A LOW NOISE, HIGH THERMAL STABILITY, 0.1 K TEST FACILITY FOR THE PLANCK HFI BOLOMETERS

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ABSTRACT

We are developing a facility which will be used to characterize the bolometric detectors for Planck, an ESA mission to investigate the Cosmic Microwave Background. The bolometers operate at 0.1 K, employing neutron-transmutation doped (NTD) Ge thermistors with resistance several megohms to achieve NEPs ~1e-17 W. Characterization of the intrinsic noise of the bolometers at frequencies as low as 10 mHz dictates a test apparatus thermal stability of 40 nK $Hz^{-1/2}$ to that frequency. This temperature stability is achieved via a multi-stage isolation and control geometry with high resolution thermometry implemented with NTD Ge thermistors, JFET source followers, and dedicated lock-in amplifiers. The test facility accommodates 24 channels of differential signal readout via NJ32 JFETs operating at ~120 K for characterization of bolometer V(I) characteristics and noise. The test facility also provides for modulated radiation in the submillimeter band incident on the bolometers, for measurement of the optical speed-of-response; this illumination can be reduced below detectable limits without interrupting cryogenic operation. A commercial Oxford Instruments dilution refrigerator provides the cryogenic environment for the test facility.

INTRODUCTION

The Planck mission is an effort led by the European Space Agency (ESA) which will map the cosmic microwave background (CMB) over the full sky from the vicinity of the L2 point. The High Frequency Instrument (HFI) will be one of two instruments on the Planck spacecraft, and will achieve spatial resolution to 5 arcminute and background limited temperature resolution, with wavelength sensitivity from 100 GHz to 850 GHz. Radiation detection in the HFI is accomplished with Si_3N_4 micromesh bolometers[1] employing NTD Ge thermistors operating at 100 mK The detectors are fabricated at the Jet Propulsion Laboratory, which supplies packaged and tested bolometers to Cardiff University for integration into the Focal Plane Unit.

Validation of bolometer performance prior to integration requires a test facility of exceptional thermal stability, low electronic noise, and controlled thermal radiation background. Below we quantify the requirements, show how they are met in the design of the test facility, and describe the overall facility configuration.

TEST FACILITY PERFORMANCE REQUIREMENTS

Figure 1 shows schematically the scan pattern of the instrument and spacecraft. The L2 point (2nd Lagrange point) is a gravitational saddle point located at 1.01 A.U. from the sun on the sun-Earth line, or ~1.5 x 10^6 km spaceward of Earth. Objects at this location orbit the sun with period 1 year, remaining in the same position relative to the Earth. Planck scans the sky in a circle nearly perpendicular to the sun-Earth-L2 line, making one rotation in 60 seconds, thus mapping the entire sky in 6 months. The minimum beam of 5 arcminutes sets the upper electrical data frequency at ~180 Hz. The 1 rpm rotation rate of the spacecraft sets the lower electrical data frequency at 16 mHz The requirement for 2π response time constants of the bolometers per beam sets the minimum thermal time constant of the bolometers (typically < 2 ms). The HFI detectors operate in staring mode (the incident radiation is not chopped); the incident radiation is modulated only by the source.

Highest-quality data reconstruction requires that the detectors exhibit no output variation larger than the photon noise, over the entire electrical bandwidth of interest. Validation of this performance requires that the detector base temperature be held sufficiently stable that thermal variation does not mimic an intrinsic noise signal. For the expected performance of the bolometer thermistors and the required NEP of the detectors, we find the required thermal stability on the base temperature as follows:

$R_{bolo} = 3 \cdot 10^{7}\ \ \Omega$ = design bolometer resistance at 100 mK,

$NEP_{bolo} = 2 \cdot 10^{-17}\ \ W\ \ Hz^{-0.5}$ = typical requirement on science channels,

$S_{bolo} = 10^{9}\ \ V\ \ W^{-1}$ = typical sensitivity on science channels,

$I_{bolo} = 2 \cdot 10^{-10}\ \ A$ = typical bias current at operation condition,

$\alpha_{NTD} = \dfrac{d \ln R_{NTD}}{d \ln T_{NTD}} = 5$ = material property of NTD Ge thermistor;

and with the requirement that the noise introduced by thermal fluctuation in the bolometer base temperature not exceed the Johnson noise of the bolometer, we find

$$\frac{dT_{base}}{dt} \leq \frac{T_{base} v_J}{\alpha I_{bolo} R_{bolo}} = 40 \quad nV \quad Hz^{-0.5}$$

as the requirement on thermal stability. As noted above, this stability must be achieved over the entire electrical bandwidth of the instrument; in particular, it must be achieved to a low frequency of 16 mHz, a challenging requirement. We have taken $\frac{dT}{dt} \leq 20 \quad nV \quad Hz^{-0.5}$ to a lower frequency of 10 mHz as a design goal for the test facility thermal stability.

