AN OBJECTIVE STUDY OF THE EVAPOROGRAPHIC

METHOD OF INFRARED IMAGING

By

JOHN WILLARD HINES

Bachelor of Science
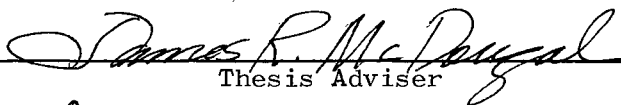Oklahoma State University
Stillwater, Oklahoma
1967

Master of Science
University of Pittsburgh
Pittsburgh, Pennsylvania
1968

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
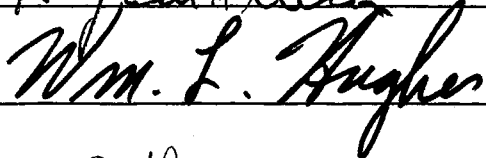for the Degree of
DOCTOR OF PHILOSOPHY
May, 1973

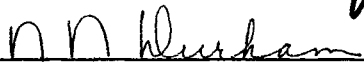AN OBJECTIVE STUDY OF THE EVAPOROGRAPHIC

METHOD OF INFRARED IMAGING

Thesis Approved:

_____
Thesis Adviser

_____

_____

_____
Dean of the Graduate College

ii

PREFACE

This research is concerned with the development of an infrared imaging device called the Evaporograph. The objective was to find out what means would be required to make the device have a resolution of .1 degree Centigrade, and to try to find what engineering developments could be used to make the device more usable as an imaging tool.

The author wishes to express his appreciation to his major adviser, Dr. J. R. McDougal, for his guidance throughout this work. Appreciation is also expressed to the other committee members, Dr. William L. Hughes, Dr. Jack Allison, and Dr. E. E. Kohnke, for their invaluable assistance in preparation of the final manuscript.

A note of thanks is given to Mr. Willard Hines for some assistance in machining some of the hardware needed in the experimental phase of this work, and for instruction in lathe operation. Thanks is also expressed to my wife, Rita, for typing some of the earlier portions of this manuscript, and to Miss Velda Davis and Mrs. Marilynn Bond for the excellent final copy of this dissertation. A final note of thanks is given to The Boeing Company and to Mr. Earl Norman, Chief of Engineering Staff, for their cooperation in allowing time off for the presentation of this work.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION

A. Historical Background

The evaporographic process is almost as old as the discovery of
infrared radiation itself. In 1840, J. F. W. Herschel (9) carried out
an experiment in which he took a blackened piece of filter paper dipped
in alcohol and exposed it to the solar spectrum. The evaporation of
the alcohol was more rapid toward the red end of the spectrum and
beyond. Herschel also noticed that there were several bands where the
alcohol evaporated more slowly and which corresponded to the absorption
bands in the solar spectrum. Since evaporation took place over the
entire surface of the paper the impression disappeared very rapidly. In
order to overcome this problem, Herschel tried impregnating the blotter
paper several times with alcohol and by adding dyes to the alcohol. He
did not meet with much success with these processes and did little more
with this phenomenon.

In the mid 1920's, Czerny (3) reviewed the work of Herschel and
concluded that to avoid the evaporation of alcohol at places where no
radiation was present the receiver of the radiation should be placed in
an atmosphere which was saturated with its vapor. He placed the support
in a chamber which could be evaluated to very near the pressure of the
alcohol. He found, however, that alcohol did not function very well, so
he replaced it with a paraffin oil. In addition, he replaced the

blackened filter paper with a thin nitrocellulose membrane blackened with "bismuth black". The "bismuth blacks", however, were found unsatisfactory because their absorption was not independent of wavelength. In 1934, Woltersdorff (17) published a paper indicating that a thin vacuum deposited layer of aluminum could absorb, depending upon its thickness, up to 50 per cent of the radiation incident upon it. Czerny (4) used these findings and adopted aluminum as the absorbing layer in his later work. The use of the aluminum absorbing layers allowed Czerny to obtain good absorption spectra in excess of 10 microns in wavelength. In addition to his experimental work, Czerny (4) made the first analysis of the potential sensitivity of the Evaporograph and derived the first equations explaining its operation.

After Czerny published his first paper on the Evaporograph in 1929, Willenberg (16) copied his apparatus. Unlike Czerny, Willenberg did not limit his work strictly to absorption spectra. Willenberg imaged hot objects such as light bulbs and for the first time used the Evaporograph as a thermographic tool.

The Evaporograph was next explored by Swings (14) as a means of obtaining absorption spectra of stars. He did little more than review the work of Czerny and conclude that the membrane structure was too thin to be made large enough for the spectrographic work he desired to do. His particular application required that the membrane be six inches in diameter.

During the early 1950's Baird Atomic, Inc. saw the potential use of the Evaporograph as a thermographic tool. While this work was done by a great many people over a period of years, McDaniel and Robinson (12) published the results of this research. The group at Baird Atomic

refined the device that Czerny had constructed and discovered a much

better oil to use than Czerny had used. The membrane was made out of

nitrocellulose, as was Czerny's, but the absorbing layer was composed of

"gold black" after the method of Harris (8). The Baird Corporation also

refined the theory of operation for the Evaporograph. Under laboratory

conditions, Baird Atomic obtained a .5 degree centigrade. By using a

rock salt window and mirror optics, Baird Atomic extended the bandwidth

to almost 20 microns.

In the early 1960's, Taquet (15) duplicated the work done at Baird

Atomic with the exception that the absorbing layer used was a 50 angstrom

thickness of gold vacuum deposited on the membrane in the same manner

that Czerny's aluminum layer was deposited. She found that at the

thickness of 50 angstroms, gold would absorb almost 50 per cent of the

radiation incident upon it. It is interesting to note that the work

published by Baird Atomic made the comment that absorbing layers of the

type used by Czerny and Taquet would not work for thermal imaging.

Not much more was done with the Evaporograph after the early 1960's

since the scanning infrared camera was introduced and most of the work

since has been in that area.

B. Definition of the Problem

With the advent of the scanning cameras, one might wonder what

could be produced from further work on the evaporographic process.

There are advantages to the process. Perhaps the most obvious is the

relative costs involved with the two processes. Compared to the scan-

ning camera, the Evaporograph is a much cheaper means of imaging. The

scanning cameras must have the detector at liquid nitrogen temperatures

or below to work properly while the Evaporograph works at room temperature. It also does not involve a scanning process, which cuts down on the resolution. While it does take much longer to produce an image than the scanning device, for a great many uses, this is not a problem. The most serious problem with the Evaporograph is its extremely thin membrane on which the absorbing layer is applied. This layer is only about 1000 angstroms thick and is very fragile.

The particular use envisioned for the Evaporograph constructed here, is to image animal bodies in order to see if fat and lean animals could be graded on the hoof. Preliminary measurements made by McDougal (13) indicate that this can be done with an infrared imaging technique. The research conducted here is aimed at improving the Evaporograph to the extent that measurements of this type might be made with this device.

Since an animal is at a temperature of approximately 300 degrees kelvin, the device must be capable of very wideband operation. A blackbody at a temperature of 300 degrees kelvin has its peak output at 9.7 microns, but its energy band extends from 5 microns to past 30 microns. The energy distribution for a 300 degree blackbody is shown in Figure 1. Hence, the Evaporograph will have to be constructed to have as wide a bandwidth as is obtainable.

Since the membrane itself is so fragile, it will have to be strengthened so as to make the device more stable.

The sensitivity of the device should be on the order of .1 degree centigrade if it is to do its job properly; hence, the absorbing layer
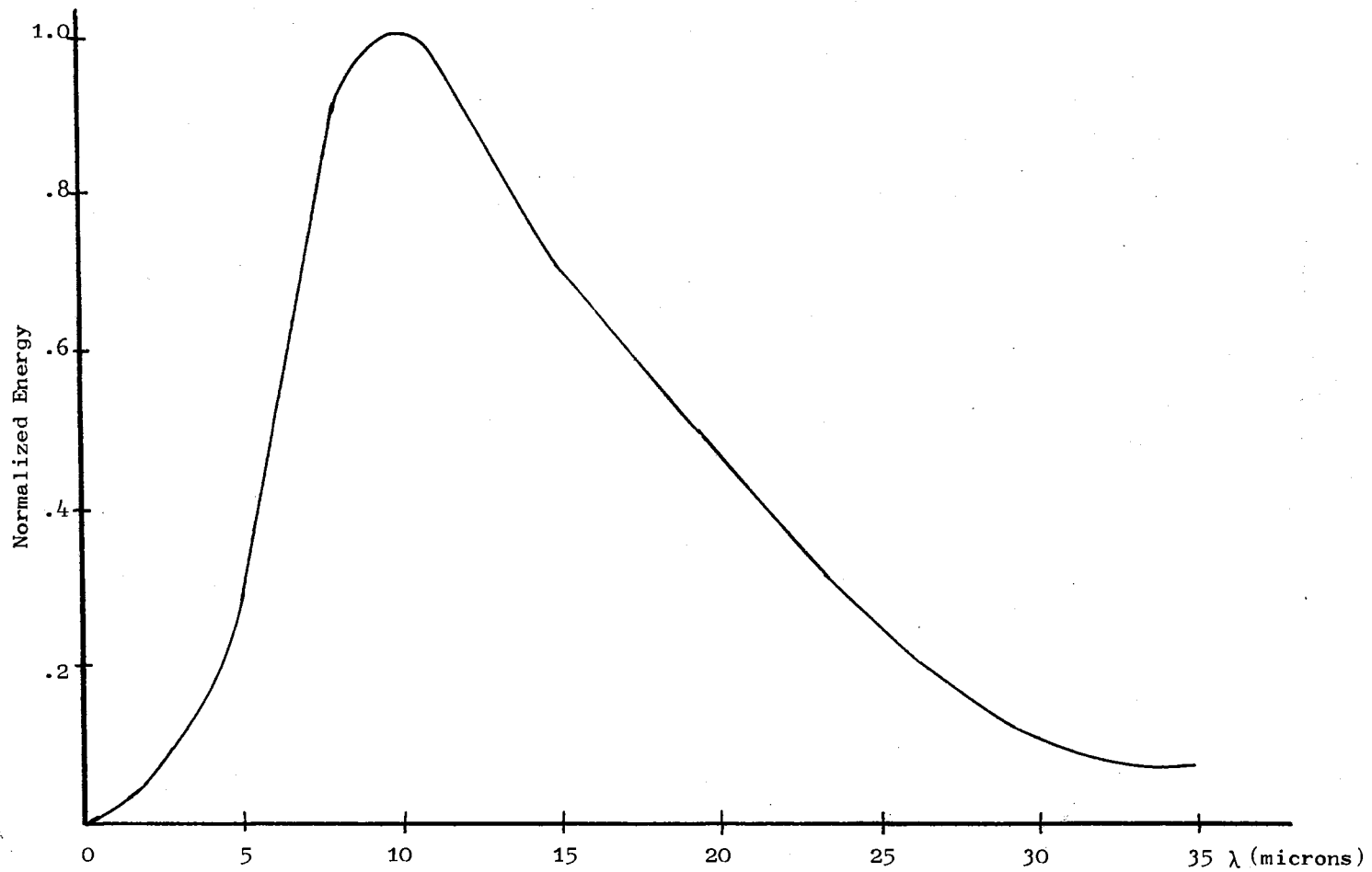
Figure 1. Plank Distribtuion for 300°k Blackbody

must be exposed to as much energy as is possible, as well as absorb as much as possible.

The research on the Evaporograph here is then to attempt to obtain the goals stated above.

CHAPTER II

DESCRIPTION OF THE APPARATUS

Shown in Figure 2 is the basic experimental setup used in conducting this research. The basic evaporographic cell shown in the figure is the heart of the device and will be discussed first. The cell itself measures four inches in length excluding the end pieces which contain the infrared and optical windows. With the addition of the ends, the cell becomes $6\frac{3}{4}$ inches. The inside diameter of the cell is two inches and the barrel measures three inches in diameter. The cell measures four inches across the flanges. Since it was anticipated that the membrane and windows might have to be changed from time to time, the cell was designed so that these parts could be easily changed. The seals at both ends, as well as the seals for the windows, are accomplished by means of O-Rings. The membrane holder itself screws in from the infrared imaging end and the membrane aperature is $1\frac{1}{4}$ inches in diameter. At the viewing end of the cell is the oil heater and oil source. The heater is a simple tube heater, which was made by wrapping a glass cylinder with nichrome wire of resistance of 1.12 ohms per foot until a resistance of 30 ohms was reached. A ceramic material was then poured around the wire to hold it in place and then allowed to harden. Next, asbestos paper was wrapped around the heater in order to insulate it from the brass barrel. The oil holder is just a piece of blotter paper formed into a cylinder small enough to just slip into the heater.
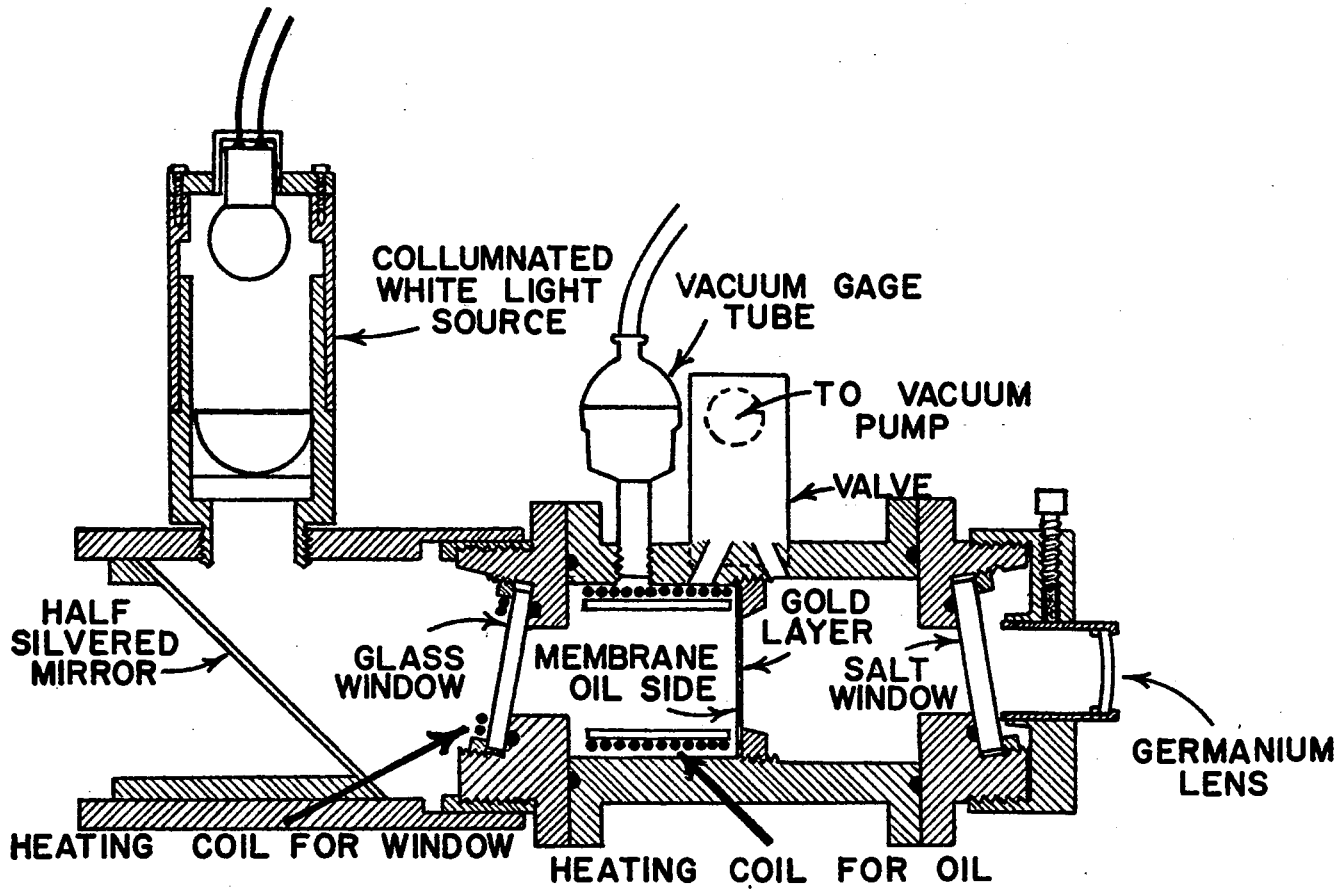
Figure 2. Diagraom Showing Construction Details of the
Oklahoma State Evaporograph

