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PHASE 2

ARRAY AUTOMATED ASSEMBLY TASK

LOW COST SILICON SOLAR ARRAY PROJECT

QUARTERLY TECHNICAL REPORT No. 8

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PREFACE

The information presented in this report for Phase 2 of the Array Automated Assembly Task (second part), represents the work performed from October 1979 through December 1979 by Sensor Technology, Inc.,* located in Chatsworth, California. This program was directed by Sang S. Rhee. Principal contributors include Gregory T. Jones, Kimberly L. Allison and Sanjeev R. Chitre. Also contributing to the microwave applications is Harold Braus from Cober Electronics Inc., Stamford, Connecticut.

The JPL Technical Program Manager during this quarter was Clay Olson.

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* Sensor Technology, Inc., is a wholly owned subsidiary of Dyneer Corporation, Westport, Connecticut. The solar energy division of Sensor Technology has become a subsidiary with the name of Photowatt International Inc.

ABSTRACT

Several microwave systems for use in solar cell fabrication were developed and experimentally tested this quarter. The first system used a standing wave rectangular waveguide horn applicator. Satisfactory results were achieved with this system for impedance matching and wafer surface heating uniformity. The second system utilized a resonant TM_{011} mode cylinderical cavity. This particular system cannot be employed due to its poor energy coupling efficiency. The third and fourth microwave systems utilized a circular waveguide operating in the TM_{01} mode exciting a conical horn and a circular waveguide operating in a cross-polarized TE_{11} mode exciting a conical horn respectively. Both systems have potential for producing good wafer surface heating uniformity. A fifth microwave system utilized a fringe field applicator which offers a possibility for control of the microwave energy penetration depth and would, therefore, be suitable for shallow heating. This system had difficult problems with impedance matching, efficiency and field uniformity. An alternate method for controlling the depth of wafer heating is being considered.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Investigation continued this quarter on five microwave systems for use in solar cell fabrication (see Quarterly Reports November 6 and 7 for initial work). The first system utilized a standing wave rectangular waveguide horn applicator with one or two silicon wafers perpendicular to the direction of wave propagation. The second system utilized a resonant TM_{011} mode cylidrical cavity with the silicon wafer parallel to the direction of wave propagation. The third and fourth microwave systems utilized a circular waveguide operating in the TM_{01} mode exciting a conical horn and a circular waveguide operating in a cross-polarized TE_{11} mode exciting a conical horn, respectively. The silicon wafers in both systems are perpendicular to the direction of wave propagation. A fifth microwave system utilized a fringe field applicator which offers a possibility of control of the microwave energy penetration depth and may be suitable for shallow heating. These systems are being developed and tested at low power (20W) to determine their potential for use in solar cell fabrication.

The basic problems encountered in all of these microwave system developments at this stage were: (1) impedance matching - so that possibly all the power delivered from the microwave source is dissipated in the processed wafer(s), and (2) wafer surface heating uniformity. There are no standard solutions ready to any of these problems, and various applicators tested provided varying degrees of success in meeting the requirements.

TECHNICAL DISCUSSION

A. Rectangular Waveguide Horn Applicator

(Experimental Results)

Initial experiments with the rectangular waveguide horn applicator shown in Figure 1 were encouraging (see Quarterly Report No. 7), and more complete tests followed to evaluate efficiency of the energy coupling (impedance matching) and the uniformity of the wafer surface heating. For this purpose a special jig was designed which allowed the positioning of one or two wafers at any distance d equal to 1.5 cm, to 4.5 cm, from the short circuit metal plate at the end of the horn (see Figure 1).

Figures 2 and 3 show the return loss as a function of frequency between 2.4 and 2.48 GHz for various distances d from the short circuit metal plate for one and two wafers respectively. The return loss is a measure of the reflected power through the following relationships:

$$\text{Return Loss} = 20 \log (|\Gamma|)$$

where Γ is the reflection coefficient, and the reflected power P_r is given by:

$$P_r = P_o \, |\Gamma|^2$$

where P_o is the incident power.

