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RADIOMETRIC COMPARISON OF A CAVITY INFRARED RADIATION SOURCE WITH A SELF-CALIBRATED CRYOGENIC BOLOMETER

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ARO, Inc.

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VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65802F.

This work was done by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was performed during the period from January 1, 1973, through April 30, 1973, under Project Number VF213, and the manuscript was submitted for publication on July 30, 1973.

This technical report has been reviewed and is approved.

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ABSTRACT

An attempt was made to confirm the calculated value of emitted radiant power from a cavity radiation source by measuring it with a self-calibrated cryogenic bolometer. The measurement was done in high vacuum with 40°K surroundings and a nominal radiant power of five nanowatts. Confirmation was not obtained because the self-calibrated bolometer could not be used as an absolute radiometer. However, the comparison effort led to improvements in the radiation source and to a better understanding of the bolometer.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A — Geometrical area of bolometer

a — Most sensitive area of bolometer receiver

A_{eff} — Effective area of bolometer

DVM	Digital voltmeter
IRS	Infrared radiation source
NEP	Noise equivalent power
R_H	Responsivity to absorbed heater power
R_R	Responsivity to absorbed radiant power
R_T	Theoretical responsivity calculated from bolometer load curve
X	Length of bolometer chip
Y	Width of bolometer chip

SECTION I
INTRODUCTION

The von Kármán Gas Dynamics Facility (VKF)Aerospace Chamber (7V) (Fig. 1) at the Arnold Engineering Development Center is equipped to test flight-rated infrared sensors which measure collimated radiation from distant targets. The usual background for these targets is cold, dark space, simulated in the 7V by gaseous helium (GHe) flowing at a temperature of 20°K through an aluminum chamber liner. Finned deeply on the inside and painted black, the liner is light-tight and prevents room temperature radiation from entering the enclosure where it could be reflected into the field-of-view of the infrared sensor. To simulate a distant target, radiation from a heated cavity infrared source (IRS) with a pinhole-sized aperture is collected by a collimating mirror and directed at the sensor.

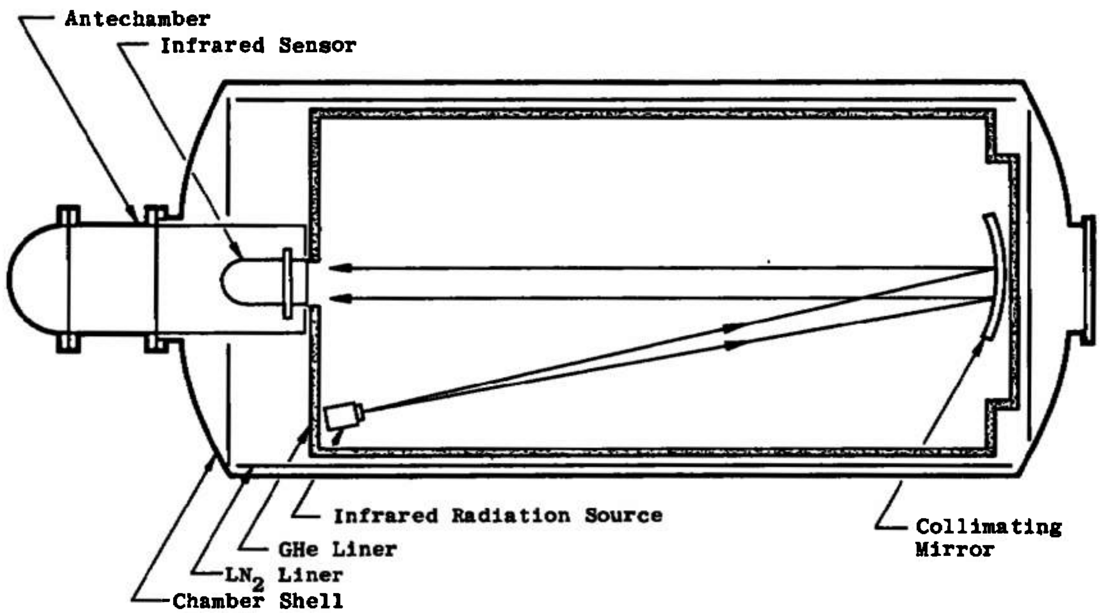


Fig. 1 Aerospace Chamber (7V)

Ideally, everything enclosed by the cold chamber liner appears black; and everything except the pinhole-sized aperture of the IRS has a temperature of 20°K. Any heat sources within the liner enclosure must be housed, therefore, in boxes actively cooled with 20°K GHe. Even with careful design of components within the liner enclosure, warm surfaces do occur occasionally and do appear as false targets to the infrared sensor.

The cavity pinhole and the collimating mirror produce a beam of collimated infrared radiation of extremely low irradiance. This beam must be defined in terms of its irradiance, spectral distribution, and decollimation. The difficulties of measuring the beam characteristics at test conditions can be appreciated when one considers the extremely low irradiance levels involved (i.e., far below 10^{-12} w/cm^2). Because of the low levels, direct measurements and calibrations of the beam characteristics have not been attempted to date. The beam characteristics are presently established by measuring the characteristics of the collimating mirror and the IRS used to generate the beam. Therefore, it is of utmost importance that the IRS be properly designed and experimentally evaluated before using it to test an infrared sensor.

The first approach to National Bureau of Standards (NBS) "traceability" was to use commercially manufactured infrared sources and to send them to NBS for calibration. This method was unsatisfactory because the commercial sources were not properly designed for the 7V optical system and because the NBS could not calibrate them under the exact conditions for which they would be used. Beam irradiance errors of up to 1000 percent were encountered. Infrared sources were then designed and built locally for the 7V test chamber, but the "traceability" problem remained.

