

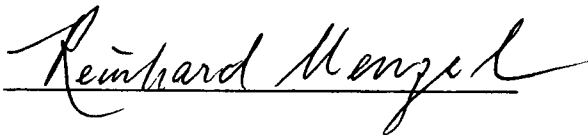
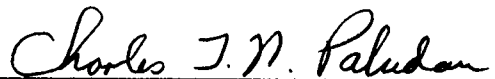
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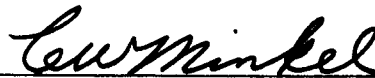


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Date March 13, 1991

APPLICATION OF AN ELECTRICALLY CALIBRATED PYROELECTRIC
RADIOMETER TO BROADBAND RADIOMETRIC CALIBRATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Christa B. Herron

May 1991

ABSTRACT

The Electrically Calibrated Pyroelectric Radiometer (ECPR) has traceability to national standards in the 0.25 - 2.0 micrometer wavelengths. Use of this device as a standard receiver is generally with lasers in this wavelength range. Application of the device to broadband blackbody calibration is an extension of its normal operation. The results indicated that use of the ECPR with a transmissive window degrades performance significantly. It was shown that by applying a black, spectrally absorbing cover over the detector aperture plate, the problem with using transmissive windows could be corrected. The conclusion formed as a result of the data acquired during this investigation was that the ECPR performs with a $\pm 3\%$ calibration uncertainty in the broadband application (1 to 22 μm). This level of performance uncertainty is comparable to that for other instruments which are also available for broadband radiometric calibration at ambient conditions.

ACKNOWLEDGEMENTS

The work represented in this thesis was obtained with the help and guidance of others. I would first like to recognize the efforts of Mr. K. Jarratt for identifying the problem presented in this thesis, purchasing the ECPR, and then providing advisement during the initial broadband radiometric experiments. Mr. K. Bynum supplied valuable instrumentation support by developing the dependent chopper drive system and software required to incorporate the ECPR into the spectral response test apparatus. A special acknowledgement goes to Mr. R. Young, Sr. for his radiometric expertise, which I frequently relied upon. He was also instrumental in identifying the primary cause of the ECPR's radiometric error. Finally, I'd like to thank the members of my committee for their guidance and assistance.

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CHAPTER I

INTRODUCTION

Design and calibration of sources which are intended to approximate ideal blackbodies and emit in the InfraRed (IR) has been a challenge. The National Bureau of Standards (NBS) closed its source calibration facility in July, 1984 and for many years there was no standard by which IR sources could be calibrated. The National Institute of Standards and Technology (NIST) has a new low background facility to provide calibration of Long Wavelength InfraRed (LWIR) sources (200-500 K) which typically operate in a vacuum and cryogenic, or low background, environment. The facility calibrated its first industry LWIR source in December, 1989. The NIST facility can also calibrate Medium Wavelength InfraRed (MWIR) (500 - 1000 K) sources which operate in a low background. Because the saturation limit of the NIST Absolute Cryogenic Radiometer (ACR) is dependent on source irradiance, the facility cannot accept high temperature and/or large aperture sources. Attaining a NIST calibration for some MWIR and all Short Wavelength InfraRed (SWIR) sources (1000 - 1300 K) is therefore not possible. The sources can achieve traceability through use of a spectrally flat reference detector to transfer a calibration from an LWIR NIST calibrated source. This type of calibration adds a level of uncertainty because of the transfer procedure. SWIR and MWIR sources are also designed for laboratory benchtop operation. Their emitting temperatures are significantly above the room temperature background.

NIST has recently announced the ability to provide calibrations on ambient operating broadband infrared emitting sources.

The NIST blackbody calibrations, whether ambient or low background, are provided by standard receivers. The cost of these calibrations and the inconvenience of shipping a source to NIST for several weeks encourages investigation of ways to transfer calibrations. The choice is whether to use another source or a receiver (radiometer). A NIST traceable receiver has the advantage of added versatility. For instance, a standard receiver could provide in situ calibration for installations where transmissive and reflective optical elements have been inserted between the blackbody and the test detector.

Standard receivers, such as the thermopile and bolometer, have existed for many years. Most were abandoned in favor of standard energy sources, when the source calibrations requirements exceeded receiver sensitivity. Calibration of these sources, or blackbodies, were provided by transfer from a source at the NBS or from a source with a calibration traceability to NBS. In 1968, NBS returned to the idea of absolute radiometry, and the first Electrically Calibrated Pyroelectric Radiometer (ECPR) was developed in 1972 as an ambient operating standard receiver. The capabilities of the ECPR have increased since that time. The new NIST facility, formerly NBS, ACR is a sophisticated electrically calibrated radiometer and is used to perform their calibration service.

The commercially available ECPR is a considerably simpler design and is therefore less expensive and accurate than the ACR used at NIST.

The commercial ECPR is also not designed to operate in a vacuum and cryogenic environment. The predominant use of these radiometers has been to calibrate the output of visible and SWIR lasers. The ECPR is quoted to have a 1% NIST electrical traceability path for the 0.25 to 2.0 μm range, although their operating range extends into the LWIR. The ECPR, therefore, is potentially one of the few ways to establish standards traceability for an ambient operating blackbody source, especially for calibration of blackbodies in the MWIR and SWIR region of the spectrum. The purpose of this thesis is to evaluate whether the ECPR can be applied to measurement of broadband radiometric energy emitted from an ambient operating blackbody.

Many articles were written in the mid-1970's which analyze the performance of ECPR's. Most articles have concentrated on errors in the electrical to radiative heating equivalency and other almost negligible ($< 1\%$) errors involving the internal electrical components of the instrument. Performance analysis in the infrared was generally limited to the wavelengths shorter than 2.0 μm . A few articles have addressed operation out to 10 μm , but discussions were confined to performance of the gold black detector coating. The specific instrument used for this evaluation was introduced on the market in 1983. No recently written articles concerning ECPR performance could be found, especially ones addressing use of these instruments into the LWIR region of the spectrum.

CHAPTER II

BACKGROUND AND THEORY

Principles of Infrared Radiation

Radiation heat transfer involves the transport of photon energy from a heated body. The photons travel in the form of electromagnetic waves at the speed of light. The velocity of light is equal to the product of the wavelength and frequency of the radiation. The electromagnetic spectrum is shown in Figure 1 [1]¹. The frequency and wavelength for various wavebands are indicated. Thermal radiation takes place in the visible and infrared regions of the spectrum, which are shown in the exploded view (Figure 1). The energy level of the photons is equal to the product of the frequency and Planck's constant, h . The first law to explain thermal radiation was Kirchhoff's Law. Introduced in 1860, Kirchhoff stated that a good absorber was also a good emitter. He also used the term "blackbody" to describe a body that absorbs all radiant energy incident on its surface. Therefore, a blackbody must be a perfect emitter of radiant energy as well. In other words, the blackbody radiates at the theoretical limit of unity emissivity and for this reason provides a standard against which other source designs are compared. Most laboratory "blackbodies" are referred to as such, because their emissivities are very nearly unity.

Planck's Law, developed in 1900, describes the spectral energy

¹Numbers in brackets refer to similarly numbered references in the Bibliography.

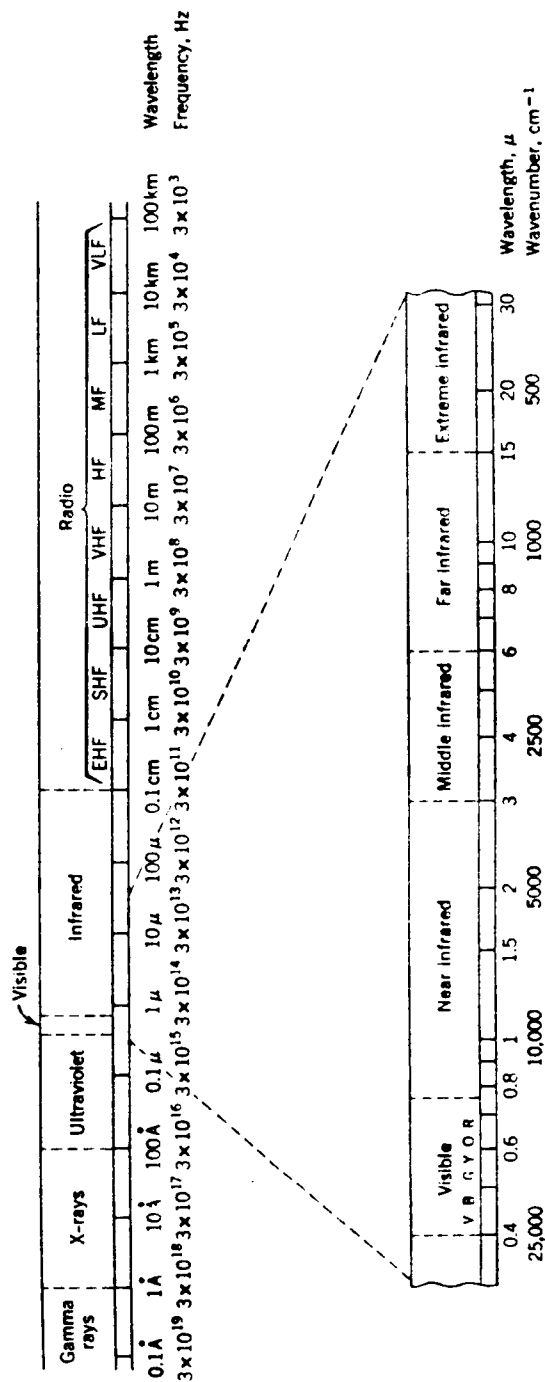


Figure 1. Electromagnetic Spectrum

distribution of a blackbody heated to any given temperature. A plot of Planck's equation for a blackbody radiating at various temperatures is shown in Figure 2 [1]. The family of curves defines the emissive power versus wavelength for each blackbody operating temperature. Figure 2 indicates that as the temperature of the blackbody increases, the photon energy is concentrated at the lower wavelengths. The wavelength at which a blackbody has maximum emissive power is given by Wien's Displacement Law. This maximum value can be found for a specific temperature by determining, from differentiation of Planck's Law, the wavelength at which slope of the blackbody curve is zero. The dashed line in Figure 2 illustrates the locus of points which are described by Wien's Law.

The total emissive power of a blackbody is given by the area under a blackbody curve, or more exactly, the integral of Planck's distribution over all wavelengths [2]. The Stefan-Boltzmann Law is the result of the integration of Planck's Law. The Stefan-Boltzmann Law reveals that total blackbody radiative energy is simply the product of a constant and the blackbody temperature to the fourth power. The Stefan-Boltzmann constant combines the constants of Planck's Law into a single value. Application of these thermal radiation laws to experimental calculations will be demonstrated in Chapter V.

Radiometric Calibration

Radiometric calibration joins two very challenging fields of study. Radiometrics, or radiometry, is a term which describes the measurement of radiant energy in the infrared region of the spectrum.

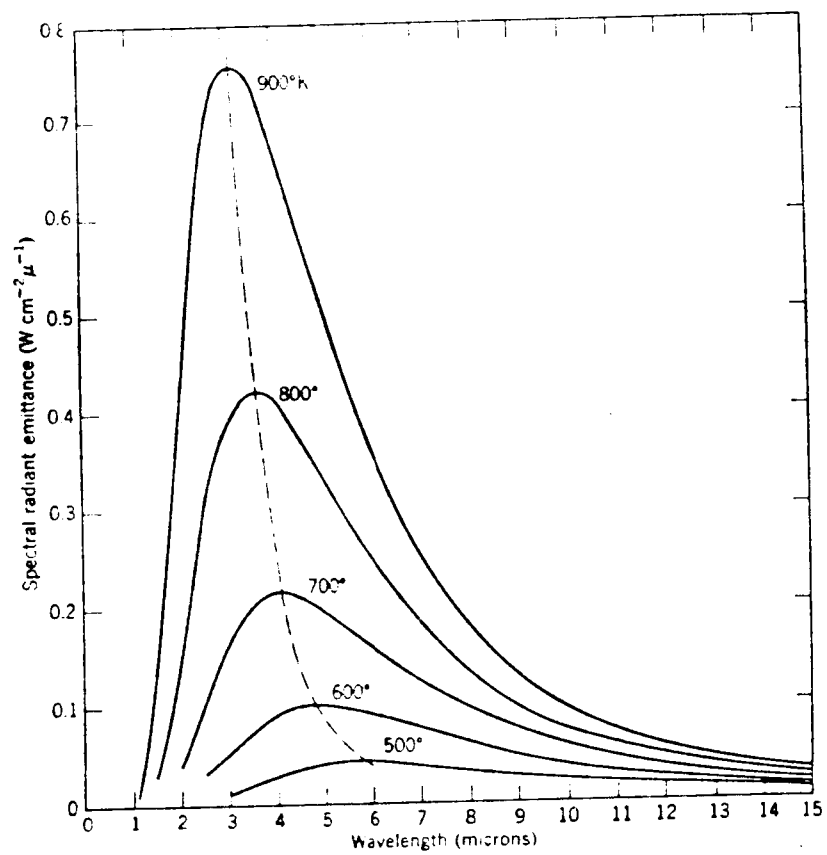


Figure 2. Blackbody Curves

Radiometers typically perform these measurements by absorbing the radiant energy and then converting that energy to another form, such as electrical, thermal, or chemical, for measurement purposes [1]. Calibration provides traceability from the response of an instrument to the true value of the quantity being measured. For an absolute calibration, the input stimulus has direct traceability to known standards maintained by NIST. The combined term, radiometric calibration, determines the traceability of a detector or radiometer's response to infrared radiation.

The calibration problem typically involves each element of an infrared system, as illustrated in Figure 3 [1]. The object to be measured is referred to as the target. A blackbody source is used in the laboratory to simulate real world targets of interest. The optical receiver can be as complicated as a telescope, designed to focus the radiation on the detector, or as simple as a transmissive filter. The radiation which passes through the optical receiver stimulates the detector. An electrical signal is then sent from the detector to the processor. There, the signal is amplified and the result is then output in some form. To determine the performance of the detector, the spectral quality and quantity of the energy which arrives at and is processed through the detector must be evaluated [3]. Calibration of the instrument then becomes a function of the characteristics of the source output, background contributions, environment, source to detector distance, optical elements, and the performance of the detector in converting radiant energy to an output signal.

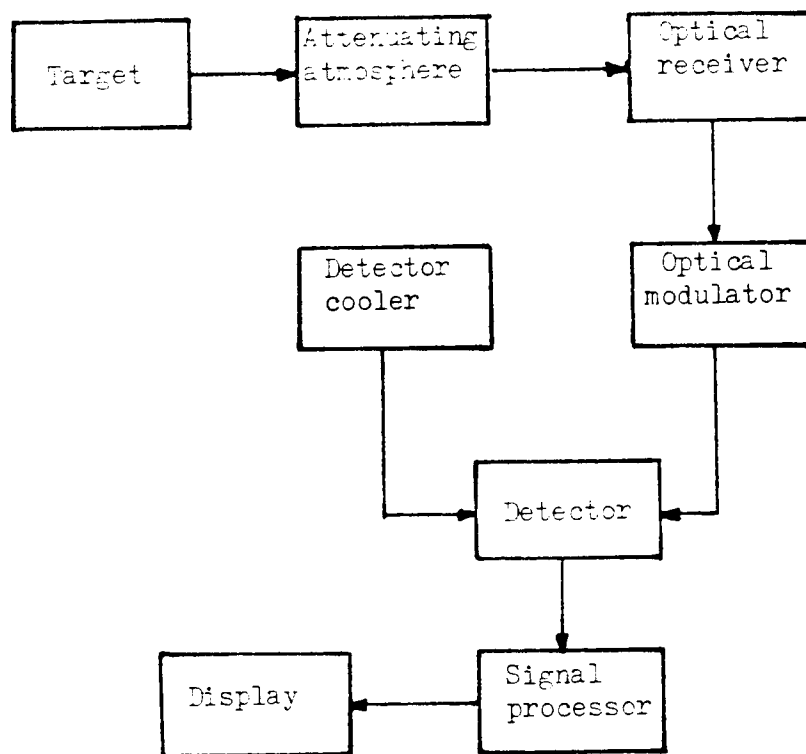


Figure 3. Elements of a Typical IR System

The term most commonly used to describe the calibration of an infrared detector is responsivity. A detector's responsivity is defined as the ratio of the detector's output (response) to the incoming radiation. Detector responsivity may vary as a function of several variables. Two variables, of primary concern in most calibrations, are detector linearity and spectral response. The term detector linearity is used to describe the data curve which results from plotting the detector response versus a range of input radiation. Each detector has a range of input radiation over which it will provide a measurement. Saturation of the detector occurs at the high end of its dynamic range and the signal is indistinguishable from the noise floor at the lower limit. To vary the incoming radiation through the dynamic range of the detector, the source temperature, source to detector distance, and the source aperture area can be varied. Aperture area variation is a convenient method, since precision apertures are available and aperture area changes do not affect the spectral content of the incoming radiation as changing the source temperature would. A log-log plot of the output voltage versus corresponding aperture area for the dynamic range of the detector will result in a slope of one for a linear detector [3]. A detector's spectral response is concerned with the detector's output versus wavelength change across the broadband operating range of the instrument. Obtaining spectral response information is more difficult than measuring detector linearity. Energy must be provided to the detector in small wavelength intervals within its operating wavelength region. In addition, the quantity of

energy reaching the detector in each wavelength interval is generally unknown. For the latter reason, the spectral response of the detector is normalized to produce a unitless value of 1.0 or less at each wavelength interval. The wavelength at which the value of 1.0 occurs is where the detector has its maximum or peak sensitivity. The spectral performance of the detector can then be evaluated by examining the normalized spectral response versus wavelength.

