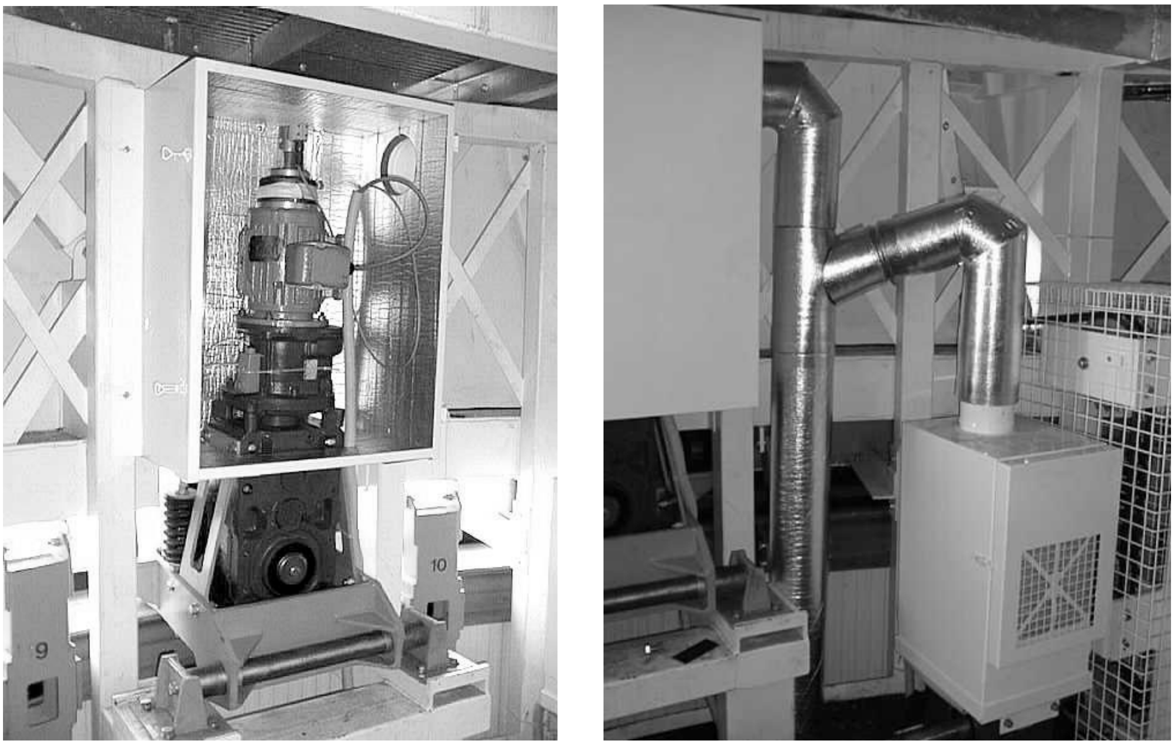

Figure 12. Drive Enclosures and Ducting to Level 1

Level 1 Ventilation System: In Series I enclosures, the exhaust ventilation system for Level 1 is required to remove approximately 12 kW of heat from this space. The ambient air cooling system maintains temperatures in the equipment area which, in combination with the floor insulation and seals, allows a maximum of 150W transmission into the observing space. For maintenance staff comfort, the temperature range in the equipment area is maintained at between 12 ^{o}C and 15 ^{o}C, outside air temperatures permitting. This is achieved by varying exhaust fan speed with temperature. In series II temperatures are controlled with a fan coil fed from the common external chiller.

The principal heat sources on Level 1 are:

- Heat generated by the equipment racks (4.5 – 10.5 kW), transformers and power supplies (operate 24 hrs/day).
- Heat from the azimuth and shutter drive motors, braking resistors and motor controllers during observing periods (<1 kW tracking to say 5.5 kW peak at maximum slew on all drives).

Summary: The design requirements for the **operational mode** are met through the following techniques:

- Thermal conditioning of the telescope structure, mirror and enclosure interior during shut down
- Optimal passive ventilation (flushing) with protection against wind shake (tracking dual shutter / windshield system, permeable floors and large, independently operable vents for passive ventilation of observing space)
- "Hot" areas thermally isolated from observing space and heat removed by high flow rate cooling using ambient air, exhausted underground, remote and down wind from the enclosure or via external glycol chiller

5. THERMAL TEST RESULTS

The first Series I enclosure was assembled in Australia on temporary foundations in 1999, to allow performance testing and a number of tests were carried out by engineers from the California Association for Research in Astronomy (CARA). These tests were designed to show that the heat generated on Level 1 would not significantly affect dome seeing. The thermal management test was based on a "heat soak" where the air in Level 1 was heated and the Observing space left open to the outside air. For this test, Level 1 was sealed and electric heaters operated for 16 hours to raise the temperature in Level 1 significantly above the temperature on the observing floor (delta $T > 10^{o}C$).