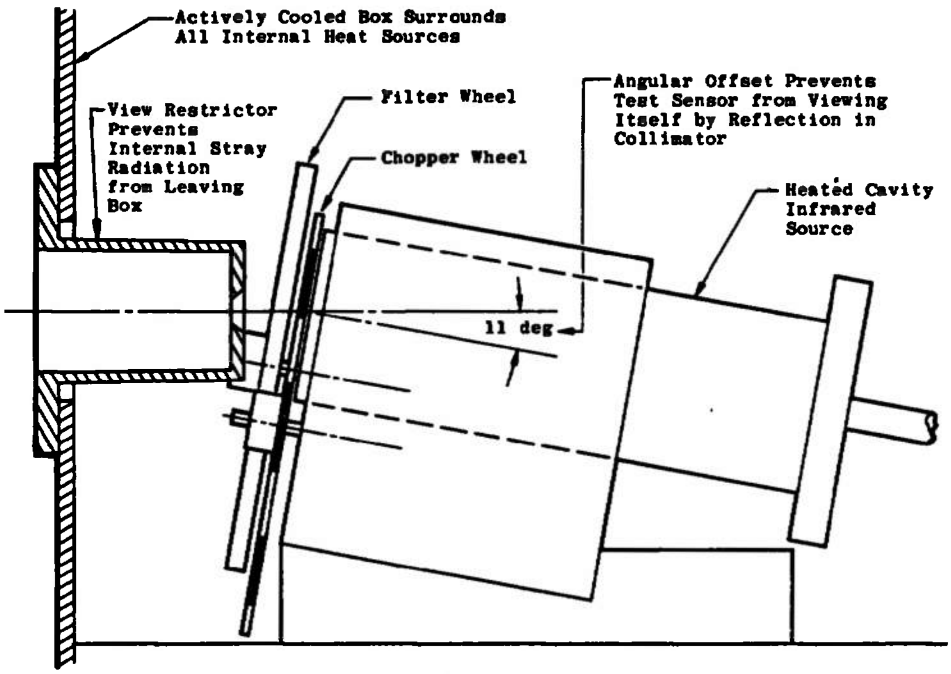
To experimentally evaluate an IRS, its radiant output must be measured with a radiation detector having the following characteristics: a uniform spectral response over the range of wavelengths emitted by the IRS, adequate responsivity to measure the low irradiance levels from the IRS, and preferably a capability for self-calibration. The choice of such detectors is severely limited. One detector, a black, cryogenic silicon bolometer, was advertised to have an in-place self-calibration feature. It was an experimental, unproven device. Nevertheless. a locally fabricated IRS and the silicon bolometer were installed in a small vacuum chamber. The object was to verify the radiant output of the IRS at cavity temperatures from 200°K to 400°K and simultaneously investigate the operating characteristics of the bolometer. Radiant power intercepted by the bolometer from the IRS was typically 5×10^{-9} w.

The benefits of this work were twofold: (1) a fully tested IRS was made available for use in 7V test projects, and (2) a procedure for testing future infrared sources was established.

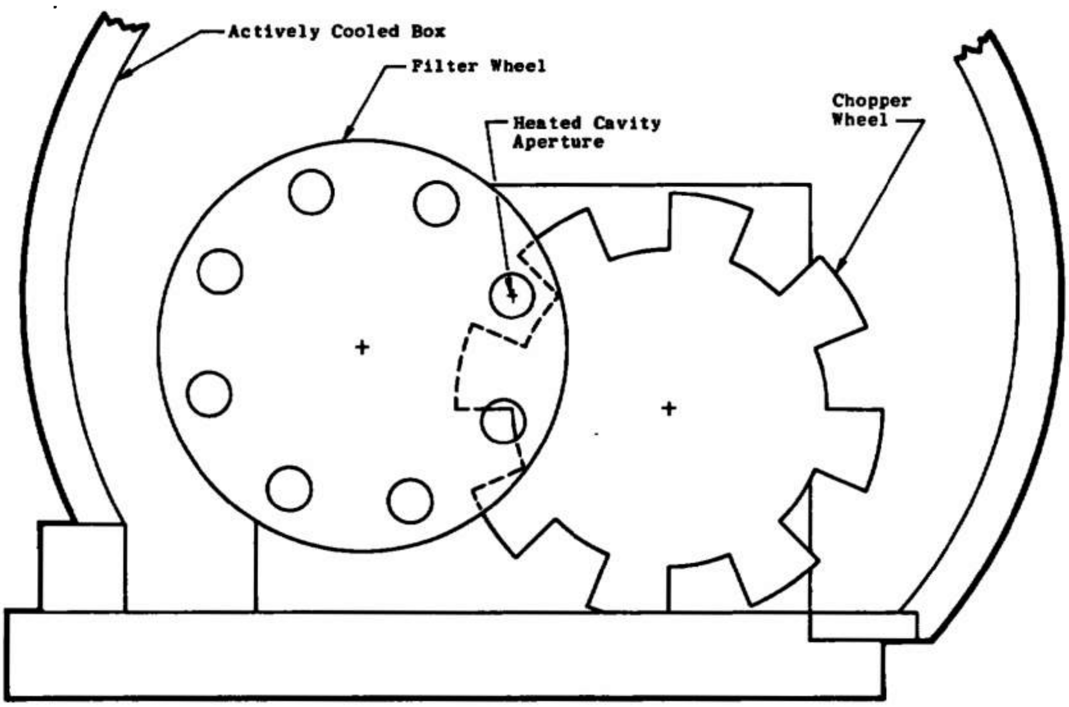
SECTION II
APPARATUS

2.1 INFRARED RADIATION SOURCE

The IRS (Figs. 2a and b) is designed to be used at the focus of the 7V collimating mirror and to emit radiant power having blackbody characteristics. Because a stable emittance is required, as close to unity as practicable, the design of the IRS begins with an off-axis re-entrant cone (Fig. 2c) of anodized aluminum. The inside of the cone is painted with a high-temperature (600°K) black paint. The conical source is mounted on a telescoped stainless-steel tube, which provides the required thermal resistance between the cavity block and the cold heat sink; the cavity block is resistance heated; and the temperature is controlled with a platinum resistance wire spiraled around the block. Cavity temperature is measured with a thermocouple which is referenced to the temperature of the IRS housing (Fig. 3). A calibrated platinum resistance thermometer measures the housing temperature at the location of the thermocouple reference junction.

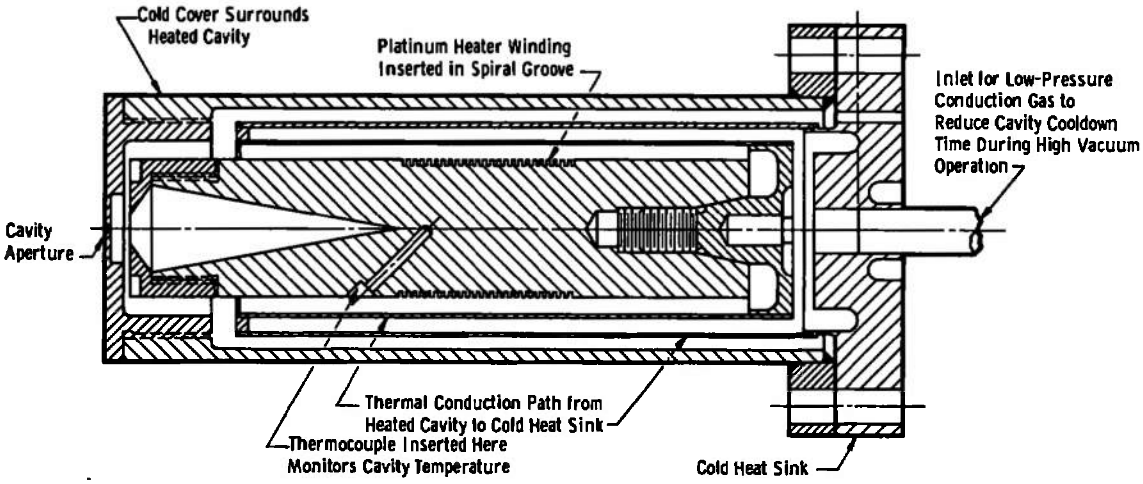


a. Side View



b. Front View (Front Cover Removed)

