GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: June 30, 1972

Project Title: Heat Pipe Cooled Microwave Window

Project No.: A-1434

Project Director: Mr. H. L. Bassett

Sponsor: U. S. Army SAFEGUARD System Command

Effective June 7, 1972 Estimated to run until: October 6, 1972 (End Work Period)

Type Agreement: Contract No. DAHC60-72-C-0144 Amount: $ 5,491 *

* Project includes sub - project E-25-627 (GE) budgeted for $6,461 with Dr. G. T. Colwell, Principal Investigator. Total Contract Estimate is $11,952.

REPORTS REQUIRED: Monthly Progress Letters; Final Technical Report

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Defense Priority Rating: DX-A2 under DMS Reg. 1.

Assigned to Special Techniques Division

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GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT TERMINATION

Date 1/25/73

PROJECT TITLE: Heat Pipe Cooled Microwave Window

PROJECT NO: A-1434 (Includes sub-project E-25-627)

PROJECT DIRECTOR: Mr. H. L. Bassett

SPONSOR: U. S. Army SAFEGUARD System Command

TERMINATION EFFECTIVE: 12/6/72 (Contract Expiration)

CHARGES SHOULD CLEAR ACCOUNTING BY: 12/31/72

Contract Closeout Items Remaining: Final Invoice & Closing Documents
Final Report of Inventions
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Georgia Tech Project A-1434

ITEM	MONTH					
	June	July	August	September	October	November
Examination, Evaluation, and Selection of Dielectric Materials						
Selection of Working Fluid						
Initial Design of Microwave Window						
Complete Design and Fabricate Heat Pipe						
Testing and Evaluation of a Design						
Submit Progress Reports						
Write and Submit Final Report						

Scheduled Event

Time Span

Completed Event

EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

17 July 1972

Director
U. S. Army Advanced Ballistic Missile Defense Agency
Huntsville Office
Attn: RDMH-D
P. O. Box 1500
Huntsville, Alabama 35807

Subject: Monthly Letter Report, "Heat Pipe Cooled Microwave Window,"
Contract DAHC60-72-C-0144, Georgia Tech Project A-1434,
Period covering 7 June 1972 to 6 July 1972

Gentlemen:

The research has been, in general, divided into two areas - the determination of a compatible heat pipe working fluid and the investigation of waveguide windows. A number of fluids have been considered which have acceptable microwave transmission properties in addition to acceptable heat transfer properties. Fluids under consideration are tetrachloraethylene, Freon 112, Freon 12, Freon 21, Freon 22, Kerosene, Napthalene, and Heptane. Wick materials are also being studied. Some wetting experiments are now in progress in an attempt to determine the compatibility of candidate wick materials and working fluids. Two of the wick materials undergoing wetting tests are Boron Nitride fibers and aluminum oxide fibers.

Microwave window measurements are being performed to determine spacing of the dual windows as a function of window element thickness and relative dielectric constant. Initial measurements have been made in S-band and X-band waveguide sizes using a plexiglass material. Candidate dry wick materials have been placed in the waveguide during these measurements. The dry wicks have shown very little effect on the transmission properties of the dual-window waveguide section.

Work will continue in the two areas described above. It is anticipated that ceramic windows will be fabricated and tested during the next reporting period. Additional property data will be found on fluids to determine applicability to the heat pipe cooled microwave window.

Respectfully submitted,

Harold L. Bassett
Project Director

Approved:

R. G. Shackelford
Associate Chief,
Special Techniques Division

ENGINEERING EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

August 16, 1972

Director
U. S. Army Advanced Ballistic Missile Defence Agency
Huntsville Office
Attn.: RDMH-D
P.O. Box 1500
Huntsville, Alabama 35807

Subject: Monthly Letter Report, "Heat Pipe Cooled Microwave Window," Contract DAHC60-72-C-0144, Georgia Tech Project A-1434, Period covering 7 July 1972 to August 1972.

Gentlemen:

The search for candidate working fluids for the heat pipe has continued. Some of the new fluids considered are water, acetone, carbon tetrachloride, and methanol. In addition, further studies have been conducted on the fluids mentioned in the previous monthly letter report. Based on theoretical computations it is predicted that an S-Band heat pipe cooled waveguide window will handle several hundred watts (thermal) with maximum temperatures near 500° F.

The mechanical design of a test rig has been initiated. This rig will be used to check the thermal performance of the window and also the microwave absorption characteristics.

An abundant supply of boron nitride fibers is on hand. Sources are being sought to spin and weave these fibers into a suitable wick structure.

Waveguide windows of slip-cast fused silica have been recently tested. The windows are 1/8-inch in thickness and are spaced approximately 15 cm apart for an optimum impedance match. This particular electrical model will be altered so that small wicks saturated with the proposed fluids can be mounted to the windows. Measurements will then be made to determine the microwave absorption of this particular cenfiguration. The very low thermal coefficient of expansion for slip-cast fused silica and its low loss characteristics make it a prime candidate for the window material. Of course, the final choice of a material will be based on its compatibility with the working fluid.

The progress to date indicates that the design of a heat pipe cooled microwave window is feasible. Although the thermal and electrical aspects of the design are being studied separately, it is felt that sufficient information is being obtained so that a practical working model might later be developed.

Respectfully submitted,

Harold L. Bassett
Project Director

Approved:

J. W. Dees, Chief
Special Techniques Division

ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

14 December 1972

Director
U. S. Army Advanced Ballistic
Missile Defense Agency
Huntsville Office
Attn: RDMH-D
P. O. Box 1500
Huntsville, Alabama 35807

Subject: Monthly Letter Reports 3, 4, & 5, "Heat Pipe Cooled Microwave Window", Contract DAHC60-72-C-0144, Georgia Tech Project A-1434, Period covering 16 August 1972 to 1 October 1972

Gentlemen:

During this reporting period, the mechanical design of a heat pipe test rig has been initiated. The rig will be used for testing thermal and microwave loss coefficients.

An unsuccessful effort has been made to locate a suitable adhesive for attaching the wick to the waveguide. Consideration is now being given to the use of a mechanical retainer to maintain good contact between wick and waveguide.

Calculations have been made on the microwave losses in a thin window placed across an S-band waveguide. Refer to Figure 1 and consider the dielectric window in the waveguide with the TE_{10} waveguide mode power incident on the Z = 0 face of the window. Assume that the waveguide is terminated in a matched impedance at Z > 10D so that only the transmitted wave exists for Z > D. The behavior of this structure inside the waveguide is equivalent to a TE wave (perpendicular polarization) incident on an infinite dielectric sheet at an angle

$$\theta = \sin^{-1}\left(\frac{\lambda_o}{2a\sqrt{\epsilon_1}}\right) ,$$

where

λ_o = free-space wavelength,

$\left(\lambda_o = \frac{29.97925}{f_{GHz}} \text{ cm}\right)$,

a = wide dimension of the rectangular waveguide, and

ϵ_1 = relative dielectric constant of air $\simeq$ 1.00.