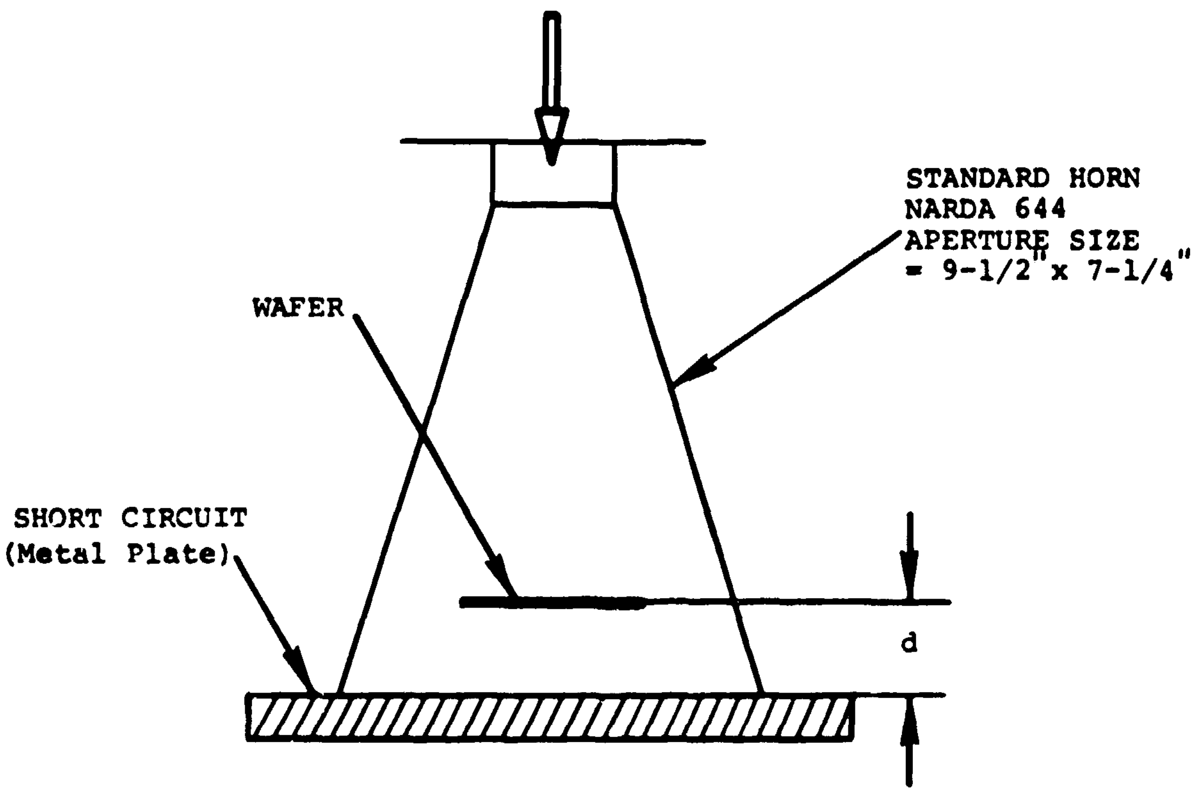


Figure 1: Schematic diagram of a rectangular horn wave guide.

