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PAPER 2.4

A BALLOON-BORNE CRYOGENICALLY COOLED FILTER RADIOMETER

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ABSTRACT

Under ARPA sponsored contracts with the Air Force Cambridge Research Laboratories, Rockwell International has built and assisted AFCRL in flying a cryogenically cooled filtered infrared radiometer, on a high altitude balloon platform.

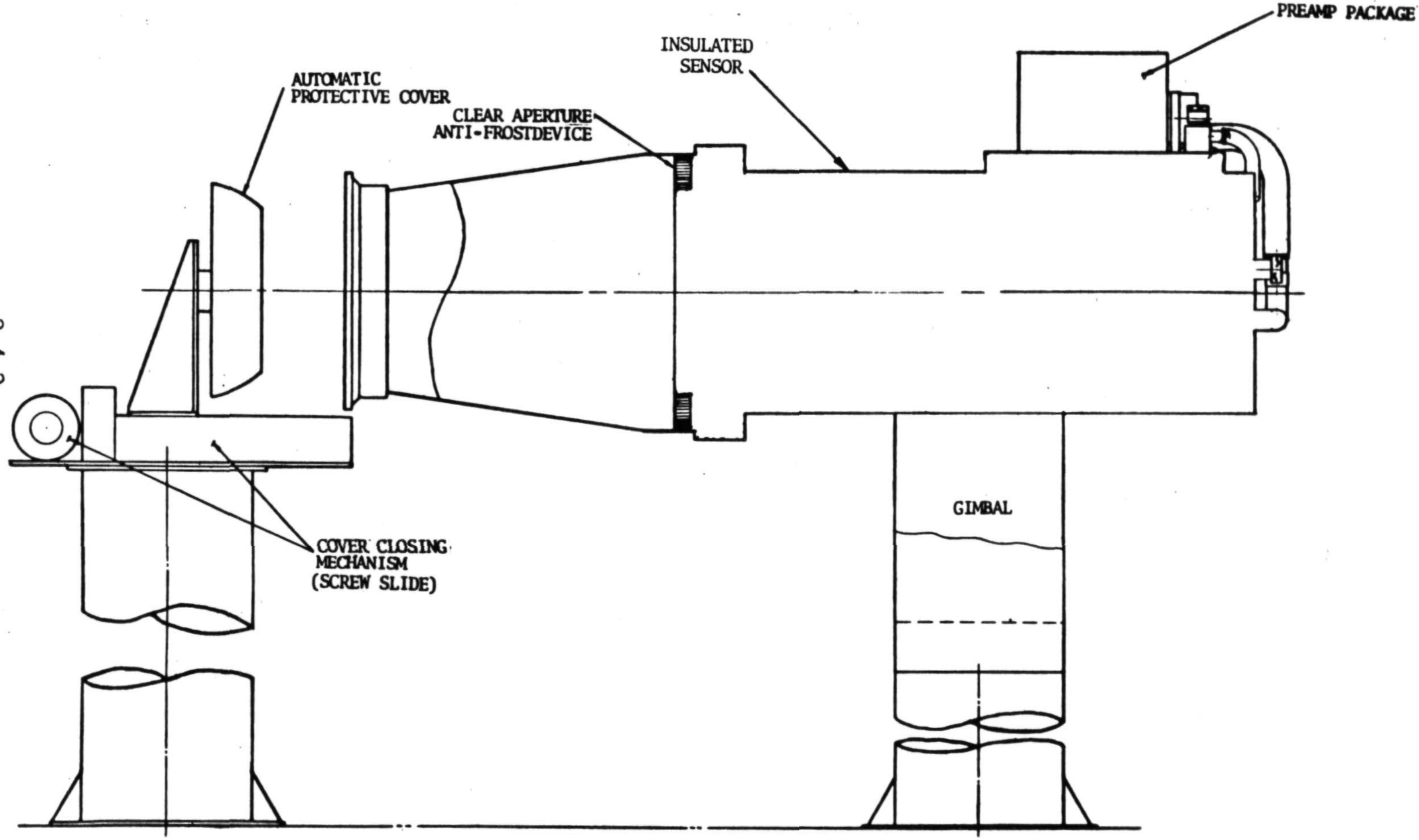
This radiometer has several unique features which include the options for the remote operation of two filter wheels each containing six filters at helium temperature, and a cryogenic rotary chopper which may be run at 200 cycles per second or positioned open or closed, and a remotely operable chopped blackbody calibration source. It contains a ten inch diameter liquid nitrogen cooled Cassegranian telescope with nine individually filtered field stops in its focal plane. Each of these field stops is reimaged for stray radiation rejection on a separate detector. The fields of view of the detectors are small and may be varied in size and shape by replacement of the field stop and detector masks. The telescope is mounted on a two-axis alt azimuth/artillery type/servo operated gimbal which is used to make sky scans under the control of an on-board programmer. The cryogenically cooled telescope is fitted with an antifrost device which protects the system from frost at altitudes above 35,000 feet. The system is capable of absolute spectral radiometry in the band from 3 to 25 microns.

OVERVIEW

Rockwell International's Contract F19628-72-C-0262 with the Air Force Cambridge Research Laboratories is one in which Rockwell International has furnished technical assistance to the Air Force in calibrating, installing and flying on a high altitude balloon platform, a radiometer which Rockwell International had previously built for AFCRL under Contract F19628-70-C-0126. Three flights were made under Air Force direction from Holloman Air Force Base, New Mexico. Rockwell International refurbished the radiometer between these flights. In the latter contract the contractor's role was largely that of an assistant wherein the contractor endeavored to provide the assistance required by AFCRL on a schedule determined by AFCRL.

During flights radiometric scans were made of the sky from an altitude of approximately 90,000 feet. The telescope was scanned 180 degrees in azimuth while it was systematically elevated at various angles from 0 to 60 degrees. Spectral filters were inserted during the scans to define various bands from 9 to 22.7 microns. Neutral density filters were inserted and gain changes were made at appropriate times. Both "AC" and "DC" signals were recorded. Calibration signals were inserted as the gimbals reversed direction at the end of each scan.

