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Calibration Technique for Heat Flux Sensors Used in Fire Experiments and Standard Fire Tests

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16. Abstract

A means for calibrating total heat flux gauges using a comparative (substitution) technique has been established. An apparatus consisting of a reference radiometer, a stable infrared radiant heater capable of producing flux levels up to 3.7 W/cm^2, and a precision alignment mechanism has been constructed. The reference radiometer was characterized by the Radiometric Physics Division of The National Institute of Standards and Technology at flux levels in the range 0.8 mW/cm^2 to 0.9 W/cm^2. Its accuracy was found to be within 3 percent over this range which spans 3 orders of magnitude. As the radiometer is a highly linear thermocouple-based device having a self-calibration feature, this accuracy is expected to hold up to 4.2 W/cm^2, the upper limit of this device. Although the overall accuracy of calibrations performed in the new apparatus must still be established, it is expected to be within 3 to 5 percent.

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INTRODUCTION

PURPOSE.

The purpose of this project is to develop an apparatus and technique for calibrating total heat flux gauges that are used in fire experiments and standard fire tests. The Gardon™ heat flux transducer shown in figure 1 is an example of this type of gauge. These devices are usually calibrated in a radiant thermal field in order to avoid the uncertainties associated with convective heating. The calibration should be carried out under conditions approximating end-use conditions; that is, the calibration apparatus should provide a thermal radiation field that approximates the intensity and spectral character of the radiation in the fire environment to which the gauge will actually be exposed. The spectral character of the radiation is important because the absorptivity of the "black" coating on the sensing element of a heat flux gauge is often wavelength dependent (i.e., it is non-grey). This translates into a requirement for a moderate temperature source that produces "fire-like" radiation in the sense that it is (1) rich in the infrared rather than the visible portion of the spectrum, and (2) intense enough to produce flux levels of several watts per square centimeter (W/cm^2).

BACKGROUND.

The calibration of a heat flux gauge is effected by exposing the gauge to a known radiant flux and measuring the output or response of the gauge. For heat flux gauges based on a thermocouple response, the output should be measured with a precision voltmeter. The calibration constant (reciprocal of responsivity) for such a gauge at the given flux is simply the flux-toresponse ratio and is typically expressed in the units (W/cm^2 -mV). Consequently, the main task is to establish a known radiant flux at a specific point in space.

There are two approaches for establishing this flux: (1) use a well-characterized source which is amenable to analysis so that the radiant flux at the measurement position can be calculated to the required degree of accuracy, or (2) measure the flux at the target point from a highly stable heat source using a calibrated reference or "standard" heat-flux sensor.

In practice, the first approach usually involves a heated blackbody cavity which delivers infrared radiation through an aperture which is small compared to the surface area of the cavity. For commonly available blackbodies, the aperture is too small to deliver fluxes of several watts per square centimeter to target points that are far enough from the aperture to preclude convective heating. Although a large-aperture, laboratory-scale blackbody is feasible, substantial resources are required for the design and fabrication of such a unit.

The second approach requires a precise reference transducer rather than a precise source. Since precision flux sensors are commercially available -- whereas large-aperture blackbodies are not -- this "substitution" approach is an attractive alternative to constructing a precision source. Moreover, the Center for Fire Research (CFR) has had satisfactory experience with the substitution technique. For more than a decade, the CFR has been calibrating heat flux gauges using a reference heat flux transducer and a high-temperature, high-intensity quartz lamp source. The reference transducer is a Gardon heat flux gauge that was calibrated by the Radiometric Physics Division (RPD) of National Institute

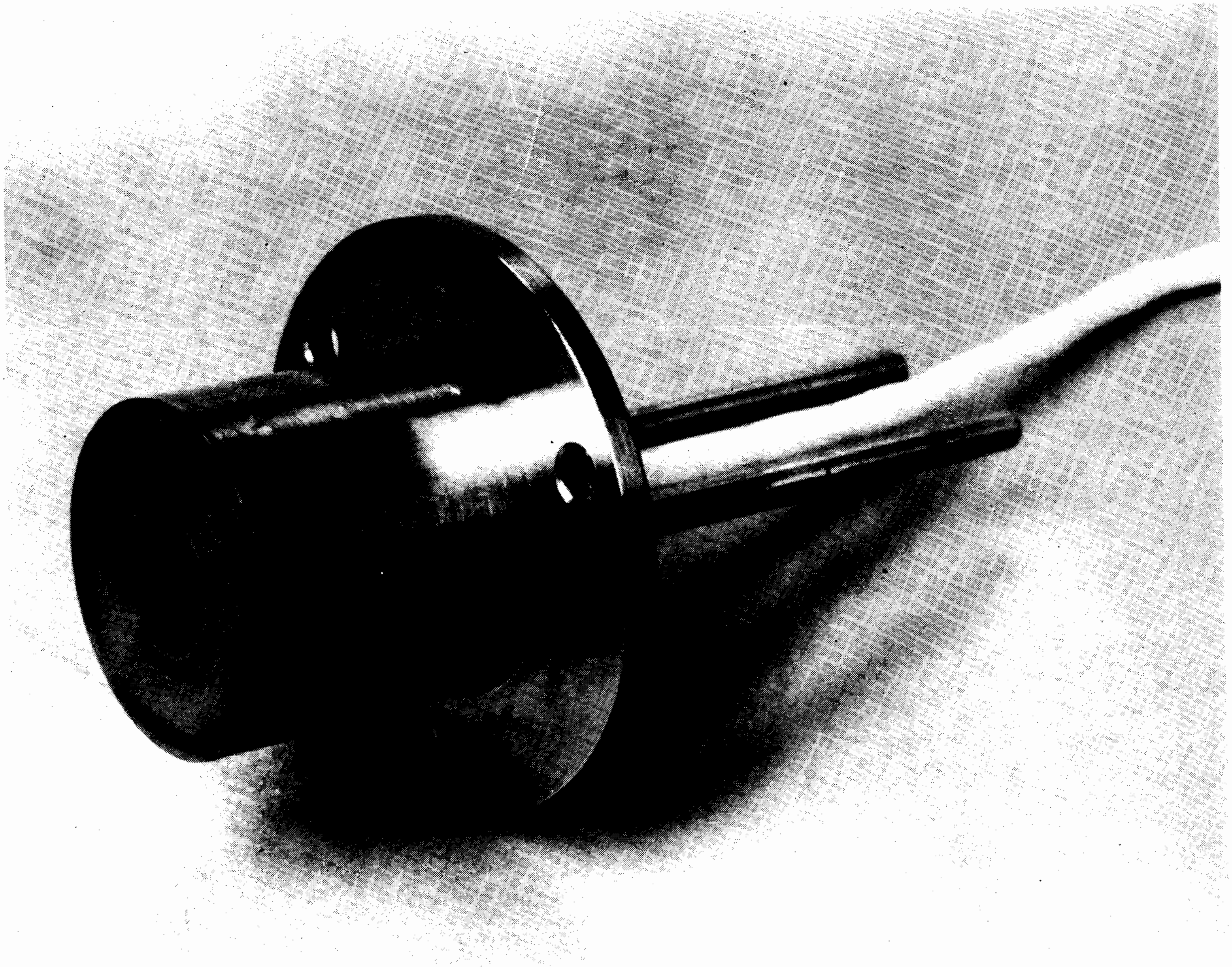

FIGURE 1. GARDON HEAT FLUX GAUGE

for Standard Technology (NIST). Although the quartz lamp and its attendant ellipsoidal mirror can provide flux levels up to 25 W/cm^2, actual calibrations have been limited to a maximum of 1.5 W/cm^2 -- the upper limit of the reference gauge. The high temperature of the source constitutes another shortcoming. The broadband radiation from the quartz lamp peaks at a wavelength of approximately 1 micrometer (μm), whereas the radiation in an enclosure-fire environment -- with contributions from the flame (references 1 and 2), hot surfaces, and hot gases (600 - 1100 °C) -- typically peaks at 2 to 3 μm. Since the absorptivity of many "black" coatings used on heat flux gauges vary significantly with wavelength, an error could occur when a gauge, which was calibrated under a quartz lamp, is used in a fire environment.

The current project seeks to provide a new calibration facility which uses the substitution technique but reduces the potential errors and limitations outlined above. This will be accomplished through the use of an improved reference radiometer and a more fire-like infrared source. The goal is ro provide calibrations at flux levels from 1 to approximately 4 W/cm^2. However, the linearity of thermocouple type heat flux meters allows satisfactory extrapolation to fluxes beyond the range of calibration. Indeed, this has been the practice for most heat flux measurements in fire conditions where flux levels often reach as high as 15 W/cm^2.

APPARATUS DESIGN

GENERAL CONSIDERATIONS.

The substitution technique is outlined in figure 2 and consists of (1) establishing a radiant field using a stable radiant heater which is surrounded by a stable ambient environment at temperature T_∞, (2) measuring the flux at a point in the field with a standard or reference radiometer, (3) substituting the "unknown" gauge for the standard radiometer at precisely the same point, and (4) measuring the response of the "unknown" gauge to the known heat flux. Note that the radiosity of the panel need not be perfectly uniform provided the panel falls entirely within the view angle θ_V of both the standard and unknown transducers (see figure 2). This means that the transducers must be positioned at a distance $d \geq d_{min}$, where d_{min} is determined by the smaller of the transducers' view angles. Consequently, the power density of the radiant panel must be sufficient to produce approximately 4 W/cm^2 at $d = d_{min}$.

