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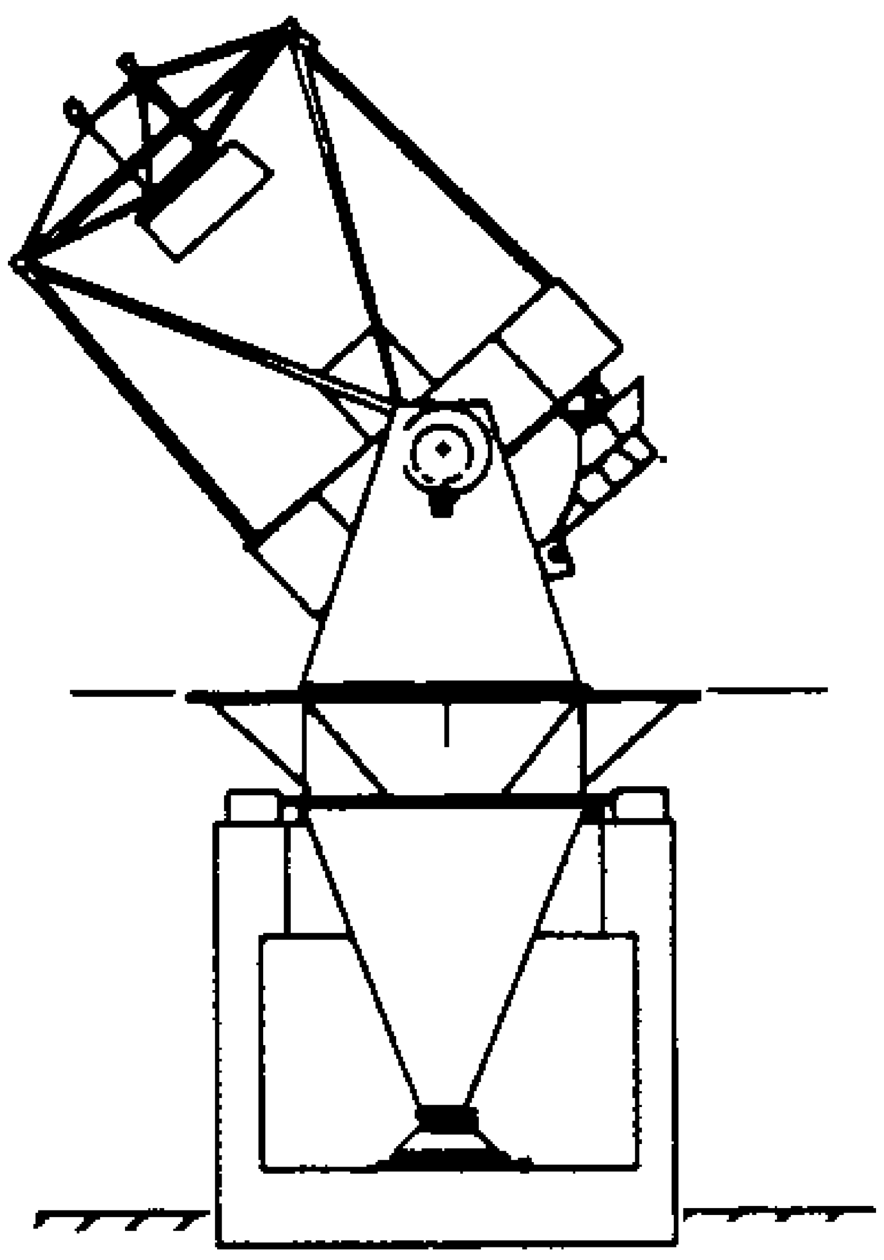

3.5 Meter Telescope

Temperature Control of the 3.5-Meter WIYN Telescope Primary Mirror

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Temperature control of the 3.5-Meter WIYN telescope primary mirror

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ABSTRACT

The WIYN telescope primary mirror is the 3.5 meter number-two-mirror cast at the University of Arizona. The Borosilicate glass temperature of the mirror is regulated during use to limit the distortions caused from thermal expansion, and to limit mirror seeing caused by natural convection. The design of the thermal regulation system includes a closed air cooling plenum within the mirror cell structure complete with blowers and heat exchangers. Heat generated by this system and also removed from the glass is carried away by another liquid cooling loop to a remotely positioned liquid chilling unit. The system can regulate the mirror temperature to +/- 0.2 degrees C from a temperature set point near ambient air for typical static and dynamic environments. Evaluation of the system includes a full laboratory optical test of the mirror, support, cell and temperature control system. Included is a description of the thermal control design. Data on the performance of the thermal control is summarized in the quantities of temperature deltas across the system components and flows of air, water, and heat.

1. INTRODUCTION

The Wisconsin-Indiana-Yale-NOAO (WIYN) Telescope is a 3.5 Meter project currently in the design and construction phase. The telescope will be located on Kitt Peak, Arizona, in the place of the now dismantled number-1 36 inch telescope. The site elevation is 2084m (6838 ft). The telescope design incorporates a lightweight Borosilicate glass primary mirror which is the second one of this size cast at the University of Arizona. Optical polishing of the mirror is in work at NOAO. Presently the mirror is finished as a f1.75 sphere and installed in the prototype mirror cell in preparation for evaluation of the design of the support and thermal control systems. Figure 1 shows the assembly tilted up on the table of our polishing machine.

Thermal control of hollow Borosilicate mirrors has long been a subject of concern for large telescopes. Thermal testing experiments have been done, the most recent by Siegmund et. al., 1990.[6] Others done by Davison,[9] Hart,[8] Angel, Cheng,[3,4] Pearson,[2] and Wong[1] date back to 1983. Finite element modeling has been done by Pearson, and Stepp to estimate mirror distortion from temperature gradient input.[2,5] It was concluded from the above that active regulation of temperature is required on the WIYN primary mirror.

Figure 1. The WIYN primary mirror-cell assembly on our 4m polishing machine and tilted 70 degrees.

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Specific design goals are based on a contribution to error in the telescope image of 0.16 arc sec FWHM. It is estimated that to achieve this, the temperature uniformity of the mirror must be better than 0.24 degree peak to valley. Also to reduce mirror seeing there is a requirement to match the mirror to the ambient air within +- 0.5 degrees.

The majority of this paper is a description of the design of the mirror thermal control system. Section 3 is brief description of the plan for testing the system. Section 4 summarizes some preliminary conclusions.