Let $T_\perp$, $R_\perp$ be the voltage transmission and reflection coefficient, respectively, of the infinite sheet for a perpendicularly polarized ($E_\perp$ to plane of incidence) plane wave incident at angle θ. Refer to Figure 2.

Let P_i = power density (watts/m^2) of incident wave,

P_r = power density of reflected wave, and

P_t = power density of transmitted wave.

Then,

$$P_t = |T_\perp|^2 P_i ,$$

$$P_r = |R_\perp|^2 P_i .$$

But conservation of power requires

$$P_i = P_t + P_r + P_L ,$$

where P_L = power absorbed in lossy panel due to ohmic (tanδ) losses. (Actually, one should use power density in the Z-direction; but since the incident and transmitted waves are in the same direction, that step can be omitted.) Therefore, the fraction of the power absorbed by the panel in the waveguide case is

$$\frac{P_L}{P_i} = 1 - |T_\perp|^2 - |R_\perp|^2 ,$$

or, multiplying by 100%, gives % power absorbed:

$$\% \text{ power absorbed} = 100 \left(1 - |T_\perp|^2 - |R_\perp|^2\right) .$$

A computer program has been formulated in which the power absorbed has been computed for the single panel case and the following parameter values:

$\epsilon_r = 3.33$,

$\tan \delta = 0.002, 0.001, 0.0005$,

$f = 2.6$ GHz,

$D = 0.125$ inches, and

$a = 2.84$ inches.

The calculated values for the absorbed power are 0.1, 0.05, and 0.027 percents for the cases of tan δ described above. The value of 0.05 percent compares favorably with the value determined from the microwave handbook which is 0.03 percent for the normal incidence case and tan δ = 0.001. For all practical purposes, the power absorbed by the window will be 0.1 percent.

As an example of the improvement of heat transfer using a heat pipe cooled window versus the conventional window, theoretical computations have been made for an S-band heat pipe of about 15 cm length. Such a pipe operating with maximum temperature of 300°F would transfer about 200 watts while an ordinary window with this maximum operating temperature would transfer only about 7.5 watts. The loss coefficient was calculated to be 0.004 for the heat pipe and 0.001 for the window alone. Thus the tube power with maximum window temperature of 300°F would be 50 kW average for the heat pipe design and 7.5 kW average for the conventional design. These computations assume that water is the working fluid in the heat pipe and that the waveguide temperature is 70°F. The water vapor film thickness used in the calculations is 0.0075-inch. Assuming that a more appropriate working fluid is found, the power handling capability of the heat pipe would be much greater than these calculations show.

It is understood after contacting the microwave personnel at the Varian Corporation that the high power operating windows in use today actually perform with a loss coefficient of 0.001. Due to heat transfer by both conduction and radiation, the windows can be designed to operate with 500 kW average incident power in the S-band frequency region. Thus, one might conclude from the data presented herein that the conventional window is by far the most practical method of sealing a waveguide. But, two arguments should be presented in favor of the heat pipe:

(1) the calculations for the heat pipe are based on heat transfer by the working fluid only, and

(2) the literature has not been sufficiently scanned to determine the optimum working fluid.

A considerable effort has been made to determine the loss characteristics of typical heat pipe working fluids, but these data are not readily available. It is contended that the microwave heat pipe dual waveguide window is a useful device that needs more than a cursory glance into its applicability. Hopefully, two additional phases of this program might be funded. The first phase would be devoted to gathering data on candidate working fluids. The second phase should allow sufficient time to build and test at least one heat pipe design. This seems very logical since verifications could then be made with the theoretical calculations to nail down the validity of a high power heat pipe design.

Respectfully submitted,

Harold L. Bassett
Project Director

Approved:

J. W. Dees, Chief
Special Techniques Division

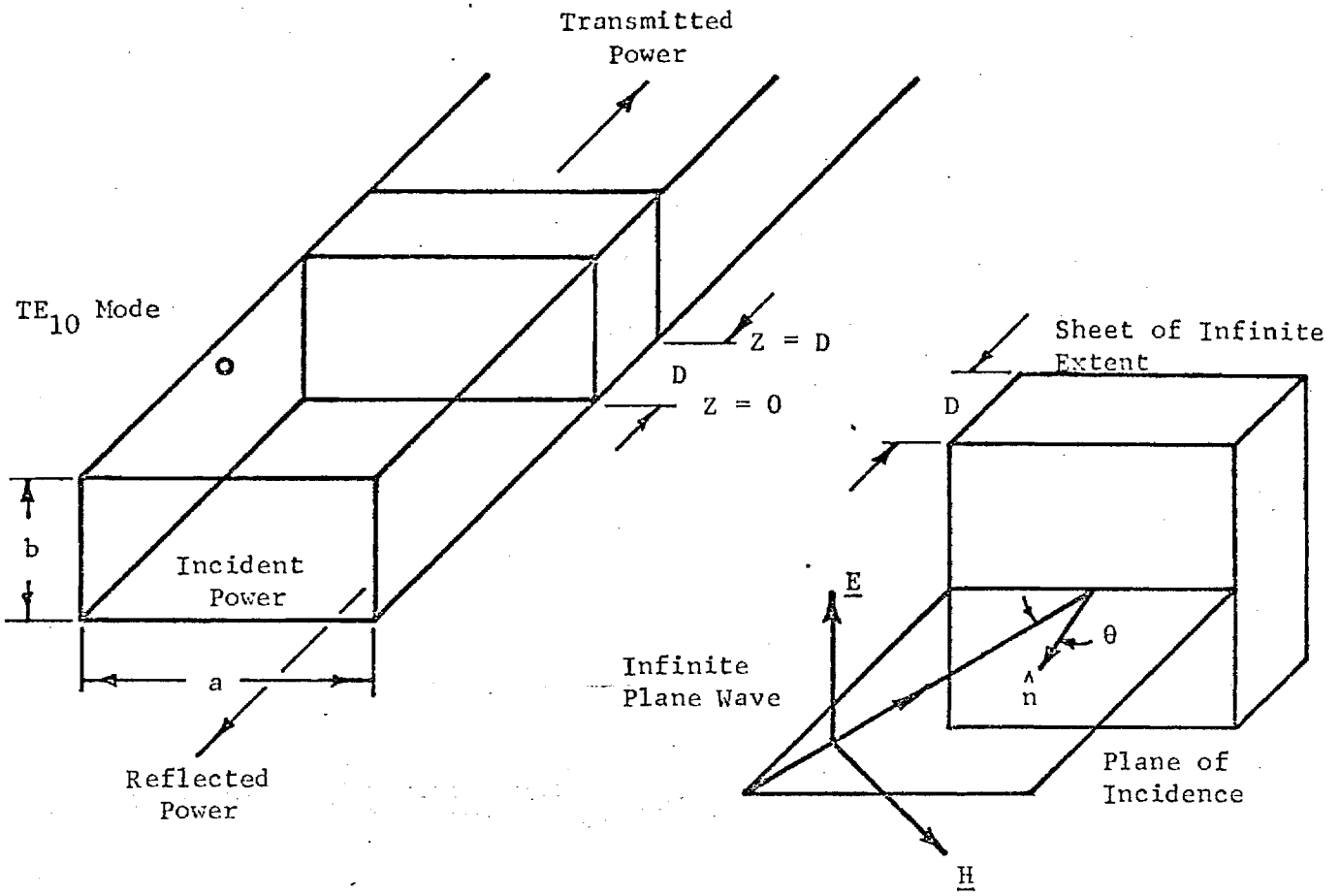

Figure 1. Waveguide and Window Nomenclature.