A unique feature of the radiometer is the capability of remotely operating its many controls by means of commands radioed from the ground. Figure 1 is a schematic of the radiometer system. Figure 2 is a photograph of the system mounted on the balloon gondola.



FIGURE]. SCHEMATIC DRAWING OF THE RADIOMETER SYSTEM

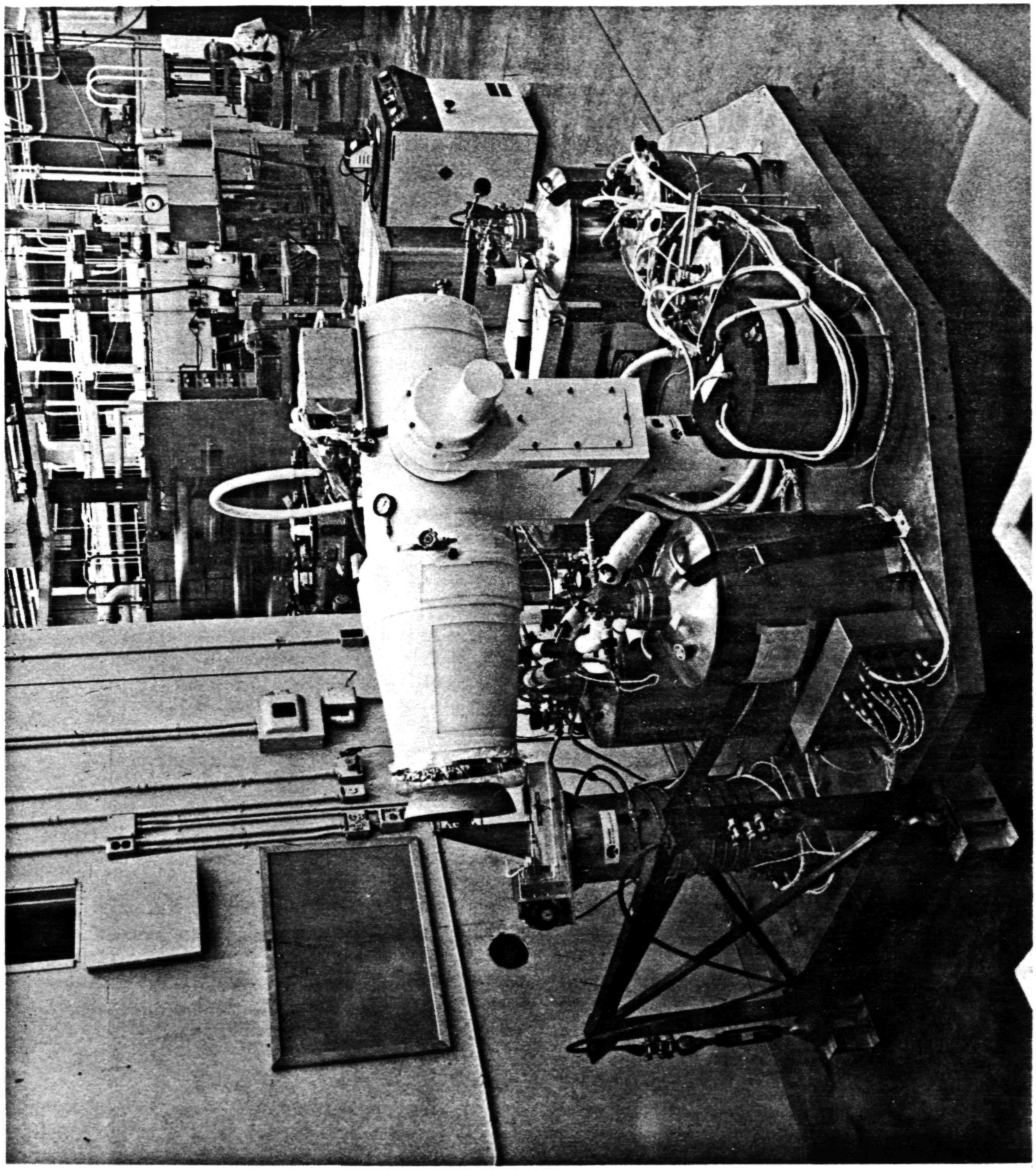


FIGURE 2. SYSTEM MOUNTED ON THE BALLOON GONDOLA

2.4-3

A light gathering system of the radiometer is a well baffled liquid nitrogen cooled Cassegranian telescope with a ten-inch diameter primary mirror. As the telescope's converging beam of radiation approaches its focus it passes through the plane of the rotary chopper. After passing through the Irtran-VI window and the Irtran-VI field lens which seal the vacuum space, the beam passes into the helium gas cooled reimaging cavity. After traversing the two filter wheels the beam comes to focus on a compound stop which contains nine individual openings each twice as large as the corresponding detector mask.

Provisions have been made so that a pair of filters can be placed at each individual field stop aperture. The converging beam(s) continue through the field stop and diverges to imping on an annular almost flat 4th order corrector mirror and still diverging is reflected back to a sphere from which they are imaged on the nine detectors. A linear demagnification of two is accomplished in the reimaging. The Cu:Ge detectors are individually masked to obtain the desired fields of view.

The detectors have FET preamplifiers mounted in close proximity to them and are biased by a feedback circuit to extend the dynamic range and frequency response.

The preamplifier of each detector feeds its signal into parallel linear and logarithmic amplifiers. The linear amplifiers have a wide range of gain settings which are controlled from the ground. The system contains an electronic calibrator which sends signals through the electronics upon command, to check the proper operation of the amplifiers.

Commanding circuitry which operates from Air Force supplied signals provides a means for the following: (1) starting and stopping the rotary chopper in flight and positioning it in a closed or open position; (2) operating the filter wheels to change the filters in the infrared energy paths; (3) changing the attenuator on the signal processing electronics; (4) operating the gaseous nitrogen flow control valves; and (5) operating the liquid nitrogen dump valves.