The incident flux can be changed in two ways: either fix the measuremnent point (i.e., the distance d) and vary the temperature of the heater, or fix the temperature of the heater and vary the distance. By adjusting both the temperature of the heater and the distance, the incident flux can be fixed while the temperature of the heater -- and therefore its spectral character -- is varied. The latter operating mode provides a means for assessing the greyness of the coating on the gauge.

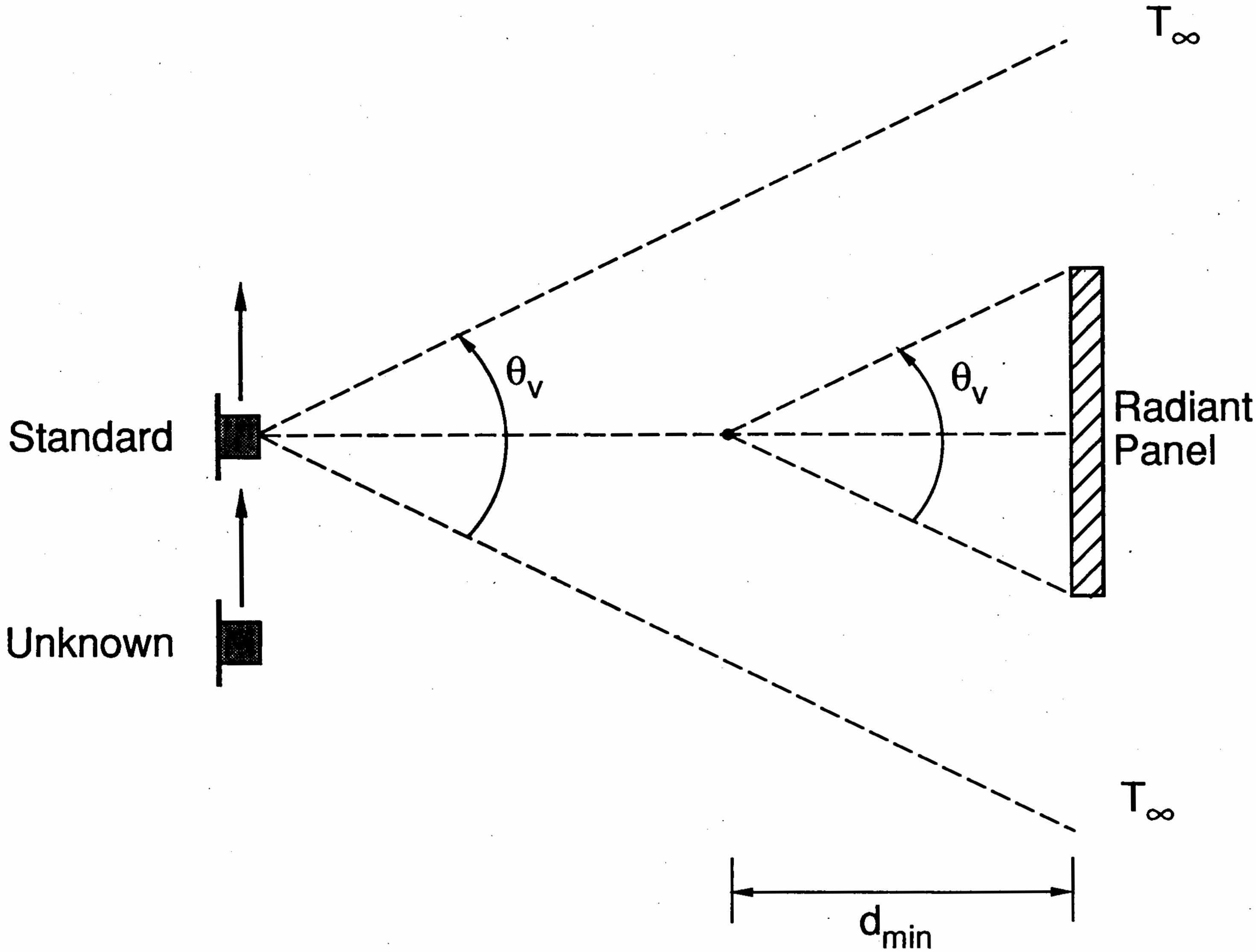

FIGURE 2. SUBSTITUTION TECHNIQUE

RADIANT SOURCE.

Following a survey of various gas-fired and electric radiant panels, a 50-degree conical infrared electric heater was selected. (This heater is similar to that used in the cone calorimeter (reference 3). The heating element is the same, but it is wound so that the open areas at the apex and base are smaller than those of the cone calorimeter.) The 5-kilowatt (kW) heating element (Model TY3272, Wellman Thermal Systems Corp., Shelbyville, IN) is shown in figure 3. (Certain commercial products and materials are identified in this document in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by NIST, nor does it imply that the product or material is the best available for the purpose.) The diameters of the base and apex are 172 and 30 millimeters (mm), respectively. The element fits into a matching insulated stainless-steel cone which supports the element and greatly reduces back-surface heat loss. The heater is powered through a solid-state relay (twin silicon controlled rectifier) connected to a digital temperature controller. Three chromelalumel thermocouples, which are in direct contact with the heating element, supply the control signal.

This arrangement produces a reasonably uniform, stable source with sufficient power to produce the necessary flux levels. At 900 °C, the peak heat flux occurs at 2.5 μm.

REFERENCE RADIOMETER.

The Radiometric Physics Division (RPD) of NIST recommended an electrically calibrated radiometer (ECR) as a reference radiometer. The RPD has been using this type instrument for more than 10 years and has found it to be highly stable and reliable. Its operating principle is depicted in the schematic shown in figure 4. Radiation entering through the aperature is absorbed on the inner surface of the cavity. The temperature of the cavity rises and induces heat transfer through the precision thermal resistor to the water-cooled body. A thermopile across the thermal resistor provides the output signal.

A second mode of operation allows the ECR to be "self-calibrated." A resistance element wound within the wall of the cavity, in conjunction with an adjustable precision power supply, permits known amounts of energy to be supplied to the cavity. Simultaneous measurement of the input power and the thermopile output allows the unit to be calibrated. Note that when this selfcalibration is carried out at a power level which is close to that produced by the flux under measurement, the small non-linear effects associated with the thermopile and heat losses from the cavity are greatly reduced, if not eliminated.

An MK IV Kendall ECR and an MK I control unit (both manufactured by Technical Measurements, Inc., (TMI) La Canada, CA) were obtained for the current project. The radiometer, hereafter referred to as the CFR ECR, is shown in figure 5. It has a 5.1-centimeter (cm) diameter and 9.2 cm length. The view angle, θ_v, is 86 degrees. The manufacturer specifies the range as 0.04 to 4.2 W/cm^2.

This radiometer and its attendant control unit were characterized by RPD. This was accomplished primarily by comparisons with a low-level (8 mW) ECR, owned by RPD, which had been well-characterized both at NIST and PTB (the German national standards laboratory). A second RPD ECR (actually a TMI MK IV), which had been