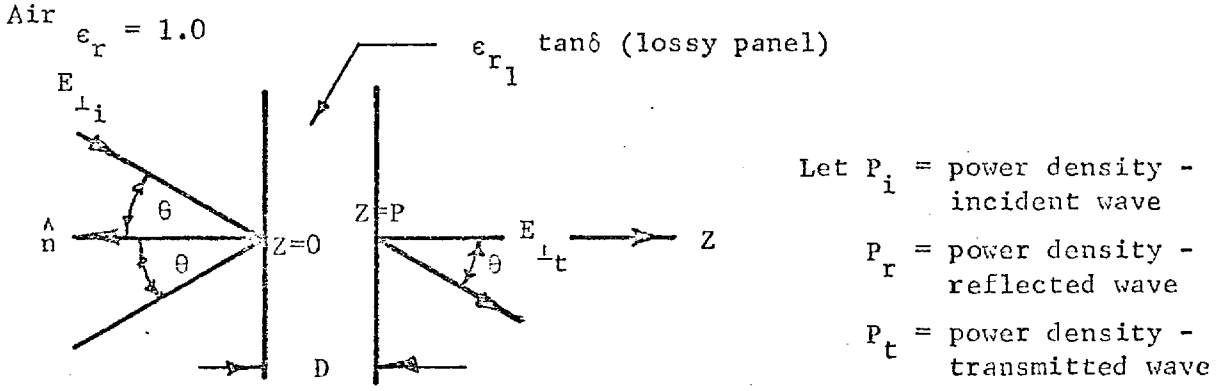

Figure 2. Description of Terms - Panel Transmission.

A-1434

HEAT PIPE COOLED MICROWAVE WINDOW

by

Harold L. Bassett, Engineering Experiment Station

Gene T. Colwell, School of Mechanical Engineering

January 1973

FINAL REPORT

on

Georgia Tech Projects A-1434 and E25-627

Prepared for

U. S. Army Ballistics Missile Defense Agency

Huntsville, Alabama 35807

Contract No. DAHC60-72-C-0144

1973

GEORGIA INSTITUTE OF TECHNOLOGY

Atlanta, Georgia 30332

HEAT PIPE COOLED MICROWAVE WINDOW

By

H. L. Bassett and G. T. Colwell
Georgia Institute of Technology
Atlanta, Georgia 30332

For

U. S. Army SAFEGUARD System Command
Huntsville, Alabama

Contract No. DAHC60-72-C-0144
Georgia Tech Projects A-1434 and E-25-627

January 1973

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ABSTRACT

The research performed to determine the feasibility of the design of a heat pipe cooled microwave window system is described in this report. The thermal analysis of heat pipes is presented as well as the electrical design of a waveguide structure.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

The research program addressed is the design feasibility of heat pipe cooled microwave windows. The program has progressed in two separate phases: one being directed toward the investigation and the study of appropriate heat pipe designs and the second concerned with the electrical design of the microwave windows and associated structure. Each of these phases will be discussed and it will be shown that feasibility of the concept has been established.

II. PROGRAM GOALS

The program to evaluate the feasibility of the heat pipe cooled microwave window has been directed toward the following goals:

(1) examination, evaluation and selection of suitable dielectric materials for the windows,

(2) examination, evaluation and selection of the proper fluid to be used in the heat pipe,

(3) study and evaluation of the RF heat loss distribution across the dielectric window,

(4) selection, design, and evaluation of the capillary pumping mechanism of the heat pipe,

(5) RF electrical design of the window, and

(6) an overall design of the heat pipe cooled microwave window.

Each of these goals is discussed somewhat in the following two sections.

III. THERMAL CONSIDERATIONS

A. Heat Pipe Limits

There are several factors which may limit heat pipe operation. The most common maximum is called a "wicking limit". This occurs when the capillary structure pumps fluid at its maximum rate. Any attempt to operate the device at higher heat fluxes will result in drying of the wick and consequent failure.

In some high power heat pipes—liquid metal working fluids—vapor velocities may become very high and even reach sonic velocity. When this occurs, "choking" results and no increase in vapor mass flow is possible; and hence, no increase in transferred energy is possible. The "entrainment limit" refers to a condition where liquid in the capillary structure is sheared out of the structure by high vapor velocities.

Another condition which may limit operation is boiling in the evaporator. Normal operation calls for conduction of the heat through the wick and working fluid and evaporation from the surface of the wick at the liquid-vapor interface. When the evaporator is subjected to extremely high radial fluxes, boiling may occur and then the normal heat pipe cycle may become unstable.

For most heat pipe designs, the wicking limit determines the maximum heat transfer rate. Several investigators have studied this wicking limit and proposed mathematical expressions for predicting it.

Kunz [1] proposes a simple expression which has been verified by experiment.

$$Q_{max} = \left(\frac{\rho_\ell \sigma h_{fg}}{\mu_\ell}\right)\left(\frac{b\delta}{1}\right)\left(\frac{1}{K_1(2\ell_{eff})r_{min}}\right) \quad , \tag{1}$$

where

ρ_ℓ = density of liquid,

σ = surface tension,

h_{fg} = heat of vaporization,

μ_ℓ = liquid viscosity,

b = circumference to mid-point of wick,

δ = thickness of wick,

K = wick friction factor,

ℓ_{eff} = effective length of liquid path, and

r_{min} = minimum radius of liquid-vapor interface (equals wick pore radius).