Thermal Imaging Tests: With the Level 1 sealed and Level 2 open to ambient air, a series of images were taken with a thermal camera on Level 2 to measure temperatures and identify areas for improvement.

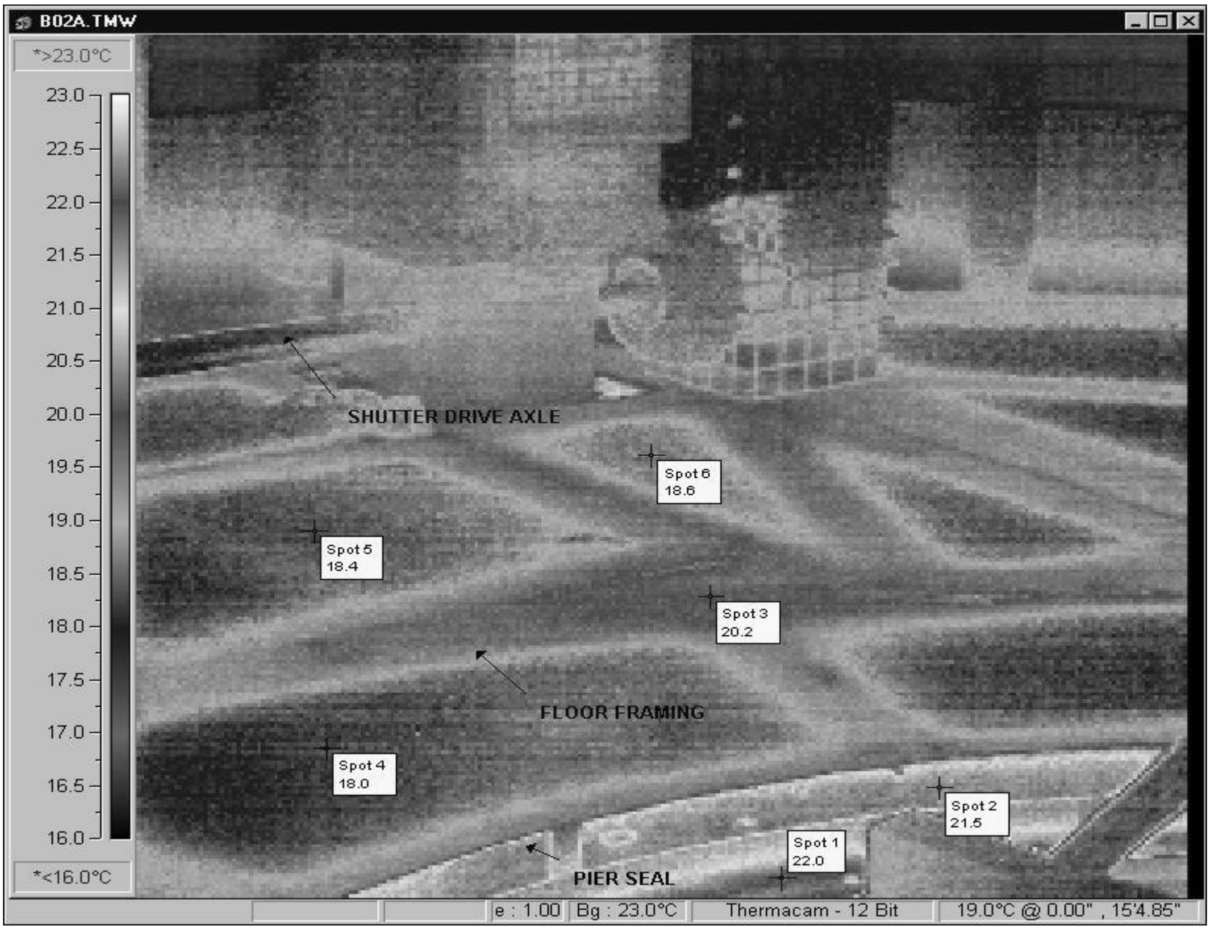

Figure 13. Thermograph B02A (Level 2 Floor and Pier Seal)