2. DESIGN DESCRIPTION

A description of the thermal control system design starts with the mirror and follows the direction of heat flow, ending at the prevailing-down-wind rejection point far from the telescope. Interleaved with the description are discussions of the reasoning that is required to optimize the system. The system is made to be integrated into the mirror cell and support system. The air plenums are also the cell structure. There are three cooling loops which act in series to move heat from the mirror to the rejection point. The first loop uses an enclosed volume of air within the mirror and cell structure to transfer heat out to the next loop. During times when the mirror must be heated the second loop simply removes less heat than the blower power which is sufficient to heat the mirror a degree per hour. The second loop, using a coolant mix of 50-50 water and glycerol, moves the heat about 30 meters off the telescope to a liquid chiller. The temperature of the chiller fluid is the variable used for control. The chiller is housed at ground level and adjacent to the telescope control room. The third loop contains a water-glycol mixture. Its function is to reject the heat from the chiller to a convection heat exchanger downwind from the telescope.

2.1 Nozzle jet thermal regulation

The method of heat transport used to regulate the mirror temperature is convection to air from all of the back-surfaces of the glass. Nozzles jet air into the back-plate hole of each cell and onto the outside and inside edges of the mirror. The nozzle design and air flows are nearly the same as proposed previously.[3,4] The dimensional details are shown in figure 2. The nozzles at the edge of the mirror are longer than at the cells. Each of the 354 units passes 5.7 l/sec at a pressure differential of 76 Pa.

2.2 Air jet temperature control

Control of the mirror temperature depends on the control of the air temperature exiting the nozzles. What temperature should the air be? Previous ideas published concentrate on the use of the ambient air temperature.[1,3,4,6] The argument is that the mirror needs to be regulated near the ambient temperature for minimizing mirror seeing, and that with convection coupling to the back of the mirror the time constants for cooling are short enough that the temperature lag effect will be less than the requirement. The first problem with this is finding the ambient air temperature, and the second is how to control all of the nozzles to use this temperature "set-point". The variation of control will cause image distortion due to mirror bending.

Two experiments to simply suck ambient air through the nozzles discovered that there is to much variation in ambient air properties to meet the requirement on mirror bending.[1,2] This is an "open" system because the air passes through one time and is exhausted. Another open system design that conditions the air with a blower and thermal servo system to improve the uniformity was tested.[6]

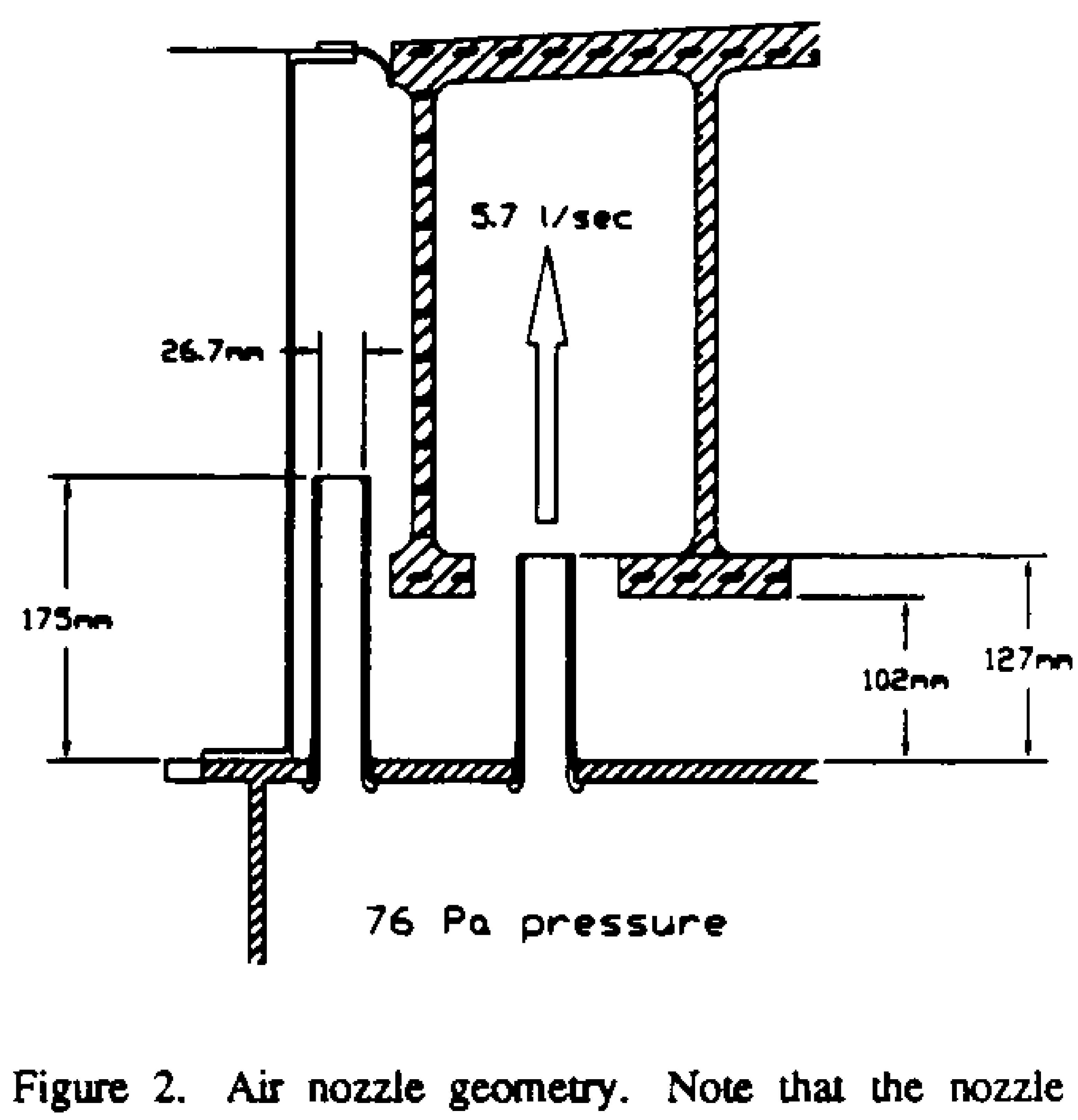

Figure 2. Air nozzle geometry. Note that the nozzle extends into the mirror back-plate.

The alternative "closed" system used for WIYN recycles the same air within a closed plenum. Heat is not carried away by air but is transferred to another liquid system. The blowers that recycle air are mounted on the mirror cell. Heat is transported away from the telescope through 25 mm diameter rubber hoses. Furthermore the air temperature is only controlled indirectly by setting the temperature of the liquid coolant.

The actively controlled open system will use more energy than a closed system because of the exhausting of the controlled air and continual conditioning of new air with larger thermal differentials. Also open systems will have problems with dust and water vapor entering the system along with the air.