The first term in the equation is determined completely by working fluid properties while the last two terms are determined by wick geometry. As an example, consider the heat pipe shown in Figure 1. The Kunz equation predicts that this heat pipe, with water as the working fluid, will reach a wicking limit of 1708 $\frac{BTU}{HR}$ when the vapor temperature is 305°F and 765 $\frac{BTU}{HR}$ when the vapor temperature is 100°F. The wicking limit at 305°F corresponds to 35,800 $\frac{BTU}{HR\text{-}ft^2}$ based on evaporator area. This flux is much below typical nucleate boiling burnout fluxes for saturated water. Giedt [2] reports that nucleate boiling begins at about 10,000 $\frac{BTU}{HR\text{-}ft^2}$ and that burnout occurs at about 300,000 $\frac{BTU}{HR\text{-}ft^2}$ for saturated water boiling on a platinum wire. Conditions in the heat pipe are quite different from those on the wire. However, it is clear that the wicking limit for this heat pipe is considerably below a boiling burnout condition.

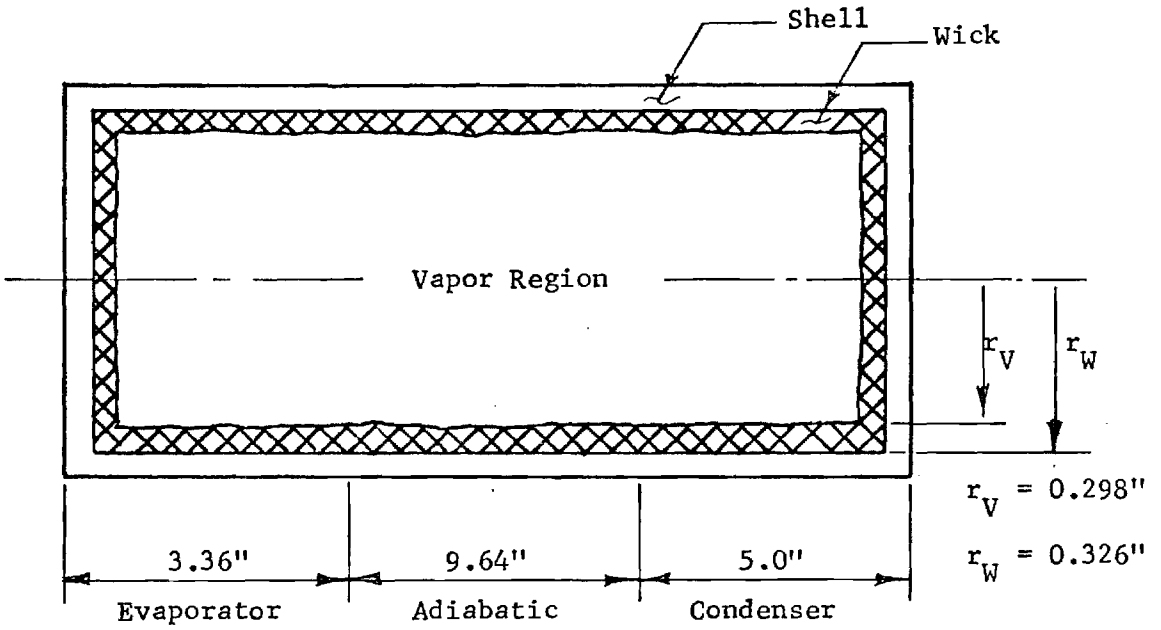

Figure 1. Sketch of a Conventional Heat Pipe.

Wicking limit is of course strongly a function of the working fluid. For example, the wicking limit for the above heat pipe operating with sodium would be about 5100 $\frac{BTU}{HR}$ at 1300°F and operating with ammonia would be about 150 $\frac{BTU}{HR}$ at -100°F.

Consider the proposed heat pipe cooled microwave window as shown in Figure 2. Assuming that the wick consists of two layers of 100 mesh screen (0.028 "thick"), that water is the working fluid, and that the vapor temperature is 300°F, the wicking limit is roughly 2600 $\frac{BTU}{HR}$ or about 42,000 $\frac{BTU}{HR\text{-}ft^2}$ at the evaporator surfaces.

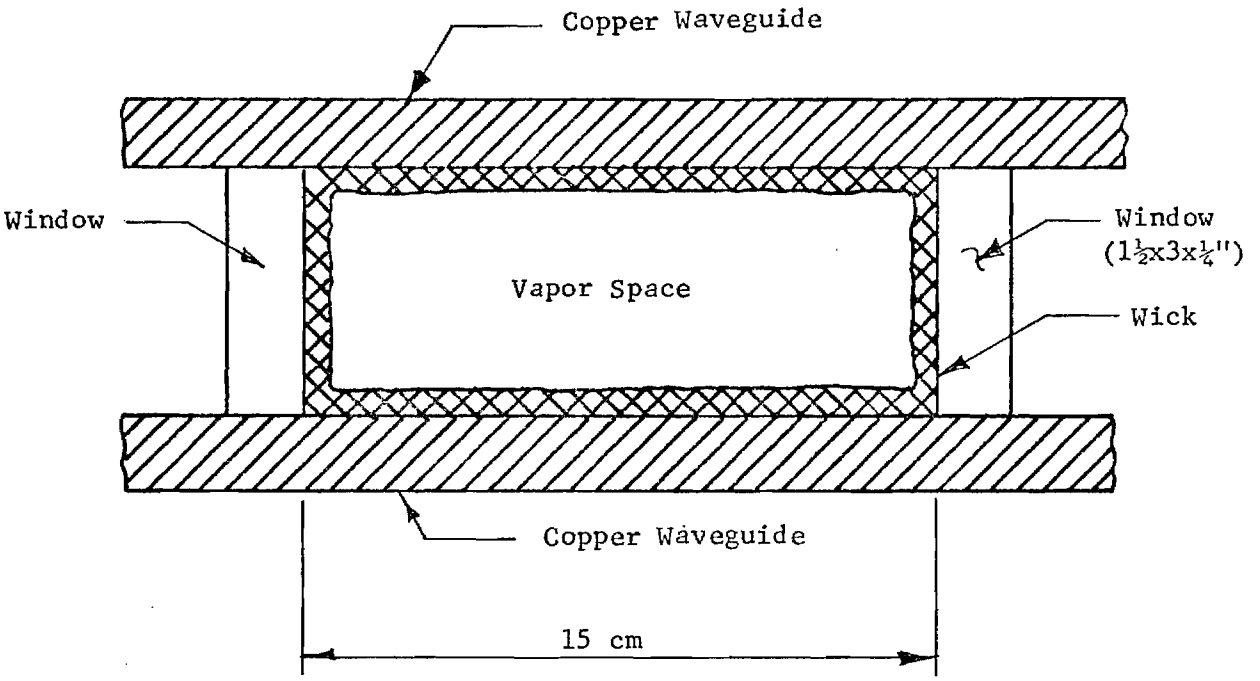

Figure 2. Sketch of Proposed Heat Pipe Cooled Microwave Window.

B. Normal Heat Operations

Heat pipes do not normally operate at their wicking limit. Figure 3 shows qualitatively heat flux as a function of vapor temperature.