Clearly the electronics employed to characterize the bolometer must also contribute noise significantly less than that due to the bolometer. The lowest possible intrinsic bolometer noise is the Johnson noise, typically ~13 nV $Hz^{-1/2}$ for the operating condition. We have taken 6 nV $Hz^{-1/2}$ as a conservative requirement on the test facility electronic noise.

THERMAL STABILIZATION STRUCTURE AND THERMOMETRY

Thermal stability is achieved with a structure providing multiple stages of thermal filtering, and PID feedback utilizing high-resolution thermometry. Figure 2 shows the mechanical structure of the 4-stage stabilization assembly. Each stage is fabricated of OFHC copper plated with gold, and the stages are joined by continuous stainless steel tubes, alloy 316, of 0.95 cm diameter with 0.07 cm wall thickness. The attachment is made with low-temperature solder of 96.3% Sn, 3.7% Ag. The structure behaves as the thermal analog of a single-pole electrical RC filter, with time constant between two stages given by

$$\tau_{thermal} = K \frac{A}{l} C_p m$$

where K = the conductivity of the stainless steel link at the operating temperature
A = the total cross-sectional area of the link
l = the length of the link
C_p = the specific heat of the lower (warmer) stage
m = the mass of the lower (warmer) stage.

The top, coldest stage is strongly linked to the cold sink (a dilution refrigerator mixing chamber, described later). Thermal power transmission between the second and first stages thus experiences attenuation given by

$$T(w) = T(w = 0) \cdot (1 + w^2 \tau^2)^{-1/2},$$

as expected for a single-pole filter. Active feedback control of the second stage, with a time constant much shorter than the interstage thermal time constant, will spread the thermal noise power over a much larger bandwidth while adding little to the total thermal noise, thus decreasing the total thermal power within the transmission bandwidth from the third stage. Power conducted from the third stage will thus be significantly reduced, as will its thermal noise PSD. As implemented, the second and third stages have mass of 233 g, which near the operating temperature of 100 mK yields a thermal rolloff frequency of 65 mHz. The fourth stage, which holds the detectors under test, has mass 2.2 Kg and rolloff frequency of 7 mHz. Calculated and measured values for the thermal time constants between stages are in reasonable agreement, with the measured values being somewhat larger, probably due to specific heat of the stainless steel supports, which is not considered in the analysis. To date, only measurements of the cooldown rate of the assembly have been made; no independent measurement of the transfer functions or specific heat of the stages is yet available.

Absolute thermometry of the stage temperatures is obtained using commercial LakeShore GRT thermometers excited with an Electronika AVS-47 AC resistance bridge. These devices are not sufficiently sensitive, and may be too slow, to provide the sensitivity required for monitoring and controlling the stage temperatures. For high resolution thermometry we use NTD Ge thermistor chips supplied by Haller&Beeman Associates[ ] of dimension 0.40 mm length and width, 0.25 mm thickness, which have resistance ~5 Megohm at 100 mK across the length. Electrical contact to the NTD Ge thermistors is via 0.0025 cm diameter gold wires attached with H20E silver-filled epoxy. The wires also support the thermistors without strain, above a sapphire substrate bearing evaporated traces to which a connector is attached. Excitation of the thermistors is sine wave bias in a resistive quasi-constant-current configuration, as shown in Figure 3. The thermistor voltage is buffered by source-follower NJ132 JFETs operating at 120 K inside the cryogenic system, processed by a warm preamplifier, and detected with a dedicated lock-in amplifier. The preamplifier and lock-in circuit is identical to that used on the Polatron[ ] instrument. The preamplifier output is available for cross-checking the absolute thermometry. The lock-in amplifier DC output is available for active feedback control of the temperature. The lock-in amplifier output is filtered below 7 mHz, and the AC-coupled output is detected in an FFT spectrum analyzer to determine the noise, and thus the thermal PSD. The contribution of the JFETs to the noise, at the lock-in frequency of ~200 Hz, is approximately equal to that of the thermistor Johnson noise. The thermal properties of these NTD Ge thermistors are quite similar to those discussed earlier, but they can be biased at considerably higher current. With recent changes in the excitation and readout circuitry we expect to have improved the NEΔT of the high resolution thermometry to 15 nK $Hz^{-1/2}$, from a previously measured value of 25 nK $Hz^{-1/2}$. Seven such channel of high resolution thermometry are incorporated in the apparatus.