2.3 Plenum layout, dividing up the air low

The air flow channels within the cell are shown in figure 3; a section through the cell and mirror center-line. The lower part of the section shows the mirror supporting structure which is a welded steel box structure. The structure is sealed and acts as a plenum for pressurized air supplied to the 354 temperature regulating nozzles. Radial shear webs define 12 pie shaped areas. Each of these is divided by a shear web that is the mounting for a fin-and-tube heat exchanger. The triangular shaped area adjacent to the heat exchanger is pressurized by 12 blowers from above. The air flows down through the blowers and back radially toward the mirror center and through the heat exchanger. The mirror is supported 102mm in front of the steel cell by 66 axial push-rods that pass through the cell and are sealed at the faces with rubber gaskets (not shown in the figure). Air injected into the core of the mirror flows back out through the annular passage around the nozzle and into the space between the mirror and cell. It is collected and returns radially back to the blower to be recycled. Note the relation of the end of the nozzle to the geometry of the hole in the mirror back plate. Also the 12 nozzles at the inside diameter and the 48 at the outside diameter are longer. Sheet metal boxes with rubber seals cover the edges of the mirror to complete the closed plenum system.

Each facet along the outside edge of the cell weldment has an access hole to the heat exchanger, and a cover. Access further into the cell is available by removing the heat exchanger. When removed from the cell the exchanger is still connected to the coolant supply by two flexible rubber hoses. The box over each blower also has a removable cover.

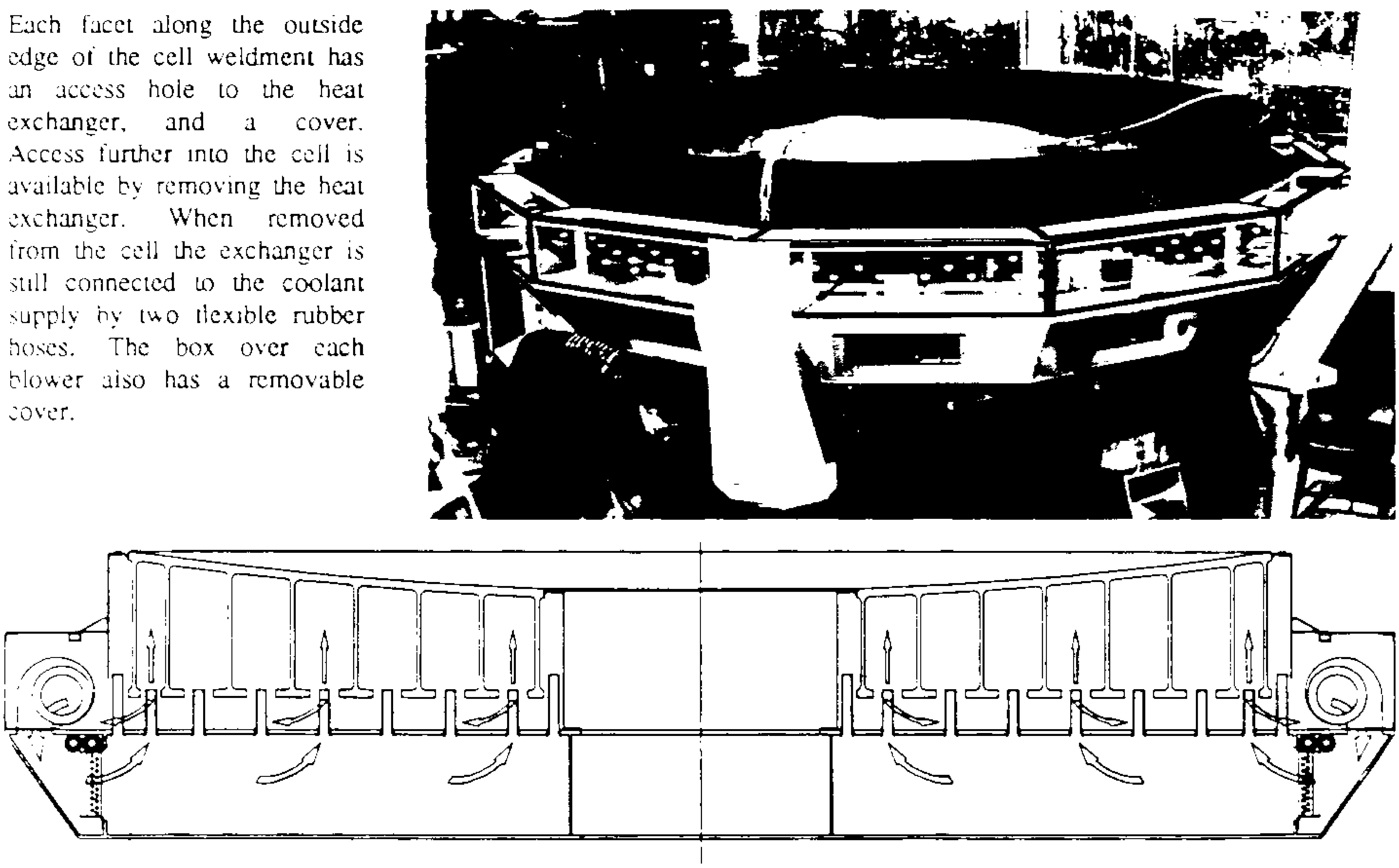

Figure 3. Air plenum layout

We believe that the 12 pie sector geometry for air flow has specific advantages. The cross-sectional areas taper down uniformly along with the flow as the air moves in toward the center and back out to the blower. Direction of the back-pressure behind the mirror is so that the effect on nozzle flow matches the direction of mirror mass variation. The radial pressure gradient measured on our system is 5 Pa. Flow of the air has a symmetry that, when transferred to the mirror as a residual thermal distortion, can be corrected by the mirror support system.

2.4 Control loop strategies

With the proposed system the most simple control strategy is to use one thermal feedback sensor and treat the entire mirror as one temperature zone. The uniformity of temperature depends on the uniformity of the blowers, nozzles, heat exchangers and plenums. Other possibilities are 12 pie shaped temperature zones that match the 12 blower-heat-exchanger circuits; and 354 zones that would coincide with each nozzle. The plan for WIYN is to try the simple solution first because it costs less. The layout of the design allows addition of more sensors, control valves and electronics if more uniformity is required.

2.4.1 Data sensing for control

The sensor chosen for feedback is a T thermocouple for several reasons.

1. The quantity to be measured is a temperature difference between the air and the mirror. The Peltier effect measures differences directly if pairs of junctions are wired in series and alternative junctions are located across the temperature difference as shown in figure 4. The air-to-mirror sensor uses four pairs wired like this at quadrants around the outside diameter. One set of junctions extends into the air covered by a aluminum foil fin and the other set is attached to the outside diameter of the mirror face. A T-type junction wired in this manner results in two copper wires to be connected to the voltmeter so that thermal gradients at the voltmeter terminals do not cause errors.