We now consider computation of parameters at heat fluxes below the wicking limit. A sketch for the momentum balance is shown in Figure 4. The momentum balance takes the form

$$|P_{E\ell} - P_{EV}| = |(P_{EV} - P_{CV}) + (P_{CV} - P_{C\ell}) + (P_{C\ell} - P_{E\ell})| \ , \qquad (2)$$

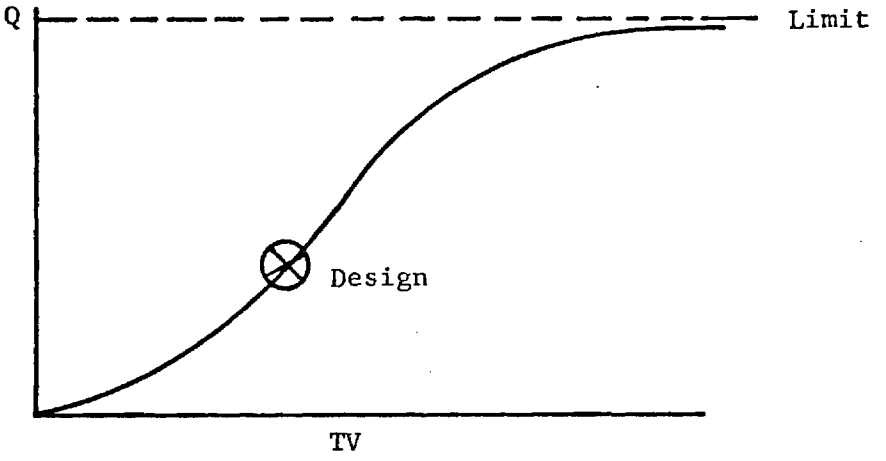

Figure 3. Heat Flux as a Function of Vapor Temperature.

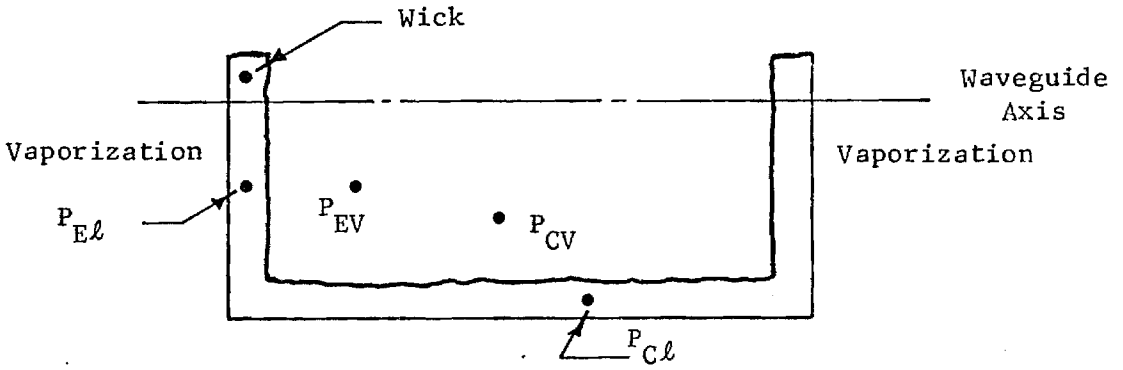

Figure 4. Sketch Indicating Momentum Balance.

where

$P_{E\ell} - P_{EV}$ = the capillary pressure rise,

$P_{EV} - P_{CV}$ = pressure drop in vapor region,

$P_{CV} - P_{C\ell}$ = pressure drop across liquid vapor interface, and

$P_{C\ell} - P_{E\ell}$ = pressure drop along liquid flow path.

A sketch which shows parameters in the energy equation is given in Figure 5.

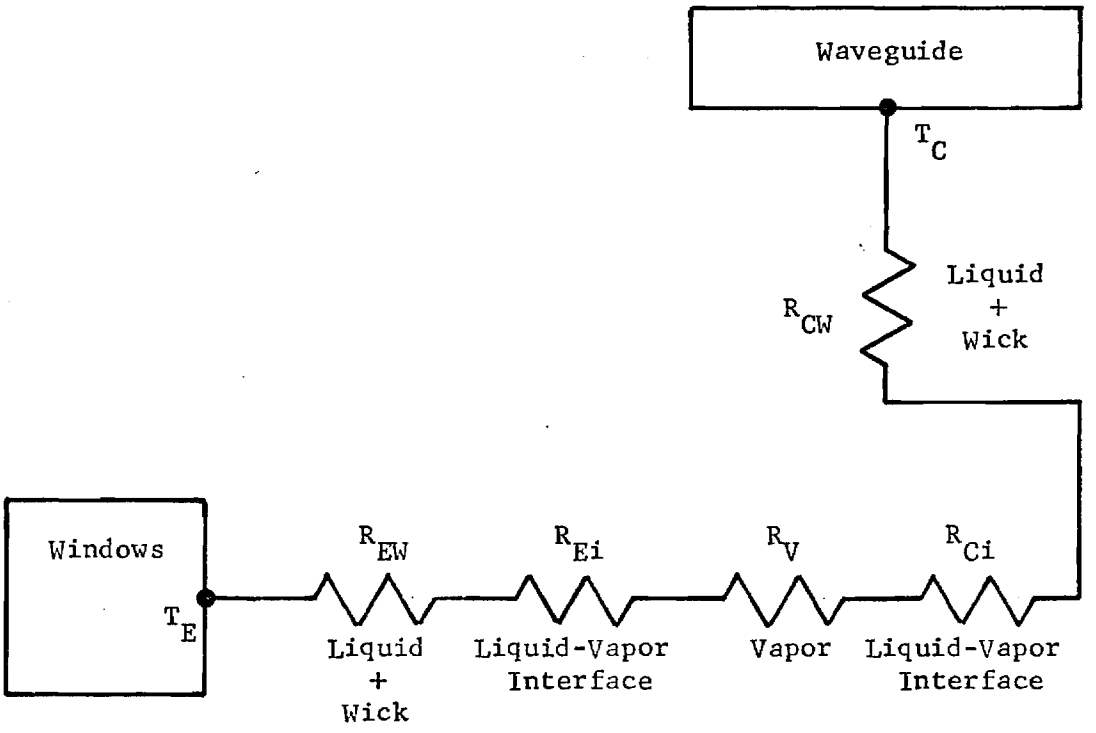

Figure 5. Sketch Showing Energy Equation Parameters.