Fig. 2 Infrared Radiation Source



c. Cavity Construction
Fig. 2 Concluded

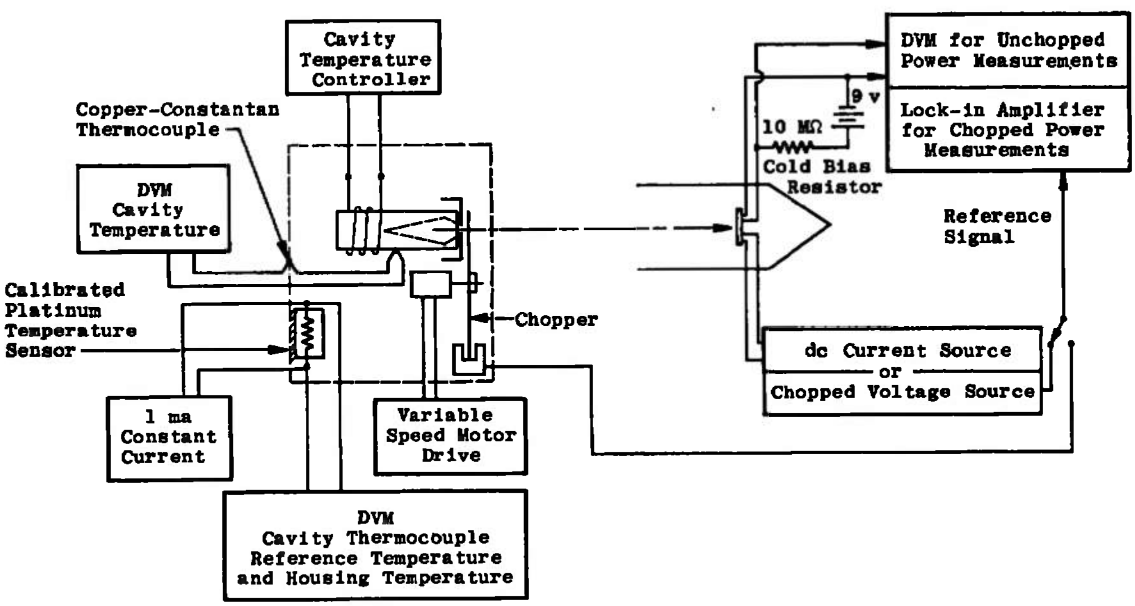


Fig. 3 Bolometer Circuit and Instrumentation

A motor-driven chopper wheel provides essentially square wave chopping of the emitted radiation over a wide range of frequencies. If unchopped radiation is required, an open sector of the chopper wheel can be aligned with the IRS exit aperture by energizing a separate "holding" coil in the permanent magnet stepping motor which drives the chopper. The chopper wheel can be driven with as little as 10-mw input to the motor.

A similar stepping motor drives the filter wheel, which contains neutral density filters having various values of transmission from unity to zero. A positive indexing mechanism and position indicator assure that the desired filter is aligned with the IRS exit aperture.

2.2 CRYOGENIC BOLOMETER DETECTOR

The bolometer (Refs. 1 and 2) used in this radiometric comparison has the following specifications:

Material - phosphorous-doped silicon
Size - 5 x 5 x 0.4 mm
Operating temperature - 1.5°K nominal
Responsivity - 375 kv/w^{-1} (dc-theoretical)
NEP - 1×10^{-13} w(Hz)$^{-1/2}$ at 20 Hz
Absorbing coating - Nextel® black paint
Self-calibrating heater - thin-film resistor deposited on bolometer chip

Mounted by its lead wires at one end of a view-restricting cylinder (Fig. 4), the field-of-view of the bolometer was limited to 10 deg. A cone-shaped rear cap completed the bolometer enclosure and absorbed target radiation not intercepted by the bolometer chip. The enclosure was mounted on a heat sink attached to a liquid helium (LHe) container (Fig. 5). A 10-MΩ bias resistor was mounted inside the vacuum chamber on a 35°K heat sink. The complete circuit and instrumentation used with the bolometer are shown in Fig. 3.

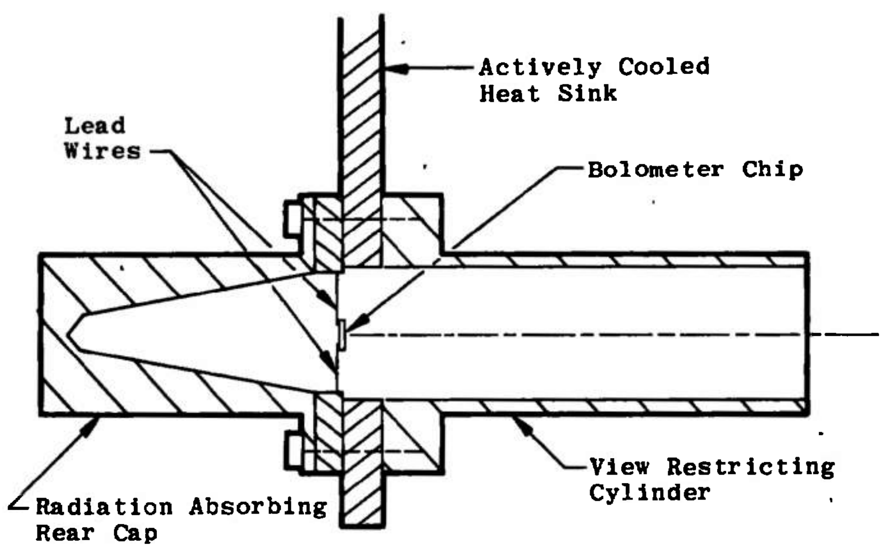
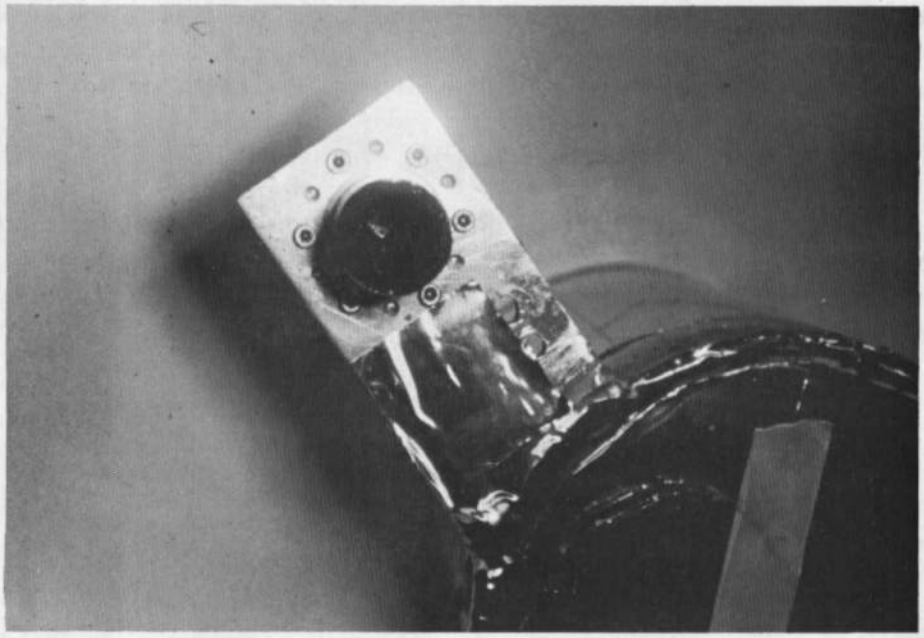
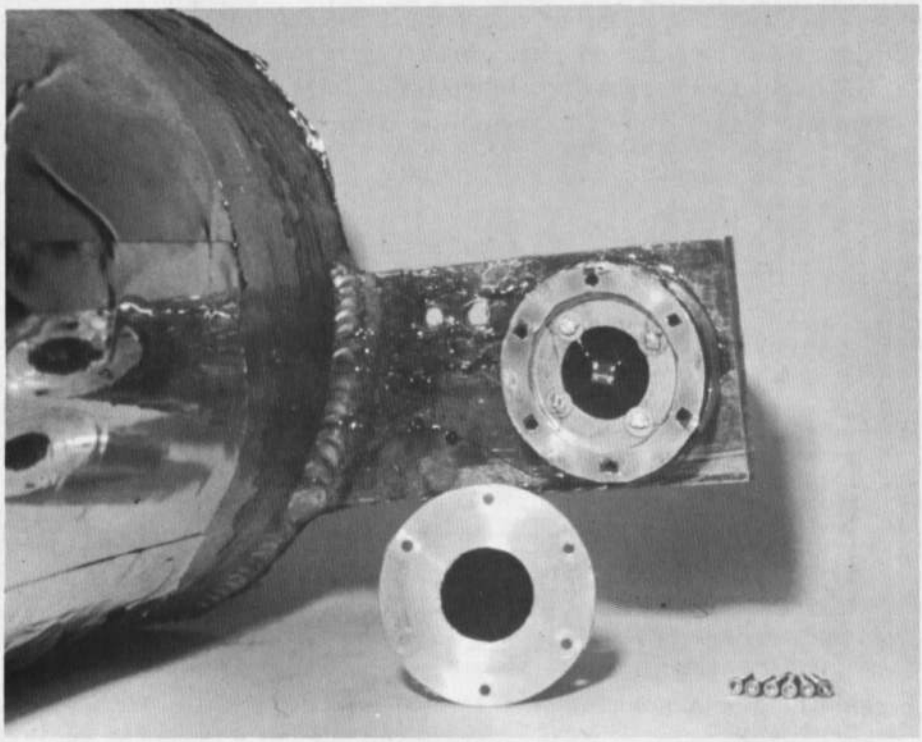