The cell used in this research was of somewhat different design than the cells that Baird Atomic (12) and Taquet (15) used. Their cells were three inches long and the barrel was $1\frac{7}{8}$ inches outside diameter. The inside diameter of the infrared imaging end was one inch and at the other end the diameter was $1\frac{5}{8}$ inches. The device was constructed so that it fit together in the center with the membrane holder joining the two halves. The heating element on the cell fit around the outside of the barrel at the viewing end. The membrane holder was constructed out of a heat insulator so that the necessary temperature difference could be obtained. The two halves were connected to a manifold arrangement and then to the vacuum pump. Because of the manifold, the membrane was rather hard to change; therefore, it is evident that they did not anticipate frequent changes of the membrane. The windows at each end of the cell were glued on in order to eliminate any seals. The membrane holder aperature in the cell was only $\frac{3}{4}$ inch in diameter. This was done so that the windows would only have to be inclined at an angle of ten degrees in order to keep internal reflections from returning to the membrane. In the cell used in this research, the angle had to be fifteen degrees to accommodate the larger membrane.

The infrared optical system used on the cell for this research is a simple one-inch diameter, four-inch focal length, germanium lens. This lens is designed to have a bandwidth of 6 to 16 microns with peak performance at 11 microns. The Baird Atomic device could alternately be fitted with either a 6-inch diameter, 12-inch focal length mirror system of the Newtonian design, or a germanium lens with an aperature of f 1.6. The system used by Taquet was a copy of the Newtonian system used by Baird Atomic.

In order to view the oil film on the membrane in the cell used for this research, a columnated beam was reflected onto a half silvered mirror inclined at an angle of 45 degrees. The beam was then reflected off of the membrane back through the mirror to the eye. Photography of the membrane was accomplished by using an Olympus Pen FT camera equipped with a 150 mm lens with a +3 diopter closeup lens on the front. Color photography was done with High Speed Ektachrome, type B, shot at an ASA rating of 320. The lens was set at f 4 and the speed used was one-fourth second. Black and white work was done with Tri-X shot at normal ASA rating using the same speed and f stop as was used with the color film. The viewing system used by Baird Atomic and Taquet is similar in design to the one used here except that their camera lens system was internal and a Contax body was fitted to the system. Also in order to view the membrane with the eye, an additional mirror was added to the system. This mirror reflected 80 percent of the light coming back through the first mirror to the camera. The other 20 percent passed through the mirror to the eye.

Upon using the Evaporograph to image objects, it was discovered that oil condensed on the inside surface of the optical window and impaired the view of the membrane. To alleviate this problem, Baird Atomic and Taquet deposited a film of conducting material on the inside surface and passed a current through it to evaporate the oil from the glass. In the work done here, the problem was solved by pressing a nichrome wire circle against the backside of the glass. The circle is about $1\frac{1}{2}$ inches in diameter and has a resistance of about six ohms. This seemed to alleviate the problem very well.

In the next chapter and following chapters, more specific details will be given for the device and improvements suggested to make it function better.

CHAPTER III

THEORETICAL CONSIDERATIONS

A. Evaluation of Sensitivity

Since the objective of this research is to find ways by which the Evaporograph may be made as sensitive as .1 degree centigrade, it is necessary to be able to compute the sensitivity of the device. Czerny (3) and Baird Atomic (12) have already derived the basic thermodynamic equations for the evaporographic process, hence, the derivation will not be shown here. Also, only those equations needed for the computation of the sensitivity will be listed.

In words, sensitivity for the Evaporograph is finding that temperature change in the scene which causes a minimum perceptible change in the thickness of the oil film. The equation for sensitivity, as given by McDaniel and Robinson (12), is:

$$\Delta T = \frac{4(e_1 + e_2)\ \gamma T_B^3,\ \Delta T' + \Delta q_4 + \Delta q_7}{4E\ \tau_A\ \tau_0 \alpha_1 e_T \gamma T_B^3 A},$$

where

$$\Delta T' = \frac{R\ \Delta d\ \delta_3\ T_B'^{5/2}}{2.92 \times 10^{-2}\ \Delta t\ \sqrt{M}\ P(2LM - RT_B')}.$$

$$\Delta q_4 = \frac{\Delta \; d \; \delta_3 \; L}{\Delta t} \; ,$$

$$\Delta q_7 = 2P_a (M_a / 2 \pi RT_B')^{\frac{1}{2}} \; K_a \; \Delta T' \; ,$$

$$E = 1/(1 + 4f^2) \; ,$$

$$\Delta d = \frac{\Delta d'}{2n} \; ,$$

where:

ΔT is the sensitivity in degrees centigrade.

e_1 is the emissivity of the front surface of the membrane.

e_2 is the emissivity of the back surface of the membrane.

γ is the Stefan-Boltzman constant and equals 1.36 cal cm^{-2} deg^{-4} sec^{-1}.

T_B' is the temperature of the absorbing layer and is taken at 300 degrees centigrade for this analysis.

T_B is the background temperature of the scene and is assumed to be 300 degrees centigrade for this analysis.

$\Delta T'$ is the temperature rise on the membrane caused by the scene temperature and is measured in degrees centigrade.

Δq_4 is a loss term associated with the latent heat of vaporization of the oil. Its units are cal cm^{-2} sec^{-1}.

Δq_7 is a loss term associated with the connection losses. Its units are also cal cm^{-2} sec^{-1}.

E is the optical efficiency of the lens and is unitless.

Δd is the minimum detectable thickness of the oil film and is measured in cm.

R   is the universal gas constant and in this case it equals 1.98 cal $\deg^{-1}$ mole^{-1}.

δ_3 is the density of the oil, which in this case is Dow-Corning 200 fluid with 3 centistoke viscosity, and is .9 gm cm^{-3}.

$\tau_A \tau_O$ is the product of the transmission of the atmosphere and the transmission of the optical system and is assumed to be .8.

α_1 is the absorption of the absorption layer on the membrane and for this analysis a value of .8 is assumed.

e_T is the emissivity of the scene and is assumed to be 1.0.

A   is a correction factor added to take into account that the optical system only passes a certain bandwidth of the incident energy. Since the salt window used only possessed a bandwidth of about 20 microns, the correction factor would be .71 for a 300 degree blackbody.

Δt is the exposure time in seconds.

M   is the molecular weight of the oil and is 480 gram mole^{-1} for the oil used.

P   is the vapor pressure of the oil at the temperature T_B, and is 60 m for the oil used.

L   is the latent heat of vaporization of the oil and is 28 cal gm^{-1}.

P_a is the partial pressure of the air on the back side of the membrane and it has a value of 60 microns.

M_a is the molecular weight of air. A value of 29 gm mole^{-1} is assumed.

K_a is the specific heat of air and has a value of .25 cal gm^{-1}.

f   is the f-stop of the lens.

$\Delta d'$ is the minimum detectable optical path length and is taken to be 250 angstroms for this analysis.

n   is the index of refraction of the oil and is 1.394 for the oil used.

Before numerical values are given for the pertinent equations, it is of value to note the individual terms in the sensitivity equation. The first term,

$$\Delta T_1 = \frac{(e_1 + e_2)\, \Delta T'}{E\, \tau_A\, \tau_O\, \alpha_1\, A} \, ,$$

is the expression for the sensitivity of an ideal thermal imaging device with no losses. The second term in the equation,

$$\Delta T_2 = \frac{\Delta q_4}{4E\, \tau_A\, \tau_O\, \alpha_1\, e_T\, \gamma\, T_B^3\, A} \, ,$$

is a loss term associated with the latent heat of vaporization of the oil. The third term,

$$\Delta T_3 = \frac{\Delta q_7}{4E\, \tau_A\, \tau_O\, \alpha_1\, e_T\, \gamma\, T_B^3\, A} \, ,$$

is a loss term associated with convection. Thus, in terms of these three expressions

$$\Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 \, .$$

As a first illustration of the sensitivity, an exposure time of 20 seconds and a lens aperature of f:2 will be assumed. Under these conditions, ΔT_1 = .0093 degrees centigrade, ΔT_2 = .3592 degrees centigrade, and ΔT_3 = .0015 degrees centigrade. Totaling the three yields ΔT = .35 degrees centigrade. ΔT is larger than the required .1 degree centigrade sensitivity under these conditions. Obviously, the sensitivity may be increased by a factor of two by doubling the exposure time. It can also be halved once again by using an f:1.4 lens. Under these conditions, the sensitivity is ΔT = .0925 degrees centigrade. The sensitivity required is obtainable under the conditions that the exposure be 40 seconds and the lens have an aperature of f:1.4.

It is interesting to note that with an f:2 lens and an exposure of 20 seconds $\Delta T_1 + \Delta T_3$ is only .0108 degrees centigrade which is well within the .1 degree centigrade required. Hence, it is the loss term associated with the latent heat of vaporization that causes any significant loss of sensitivity. An observation of the equation for Δq_4 quickly shows that there are four variables which can be adjusted. These are Δd, δ_3, L, and Δt. The density, δ_3, of most of the oils which seem best suited for the Evaporograph have a density of around .9 gm cm^{-3}; hence, this term is not one which can be adjusted to any degree. The exposure time, Δt, can be increased but it is desirable to have this as low as possible; hence, this term also is not adjustable to any great degree. The latent heat, L, is a different story. For the oil used, which is the Dow-Corning 200 fluid with 3 centistoke viscosity, a latent heat of 28 cal gm^{-1} is obtained. If an oil could be found with a significantly lower latent heat, then the sensitivity could be increased without having to adjust the exposure time. Unfortunately, the

oil used in the Evaporograph must fulfill other requirements other than just the latent heat. It must also have a high molecular weight so that $\Delta T'$ is low, a vapor pressure less than about 200 microns so that Δq_7 does not become too large, and it must not corrode the cell or attack the membrane. Czerny (3) used paraffin oils. Baird-Atomic (12) initially found hexadecane to be quite good, but later found the tetra methyl siloxane polymers such as the Dow-Corning 200 fluids to be superior. Taquet (15) also used the Dow-Corning 200 fluid with 3 centistoke viscosity as her oil. A great deal of effort was put into finding a new oil for this research. Most of the work was centered around finding another siloxane polymer that had a lower latent heat as well as the other desired characteristics. Work was centered in this area since these polymers can be generated from basic groups of radicals. Unfortunately, all of the combinations which looked promising had almost the same latent heat as the 3 centistoke oil. Some effort was also put into trying to find a flouro-carbon oil which would have a significantly lower latent heat. These efforts were also futile. It is not to be said that there are not oils which have lower latent heats, but only that this researcher was able to find none.

Since no oil was found which had a significantly lower latent heat, the only other possible variable is the minimum detectable thickness of the oil film, Δd. The only factor really controlling Δd is $\Delta d'$ which is the minimum detectable optical path difference. According to Baird-Atomic (12), 250 angstroms is a realistic number for $\Delta d'$ since the membrane and oil film are not really uniform. Kubota (11), however, has stated that under ideal conditions optical path differences as small as 8.7 angstroms could be detected. There is significant room for

improvement in this area and in Section C of this chapter a means for overcoming part of the nonuniformities of the membrane will be discussed.

One other way to increase the sensitivity of the Evaporograph is to maximize the denominator of the sensitivity equation. Unfortunately, there is not much latitude in this area. Practically, the optical efficiency, E, is limited by an $f:1.4$ lens so that little adjustment can be made with this factor. The emissivities are also at about their practical limits, hence little adjustment can be made with these factors. This leaves only α_1 and A which can be adjusted. The amount of energy reaching the membrane can be increased by choosing a window material which has a greater transmission. A window made from potassium bromide or coated germanium would increase the energy input by as much as 10 percent. This would help somewhat but not significantly. The other factor is the absorption of the absorption layer on the membrane. A value of 80 percent was assumed for these calculations. This is the same number that Baird-Atomic (12) used in their calculations. It is, however, interesting to note that this number is the same number which Harris (8) gave in a comparison with carbon black. It is also interesting that most quantitative data which appeared in the article by Baird-Atomic also appeared in articles in their bibliography. The article by Baird-Atomic gave no data on actual absorption of layers used by them. They gave only data already published by Harris. Also, the article by Baird-Atomic stated that absorption layers of the type used by Czerny (4) and Taquet (15) would not work. Hence, it seems that Baird-Atomic intentionally left out and clouded many of the actual results obtained in their research. This number of 80 percent is, therefore, subject to

question. A discussion will be given later as to why films of the type used by Czerny (4) and Taquet (15) are superior to those of the type used by Baird-Atomic. The only problem with these films is that they can only attain a 50 percent absorption. However, by using antireflection coatings on these layers, absorptions of 83 percent can be achieved over a substantial bandwidth. In later sections of this chapter, a new synthesis procedure, which will allow the attainment of any absorption, will be developed and demonstrated.

The over-all objective of .1 degree centigrade can be achieved with the use of an f:1.4 lens, an absorption of 80 percent, and an exposure time of 40 seconds. In order to make much improvement upon the 40 second exposure time, either new oils must be found possessing lower latent heats or the minimum detectable oil film thickness must be decreased. It has already been stated that a new oil could not be found. So at least presently, the minimum detectable oil film thickness seems the most realistic approach to increasing sensitivity. A possible means of accomplishing this lies embodied in the new dielectric coated absorbing layers. The exact reasons for this will be given in later chapters. The important thing is that the Evaporograph is capable of attaining a sensitivity equal to that required.

B. The Infrared Absorbing Layer

The heart of the Evaporograph is the absorbing layer. Theoretically, this layer should absorb 100 percent of the energy incident upon it. Practically, this is impossible. However, it is possible to attain absorptions of 80 to 85 percent.