To date, a thermal problem has prevented implementation of active feedback on more than one stage of the stabilization structure. With the first stage under active control, the thermal noise PSD in the final stage, which houses the detectors under test, was measured to be <25 nK $Hz^{-1/2}$ to a lower frequency of ~100 mHz, near the required operating temperature of 100 mK It is expected that we achieve the required stability with PID control added to the second stage of the stabilization structure.

BOLOMETER CHARACTERIZATION ELECTRONICS

The biasing and readout electronics for bolometer characterization are shown schematically in Figure 3. Biasing is either AC or DC; both have produced comparable results. The load resistor module is maintained at a temperature near 100 mK, to suppress thermal noise. The JFET design is identical for the signal and thermometry sections. Both the load resistor and JFET packages are identical to those used on the Bolocam[ ] instrument. The antiphase bias excitation minimizes contribution from ground currents. We good result. Twenty-four measurement channels are available in the cryogenic apparatus. Bolometer voltage is processed by dedicated warm amplifiers of a design developed for the SPIRE[ ] instrument, which utilize an INA103 front-end preamplifier with noise <2 nV $Hz^{-1/2}$. The JFET noise contribution is <6 nV $Hz^{-1/2}$ for each channel, well below the bolometer Johnson noise. The preamplifier box forms a Faraday cage with the dewar structure, to minimize RF interference; filters from Spectrum Control[ ] are inserted in the signal wiring to suppress RF transmission.

Bolometer electrical responsivity is determined from bolometer voltage as a function of current, at several temperatures around 100 mK. The preamplifier box contains a single channel lock-in amplifier, identical to those used in the thermometry channels, for bolometer noise measurement. We expect to implement a separate bank of 24 lock-in amplifiers in the near future. From the measured V(I) and noise data we calculate the bolometer electrical NEP according to the equations given by Mather[ ].

Thermal time constant of the bolometers is measured by exposing them to a modulated radiation source, and observing the response as a function of modulation frequency. Radiation from a 1000 K blackbody and chopper[ ] located at the dewar top flange is coupled into the bolometer hermetic can via a light pipe (both are discussed below). The behavior of the bolometer is modified by electrothermal feedback from that of a simple thermal filter, but the bolometer exhibits a single-pole rolloff in response versus optical modulation frequency. For bolometers of high resistance or slow response, it is necessary to take account of the electrical transfer function of the test facility; the existence of capacitance in the JFET gates and elsewhere produces a rolloff in the transfer function comparable to the thermal response of the bolometers.

FACILITY DESIGN AND IMPLEMENTATION

As indicated above, the operating temperature of the Planck bolometers is 100 mK. An Oxford Instruments Kelvinox-25 dilution refrigerator was selected as the basis of the cryogenic system. An oversize Instrument Vacuum Can was specified, of 21 cm diameter and 45 cm length. As delivered, with no load other than radiation from the 4.2 K IVC, the mixing chamber achieved a lowest temperature of 21.8 mK, with cooling power at 100 mK of 23.8 μW.

Figure 4 shows the thermal stabilization structure thermally attached to the mixing chamber. All OFHC copper components intended for operation at the mixing chamber temperature were vacuum annealed to remove entrained molecular hydrogen[ ]. Struts from the IVC flange assist in supporting the approximately 4 Kg mass of the thermal stabilization structure; these are 0.32 cm diameter, 0.03 cm wall 316 stainless steel, with thermal intercept to the 4He pot to reduce thermal load to the mixing chamber.