Fig. 4 Bolometer Detector (Schematic)



a. Front View



b. Rear View
Fig. 5 Bolometer Detector (Photographs)

2.3 VACUUM CHAMBER

Both the IRS and the bolometer were mounted in a vacuum chamber (Fig. 6) which contained a GHe-cooled liner. Surrounded by a blackened enclosure at a temperature less than 50°K and ambient gas pressure less than 10^{-6} torr, the IRS and the bolometer had minimal heat transfer to their surroundings. Gaseous helium from a cryostat was used to cool the chamber liner and the IRS chassis (in series on the same circuit). The bolometer LHe reservoir (five liters) was filled from a Dewar flask through a vacuum-jacketed transfer line. After filling the reservoir with LHe, the bolometer temperature was lowered from 4.2°K by reducing the pressure above the LHe with a rotary pump.

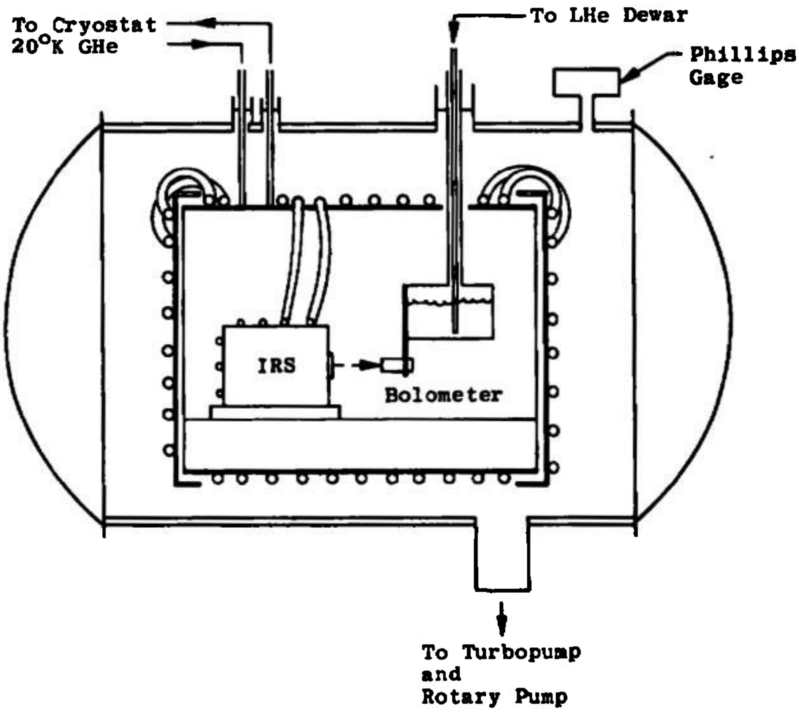


Fig. 6 Vacuum Chamber Installation

SECTION III
PROCEDURE

Five pumpdown cycles during a six-week period were required to evaluate the operation of both the IRS and the bolometer. Only one pumpdown cycle per week was possible because of the long cooldown and warmup periods required. The cryostat which produced the cold He gas used to cool the vacuum chamber liner and the IRS provided only 200 w of cooling and resulted in a cooldown period of roughly 24 hours from room temperature to 35°K. After cooling the IRS, the LHe reservoir on the bolometer was filled from a Dewar, with the Dewar pressure forcing the LHe into the reservoir. Using a 13-cfm rotary pump to reduce the pressure within the reservoir, a pressure of two torr, corresponding to a LHe temperature of 1.4°K, could be obtained in one hour. Liquid helium in the bolometer reservoir would normally last for 24 hours.

Upon completion of testing, the LHe reservoir was repressurized to 760 torr with GHe, and the temperature of the liner and IRS was allowed to increase to 80°K. Pressure in the vacuum chamber was then increased to 300 torr with dry GN_2 to enhance heat transfer to the cold liner and IRS and thereby shorten the warmup period.

SECTION IV
RESULTS AND DISCUSSION

4.1 IRS

The previously untried IRS required some attention during the initial attempts at the radiometric comparison. The most serious problem was chopper heating which would gradually reduce the magnitude of the chopped radiant signal; after continuous operation for an hour, the signal would be half of its initial value. Calculations showed that a temperature rise in the chopper blades from 50 to 62°K would account for the loss of signal. Power input to the motor was 13 w, the rated power for the motor, though an excessive amount for this particular application. An adjustable constant-current circuit was later added to the motor driver which allowed the motor to be started, gradually brought up to speed, and operated continuously with minimum power input. With only 10 mw actually required to operate the chopper motor, chopper heating should have been no problem; however, this modification was not made until after the comparison tests were terminated.