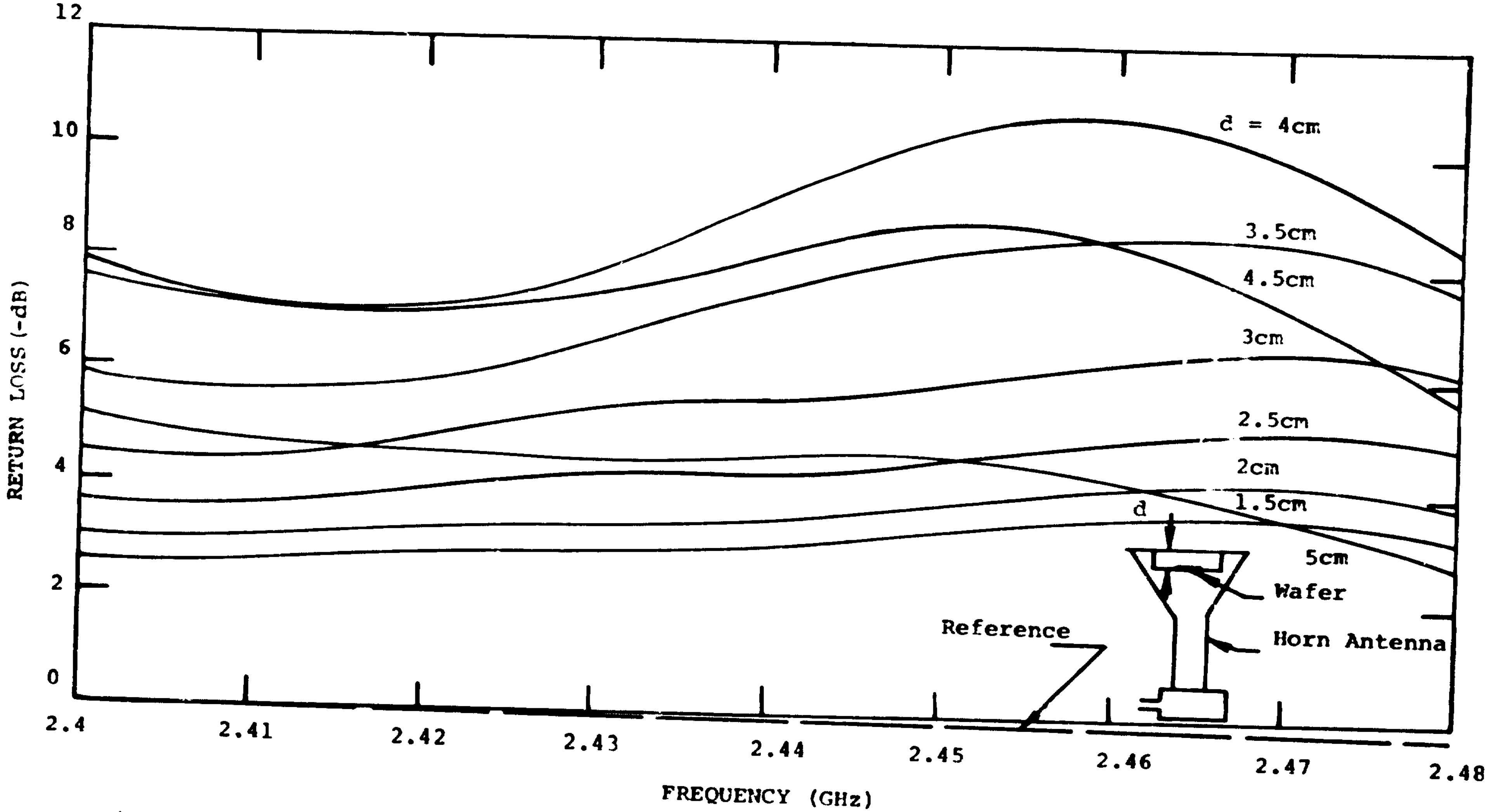


Figure 2: Impendance matching (return loss) for a single wafer for distances, d, from the short circuit metal plate to the wafer between 1.5cm and 5cm.