2. The accuracy of the reading needs to be +- 0.01 C. This is +- 0.4 microvolts for one junction pair and multiple pairs multiply the voltage. Commercial voltmeters are available to measure these levels and interface directly with RS-485 serial to any computer.

3. The sensor must not generate heat while being read. Thermocouples generate voltage directly and can be read by applying a very small current. Therefore there is no heat generated by the junctions.

4. There is time to read the sensor accurately. Multiple readings can be taken and averaged to reduce the noise in the data. We are averaging 60 readings over a 5 minute time interval. The typical noise associated with a specific reading at these low voltage levels comes from the amplifier and A/D converter in the voltmeter. There is a trade here between the cost of the voltmeters and the amount of readings that are averaged.

5. Offset errors are the most detrimental to system operation. Linearity and scale factor errors can be large and still not effect the operation of the servo control algorithm. Thermocouple junction pairs have no offset at zero output. The voltmeters used have up to 5 microvolts of offset which does not drift rapidly. The offset in the voltmeters can be divided by wiring more sensor pairs in series, or can be nearly eliminated if a computer driven latching relay is used to periodically reverse the input leads to the voltmeter. We have experimented with several relays and found one that works well.

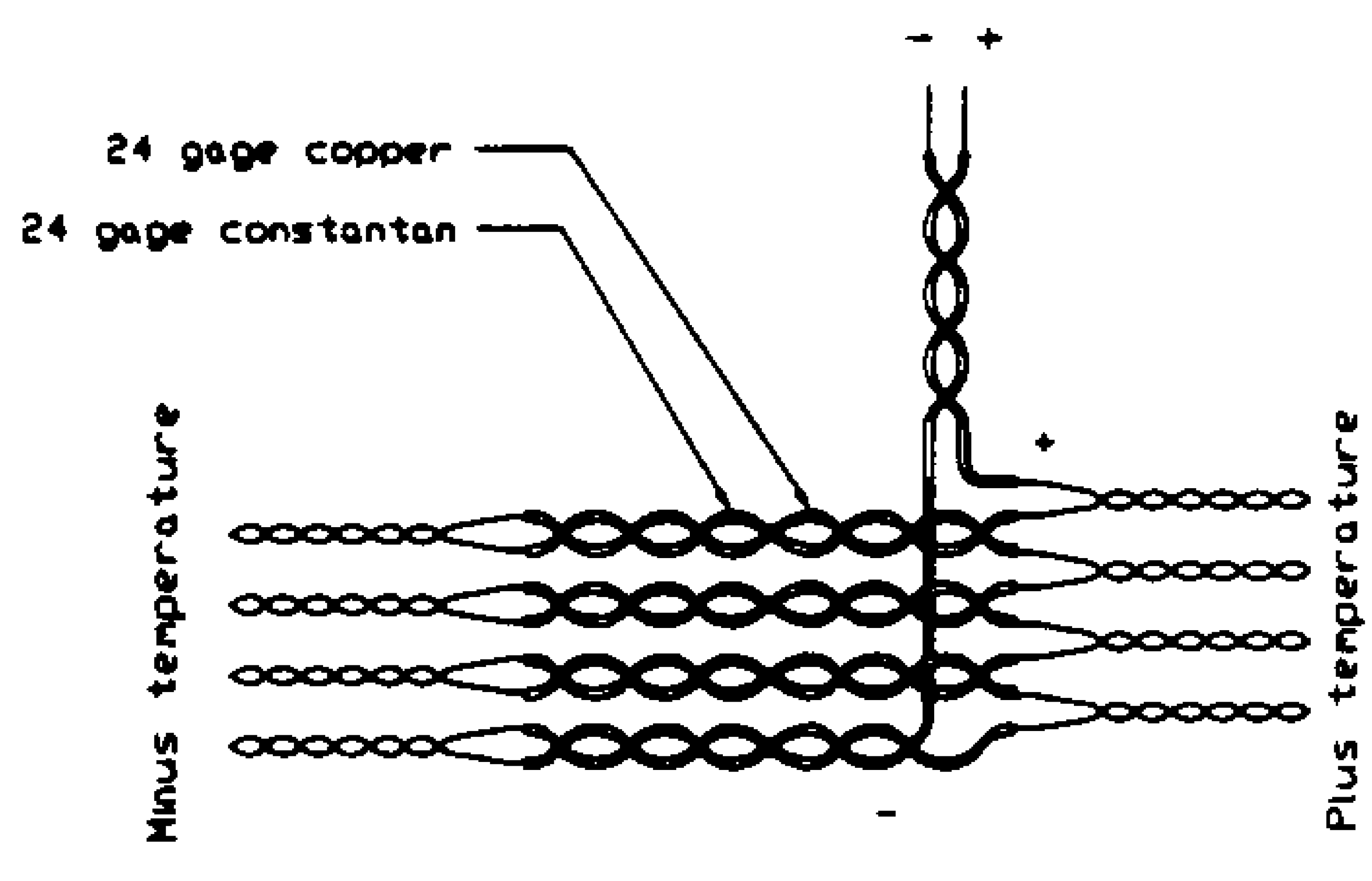

Figure 4. Thermopile connections for sensing air-to-mirror temperature differential

2.4.2 The control algorithm

A Proportional-Integral-Derivative (PID) control algorithm is used to calculate new values for the temperature of the coolant entering the mirror cell.[11] The values from the feedback sensor are used to update the servo at 5 minute intervals. The system is tuned at a gain of 10.5, a integration time of 17.5 minutes, and a derivative time of 5.72 minutes. The coolant temperature is limited in the software to +- 3 degrees from the ambient air to prevent excessive integrated winding of the control when the error signal is large. The software also allows input to put the mirror temperature at a fixed temperature difference from the air. The system will track the air temperature in our optics shop to +- 0.02 degrees. Response to a step change for the mirror set point is about 60 minutes if the step is within the capacity of our chiller unit.

2.5 Air movers

Transportation of heat by moving a fluid such as air requires the addition of energy to move the fluid against friction losses. Generally the friction losses are greater when the fluid is air rather than water. Air fans tend to have mechanical efficiencies around 20 percent. This means that for 1000 watts into the fan motor only 200 watts of air-velocity energy come out of the fan and 800 watts of heat increase the temperature of the air as it flows through the fan. In the case of our closed system the other 200 watts is also changed to friction heat as the air flows around the plenums, heat-exchangers, and nozzles. There are different designs for the fan impellers depending on the motor speed and the required output pressure. Our pressure of 120 Pa is on the high end of fans with forward curved blade impellers and in the lower-to-middle range for backward curved impellers. We tried both types on a test plenum box made from wood and found out that for our design the forward curved impeller squirrel cage type blower used less energy. This is a result of the favorable placement of the squirrel cage so that the spinning action of the blower tends to direct the air back through the heat exchanger. Preliminary data from testing the complete system indicates a blower efficiency of 22.5 percent. For this particular test run the set of 12 blowers were running on 108 volts AC, supplying 2010 l/sec, and pumping 113 Pa. Electrical power input was 1212 watts and the air temperature across the blower was 0.43 degrees (939 watts).