Another problem with the IRS was discovered concurrently with the chopper heating: a gradual loss of radiant signal to one-third the initial value. The radial signal did not return after the chopper was allowed to cool. Apparently, a volatile oil in the paint which was used inside the cone-shaped cavity and as a covering for the cavity heater had condensed on the cold pinhole-sized (0.015-in.) aperture and effectively reduced the aperture size. This occurred while the cavity temperature was maintained at 400°K for several hours. After the IRS was removed from the vacuum chamber for inspection and the aperture was cleaned, the problem did not recur during the remainder of the radiometric comparison. Cavity temperature was limited to 300°K.

4.2 BOLOMETER

During the initial comparison between the IRS and bolometer when the bolometer did not measure what the IRS should have been emitting, the unproven IRS was assumed faulty. But after the two IRS problems described above were remedied and agreement was still not reached, the bolometer was suspected. The calculated irradiance from the IRS at the bolometer involved only cavity temperature and emittance, aperture area, and distance between aperture and bolometer. These factors were believed to be accurately known. But when two bolometer signals resulting from supposedly equal power inputs from the IRS and from the integral bolometer heater were compared, the IRS signal was significantly smaller. This would result if the Nextel® black coating on the bolometer was too thin to be absorbing efficiently; additional Nextel was then applied until a visibly black surface was obtained. The result was an increase in the response of the bolometer to the IRS along with an increase in its response time; absorptance of the receiving surface had apparently been increased by 39 percent. Now the bolometer's IRS response agreed reasonably well with its heater response. The comparison was done in terms of bolometer responsivity:

$$R_H = 16.7 \text{ kv/w at } 17 \text{ Hz}$$

$$R_R = 18.4 \text{ kv/w at } 17 \text{ Hz}$$

According to these values of responsivity, one of two things had occurred: Either the heater was now less efficient at producing a given change in the bolometer resistance than was the absorbed radiant power, or else the IRS radiant output was greater than it should have been. It was easier to suspect heater inefficiency.

Another measurement of bolometer performance indicated heater inefficiency of much greater magnitude. This measurement produces the load curve, a plot of bolometer current versus bolometer voltage (Fig. 7). From the load curve, a theoretical responsivity can be calculated (Ref. 2). This value of responsivity is usually quoted by a manufacturer, probably

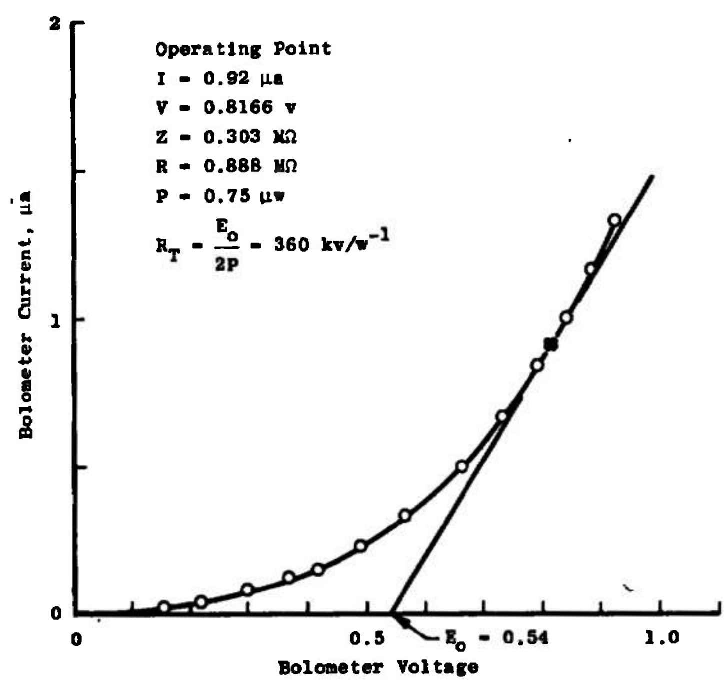


Fig. 7 Bolometer Load Curve

because it is much easier to measure a load curve than to determine the responsivity radiometrically. For the given operating point, the load curve theoretical responsivity (R_T) was 360 kv/w at zero frequency, but the zero frequency responsivity (R_H) obtained using the bolometer heater was only 40 kv/w.

This discrepancy between theoretical load curve responsivity and measured heater responsivity can be explained in terms of "The Principle of Operation of an Absolute Radiometer" (Ref. 3):

> If (a) irradiation of the receiver with radiant power and dissipation in the receiver of electrical power result in the same temperature distribution throughout the entire radiometer, then (b) the amount of radiant power absorbed by the receiver must equal the amount of electrical power absorbed by the receiver.

It is evident from the physical arrangement of the bolometer and heater, shown in Fig. 8, that the temperature distribution in the bolometer will be different for the three cases: (1) dissipation in the receiver of electrical power caused by bolometer bias current,