The heat transfer is

$$Q = \frac{T_E - T_C}{R_{EW} + R_{Ei} + R_V + R_{Ci} + R_{CW}} \quad . \tag{3}$$

For the proposed heat pipe, interfacial resistances (R_{Ei} and R_{Ci}) and vapor resistance are quite small. Thus the major resistances are due to conduction across the wick-working fluid combination at the evaporator and the condenser.

$$Q = \frac{T_E - T_C}{R_{EW} + R_{CW}} \quad , \tag{4}$$

or

$$Q = \frac{T_E - T_C}{\frac{1}{A_E} + \frac{1}{A_C}} \left[\frac{k_{eff}}{\delta}\right] \quad , \tag{5}$$

where

T_E = temperature on inside of window (window wick interface),

T_C = temperature on inside of waveguide inside,

A_E = inside surface area of windows,

A_C = inside surface area of waveguide,

k_{eff} = effective thermal conductivity of wick-fluid combination, and

δ = wick thickness.

The effective thermal conductivity of the wick depends upon wick geometry and conductivities of the liquid and the solid material. It may be computed by considering a combination of parallel and series resistances through the pores and layers.

Using water as a working fluid (with inside window temperature of 300°F), two layers of 100 mesh boron-nitride wick and assuming inside waveguide temperature to be 70°F gives a heat flux into the waveguide of about 680 $\frac{BTU}{HR}$. This gives an evaporator flux of about 11,000 $\frac{BTU}{HR\text{-}ft^2}$ which is far below the wicking limit. Thus, heat transfer is limited by the poor conductivity of the wick material.

For comparison, a computation was performed assuming a thin conventional window as shown in Figure 6 where heat can be transferred only by conduction through the window to the waveguide: a = 1.5", b = 0.75, t = ¼"

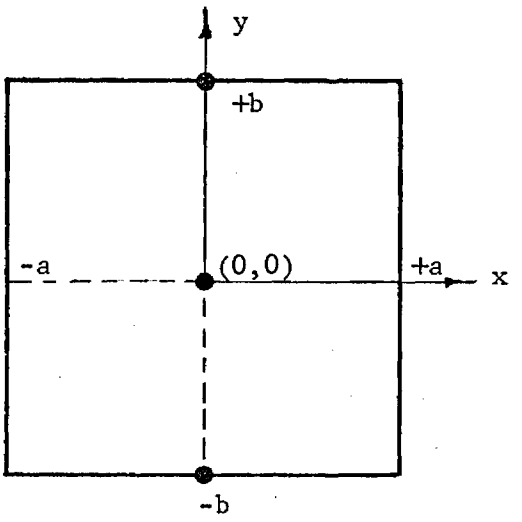

Figure 6. Conventional Thin Window Used in Computations.

(thickness). Assuming uniform signal loss (actually the loss is probably sinusoidal in one direction and uniform in the other), the temperature distribution is given by

$$T - T_W = \frac{A_o(a^2 - x^2)}{2K} - \frac{16\, A_o a^2}{K\pi^3} \sum_{n=o}^{\infty} \frac{(-1)^n \cos\left[(2n+1)\frac{\pi x}{2a}\right] \cosh\left[(2n+1)\frac{\pi y}{2a}\right]}{(2n+1)^3 \cosh\left[(2n+1)\frac{\pi b}{2a}\right]}, \quad (6)$$

where

T_W = waveguide temperature,

K = conductivity, and

A_o = signal power loss per unit volume.

The maximum temperature will occur at the center of the window (0,0). Results of the computations are

Max Window Temperature (^oF)	Heat Transfer (watts)
300	15
400	22
600	35
800	48
1,000	61
2,000	126

It is clear that the heat pipe will transfer much more energy than the conventional window under the assumed conditions.

C. High Temperature Windows

Both the heat pipe window and the conventional window have been considered under conditions which do not represent current "state-of-the-art". Temperatures are allowed to go much above 300°F and single plane windows are very thick which makes much higher heat dissipation possible. Thus, a heat pipe window system must be designed which operates at about 1000°F and has good thermal conductance in the wick and window. Water can not be used as a working fluid since it is unacceptable on two counts. At high temperatures, water has a high vapor pressure which would cause structural problems. In addition, water has high loss characteristics when transmitting microwave signals.

A working fluid must be found which has a vapor pressure near one atmosphere at 1000°F, has good thermal conductivity, has a reasonable surface tension, and is a good transmitter of microwave signals. Much effort has already gone into the search for a suitable fluid. However, at this time the search is continuing. It is expected that the fluid or fluids which are finally selected will result from a compromise between heat pipe requirements and transmission requirements.

IV. ELECTRICAL DESIGN OF WAVEGUIDE WINDOW

A. Electrical Analysis

A computer program was developed in which calculations were made on the microwave losses in a thin window placed across an S-band waveguide of cross-section 3" x 1½". Refer to Figure 7 and consider the dielectric

window in the waveguide with the TE_{10} waveguide mode power incident on the $Z = 0$ face of the window. Assume that the waveguide is terminated in a matched impedance at $Z > 10D$ so that only the transmitted wave exists for $Z > D$. The behavior of this structure inside the waveguide is equivalent to a TE wave (perpendicular polarization) incident on an infinite dielectric sheet at an angle

$$\theta = \sin^{-1}\left(\frac{\lambda_o}{2a\sqrt{\epsilon_1}}\right) , \tag{7}$$

where

λ_o = free-space wavelength,

$(\lambda_o = \frac{29.97925}{f_{GHz}}$ cm),

a = wide dimension of the rectangular waveguide, and

ϵ_1 = relative dielectric constant of air $\simeq 1.00$.

Let $T_\perp$, $R_\perp$ be the voltage transmission and reflection coefficient, respectively, of the infinite sheet for a perpendicularly polarized ($E_\perp$ to plane of incidence) plane wave incident at angle θ. Refer to Figure 8.

Let P_i = power density (watts/m^2) of incident wave,

P_r = power density of reflected wave, and

P_t = power density of transmitted wave.