There is a question about vibration because the blowers are mounted directly on the cell. The attachment of the motor to the blower housing is modified to incorporate a rubber isolator as shown in figure 5. Relative motion due to isolation of the motor and squirrel cage is allowed by the air gap between the squirrel cage and the housing inlets. The housing of the blower is attached to the cell using a gasket made from 3 mm sheet isodamp rubber.

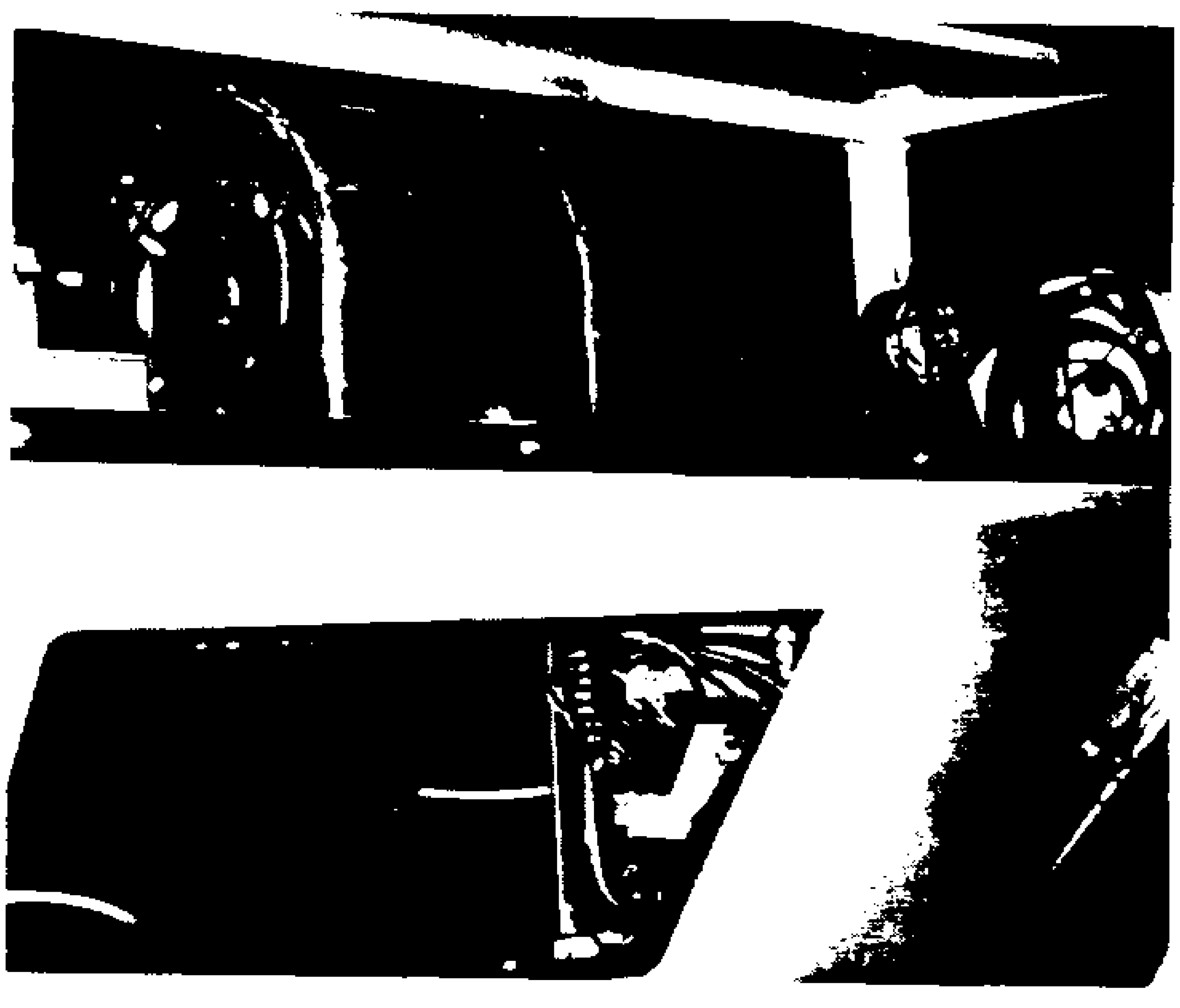

Figure 5. The blowers mounted on the mirror cell are shown with the covers removed. The black square attached to the side of the housing with rubber spacers is the vibration isolator.

2.6 Heat exchangers

Coolant supplied to the 12 heat exchangers on the cell is connected at the edge of the cell on the 2 o-clock position as one looks into the bore of the horizon pointed telescope. The connections have pairs of ball valves with a pipe union between to allow a disconnect with minimum loss of coolant. Two rubber hoses connect to the telescope yoke with a loop to allow the elevation motion of the telescope. At the edge of the cell the upper connection extends around the inside in a counter-clockwise direction to make a supply manifold. The lower connection is extended in the clockwise direction to form a return manifold. The manifolds fit into the internal niche of the cell weldment directly between the blower and the heat exchanger as can be seen in figure 6.

These are made of one-inch-copper pipe in 12 sections connected with pipe unions so that removal is possible. Extension of the manifolds in opposite directions forms a equal length path for the fluid to each heat exchanger in order to balance the flow. Insulation over the pipes reduces temperature differences due to heat transfer from the manifold.

The heat exchanger used is made with 3/8 inch copper tube and copper fins. The design maximum pressure for the liquid is 1380 Kpa. The tubes pass through the fins 20 times in a series-serpentine manner. The cross sectional area for air flow is 0.091 m^2. As shown in figure 7 the exchanger is connected to the supply on the air-flow down-stream side. The cooler fluid follows the serpentine path to the top and then returns back across the up-stream side to the return manifold. The copper fin connecting the two planes of tubes averages the coolant temperature differential caused from the heat transfer. Because of this geometry the variation of the exit air temperature across the area of the fins is reduced.

Heat exchangers are rated with respect to energy exchanged per unit of inlet temperature difference for any given fluid and air flow condition. Measurements from our system of 12 exchangers indicate an air flow of 2010 l/sec with a pressure drop of 35 Pa. A fluid (water) flow of 0.61 l/sec with a pressure drop of 138 Kpa (at the pump). At these flow rates and an inlet temperature difference of 1.29 degrees C the heat transferred is 1270 watts/degree.