The layer used by Baird-Atomic (12) was a "gold black" layer formed

after the method of Harris (8). This layer had an absorption of 80 per-
cent out to at least 15 microns. There is, however, no theoretical
treatment of the absorption mechanism for this type of film. There is
only the experimental data proffered by Harris (8).

The thin vacuum deposited layers used by Czerny (4) and Taquet (15)
follow a theoretical base quite well. Woltersdorff (17) developed the
theory and verified its results using aluminum films. Later Hadley and
Dennison (6) also developed and expanded the theory to include angles
other than normal incidence. At any rate, the theory is well documented
in the literature. Since this is such an important portion of the later
developments of this thesis, a detailed derivation of the absorption
will be given.

B1. Analysis of the Thin Metallic Film

Assuming sinusoidal time variations, Maxwell's equations may be
written as:

$$\nabla \times \overline{E} = -j\omega\overline{B} \tag{3.1}$$

$$\nabla \times \overline{H} = j\omega\overline{D} + \overline{J} \tag{3.2}$$

$$\nabla \cdot \overline{D} = \rho \tag{3.3}$$

$$\nabla \cdot \overline{B} = 0 \tag{3.4}$$

where:

$\overline{E}$ is the electric field vector in Volts/M.

$\overline{H}$ is the magnetic field vector in Amp-Turn/M.

$\overline{D}$ is the electric displacement in Coulomp/M^2.

$\overline{B}$ is the magnetic induction in Weber/M^2.

ω is the angular frequency in rad/sec.

ρ is the charge density in coul/M^3.

j is $\sqrt{-1}$.

In addition to the four Maxwell equations, the three side constraints

$$\overline{D} = \epsilon_0 \overline{E} \tag{3.5}$$

$$\overline{B} = \mu_0 \overline{H} \tag{3.6}$$

$$\overline{J} = \sigma \overline{E} \tag{3.7}$$

are introduced. Where:

ϵ_0 is the permittivity of the medium and is 8.8552 x 10^{-12} fd/M.

μ_0 is the permeability of the medium and is 4π x 10^{-7} Hen/M.

σ is the resistivity of the medium and has units of dm $\cdot$ M.

The factors μ_0 and ϵ_0 are used here since it is assumed that the metallic layer is non-magnetic and non-dielectric. Introducing the constraints of Equations (3.5) through (3.7) into the Maxwell equations and rearranging yields

$$\nabla \times \overline{E} = -j\omega\mu_0\overline{H} \tag{3.8}$$

$$\nabla \times \overline{H} = (\sigma + j\omega\epsilon_0)\overline{E} \tag{3.9}$$

$$\nabla \cdot \overline{E} = \rho/\epsilon_0 \tag{3.10}$$

$$\nabla \cdot \overline{H} = 0 . \tag{3.11}$$

Utilizing Equation (3.9) and taking its divergence yields the result

$$\nabla \cdot (\nabla \times \overline{H}) = (\sigma + j\omega\epsilon_0) \nabla \cdot \overline{E} .$$

Now the divergence of a curl is by definition 0; hence, there are no free charges in the assumed medium, and Equation (3.10) is reduced to

$$\nabla \cdot \overline{E} = 0.$$

In the case of thin metallic films, the normal bulk resistivities no longer hold. In general, these resistivities can be as much as two orders to magnitude less than the bulk properties. Upon exploring Equation (3.9) the ratio,

$$\frac{\sigma}{\omega \epsilon_0},$$

becomes the factor σ is more than two orders of magnitude greater than $\omega \epsilon_0$ providing that ω is less than 1.8×10^{-15} rod/sec. This corresponds to a wavelength on the order of 2 microns. Hence, for wavelengths greater than two microns, Equation (3.9) reduces to

$$\nabla \times \overline{H} = \sigma \overline{E}. \tag{3.13}$$

Hence, the Maxwell equations reduce, in this case, to the Eddy current equations.

Taking the curl of Equation (3.8) yields

$$\nabla \times \nabla \times \overline{E} = -j\omega\mu_0 \nabla \times \overline{H}. \tag{3.14}$$

Substituting the results of Equation (3.13) into Equation (3.14) yields

$$\nabla \times \nabla \times \overline{E} = -j\omega\mu_0 \sigma \overline{E}. \tag{3.15}$$

Now, by definition

$$\nabla \times \nabla \times \overline{E} = -\nabla^2 \overline{E} + \nabla(\nabla \cdot \overline{E}),$$

but

$$\nabla \cdot \overline{E} = 0 \ ,$$

hence

$$\nabla \times \nabla \times \overline{E} = -\nabla^2 \overline{E} .$$

Finally then, Equation (3.15) becomes

$$\nabla^2 \overline{E} - j\omega\mu_0 \sigma \overline{E} = 0 \ . \tag{3.16}$$

Similarly, Equation (3.14) may be reduced to

$$\nabla^2 \overline{H} - j\omega\mu_0 \sigma \overline{H} = 0 \ . \tag{3.17}$$

Equations (3.16) and (3.17), when solved, give the $\overline{E}$ and $\overline{H}$ fields within the metallic film.

In order to simplify the solution of the wave equations, it is convenient to let

$$K^2 = j\omega\mu\sigma . \tag{3.18}$$

Hence, Equations (3.16) and (3.17) may be written in the form

$$\nabla^2 \overline{E} - K^2 \overline{E} = 0 \ . \tag{3.19}$$

Assuming a wave in the medium propagating in the +z direction and having only an x component of $\overline{E}$, Equation (3.19) reduces to

$$\frac{\partial^2 E_x}{\partial z} - K^2 E_x = 0 \ . \tag{3.20}$$

The solution to Equation (3.20) is

$$E_x = C_1 \exp(KZ) + C_2 \exp(-KZ) \ , \tag{3.21}$$

where:

C$_1$ and C$_2$ are constants to be determined.

Taking the square root of Equation (3.18) yields

$$K = \frac{\sqrt{\omega\mu\sigma}}{2} (1 + j) . \qquad (3.22)$$

For any film that is resistive in nature, the relationship,

$$\sigma = \frac{1}{rd} , \qquad (3.23)$$

holds.

Where:

r   is the resistance of the film in ohms/square.

d   is the thickness of the film.

For the medium at hand

$$\omega = 2\pi c/\lambda , \qquad (3.24)$$

where:

c   is the velocity of the wave in a vacuum and is approximately

3×10^8 M/sec.

λ is the wavelength of the wavefronts in meters.

The relationship,

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} , \qquad (3.25)$$

aids in reduction of the variables at hand, multiplying Equation (3.25)

by, μ_0, yields the relation

$$z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377 \text{ ohm/sq} , \qquad (3.26)$$

which is the impedance of free space. Now utilizing Equations (3.23),
(3.24), and (3.26) to simplify Equation (3.22) yields

$$K = \frac{\sqrt{\pi Z_0}}{\lambda_r d} (1+j) . \qquad (3.27)$$

Defining the ratio

$$R = \frac{Z_0}{r} ,$$

leads finally to the relationship

$$K = \frac{\sqrt{\pi R}}{\lambda d} (1+j) . \qquad (3.28)$$

Finally, Equation (3.21) may be written as

$$E_x = c_1 \exp\left[\frac{\sqrt{\pi R}}{\lambda d}(1+j)\right] z + c_2 \exp\left[-\frac{\sqrt{\pi R}}{\lambda d}(1+j)\right] z . \qquad (3.29)$$

Now utilizing the Equation (3.8), the $\overline{H}$ field can be found to be

$$H_y = \frac{\sqrt{R\lambda}}{4\pi d} \frac{(1-j)}{Z_0} \left\{ c_2 \exp\left[-\frac{\sqrt{\pi R}}{\lambda d}(1+j)\right] z - c_1 \exp\left[\frac{\sqrt{\pi R}}{\lambda d}(1+j)\right] z \right\} . \qquad (3.30)$$

Equations (3.29) and (3.30) are the field equations for inside the film.

In order to apply Equations (3.29) and (3.30) to the actual situa-
tion, the actual geometry of the problem must be defined. Figure 3
shows the situation at hand in the Evaporograph cell assuming normal
incidence of the wavefront. Also, the polarization assumed is per-
pendicular. However, since the wavefront is at normal incidence, the
end result is the same for the parallel polarization. Hence, only the
perpendicular case will be fully derived. There are three regions to

I

Vacuum

Zo, Hy, Ex_1

II

Metallic Film

Ex_2, Hy_2

III

Oil Vapor

Ex_3, Hy_3

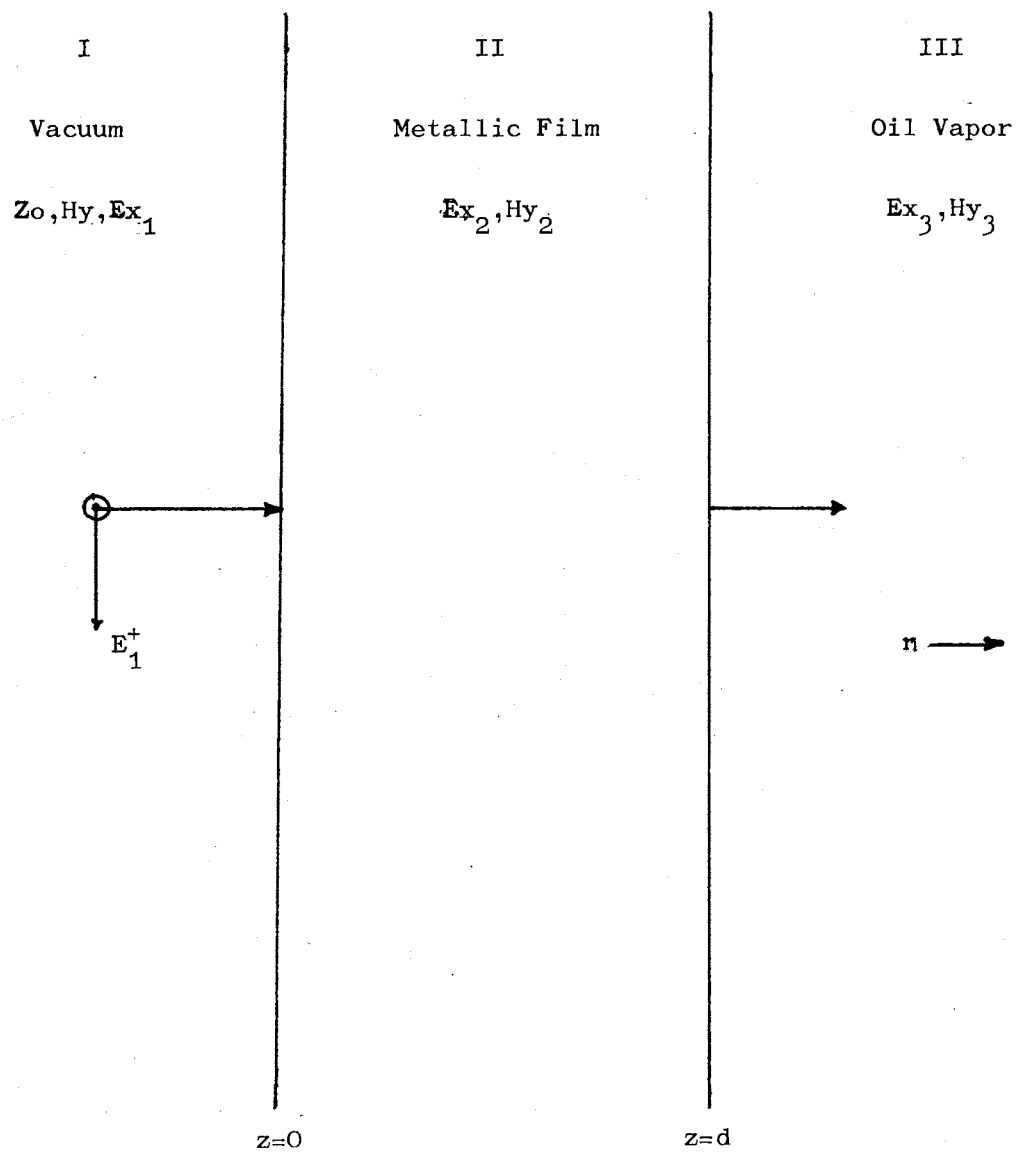E_1^+

$n \longrightarrow$

z=0

z=d

Figure 3. Geometry of the Metallic Film in the Evaporograph

the situation portrayed in Figure 3. The Region I is air and for it

the equations are:

$$E_{x1} = E_1^+ \exp(-j\frac{2\pi z}{\lambda}) + E_1^- \exp(j\frac{2\pi z}{\lambda}) . \tag{3.31}$$

$$H_{y1} = \frac{E_1^+}{Z_0} \exp(-j\frac{2\pi z}{\lambda}) + \frac{E_1^-}{Z_0} \exp(j\frac{2\pi z}{\lambda}) . \tag{3.32}$$

For Region II, the equations are of the form derived in Equations (3.29)

and (3.30). These equations are:

$$E_{x2} = E_2^+ \exp(-KZ) + E_2^- \exp(KZ) \tag{3.33}$$

$$H_{y2} = \frac{\sqrt{R\lambda}}{4\pi d} \frac{(1-j)}{Z_0} \left[E_2^+ \exp(-KZ) - E_2^- \exp(KZ) \right] . \tag{3.34}$$

The Region III is the oil vapor and it has no reflected waves. Hence,

its equations are:

$$E_{x3} = E_3^+ \exp(-j\frac{2\pi z}{\lambda}) . \tag{3.35}$$

$$H_{y3} = \frac{E_3^+}{Z_3} \exp(-j\frac{2\pi z}{\lambda}) . \tag{3.36}$$

In the above equations, the unknowns are the coefficients E_1^+, E_1^-,

E_2^+, E_2^-, and E_3^+. In order to solve for these, the boundary conditions

are used. At the boundary, $Z = 0$, the conditions which apply are:

$$E_{x1} = E_{x2} . \tag{3.37}$$

$$H_{y1} = H_{y2} . \tag{3.38}$$

Expanding (3.37) and (3.38) yields the results:

$$E_1^+ + E_1^- = E_2^+ + E_2^- . \tag{3.39}$$

$$E_1^+ - E_1^- = \sqrt{\frac{R\lambda}{4\pi d}}\,(1-j)\,(E_2^+ - E_2^-)\ .\tag{3.40}$$

At the boundary, $Z = d$, the pertinent conditions are:

$$E_{x2} = E_{x3}\ .\tag{3.41}$$

$$H_{y2} = H_{y3}\ .\tag{3.42}$$

Expanding Equations (3.41) and (3.42) yields the results:

$$E_2^+ \exp(-Kd) + E_2^- \exp(Kd) = E_3^+ \exp\left(-j\frac{2\pi d}{\lambda}\right)\ .\tag{3.43}$$

$$\sqrt{\frac{R\lambda}{4}}\,(1-j)\left[E_2^+ \exp(-Kd) - E_2^- \exp(Kd)\right] = \frac{Z_0}{Z_3}E_3^+ \exp\left(-j\frac{2\pi d}{\lambda}\right).\tag{3.44}$$

At this point, it is convenient to define the particular waves of interest. The incident wave

$$\overline{E}_i = \overline{a}_x E_1^+ \exp\left(-j\frac{2\pi z}{\lambda}\right)\ .\tag{3.45}$$

The reflected wave is

$$\overline{E}_r = \overline{a}_x E_1^- \exp\left(j\frac{2\pi z}{\lambda}\right)\ .\tag{3.46}$$

The transmitted wave is

$$E_{x3} = \overline{a}_x E_3^+ \exp\left(-j\frac{2\pi z}{\lambda}\right)\ ,\tag{3.47}$$

where:

$\overline{a}_x$ is the unit vector in the +x direction.