FIGURE 3. INFRARED HEATING ELEMENT

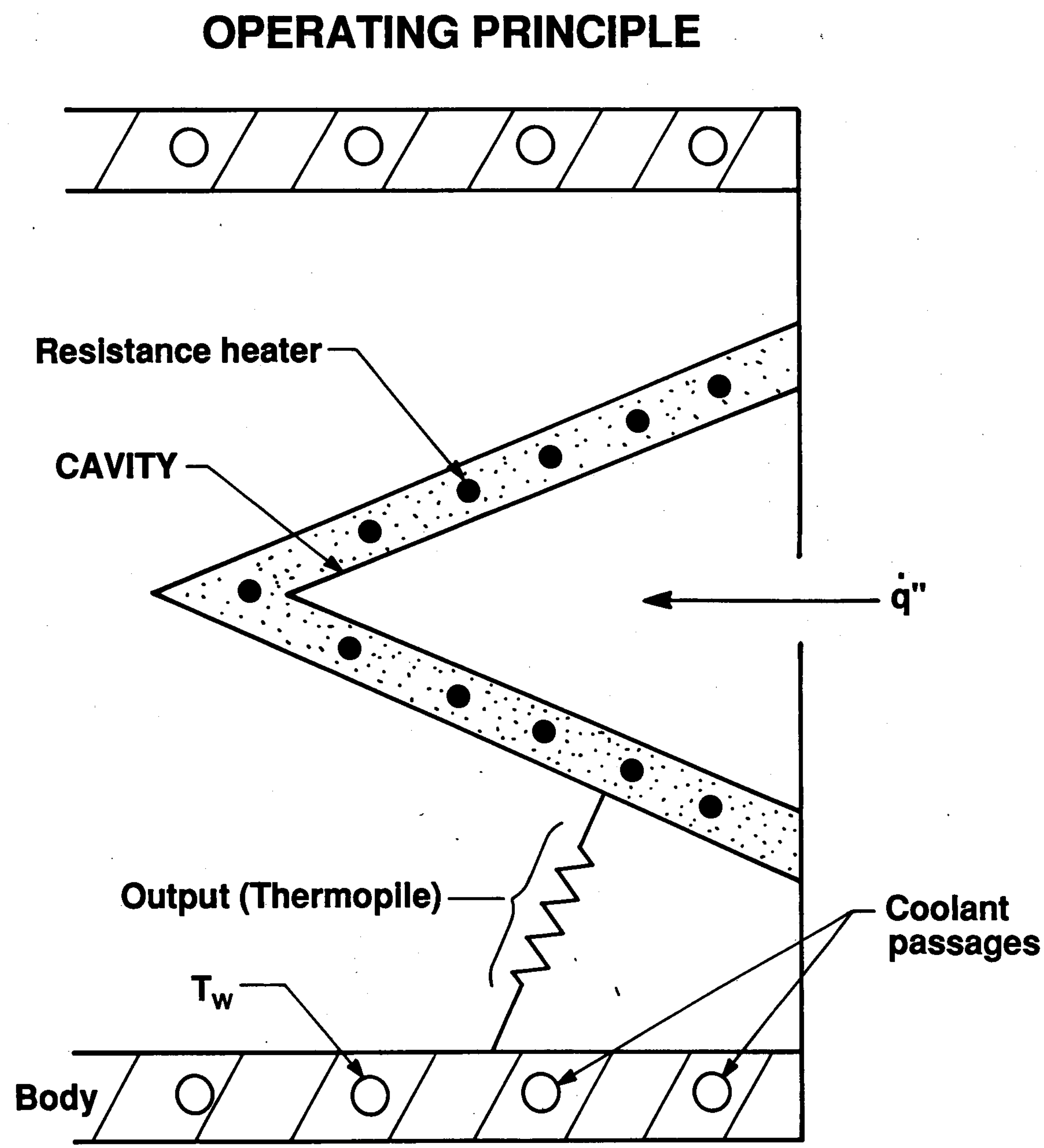

FIGURE 4. OPERATING PRINCIPLE OF ECR

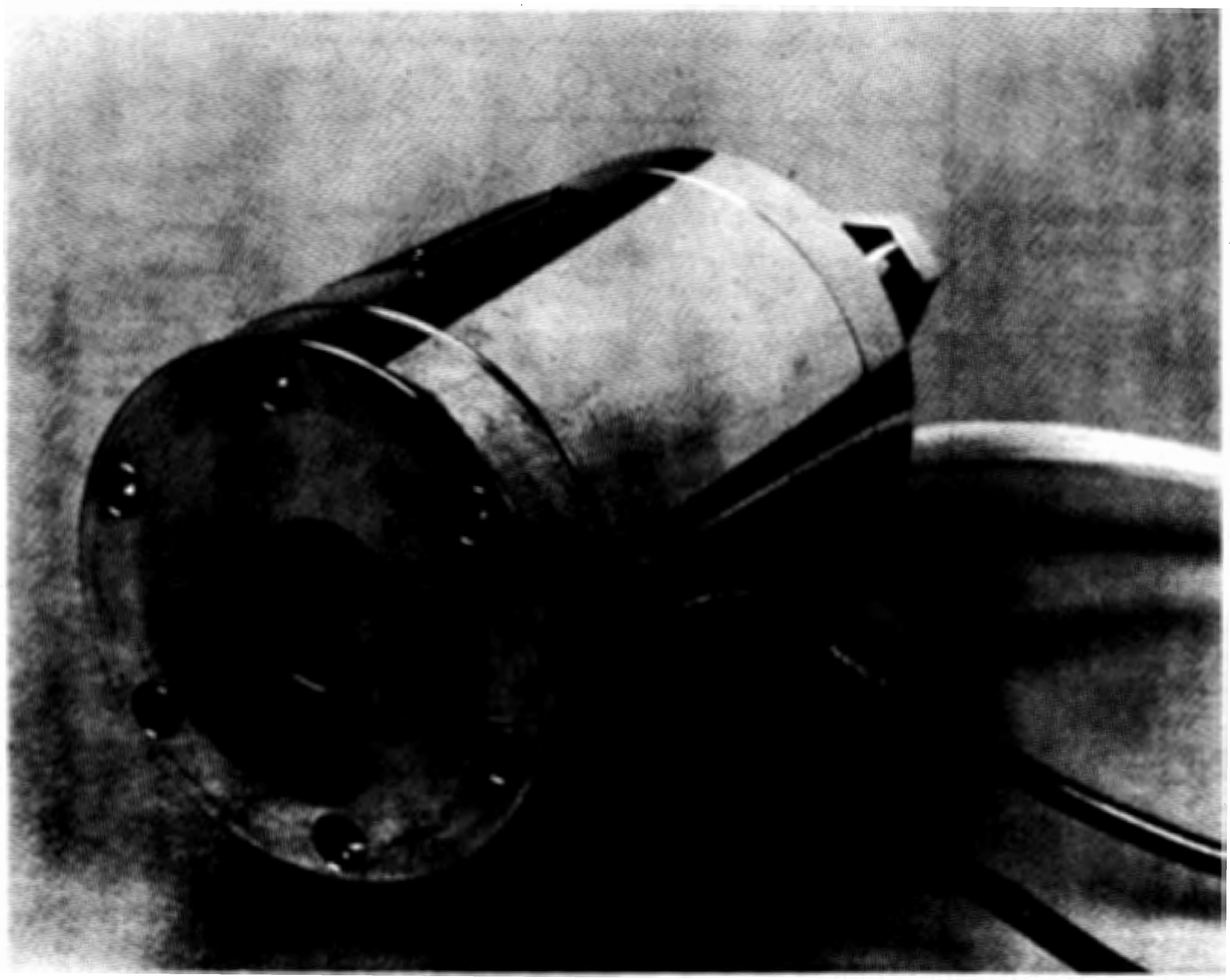

FIGURE 5. REFERENCE RADIOMETER (CFR ECR)

characterized by RPD, was used to confirm measurements. Four separate experiments were performed with the CFR ECR: (1) comparisons with both RPD ECRs using various laser sources to measure blackness (losses due to reflectance through the aperature) and response for flux levels from approximately 0.001 to 0.1 W/cm^2, (2) measurement of response using two broadband standard lamp sources at flux levels of 0.033 and 0.144 W/cm^2, (3) measurement of response at flux levels of approximately 0.2 and 0.9 W/cm^2 by direct comparison with the RPD/TMI ECR using a specially constructed broadband infrared source, and (4) confirmation of the manufacturer's specifications for angular sensitivity. The complete report on the evaluation of the CFR ECR is presented as appendix A. The overall accuracy of the CFR ECR as determined by RPD can be summarized as follows:

Source	Imposed Flux (W/cm^2)	Accuracy of CFR ECR
Laser	0.008 to 0.116	within 2%
Broad Band	0.2 to 0.9	within 3%

It should be noted that the maximum flux used in this evaluation was 0.9 W/cm^2 -- the maximum that could be produced by the RPD broad-band infrared source. The comparison carried out in experiment three will be extended to approximately 4 W/cm^2 using the conical radiant source described above, as soon as the RPD/TMI ECR becomes available to CFR. It is important to note, however, that the RPD/TMI ECR has not been characterized above 1 W/cm^2. Nevertheless, the linearity exibited by this device over 3 orders of magnitude of flux up to 1 W/cm^2 and the fact that it is a highly linear thermocouple-based device with integral electrical calibration suggest that an extrapolation of 3-percent accuracy to 4 W/cm^2 is reasonable.

Practical considerations preclude using the CFR ECR as a reference radiometer on a day-to-day basis. Instead, the CFR ECR is used to calibrate and periodically check a "secondary" reference (Gardon gauge) which is used routinely in the calibration apparatus.

OVERALL APPARATUS.

An elevation view of the calibration apparatus is shown in figure 6. The conical radiant heater is mounted within a 203-mm-diameter hole in the center of a horizontal 6.4-mm-thick, water-cooled copper plate. Tap water, which is heated to room temperature with an in-line electric heater, circulates through 9.5-mm-diameter copper tubing attached to the upper face of the plate. The lower face is painted flat black to eliminate reflections. Similar, but thinner (3.2 mm), vertical side panels extend 30 cm downward from the edge of the horizontal plate. This arrangement insures that a heat flux sensor in the measurement plane "sees" only a heat source within a well-defined area surrounded by a black surface at ambient temperature. Since the view angle of the CFR ECR is smaller than that of a Gardon gauge (86 verses 180 degrees), d_{min} for these sensors in this geometry is 109 mm.

The remainder of the structure in figure 6 is designed to place alternately and precisely the reference gauge and the unknown gauge at a given point on the centerline of the infrared heater. Each gauge sits on a precision elevating table which facilitates mounting and removing a gauge (e.g., right-hand