The sensor is mounted in a gimbal system which is driven by position servos in both azimuth and elevation. The gimbals are caused to position the sensor within their 210 degree azimuth and their 90 degree elevation range by commands from an Air Force supplied programming device.

A sectional view of the radiometer is shown in Figure 3. The radiometer housing is composed of two main sections, the front containing the radiometer telescope and the rear containing the reimaging system, detectors, chopper assembly, and filter assembly. The outer jackets of both sections are machined from aluminum alloy forgings which have been heat treated and cryogenically cycled during the interval between rough and finish machining so that thermally stable structures result. The outer jackets of both sections contain liquid nitrogen, as does the spider which supports the secondary mirror.

The telescope section has been designed so that the metal optical elements are mounted in a stress free fashion and are well cooled both by conduction to liquid nitrogen and by exposure to a purge of gaseous nitrogen at the temperature of the liquid. A heat exchanger, equilibrates the temperatures of the gaseous and liquid nitrogen before the gaseous nitrogen passes through the purge system to cool the mirrors.

The reimaging section contains a liquid helium tank, mounted in a vacuum space for thermal isolation from the outer jacket. It is supported by a fiberglass cylinder to control the conductive heat load. Mounted in this torroidal tank's center are the reimaging optics, detectors, and filter wheel assembly, all maintained at liquid helium temperature. The chopper wheel assembly attaches to the front of the rear section, and operates at liquid nitrogen temperature.

The optical system is designed so that the complete telescope section and the complete reimaging section are, as far as possible, each separate package subassemblies, and could be optically worked and tested as such. The supporting parts were toleranced so that focusing could be performed during the final assembly by optically lapping easily accessible surfaces.

The various demountable gas and liquid seals on the sensor body are accomplished by compressing round indium wire into a rectangular groove which is just a little too small to contain the volume of indium. The resulting overflow is pressed between the mating flat surfaces and forms a tight seal which will withstand cryogenic temperatures.

SENSOR

The sensor radiometer system consists of a paraboloidal primary mirror, a hyperboloidal secondary mirror, a "flat" mirror, an spherical reimaging mirror, an Irtran-VI window, an Irtran-VI field lens, a set of interchangeable filters, a field stop, and various masks and baffles.

The mirrors were all made from forged billets of aluminum alloy which were cut from the central portions of multi-ton ingots in order to avoid inclusions. The mirror blanks were then heat treated and thermally cycled several times during the process of fabrication so that their shapes remain stable when they are cooled to cryogenic temperatures.

After machining to spherical surfaces close to the optical surfaces required, the aluminum blanks were then ground and lapped to standard optical fabrication techniques to within a thousandth of an inch of the proper figure. Then a thick electroless nickel deposit was placed over the aluminum surface, and the final surface developed by further lapping and polishing of the electroless nickel coating. After testing, the optical surfaces were coated with electroless gold plate for durability and high long-wavelength infrared reflectivity.

The optical system is extensively baffled to reduce the sensitivity of the instrument to radiation from sources from outside of the field of view. In addition to the conventional baffles in the main telescope, additional baffles are included in the reimaging optical system to reduce the effects of diffraction by the spider and central obscuration. These baffles prevent the detectors from viewing these illuminated edges directly.

Figure 4 illustrates schematically the laboratory set up which was used to accomplish the radiometric calibration of the instrument. The laboratory calibrator which is the key piece of equipment used in the calibration is unique and requires description.