The respective waves are not actually the final desired results. Only the relative amounts of the reflected and transmitted waves are of interest. Hence, it is convenient to define the following

$$Ref = \left(\frac{E_r}{E_i} \right)^2. \tag{3.48}$$

$$Tr = \left(\frac{E_{x3}}{E_i} \right)^2 \tag{3.49}$$

$$Abs = 1 - Ref - Tr , \tag{3.50}$$

where:

Ref is the relative reflected power ratio.

Tr is the relative transmitted power ratio.

Abs is the relative absorbed power ratio.

Equations (3.48), (3.49), and (3.50) are the equations of interest. It is these equations which give the solution to the absorption of the metallic film.

In the case at hand the ratio λ/d, is on the order of 400 or greater for wavelengths greater than 2 microns. Using this fact, Equations (3.43) and (3.44) may be written

$$E_2^+ + E_2^- = E_3^+ . \tag{3.51}$$

$$E_2^+ \left[\sqrt{\frac{R\lambda}{4\pi d}} (1-j) - R \right] - E_2^- \left[\sqrt{\frac{R\lambda}{4\pi d}} (1-j) + R \right] = \frac{Z_0}{Z_3} E_3^+ . \tag{3.52}$$

The relationship

$$E_2^+ - E_2^- = \frac{(R + \frac{Z_0}{Z_3}) E_3^+}{\sqrt{\frac{R\lambda}{4\pi d}} (1-j)} \tag{3.53}$$

is easily derived by using Equations (3.51) and (3.52). Equations (3.51) and (3.53) can now be substituted into Equations (3.39) and (3.40) to obtain

$$E_1^+ + E_1^- = E_3^+ \ .$$

$$(3.54)$$

$$E_1^+ - E_1^- = (R + \frac{Z_0}{Z_3}) \ E_3^+ \ .$$

$$(3.55)$$

Equations (3.54) and (3.55) may now be solved for the ratios

$$\Gamma = \frac{E_1^-}{E_1^+} = - \frac{R + \frac{Z_0}{Z_3} - 1}{R + \frac{Z_0}{Z_3} + 1} \ ,$$

$$(3.56)$$

$$\frac{E_3^+}{E_1^+} = \frac{2}{R + \frac{Z_0}{Z_3} + 1} \ ,$$

$$(3.57)$$

where:

Γ is the standard reflection coefficient.

The desired results may now be found by squaring Equations (3.56) and

(3.57) and using (3.51). The desired results are

$$Tr = \frac{4}{(R + \frac{Z_0}{Z_3} + 1)^2}$$

$$(3.58)$$

$$Ref = \left[\frac{(R + \frac{Z_0}{Z_3} - 1)}{(R + \frac{Z_0}{Z_3} + 1)} \right]^2$$

$$(3.59)$$

$$Abs = \frac{4(R + \frac{Z_0}{Z_3} - 1)}{R + \frac{Z_0}{Z_3} + 1)^2} \ .$$

$$(3.60)$$

Now by definition:

$$Z_0 = \frac{\mu_0}{\sqrt{\epsilon_0}} , \qquad\qquad (3.61)$$

$$Z_3 = \frac{\mu_0}{\sqrt{\epsilon_{r3}\epsilon_0}} , \qquad\qquad (3.62)$$

where:

E_r is the relative dielectric constant of Region III.

Utilizing Equation (3.61), Equation (3.62) may be written

$$Z_3 = \frac{Z_0}{\sqrt{\epsilon_{r3}}} . \qquad\qquad (3.63)$$

By definition the term, $\sqrt{\epsilon_{r3}}$, is the index of refraction, n_3, of Region III, i.e.,

$$n_3 = \sqrt{\epsilon_{r3}} . \qquad\qquad (3.64)$$

Utilizing Equation (3.67), Equation (3.63) may now be written

$$Z_3 = \frac{Z_0}{n_3} . \qquad\qquad (3.65)$$

Equation (3.65) is an important result which holds for any medium.

Utilizing Equation (3.65), the ratio

$$\frac{Z_0}{Z_3} = n_3 .$$

Hence, Equations (3.58), (3.59), and (3.60) may now be written as

$$Tr = \frac{4}{(R + n_3 + 1)^2} \; . \tag{3.66}$$

$$Ref = \left[\frac{R + n_3 - 1}{R + n_3 + 1}\right]^2 \; . \tag{3.67}$$

$$Abs = \frac{4(R + n_3 - 1)}{(R + n_3 + 1)^2} \; . \tag{3.68}$$

The maximum absorption may be found by taking the derivative of Equation (3.68) and setting it equal to zero. The derivative is

$$\frac{d\ Abs}{dR} = \frac{(R + n_3)^2 - 2(R + n_3) - 3}{[R + n_3 + 1]^4} \; . \tag{3.69}$$

Setting Equation (3.69) equal to zero and solving for, $R + n_3$, yields

$$R + n_3 = 3 \; . \tag{3.70}$$

Substituting the results of Equation (3.70) into Equation (3.68) yields the result

$$Abs\Big|_{R + n_3 = 3} = .5 \; . $$

This means that a maximum absorption of 50 percent is obtainable from a metallic film. Note also that under the conditions that, $\lambda/d \gg 1$, this absorption is independent of wavelength. In the next section, it will be shown that by using dielectric layers on the absorption layer, the absorption may be increased to 83 percent.

B2. Synthesis of Antireflection Layers for

the Metallic Layer

Before the synthesis of the antireflection layers is undertaken, one further relationship must be obtained. By definition, the reflection coefficient for the single film in air is

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \; ,$$ (3.71)

where:

Z_L is the impedance seen at the front surface of the film. Equation Equation (3.56) with Equation (3.71) and using Equation (3.65) yields the result

$$Z_L = \frac{Z_0}{(R + n_3)} \; .$$ (3.72)

Optically speaking, this means that the metallic film, as seen by the incident wave, acts like a semi-infinite medium with index of refraction $(R + n_3)$. This fact makes the synthesis procedure very simple.

Young (18) has shown the exact correlation between dielectric layers upon a substrate and transmission line sections matching a resistive load. In essence, the transmission line equations are directly applicable to an optical system. Synthesis techniques for matching a resistive load over a prescribed bandwidth is well known and one of these techniques will be used for this work. Collin (2) has developed one of the better techniques for synthesizing a set of "quarter wave transformers" to match a resistive load for a prescribed set of conditions. This technique will be used to design the optical matching network for the absorbing layer. In terms of the transmission line, the

model of the problem is shown in Figure 4. The particular notation in Figure 4 is:

L_i is the length of the ith section.

Z_i is the impedance of the ith section.

N_i is the index of refraction of the ith transmission line section.

Z_L is the load impedance.

$R + n$ is the index of refraction of the load.

The problem in terms of impedances is to match the free space impedance, Z_0, to the load impedance, Z_L, over a prescribed bandwidth. Optically speaking, the procedure is to match a substrate with an index of refraction, $R + n$, to free space with an index of 1.0.

There are two basic methods of accomplishing a match of the type mentioned above. The first is to use a constant quarter wavelength for each transmission line segment and then solve for the characteristic impedance of the line. In the optical case, this means solving for the index of refraction of each quarter wavelength dielectric layer. The second method is to use lines with known characteristic impedance and solve for the line lengths. In the optical sense, this means that the indices of refraction are known and the thickness of the dielectric layers are unknown. The first method is considerably easier to employ and is the one used in this research.

Young (18) has shown that the greatest bandwidth with the fewest sections can be obtained by having an equi-ripple passband characteristic. This is the basic procedure used in this research. However, before the synthesis technique is given, a brief theoretical treatment of the method will ensue.

$$Z_q = \frac{Z_o}{Z_q}$$

$$Z_1 = \frac{Z_o}{N_1}$$

L_1

Z_o

Z_L

$$\Gamma_0 = \frac{Z_1 - Z_0}{Z_1 + Z_0} \qquad \Gamma_1 = \frac{Z_2 - Z_1}{Z_1 + Z_2} \qquad \Gamma_q = \frac{Z_L - Z_q}{Z_L + Z_q}$$
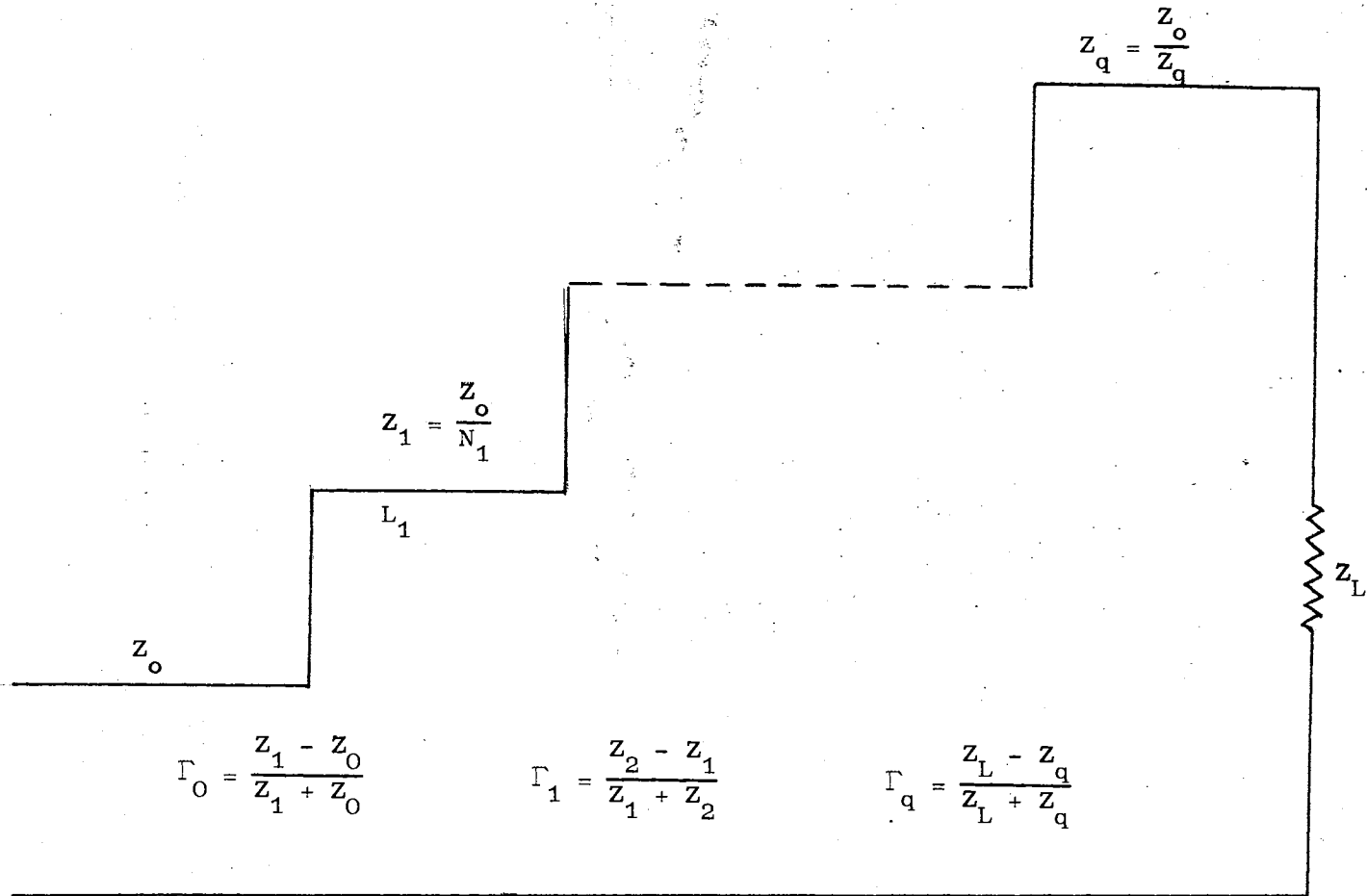
Figure 4.   Transmission Line Equivalent of Dielectric Layers
On a Substrate

In referring to Figure 4, the various reflection coefficients are:

$$\Gamma_0 = \frac{Z_1 - Z_0}{Z_1 + Z_0} = \rho_0 \tag{3.73}$$

$$\cdot$$
$$\cdot$$
$$\cdot$$

$$\Gamma_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} = \rho_i$$

$$\cdot$$
$$\cdot$$
$$\cdot$$

$$\Gamma_q = \frac{Z_L - Z_q}{Z_L + Z_q} = \rho_q \quad .$$

To a first approximation the total reflection coefficient is the summation of the first-order reflected waves. That is, the total reflection is

$$\Gamma = \rho_0 + \rho_1 e^{-2j\theta} + \rho_2 e^{-4ji\theta} + \text{---} + \rho_K e^{-jq\theta} , \tag{3.74}$$

where:

$e^{-ji\theta}$ is the ith phase retardation term.

Assuming that the transformer is symmetrical yields the result

$$\rho_0 = \rho_q \tag{3.75}$$

$$\rho_1 = \rho_{q-1}$$

$$\cdot$$
$$\cdot$$
$$\cdot$$

etc.

Under these conditions, the reflection coefficient may be written in the form of a Fourier cosine series as

$$\Gamma = 2e^{iq\theta}\left[\rho_0 \cos q\theta + \rho_1 \cos(q-2)\theta + \text{---} + \cos(q-2i\theta) + \text{---}\right] . \tag{3.76}$$

In order to obtain the equi-ripple response function, it is only necessary to equate the Chebyshev polynomial to the reflection coefficient, Γ. That is

$$\Gamma = Ae^{-q\theta}T_q\left(\frac{\cos\theta}{\cos\theta_m}\right) = Ae^{-n\theta}\cos q\left(\cos^{-1}\frac{\cos\theta}{\cos\theta_m}\right) , \tag{3.77}$$

where:

T_q is the nth degree Chebyshev polynomial.

θ_m represents the passband angle such that the response function will be confined to the range, $\theta_m < \theta < \pi - \theta_m$

A is a coefficient to be determined.

In order to find the coefficient, A, it is necessary to equate Equations (3.76) and (3.77). That is

$$A T_q(\cos\theta/\cos\theta_m) = 2\left[\rho_0 \cos q\theta + \rho_1 \cos(q-1)\theta + \text{---}\right] . \tag{3.78}$$

Now when $\theta = 0$, the result is

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = A T_q(\sec\theta_m) . \tag{3.79}$$

Hence:

$$A = \frac{Z_L - Z_0}{(Z_L + Z_0) T_q(\sec\theta_m)} . \tag{3.80}$$

Finally, for the equi-ripple passband characteristic, the reflection coefficient is

$$\Gamma = e^{iq\theta} \frac{Z_L - Z_0}{Z_L + Z_0} \frac{T_q(\cos\theta/\cos\theta_m)}{T_q(\sec\theta_m)} \, . \tag{3.81}$$

In the passband, the maximum value of the Chebyshev polynomial is one, thus

$$\rho_{max} = \frac{Z_L - Z_0}{(Z_L + Z_0)\, T_q(\sec\theta_m)} \, . \tag{3.82}$$

From Equation (3.82), it is easy to see that if the passband is predetermined for a given polynomial then the ripple is also determined. Conversely, if a certain ripple level is chosen for any polynomial, then so also is the passband determined.