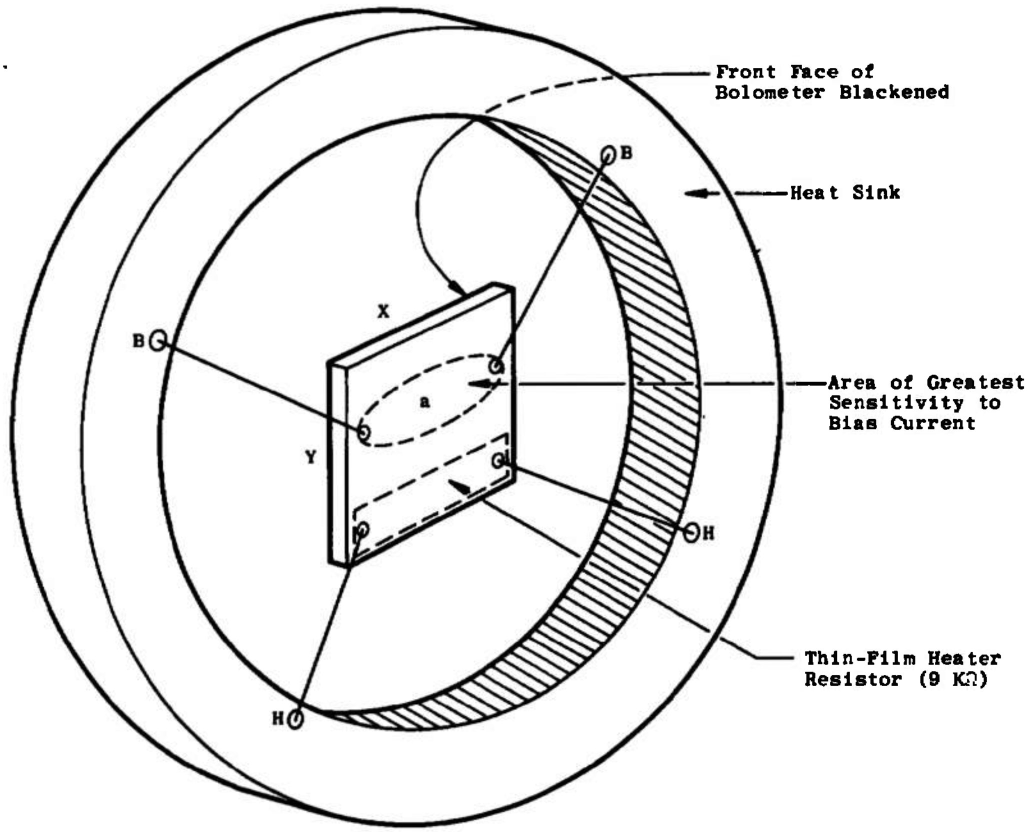


Fig. 8 Bolometer Chip and Mounting

(2) irradiation of the receiver with radiant power, and (3) dissipation in the receiver of electrical power caused by heater current. In case (1), the electrical power caused by bias current is nearly all confined to the most sensitive area "a" between the two bolometer contacts. Hence, the bias power is introduced into the bolometer resistance at the optimum location to produce a change in bolometer resistance. Likewise, any other power introduced into the bolometer chip must produce a temperature change within the area "a" if it is to be detected. In case (2) the radiant power is uniformly distributed and absorbed over the receiver area A = XY, but only the portion absorbed within the area "a" is efficient in changing the bolometer resistance. In case (3) the heater power is introduced at an area remote from area "a" and must travel through the bolometer chip to reach area "a."

If the bolometer chip consisted only of area "a," better agreement between R_T and R_R should result. When the theoretical responsivity at zero frequency is determined from the load curve (Ref. 2), the assumptions are made that there are no temperature gradients in the bolometer volume and that joulean heating caused by bolometer current is indistinct from radiation heating. The discrepancy between R_T and R_R could be eliminated by assuming that the bolometer receiver has an "effective area" A_{eff} = A R_R/R_T = XY/9 which is roughly the area "a."

If the thin-film heater resistor were deposited over the area "a," better agreement between R_H and R_T should result. Perfect agreement would probably be impossible to obtain. As it is, the heater is useful in checking operation of the bolometer, and it should be possible to correct the responsivity for changes in bolometer temperature (Fig. 9) using the heater; but the bolometer with its integral heater cannot be used as an absolute radiometer having receiver area XY.

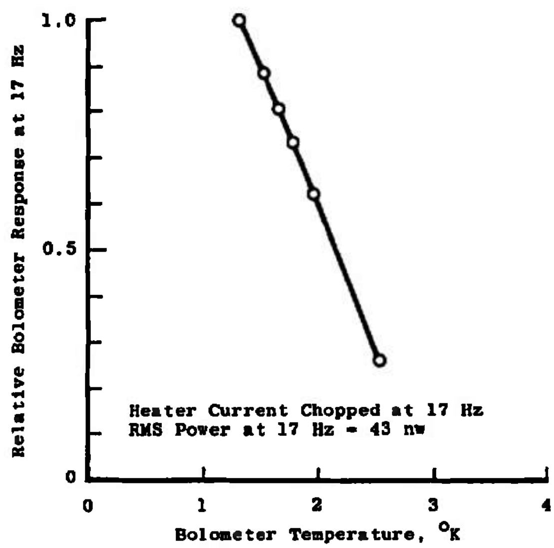


Fig. 9 Bolometer Temperature Response

In the process of checking out the bolometer, several of its performance characteristics were measured. Frequency response to a chopped dc heater current (Fig. 10) was measured before and after the additional black paint was applied to the receiving surface. As expected, the response time increased. Also, the frequency response was measured using the chopped IRS radiation (Fig. 11). A slightly lower relative response to the heater is probably a result of the greater distance the heater power must travel and, consequently, the longer time required to reach the most sensitive bolometer area.