From the above thermograph, it can be seen that the average temperature differentials between the Level 1 ceiling (29.3 ^{o}C) and the floor (20.2 ^{o}C over the beams, 18.3 ^{o}C over the balance) are -11 ^{o}C and –9.1 ^{o}C respectively. From the spot temperature measurements and areas, the heat leakage from Level 1 to Level 2 was calculated to be approximately 245 W. As in Blanco & Johns[1], a hand held temperature probe was used to verify surface temperatures and account for differences in the emissivity of the various surfaces. In this thermograph, the insulating of the floor in the areas without beams is R3 (3.17 m^2K/W) i.e. meets specification, but over the beams, this reduces to R1 because of the conduction path through the framing.

To obtain the reduction in heat transfer required to meet the specification, two measures were adopted:

- Conduction through the floor framing was reduced by installation of transverse 90mm light weight battens between the ceiling (MDF) and the floor framing (steel) and the gap partially filled with an additional 30mm of PS FR foam. The thermal break between the ceiling material and the conductive steel framing and extra layer of foam effectively adds R1 to the floor insulation overall (to obtain R4 where there are no beams and R2 over the beams),. This is expected to reduce heat transfer by almost 50W through the floor areas containing beams, and a further 35 to 40W (including air gaps) over the rest of the floor

- An insulating collar (MDF backed by 60mm FR PS foam) was added under the metal pier seal carrier plate, which was previously exposed directly to the hot air in Level 1. Because the seal plate area is small, this will not reduce overall heat transfer rate significantly (about 5W) but it does remove a "hot spot" directly under the telescope.

These changes reduce heat transfer from Level 1 by close to 100W.