For this particular research it was concluded that the three dielectric layers would probably be sufficient to accomplish a band-width of 5 to 20 microns with an absorption of around 85 percent. Furthermore, an R value of 5 was chosen so that with the addition of the index of refraction of the oil a value of 6.394 would be obtained for the index of the substrate. Figure 5 shows the actual graph of the reflection coefficient for the three-layer system. The angle $\pi/2$, corresponds to the center wavelength of 10 microns and θ_m corresponds to the lower passband wavelength of 4 microns. Choosing the lower passband wavelength at the 4 micron point makes the angle, θ_m, have the value of 36°. The angle, θ_z, is found by setting the relationship,

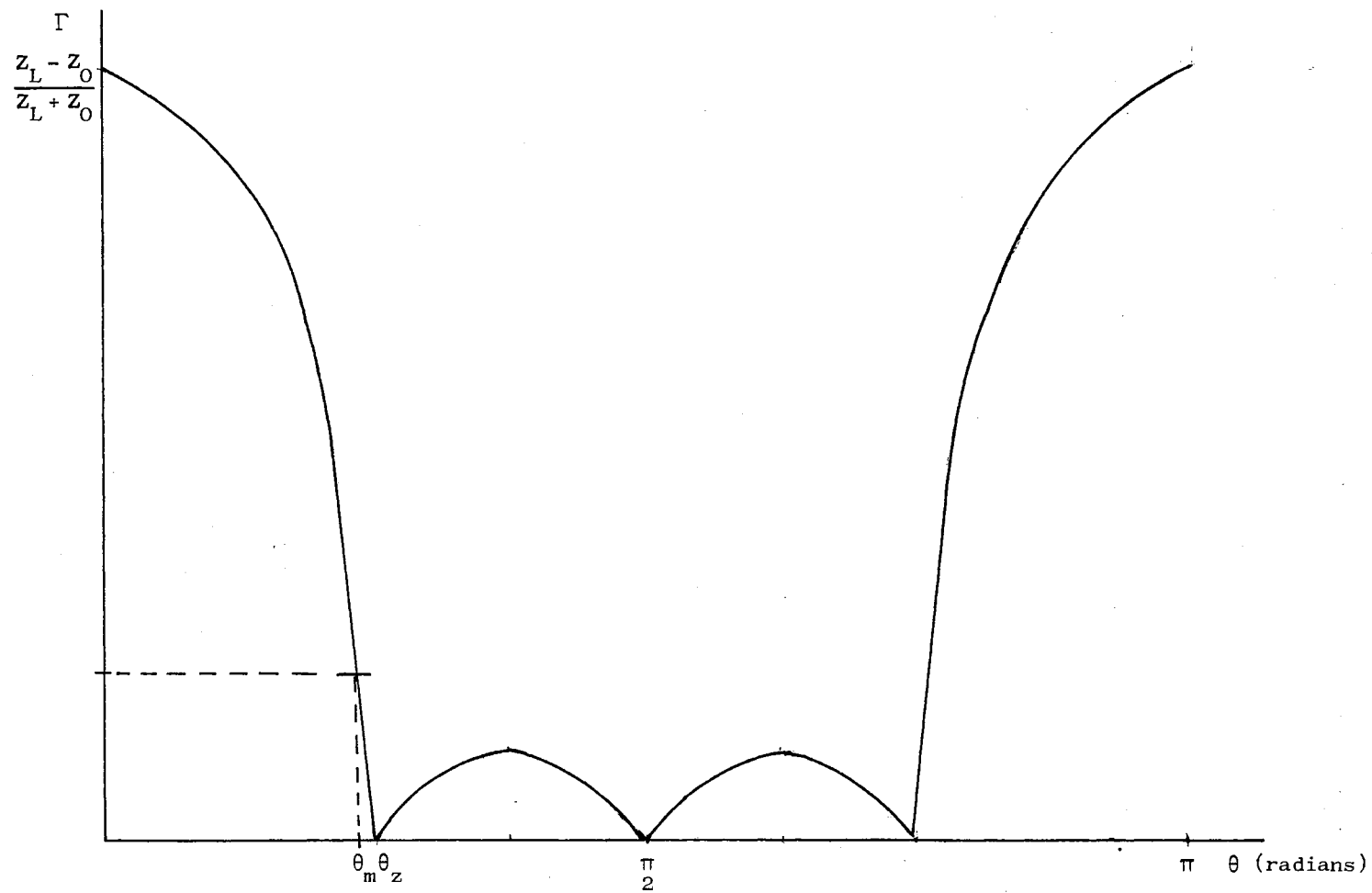$$T_3\left(\frac{\cos\theta}{\cos\theta_m}\right) \, ,$$

Figure 5. Reflection Coefficient for Three Layer System

equal to zero and solving for the roots. When this is done, the relationship that evolves is

$$\theta_z = \cos^{-1}\left(\frac{\sqrt{3}}{2}\cos\theta_m\right) .$$

(3.83)

In this case, the angle, θ_z, has a value of 45.6°.

The required characteristic impedances are obtained by utilizing the relationship 3.77 along with the value of A obtained in Equation (3.80). This result for the three-layer case is:

$$\frac{Z_L - Z_0}{Z_L + Z_0} \frac{T_3(\cos\theta/\cos\theta_m)}{T_3(\sec\theta_m)} = 2\frac{Z_1 - Z_0}{Z_1 + Z_0}\cos 3\theta + \frac{Z_2 - Z_1}{Z_1 + Z_2}\cos\theta .$$

(3.84)

When the right hand side of Equation (3.84) is equated term by term to the left hand side, the following results are obtained.

$$\frac{Z_L - Z_0}{\mathrm{Tan}^2\theta_z} = \frac{Z_1^2}{Z_0} + 2\left(\frac{Z_L}{Z_0}\right)^{\frac{1}{2}}Z_1 - \frac{Z_L Z_0^2}{Z_1^2} - 2\left(\frac{Z_L}{Z_0}\right)^{\frac{1}{2}}Z$$

(3.85)

$$Z_2 = (Z_L Z_0)^{\frac{1}{2}}$$

(3.86)

The third impedance ensues from the property of symmetry shown in Equation (3.75). This impedance is given by the relationship

$$Z_3 = \frac{Z_L Z_0}{Z_1} .$$

(3.87)

Substituting the impedances in Equations (3.85), (3.86), and (3.87) in terms of the indices of refraction yields the results

$$\frac{N_1^4}{N_L} + \frac{2N_1^3}{\sqrt{NL}} + \frac{(1-N_L)}{N_L\,\mathrm{Tan}^2\theta_z}N_1^2 - \frac{2N_1}{\sqrt{N_L}} - 1.0 = 0 ,$$

(3.88)

$$N_2 = \sqrt{N_L} \,, \tag{3.89}$$

$$N_3 = \frac{N_L}{N_1} \,. \tag{3.90}$$

Upon substituting the values chosen for N_L and θ_z into Equations (3.88), (3.89), and (3.90), the required indices are

$$N_1 = 1.62$$

$$N_2 = 2.53$$

$$N_3 = 3.96 \,.$$

In terms of physically obtainable materials, N_3 can be germanium of index 4.0 and N_2 can be thallous chloride of index 2.6. N_1 does not correspond exactly to any real material. Fujiwara (5), however, has developed a technique by which a desired index of refraction may be manufactured out of two materials. A detailed explanation of this procedure will be covered in the next chapter.

Now that the indices of refraction have been determined, the last step in the solution is to find the maximum power lost due to the ripple. This is computed from Equation (3.82) and the relation

$$\text{Maximum Normalized Reflected Power} = \rho^2_{max}. \tag{3.91}$$

Utilizing Equations (3.82) and (3.91), a value of 3.6 percent is obtained for the lost reflected power. This is an acceptable value, hence no adjustments will have to be made to the bandwidth requirement in order to lessen the ripple losses.

In order to check the validity of the synthesis procedure developed here, the matrix-analysis technique developed by Heavens (7) was employed. The procedure is quite straightforward and is shown quite clearly by Heavens. Hence, the monotonous copying of the work will not be shown. The results of the analysis are shown in Figure 6. The actual reflection loss in the system is actually on the order of 5.8 percent. The maximum absorption of the system is 84.3 percent. This is much better than the value of 50 percent that is obtainable from the single film. There are other advantages to the dielectric layers on the absorbing layer other than the increased absorption. However, a discussion of these will be left to Chapter V.

This section concludes the theoretical phase of the work done in this research. Chapter IV will give a description of the experimental procedures which were used in conducting this research.
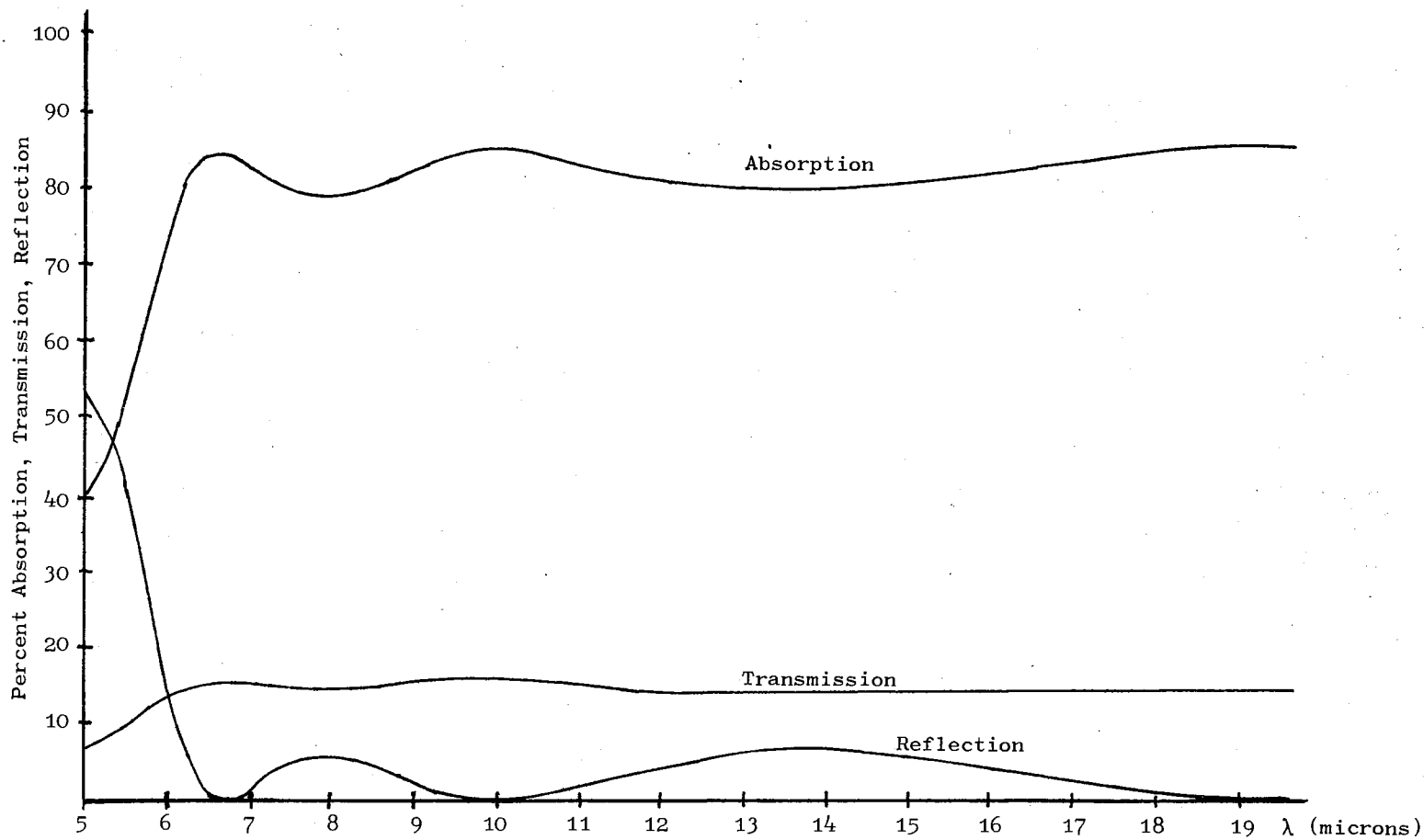
Figure 6. Absorption Data for Film With Three Dielectric Layers

CHAPTER IV

EXPERIMENTAL CONSIDERATIONS

A. Construction of the Membrane

One of the more important structures in the Evaporograph is the

membrane. While this structure is used only to support the absorbing

layer, it also serves as the portion of the apparatus on which the oil

film is condensed. The basic property of the membrane must be that of

mechanical strength for the support of the absorbing layer as well as

for withstanding any transients introduced by the vacuum system in pump-

ing the cell to the prescribed pressure. Unfortunately, while the basic

requirement is strength, it must also pass all wavelengths of the infra-

red spectrum completely. This poses a rather interesting materials

problem. In order to accomplish the latter requirement, a dielectric

material must be used. To insure that the material not interfere with

the transmission of the infrared energy to the absorbing layer, it must

be less than .1 micron in thickness.

In order to satisfy the requirement of obtaining uniform films of

0.1 micron or less in thickness, a water flotation method has proved to

be the easiest and most consistent. In this method the membrane mate-

rial is dissolved in a suitable solvent and then a drop is placed upon

water and allowed to spread to its full limits. The solvent is allowed

to evaporate and then the membrane material is collected upon a round

washer-like structure five inches in diameter with a hole $3\frac{1}{4}$ inches in

diameter. The membrane is collected by placing the washer down on top of the film on the water, clearing the excess material from around the washer, and then bringing the washer out of the water at an angle of about 20 degrees. This is the best procedure to follow to keep the surface tension of the water from having an effect on the membrane.

After the membrane has been collected, it is placed in a dust free container so that any water still clinging to it may evaporate. When the membrane is dry, it can be placed on the membrane holder simply by pushing the holder through the hole in the washer. Since the hole in the washer is a good bit larger than the two-inch diameter of the membrane holder, one can select the best portion of the membrane to put on the holder. Reasonably uniform membranes can be made in this manner.

The actual hardware required to make the membrane is very simple. Other than the washer already mentioned, the only other apparatus required is the pan in which the membrane is formed. Since the membrane is formed on the surface of the water, a very shallow pan may be used. The only dimensional requirements being that the pan be wide enough and long enough to let the film spread to its maximum limits. Experimentation has indicated that a pan with a depth of one inch, a width of ten inches, and a length of fifteen inches is suitable for making the membrane. A pan of these dimensions can be obtained from the cookware section of most any variety store.