The JFETs are contained within OFHC copper shields maintained at 4.2 K inside the IVC; thermal standoffs of 0.064 cm FR-4 fiberglass-epoxy plates allow the JFETs to self-heat to ~100 K, with supplemental heaters in active feedback loops maintaining the JFET temperature at ~120 K, where the noise is minimum. Bias inputs, signal outputs, and JFET power enter the dewar helium space via Detoronics[] 55-pin hermetic connectors at the top flange, and penetrate the IVC flange via similar connectors. Cryogenic wiring, except where isothermal, is a loomed, 12- or 24-twisted-pair flat cable of 0.0076 cm diameter manganin or constantan wire, manufactured by TekData[]. Wiring between the have used a Stanford Research Instruments DS360 function generator as a bias source, with good result. Twenty-four measurement channels are available in the cryogenic apparatus. Bolometer voltage is processed by dedicated warm amplifiers of a design developed for the SPIRE[ ] instrument, which utilize an INA103 front-end preamplifier with noise <2 nV $\mathrm{Hz}^{-1/2}$. The JFET noise contribution is <6 nV $\mathrm{Hz}^{-1/2}$ for each channel, well below the bolometer Johnson noise. The preamplifier box forms a Faraday cage with the dewar structure, to minimize RF interference; filters from Spectrum Control[ ] are inserted in the signal wiring to suppress RF transmission.

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The light pipe penetrates the IVC flange from the liquid helium bath, thermalizes at the 4He pot and at the mixing chamber, and accesses the hermetic bolometer volume. It has proven a challenging task to achieve sufficient optical modulation into the bolometer volume within the band of interest (0.3—1.0 mm), while maintaining a light pipe design which satisfies the thermal and vacuum requirements of the system. The present design has an upper section of 0.95 cm diameter, 0.015 cm wall 316 stainless steel with 25 um of gold plated on the inner surface, which couples to the lower section via a threaded joint in the liquid helium bath and is removable during operation. Radiation is coupled into the upper section from a blackbody at the dewar top flange. The lower section is 0.064 cm diameter, 0.030 cm wall 316 stainless steel, unplated, with a vacuum window of 0.1 cm thick Pyrex as a vacuum seal in the helium bath. We are not yet completely satisfied with the functioning of the light pipe, so it will not be detailed further here.

The total thermal load due to wiring, support struts for the thermal structure, and light pipe, have added approximately 7 μW to the mixing chamber, with the result that the lowest temperature now achievable is about 50 mK.

Figure 5 shows the entire cryogenic insert mounted on a sliding fixture for insertion into the dewar.

CONCLUSIONS

We are nearing completion of a test facility for the Planck HFI bolometers. The facility is required to have high thermal stability to low frequency, low electronic noise, and the capacity to inject modulated submillimeter optical radiation into a cryogenic hermetic container. We have demonstrated all requirements related electronic noise levels, we have approached the requirements related to the thermal stability, and it is expected that the remainder of the requirements will be met in the near future.