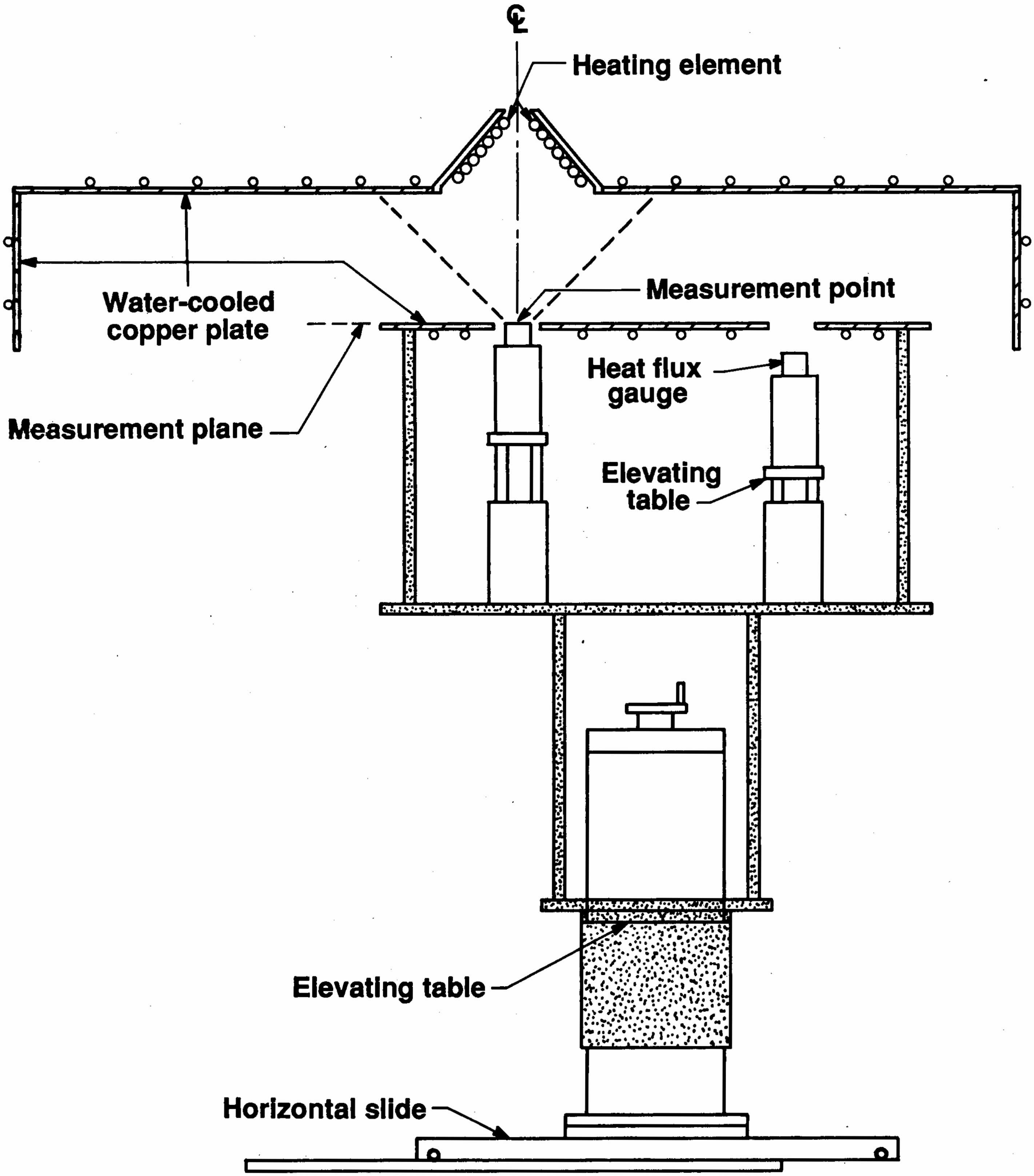

FIGURE 6. CFR CALIBRATION APPARATUS FOR HEAT FLUX SENSORS

gauge/table in figure 6) as well as the precise positioning of the gauge in the measurement plane (left-hand gauge/table in figure 6). A water-cooled copper plate, which is located at or just below the measurement plane, shields the operator from the radiant heater during the mounting and positioning phase of the calibration. The entire assembly sits on another elevating table, which sits on a precision horizontal slide. This arrangement allows both gauges to be precisely positioned at the same measurement point along the axis of the heater and also allows the distance between the measurement point and source to be varied. These and other features of the actual calibration apparatus are evident in the photographs presented in appendix B.

Coolant for the flux gauges is obtained from a constant temperature ($\pm$0.01 °C) bath which, in conjunction with an auxiliary pump, can supply water at 120 milliliters per second (mL/s) at 276 kPa and 20 °C to 60 °C. A precision voltmeter with a resolution of 1 microvolt is used to measure the response of the heat flux gauges.

CONCLUSIONS

An apparatus for calibrating heat flux gauges at flux levels up to 3.7 W/cm^2 has been constructed. The reference radiometer was characterized and was found to be accurate to within 3 percent in the range 0.8 mW/cm^2 to 0.9 W/cm^2. As this range spans 3 orders of magnitude and since the ECR is a self-calibrating device, it is assumed that 3-percent accuracy can be extrapolated to 4 W/cm^2. Nevertheless, the overall accuracy of a calibration carried out in the new apparatus must still be determined. This is expected to be within 3 to 5 percent.

A consistancy check via a round-robin calibration of a heat flux sensor by several fire research laboratories including the calibration facility is recommended.

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APPENDIX A

REPORT ON CHARACTERIZATION OF CFR ECR BY THE RADIOMETRIC PHYSICS DIVISION, NIST

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
[formerly National Bureau of Standards]
Gaithersburg, Maryland 20899

June 21, 1989

MEMORANDUM for: Dr. James Quintiere, Chief
Fire Science and Engineering Division (Div. 752)

Through: Robert D. Saunders
Group Leader, Thermal Radiometry Group
Radiometric Physics Division (Div. 534) J H Walker for R.D.S.

From: William Waters, Thermal Radiometry Group W.R. Waters
Radiometric Physics Division (Div. 534)

Subject: Characterization of an Electrically Calibrated Radiometer for the FAA Flammability Testing Program

Introduction

Discussions among personnel from Div. 752, Div. 534, and the FAA led to the conclusion that the recently promulgated FAA regulations on materials flammability in commercial aircraft required a long term, scientifically sound measurement base and testing protocols. The Center for Fire Research (CFR) undertook to maintain the measurement base and develop the testing protocols with support from the Radiometric Physics Division (RPD). RPD support was to consist of advice on the choice of a suitable commercial instrument, and periodic recalibration of the instrument which is to be maintained in CFR. This memo describes the initial characterization of an electrically calibrated radiometer (ECR) procured by CFR for this work.

Material

The test ECR was manufactured by Technical Measurements Inc., of La Canada, California. It consisted of:

1. One model Mark IV radiometer head (with 86° and 106° view limiting apertures) - serial no. 48811

2. One model Mark I control unit - serial no. 18750

As requested by CFR personnel, the unit was operated with water cooling at a temperature of 25°C ± 0.5°C using a circulating water bath having a flow rate of about 0.5 liter/minute.

Parameters Measured

The CFR ECR was evaluated at specific irradiance levels to determine its response (mW/cm^2) over the range of $0.8mW/cm^2$ to $0.9W/cm^2$. The cavity blackness was measured at selected wavelengths from 0.488μm to 3.390μm. In addition, the cosine dependence of the ECR was measured.

Standards

RPD standards used for the measurements included:

1. A low-level(8mW) ECR, serial no. 2, previously characterized at NIST and PTB (German National Standards Lab)

2. NIST lamp standards of total irradiance ST-1 and T3.

Method

RESPONSE MEASUREMENTS

Laser Measurements. The responses of the test ECR and a similar RPD ECR were measured at five irradiance levels in the $0.8mW/cm^2$ to $116mW/cm^2$ range by intercomparing with the low-level (8mW) ECR using various lasers as sources. The RPD TMI ECR was included in the intercomparisons since it had been previously compared to NIST lamp standards of total irradiance in 1976. The automated instrumentation shown in Fig. 1 was used for the measurements. The translation table allowed the ECRs to be directly intercompared by alternately positioning them in the same location relative to the beam of each laser being used as a source. Apertures were placed as shown to limit scattering of the laser beam. The spherical mirror shown was used for the blackness measurements to be described under "CAVITY BLACKNESS MEASUREMENTS". (For this experiment the mirror was positioned as shown and had no effect on the measurements). The silicon monitor detector shown in the figure was used in intercomparing the ECRs for laser power levels greater than 8mW. This was done by first measuring the responsivity (V/mW) of the monitor using the low-level (8mW) ECR. The linearity of this stable silicon photodiode detector had previously been established to about 0.1% for irradiance levels ranging over several orders of magnitude. The monitor detector was used to determine the laser beam power at higher power levels and then the beam was measured with the TMI ECRs. The TMI control unit panel displays, which read directly in mW/cm^2 units, were used in obtaining the ECR responses.

Lamp Measurements. Both the RPD and the CFR TMI ECRs were compared to NIST lamp standards of total irradiance ST-1 ($33mW/cm^2$) and T3 ($145mW/cm^2$) under all conditions specified for their use. The specified standard lamp calibration distances, 50cm and 40cm respectively, were measured to the planes of the cavity receiving apertures of the ECRs. Again, the TMI control unit panel displays were used in obtaining the ECR responses. The supplied 86° view limiters were used with both ECRs to minimize thermal background radiation.

Infrared Source Comparisons. Both TMI ECRs were intercompared using a specially constructed broad band source as a transfer device. This was done, (1), to extend the response characterization to higher irradiance levels than the laser experiment permitted, and (2), to obtain measurements using a source more closely approximating those to be used at CFR in terms of greater infrared radiation. The source, shown in Fig. 2, contains two 15cm diameter arrays of nichrome wire heating elements spaced 6cm apart, mounted collinearly relative to the radiometer location. Thus, the windings which are perpendicular to each other, produce relatively uniform irradiance. A translation stage was used to alternately position each ECR at the same point in space, 30cm from this source. Comparisons were made without view limiting at irradiance levels of about $0.2W/cm^2$ and $0.9W/cm^2$. The higher irradiance was achieved by placing the highly reflective (tin-plated), open-ended, metallic cylinder in front of the source. The source radiance temperature at $0.650\mu m$ was about 830°C. Again, the TMI control unit displays were used in reading the radiometer responses.

CAVITY BLACKNESS MEASUREMENTS

Cavity reflectance losses for both TMI ECRs were measured at five wavelengths in the $0.488\mu m$ to $3.390\mu m$ range using the instrumentation and methods previously described under "Laser Measurements". At each wavelength, the TMI ECR responses were taken with the rotatable mirror positioned "out", as shown in Fig. 1, such that any irradiance reflected from the cavity would not re-enter it.