At this point a word or so must be said about the water used to make the membrane. While good results have been obtained with plain tap water, membranes made with distilled water are less apt to have dust particles stuck to the surface. Hence, while not absolutely necessary to make good membranes, distilled water makes it an easier job.

Many different materials have been used over the years by many different researchers to make membranes. The Baird Atomic Corporation (12) tried several different solution. They tried amylacetate, polyvinyl formal in dioxane, polystyrene or benzene solution of resogloz, and nitrocellulose in acetone. The first and the last of these solutions were tried in this research. The amylacetate films were not strong enough to be of much use. The nitrocellulose dissolved in acetone did not spread out over the surface of the water because the acetone evaporated too fast. Using chilled water to slow down the evaporation of the acetone did not seem to help in this problem. Due to failures with these materials, other solutions were sought.

It was thought that a good film might be produced by using butarate dopes used in model airplane construction. Several of these materials were tried as well as a material called "Microfilm B", which is a solution for making thin skins for model airplanes. The films made from these solutions were stronger than the amylacetate films but were not strong enough to be of much use in the thickness required.

Czerny (3) and Taquet (15) had used collodion, which is notrocellulose dissolved in an alcohol solvent, for making membranes. Iso-amylacetate was mixed with the collodium in order to have a solvent that would evaporate slowly enough to allow the film to spread to its fullest extent.

In the researched conducted at Oklahoma State University, initially the only collodion that was available was a small amount in which the solvent had evaporated. Iso-amylacetate was added to this solidified mass until a consistency somewhat like mineral oil was attained. Membranes made from this solution were of reasonable quality and of

sufficient mechanical strength to suffice. They were, however, somewhat
brittle, and membranes on the order of .03 microns formed with stria-
tions in them. In an effort to overcome the striation problem, wetting
agents were added to the water after the membrane had dried but before
it was raised from the surface of the water. The wetting agents did
break the surface tension between the film and the water as expected.
However, the collodion was soluble to some degree in all of the wetting
agents so that membranes produced in this manner were too weak to be
plated.

After the wetting agents failed to solve the striation problem, it
was concluded that it might be possible to add a material to the collo-
dion which would make it more pliable and hence have less tendency to
form striations. Upon researching this concept, it was found that the
Mallinckrodt Chemical Works produced a collodion in which camphor was
added as a plasticizer. This material is commercially available under
the name "Collodion Flexable". This material is essentially nitro-
cellulose dissolved in ethanol with a small amount of camphor added.
After several trials, a procedure was developed which seems to produce
very good membranes. The first step in making the membrane is to pour
50 millimeters of the collodion into a beaker or other suitable con-
tainer. When this has been accomplished a filter paper is placed on top
of the beaker to keep out dust. The solution is then allowed to set
until all of the alcohol has evaporated. This takes about 12 hours at
room temperature. When the alcohol has completely evaporated, 50 milli-
meters of iso-amylacetate. The solution is then ready to make membranes.
Membranes made with this solution were better than the ones made with

the collodion without the plasticizer added. However, the striations were still present in membranes less than about .03 microns in thickness.

Attempts were also made at fabricating membranes out of nylon. It was thought that the nylon would allow the construction of membranes on the order of .01 microns which would still be sufficiently strong. Brown (1) had given a method of producing a solution of nylon dissolved in isobutyl alcohol. The procedure was to take nylon shavings and add the isobutyl alcohol then heat the solution until sufficient nylon had dissolved to make membranes. Unfortunately, Brown did not give which particular type of nylon was used in this process, but none would dissolve in the alcohol mentioned. Attempts were made at dissolving the nylon in hydrochloric acid and then mixing the alcohol, but when this solution was placed on the water it would either drop to the bottom of the pan or not spread at all depending upon the type of nylon used. Since no nylon could be found that would dissolve in the alcohol, superior films might be made. Until this is accomplished, however, the collodion films seem to be the best.

B. Plating the Membrane

Three different types of depositions for the absorbing layer has been discussed to some extent previously. The first of these was the "gold black" developed by Harris (8) and used by Baird Atomic (12). The second is the vacuum deposition used by Czerny (4) and Taquet (15). The third is the deposition of the dielectric antireflection coatings suggested in the last chapter. These three methods will be discussed in turn and the specific advantages discussed.

B1. The "Gold Black" Method
_____

This is the method developed by Harris and used by Baird Atomic

(12). In this method, a gas is introduced into the vacuum system until

the pressure is in the millimeter range; the gold is then evaporated

very slowly in this atmosphere until the desired thickness is obtained.

The texture of this deposition is very similar to that obtained by

taking a candle and smoking a glass sheet.

Harris (8) used an apparatus in which the filament was placed a

distance of seven centimeters from the target. Also, a shutter was

placed a distance of 1.3 centimeters from the filament so that the

nitrocellulose target might be shielded from as much heat from the fil-

ament as possible. In addition to the shutter, a place of brass was

placed one millimeter behind the nitrocellulose target so that the heat

could be dissipated from the nitrocellulose target. The gas explored by

Harris was nitrogen.

The exact procedure used by Harris is as follows: A 5 centimeter

length of 20 mil gold wire was placed in the "V" of a 30 mil tungsten

filament. A high vacuum was introduced and then the gold was heated

until it melted and formed a droplet in the "V" of the filament. The

current was then raised until the "splitting" of impurities ceased. The

current was then reduced and the gold kept just molten. At this point,

the nitrogen was introduced and the pressure adjusted to the desired

level. When this was accomplished, the current was raised to the de-

sired level and the gold evaporated. The shutter was then opened for

the desired length of time to get the thickness required. In this

manner, a film of 350 angstroms thickness reportedly yielded 80 percent

absorption from 3 to 15 microns. Through experimentation, Harris found

that the most optimum pressure to use was 1 millimeter of mercury. He

also found that a rate of deposition of less than 3×10^{-10} gram per

second gave the best films.

The method employed by Baird Atomic (12) was a variation of the

method of Harris. The distance from the filament to the membrane had

to be further to obtain a uniform thickness over the membrane. Hence,

hydrogen was used at a pressure of 5 to 10 millimeters of mercury.

Baird Atomic (12) does not state the exact pressure or the distance

used from filament to target although the distance was probably on the

order of 25 centimeters. The Baird Atomic paper also does not state

what results were obtained.

A variation of the method used by Harris was also attempted in the

research conducted at Oklahoma State University. No shutter was used

and a heat shield was employed at 2 centimeters above the filament. The

backing plate was a 25-centimeter square of aluminum 3 millimeters in

thickness. This plate was placed approximately one millimeter in back

of the membrane. The distance to the membrane was 25 centimeters.

Nitrogen was first used as the gas, but at a pressure of one millimeter

of mercury the mean free path is only .01 centimeter. For this reason,

it took massive amounts of gold in order to get any deposition on the

membrane at all. With the nitrogen atmosphere, 10 centimeters of 20 mil

wire produced membranes of only a few percent absorption. It was con-

cluded that a much lighter gas might help the problem of the mean free

path. Since hydrogen is potentially dangerous, helium was obtained and

used. The pressure used was still one millimeter and the distance from

filament to the membrane was maintained at 25 centimeters. With the

helium, 10 centimeters of 20 mil gold wire gave films with only 10

per cent absorption; moreover, the films produced by this method had the consistency of lampblack and would not adhere to the membrane very well. When these membranes were placed into the Evaporograph, any oil that managed to get on the back side of the membrane easily washed off these backs. For these reasons, this type of black was abandoned in lieu of the vacuum deposited films.

B2. Vacuum Deposited Films

This is the method used by Czerny (4) and Taquet (15). In principle it is considerably easier to do than the method that Baird Atomic used. In the vacuum deposition method, the pressure in the bell jar is maintained at 10^{-5} millimeters of mercury or less. The distance to the membrane is around 30 centimeters. Taquet (15) used 28.5, but 30 was used for the best results obtained in the research at Oklahoma State University. Since the mean free path is great compared to the distance to the membrane, the formula for thickness of the film is

$$t = \frac{w \cos e}{4 \pi r^2 p}$$

where t is the thickness of the film, w is the weight of the metal, r is the radial distance from the membrane to the filament, p is the density of the metal, and e is the angle between the perpendicular line through the filament and the radial vector to the membrane. This formula assumes a helical filament. The angular dependence, is important here because the membrane can be placed at an angle of 45 degrees and receive much less heat than is obtained with the membrane directly over the filament. This formula is very useful in that a known weight of

metal can theoretically be used to obtain a desired thickness of the metallic film. The only drawback in this method is that the metal must be flashed onto the membrane with a large current pulse. Currents in excess of 100 amperes were not uncommon in the depositions at Oklahoma State University. Because of this large current pulse, a large heat pulse is formed. This heat pulse is very detrimental to the membrane and it is difficult to flash the metal on the membrane unless one uses some method to control this heat pulse.

Czerny (4) used aluminum as the metal in his experiments. While aluminum is relatively easy to flash onto the membrane, it forms oxides very rapidly and loses its absorptive properties with age.

Taquet (15) found that gold formed much longer-lasting films. She also ran curves of absorption versus thickness of the gold deposits. This data is very useful in determining how much gold to use for the deposition. In her system, the membrane formed an angle of 45 degrees with the filament; and the distance was 28.5 centimeters. The gold was placed on the filament and system pumped down to 10^{-5} millimeters of mercury or less. The current in the filament was raised until the gold melted and all impurities were expelled. The filament was then given a large pulse of current to evaporate the gold. For some reason Taquet gave no description of the actual hardware used to deposit her films. However, whatever method used, she reportedly obtained a maximum of 47 percent absorption with a 50 angstrom thickness of gold.

For the research conducted at Oklahoma State University, a VEECO 400 system was used. Although a large bell jar was available, it was awkward to use. Hence, an attempt was made at using a small bell jar 8 inches in diameter and 12 inches in height. Because the bell jar had

a rounded top, a distance of only 20 centimeters from the filament to the membrane could be obtained. Furthermore, the angle between filament and membrane was limited to 25 degrees. The filament used was helix constructed from 60 mil stranded tungsten wire. Initially 8 mil gold wire was used as the evaporant. In the small bell jar, the membrane readily burned when attempts were made to flash gold upon it. Hence, slower deposition rates were tried. The gold evaporated easily in this manner. However, when transmission measurements were made with a Beckman IR-7 spectremeter, it was found that the films were almost transparent in the region from 5 to 15 microns. From these measurements it was concluded that the gold had to be flashed on the membrane in order to achieve the desired absorptive characteristics.

When the reduced rates of evaporation failed, a compromise solution was attempted. The concept was to increase the current sharply in order to flash gold onto the membrane and then reduce it before the membrane burned. Not all of the gold was evaporated in this procedure; however, films which absorbed about 7 percent of the radiation over the bandwidth from 5 to 16 microns were formed. An attempt was made at making several depositions in this manner on the same membrane. However, when this was done the absorption actually decreased. One of the 7 percent absorbing membranes were placed into the Evaporograph cell and pictures of hot objects taken. These will be shown and discussed in the next chapter.

From the results obtained by using the small bell jar, it became obvious that the large bell jar would have to be used.

The large bell jar made it possible to obtain distances of 30 centimeters and an angle of 45 degrees. When attempts at flashing the gold were made, the membrane again burned. Again, as gold was flashed, the

current was turned down before all of the gold had evaporated. In this manner an absorption of about 15 percent could be obtained. When the membranes which absorbed 15 percent were placed in the cell, there was no apparent improvement in the sensitivity of the instrument over the membranes with 7 percent absorption. However, the images did seem to form somewhat faster. These results will also be shown in the next chapter.

Since the gold could only be deposited to obtain an absorption of about 15 percent, it was decided that other metals might be easier to deposit. Nickel was tried but it took so much heat to melt it that the membrane crinkled under this heat. It was next decided that chromium might be easier since it sublimes. Unfortunately, chromium does not wet the tungsten filament. However, there are two methods that can be used to induce chromium to adhere to the filament. The more difficult method is to place the filament in an atmosphere of hydrogen or helium, with a piece of chromium placed inside the helical, filament. When current is applied, the chromium sublimes and as it does some of it adheres to the filament. In this method there is, of course, little control over the amount of chromium deposited upon the filament. The second method is to electroplate chromium onto the filament. This proved to be the better method, in that the weight of chromium on the filament could be accurately determined from the current and length of time of electrolysis. The electrolyte solution used to plate the filament was made by adding 160 milliliters of water to 40 milliliters of chromium trioxide. The power source was a 6-volt battery charger. It was found that a current of one ampere would deposit the required amount of chromium on the filament in about ten minutes. When the chromium was flashed upon the

membrane, it crinkled under the heat just as in the case of the nickel. For this reason the chromium was also abandoned.

The next metal attempted was lead. Since lead evaporates at a very low temperature, it was thought that it would deposit completely without damaging the membrane. This was the case. However, examination of the lead films on the spectrometer showed that the films had poor absorptive properties. Hence, lead was also abandoned.

Czerny had used aluminum as his film, but he found that the absorption of these films deteriorated with age. However, since aluminum does evaporate at about 100 degrees less temperature than the gold, it was thought that the degradation of performance with age would be acceptable if greater absorption could be obtained. This, however, was not the case. Like the gold, absorptions of only about 15 percent were obtained before the membranes burned. Films of aluminum were placed into the Evaporograph and images taken. These results will be given in the next chapter.

From the attempts at depositing the various metals upon the membrane, it is apparent that Taquet (15) must have had some specialized type of deposition equipment in order to be able to flash gold films with absorptions of 50 percent upon the membrane material.

An observation of the actual deposition process, gives some insight into the method that Taquet must have used to accomplish her ends. The current is raised slowly until the metal melts and wets the tungsten filament. After the metal has wetted the filament, the current is abruptly raised so that the metal is flashed. Because the filament must supply the necessary heat to the evaporating metal, it actually does not glow at its brightest until all of the metal has been deposited. If in

the time period before the heat radiated is at its peak, but after all
of the metal has been deposited, a shutter is closed then the membrane
could be kept from being burned. Since this time interval is only on
the order of one-half second, a very precise shutter mechanism would be
required to perform this function. It would allow one to vary the time
in which the shutter was open. The deposition system used at Oklahoma
State University in this research was not equipped with one of these
devices, and one could not be constructed with the materials available.
It is almost a certainty, however, that Taquet had such a device.

B3. The Dielectric Coated Absorbing Layers

Because the vacuum deposited absorbing layers can have at most a
50 percent absorption and are difficult to plate on the membrane mate-
rial, the dielectric coated absorbing layer offers many advantages. In
fact, the nitrocellulose membrane can be eliminated all together.
Unfortunately, the actual deposition of these films could not be accom-
plished with the equipment available. However, a description of a
deposition process which might be used will be given.

The first thing that must be done in order to deposit the dielec-
tric layers is to choose a suitable backing on which to plate the
dielectric layers. This backing must be easily dissolved after all of
the depositions have taken place and the solvent used must not attack
the dielectric layers. This material could easily be nitrocellulose
since it dissolves in most organic solvents. Because the nitrocellulose
serves only as a backing on which the layers are deposited, it can be
made somewhat thicker than the membranes. Thickness as much as 2000

angstroms would not be hard to handle, and would be more resistant to heat than the thinner membrane.