ACKNOWLEDGEMENTS

The research descrubed in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

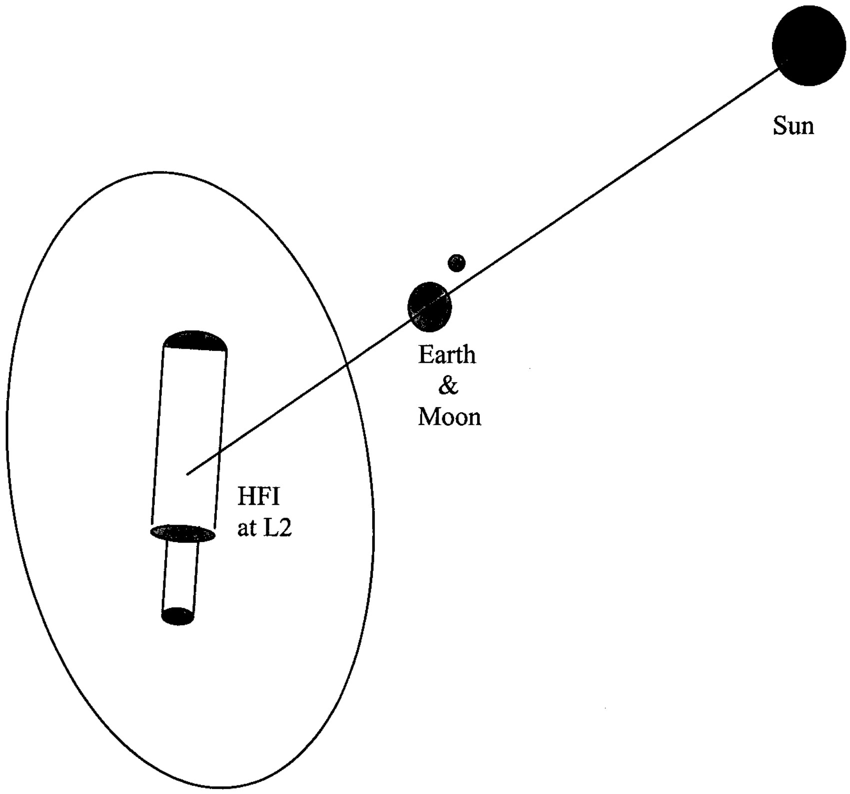

FIGURE 1. Schematic representation of scan plane of Planck instrument at L2. The instrument makes one revolution per minute in the plane perpendicular to the Sun-Earth-L2 line, and rotates with the Earth to map the entire sky in 6 months.

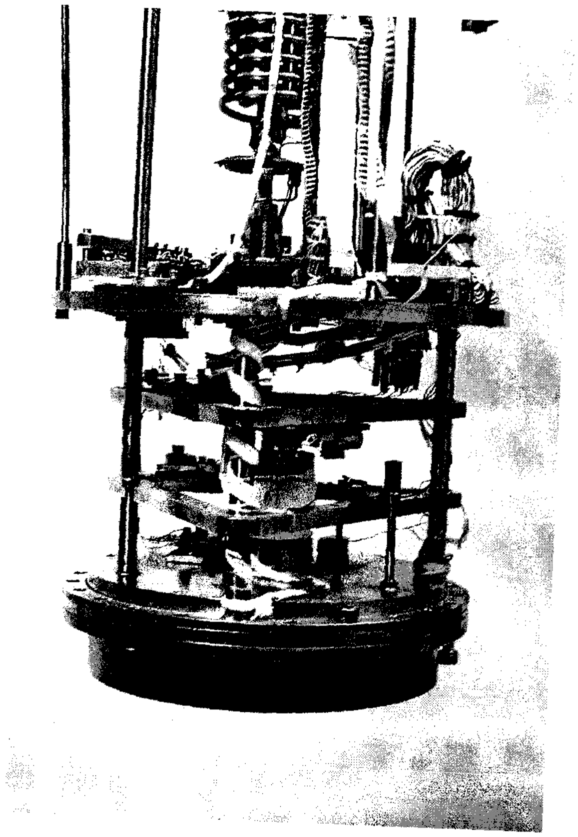

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FIGURE 2. Drawing of the Thermal Stabilization Structure, showing the four copper stages connected by stainless steel struts. The upper stage is shown connected to the dilution refrigerator mixing chamber.