2.7 Secondary liquid coolant loops

In selecting a design for a liquid chiller we first studied commercial freon coolers and found out that most of them loose their capacity when the condenser temperature drops to zero degrees or lower. The temperature on Kitt Peak sometimes drops to -16 degrees. Also unlike normal air-conditioning, we are always requiring an output that is less than five degrees offset from the ambient outside temperature. For these two reasons we decided to look at a chiller design that uses Thermo-Electric-Cooling (TEC). Peltier effect cooling devices overcome some low efficiency problems when they are used across smaller temperature differentials. There are some advantages from the view of ease of control, heat or cool from the same device, and noise generation. There is a cost disadvantage of about 30K dollars. We have designed and are currently constructing a cooler that will have a 4KW cooling capacity at a temperature difference of 5 degrees C. The part of this that required the most engineering work is a plate heat exchanger that incorporates 384 separate TEC cooling modules between the hot and cold plates.

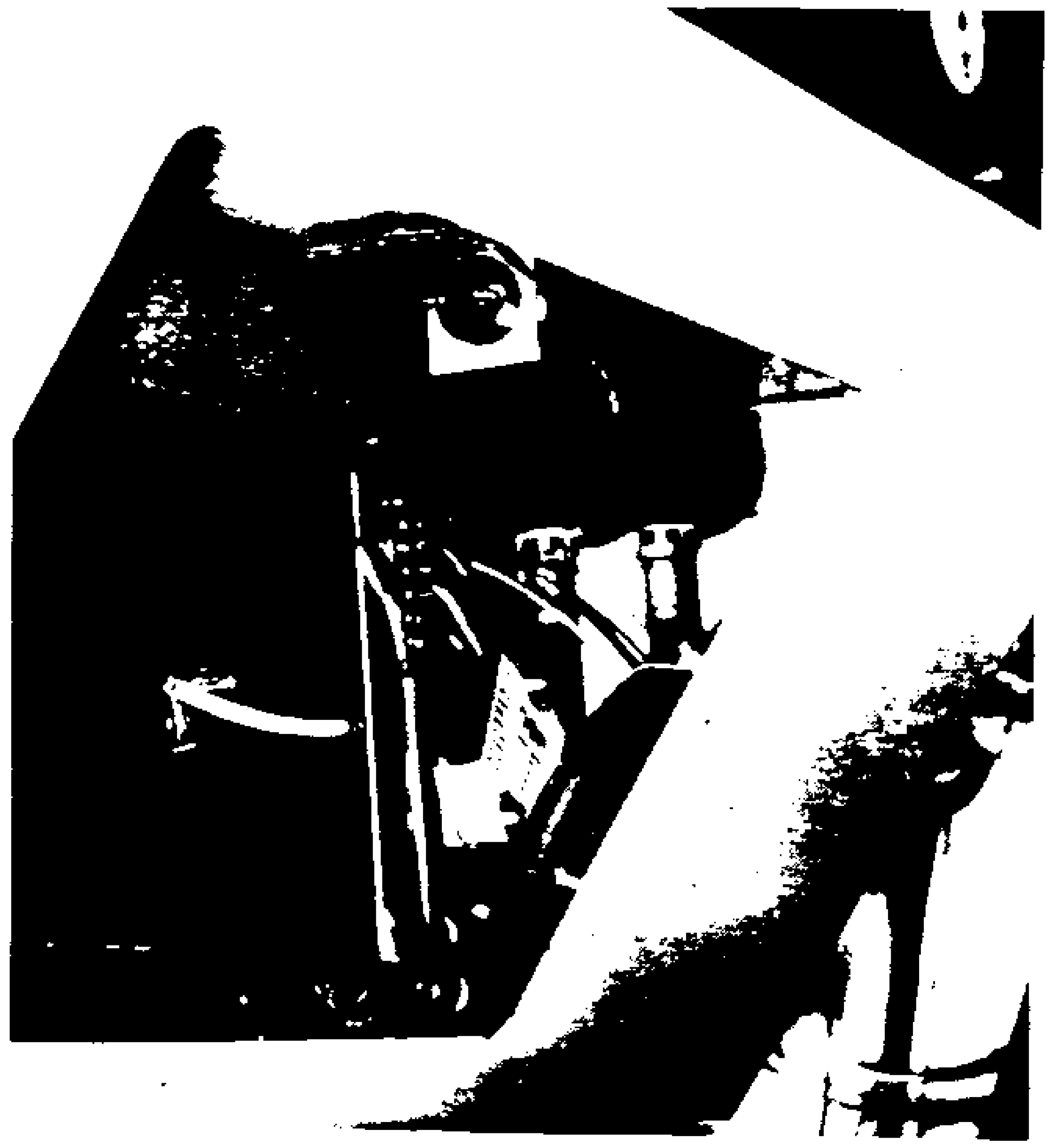

Figure 6. Heat exchanger mounting and connection details. The three foil fins in front of the air flow path are thermocouples. The device directly below the blower is a paddle flow switch. One of the thermocouple amplifier interfaces is visible.