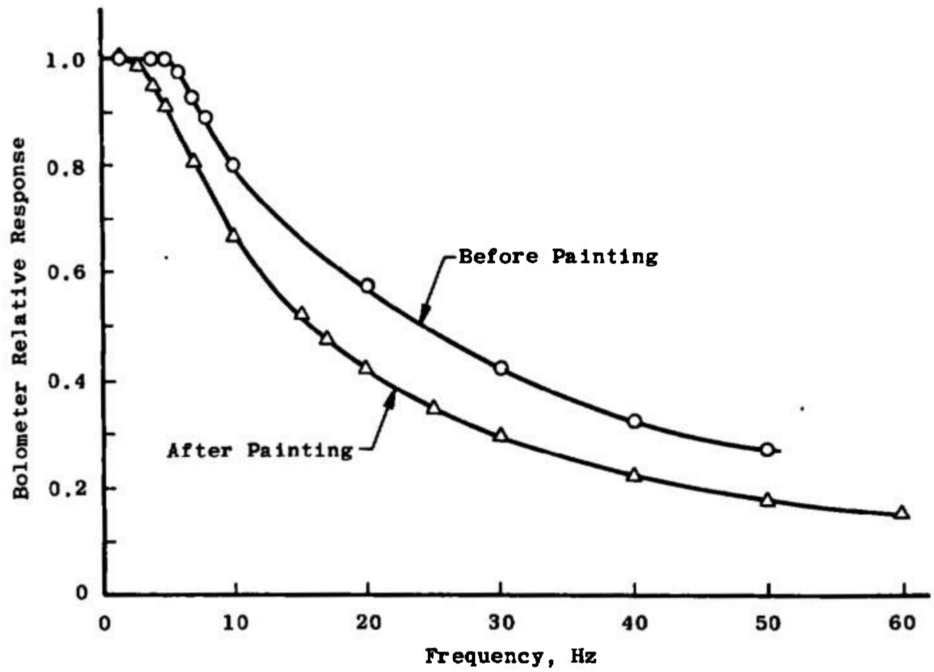


Fig. 10 Bolometer Frequency Response to Chopped dc Heater Current

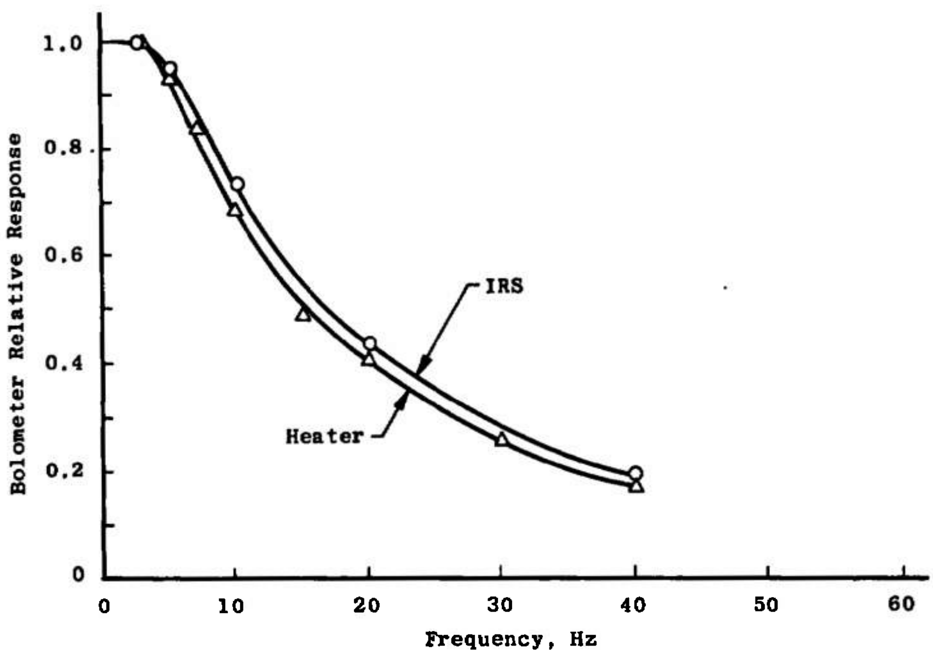


Fig. 11 Bolometer Frequency Response to Infrared Radiation Source and Heater

Bolometer output linearity was measured with both chopped and unchopped heater current (Figs. 12 and 13). It appeared to be linear up to a 1-μw input, which was approximately the power input produced by the bias current.

Relative response versus bias current was measured at two frequencies (Fig. 14). The optimum bias current was about 0.3 to 0.5 μa.

The bolometer load curve was measured with the bolometer at 1.4°K (Fig. 7). From this curve, the theoretical responsivity was 360 kv/w at the operating point: I_b = 0.92 μa, V_b = 0.817 v.