Pyroelectric Detectors

Pyroelectric detectors were developed out of the need for an ambient operating detector with sensitivity in the infrared. Beyond resolving these original issues, the pyroelectric detector also provided faster time response than previous thermal detectors. The time response is attributed to the detector's unique theory of operation [4].

The pyroelectric detector consists of crystalline dielectric materials. Characteristics of several of the most common materials are provided in Table 1 [4]. The crystals are electrically polarized so that at a constant temperature there is no detector response. When thermal energy, or radiation, strikes the crystal a temperature change in the material occurs. The heating expands the crystal lattice spacing which, in turn, produces a change in the electrical polarization. The polarization change then causes a change in charge which produces a charge flow in the detector circuit. Because this reaction is at the molecular level, the pyroelectric reacts quickly to

Table 1. Characteristics of Pyroelectric Materials

Material	Pyroelectric Coefficient, p [C cm ⁻² K ⁻¹]
Turmaline	4×10^{-10}
BaTiO ₃	2×10^{-8}
TGS	$(2-3.5) \times 10^{-8}$
Li ₂ SO ₄ H ₂ O	1.0×10^{-8}
LiNbO ₃	4×10^{-9}
LiTaO ₃	6×10^{-9}
SbSI	2.6×10^{-7}
NaNO ₃	1.2×10^{-8}

these energy changes. The different pyroelectric materials, with which detectors can be manufactured, do vary in performance. The pyroelectric coefficient can be used to compare pyroelectric material response time (Table 1). The pyroelectric coefficient represents the rate of change of the electric polarization with respect to a temperature change. The larger value, therefore, represents a faster response [4].

Uniform spectral absorption of infrared radiation on the surface of the pyroelectric detector requires that it be coated black. One type of black coating, which provides this spectral absorption, is called gold black. This coating has low reflectance, high thermal conductivity, and is spectrally flat into the LWIR [5]. Performance of the coating is not only driven by its absorption characteristics, but also its thickness. Establishing the thickness of the coating is a trade-off between sensitivity and response time. Sensitivity, or detectivity, is improved by applying a thick coating, because it provides a greater thermal capacity. On the other hand, the thicker coating slows the transfer of heat to the detector, thus lengthening the time response [1]. A final note should be given regarding these coatings. The coatings are relatively thin and, therefore, their absorption performance can easily be degraded or destroyed by touching them.

ECPR Development

The standard receiver has existed since Angstrom developed an electrically calibrated bolometer in 1893. These early radiometers were not sensitive enough to measure the output of many types of

sources. This forced the use of the blackbody as the calibration standard until the mid-1970's. The need to revisit calibration through use of standard radiometers surfaced in the 1960's, however, because of the need to accurately measure the output of lasers [5].

In 1968, the NBS got involved in a program devoted to absolute radiometry. Thermopile detectors were used as the first electrically calibrated radiometers. These had relatively limited measurement application compared to later radiometers, which have more broadened uses. The development of the ECPR was the result of seeking a more versatile device. The ECPR provided a larger detector area and faster response times. In addition, the need to modulate the incoming radiation to stimulate energy changes in the pyroelectric material had an added benefit. The signal modulation separated the source energy from the background radiation. Robert Phelan, Jr. of the NBS demonstrated the first ECPR in 1972 [5].

ECPR as a Calibration Tool

Radiometric calibration of the energy emitted by a thermal source can be achieved by an absolute radiometer. NIST currently performs calibrations on infrared blackbodies using an absolute radiometer which is traceable to electrical standards. The operating principle for such a radiometer is described by the following statement of the law of conservation of energy:

"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" [7].

As described in Chapter I, the NIST ACR is a unique and expensive custom design for calibration of LWIR blackbodies in a low background environment. The ECPR featured in this thesis is based on the same principle of electrical calibration traceability. This instrument, however, is a relatively low cost, commercially available instrument which is primarily manufactured for calibrated laser power measurements in an ambient environment. The laser application is limited to specific wavelengths, usually in the visible and near infrared. The issue of whether the design and operating principles of the ECPR allow it to be used as a calibration tool for ambient operating broadband infrared emitting blackbody sources is the subject of this paper.

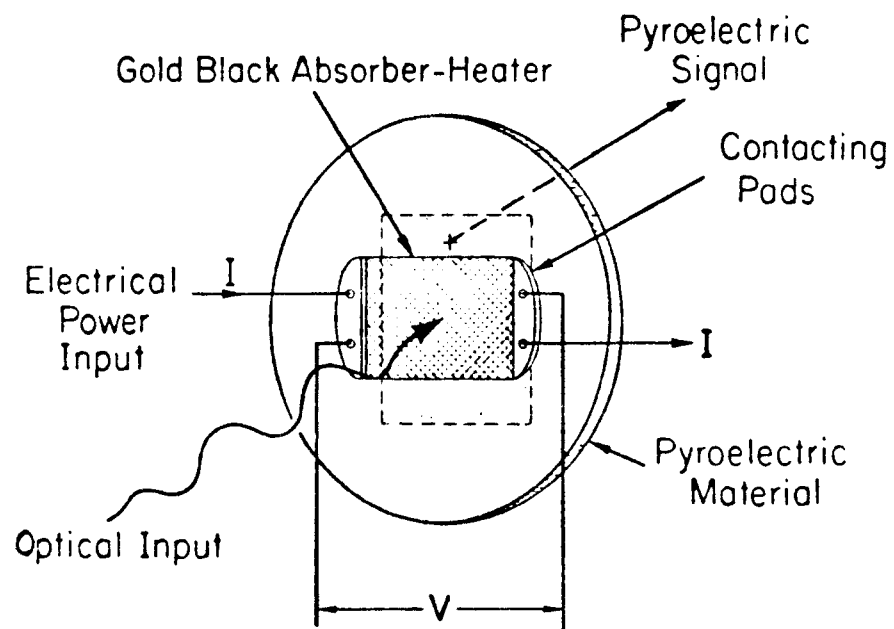
CHAPTER III

EXPERIMENTAL APPARATUS

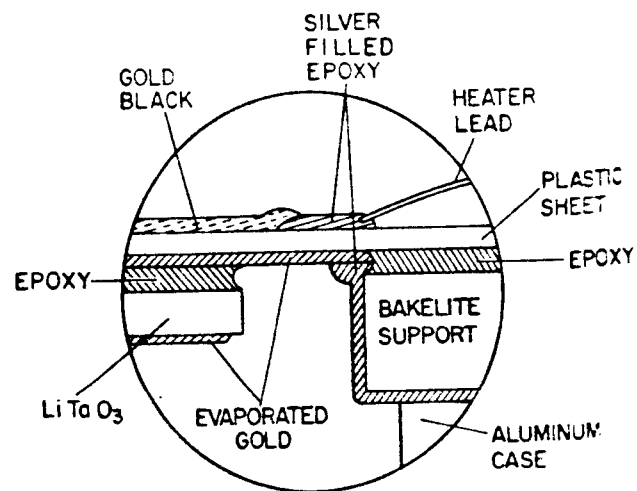
Resolution of the ECPR's ability to perform broadband radiometric calibrations required various types of equipment. The primary apparatus was, of course, the ECPR which was purchased from the Laser Precision Corporation. The broadband radiometric energy was supplied from a blackbody source manufactured by Infrared Industries, Inc. As discussed in Chapter II, a pyroelectric detector requires a change in energy. Therefore, a signal modulator was provided between the ECPR and the blackbody. The ECPR's spectral response was investigated in addition to its broadband response. The equipment necessary to make these spectral response measurements is described in this chapter, along with the three basic components required for the broadband application.

Laser Precision ECPR

The Laser Precision ECPR is a radiometer which uses a lithium tantalate (LiTaO_3) pyroelectric detector to supply an electrical calibration of incoming radiation. The conversion of the incoming radiation to an electric signal takes place in the detector. Figure 4 shows two views of the detector construction. Figure 4a illustrates how the incoming radiation or an electrical power input causes heating of the gold black absorber [7]. Figure 4b is a sectional view of the detector construction [8]. The conductive path for the transfer of heat between the gold black coating and the pyroelectric detector is



a. Plan View



b. Sectional View

Figure 4. ECPR Detector Construction

clearly shown in this view. As discussed previously, the performance of the gold black coating is key to the ECPR. The spectral reflectance characteristics in the wavelength range of the incoming radiation are of particular importance for this thesis. The manufacturer-provided spectral reflectance of the ECPR detector is shown in Figure 5 [9].

The Laser Precision ECPR uses a null balance technique for electrical calibration. The incident radiation is chopped with a 50% duty cycle. During the open portion of the cycle, radiation is absorbed in the detector surface. During the closed portion, the radiation is blocked by the chopper blade. At this time, an electrical signal is applied across the heater on the detector surface. The response of the detector to the input radiation and electrical heat are amplified and demodulated to produce an output from the lock-in amplifier proportional to the difference between the signals. The difference signal is fed back to the electrical heat input circuit to adjust the signal applied across the heater during each chopper cycle, until the difference signal reduces to zero. The upper loop of the block diagram of Figure 6 shows the null balance operating circuit [7]. The electrical power required to match the radiative energy is calculated using the measured detector heater voltage and current as shown in the lower loop of Figure 6.

The ECPR unit can be used with a Zinc Selenide (ZnSe) or quartz window attachment which screws onto the front of the instrument. The windows transmit in the infrared and have the effect of reducing erroneous data by preventing convective air currents from directly

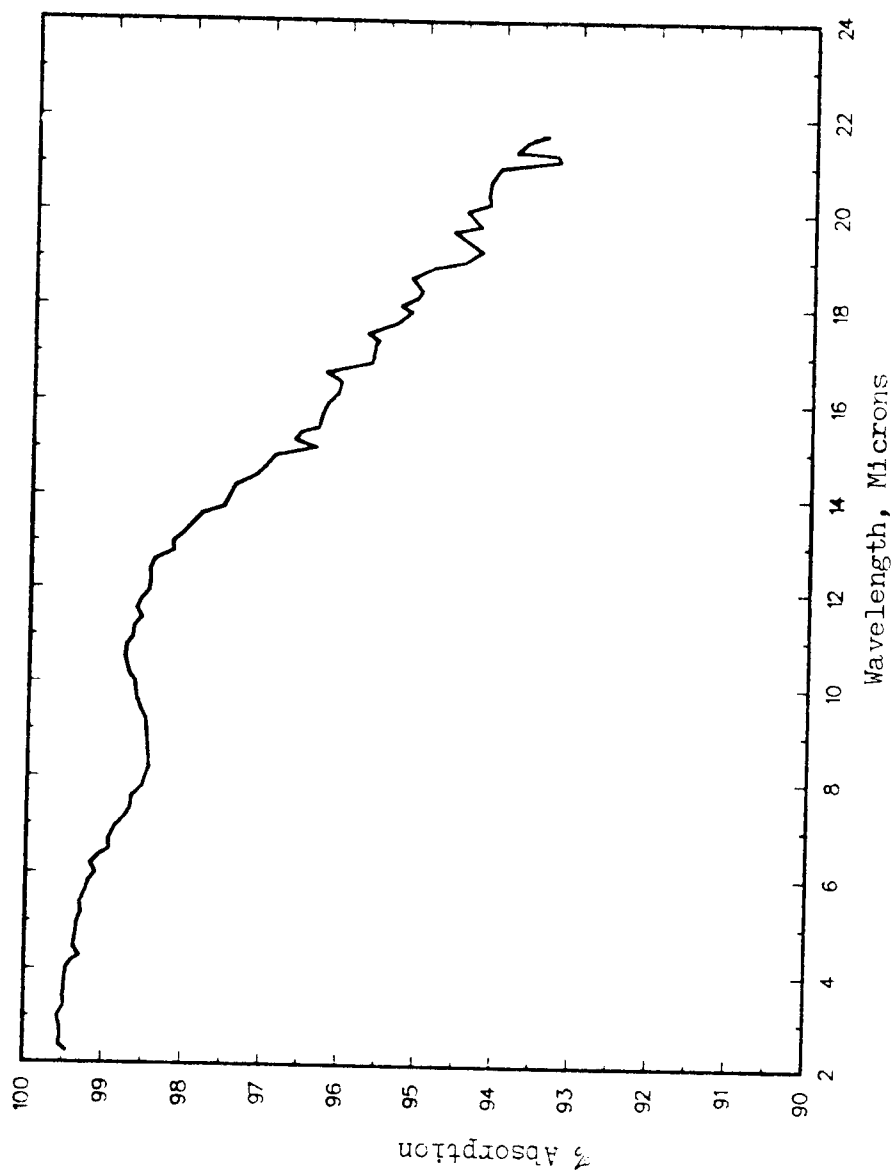


Figure 5. ECPR Detector Spectral Absorption

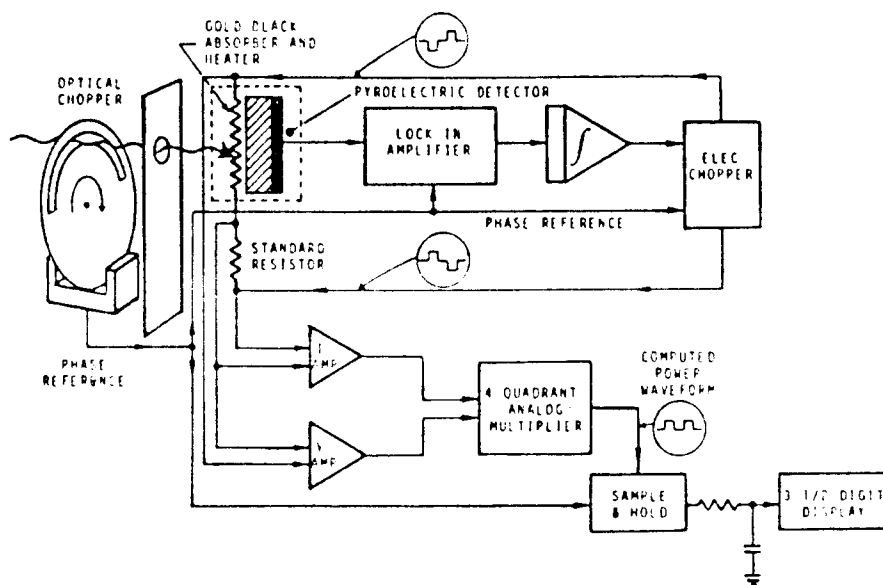


Figure 6. ECPR Operational Circuit

impinging on the detector surface. A window also allows the unit to be evacuated for further reduction of convective heat transfer, which results in a lower noise level in the data. The manufacturer-provided ZnSe window transmittance is shown in Figure 7. The ZnSe window and the gold black coating both degrade the blackbody distribution of energy with wavelength. Combination of the detector spectral reflectance (Figure 5) with the effect of the ZnSe transmission yields a theoretical curve for spectral absorption of incoming radiation. The overall spectral absorption data are calculated by multiplying the value of the ZnSe transmission by one minus the gold black reflectivity at each wavelength. This resulting curve is provided in Figure 8. Since the detector gold black is nearly 100% absorbing, the effect is only a slight drop in total absorption at the longer wavelengths. The spectral absorption for the ECPR configuration is important for correct calculation of the total energy reaching the pyroelectric material. The quartz window transmission curve is provided in Figure 9 [9].