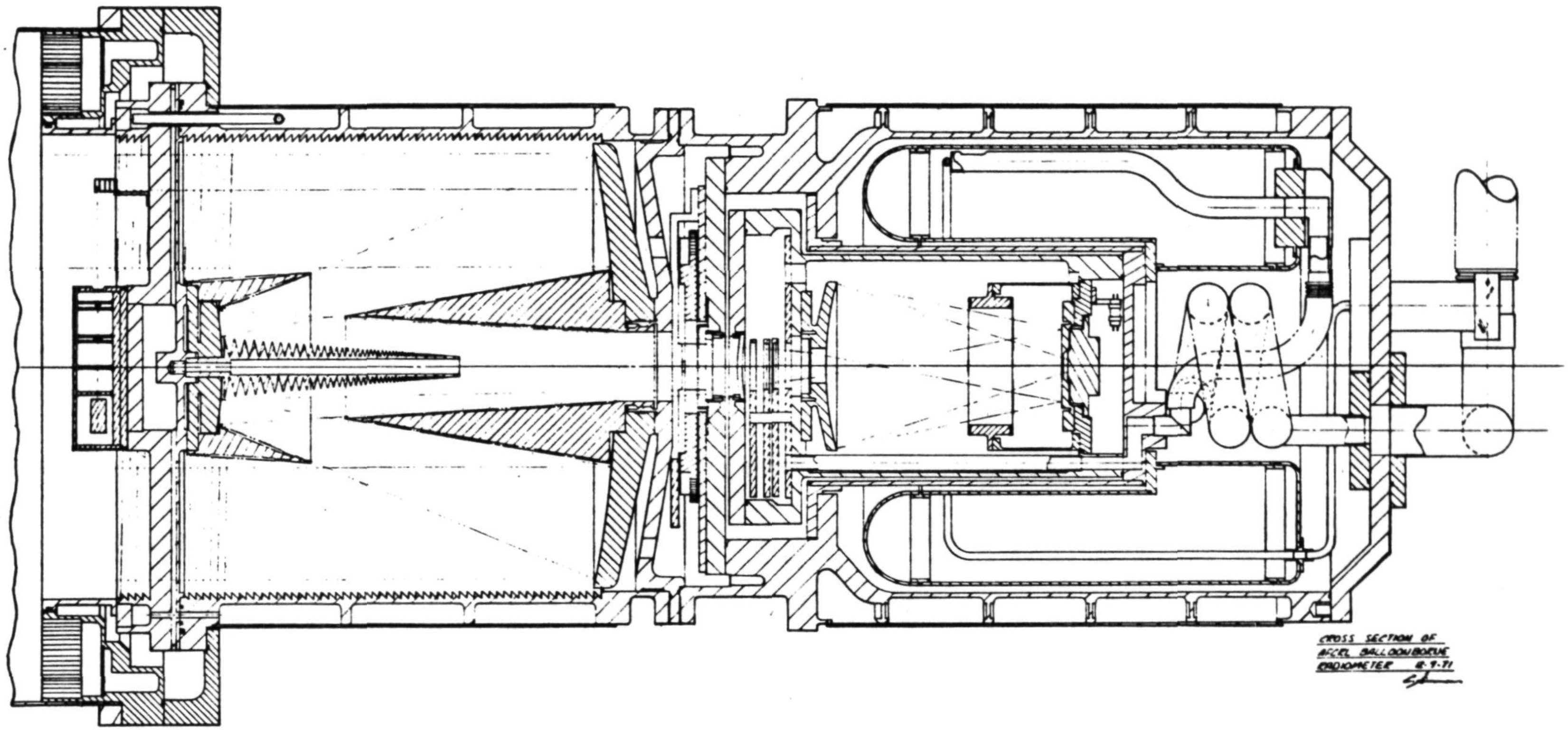


FIGURE 3. SECTIONAL VIEW OF RADIOMETER

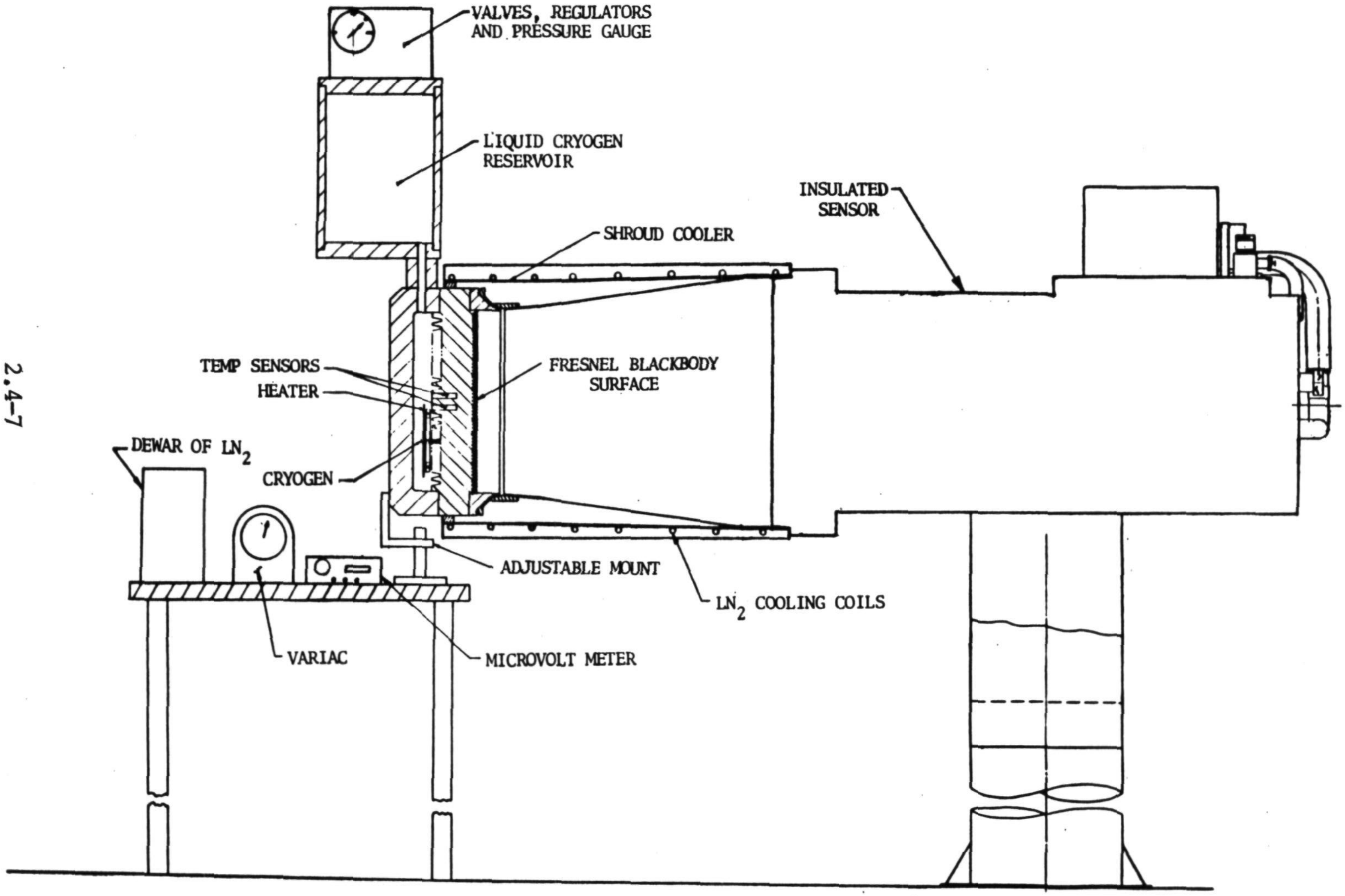


FIGURE 4. SCHEMATIC - RADIOMETRIC CALIBRATOR LABORATORY SET UP

CALIBRATION

The laboratory calibrator is a variable temperature blackbody source which is used for the preflight calibration of the infrared sensor. The device consists essentially of an insulated cryogenic pressure vessel in which the blackbody source, a circular, grooved plate, forms part of the wall. The heavy vessel can be operated at any pressure up to approximately 300 psi. The temperature can be varied almost continuously from under 77K to 300K. Large incremental changes of temperature previously had been achieved by using different cryogens. For a given cryogenic liquid, controlled, continuous changes of temperature are created at present by varying the pressure with the dewar.