The measurements were then repeated but with the mirror rotated "in" (counter-clockwise about a vertical axis until its center of curvature was located within each ECR cavity receiving aperture plane). Under this condition, about 99% of any irradiance reflected from the cavity would return to the cavity and be included in the response of the ECR. (See Note 1 at the end of the section Discussion and Uncertainties.) By this method, the ratios of a series of "in" and "out" measurements at different wavelengths provided an indication of cavity reflectance losses.

ANGULAR RESPONSIVITY

The angular responsivity (cosine dependence) of the CFR ECR was evaluated by measuring responsivity changes for irradiances of a 1000 watt tungsten quartz halogen lamp positioned at various angles up to ±15° from the normal to the radiometer cavity aperture. The lamp filament was placed at a distance of 35.6 cm from the radiometer. No view limiter was used.

Results

RESPONSE MEASUREMENTS

Laser Measurements. A summary of the laser measurements described under "RESPONSE MEASUREMENTS", is given below:

		Response Ratio	
Laser Power (mW)	Laser Wavelength (μm)	RPD TMI ECR	CFR TMI ECR
0.8	3.390	0.978	0.994
0.8	3.390	0.995	0.987
3.0	1.150	1.003	1.008
3.0	0.514	0.983	0.994
5.0	0.488	0.981	0.994
64.0	0.488	0.982	0.992
116.0	0.488	0.987	1.003

The above ratios are the result of the measured TMI ECR response divided by the Low-level(8 mW) ECR response (or the calibrated monitor detector response as discussed). Each value above is the mean of three to five individual intercomparisons. Three times the standard deviation of an individual intercomparison varied from about 0.1 to 0.3%. The data was subjected to a least squares fitting (see Fig. 3) to check for a discernible trend.

Lamp measurements. The following results were obtained for the lamp comparisons:

Lamp ST-1

	Assigned lamp total irradiance (mW/cm^2)	ECR response (mW/cm^2)	Difference (%)
RPD ECR	33.04	32.83	-0.6
CFR ECR	33.04	33.14	0.3

Lamp T3

	Assigned lamp total irradiance (mW/cm^2)	ECR response (mW/cm^2)	Difference (%)
RPD ECR	144.65	144.83	0.1
CFR ECR	144.65	147.10	1.7

Each response value above is the mean of from two to three individual readings. The range for each set of readings varied from 0.1 to 0.3%.

Infrared Source Comparisons. The CFR ECR response at $0.2W/cm^2$ was 0.9% higher than that of the RPD ECR (based on the mean of seven comparisons with three times the standard deviation of each comparison being 1.2%). Similarly, the CFR ECR response at $0.9W/cm^2$ was 1.6% higher (based on the mean of five comparisons with three times the standard deviation being 0.9%).

CAVITY BLACKNESS MEASUREMENTS

A summary of the results obtained for the measurements described under "CAVITY BLACKNESS MEASUREMENTS", is given below:

Laser Wavelength (μm)	ECR Cavity Reflectance Ratio ("in"/"out") RPD	CFR
0.488	0.994	0.996
0.514	1.011	1.010
0.633	1.005	1.001
1.150	1.015	1.003
1.150	1.003	1.002
3.390	1.028	1.011
3.390	1.006	1.013

Each value above is the mean of from three to five individual "in" and "out" comparisons. Three times the standard deviation of an individual comparison varied from about 0.1 to 0.3%. The data was subjected to a least squares fitting (see Fig. 4) to check for a discernible trend. Note that the ratios less than unity shown for .488μm are due to the measurement uncertainties resulting from the limited amount of data taken.

ANGULAR RESPONSIVITY

The experiment performed under "Angular Responsivity", confirmed adherence to a cosine dependence within about 1% for angles up to ±15° from the normal to the CFR radiometer cavity aperture.

Discussion and Uncertainties

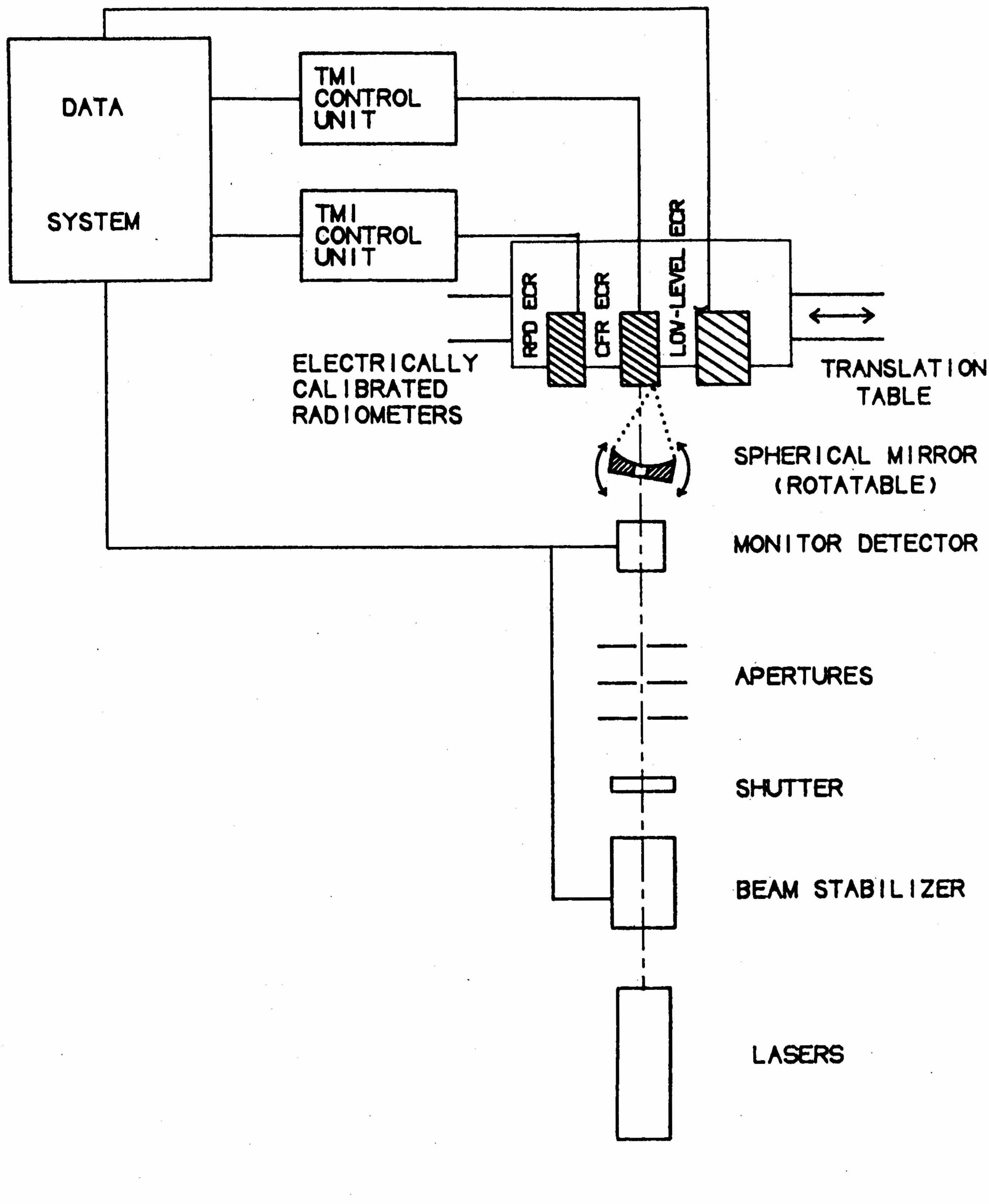
The laser response measurements establish the accuracy of the CFR radiometer to be in the range of 1 to 2% at the 5 irradiance levels measured from 0.8mW/cm^2 to 116mW/cm^2. The lamp measurements at 33mW/cm^2 and 145mW/cm^2 levels using the CFR ECR confirm the laser results. Though used sparingly, the standard lamps were last calibrated during the period 1974-1976. Thus, the lamp measurements should be considered as a check of the laser experiment. The RPD ECR responses for both lamps were within about 0.5% of those previously measured under the same conditions in 1976. At that time, the RPD ECR was characterized in the 33mW/cm^2 to 1W/cm^2 range in connection with NIST heat flux transducer calibrations. The accuracy of the ECR in the above range was then estimated to be 2%. These factors, in addition to the observed differences at 0.9W/cm^2 between the RPD and CFR ECRs with the infrared source, would indicate the accuracy for the CFR ECR at the 0.9W/cm^2 irradiance level to be in the range of 2 to 3%. The response accuracy in the range 0.8mW/cm^2 to 0.9W/cm^2 indicates that the CFR ECR is also linear to the same degree of accuracy over this range. The cavity blackness experiment showed a variation in reflectance for the CFR ECR of about 1 to 2% for the 5 wavelengths investigated. Based on the limited data obtained, no trends were discernible from the least squares fittings shown in Figures 3 and 4. Therefore no corrections were applied to either the response or blackness data. The uncertainty of the results obtained for the angular responsivity check is about 1%.