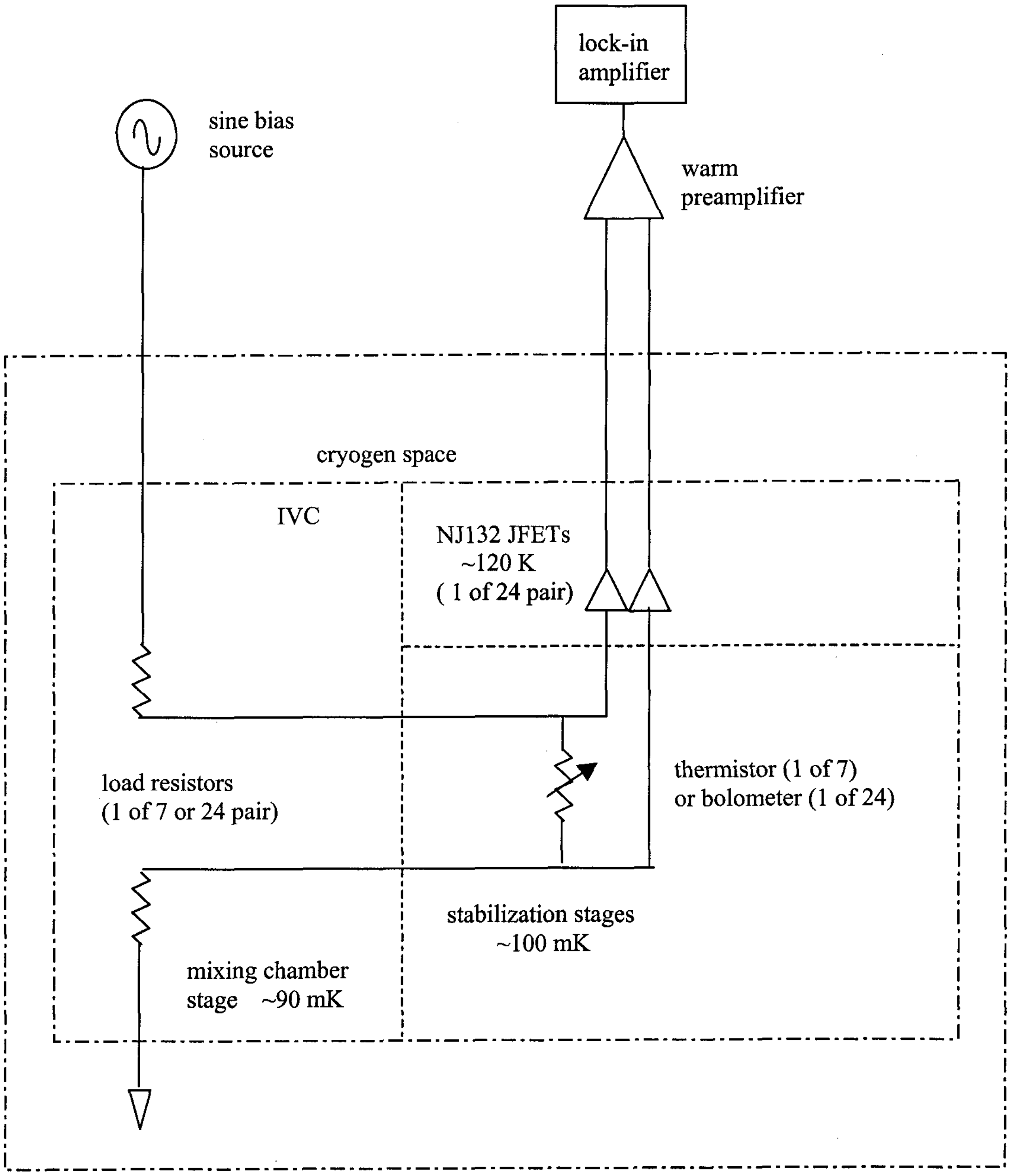

FIGURE 3. Schematic of bias and readout cicrut for high-resolution thermometry and bolometer characterization. Thermometry circuit is as shown; bolometer circuit uses balanced AC or DC bias rather than single-ended as shown.

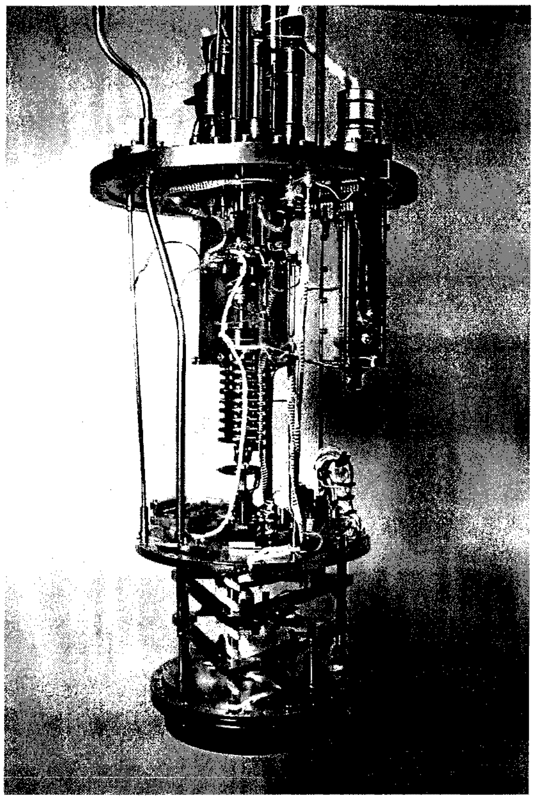

FIGURE 4. Instrument vacuum can volume with attached Thermal Stabiliztion Stage