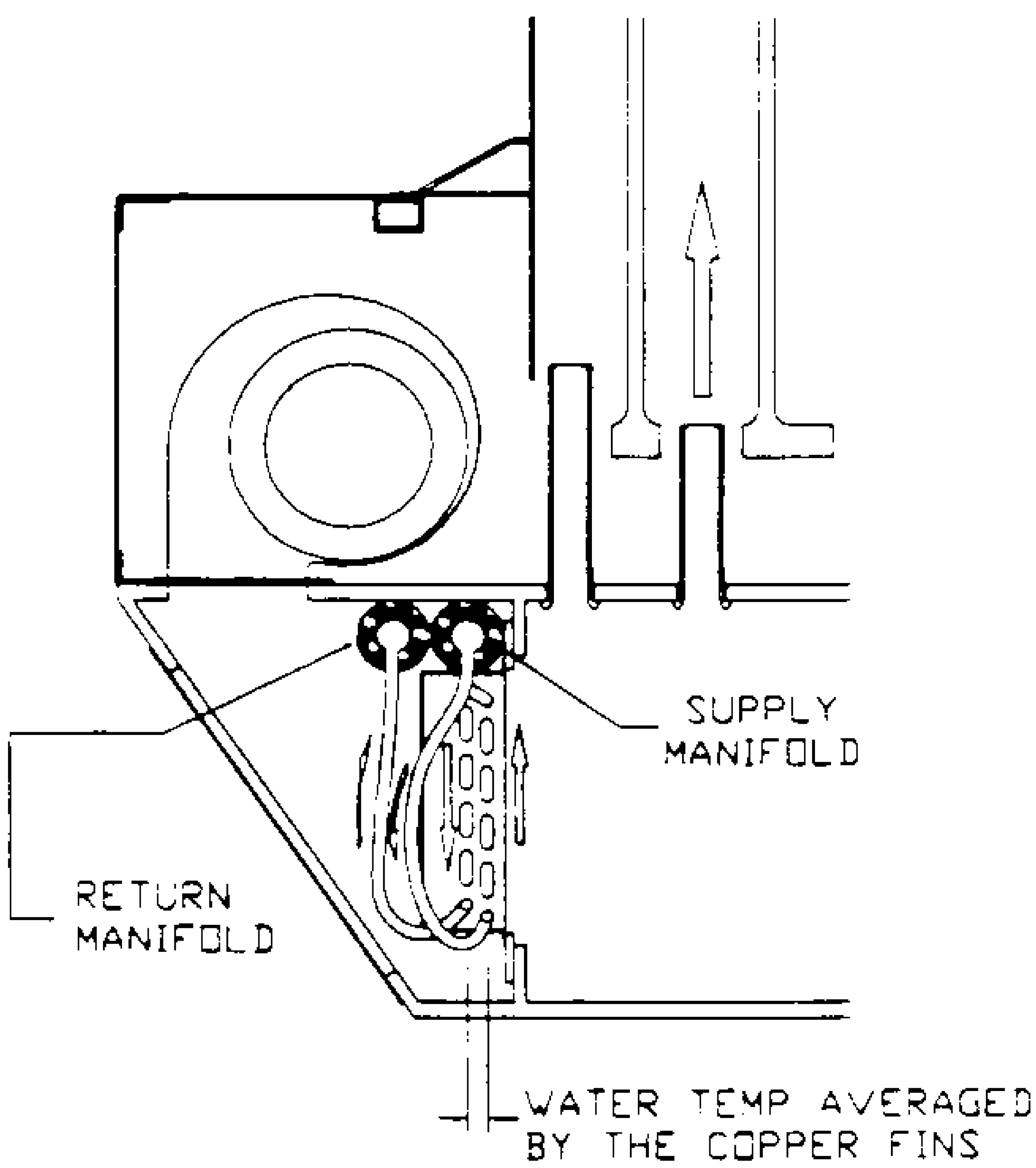

Figure 7. Heat exchanger connections

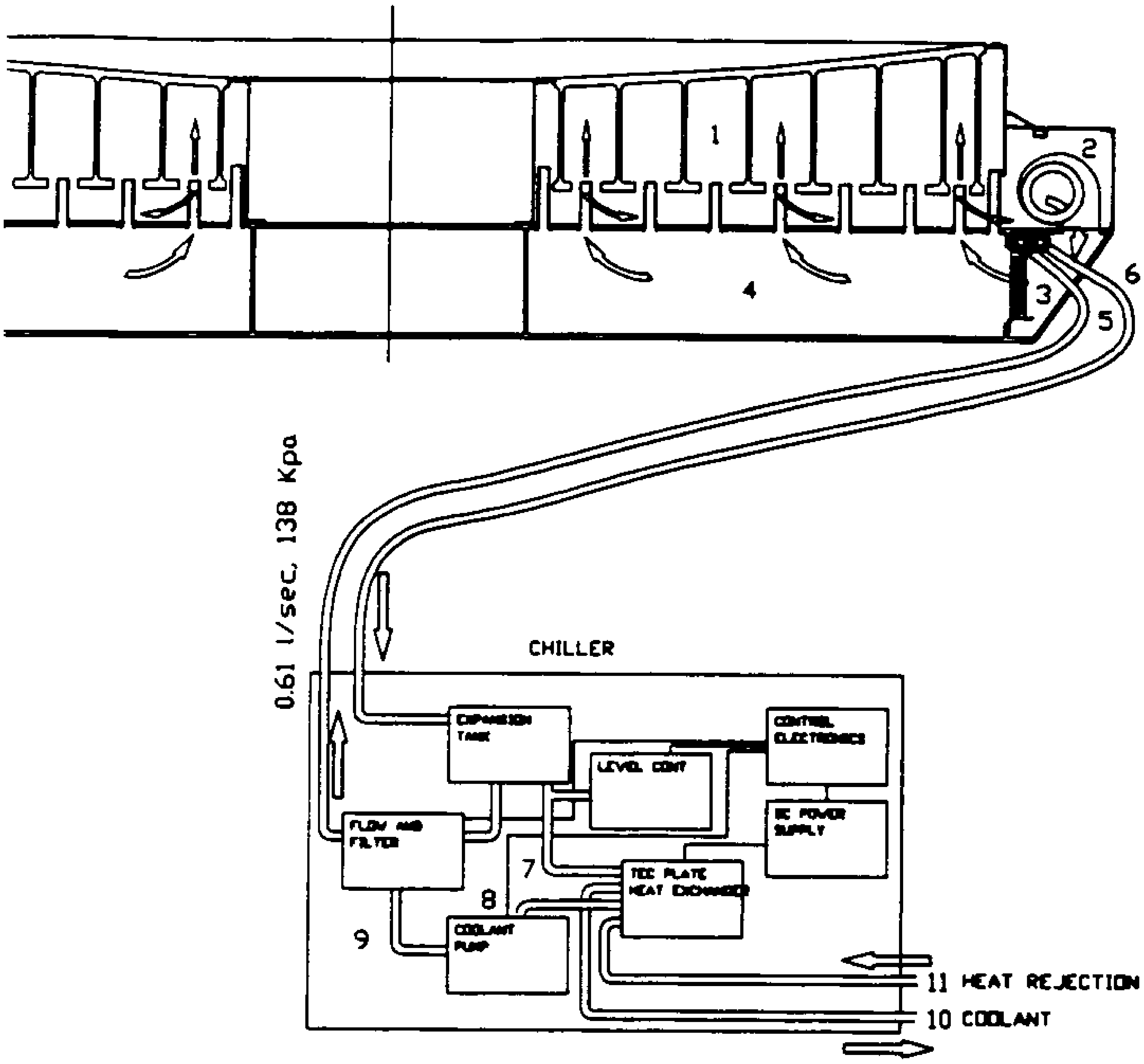

Figure 8. TEC chiller block diagram

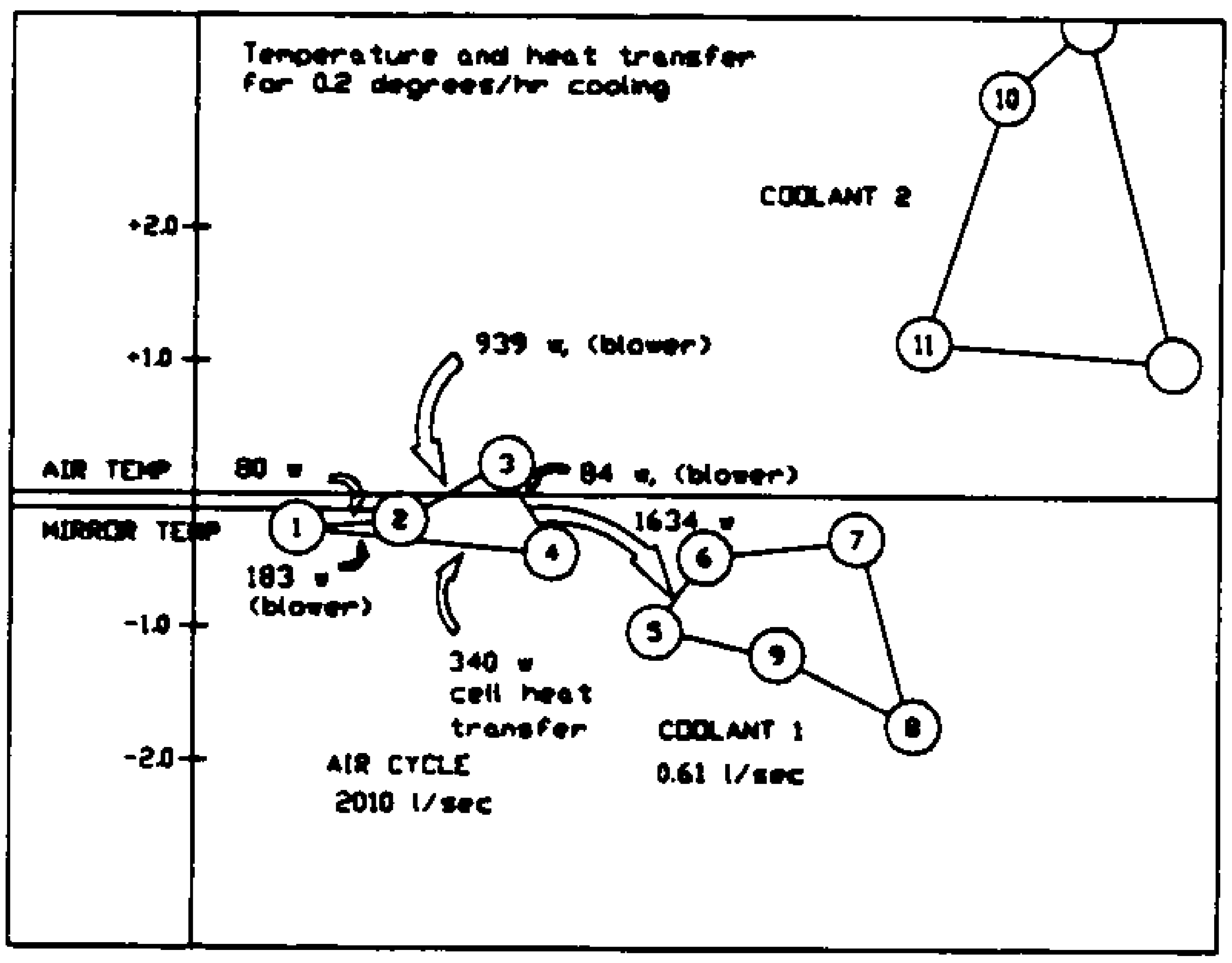

Figure 9. These are some measured performance values for a cooling rate of 0.2 degrees/HR. Temperatures for 7, 8, 9, and coolant loop 2 are estimated.

The pair of figures 8 and 9 show a block diagram of the TEC chiller and some typical performance values for the heat transfer in the mirror cell. The numbers in the balloons on figure 9 correspond to the locations indicated on figure 8.

3 TESTING

There are a series of tests planned for the WIYN 3.5m mirror that will be run in the NOAO optics polishing facility. [10] The attachment of the assembly to the tilt table of the 4m polishing machine allows testing at two positions; zenith pointing and zenith-82 degrees. The test setup allows a comparison of optical wavefront errors and thermal control performance. The mirror and cell prototype design also includes a 66-point active axial-mirror-support system that will be used to study the compensation of thermal bending with active supports. The initial tests are being done with a NESLAB water chiller which will be replaced by the TEC chiller when it is available.

Temperature in and around the mirror is recorded using a system of 1024 sensors. [7] Sensors are located inside each cell of the mirror and around the outside and inside diameter. Data from the mirror sensors is reduced to thermal contour maps that show the back-plate and face-plate temperature variations. A map of the air variation at the mid-plane of the cells is also generated. The variation on the outer and inner diameter ribs at the mid-plane is shown on the maps. Additional temperatures are measured at various points in the temperature control system. Flow of air in the system is calculated from measured electrical power to the blowers and differential temperatures measured across the components. Pressures are measured at the coolant supply pump, and across the components in the mirror cell. Heat transfer values are computed using the specific heats of the fluids and the measured flow rates.