In order to proceed expeditiously with the wide range calibration which was required, a 1000 watt calrod type heater was mounted inside the cryogen pressure cavity. When an electrical input to this heater is controlled by a continuously variable transformer, and the cavity contains pressurized gaseous nitrogen or a mixture of gaseous and liquid nitrogen, and the pressure adjusted as required, a wide range of stable temperatures may be obtained much more easily and quickly than by changing cryogens.

Figure 5 is a schematic drawing which shows the calibration device as it appears when attached to the shroud of the infrared sensor. The basic parts are the pressure vessel, calibration source plate, valves and pressure regulators, temperature sensors, and mounting devices. The outside of the calibration source plate is machined with concentric circular grooves, and then sandblasted and black anodized in order to provide a high emissivity.

Concentric circular grooves are also machined on the inside of the plate in order to increase the heat transfer between the cryogen and plate. Mounted on the top of the dewar are a fill valve, vent valve, multi-pin electrical feedthrough connector, burst disk, pressure relief valve, and pressure gauge. The temperature is monitored at a number of points within the source plate by copper constantan thermocouples. The sensor output leads are connected to the multi-pin electrical connector. Rigid attachment of the calibration device to the sensor is accomplished by clamps (not shown) which hold the sensor shroud against the mounting ring. The bottom mount supports the calibration device on a table. The pressure vessel is covered with Armaflex insulating material.

Proper calibration of the radiometer with the laboratory calibration device required that the faceplate of the laboratory calibrator be positioned at the end of the antifrost shroud and that no significant radiant energy be allowed to get into the radiometer except that emitted from the calibrator faceplate. This requires that the antifrost shroud be cooled to 77K, so that any radiance emitted from its inside surface, when reflected by the faceplate into the radiometer, will be very small compared to the emitted radiance of the faceplate itself. For this purpose a shroud cooler has been constructed for use with the laboratory calibrator.

The shroud cooler consists of an aluminum cylinder which fits around the antifrost shroud and attaches to the radiometer and the laboratory calibrator. A coil of one-half inch aluminum tubing is welded around this cylinder. Liquid nitrogen flowing through the tubing maintains the shroud cooler at 77K, and the shroud itself is then cooled by convection and radiation until it reaches an equilibrium temperature near 77K.

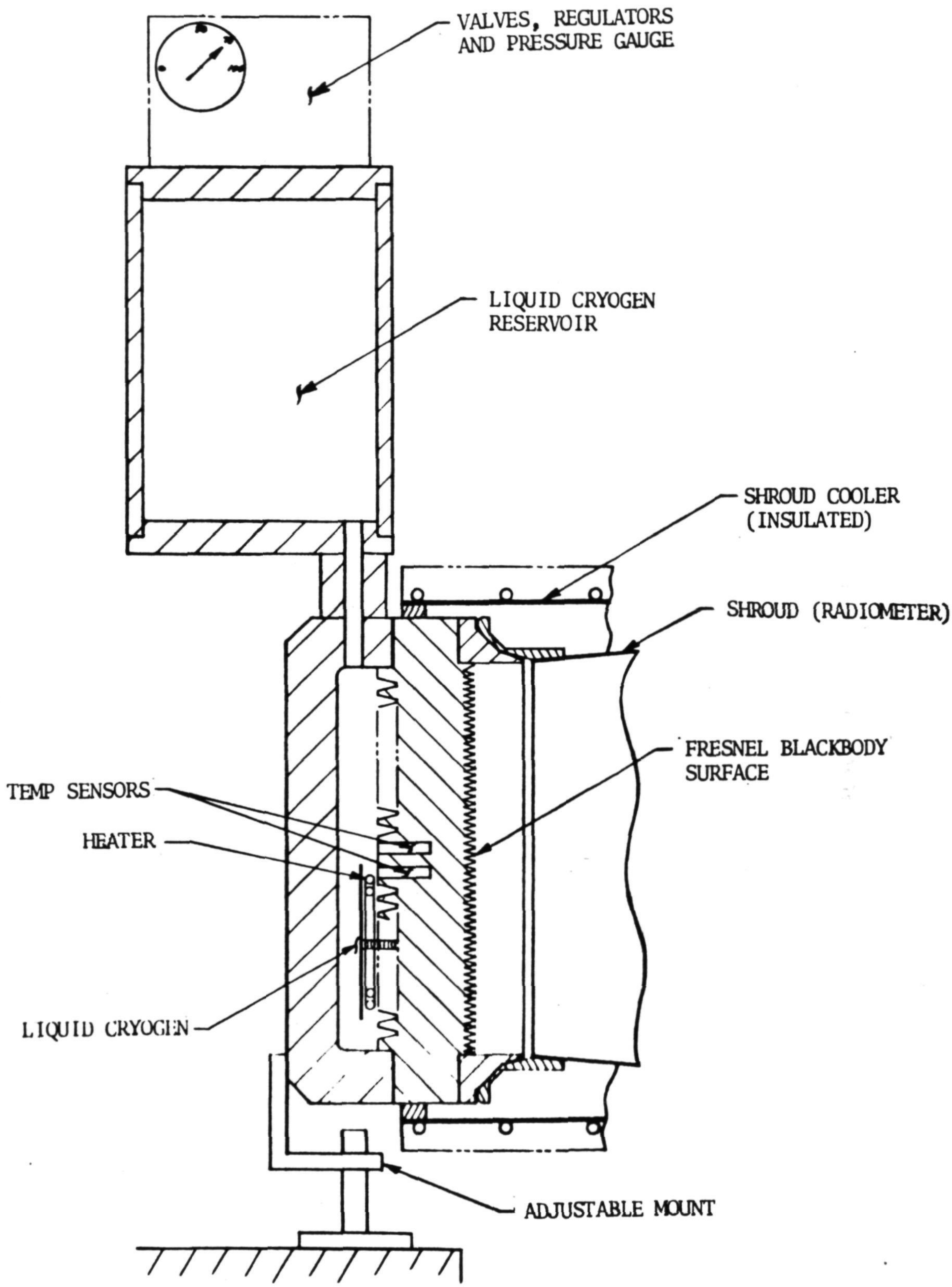


FIGURE 5. SCHEMATIC OF LABORATORY CALIBRATOR ATTACHED TO SENSOR HEAD

The AFCRL personnel determined the range of radiance over which calibration was desired and then prepared a list of temperatures at which these radiances would be emitted by the blackbody calibrator. Thermocouple EMF's (using a liquid nitrogen reference) were then tabulated for the listed temperatures. A digital microvoltmeter which displayed the thermocouple EMF was used as an indicator as the temperature and the radiance of the blackbody was set at each of the required steps. By manipulating the pressure of the gaseous nitrogen over the liquid nitrogen in the calibrator, and the electrical input to the 1000 watt heater in the calibrator the temperature could usually be held to 1/3 degree centigrade.