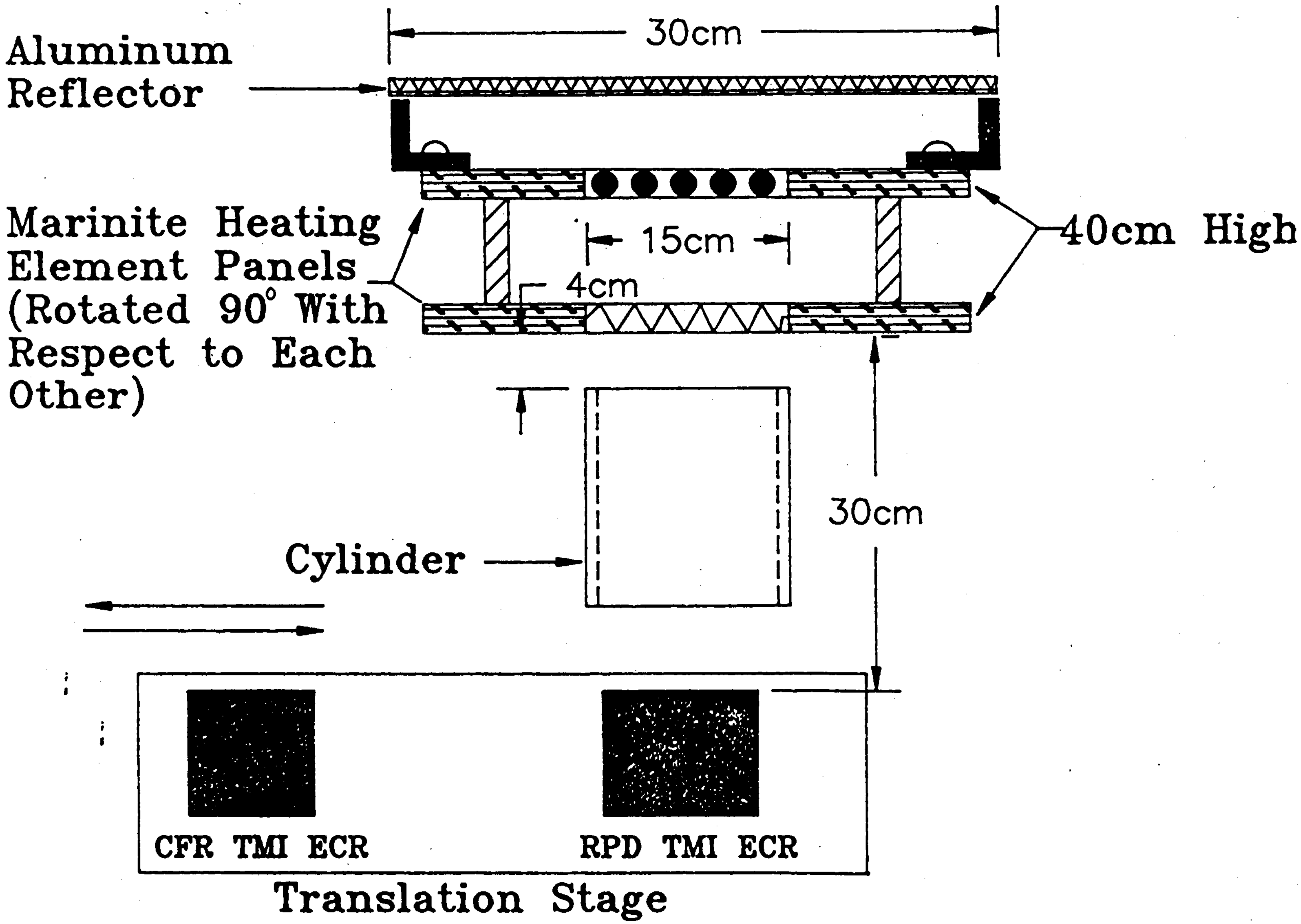
The TMI ECR design employs thermocouples which are inherently linear devices. Based on this fact and the above discussion, an uncorrected response reading measured with the CFR ECR is accurate to within 1 to 2% for irradiance levels in the 0.8mW/cm^2 - 116mW/cm^2 range and to within 2 to 3% for levels in the 116mW/cm^2 - 0.9W/cm^2 range.

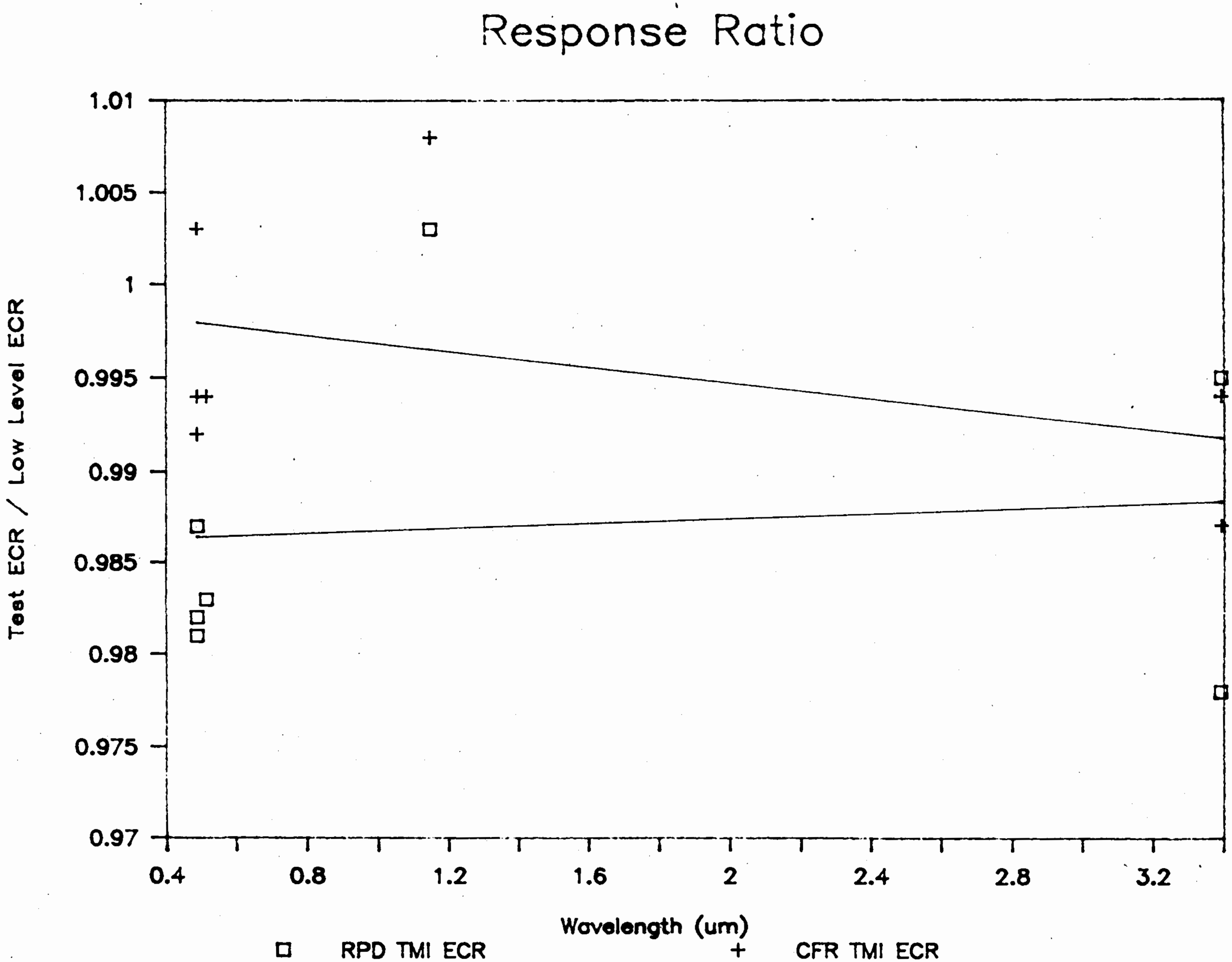
NOTE

(Referenced from the section, Cavity Blackness Measurement)