The ECPR display/control box shown in Figure 10 plays an important role in correct operation of the instrument [9]. It contains the connections for the input for the chopper sync signal and the ECPR and contains the microprocessor responsible for the control and measurement system. The twelve button key pad interfaces to the microprocessor and provides selectable functions. Selection of the units in which the power is displayed is available as either watts, which is radiant flux, or watts/sq. cm, which is irradiance. To convert between the two outputs, the radiant flux is divided by the detector aperture area (0.5

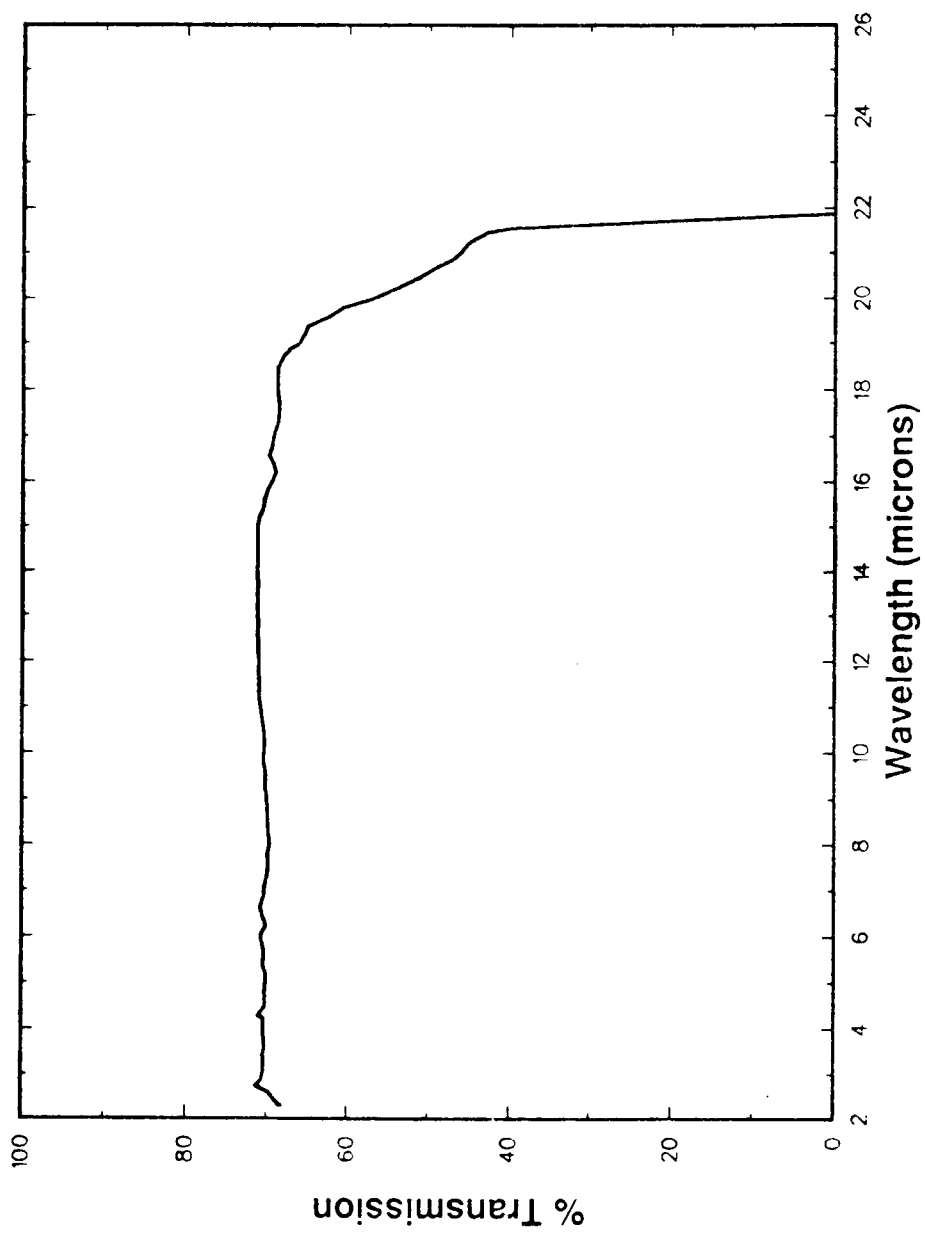


Figure 7. ZnSe Window Spectral Transmission

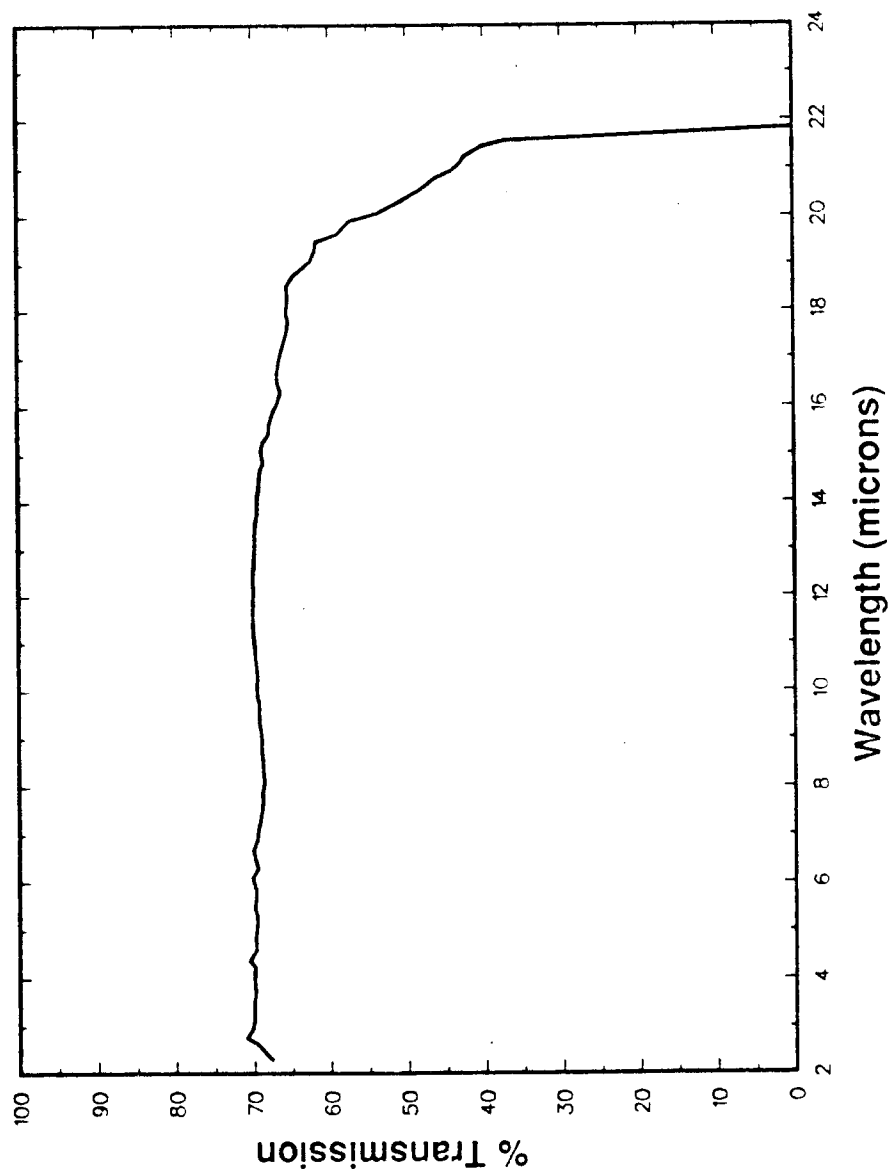


Figure 8. ECPR Spectral Absorption with ZnSe Window Option

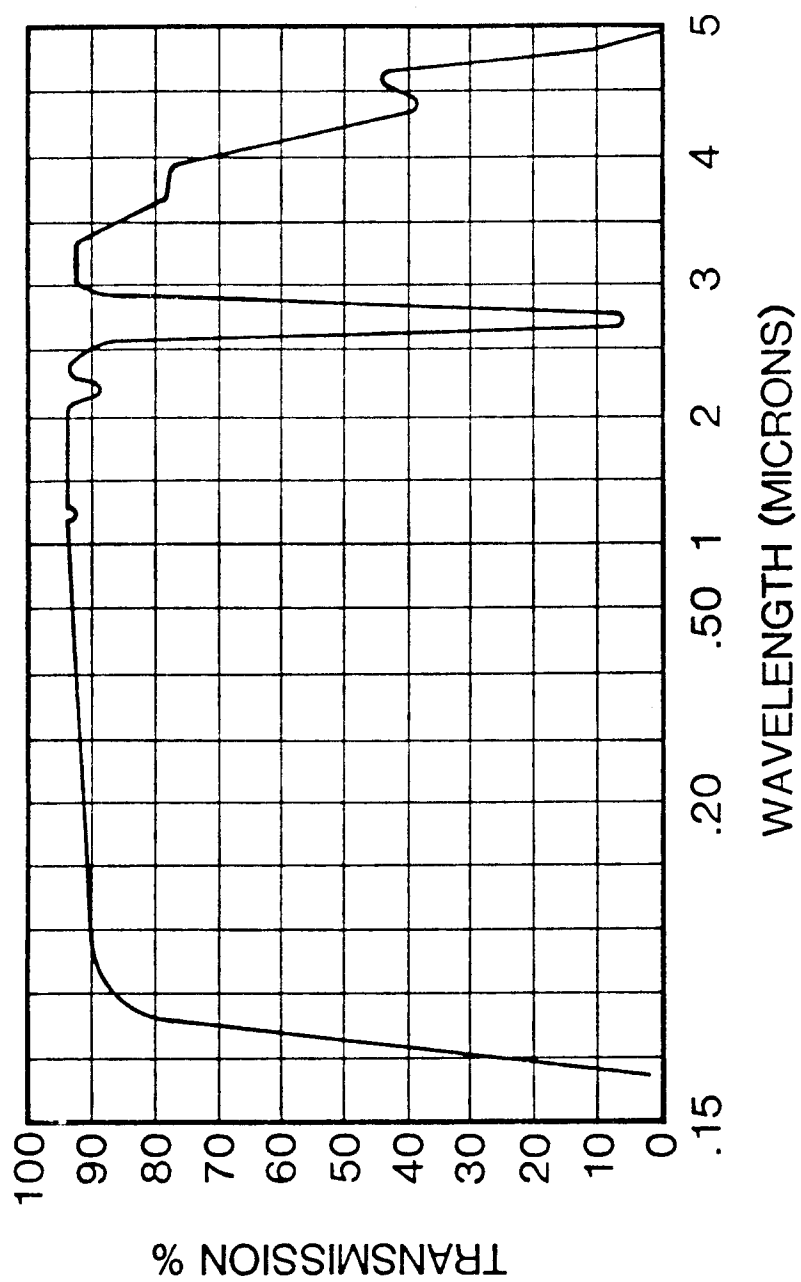
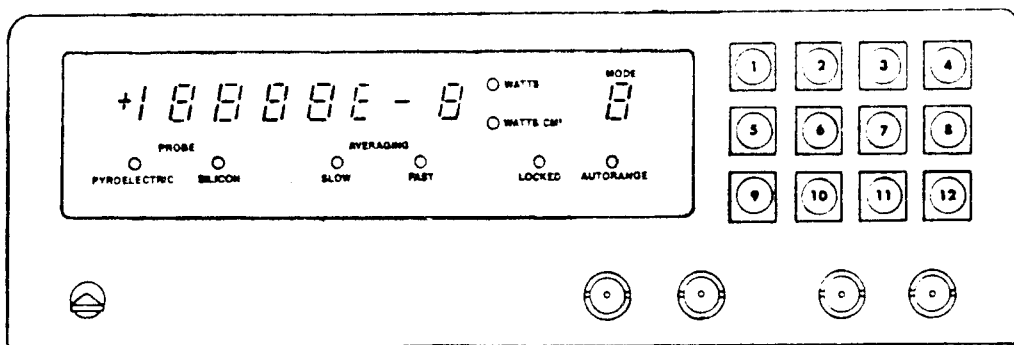


Figure 9. Quartz Window Spectral Transmission



1	Probe	Probe Select	7	TEST	Test Key
2	UNITS	Units Select	8	CONT	Continue/Exit
3	AVG	Averaging	9	RCL CAL	Recall Calibration Factor
4	AZ	Autozero	10	CAL	Increment Calibration Factor
5	RANGE	Increment Range	11	CAL	Decrement Calibration Factor
6	RANGE	Decrement Range	12	STO CAL	Store Calibration Factor

Figure 10. ECPR Power Meter Features

cm²). Fast or slow averaging can be selected as well. The autozero function can be used to zero the instrument. This is valuable for automatically removing background effects (tare) from the data. The remaining keys allow the user to check or revise the instrument's calibration.

Signal Modulator

Operation of the ECPR requires modulation of the continuous black-body output to produce thermal change on the pyroelectric surface (Figure 6, page 21). The ECPR manufacturer included a signal modulator, commonly referred to as a chopper wheel, with the instrument to fulfill this requirement. The signal modulator is a wheel composed of two opposing 90 degree blades, which rotates at 15 Hz. The radiation entering the ECPR is disrupted as a blade passes in front of the detector, causing a thermal change on the pyroelectric material.

The ECPR operation depends on a reference signal from the optical chopper (Figure 6) to coordinate the application of the electrical heating. The reference signal is produced by an emitter/detector pair mounted perpendicular to the blade path. When a 90 degree opening occurs in the wheel rotation, the energy from the emitter strikes the detector and a signal is produced. When a blade of the chopper passes between the emitting and sensing element, no signal is generated. The result is a square wave signal from the reference detector to the ECPR control unit. The reference signal generator is positioned 180 degrees from the radiation path. The chopper is built into a housing assembly with an opening for the source energy to pass through to the ECPR.

Manual phase adjustment is provided through rotation of the opening relative to the reference signal generator.

The chopper position in the experimental setup, shown in Figure 11, is critical for acquiring good data. The chopper should be located between the blackbody and the blackbody's exit aperture. In that position, the difference between the blocked and unblocked beam can be attributed only to the source output. This results in removal of all background contributions and heating of the aperture plate from the ECPR reading. The thickness of the manufacturer's chopper housing and the blackbody mounting structure makes this ideal installation difficult. The chopper had to be located directly in front of the aperture on the ECPR side. Cooling water circulating through the aperture plate helped minimize the heat buildup around the aperture.

Use of a different signal modulation system was required to operate the ECPR with the spectral response apparatus, described in the next section. In order to provide an acceptable reference signal to the ECPR, the requirements for the chopper were that its reference signal interface to the ECPR controller and that it have phase correction capability. Interface to the ECPR controller requires a 15 Hz input. Since the spectral response apparatus was designed to accommodate a variety of chopper speeds, obtaining the 15 Hz speed was not a problem. The system was also designed with a reference signal generator, consisting of a photodiode and emitter pair. The photodiode output provided the necessary input signal to the ECPR system. The chopping system was not, however, contained in a rotatable housing to

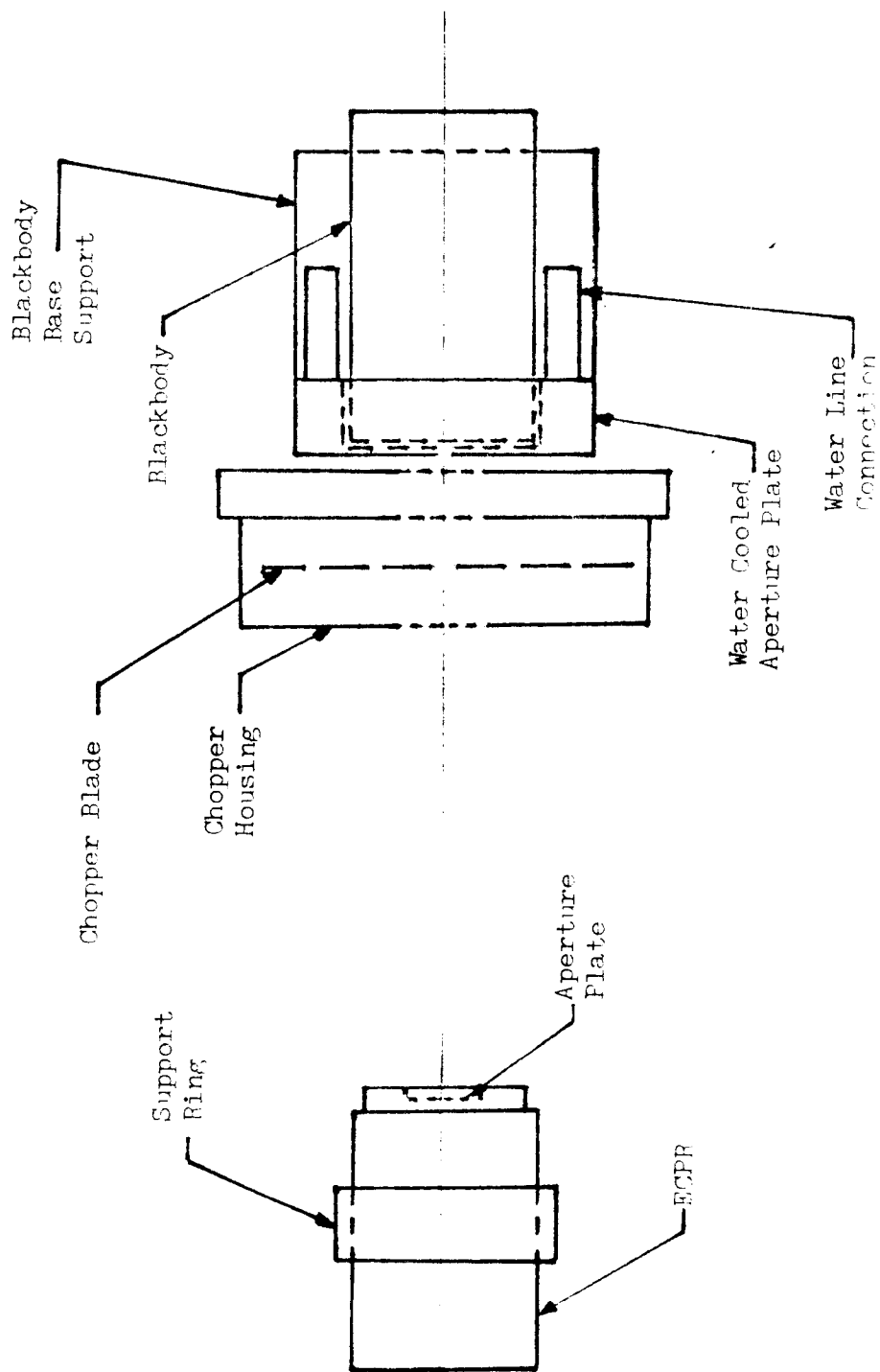


Figure 11. ECPR Broadband Radiometric Measurement Setup

provide tuning of the signal phase. This tuning was provided by electrically adjusting the signal phase prior to the reference signal reaching the ECPR.