The actual deposition sequence, which would be the easier to perform, would be to plate the material with the refractive index of 1.62 first. Since this material must be manufactured from two different materials, this layer is the most difficult to produce. However, Fujiwara (5) has developed a technique which should work very well. The materials which can be used are Zinc sulfide and Cerium dioxide. These two materials are placed in separate boats with the cerium dioxide in a tungsten boat and the zonc sulfide in a molybdenum boat. There is, of course, a different current source for each boat. The currents are adjusted separately to achieve the proper rates so that the desired index of refraction is obtained when the layer has built up to the proper thickness of 2.51 microns.

The second layer which is composed of thallows chloride is much easier to deposit. This material sublimes at about 150 degrees centigrade at pressures less than 10^{-4} torr. A quartz crucible must be used as the source but this is no problem. The rate of deposition is just controlled until the desired thickness of .95 micron is attained.

Germanium is used for the third layer, and should be sputtered on for best results. The rate must again be controlled until a thickness of .625 microns is achieved.

After the germanium has been deposited, the structure should be removed and placed in the holder which will be placed in the Evaporograph. The system is then placed in an acetone bath until the nitrocellulose backing has dissolved. The structure is then to be placed in the vacuum chamber once again and the gold flashed directly upon the

germanium. The structure has now attained a thickness of 3.09 microns and should be very much stronger than the nitrocellulose membranes with gold, since the structure is now some thirty times thicker than the nitrocellulose membranes.

Actually, since the dielectric layers are not subject to the heat transients that the membranes were, chromium, nickel, or other metals could be used for the absorbing layer. However, if these were to be used, the thickness versus absorption curves would have to be determined for the metal in question. As far as that goes, the absorption versus thickness for gold would have to be determined because this property is dependent upon the substrate used.

The above procedure is not one that has actually been used since the equipment available was not capable of such a task. It is not intended that the above procedure be construed to be the only possible procedure for the deposition of dielectric layers. It is only suggested that this procedure is one which could possibly be used to achieve the desired ends.

C. Operating Procedure

The operating procedure for the Evaporograph had to be worked out by trial and error since none of the other researchers in the field gave a clear outline of the procedure which was used to image objects with the Evaporograph. There are, however, two basic procedures by which images are obtained by means of the Evaporograph. The first of these is the method first used by Czerny (3). In this method, oil is allowed to condense on the membrane before the image is focused upon it. As the oil evaporates from the exposed area, the image is formed. This method

is the least sensitive of the two and was discarded almost from the first in the research conducted at Oklahoma State University. The second method was developed by the Baird Atomic Corporation (12). In this method the image is focused on the membrane and then the oil is allowed to condense upon it. The image is formed on the membrane as the oil condenses at different rates depending upon the temperature of the point in question. This is the method used in the research conducted at Oklahoma State University.

The actual operational process is as follows: The first step is to make sure that the vacuum valve in the main line to the Evaporograph is closed. If it is not, experience has shown that the membrane will almost certainly be broken by the transient induced when the pump is turned on. With the valve closed, the vacuum pump can be started. Next, the power is applied to the lamp illuminating the membrane, the heater to the back window, and the vacuum gauges. While observing the membrane, the vacuum valve is slowly opened. The valve must be opened slowly because the two halves of the cell are not quite of the same volume and since the membrane is so fragile, any undue pressure differences would readily cause it to puncture. Initially, the valve should be opened no more than three turns. When the membrane has returned to normal, as observed through the half silvered mirror, the valve can be opened another turn. This procedure is repeated until the valve is completely opened. When a pressure of 100 microns of mercury is attained, the power is applied to the oil heater. The voltage is adjusted so that a voltage of two volts is attained across the heater coils. At this point, the lens is focused. Since no optical image is observed until the image is formed on the membrane, the lens must be focused by

measurement according to the formula

$$1/O + 1/I = 1/Fl.$$

Where:

    O   is the object distance,

    I   is the image distance,

    Fl is the focal length of the lens.

With experience the lens can be focused quite easily in this manner. As the oil heats, it begins to condense on the membrane. As it does the image appears on the membrane, first as shades of blue, then, as the oil becomes thicker, as shades of red just before the oil begins to run down the membrane. The image is erased from the membrane by turning on a 100 watt bulb and placing it just in front of the lens. It takes from a few seconds up to about a minute for the membrane to be erased depending upon the thickness of the oil film. After the membrane has been erased, the bulb can be turned off then removed from in front of the lens so that another image may be formed. For the steam iron used as a target in these experiments, it took only a few seconds for the image to appear. However, the time that it takes to form an image can be controlled to some degree by adjusting the voltage to the oil heater. The time to observe the iron could be controlled from about a minute by setting the voltage to $^1/2$ volt to about 10 seconds at 2 volts.

The above is essentially the procedure used in obtaining an image. In order to photograph the image, one must have special equipment. The basic apparatus and films used have already been discussed in the first chapter. The procedure to photograph the image is quite simple with the equipment used. The setting for the camera was obtained simply by

measuring the reflected light on its internal light meter. With the lens setting determined, the procedure is just to focus and shoot. Since the film used to take the color images was used at ASA 320 instead of its normal rating, it required special handling. All of the photographic processes used in this research had to be done by hand.

The above paragraphs outline the procedure used in obtaining and photographing the image. The next chapter contains the results and conclusions.

CHAPTER V

SYNOPSIS AND ANALYSIS OF RESULTS

A. Analysis of Results

Although the experimental results of the research conducted at

Oklahoma State University could not be carried to the extent desired due

to the lack of equipment, enough data was taken to give an objective

evaluation of the evaporographic process. As was stated in Chapter IV,

there were three types of absorption layers used to image objects with

Evaporograph. The first was a gold absorption layer of about 7 percent

absorption; the second was a gold layer of about 15 percent absorption;

and the third was an aluminum layer of about 15 percent absorption. The

object chosen to be imaged on a comparative basis was a steam iron. The

surface temperature of the iron was set at a temperature of 240 degrees

Fahrenheit, as measured at the tip, so that a peak point wavelength of

7.5 microns would be obtained.

The first image of the iron, which is shown in Figure 7, was taken

with a gold absorption layer having about 7 percent absorption. This

particular photograph was taken after the image had formed for about

20 seconds. The oil film is, thus, relatively thick after an exposure

of this long since it only takes about 60 seconds for the oil to begin

to run down the membrane. The temperature gradients across the iron

are quite marked for an image exposed this long. The photograph shows

very vividly that the tip of the iron is much warmer than the rest

of the surface. Also, the steam holes show up as much warmer than
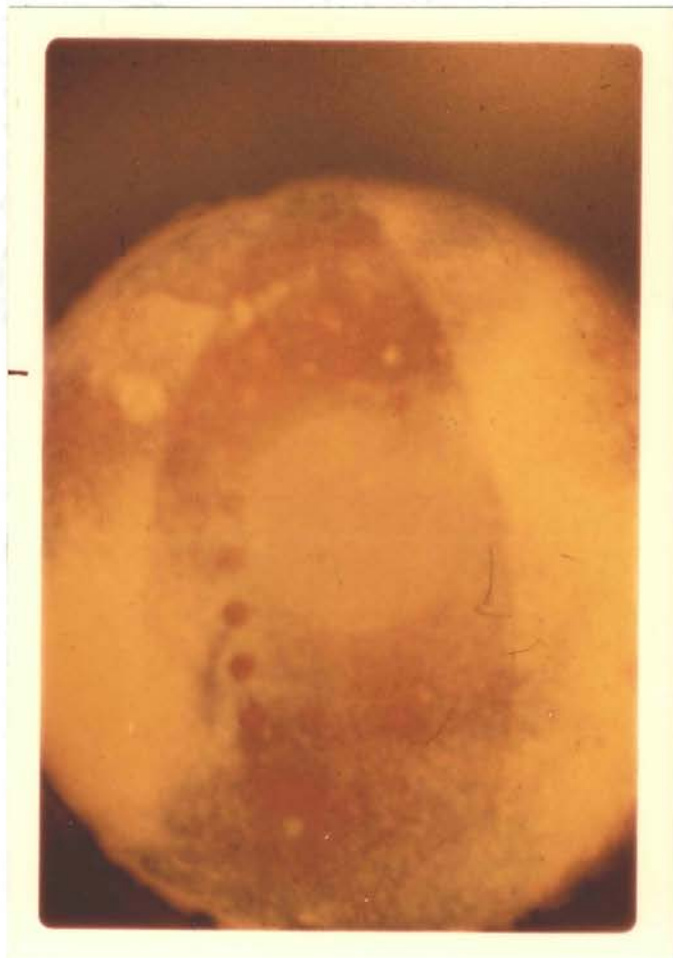
Figure 7. Seven Percent Gold Film

the rest of the iron. The circle visible in the center of the photo-

graph is a reflection off of the germanium lens. It will be remembered

that the membrane plus absoring layer is transparent to the visible to

some degree. The problem of this reflection only showed up with the

very thin absorption layers so it is not a problem which has to be

solved by using special filters to filter out the visible.

The second image of the iron, shown in Figure 8, was taken with a

gold film of about 15 percent absorption. The photograph was taken just

after the image began to appear upon the membrane. This was only about

three seconds after imaging was begun. Note that this image is not as

well defined as the one taken with the 7 percent absorption layer. This

is because the oil is not as thick and the image has not had time to

form completely. It will be noticed that the upper left hand corner of

the picture is a different color than the lower right hand corner. This

is because the membrane is not uniform and this difference in thickness

shows up as the difference in color. That the membrane is not uniform

is one of the major contributors to losses in sensitivity of the device.

The solution to the problem of the non-uniform membrane will be given

in the other half of this chapter, and hence, will not be discussed

further here. The brown colored spots around the outside rim of this

photograph is caused by oil buildup around the rim. The actual cause of

the problem is that the two halves of the Evaporograph cell are not

pumping down at the same rate and there is a strain on the membrane.

This effect will disappear after the pressure on both sides of the mem-

brane equalizes. This does show what happens to the membrane when pump

down conditions before equilibrium have been fully attained. If one

observes the photograph very closely, he can see the strain lines
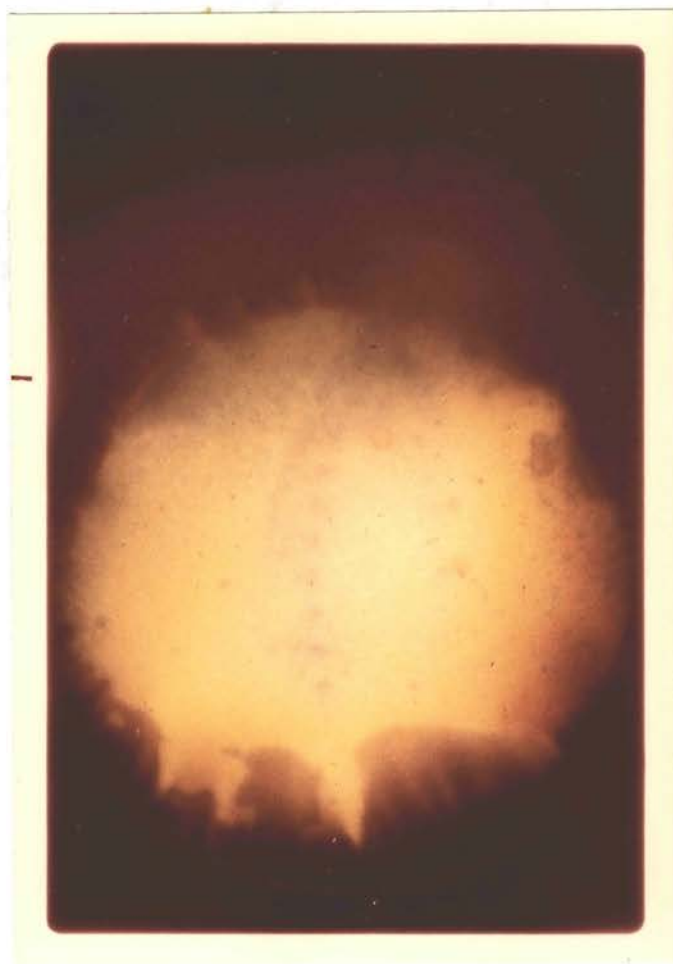
Figure 8.   Fifteen Percent Gold Layer

around the periphery of the membrane. Unfortunately, since the membrane is so thin, it does not take much of a pressure differential to puncture it. From observing this photograph, one can readily observe that great care must be exercised in pumping the cell down.

The third photograph, which is shown in Figure 9, is of an image formed by an aluminum absorption layer with 15 percent absorption. The photograph was taken after the image had formed for about 45 seconds. If one looks closely, he can see droplets of oil beginning to form in the upper left hand corner of the picture. In a few more seconds, the oil would begin to drip down the membrane. This particular picture, however, was chosen to show one of the largest factors which limit the sensitivity of the Evaporograph, rather than the oil droplets. Upon observation of the picture, one quite readily focuses his attention to the narrow band across the center of the membrane. This narrow band is caused by the variation in thickness of the membrane. Admittedly, this particular case is much more severe than most of those encountered but it does show the problem very vividly. When this particular membrane was made, there were no indications of imperfections. This might seem odd, but since the actual thickness of the membrane is only about 500 angstroms, the interference color observed from the membrane was black. It is impossible to see any variations in thickness across the membrane under these conditions with the naked eye. Fortunately, there is a solution to the problem of non-uniform membranes. This solution will be given in the next section to this chapter.

The next topic which should be touched upon is sensitivity of the device in imaging the pictures shown in Figures 7, 8, and 9. It has already been mentioned that the tip of the iron was measured at about
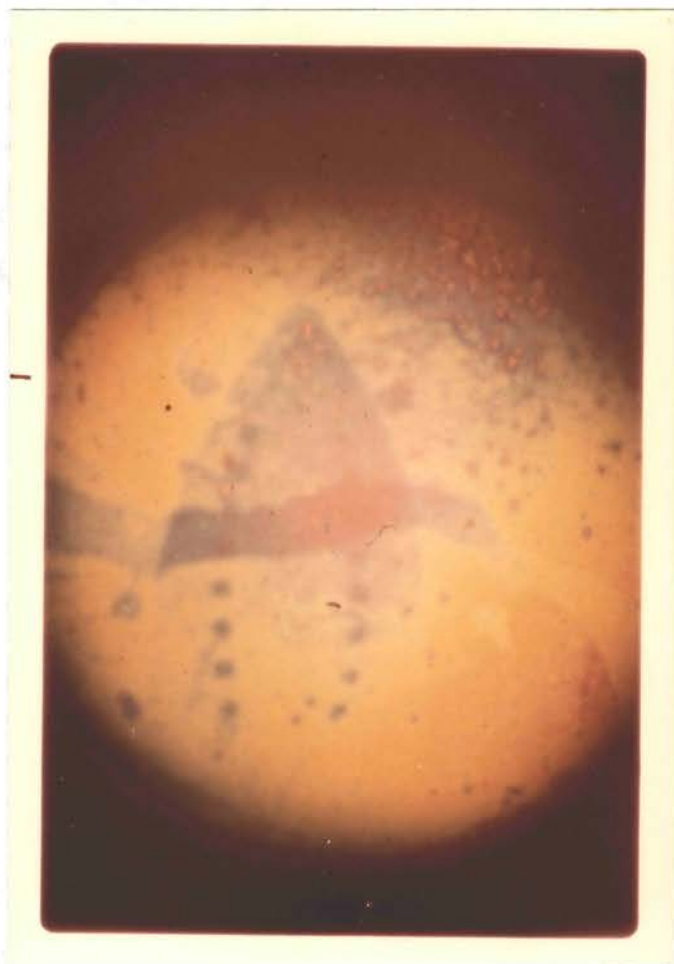
Figure 9.   Fifteen Percent Aluminum Film

240 degrees. The tip and the steam ports are obviously the hotter portions of the iron. An attempt was made at using the thermometer to measure various points across the surface of the iron, and as closely as could be measured the maximum temperature differential across the iron was about 25 degrees Fahrenheit. No numbers can be given to show exactly how small a temperature variation that the Evaporograph is indicating since there was no equipment available which could measure small temperature differentials. It was not really the intention to show how sensitive the device was under the conditions shown in the photograph. The pictures were chosen more to show the type of image one can expect from the Evaporograph and the problem associated with the membrane.