Then,

$$P_t = |T_\perp|^2 P_i , \tag{8}$$

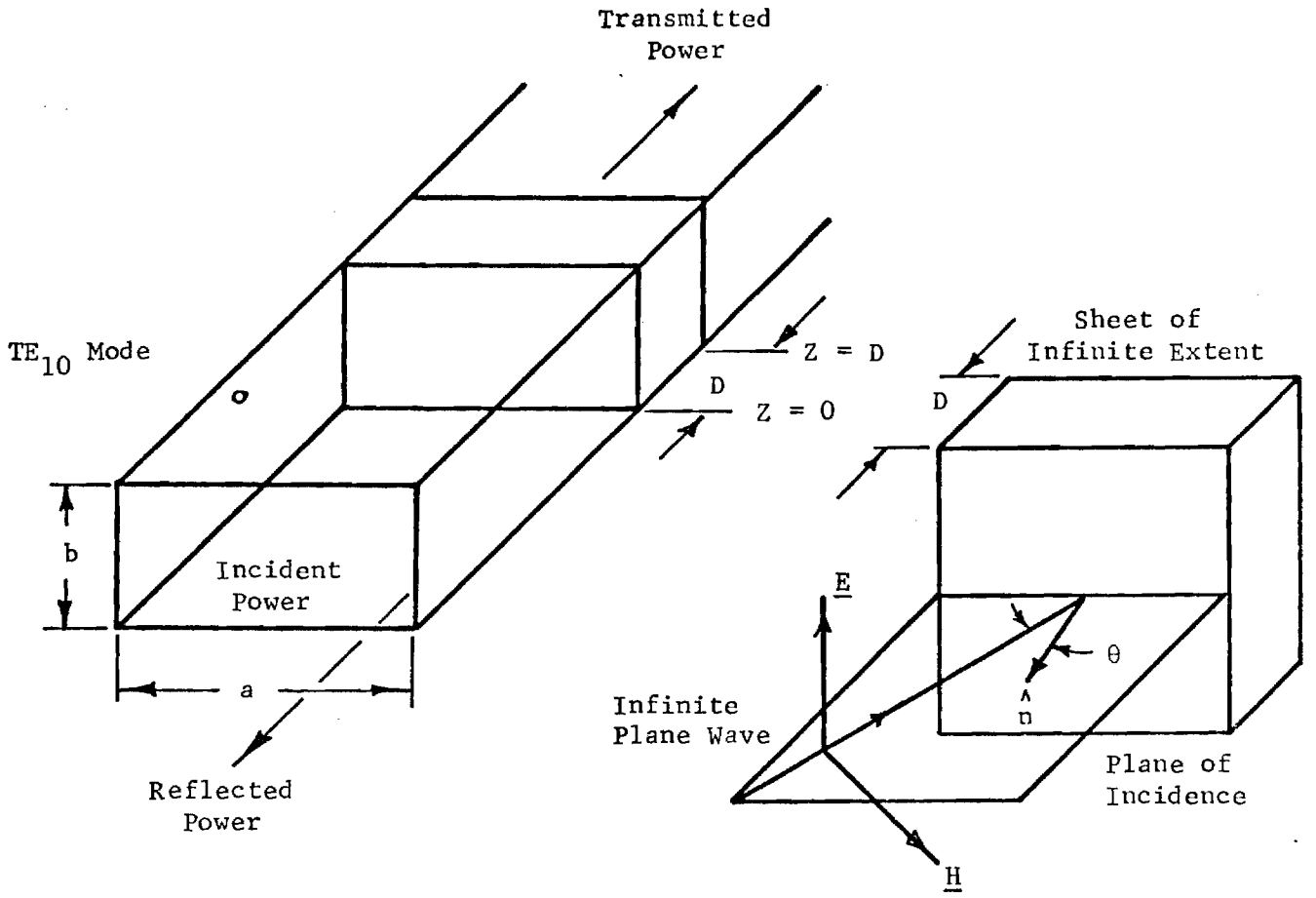

Figure 7. Waveguide and Window Nomenclature.

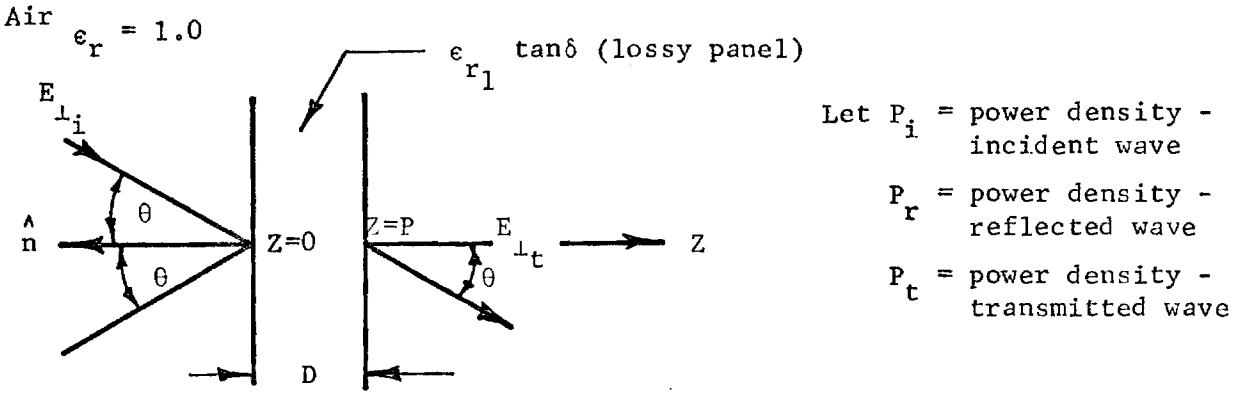

Figure 8. Description of Terms - Panel Transmission.

$$P_r = |R_\perp|^2 P_i \ . \tag{9}$$

But conservation of power requires

$$P_i = P_t + P_r + P_L \ , \tag{10}$$

where P_L = power absorbed in lossy panel due to ohmic (tanδ) losses. (Actually, one should use power density in the Z-direction; but since the incident and transmitted waves are in the same direction, that step can be omitted.) Therefore, the fraction of the power absorbed by the panel in the waveguide case is

$$\frac{P_L}{P_i} = 1 - |T_\perp|^2 - |R_\perp|^2 \ , \tag{11}$$

or, multiplying by 100%, gives % power absorbed:

$$\% \text{ power absorbed} = 100 \left(1 - |T_\perp|^2 - |R_\perp|^2\right) \ . \tag{12}$$

A computer program has been formulated in which the power absorbed has been computed for the single panel case and the following parameter values:

$\epsilon_r = 3.33$,

$\tan \delta = 0.002, 0.001, 0.0005$,

$f = 2.6$ GHz,

$D = 0.125$ inches, and

$a = 2.84$ inches.

The calculated values for the absorbed power are 0.1, 0.05, and 0.027 percents for the cases of tan δ described above. The value of 0.05 percent compares favorably with the value determined from the Microwave Handbook which is 0.03 percent for the normal incidence case and tan δ = 0.001. For all practical purposes, the power absorbed by the window will be 0.1 percent.

It is understood after contacting the microwave personnel at the Varian Corporation that the high power operating windows in use today actually perform with a loss coefficient of 0.001. Due to heat transfer by both conduction and radiation, the windows can be designed to operate with 500 kW average incident power in the S-band frequency region.

These calculations are used in the heat transfer analysis to determine the heat pipe operating temperatures. Typically, a beryllium oxide or an aluminum oxide window would have a loss tangent less than 0.0005.

B. Microwave Measurements

The dual window design concept was used to prove the feasibility of the heat pipe design configuration as described in Enclosure A of the Scope of Work SW-A-80-72. The particular window material used in the VSWR measurements was slip-cast fused silica. It is proposed that a material such as beryllium oxide, aluminum oxide, or fused quartz be used in a working heat pipe model.