Infrared Industries Blackbody

The ECPR was evaluated using an Infrared Industries Blackbody. The manufacturer's performance specifications for the blackbody are shown in Table 2 [9]. The design of the Infrared Industries blackbody incorporates a 20 degree conical stainless steel cavity with a uniformly oxidized inner surface of high emissivity. The effective cavity emissivity for the blackbody very nearly approaches the ideal unity emissivity. The cavity is heated by a resistance heating element which is powered through the temperature controller. Feedback is provided by a platinum resistance thermometer located between the steel cylinder and the heating element [10].

The blackbody uses a Type S thermocouple, Platinum versus Platinum - 10% Rhodium, which requires an ice water bath for a 0°C reference junction for accurate use of conversion charts. Across the temperature range of the Infrared Industries source (500 to 1000°C) it was found that the temperature controller setting kept the source within 3°C of the thermocouple measurement of the blackbody core temperature.

As shown in Figure 11, page 28, the source was mounted on a support stand. The front of the blackbody was located behind an aperture aperture plate that had a fixed 2.6 mm diameter opening. A precision manufactured 0.1000-in. aperture was mounted behind the 2.6 mm

Table 2. Blackbody Performance Specifications

Item	Description								
Control Range	100°C to 1000°C								
Control Accuracy	± 1°C								
Sensing Element	Platinum Resistance Thermometer								
Cavity Type	Recessed 20° cone								
Cavity Opening	0.250 in. (6.4 mm)								
Cavity Emissivity	0.99 ± 0.01								
Radiation Distribution	Cosine Distribution over 90° cone								
Power Consumption (maximum)	150 Watts								
Warm-up Time	10 minutes from ambient to 1000°C								
Dimensions	<table><tr><td><u>Height</u></td><td><u>Width</u></td><td><u>Depth</u></td><td><u>Weight</u></td></tr><tr><td>(140mm)</td><td>(76mm)</td><td>(118mm)</td><td>(900gm)</td></tr></table>	<u>Height</u>	<u>Width</u>	<u>Depth</u>	<u>Weight</u>	(140mm)	(76mm)	(118mm)	(900gm)
<u>Height</u>	<u>Width</u>	<u>Depth</u>	<u>Weight</u>						
(140mm)	(76mm)	(118mm)	(900gm)						

(0.1024-in.) aperture plate opening. Active cooling was provided to the aperture to counteract blackbody heating by circulating 25°C water through the plate.

Spectral Response Apparatus

Spectral response measurements were taken using an integrated benchtop setup. The setup consists of a Jarrell-Ash Monospec 27 grating monochromator, a high temperature IR source, and a monitor detector. A diagram of the apparatus is provided in Figure 12.

The high temperature (1275K) IR source provides a large quantity of broadband energy to the system. The energy is imaged on the monochromator inlet slit using a concave focusing mirror and a folding flat mirror. The source energy is modulated using a chopping wheel mounted at the monochromator entrance slit.

The grating monochromator provides a spectral range of 2.2 to 32 μm with a wavelength resolution of less than 0.1 μm . The instrument has three gratings which are mounted on a hand-operated turret assembly. An order sorting filter wheel is located at the monochromator exit slit. The beam is then collimated and directed into the reference detector or ECPR.

The reference detector for the spectral response setup is a pyroelectric element which is considered to have a flat spectral response. The detector is inserted or retracted from the collimated beam using a translation drive system. A Thallium Bromiodide (KRS-5) window is mounted in front of the monitor detector.

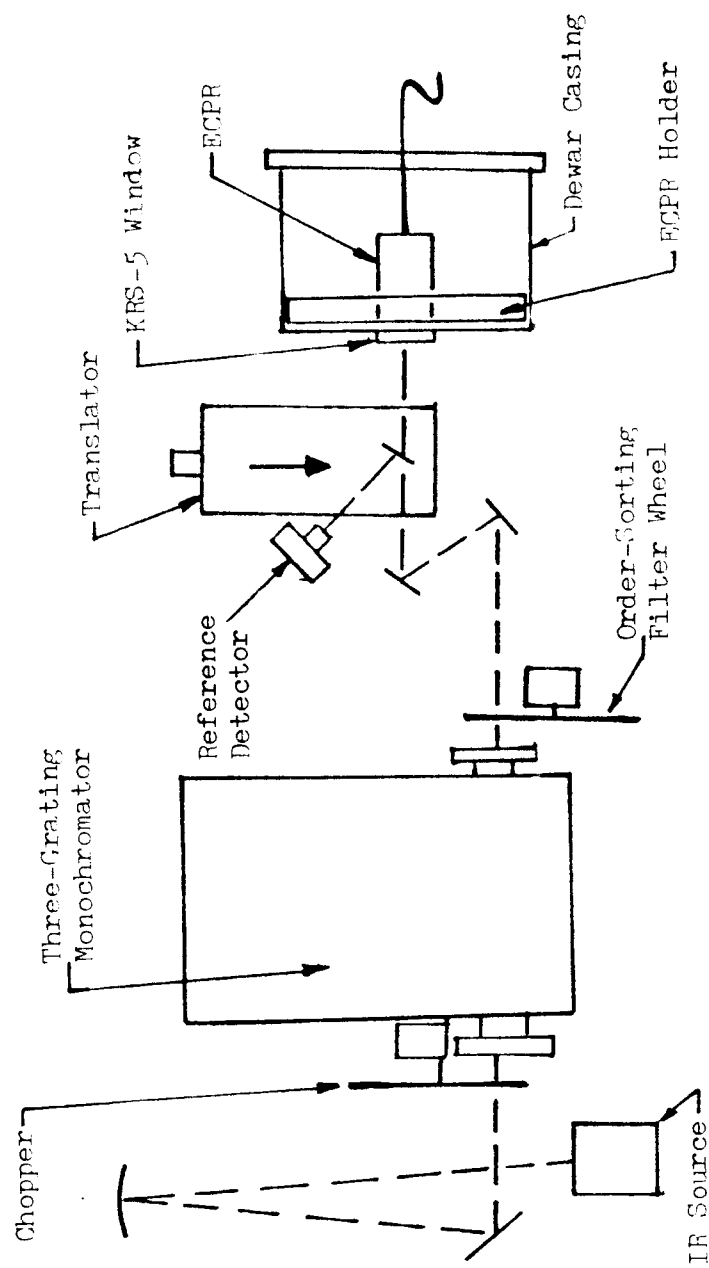


Figure 12. Spectral Response Apparatus

The reference, or monitor detector, is critical to acquiring spectral response measurements. Since the energy reaching the test detector in each narrow bandpass is unknown, a reference detector with a flat spectral response is needed. The profile of the monitor detector response across the wavelength range therefore provides the knowledge of the energy which will reach the test detector.

The spectral response apparatus is normally used for testing of detectors which require dewars to maintain optimum detector operating temperature. The cap of the dewar casing front end contains a KRS-5 window. The spectral effects of this window on the spectral response data are not a factor since the monitor detector views the beam through an identical window (Chapter V). In order to minimize impact to this critically aligned setup, an adapter piece was designed and fabricated to position the ECPR within the existing setup. The holder design is shown in Figure 13. With the front casing of the dewar remaining, the holder positioned the ECPR inside the casing (behind the KRS-5 window) and centered on the ECPR detector on the monochromator exit beam.

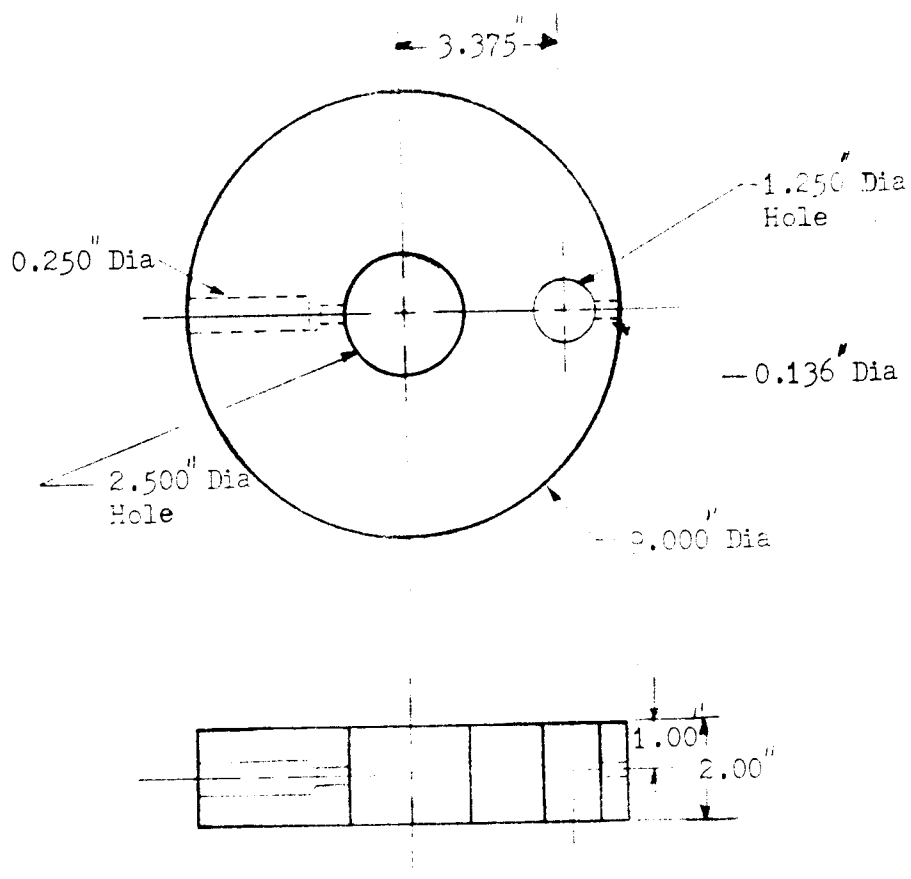


Figure 13. ECPR Holder for Spectral Response Measurement

CHAPTER IV

EXPERIMENTAL PROCEDURES

Broadband IR Measurements

Broadband IR measurement with the ECPR requires that the output from a blackbody source be aligned behind a chopper, and directed into the ECPR. At ambient room conditions (27°C), the source temperature must be set sufficiently high (approximately 500°C) to provide a readable signal above the warm background. The radiation reaching the ECPR must also fall within the measurement range of the instrument. The energy level arriving at the ECPR is a function of not only source temperature, but also the source aperture size, and the distance between the ECPR and source. The distance between the source aperture and the detector surface, and the aperture diameter, therefore, must be measured and recorded. This information will be used to calculate the irradiance arriving at the ECPR.

The ECPR was initially evaluated under ambient conditions using a Barnes manufactured blackbody. This source was used because it had an aperture wheel attachment that permitted selection of several different aperture diameters. The aperture diameters and areas are shown in Table 3. The ECPR chopper could not be located between the source and the aperture due to the nature of the aperture plate attachment to the source package. The disadvantage of this configuration was that the aperture plate could not be cooled which allowed the blackbody to heat

Table 3. Barnes Selectable Apertures

Diameter, in.	Area, sq. in.
0.0081	5.15 E-05
0.0140	1.54 E-04
0.0256	5.15 E-04
0.0444	1.55 E-03
0.0810	5.15 E-03
0.1405	1.55 E-02
0.2564	5.14 E-02

the aperture plate. The chopper was not in a position to separate the desired signal from the heated aperture plate. To remedy this, tare readings were taken with a thin stainless plate between the source and aperture. The plate was then removed and a reading taken when the output stabilized. In the 0.0081-in.-diameter aperture position, the ECPR reading never stabilized and the data points for that aperture were disregarded. It became obvious that the aperture heating was occurring very rapidly and that the energy from the heating effect was greater than that emitted through the small aperture. The data from the larger apertures was useful in determining the detector linearity. However, for evaluation of broadband calibration a blackbody setup without heating effects was necessary.

The ECPR broadband performance was evaluated using an Infrared Industries blackbody. The blackbody source was mounted behind an aluminum aperture plate that had a fixed 2.6 mm diameter opening. A precision 0.100 in. (2.54 mm) aperture was placed behind this opening. Black flocking paper was applied to the front surface of the source aperture plate to prevent background energy sources, which are normally out of the field of view, from being reflected into the ECPR. The aperture plate did not allow for insertion of a chopper blade between the source opening and the aperture. Therefore, the chopper was placed in front of the aperture assembly toward the ECPR. To prevent an aperture heating problem similar to the Barnes blackbody, the aperture plate for this blackbody was designed with passages around the inset region for the aperture to flow cooling water. Inlet and outlet hoses

to a water recirculator and cooler were attached to the aperture plate. The water temperature was set at 26°C. Since the controller setting proved to correlate well with the thermocouple readings (Chapter III), the thermocouple reference and readout was eliminated for many tests.

The IR Industries blackbody is equipped with a "Ready" light to indicate when the source has reached the set point temperature. After watching the ECPR output while the blackbody temperature setting was increased, it was noticed that the output varied after the "Ready" indication was given. The blackbody heater seemed to overshoot the temperature and then damp out to a stable temperature. Following this realization, the final data were taken at least 10 minutes following the source ready indication.

Spectral Bandpass Measurements

An initial evaluation was needed to determine if the ECPR's broadband response results were due to a spectral influence other than those indicated by the spectral transmission and absorption curves. The measurements were performed by inserting different spectral bandpass filters in the optical path of the same setup used for broadband IR measurements. These filters were mounted in a holder directly in front of the ECPR at a similar distance from the detector element as the manufacturer's ZnSe and quartz window attachments. The blackbody source was set at 900°C to provide adequate amounts of energy.

Spectral transmission curves for the filters were obtained using a Beckman Spectrophotometer. The instrument provided transmission data over a 2.5 to 50 μm range. The filters were assumed to have constant

transmission from 1 to 2.5 μm at the percent transmission measured at 2.5 μm . The analog curves were digitized and stored as data files for calculation of irradiance. A list of the spectral bandpass filters and the approximate wavelength range of each are provided in Table 4.

Window Interaction Effects

The effect of a window attachment, or transmissive filter, on the ECPR data was examined by varying the distance of the window from the detector and the angle of the window. The same experimental setup as used for the broadband IR and spectral bandpass measurements was again used. An ECPR window was mounted in an optical holder rather than screwed onto the ECPR. The holder permitted rotation of the window at any angle in the upward or downward direction. The holder was mounted on an optical rail aligned between the ECPR and the chopper housing. The rail provided a convenient way to quickly change the distance of the window from the ECPR, without altering the alignment of the setup.

ECPR data, during the window interaction investigation, were acquired for both the quartz and ZnSe window attachments. The window distance was varied at 1-in. intervals out to nearly 6 in. from the ECPR detector. The plane of the window was either perpendicular to the beam or rotated at an angle. Only a small angle was required to determine if any interactions existed. The angle used was measured to be 6 degrees. Another variable in the window interaction data was the addition of a black flocking paper cover to shield the metallic surface of the detector aperture. The reflectivity of the metal surrounding the

Table 4. Spectral Bandpass Filters

Bandpass Filter	Wavelength Range, μm
ECPR ZnSe Window	1 to 22
ECPR Quartz Window	1 to 5
5 μm Long Pass	5 to 22
Bandpass Filter	4 to 8
Barium Fluoride	1 to 17
Calcium Fluoride	1 to 13

aperture opening was suspected to be a major contributor of window interaction effects.

Spectral Response Evaluation

Spectral response measurements were performed by integrating the ECPR into the spectral response apparatus. The ECPR was installed in the setup in the test detector position. Data were acquired for the monitor detector and the ECPR at 0.2 μm wavelength increments. The monochromator IR source was maintained near its peak temperature limit of 1004 to 1008°C. The high source temperature was required to obtain the maximum amount of energy in each narrow wavelength increment. Even at this temperature, the ECPR operated at the lower limits of its sensitivity.

A monitor detector run was made only once each day, at either the beginning or end of the session. A total of six ECPR test runs were made. The ECPR configurations for the spectral response evaluation were no window, the ZnSe window, and the quartz window. For each window, a run was made with the detector aperture plate uncovered, as provided by the manufacturer, and with the metallic surface covered by the black flocking paper. The KRS-5 window in the dewar casing remained in front of the ECPR for all six test runs. For the no ECPR window and the ZnSe window cases, data were acquired from 2 to 20 μm . The lower limit of 2 μm was determined by the capabilities of the monochromator. The upper limit of 20 μm was chosen because ZnSe has almost no transmission at that wavelength. Quartz data were obtained from

2 μm to 7 μm . Quartz transmission falls off at approximately 5 μm , and signal levels beyond 5 μm were generally in the noise.