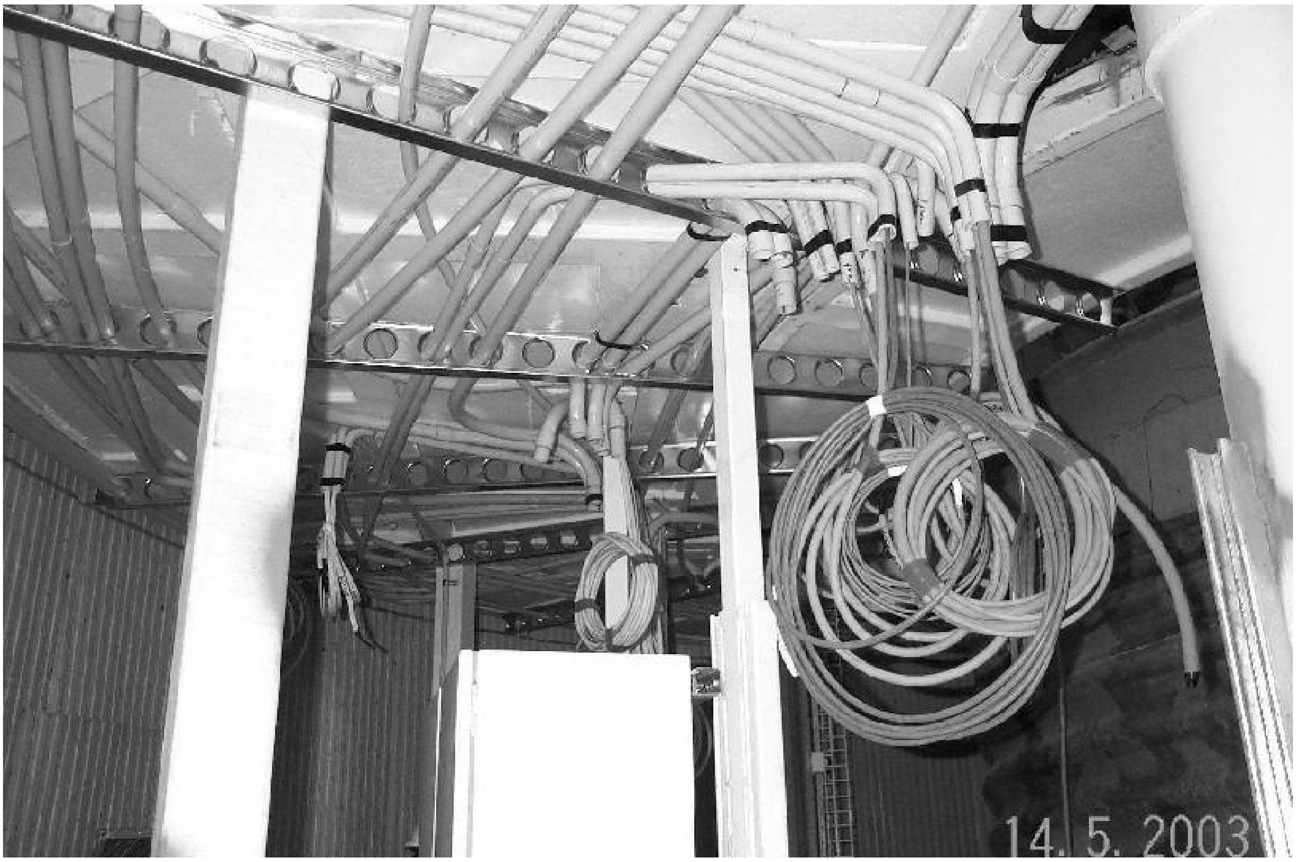

Figure 14. Thermal Break (90mm x 0.6mm Ritek Batten) Installed in level 1 ceiling

6. OBSERVATIONS

Enclosure costs have reduced remarkably over the last three decades, from 50% to 30% of total project cost. If extensive site works are required, the enclosure kit cost may even be below 20% of total project cost. This change has principally been due to reductions in enclosure size made possible by more compact telescopes (Alt over Az construction, faster optical prescriptions). Smaller enclosures are easier to cool and flush more rapidly than larger enclosures, but may expose the telescope to higher wind speeds which can cause image degradation. Although this is compensated to a large extent for by the fact that telescopes have become stiffer and now have much more sophisticated drive systems, protection against wind shake remains a critical design requirement.

For large telescope enclosures, as well as observing the usual rules for thermal isolation of all heat sources and providing active cooling for athermalisation during shut down, balancing the need for effective flushing with protection against wind shake remains a major challenge. For "small" enclosures (< 10m) provision of adequate ventilation is obtained at a disproportionately high cost compared to larger enclosures, as the cost of providing a well sealed opening is not strongly size dependant. In particular, the cost of insulated louver shutters and / or variable permeability wind shields reverses the downward trend in enclosure cost as a proportion of total project cost.

In the design of future enclosures, the challenge is to increase performance under increasing cost pressure. Consideration should be given to the use of the following design elements introduced in the IceStorm enclosure:

- Tracking wind shields which also function as the slit closure
- Full perimeter sliding doors for maximum venting;
- Molded highly reflective, low thermal mass, low maintenance composite paneling with integral insulation;
- Light weight (thin wall) internal structures and galvanized, open mesh gratings;
- Proportionally controlled fan coils for athermalization and active cooling, fed from a remote, external chiller
- Pressure tight seals.

REFERENCES

1. Blanco, D., Johns, M. "Thermal design of the WIYN 3.5-meter telescope enclosure". *SPIE* **2199,** 743. 1994
2. Hawarden, T. G., Cavedoni, C. P., Rees, N. P.., Chuter, T. C. "UKIRT Upgrades Program: preparing for the 21st century". *SPIE* **2199,** Section 4. (1994)
3. Cavedoni, C. P., Hawarden, T. G., Chuter, T. C. , Look, I. A. "UKIRT Upgrades Program: control of the telescope thermal environment". *SPIE* **2871,** 687. (1997)
4. Siegmund, W. A. "Design of the Apache point Observatory 3.5 m telescope. V – Telescope enclosure thermal modelling". *SPIE* **1236** Advanced Technology Optical telescopes IV (1990)
5. Wong, W-Y., Barr, L. D. "Planning the National New Technology Telescope (NNTT). V – Enclosure design options". *SPIE* **628** Advanced technology Optical telescopes III. (1986)
6. Barr, L. D., Fox, J., Poczulp, G. A., Roddier, C. A. "Seeing Studies on a 1.8m mirror". *SPIE* **1236** Advanced Technology Optical telescopes IV. (1990)
7. DeYoung, D. S., "Numerical Simulations of Airflow in Telescope Enclosures", Kitt Peak National Observatory, NOAO, Gemini Preprint #17, p 5
8. Zago, L. "The design of Telescope Enclosures for the VLT", p 236
9. Cooling and Ventilation-Carrier System Design Manual-Part 1 Load estimating and Psychometrics (Australian version of *Handbook of Air Conditioning Design* by Carrier International Corporation).