B. Recommendations and Conclusions

In Chapter II it was shown that the Evaporographic technique of infrared imaging could achieve a sensitivity of .1 degree centigrade with a 40-second exposure time. In those calculations it was assumed that the Evaporograph taking the image had an f:1.4 lens which passed 90 percent of the incident energy and an absorbing layer which absorbed 80 percent of the incident energy. It has also been shown that there are only two ways to improve the sensitivity and lessen the exposure time.

The first solution was to find an oil with a much smaller latent heat of vaporization. However, since no oil could be found which had a significantly lower latent heat than the oil in present use, more research is needed in this area.

The second way to improve the sensitivity was to be able to detect a smaller change in oil thickness. Baird-Atomic (12) had shown that

realistically only a 250 angstrom change could be detected, while

Kubota (11) indicated that a difference as small as 10 angstroms could

be detected. The factors which limit $\Delta d'$ to 250 angstroms were

variations of thickness in the oil film and variations of thickness in

the membranes. The variations in thickness of the oil film are related

to some degree to the imperfections in the membrane since any anomalies

no matter how small on the surface of the membrane will make the oil

film uneven. The membrane itself is, then, the primary cause of vari-

ations in thickness. This was shown very vividly in the picture of the

flat iron taken with the aluminum absorbing layer. These variations are

not readily observable with the eye since the membrane is less than 500

angstroms in thickness. Since the membrane is made by flotation of a

solution on water, it is very difficult to control the thickness. The

best solution to this problem is obviously to do away with the membrane.

Fortunately, this can be accomplished by using the absorbing layer

directly on the dielectric anti-reflection coating and letting the oil

condense directly upon the absorbing layer. Since the absorbing layer

is very uniform in thickness, there should be a significant increase in

sensitivity.

The other main problem with the evaporographic process was that the

thin nitrocellulose membrane was very susceptible to breakage. This

problem would also be solved to a great degree by utilizing the dielec-

tric anti-reflection layers since the structure is some 60 times thicker

than the membrane.

As the dielectric absorption layers added to the Evaporograph

should improve the performance of the device to a great degree, there is

another improvement which this researcher feels is necessary. This is,

a redesign of the basic Evaporograph cell. It will be remembered that the Baird-Atomic (12) cell was composed of twl halves which fit together with the membrane holder separating them. A manifold then joined the two halves, thus making entrance to the cell very difficult. This cell did have the advantage that the oil heater was external to the cell. The cell used in the research at Oklahoma State University and shown in Figure 2 had the advantage of easy access; but since it was constructed from one piece of brass, the oil heater had to be provided inside the cell. This is not desirable because it makes two more vacuum seals which must be used. The obvious solution of the problem is to use a cell similar in construction to that shown in Figure 10. An observation of the cell shows that it encompasses the advantages of easy accessibility to the interior of the cell and the advantage of an external oil heater. This is possible by constructing the cell out of two materials. The left half of the cell can be made from brass and the right half from plexi-glass or similar material. This allows the temperature differential necessary for operation since plexi-glass has a much lower thermal conductivity than the brass.

Another advantage of the construction is that there is only one "o" ring seal holding in the vacuum. All other seals in the cell are permanent. Both windows are put in permanently with epoxy since they should not have to be replaced. The plexi-glass to brass seals can also be made with epoxy with little difficulty.

It will be noticed that the use to have both windows inclined is eliminated by using the dielectric coating since there is very little reflection of the infrared energy from the right hand side of the dielectric layers and there is no transmission of the visible through

the absorption structure. For this reason the infrared window does not have to be inclined at an angle. On the other hand there is some infrared transmission through the absorption structure, hence the visible window is inclined at an angle of 15 degrees so that no reflections can get back to the absorbing layer.

It was mentioned earlier that the right hand side of the cell was constructed out of plexi-glass. The manifold structure as well as the visible window holder are also constructed out of this material. Since the emissivity of the infrared half of the cell should be at least .8 or higher, it is necessary to vacuum deposit a metallic layer on the inside of the side of the cell. The visible window holder should also have a vacuum deposited metallic layer to keep out stray light rays. The manifold structure needs no special treatment since it does not enter into the imaging process.

So far nothing has been said about the dimensions of the suggested cell. The drawing in Figure 10 is drawn to full scale and is thus shown actual size. The overall structure is about $3\frac{5}{8}$ inches long less the lens holder and is $2\frac{4}{10}$ inches in diameter not including the manifold structure. The absorption structure is only .8 inches in diameter in this cell as contrasted with $1\frac{1}{4}$ inches in the cell shown in Figure 2. The absorption structure was made smaller in this case only because the $f:1.4$ lens can be obtained in a 1-inch diameter with little difficulty.

Although the addition of the dielectric anti-reflection coating and the use of the suggested Evaporograph cell should improve the sensitivity of the device substantially, there are several areas of research which need to be explored further with the hope that the evaporographic method might be made still more sensitive. The first and primary area

Plexiglass

Plexiglass

Lens Holder

Oil
Blotter

Absorber

Germanium
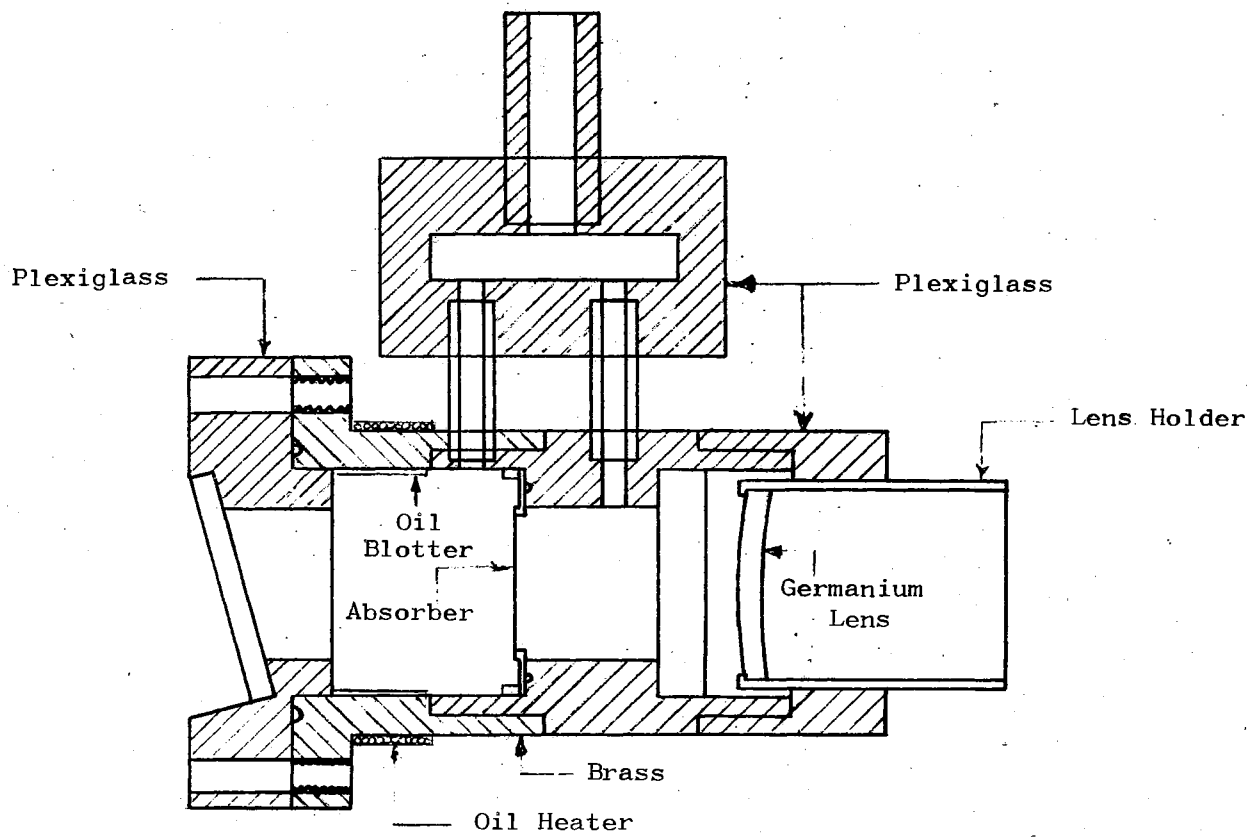Lens

— — Brass

— Oil Heater

Figure 10. Suggested Evaporograph Cell

of research should be the search for a new oil which has a lower latent heat of vaporization. The second objective should be to explore the use of dielectric reflection layers further in an attempt to find better synthesis techniques. It will be included that the procedure used in Chapter III used quarter wavelength layers and solved for the indices of refraction. This is a good method in that it is simple. The problem is that if a lower cutoff frequency of less than half the center frequency is desired one has to contend with a singularity at half the center frequency. It might be possible to devise a synthesis procedure which uses layers of known index of refraction and solves for the thickness of each layer than the quarter wave procedure. If, however, the singularity at the half frequency point could be alleviated, the addition of more layers would be worthwhile.

In addition to the study of better synthesis techniques, much research needs to be done on the absorption layer. As was discussed in Chapter IV, the absorption layer, which is metallic, is vacuum deposited upon the substrate. Unfortunately, the resistive characteristics of the film vary with the type of substrate upon which it is deposited (7). For example: A 50 angstrom film of gold deposited upon the nitrocellulose has an impedance of 189 ohms per square. A 50 angstrom film of gold upon the germanium dielectric layer will have a different impedance. Hence, there is a great need for research in the area of absorbing layers both in finding metals which can be used for absorption layers and the effects of substrate on the resistive properties of the absorption layers.

SELECTED BIBLIOGRAPHY

(1) Brown, J., F. J. Richards, and D. Saxon. "On Making Thin Nylon
        Films." Rev. Sci. Instr., Vol. 19 (1946), 818.

(2) Collin, R. F. "Theory and Design of Wide Band Multilayer Quarter
        Wave Transforms." Proceedings of the IRE (Feb., 1955), 179-
        185.

(3) Czerny, M. "Veber Photographic in Ultract." Zeitschrift for
        Physik, Vol. 53 (1929), 1.

(4) Czerny, M., and P. Mollet. "Neve Versuche Zer Photographic in
        Ultraoten." Zeits, Phys., Vol. 108 (1937), 85.

(5) Fujiwara, S. "Refractive Indies of Evaporated Cerium Dioxide -
        Sulfide Films." J. Opt. Soc. Am., Vol. 53 (1963), 1317-1318.

(6) Hadley, L. N., and D. M. Dennison. "Reflection and Transmission
        Interference Filters." J. Opt. Soc. Am., Vol. 37, No. 6
        (1947), 451-465.

(7) Heavens, O. S. Optical Properties of Thin Solid Films. New York:
        Dover Publications, 1964, 46-95 and 161-203.

(8) Harris, Louis, and T. T. McGinnis. "The Preparation and Optical
        Properties of Gold Blacks." J. Opt. Soc. Am., Vol. 38, No. 7
        (1948), 582-589.

(9) Herschel, J. F. W. Phil. Thans Roy. Soc. Lond., Vol. 130 (1840),
        52.

(10) Hilsum, C. "Infrared Absorption of Thin Metal Films." J. Opt.
        Soc. Am., Vol. 44, No. 3 (1954).

(11) Kubota, H., Ara, and H. Saito. "On the Sensitive Color of Chro-
        matic Polorization." J. Opt. Soc. Am., Vol. 41 (1951), 537.

(12) McDaniel, G. W., and David Z. Robinson. "Thermal Imaging by
        Means of the Evaporograph." Applied Optice, Vol. 1, No. 3
        (1962), 311.

(13) McDougal, J. R., and L. E. Walters. "Physio-Electrical Methods of
        Live Evaluation." 1971 SWIEECO Conference and Exhibition
        (April, 1971).

(14)   Swings, P. "The Evaporographic Method of Infrared Photography."
        Public. Astrom. Soc. Pac., Vol. 56 (1944), 220.

(15)   Taquet, Giselle. "Etude et Realization of D'un Evaporographe."
        Science Et Industries Photographiques, 2 Serie Tome 34 (1963),
        253-270.

(16)   Willenberg, H. "Ultrarotphotographie" Zeits Phys, Vol. 74
        (1932), 663-680.

(17)   Woltersdorff, W. "Uber die Optischem Konstanten dunner
        Metallschichten in Languelligen Ultrarot." Zeits Phys.,
        Vol. 91 (1934), 230.

(18)   Young, L. "Synthesis of Multiple Antireflection Films Over a
        Prescribed Frequency Band." J. Opt. Soc. Am., Vol. 51
        (1961), 962-974.

VITA

John Willard Hines

Candidate for the Degree of

Doctor of Philosophy

Thesis: AN OBJECTIVE STUDY OF THE EVAPOROGRAPHIC METHOD OF INFRARED
         IMAGING

Major Field: Engineering

Biographical:

    Personal Data: Born in Corpus Christi, Texas, December 26, 1944,
        the son of Mr. and Mrs. Willard V. Hines.

    Education: Graduated from John Marshall High School, Oklahoma City,
        Oklahoma in May, 1963; received the Bachelor of Science degree
        in Electrical Engineering from Oklahoma State University on
        July 28, 1967; received the Master of Science degree in Elec-
        trical Engineering from the University of Pittsburgh in
        August, 1968; completed requirements for the Doctor of Philos-
        ophy degree at Oklahoma State University, with a major in
        Electrical Engineering, in May, 1973.

    Professional Experience: Graduate Research Assistant on NASA pre-
        doctoral fellowship at the University of Pittsburgh School of
        Electrical Engineering August, 1967 to August, 1968; Research
        Engineer at the Westinghouse Research and Development Center
        September, 1968 to January, 1969; Graduate Research Assistant,
        Oklahoma State University School of Electrical Engineering,
        January, 1969 to May, 1972; Member of Engineering Staff with
        The Boeing Company August, 1972-present.