CHAPTER V

RADIOMETRIC CALCULATIONS

Broadband Irradiance

The calculation of broadband irradiance from a blackbody begins with Planck's law. Planck's law provides the spectral radiant emittance from a blackbody. Planck's law is written as follows:

$$W_{\lambda} = \frac{c_1}{\lambda^5} \frac{1}{e^{\frac{c_2}{\lambda T}} - 1}$$

where,

W_{λ} = Spectral radiant emittance, $W \text{ cm}^{-2}\mu\text{m}^{-1}$

λ = wavelength, μm

T = absolute temperature, K

c_1 = first radiation constant ($3.7415 \times 10^4 \text{ W cm}^{-2}\mu\text{m}^4$)

c_2 = second radiation constant ($1.43879 \times 10^4 \mu\text{m K}$)

Integration of Planck's law over the wavelength limits from zero to infinity results in the Stefan-Boltzmann's law. The Stefan-Boltzmann law calculates the total radiant emittance of a blackbody. The Stefan-Boltzmann law is as follows:

$$W = \sigma T^4$$

where,

σ = Stefan-Boltzmann constant ($5.6697 \text{ E-12 W/cm}^2 \text{ K}^4$)

T = blackbody operating temperature, K

W = radiant emittance, W/cm².

Use of the above equation assumes that the laboratory blackbody approximates an ideal blackbody.

Irradiance is the radiant flux arriving at a surface, whereas, the radiant emittance describes the flux emitted by a source. The irradiance at a specific distance from a source is described by:

$$H = \frac{J}{d^2}$$

where,

H = irradiance, W/cm²

J = radiant intensity, W

d = distance from the source, cm [1].

This equation is correct for a point source, where the distance is at least ten times greater than the source aperture diameter [1]. Radiant intensity is linked to the Stephan-Boltzmann law by the following:

$$J = \frac{WA}{\pi}$$

where A is the source aperture area [1]. Combination of the above equations results in the following calculation of irradiance from a blackbody on a particular surface:

$$H = \frac{\sigma A T^4}{\pi d^2}$$

The calculation of irradiance must be modified for the measurement application. The ECPR data was acquired with an ambient background and chopper blade. The use of a modulated input signal means that ECPR measured only the energy above the background level seen when the chopper blade blocked the source aperture. The revised irradiation equation is as follows:

$$H = \frac{A_o}{\pi d^2} (T_{bb}^4 - T_o^4)$$

T_o = Ambient Temperature, 300 K

T_{bb} = Blackbody core temperature, K.

Use of this equation assumes that the detector reflectivity is negligible over the wavelengths that the blackbody emits. Recall that the maximum energy emitted by a blackbody shifts to shorter wavelengths with an increase in temperature. The background temperature can be eliminated from the calculations at higher temperatures such as 1173K (900°C), where the subtraction of 300K to the fourth power becomes negligible in comparison. In most cases, this method of calculating irradiance provides an approximate result, but one that can be derived quickly.

A more exact method of calculating irradiance is by direct application of Planck's law. Performing Planck's integration allows for specifying an exact wavelength band. Use of Planck's law also

allows for multiplication of applicable transmission and reflectivity terms at each discrete wavelength interval. Use of a computer program is clearly the most efficient way to accomplish this method of calculating irradiance, and such a program was used to perform the calculations required for the majority of the data which is presented. The program used Simpson's Rule to perform Planck's integral. The program user had the freedom to input the wavelength range and number of intervals. Other user input variables included the source temperature, aperture area, and source to detector distance. The program was also written to reference digitized files containing normalized spectral response (or ECPR reflectivity) for several detectors and transmission characteristics for various optical filters and windows. For each run of the program, the user selected one detector and one filter from the list provided.

Effective Transmission

Calculation of the effective transmission of an optical filter or window was useful to analyzing the results of the window interaction effects data described in Chapter IV. The effective transmission was calculated as follows:

$$T_e = \frac{\text{Measured Irradiance with window}}{\text{Measured Irradiance without window}}$$

The effective transmission result will approximate the actual transmission for broadband filters with constant transmission levels. Examples of broadband, constant transmission filters are ZnSe (Figure

7, page 22), Barium Fluoride (BaF12), and KRS-5. For these filters, the distribution of blackbody energy falls within the cut-on and cut-off wavelengths of the filter. The result is that the same portion of blackbody energy curve is measured whether the window is in place, or not. Conversely, the effective transmission of a bandpass filter such as quartz, would be very different from its actual transmission. The measured irradiance without the window will be significantly higher, since the ECPR will detect broadband energy. The effective transmission in this case essentially calculates a transmission that has been averaged across the operating range of the detector, or the blackbody wavelength distribution.

Normalized Spectral Response

Spectral response measurements are calculated using a detector response versus wavelength data set for both the monitor detector and the ECPR. The units of detector response do not need to be the same for the two detectors. The data points in each set at the same wavelength are divided to eliminate effects seen by both detectors and create a single resulting data set. These effects are spectral response apparatus contributions (Figure 12, page 32) and not unique spectral response issues concerning the test detector's performance. The detector response ratio is calculated as follows:

$$K_{\lambda} = \frac{V_{md_{\lambda}}}{ECPR_{\lambda}}$$

where,

K_{λ} = Detector response ratio at each wavelength

$V_{md_{\lambda}}$ = Monitor detector output voltage at each wavelength

$ECPR_{\lambda}$ = ECPR output at each wavelength.

The data set, K , is then scanned for the wavelength at which the ECPR indicates peak spectral response (R_p). Every data point in the set is then divided by R_p to form a normalized set of dimensionless numbers between zero and unity. The value of unity indicates the wavelength of peak response, where K equals R_p .

$$R_{\lambda} = \frac{K_{\lambda}}{R_p}$$

where,

R_{λ} = Normalized spectral response at λ .

The final result is a data file of normalized spectral response versus wavelength. The normalized spectral response should not be confused with the detector spectral absorption. The normalized spectral response is a factor in the spectral absorption, but also includes the detector's efficiency in translating photons of various wavelengths into an output response. In addition, the normalized spectral response curve will always contain at least one data point of unity. A detector does not necessarily have a spectral absorption that reaches 100%.

CHAPTER VI

EXPERIMENTAL RESULTS

Broadband IR Measurement Results

Broadband calibration data were acquired on the ECPR using the setup described in Chapter IV. ECPR measurements were recorded while varying many parameters. The three main variables in the calculation of irradiance, temperature, source to detector distance, and aperture diameter, were all changed to analyze the effects. In addition, the ZnSe window was used as a variable. Repeatability data were also acquired.

The ECPR measurement results for varying the source to detector distance and the source temperature are provided in Table 5. The data shown is the ratio of the broadband irradiance measured by the ECPR to the calculated broadband irradiance. Table 5a and 5b indicate the results for the ECPR configured without and with the ZnSe window, respectively. Analysis of Table 5a reveals that, overall, the ECPR performed well. The majority of the ECPR measurements were within 10% of the calculated irradiance. The data degrades at both lower temperatures and longer distances. This is not unexpected, since signal levels are lower in both cases. The results shown in Table 5b, where the ZnSe window is installed, are not as favorable as those shown in Table 5a. The ECPR measurements are all a minimum of 20% greater than the calculated irradiance. Once again, the lower temperatures and longer distances produce the worst results.

Table 5. Broadband Irradiance Data Results

a. Ratio of Measured to Calculated Irradiance - No Window

Distance, in.	Blackbody Temperature				
	500°C	600°C	700°C	800°C	900°C
5.37	1.07	1.04	1.02	1.00	0.99
7.37	1.07	1.03	1.01	0.99	0.98
10.37	1.09	1.06	1.01	0.99	0.97
15.37	1.15	1.08	1.03	1.00	0.97
20.37	1.25	1.13	1.06	1.02	0.99

b. Ratio of Measured to Calculated Irradiance - ZnSe Window

Distance, in.	Blackbody Temperature				
	500°C	600°C	700°C	800°C	900°C
5.37	1.29	1.28	1.26	1.24	1.23
7.37	1.29	1.26	1.24	1.22	1.21
10.37	1.31	1.27	1.24	1.21	1.20
15.37	1.42	1.33	1.27	1.23	1.21
20.37	1.58	1.43	1.33	1.27	1.23

Repeatability of the ECPR was also investigated. Table 6 is arranged in a similar format to Table 5. In Table 6, however, the ECPR measured irradiance level is provided rather than a ratio. The mean value of each group has been shown. The ECPR readings were within 1% or less of the average for each group. The results indicate that the instrument is indeed very repeatable. This portion of the experiment was conducted without disturbing the alignment of the system or the temperature of the blackbody source. For this reason, the repeatability results do not incorporate factors involving the setup of equipment or long term repeatability of the ECPR.

The linearity of the ECPR was determined from the results of varying the source aperture area. The calculation of irradiance (Chapter V) shows that aperture area and irradiance are linear relationships. Therefore, when analyzed on a log-log graph, a linear detector has a slope of unity over its range measurement sensitivity. Table 7 provides the results of the ECPR linearity evaluation. Table 7a calculates the nonlinearity by comparing the aperture area to that area calculated using the slope of the data. Table 7b defines the irradiance divided by the aperture area as a constant, K . The variation of K from the average also indicates nonlinearity in the ECPR response. However, a large deviation is indicated for the first aperture. Table 7c repeats the calculation of Tables 7a and b with the data from the first aperture removed. These results indicate that the ECPR is linear across the higher three orders of magnitude of its dynamic range.

Table 6. Broadband Irradiance Results - ECPR Repeatability

a. ECPR Data (Watts/cm²) - No Window

Distance, in.	Blackbody Temperature				
	500°C	600°C	700°C	800°C	900°C
5.37	1.817E-04	2.897E-04	4.395E-04	6.409E-04	9.022E-04
	1.825E-04	2.900E-04	4.396E-04	6.436E-04	9.020E-04
	1.792E-04	2.907E-04	4.423E-04	6.434E-04	9.068E-04
Mean	1.811E-04	2.901E-04	4.405E-04	6.426E-04	9.037E-04
7.37	9.630E-05	1.527E-04	2.315E-04	3.369E-04	4.739E-04
	9.630E-05	1.530E-04	2.310E-04	3.372E-04	4.736E-04
Mean	9.630E-05	1.529E-04	2.313E-04	3.371E-04	4.738E-04
10.37	4.955E-05	7.880E-05	1.170E-04	1.689E-04	2.385E-04
	4.955E-05	7.780E-05	1.169E-04	1.696E-04	2.380E-04
	4.900E-05	7.810E-05	1.177E-04	1.706E-04	2.399E-04
Mean	4.937E-05	7.823E-05	1.172E-04	1.697E-04	2.388E-04
15.37	2.385E-05	3.655E-05	5.410E-05	7.810E-05	1.088E-04
	2.385E-05	3.660E-05	5.420E-05	7.760E-05	1.088E-04
Mean	2.385E-05	3.658E-05	5.415E-05	7.785E-05	1.088E-04
20.37	1.475E-05	2.190E-05	3.175E-05	4.542E-05	6.270E-05
	1.475E-05	2.190E-05	3.180E-05	4.540E-05	6.280E-05
	1.460E-05	2.195E-05	3.210E-05	4.550E-05	6.310E-05
Mean	1.470E-05	2.192E-05	3.188E-05	4.544E-05	6.287E-05

Table 6. Concluded

b. ECPR Data (Watts/cm²) - ZnSe Window

Distance, in.	Blackbody Temperature				
	500°C	600°C	700°C	800°C	900°C
5.37	1.396E-04	2.265E-04	3.458E-04	5.052E-04	7.154E-04
	1.398E-04	2.258E-04	3.456E-04	5.083E-05	7.165E-04
	1.376E-04	2.270E-04	3.481E-04	5.095E-04	7.238E-04
Mean	1.390E-04	2.264E-04	3.465E-04	5.077E-04	7.186E-04
7.37	7.370E-05	1.183E-04	1.799E-04	2.636E-04	3.716E-04
	7.370E-05	1.183E-04	1.804E-04	2.645E-04	3.728E-04
Mean	7.370E-05	1.183E-04	1.802E-04	2.641E-04	3.722E-04
10.37	3.805E-05	6.040E-05	9.080E-05	1.322E-04	1.865E-04
	3.820E-05	6.000E-05	9.070E-05	1.328E-04	1.861E-04
	3.780E-05	6.080E-05	9.200E-05	1.335E-04	1.885E-04
Mean	3.802E-05	6.040E-05	9.117E-05	1.328E-04	1.870E-04
15.37	1.872E-05	2.875E-05	4.250E-05	6.100E-05	8.551E-05
	1.875E-05	2.875E-05	4.260E-05	6.130E-05	8.530E-05
Mean	1.874E-05	2.875E-05	4.255E-05	6.115E-05	8.541E-05
20.37	1.184E-05	1.757E-05	2.530E-05	3.582E-05	4.971E-05
	1.185E-05	1.747E-05	2.535E-05	3.598E-05	4.957E-05
	1.180E-05	1.758E-05	2.554E-05	3.610E-05	5.000E-05
Mean	1.183E-05	1.754E-05	2.540E-05	3.597E-05	5.976E-05

Table 7. Broadband Irradiance Results - ECPR Linearity

a. Method 1

Aperture Area cm ²	Log Area	ECPR W/cm ²	Log Irradiance	Area [*] 1.0759	Percent Difference
9.94E-04	-3.0026	3.20E-06	-5.4949	5.88E-04	40.83
3.32E-03	-2.4789	1.72E-05	-4.7645	2.15E-03	35.16
1.00E-02	-2.0000	5.72E-05	-4.2426	7.05E-03	29.50
3.32E-02	-1.4789	1.87E-04	-3.7282	2.56E-02	22.78
1.00E-01	-1.0000	5.49E-04	-3.2604	8.40E-02	16.03
3.32E-01	-0.4789	1.91E-03	-2.7190	3.05E-01	8.03

Log-Log Slope = 1.0759

b. Method 2

Aperture Area cm ²	ECPR W/cm ²	Ratio, K W/cm ² /cm ²	Difference K - Kavg	Percent Difference
9.94E-04	3.20E-06	3.22E-03	-1.95E-03	-37.68
3.32E-03	1.72E-05	5.18E-03	1.48E-05	0.29
1.00E-02	5.72E-05	5.72E-05	5.54E-04	10.73
3.32E-02	1.87E-04	5.63E-03	4.67E-04	9.03
1.00E-01	5.49E-04	5.49E-03	3.24E-04	6.27
3.32E-01	1.91E-03	5.75E-04	5.87E-04	11.36

Kavg = 5.17E-03

Table 7. Concluded
c. Aperture 1 Removed

Method 1			Method 2		
Aperture Area, cm ²	Area ^{1.0146}	Percent Difference	Constant, K	Difference K-Kavg	Percent Difference
3.32E-03	3.05E-03	8.00	5.18E-03	-3.75E-04	-6.74
1.00E-02	9.35E-03	6.50	5.72E-03	1.65E-04	2.97
3.32E-02	3.16E-02	4.85	5.63E-03	7.73E-05	1.39
1.00E-01	9.67E-02	3.31	5.49E-03	-6.53E-05	-1.17
3.32E-01	3.27E-01	1.60	5.75E-03	1.98E-04	3.56

Log-Log Slope = 1.0146

Kavg = 5.56E-03

Spectral Bandpass Measurement Results

The broadband calibration data in Table 5b, page 50, for the ECPR with the ZnSe window installed led to acquiring data for various other optical filters. Analog curves of percent transmission versus wavelength for the bandpass filters were digitized and used to calculate the source irradiance for each configuration. Table 8 shows the results for each of the selected filters in terms of the irradiance measured by the ECPR as compared to the calculated irradiance.

All of the ECPR measurements in Table 8 are greater than the calculated value. The data were acquired at approximately 900°C and 10.72 in. Under these conditions, the data in Table 5a, page 50, would have predicated a 3% low reading rather than a 4% high reading. The data in Table 5b, page 50, would have predicted a 20% high reading, but the data for this configuration show a 29% result. In both cases the ECPR reads higher than the series of readings taken for Table 5, page 50. Recall, however, that the repeatability results described earlier pertained only to the short term performance of the ECPR. The results compared with regard to the spectral bandpass measurement have other effects introduced. For instance, the data sets were acquired nine months apart. This means that the results are most likely explained by differences in source temperature, alignment, and possibly changes in the ECPR calibration. Although this indicates a long term repeatability problem, both sets of data reveal a major radiometric error when the ZnSe window is introduced to the setup.

Table 8. Spectral Bandpass Measurement Results

Filter Type	Wavelength Range, μm	Average Trans- mission, %	ECPR W/cm^2	Calculated W/cm^2	ECPR/ Calc.
None	1 - 22	100	2.430E-04	2.327E-04	1.04
Quartz	1 - 5	90	1.390E-04	1.261E-04	1.10
Calcium Fluoride	1 - 13	90	2.340E-04	2.090E-04	1.12
Barium Fluoride	1 - 17	90	2.410E-04	2.085E-04	1.16
Bandpass Filter	4 - 8	80	6.900E-05	5.439E-05	1.27
Zinc Selenide	1 - 22	70	1.900E-04	1.476E-04	1.29
5 μm Long Pass	5 - 22	65	6.060E-05	4.035E-05	1.50

The data in Table 8 have been arranged by increasing measurement error. The average percent transmission decreases along with this decline in ECPR performance. The results of the bandpass measurements clearly show the effect of window transmission on the ECPR measurement performance. This provided an interesting lead toward a resolution of the radiometric calibration problem.