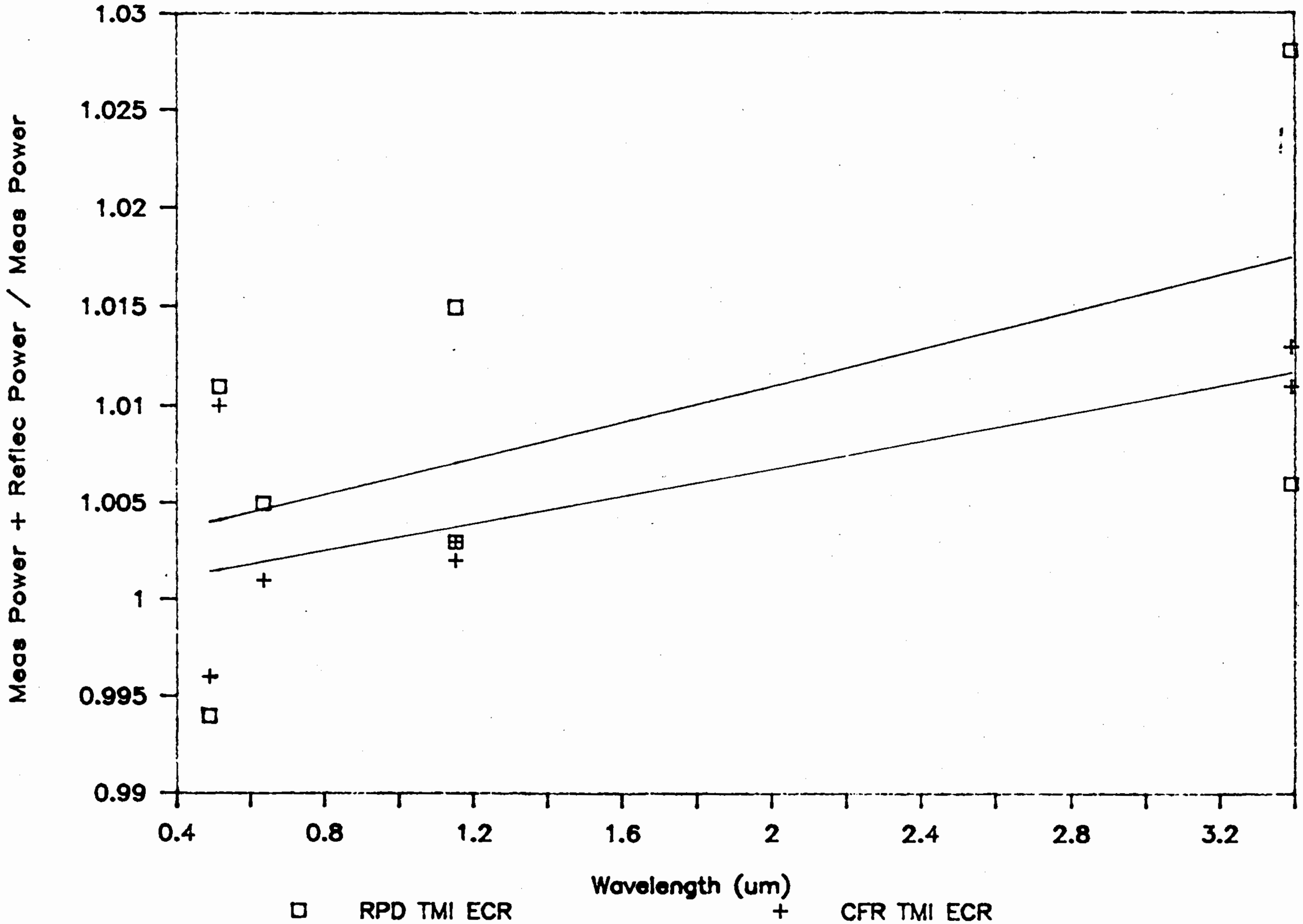
This estimate is based on a calculated mirror hole loss of 0.4% and a mirror reflectance of 99%. Although the reflectance of gold as a mirror coating decreases significantly from this level for wavelengths below 0.7μm, the influence of this effect is not apparent from this experiment due to the small values of cavity reflectance involved.


DATA
SYSTEM
TMI CONTROL UNIT
TMI CONTROL UNIT
RPD ECR
CFR ECR
LOW-LEVEL ECR
ELECTRICALLY CALIBRATED RADIOMETERS
TRANSLATION TABLE
SPHERICAL MIRROR (ROTATABLE)
MONITOR DETECTOR
APERTURES
SHUTTER
BEAM STABILIZER
LASERS


Aluminum Reflector
30cm
Marinite Heating Element Panels (Rotated 90° With Respect to Each Other)
15cm
4cm
40cm High
30cm
Cylinder
CFR TMI ECR
RPD TMI ECR
Translation Stage


Response Ratio
Test ECR / Low Level ECR
1.01
1.005
1
0.995
0.99
0.985
0.98
0.975
0.97
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
Wavelength (um)
RPD TMI ECR
CFR TMI ECR