At each radiance step (temperature) the output of each detector through each amplifier and with a representative selection of gain steps and filter combinations was recorded. System noise was recorded from a true RMS voltmeter at the point where the radiance of the blackbody equaled the radiance of the chopper.

FILTER WHEELS

The two remotely operated filter wheels are located in planes between the field lens and the field stop. Each wheel has six positions, each position has the capability of containing two filters either spectral or neutral density. The filter wheels (as well as the reimaging mirrors and baffles) are cooled by liquid helium boil-off and operate at about 10K. The filter wheels can be independently rotated by remote control (onboard programmer or telemetry) to change filter combinations. The assembly is illustrated in Figure 6.

Each filter wheel is rotated by a solenoid-driven ratchet which engages teeth around the wheel perimeter. When a filter change command is received, The logic circuitry causes the ratchet mechanism to advance the wheel, stopping it automatically when the next filter is in position.

Signals representing the position of the filter wheels are transmitted to the ground by telemetry. A temperature sensor mounted on the assembly (but thermally isolated from it) reports the temperature of the helium gas surrounding the assembly.

CHOPPER

The chopper wheel is a three-bladed wheel rotating at 2000 rpm, resulting in a signal chopping frequency of 100 Hertz. The chopper is driven by a hysteresis synchronous motor and is capable of being stopped in either a closed or open position. The entire assembly is operated at a temperature of 77K. A photograph of the chopper wheel assembly is shown in Figure 7.

Normally stocked motors available from the vendors will not operate at 77K due to the freezing of their bearing lubricant. The bearings of a small synchronous motor were therefore replaced with special "BARTEMP" low-temperature ball bearings containing a sacrificial lubricating retainer. The motor runs at 12000 rpm and is powered by a 400 cycle inverter.

BARTEMP ball bearings are also used in the chopper wheel and in the idler gear. In addition, the idler gear itself is made of Rulon to avoid the necessity of lubricating the gear teeth.