Window Interaction Results

The results of the spectral bandpass measurements lead to an investigation of how a window or filter is affecting the ECPR measurements. The ZnSe and quartz windows provided with the ECPR were used in the window interaction effects experiment. The distance of the window from the ECPR and the angle of the window were both varied. The window distances are relative changes in distance from where the window is normally positioned. The window angle provided is the angle rotated from perpendicular to the beam. Window angle data is not provided at close distances because the window cannot be rotated while it is partially screwed onto or in close proximity of the ECPR housing. Table 9 summarizes the results in terms of the effective transmission of the window. Effective transmission is a convenient method of demonstrating the effects of the experimental variables, since the transmission of an optical element should obviously remain constant.

Table 9a provides the effective transmission of the ZnSe window with changes in both window angle and distance. The phrase "no aperture cover" refers to the condition of the surface surrounding the detector aperture. The surface being referred to is the recessed

aperture plate shown in Figure 11, page 28. An uncovered aperture plate is the condition of the ECPR as provided by the manufacturer. The source temperature was set at 900°C. At this temperature nearly all of the blackbody energy is emitted within the transmission wavelengths of ZnSe, and the effective transmission and the measured transmission should be the same (approximately 70%). The results with no window angle show an effective transmission 82.47% at 0.28 in. The transmission drops to 74.03% at 5.28 in. The 6 degree rotation of the window produces a similar trend in the data, except the angle reduces the effective transmission. These results agree with earlier data which showed that more energy reaches the detector when a window is installed than is calculated from theory. The data led to the observation that the detector aperture plate is an unpainted, reflective aluminum surface, whereas the rest of the instrument is black. In addition, if ZnSe is 70% transmissive, the window will act as a 30% reflective mirror. Together, the window and detector aperture are causing multiple reflections of energy onto the detector which are not accounted for in the theoretical calculations.

Table 9b summarizes the effective transmission for the ZnSe window with a flocking paper cover is placed over the metallic portion of the aperture. The paper has a textured black surface that is highly absorbing of IR radiation. The results with a window angle in Table 9b show very little difference to the results in Table 9a. The only significant change is at 1.28-in., where the 6 degree angle is apparently not enough to reflect all of the additional energy out of

Table 9. Window Effective Transmission

a. No Aperture Cover - ZnSe Window

Window Angle, deg	Window Distance, in.					
	0.28	1.28	2.28	3.28	4.28	5.28
0	82.47	85.71	86.36	83.77	81.17	74.03
6	--	77.92	71.43	70.13	69.48	69.48

b. Covered Aperture - ZnSe Window

Window Angle, deg	Window Distance, in.					
	--	1.28	2.28	3.28	4.28	5.28
6	--	73.46	71.46	70.77	70.46	70.46

Window Angle, deg	Window Distance, in.					
	0.34	1.34	2.34	3.34	4.34	5.34
0	71.38	71.54	73.15	76.23	76.38	73.00

c. Quartz Window

Aperture Status	Window Distance, in.						
	0.22	0.34	1.34	2.34	3.34	4.34	5.34
Uncovered	59.56	60.00	62.50	63.75	64.37	64.37	63.12
Covered	58.59	58.67	59.04	60.15	60.89	61.48	61.11

the detector field of view. Here, the addition of the cover improves the results by 4.5%. The results are clearly improved at all window distances with a 0 degree window angle. The marked improvement at the 0.28-in. or 0.34-in. reading is significant, with the effective transmission dropping from 82.47% to 71.38%.

Table 9c shows the effective transmission results for the quartz window. Although quartz is highly transmissive, its cutoff at 5 μm makes the effective transmission much lower. The results show a much smaller improvement with the cover in place for the quartz window. This result supports the data in Table 8, page 57 which indicated that the ECPR performed reasonably well with the quartz window. The results also support the theory that the high ECPR measurements were caused by multiple reflections between the window and the aperture plate. Since the average transmission of quartz is approximately 90%, the quartz window is only 10% reflective. However, the drop in transmission of quartz at 2.7 μm (Figure 9, page 24) probably contributes to the 10% high reading for quartz shown in Table 8.

The results obtained during the window effects investigation can also be examined from a radiometric calibration standpoint. Table 10 is set up identically to Table 9, except the ratio of the measured irradiance to the calculated irradiance is provided rather than the effective transmission. The window effects data shown in Table 10a can be easily compared to the results provided in Table 5b, page 50. Table 5b would predict that for the conditions of Table 10a, a source temperature of 900°C and a source to detector distance of 8.87 inches,

Table 10. Window Interaction Effect on Broadband Irradiance

a. No Aperture Cover - ZnSe Window

Window Angle, deg	Window Distance, in.					
	0.28	1.28	2.28	3.28	4.28	5.28
0	1.2	1.24	1.25	1.22	1.18	1.07
6	--	1.13	1.04	1.02	1.01	1.01

b. Covered Aperture - ZnSe Window

Window Angle, deg	Window Distance, in.					
	--	1.28	2.28	3.28	4.28	5.28
6	--	1.07	1.04	1.03	1.03	1.03

Window Angle, deg	Window Distance, in.					
	0.34	1.34	2.34	3.34	4.34	5.34
0	1.04	1.04	1.07	1.11	1.11	1.06

c. Quartz Window

Aperture Status	Window Distance, in.						
	0.22	0.34	1.34	2.34	3.34	4.34	5.34
Uncovered	0.99	0.99	1.03	1.05	1.06	1.06	1.04
Covered	0.97	0.97	0.98	1.00	1.01	1.02	1.02

the ECPR output would be a factor of between 1.20 and 1.21 higher than the calculated. Table 10a shows a ratio of 1.20 at a window distance of 0.28 in. The data are in excellent agreement, although it should be noted that the window distances differed by 0.28 in.

Normalized Spectral Response

The results presented above reveal that the combination of a reflective aperture plate and a window attachment degrades ECPR performance. Normalized spectral response of the ECPR was measured in an attempt to understand how the multiple reflections were affecting the broadband response of the instrument. Unfortunately, the available test setup required that a KRS-5 window be installed in front of the ECPR. KRS-5 is an approximately flat 70% transmissive, which is similar to ZnSe (Figure 7, page 22). KRS-5, however, remains transmissive to 30 μm . The existence of the KRS-5 means that spectral response data could not be acquired for the case where there were no window effects. Additional reflectivity problems will also occur between the KRS-5 and ECPR windows.

Low signal levels were also a problem in acquiring spectral response data, due to the limited amount of energy in each narrow bandpass. The source was operated at its maximum temperature, which provided more energy, especially at the shorter wavelengths. Measurement at the longer wavelengths, beyond 14 μm , was difficult. The ECPR was operating at the limit of its sensitivity which resulted in a lack of stability in the output. The recorded measurement was often taken as an average of the fluctuations. The low signal problem was com-

pounded by the windows in the optical path. The KRS-5 window reduced the signal by approximately 30%, and then the window under test reduced the signal once more.

In spite of the problems described above, useful data were acquired. Figure 14 shows a plot of the normalized spectral response with only the KRS-5 window installed and the aperture plate uncovered. The response of the ECPR begins to decrease at 11 μm . This result is supported by the gold black absorption data which was presented in Figure 5, page 19. However, Figure 5 indicates only a 6% decrease in absorption over the entire range of measurement. The data presented in Figure 14 begins to fluctuate dramatically at 15 μm . The low signal problems described above are the most likely reason for this affect. The results with the aperture plate covered are provided in Figure 15. This curve also shows a distinctive drop in response, and erratic data at the longer wavelengths. To determine any unique spectral influences due to reflections between the aluminum and KRS-5, the shapes of the two curves must be compared. To accomplish this comparison, the covered run was ratioed to the uncovered run using the actual ECPR output at each wavelength. Figure 16 is a plot showing the results of this ratio. The use of the aperture cover appears to decrease the output of the ECPR by an average of 12%, which supports the changes in the effective transmission shown in Tables 9a and 9b, page 60. The ratio does not indicate any clear effect with wavelength. This result is reasonable since both KRS-5 and aluminum have constant transmission or reflectance performance with wavelength.

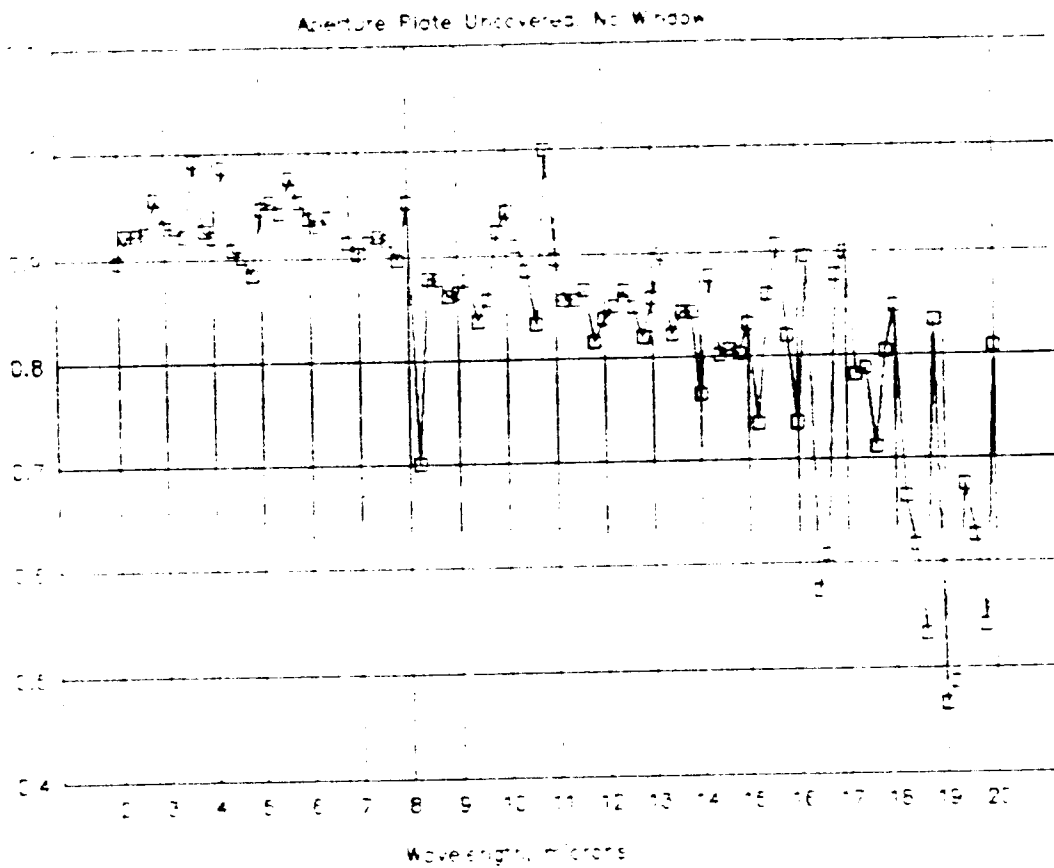


Figure 14. ECPR Normalized Spectral Response - Uncovered, No Window

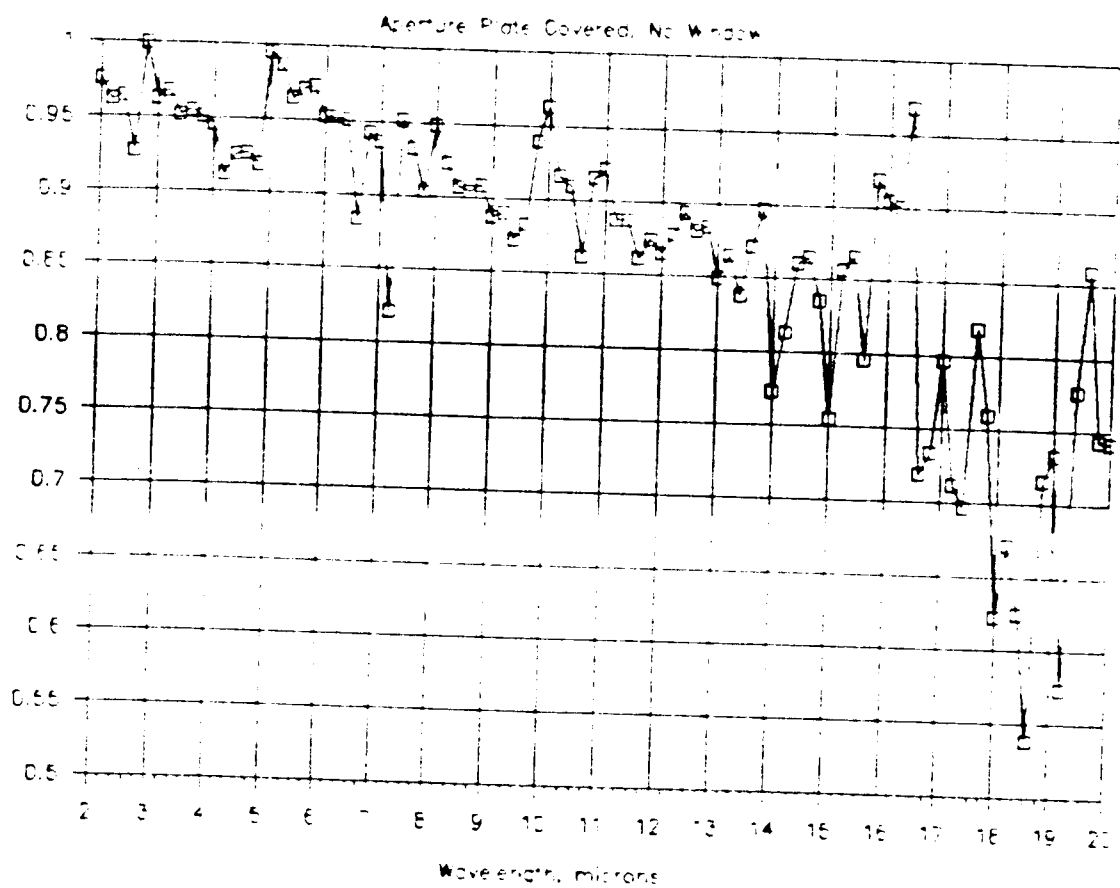


Figure 15. ECPR Normalized Spectral Response - Covered, No Window

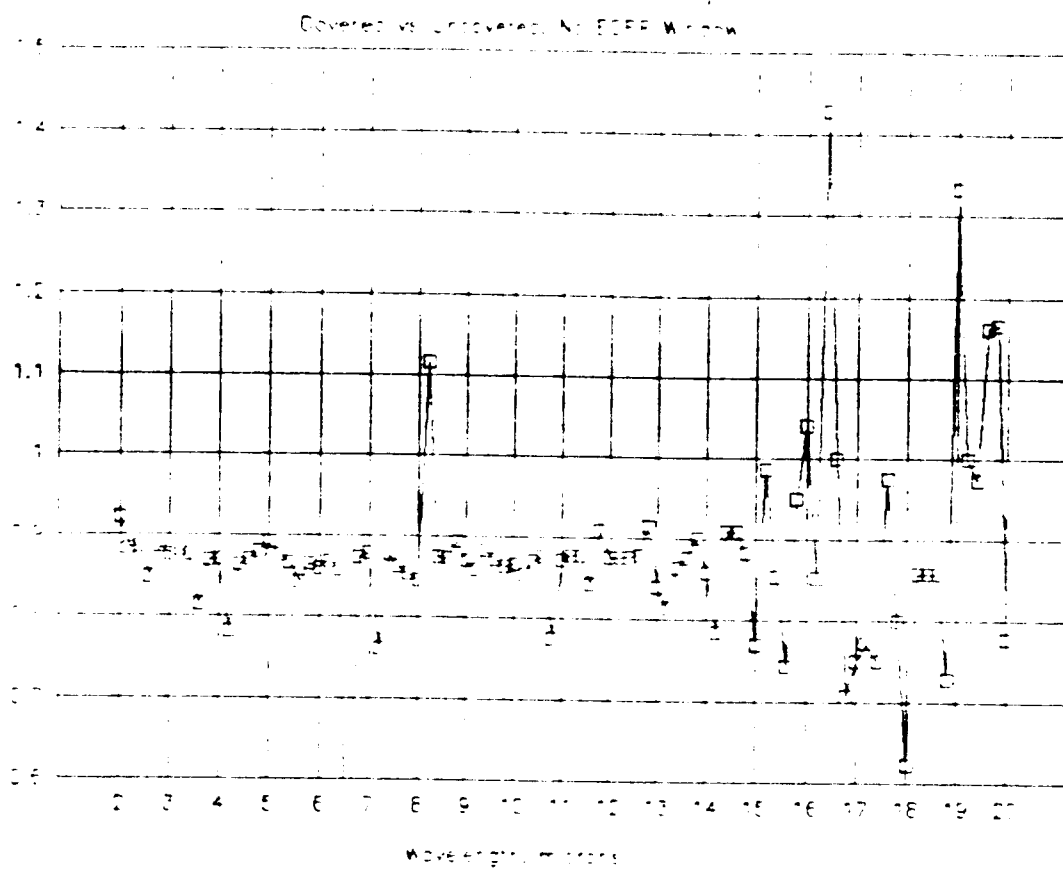


Figure 16. ECPR Performance Comparison - Covered versus Uncovered, No Window

Figure 17 shows the normalized spectral response with the ZnSe window installed and the aperture plate uncovered. Although the signal levels were lower than for the data presented in Figures 14 and 15, the long wavelength data is less erratic. The drop-off in response is not as apparent at 11 μm , but becomes very distinctive at 17 μm . Figure 7, page 22, indicates that the transmission of ZnSe begins to decrease at 18 μm . The results in Figure 17 may be showing this characteristic of ZnSe, but at a slightly shorter wavelength. The results for the ZnSe window with the aperture plate covered are provided in Figure 18. This curve also shows a distinctive drop in response at 17 μm , and less noise in the data as compared to the KSR-5 only data. To determine any unique spectral reflection performance issues, the shapes of the two curves were compared as done for the KRS-5 case. Figure 19 is a plot showing the results of the ratio of Figures 17 and 18. The results are the same as shown in Figure 16. The aperture cover continues to provide a reduction in reflections of 10 to 15%. Figure 19, however, supports this trend out to 20 μm , where the data in Figure 16 fluctuated too badly to make this observation.