Cavity Reflectance Ratio



APPENDIX B

PHOTOGRAPHS OF CFR CALIBRATION APPARATUS

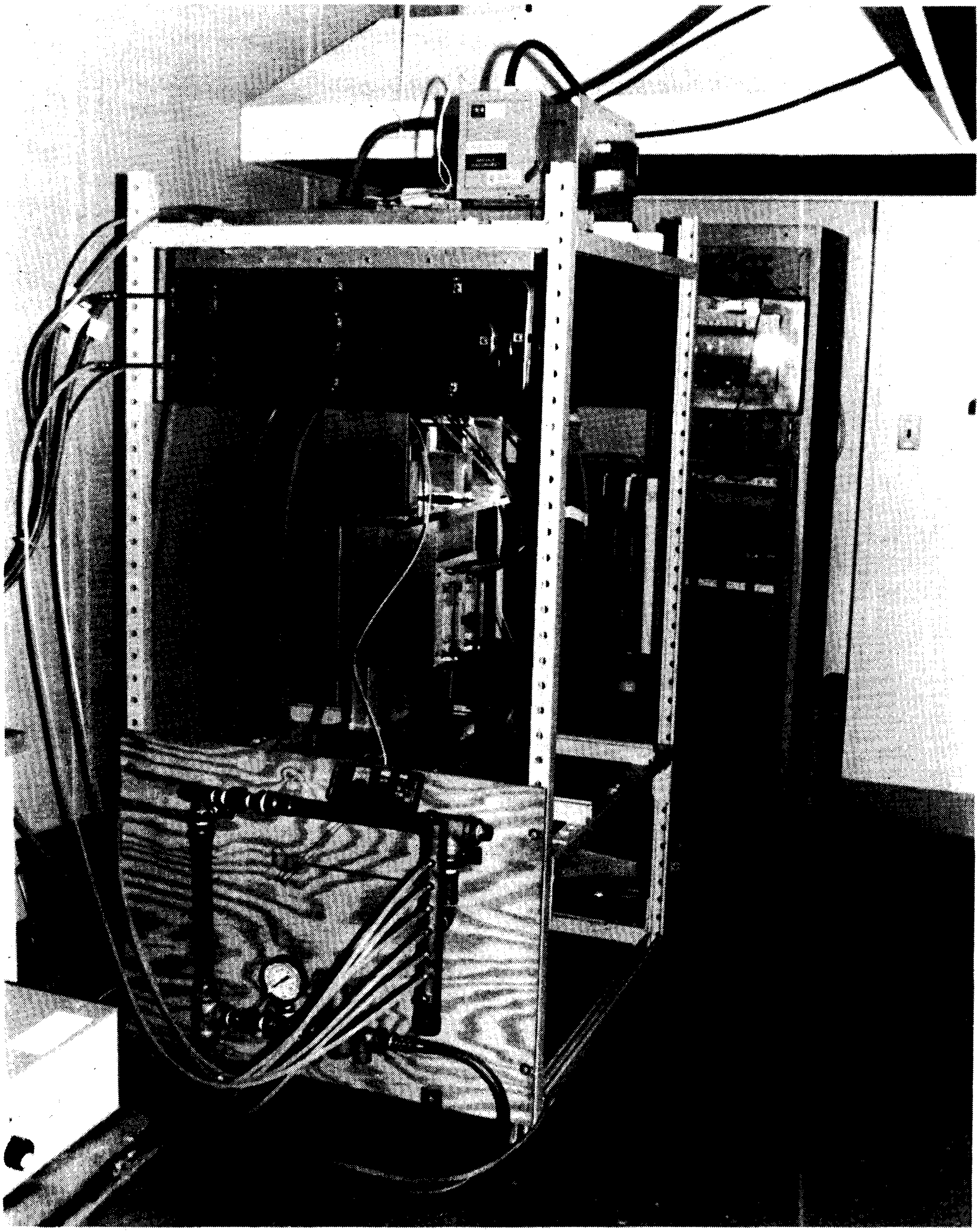


FIGURE B-1. OVERALL VIEW OF CALIBRATION APPARATUS

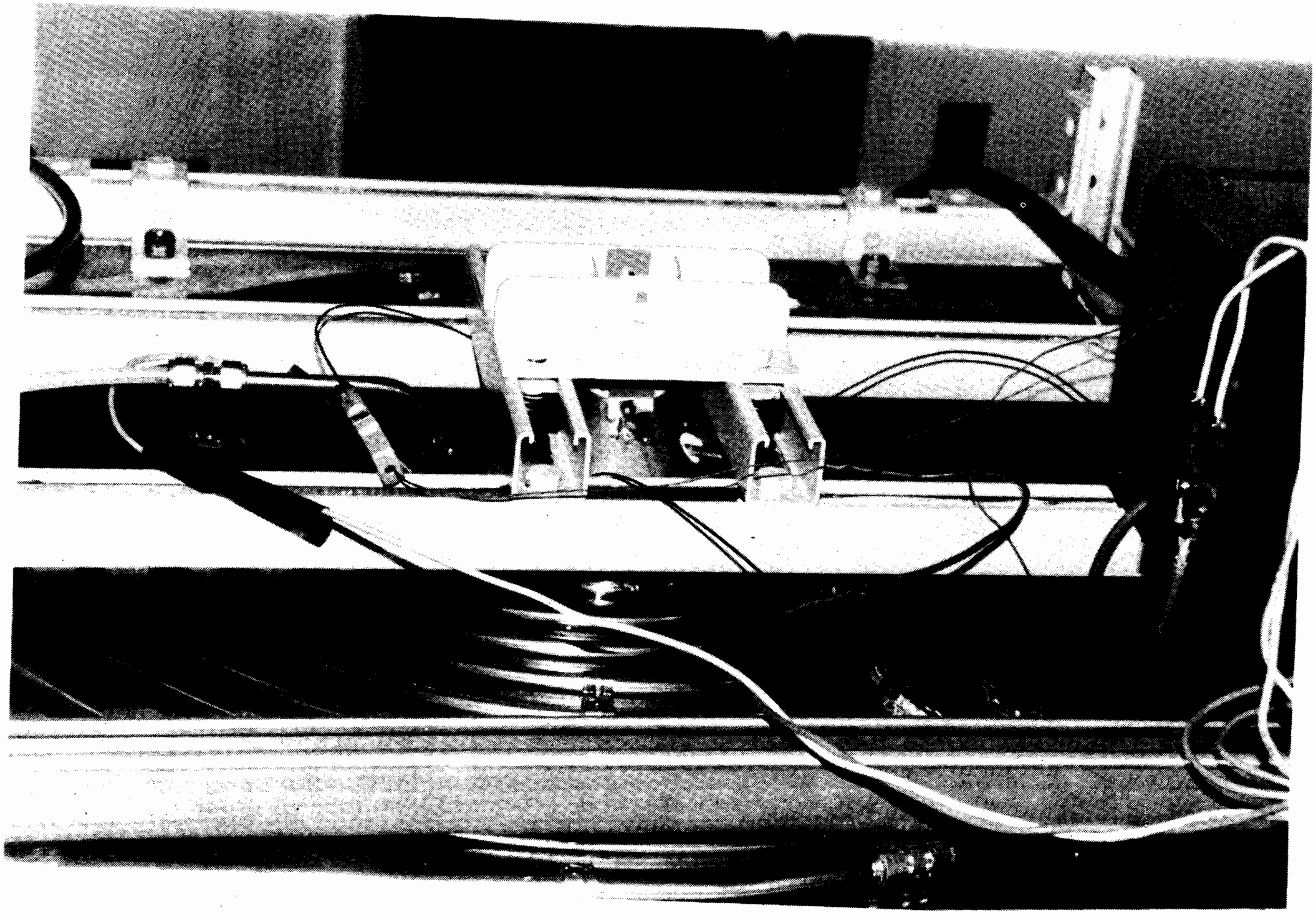


FIGURE B-2. VIEW OF TOP OF APPARATUS SHOWING COOLING COIL ATTACHTED TO COPPER PLATE AND HEATER-SUPPORT ASSEMBLY (Center)

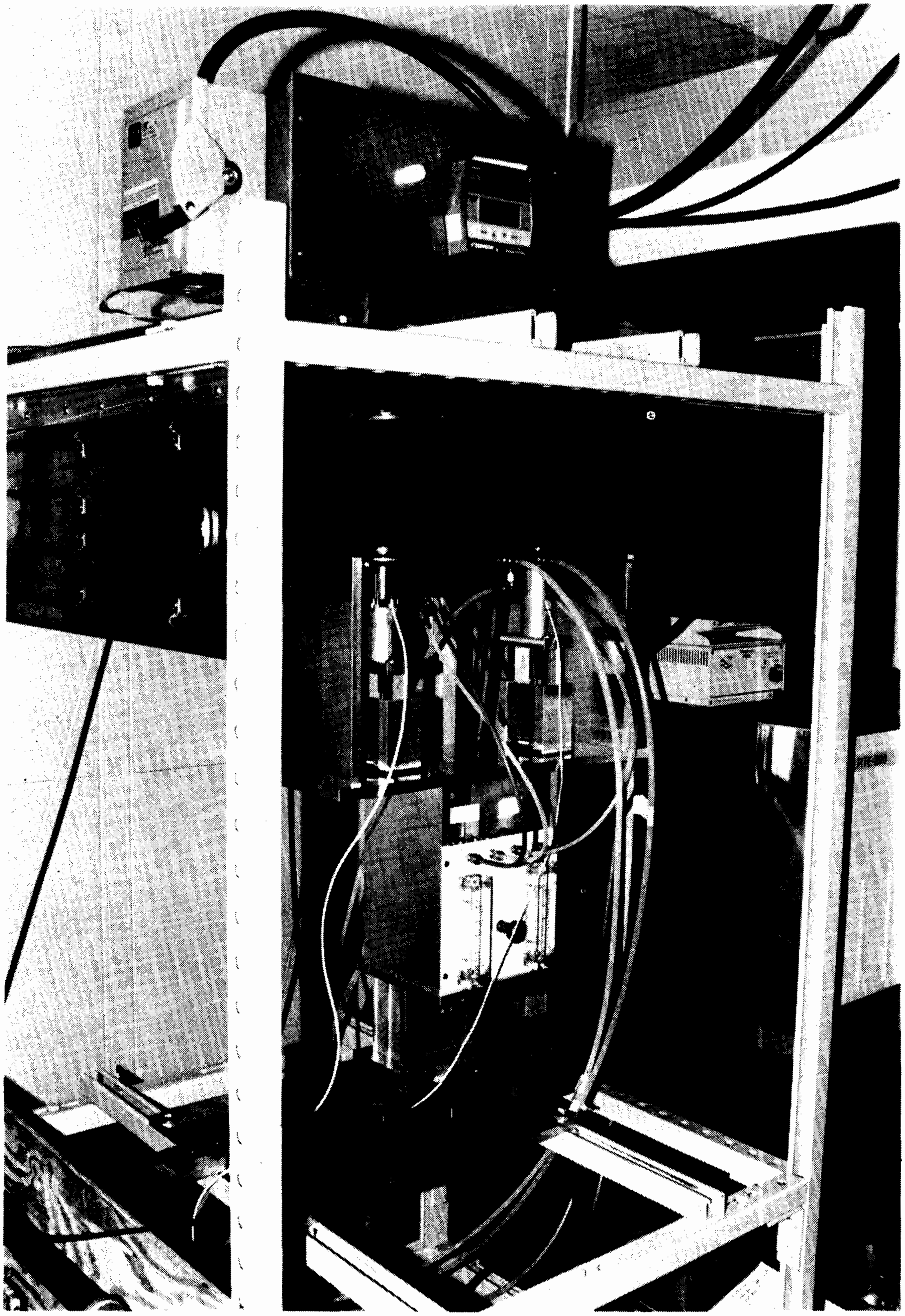


FIGURE B-3. FRONT VIEW WITH FRONT SIDE PANEL REMOVED

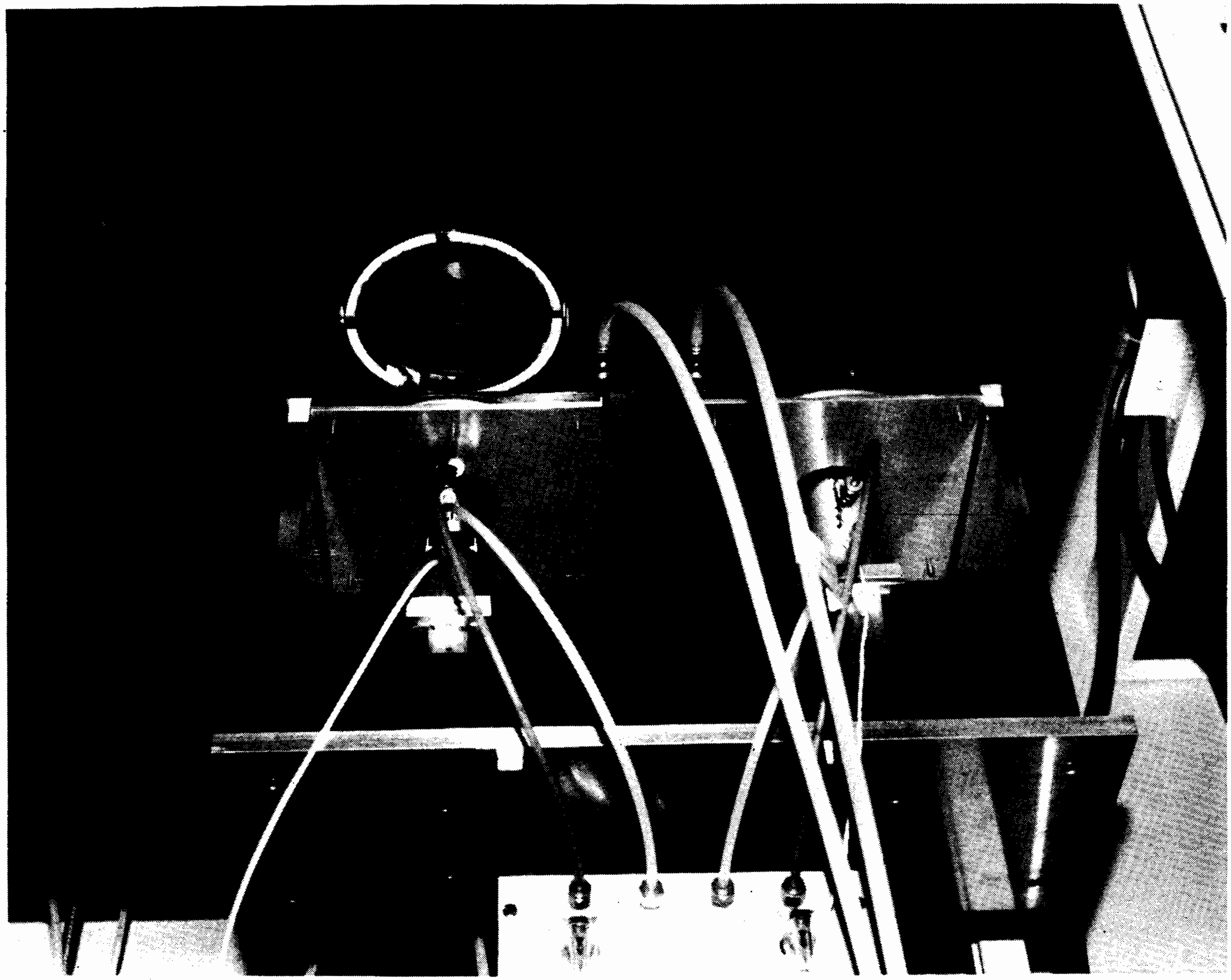


FIGURE B-4. VIEW FROM BELOW LOOKING UP TOWARD RADIANT HEATER

*U.S. GOVERNMENT PRINTING OFFICE: 1990-704-061/20089