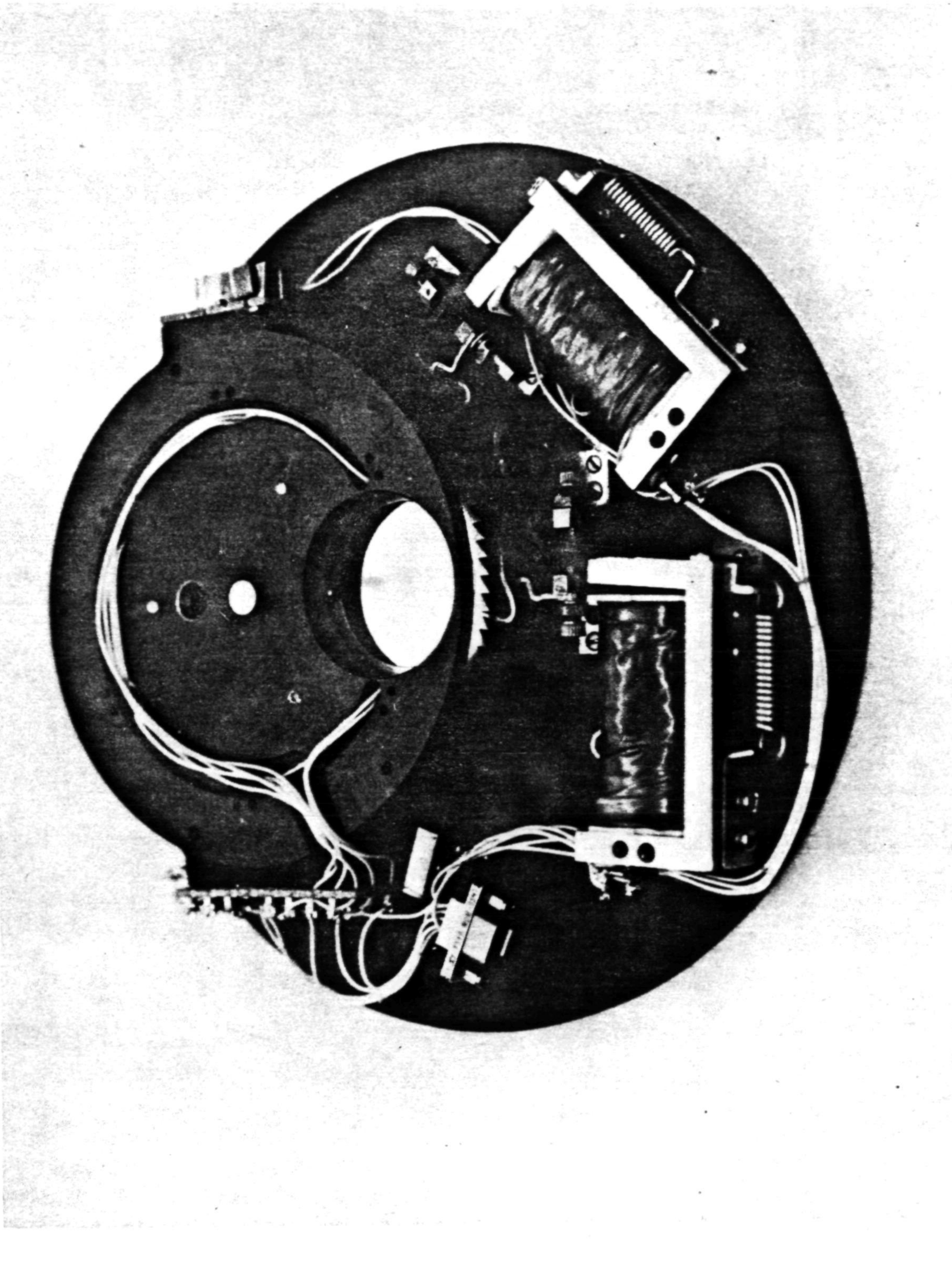


FIGURE 6. FILTER WHEEL ASSEMBLY
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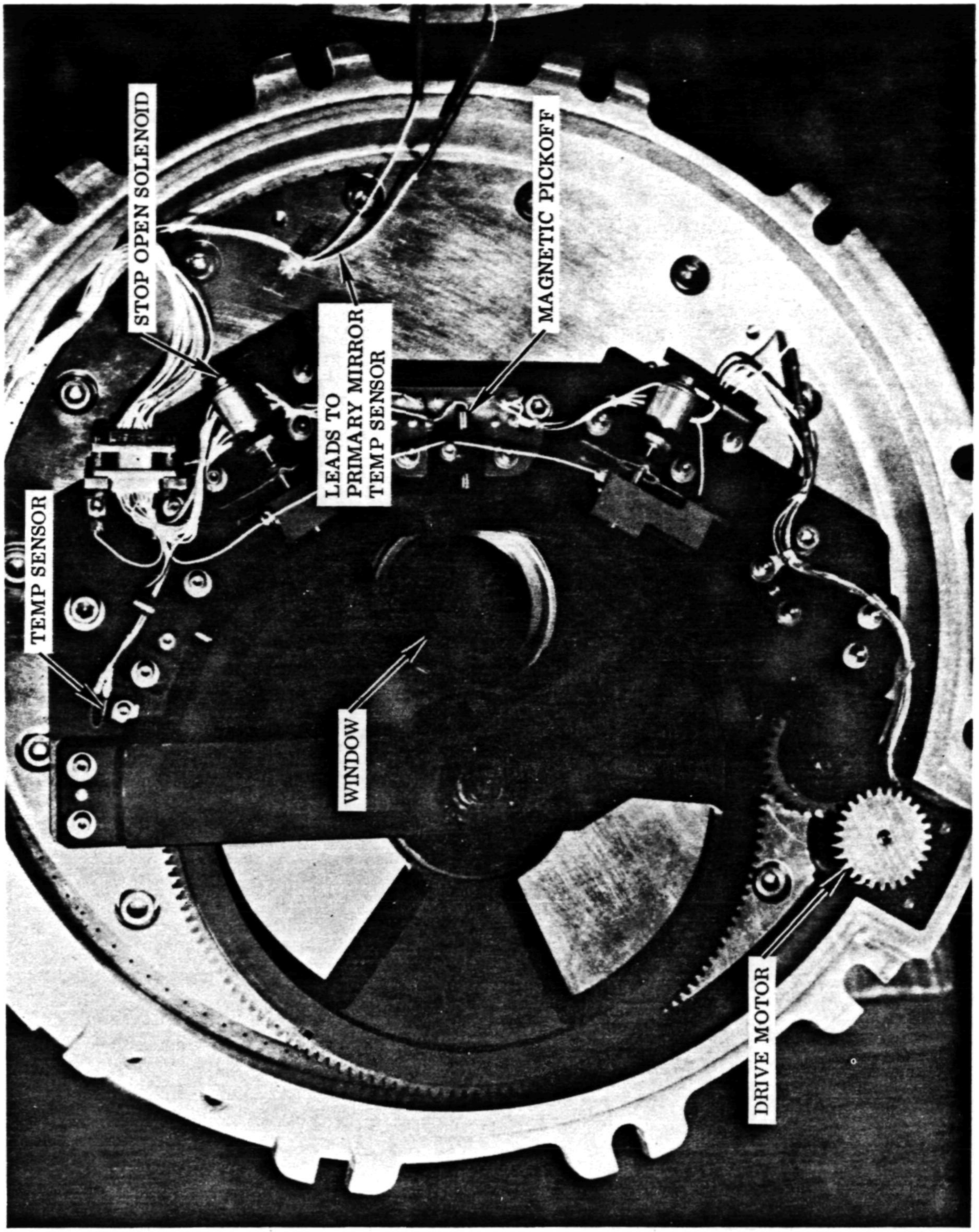

FIGURE 7. CHOPPER WHEEL ASSEMBLY

In the mechanism which was developed to selectively stop the chopper wheel in the open or closed position, a small linear solenoid is used to push a small steel pin into a hole in the chopper periphery. This provides a positive positioning action, and also permits remote verification of proper operation by simply monitoring the position of the locking pin with an electrical contact. Three holes in the chopper wheel allow it to be stopped with any of its three blades in the "closed" position, and a second solenoid angularly displaced from the first and working into the same set of three holes allows stopping in any of the chopper's three "open" positions.

The chopper can be remotely commanded to run or to stop in either the open or closed position. A time delay in the command logic prevents the stopping pins from being pushed into the wheel before it has coasted to a stop. Upon switching from the "running" mode to a stop mode, the following sequence of events is activated automatically: (1) the chopper motor is turned off; (2) after a preset time delay (90 seconds) to allow the chopper to stop, the stop pin is pushed against the wheel rim by the solenoids; and (3) the drive motor is pulsed to rotate the chopper wheel slowly until one of the three holes reaches the pin. Upon completion of this sequence the electrical contact on the solenoid mechanism will signal positive confirmation of chopper position ("open" or "closed").