The normalized spectral response data for the quartz window is summarized in Figures 20 and 21. As with the results for the ZnSe window, both figures show the influence of quartz transmission (Figure 9, page 24). The only recognizable bad data point is at 2 μm in Figure 20. A comparison of the curves reveals that the distinctive quartz absorption band at 2.8 μm in Figure 21 is much more dramatic in Figure

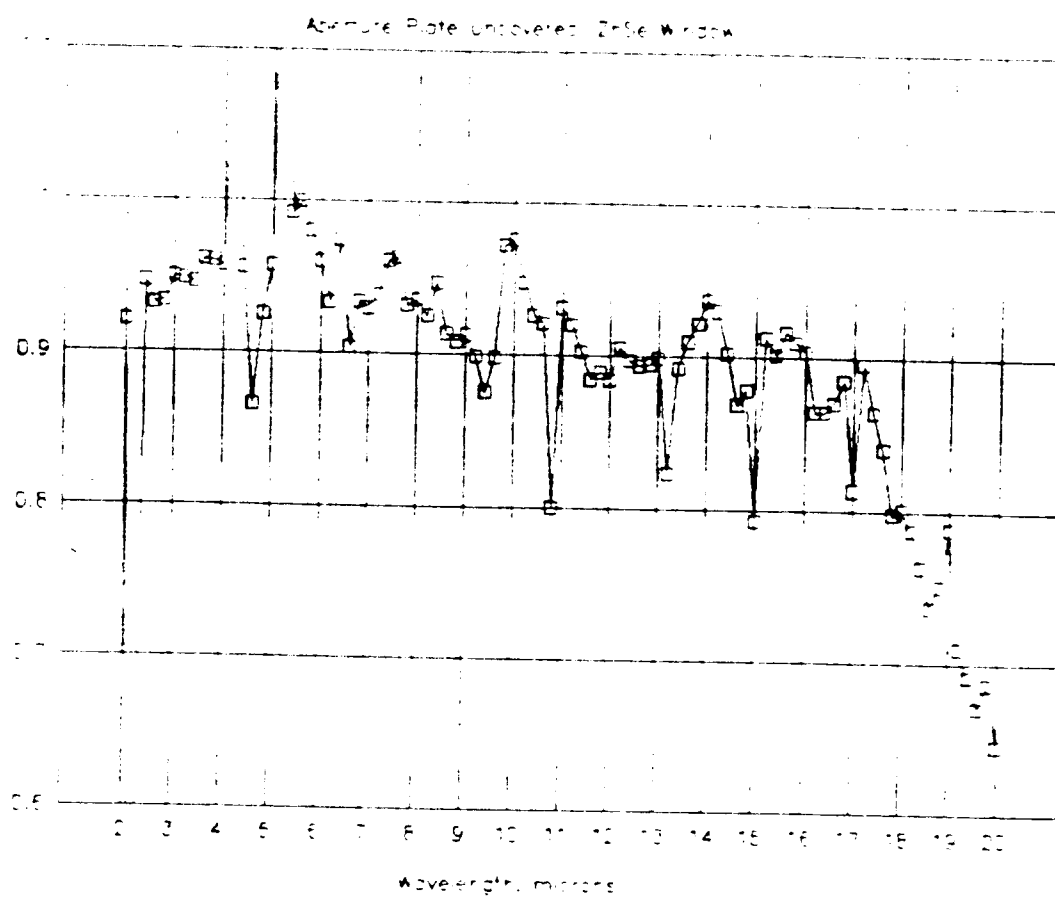


Figure 17. ECPR Normalized Spectral Response - Uncovered, ZnSe Window

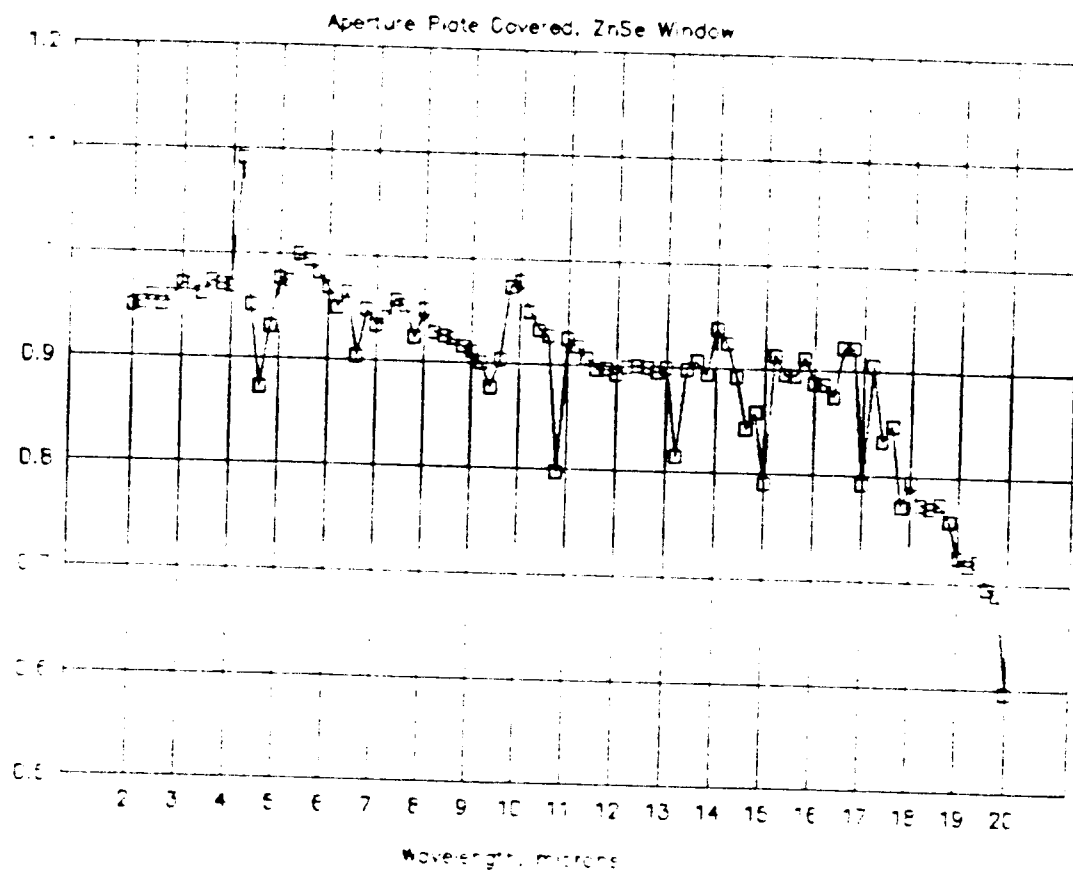


Figure 18. ECPR Normalized Spectral Response - Covered, ZnSe Window

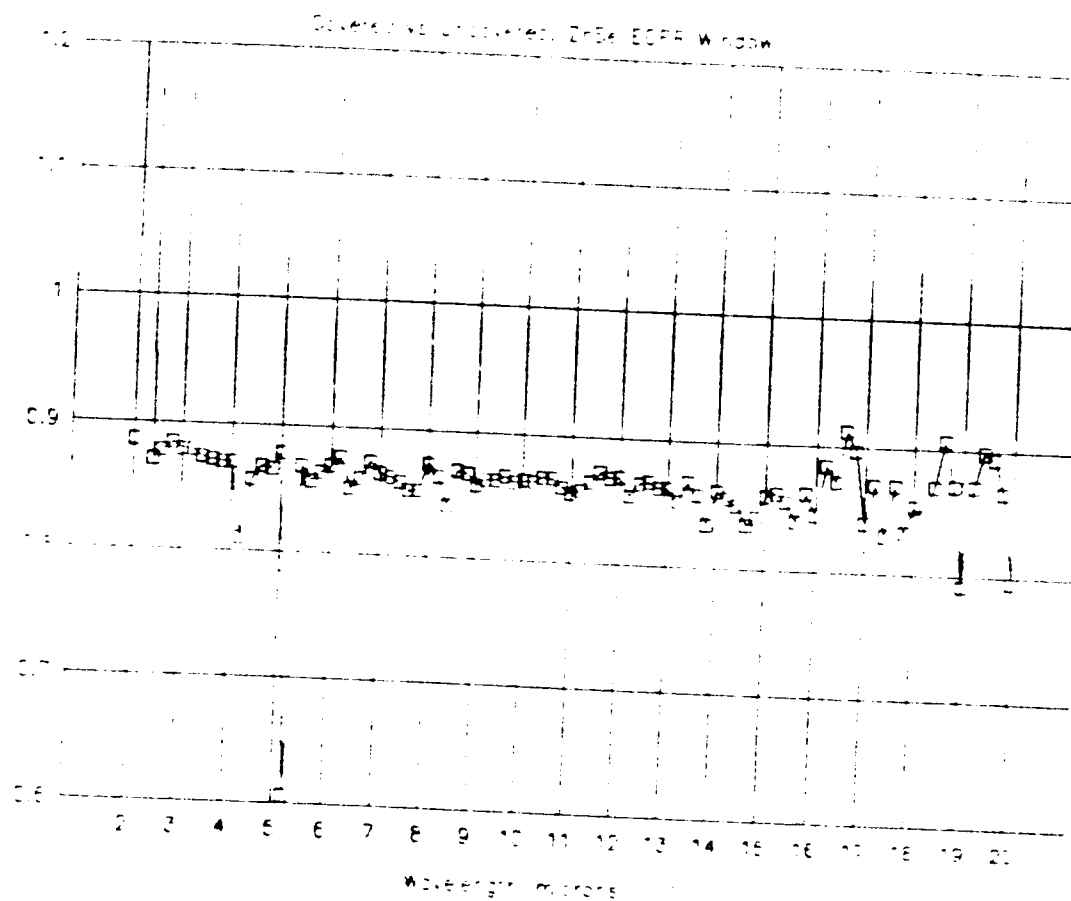


Figure 19. ECPR Performance Comparison - Covered versus Uncovered, ZnSe Window

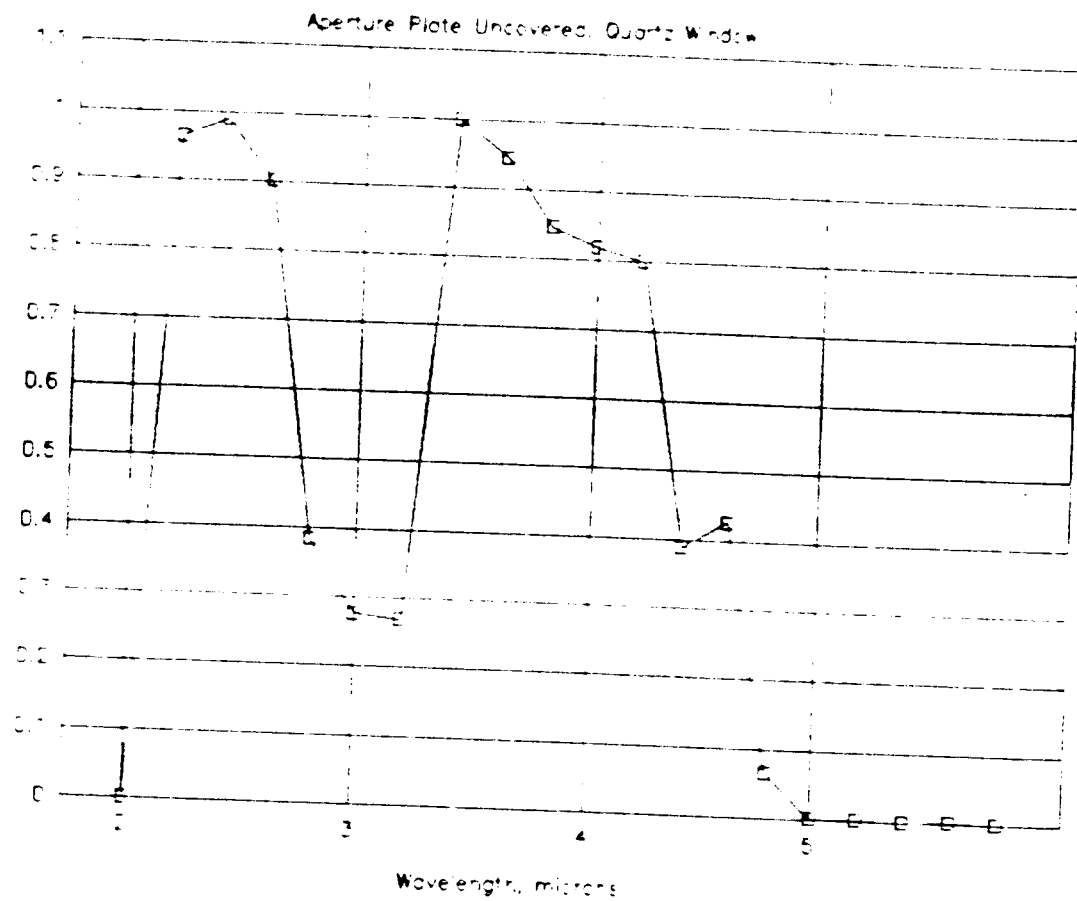


Figure 20. ECPR Normalized Spectral Response - Uncovered, Quartz Window

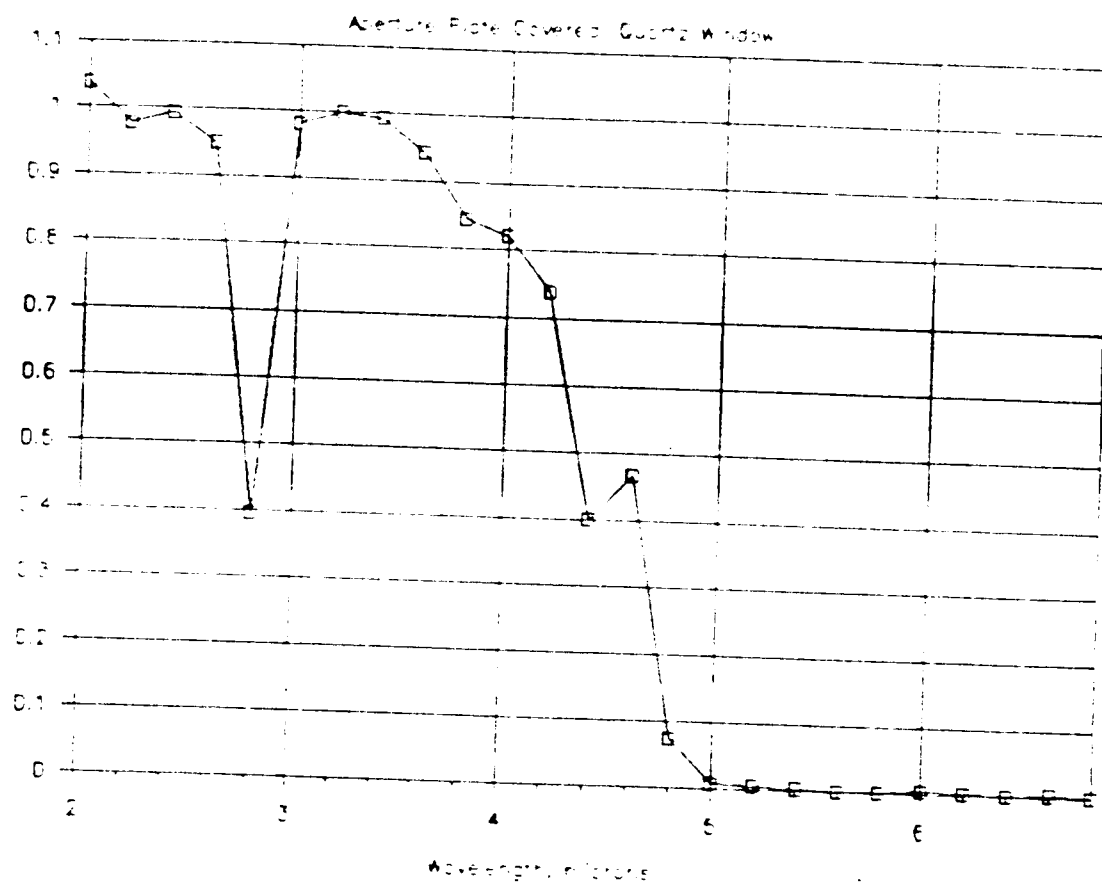


Figure 21. ECPR Normalized Spectral Response - Covered, Quartz Window

20. Figure 21, however, much more closely resembles the actual transmission of quartz. In Figure 20, the response at 2.8 μm and 4.4 μm is nearly identical to the covered aperture case in Figure 21. The following two data points, at 3.0 and 3.2 μm , differ greatly. Figure 22 plots the ratio of the uncovered and covered quartz data. The difference between the two data sets at 3.0 and 3.2 μm is clearly indicated. Interpretation of the meaning of the data is difficult because the data cannot be easily labeled as noise. The ratio of the data would indicate that the aperture cover decreases the ECPR output by 10%, except at these wavelengths. The quartz data presented in Table 8, page 57, support this result. The data presented in Table 10c, page 62, however, show a 2 to 4% difference between the covered and uncovered cases. The reasons for disagreement between Tables 8 and 10 were discussed under the spectral bandpass measurement results.