The following is a summary of the planned test procedures.

1. Measurement of the vibration caused by the blowers and/or water flow.
2. Verify the calibration of the thermal temperature sensors by variation of the heat flow direction.
3. Test the ability of the system to negate an external thermal disturbance.
4. Test the control with a simulated dynamic thermal environment

4 PRELIMINARY RESULTS AND CONCLUSIONS

We have determined a few conclusions based on preliminary tests of the system. The findings are mostly positive but one must note that we are in the process of checking out the system.

The blowers can operate within the mirror cell without a problem of vibration. We have taken numerous scatter-plate interferograms with the system running and cannot see a difference when the blowers are switched. We looked at a point image with an auto-collimating microscope while switching the blowers and could see about 1/20 arc second of motion only during starting and stopping. Otherwise we could not see the effect of the blowers. We investigated the vibration at slower blower speeds and noticed a motion similar to the starting motion.

We could not detect image motion from the water flow.

We have measured some variation in air temperature across the individual heat exchangers. We suspect the major part of the cause to be variation in blower output. We will need to test the blowers and adjust them to a matched output.

The thermal servo is doing a fine job with matching the mirror to the air temperature. It has run now in the shop for days and controls to within +- 0.02 degrees. Even when temperature gradients are increased by opening doors the control is better than +- 0.2 degrees. The transient time for a stepped change in the mirror temperature is one hour.

Our temperature maps show an improvement in the mirror uniformity by a factor of two when compared with the system not running. The peak-to-valley readings go from 0.8 to 0.4 degrees. A portion of the improved 0.4 value appears to be offsets in the temperature readout.

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