CRYOGENIC SYSTEMS

The requirement that the radiometer must operate frost free and produce no fog, dictates the use of ambient temperature antifrost gas. A clear aperture antifrost device is fed dry nitrogen at approximately ambient temperature (260K) to prevent the formation of fog. The flow rates required depend upon the ambient pressure which controls the expansion and hence the flow velocity, and whether or not the balloon is ascending and producing a relative wind. In order to conserve the weight of antifrost nitrogen, weight of the water to vaporize it and the container weights, the system has been designed to utilize three different flow rates. Estimates based on laboratory and field experiments indicate that at altitudes between 80,000 and 120,000 feet, ten pounds of gas per hour will be sufficient to keep the aperture frost free. Twenty-five pounds per hour will be sufficient between 50,000 and 80,000 feet, while 50 pounds per hour will be required for operation between 35,000 and 50,000. The low altitude capability adds considerable weight to the system. The system has been built so that these flow rates can be preset before the flight or they can be programmed during a flight to allow measurements at several altitudes.

The gaseous nitrogen supply for the antifrost device consists basically of three liquid nitrogen storage containers, three heat exchangers, two temperature control valves, a gas mixer, and a gas flow control section.

The delivery liquid nitrogen container is vacuum insulated and contains liquid nitrogen at 60 psig. The pressure is maintained by a heater and controlled by a pressure switch and protected by a pressure relief valve and a disc.

The first heat exchanger converts liquid to gas by absorbing heat from a water bath. The heat exchanger is a coil of tubing immersed in a tank of water. The second heat exchanger is a coil of tubing in a smaller tank of water.

The gas flows through this exchanger system depending upon the operation of a temperature control. The third heat exchanger is a coil of tubing exposed to the ambient atmosphere. This exchanger is used to smooth out gas temperature fluctuations and to bring the gas temperature closer to the ambient temperature.

The liquid nitrogen supply system for cooling the telescope consists of a vacuum insulated liquid storage container, a liquid nitrogen delivery control device, and insulated delivery lines. The system delivers liquid nitrogen, on demand, to the liquid nitrogen jacket on the telescope. The telescope jacket is built around the liquid helium tank and acts as a cooled heat shield for the helium. The jacket also cools the telescope optics by conduction. The secondary mirror has a mounting which is in contact with a liquid nitrogen pool in the spider body. The spider pool is fed liquid nitrogen through drilled holes in the spider legs. The boil-off gas from the jacket is used as a continuous low temperature dry gas purge for the telescope, and provides additional cooling to the primary mirror and chopper. Conduction through the jackets foam insulation controls the production rate of the boil-off gas.

To operate the delivery system, the liquid container is filled with liquid nitrogen and pressurized by a heater which boils some of the liquid. The liquid is then transferred to the telescope jacket through insulated tubing, a section of which is flexible to allow telescope movement. The jacket level is sensed by a carbon resistor element in a control circuit which regulates the flow in the transfer line, thus maintaining the correct liquid level in the telescope jacket.

The helium-cooled subsystem consists of the reimaging package and the helium dewar. The reimaging package contains the detector package, the reimaging optics and field lens, and the two filter wheels. The subsystem is supported from its liquid nitrogen-cooled surrounding structure by a low thermal conductance glass epoxy tube, about six inches in diameter. This support cylinder lies within a well which extends the full length of the dewar, and attaches to the dewar at a step in the well somewhat more than halfway through the dewar. The reimaging package occupies the volume within the support tube, and is connected to the support tube and the dewar at the step in the well of the dewar.

The space between the helium-cooled subsystem and its LN_2 surroundings is evacuated to provide insulation for the helium subsystem. (Included in the evacuated volume is the annular space on either side of the support tube.) The LN_2 temperature of the surroundings and the 0.1 emittance of the clean aluminum surfaces of the various components result in a low radiative heat transfer to the helium subsystem. The radiative load is 0.002 watt to the reimaging package and 0.009 watt to the dewar. The primary thermal load is 0.016 watt to the reimaging package via the support tube. The total loads on the system are 0.018 watt to the reimaging package and 0.010 watt to the dewar.

The entire reimaging package is maintained below 10 K by flowing the gas evaporating from the dewar past the detector package, through the body of the reimaging package, and across the faces of both filter wheels before venting the gas from the system. The field lens is vacuum sealed to the front of the reimaging package to prevent the leakage of the helium gas into the vacuum space.

The gas evaporating from the dewar provides cooling equivalent to one latent heat of evaporation for every four degrees K the gas is warmed. Hence, the natural boil-off from the dewar (due to the 0.010 watt heat leak) is slightly less than that required to overcome the 0.018 watt thermal load on the reimaging package while maintaining the detectors below their maximum 10K operating temperature. Hence, a thermal shunt on the dewar has been chosen which will deliver about 0.04 watt to the liquid helium, sufficient to supply enough cold gas to keep the detectors below 7K. These calculations indicate that the dewar will contain sufficient helium for 14 hours operation.

This arrangement for flowing the vent gas through the reimaging package was designed for the express purposes of operating the filter wheels at a temperature specified to be no greater than 40K (and preferably below 35K) and of cooling the filter wheels to operating temperature in a reasonable time. In this design the entire reimaging package, including filter wheels, are rapidly cooled by the large quantities of gas produced during the cool-down and filling of the helium dewar. The filling of the dewar and the cooldown of the reimaging package take one hour. The operating temperature of the spectral and neutral density filters is near 10K.

DISCUSSION SUMMARY — PAPER 2.4

This system was used by the Air Force during four flights to study atmospheric constituents. Typical flight altitude was 90 to 96,000 feet. It was not developed as a shuttle prototype and is now in storage.

The instrument operated between 3 and 25 microns and it uses refractive optics. It includes filters mounted in a filter wheel and achieves 2-micron bandwidths. The performance was characterized as being within 50 percent of the theoretical limit for gallium doped germanium detectors.

Part of this system was cooled with liquid helium and part with liquid nitrogen. Therefore the detectors operated at 8° K, the reimaging optics at about 12° K to 15° K, the filters at less than 40° K and the primary, secondary and housing were cooled to liquid nitrogen temperatures.

A year and a half were used to design and build this system at a cost of $350,000. $125,000 was spent for flight operations over the next year and a half.