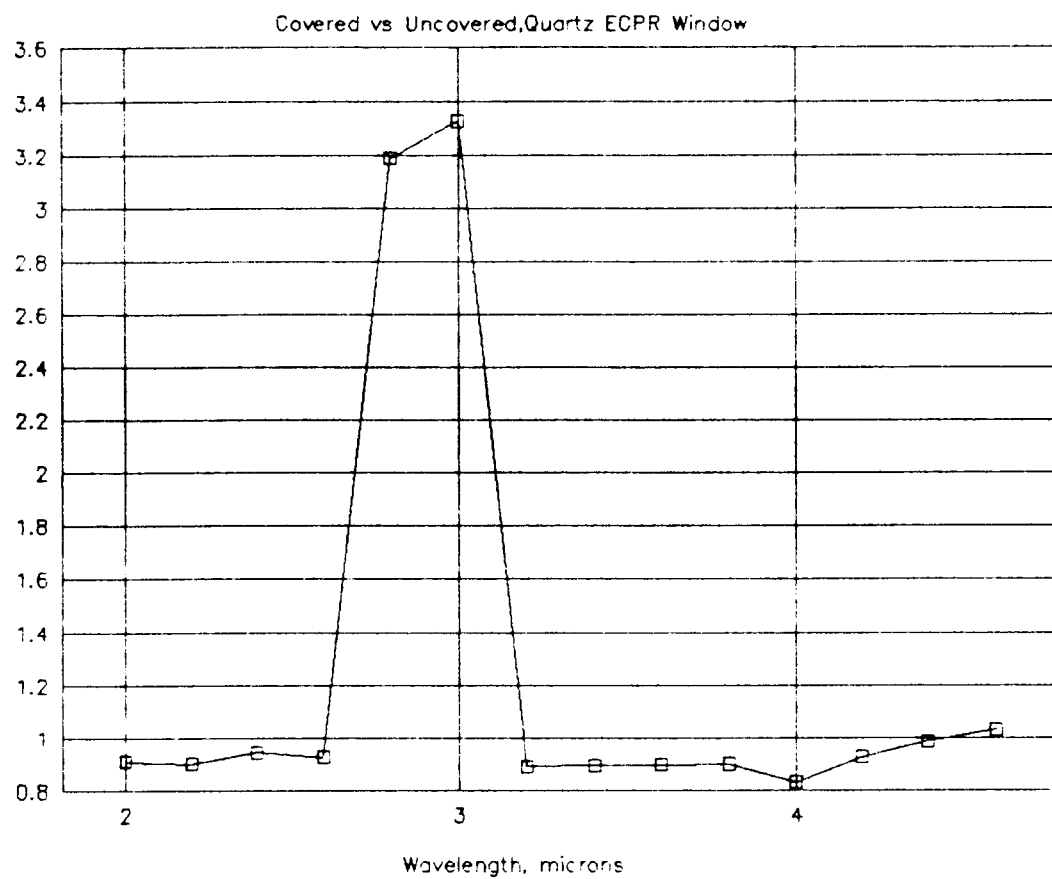


Figure 22. ECPR Performance Comparison - Covered versus Uncovered, Quartz Window

CHAPTER VII

DISCUSSION OF ERROR SOURCES

There are many sources of error in the measurement procedures and corresponding results presented in the previous chapters. Error contributors fall into two principal categories, those that are related to the components of the experimental setup, and those which are associated with the operation of the ECPR. These sources of measurement uncertainty are discussed and analyzed in the sections to follow.

Experimentally Induced Errors

The experimentally induced errors which are described below exclude those errors associated with the function of the ECPR. The experimental errors focus on contributions to the measurement uncertainty associated with all aspects of the equipment setups as described in Chapter IV.

The Infrared Industries, Inc. blackbody source was not calibrated at the new NIST facility. The blackbody was used in all of the experimental setups except the spectral response. The manufacturer data specifies that the core emissivity is 0.99 ± 0.01 and the temperature controller setting accuracy is $\pm 3^{\circ}\text{C}$. The effect of the 3°C temperature accuracy lessens as the operating temperature increases. Since radiometric data is a function of temperature to the fourth power, a 3°C error at 500°C corresponds to a radiometric error of 1.5%. At 900°C , the radiometric error caused by a 3°C temperature error is only

1.0%. Cooling of the aperture plate was supplied to eliminate the aperture heating.

Physical errors are also present in the experimental setup. These errors primarily involve two physical measurements, the aperture diameter and the distance between source and detector apertures. The accuracy of the aperture diameter measurement is critical since the quantity is so small to begin with. In radiometric terms, the aperture diameter is used to calculate the aperture area. Therefore, when the diameter is squared in the radiometric calculation an increased effect of the error is produced as was demonstrated for temperature. A 0.100 in. aperture was used with the blackbody source. The manufacturer of these precision apertures claims a ± 0.00008 in. uncertainty in the diameter. In terms of area, this uncertainty equates to $\pm 0.16\%$. The distance between the apertures, on the other hand, is generally very large but the measurement accuracy is not as precise. The accuracy of the distance measurement is ± 0.025 in. The shortest distance used in the data presented is 5.37 in. This represents a $\pm 1\%$ error in irradiance.

The ECPR linearity results were obtained using a Barnes blackbody and aperture wheel. The uncertainty in the output of the blackbody does not effect the linearity data, assuming that the output remained constant. The uncertainty in the aperture diameters does impact the results, since it will be greater for the smaller apertures. No information on the uncertainty was available. Assuming that these apertures have a ± 0.0001 -in. uncertainty in the diameter, the result is

a range of uncertainty on the area of $\pm 2.48\%$ and $\pm 0.08\%$ for aperture diameters of 0.0081-in. and 0.2564-in., respectively. As discussed in Chapter IV, the data for the 0.0081-in. aperture were not used due to aperture heating problems. Following review of the linearity results, the data for the next smallest aperture (0.0140-in.-diameter) also became suspect. The uncertainty for the area of this aperture is $\pm 1.43\%$.

Measurement of window and filter transmissions were performed using a Beckman spectrophotometer. The transmission results obtained for the ECPR windows were used in the radiometric calculations that the ECPR measurements were compared to. However, the transmission results for the windows averaged 5% lower than the data provided by the manufacturer. If the manufacturer data are correct, the ECPR results with a window and the calculated results would be 5% closer. A measured transmission lower than the actual is most likely due to the window holder blocking a portion of the beam in the spectrophotometer. The 100% transmission reference run (no window) is then ratioed to the window run and produces an artificially low transmission.

The spectral response test station has very different sources of error. The temperature of the source was operated between 1000°C and 1010°C. During a test run, the temperature varied up to 3 or 4°C. The reference detector removes from the data effects of the spectral response equipment when its output is ratioed to the ECPR output. These effects concern spectral distribution of the energy emitted by the source, reflectivity of the mirrors, monochromator losses versus

wavelength, and transmission of the order sorting filters. The reference detector does present another source of uncertainty in itself. The detector is a pyroelectric, which is assumed to have a uniform spectral response. The actual spectral response of the detector has never been measured. NIST is currently in the process of examining a way to establish a standard by which this detector can be measured. As discussed in Chapter VI, the spectral response data were handicapped by low signal levels. The presence of the KRS-5 window also prevented acquisition of a baseline, no window case for comparison. Combining these error sources and examining the data plots, the uncertainty appears to be no better than $\pm 5\%$. Beyond 13 or 14 μm , $\pm 5\%$ would be the minimum error. Repeat data sets would have been valuable toward resolving the error in the spectral response data for the ECPR. The spectral response data, however, were not used to determine the broadband calibration abilities of the ECPR. The data were used only as an investigative tool. Therefore, the errors in the spectral response data need not be considered in the evaluation of the ECPR's broadband calibration performance.

ECPR Error Sources

ECPR error sources consist of the those errors which are caused by internal ECPR operations. The errors in this category are numerous, and include electrical, thermal, and radiometric contributions. Electrical errors are focused at the heater element of the ECPR. The concerns involve the accuracy of applying current to the heater to match

the incoming radiation. The current and voltage at the heater is another critical measurement, since the final output of the ECPR is based on the calculation of the electrical power required to match the optical power. The timing between the electrically and optically applied signals also plays a role in the accuracy of the final ECPR output. The timing is dependent on the chopper reference signal. Thermal errors inside the ECPR are generated by either lead heating or the thermal resistance of the heater coating.

Radiometric errors are concerned with how the incoming radiation enters the ECPR and is converted to an electrical signal by the pyro-electric detector. Many radiometric errors have been described by the NBS. Some of these errors are summarized in the following [6]:

- 1) Not all of the electrical power generated in the heater is absorbed by the receiver.
- 2) Power generated in the heater leads modifies the temperature distribution within the radiometer.
- 3) Flux incident on the thermal environment of the receiver modifies the temperature distribution within the radiometer.
- 4) The temperature distribution in the receiver and high absorptance coating during radiant heating is different from that during electrical heating.
- 5) Not all of the radiant power incident on the high absorptance (gold black) coating is absorbed by it.

Radiometric measurements can also be in error due to detector nonlinearities and detector noise.

The largest single ECPR error occurs with the use of the manufacturer provided window attachment. As described previously, multiple reflections between the ECPR aluminum aperture plate and the window increase the amount of energy detected. Figure 23 is a full scale sketch showing the geometry between the window, aperture plate, and detector. All surfaces are black with the exception of the aperture plate and window. It is also reasonable to question whether the backside of the aperture plate is also reflective. If it were, this would attribute additional reflections at the longer wavelengths where the gold black reflectance increases. The data presented in Table 5, page 50, indicate that the instrument's radiometric performance degrades 20 to 25% due to the reflection problem.

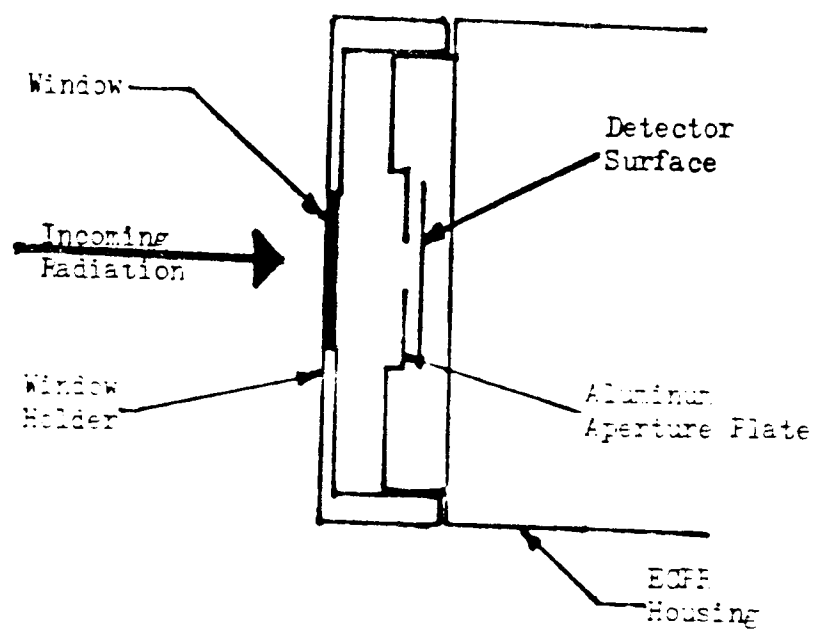


Figure 23. Geometry of Window Interaction Error

Summary of Errors

A discussion of the experimentally induced and ECPR errors has been provided. The experimentally induced errors can be consolidated to look at the overall error in calculating the energy reaching the ECPR. The ECPR errors involve how accurately the ECPR converts the entering photons to an output signal. The uncertainty in using the ECPR to make broadband irradiance measurements must be examined with and without the manufacturer's window attachments.

When no window attachment is used, the ECPR's measurement errors are summarized by the following:

Blackbody Emissivity: $\pm 1\%$

Blackbody Temperature (fourth power): $\pm 1.5\%$

Aperture Area: $\pm 0.16\%$

Distance (squared): $\pm 1\%$

ECPR Internal: $\pm 1\%$

Short-term Repeatability: $\pm 1\%$.

The ECPR internal error of 1% was used since this was the instrument's quoted uncertainty to NIST. A Root-Sum-Square (RSS) of these errors results in an overall measurement uncertainty of 2.5%.

Use of one of the manufacturer's windows increases the measurement uncertainty. The five error sources listed above are still valid. In addition, the following errors must be considered:

Uncertainty (No Window): $\pm 2.5\%$

Transmission Measurement: $\pm 5\%$.

The final evaluation is $\pm 5.6\%$ uncertainty in the ECPR measurements made with the window attachment. The effect of the multiple reflections was a 20-25% increase in signal. For the worst case, the error in using the ECPR in this configuration, without correcting the reflection problem, is an additional $25\% \pm 5.6\%$ error over the true irradiance entering the instrument.

CHAPTER VIII

CONCLUSIONS

The objective of this paper was to determine whether an ECPR could be applied to broadband radiometric calibrations at ambient background conditions. The manufacturer had claimed a 1% calibration, traceable to NIST, in the wavelength region from 0.25 to 2.0 μm . The wavelength range of the data presented in this paper was limited by the blackbody temperatures used, which were 500 to 900°C. The majority of the data were acquired at a blackbody temperature of 900°C, however. At this temperature, 99% of the energy lies between 0.8 and 19.5 μm , which is within the detector coating performance range.

Broadband irradiance measurements provided in Table 5a, page 50, revealed an important conclusion regarding the ECPR's broadband performance. Using no window attachment, the ECPR performed very well at higher blackbody temperatures (700-900°C). At these temperatures, there is more energy and the energy distribution shifts to shorter wavelengths. The result was an ECPR measurement within 3% of the calculated value. Recall from Chapter VII, that the calculated measurement uncertainty was 2.5%. This means that the measurements support the calculated uncertainty. The 1% ECPR calibration cannot be proven or disproven, mainly because of the effects of the experimentally reduced errors. The broadband irradiance experiments also investigated ECPR linearity and repeatability. The linearity results in Table 7, page 54, show nonlinearity at the smaller apertures which

represents the lower end of the ECPR operating range. This data supports the results shown at 500 and 600°C in Table 5. The repeatability data showed very good short term results for the ECPR. Long term repeatability was not examined. Accomplishing the manufacturer recommended yearly calibration check will help maintain long term performance.

The broadband irradiance results provided in Table 5b, page 50, indicate a significant degradation of performance (20 to 25%) with the manufacturer's ZnSe window attachment. Measurements acquired using the quartz window attachment and other transmissive filters show similar problems. The results clearly indicated that the presence of a transmissive window or filter caused the ECPR to measure a greater amount of energy than was actually present. The magnitude of the error increased as the transmission of the optical element decreased. Use of a black and spectrally absorbing flocking paper over the aluminum detector aperture plate drastically reduced the effects. The cause of the increased readings was therefore attributed to multiple reflections between the aperture plate and the reflective properties of the windows. Use of the ECPR with a window or filter, without the flocking paper insert, is not suggested because of this design flaw. A more permanent solution to the problem would be to remove the aperture plate and have it black anodized. The removal and re-installation of the aperture plate will pose some risk to the ECPR. The process must be accomplished without contacting the fragile surface of the detector

element and the exposed surface must be temporarily protected between the two procedures.

The broadband measurement performance of the ECPR was found to be comparable to other available radiometers. This statement holds only when no windows are present or when the paper cover is used in conjunction with a window or filter. The data acquired in this experiment show the ECPR to have a $\pm 3\%$ calibration when used with ambient operating high temperature blackbodies (700-900°C) located less than 20-in. from the ECPR. This result certainly makes the ECPR an acceptable broadband irradiance measurement tool.

Further characterization of the ECPR is recommended to fully understand its broadband performance. Following black anodization of the detector aperture, the broadband response should be repeated with and without the window attachments. Use of a calibrated blackbody for this work would also reduce the measurement uncertainty. Continuation of the spectral response measurements would be valuable if the energy levels were increased and repeat data sets were acquired. The normalized spectral response data could then be used in calculations to more accurately predict the output of the ECPR.

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VITA

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