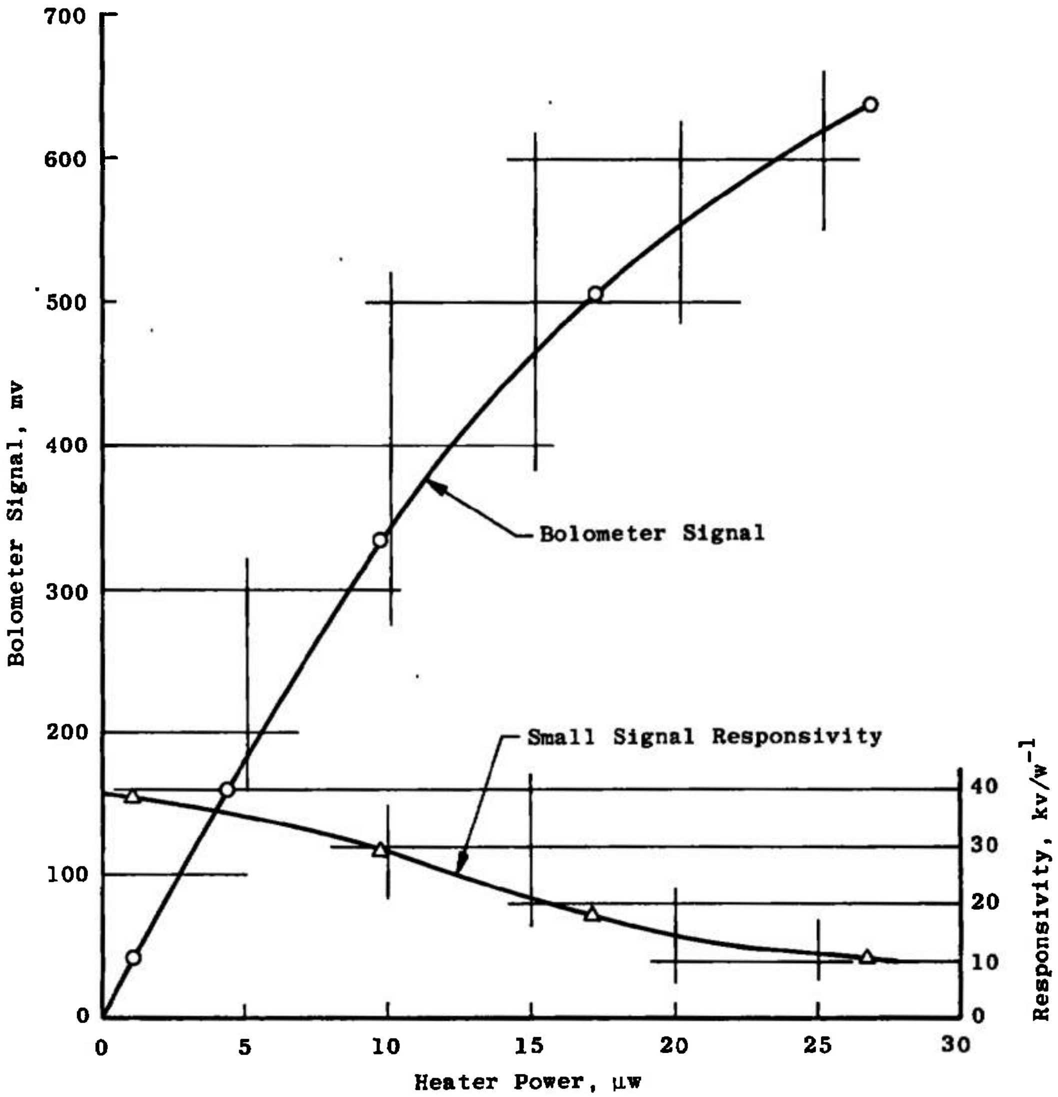


Fig. 12 Linearity of Bolometer Response to Unchopped Heater Current

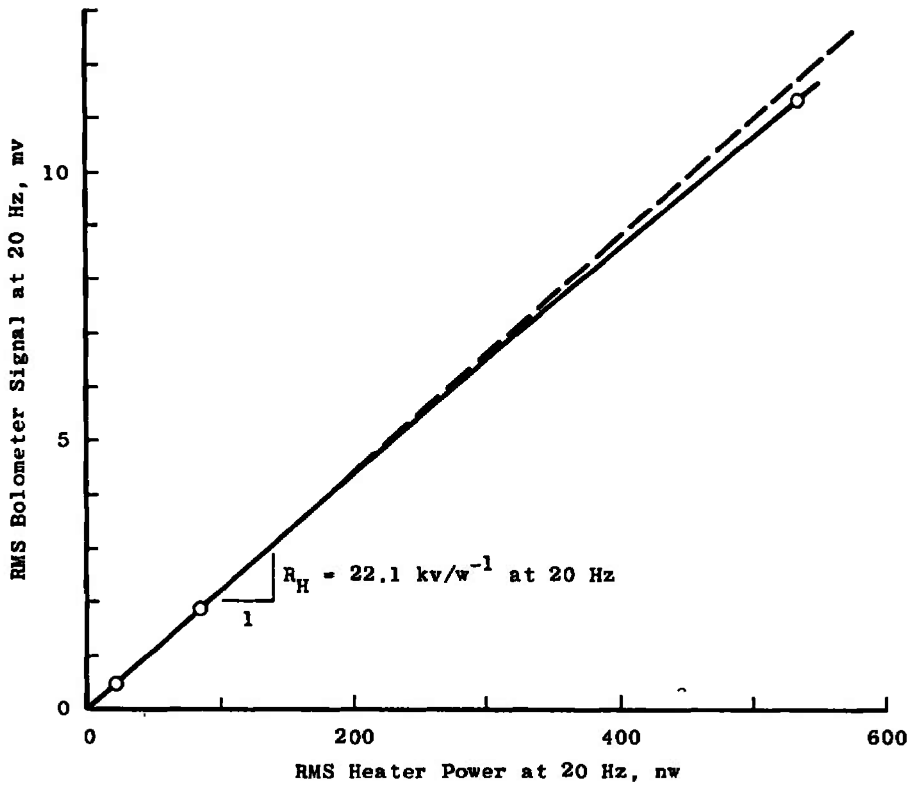


Fig. 13 Bolometer Response to Chopped Heater Current at 20 Hz before Painting

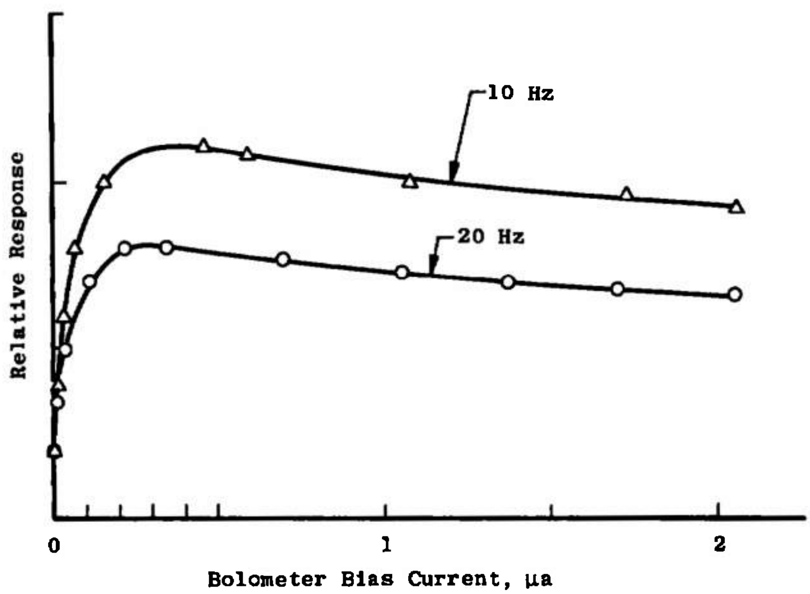


Fig. 14 Bolometer Response versus Bias Current

Bolometer response to the chopped IRS signal was measured at three IRS cavity temperatures (Fig. 15) as a check on the spectral absorptance of the black receiver coating of the bolometer and spectral emittance of the IRS. The point at 200°K is 20 percent low, indicating the possibility of decreased absorptance or emittance at the longer wavelengths.

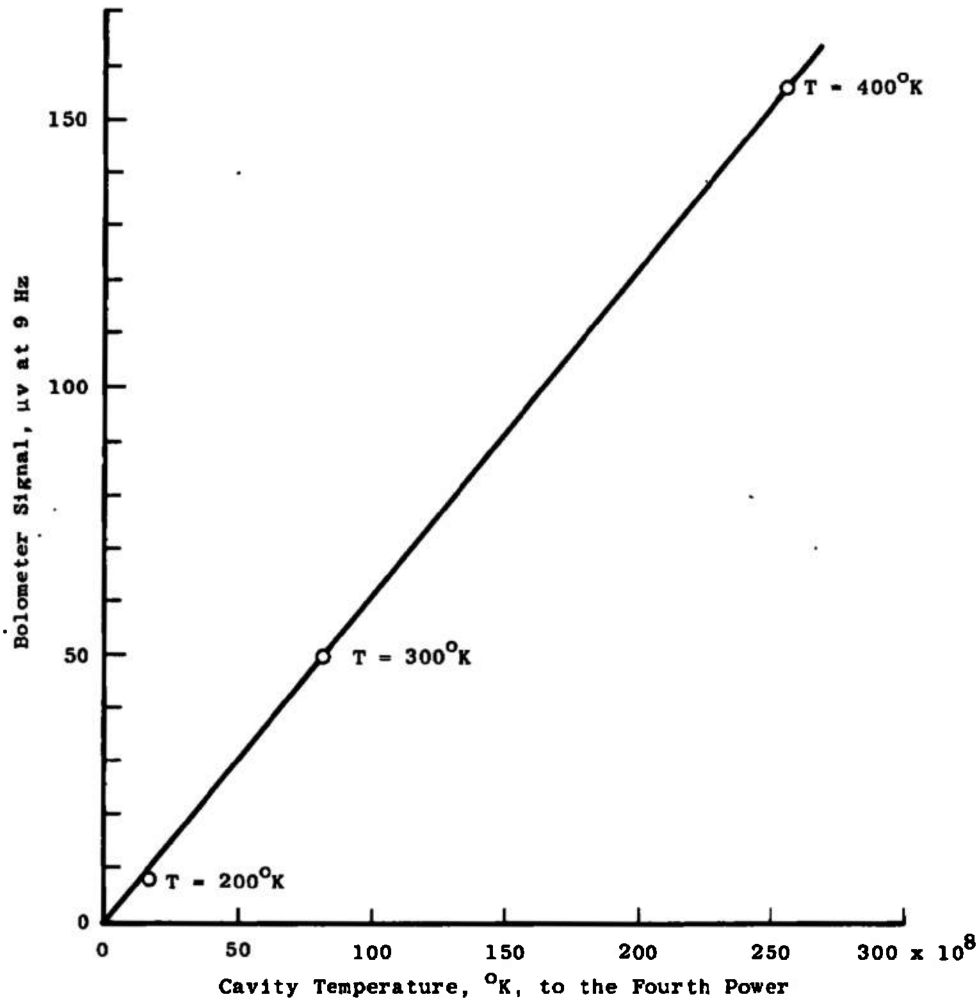


Fig. 15 Bolometer Response at Three Infrared Radiation Source Cavity Temperatures

Finally, bolometer response versus bolometer temperature was measured (Fig. 9) from 1.3 to 2.5°K using the heater. Since the responsivity is strongly dependent on temperature, repeatability of measurements would require accurate control of bolometer temperature or, more easily, correction for temperature using the integral heater.

Bolometer noise measurements were not made.

SECTION V
CONCLUSIONS

Proof that the IRS was emitting blackbody radiation of the proper magnitude was not obtained by radiometric comparison to the self-calibrated bolometer, because the bolometer could not be used as an absolute radiometer. However, the response of the bolometer to its integral heater was repeatable throughout the six-week test period and provided the necessary reference for evaluating changes in the IRS radiant signal caused by chopper heating and aperture restriction. When other IRS designs are radiometrically compared to the bolometer, they will in effect be compared to each other. Confidence in the bolometer as a transfer device will be developed. In this way the bolometer will become a calibrated, although not an absolute, detector.

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cryogenic bolometer						
radiant energy						
radiometers						
blackbody radiation						
high vacuum						

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