The VSWR measurements were made to determine the optimum spacing of the two windows for maximum RF power transmission. This spacing then will provide the minimum VSWR, which is of prime interest since the windows

will be used with a high power RF tube. The spacing for minimum VSWR was $\lambda_g/4$. For the design considered, it was decided to use the $3\lambda_g/4$ spacing, since this would allow a needle valve and thermistor to be mounted between the windows and also would allow sufficient space to have a joint between the windows. See Figure 9 for a view of the microwave model.

The power transmission measurements indicated a negligible loss through the two slip-cast fused silica windows. Boron nitride fibers were placed across the inner surfaces of the windows and the windows were again positioned for a minimum VSWR and maximum power transfer. The additional loss due to the fibers was insignificant. It was later determined that these fibers do not easily "wet", so the type of wick material to be used has not been determined. This material will depend on the choice of the working fluid.

Some measurements were performed using windows that were coated with a very thin layer of distilled water. The measurements showed a slight loss in transmitted power. These measurements were performed because it was felt at that particular time that a working heat-pipe should be developed. It was felt later that the use of water would create more problems than it would solve, and this approach was finally abandoned.

The results of the microwave measurements supported the view that two thin windows placed a $\lambda_g/4$ apart or $3\lambda_g/4$ apart would act as a transmission line matching network. The measurements also indicated that the addition of the wick material did not disturb the relatively good impedance match of the dual-window system.

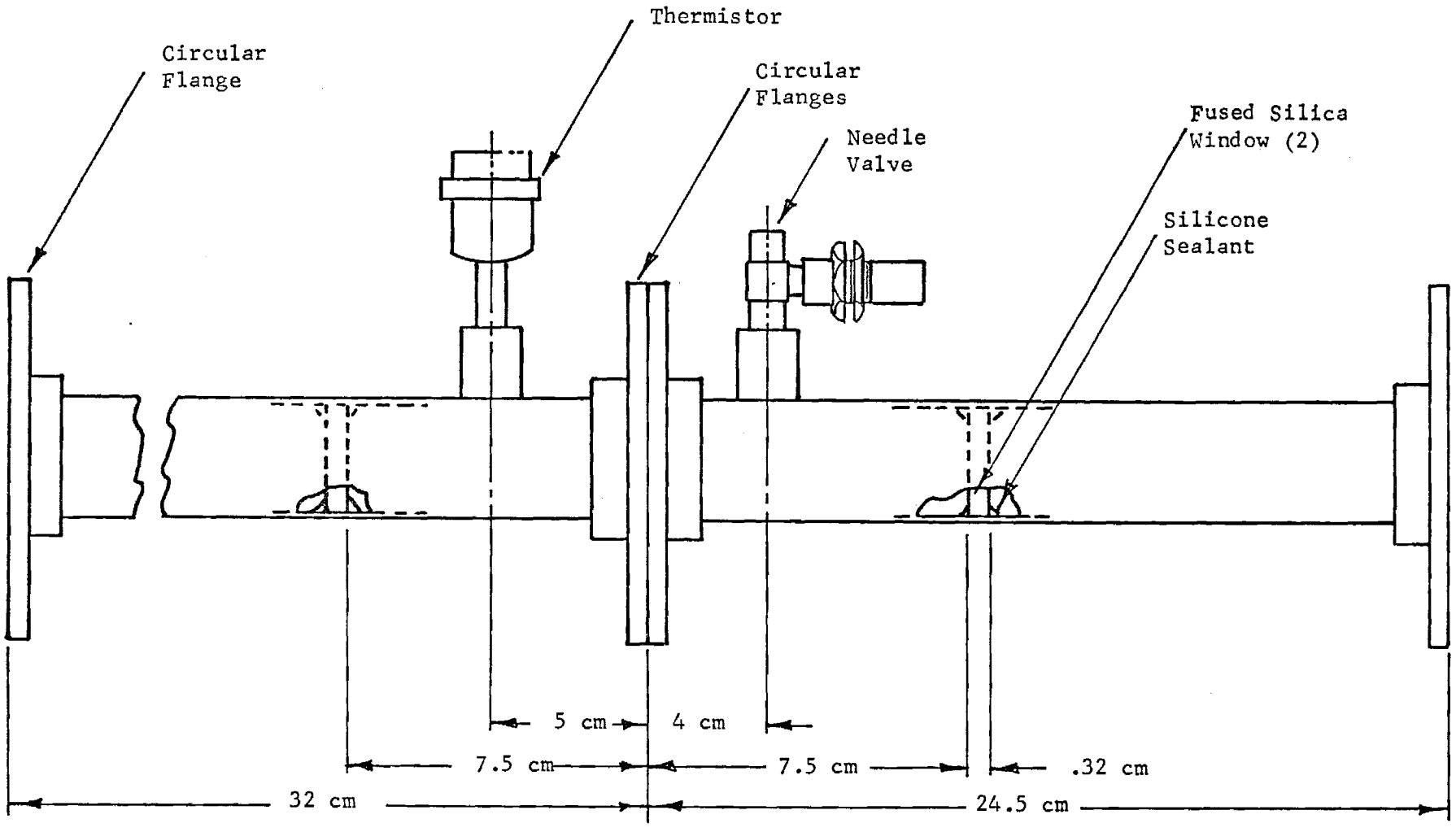

Figure 9. Sketch of S-Band Waveguide RF Absorption Test Unit.

V. CONCLUSIONS AND RECOMMENDATIONS

The work performed to date has yielded information which encourages the investigators to continue the project. Some difficult problems must yet be solved before a heat pipe cooled window can be placed in regular service. However, based on this preliminary work, it is expected that such a device may in fact exhibit a number of advantages over a conventional window. The impedance matching properties of the dual window is a definite plus. Once a suitable working fluid is selected, it is felt that higher average power ratings will be obtained with the heat-pipe cooled windows. At given power levels, the dual windows will operate at a constant temperature. In addition, one has a much wider range in the choice of window materials. Thus, beryllium oxide which is in current use and which poses a health hazard in the machining process would not necessarily be used.

It is felt that additional work should be concentrated in this area. First, a working fluid compatible with microwave transmission must be found. Considerable effort has been spent in finding a fluid but, as yet, the fluid with the desired characteristics has not been found. Once a desirable fluid is found, an operating heat-pipe should be assembled and tested. Since "high average power" seems to be the main design goal, the heat-pipe would be designed to operate at the high power levels. In addition, some effort should be devoted to metallic loading of the window material. This would increase the heat conduction along the Z-axis toward the heat pipe and would result in a more efficient device.

In summary, the following steps are required to complete the heat-pipe cooled waveguide window:

(1) find better working fluids,

(2) increase the heat conductance of the window in the Z-direction, and

(3) assemble and test an operating heat-pipe window design.

VI. REFERENCES

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