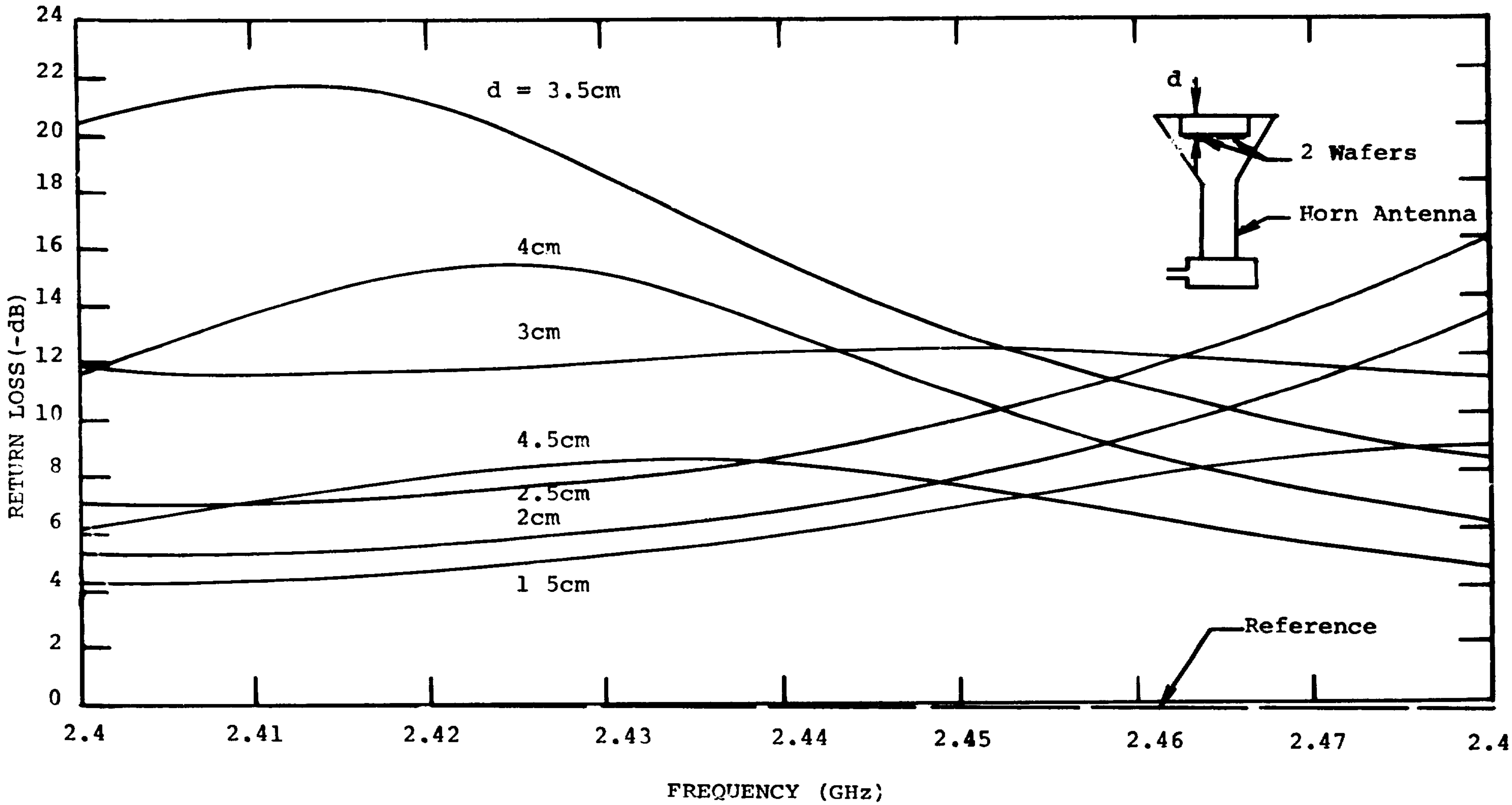


Figure 3: Impedance matching (return loss) for two wafers side by side for distances, d, from the short circuit metal plate to the wafer between 1.5cm and 4.5cm.

The results for one wafer are shown in Figure 2. The best impedance matching in the frequency range 2.4 - 2.5 GHz is for d = 4 cm. For this distance the reflected power is below 15% of the incident power within 2.45 $\pm$ 0.25 GHz, which is the frequency range of operation of the power source used in the heating experiments. For distances between 3.5 and 4.5 cm., the reflected power is below 25% of the incident power.

It can be seen from Figure 3 that smaller reflections are obtained for two wafers side-by-side. For d = 3 cm., the reflected power is less than 5% of the incident power at frequencies 2.45 $\pm$ 0.25 GHz, and for d = 2.5 - 3.5 cm, the reflected power is less than 15% of the incident power. The power reflections can be further decreased by designing a special matching network.

Heating uniformity was investigated for one and two wafers placed at different distances from the short circuited metal end plate in the applicator. To monitor the temperature wafers were coated with Parker liquid crystal ink (from Edmund Scientific Co.). The ink changed color from red to blue for the temperature difference of $1^{\circ}C$, between 35 and $36^{\circ}C$. The change in color from red through yellow to green corresponds to 0.5^{o}C. The heating was obtained with 25W at 2.45 GHz delivered to the applicator. Photographs were taken during the heating when the wafer temperature was reaching the range for which the liquid crystal was sensitive.

The best wafer surface heating uniformity for a single wafer was obtained for d equal to 1.5 cm, and 2 cm. Relatively poor impedance matching was obtained at these distances ($P_r = 0.3\ P_o$), however, improvement can be made by a modification of the applicator.

The best wafer surface heating uniformity for two wafers side-by-side was obtained for d equal to 2.5 cm, with only a slight deterioration at d equal to 3 cm. These distances coincide with those at which there is little reflection of the delivered power.

It can be concluded that the low power experimental results on the impedance matching and wafer surface heating uniformity for the waveguide horn applicator are satisfactory. Further experiments with the rectangular waveguide horn applicator at high power will be performed next quarter.

B. Cylindrical Cavity Applicator

(Development and Experimental Results)

A single mode TM_{011} cavity was selected (see Quarterly Report No. 7) as a potential applicator for heating silicon wafers. The distribution of the electric field in the resonator and the wafer placement are shown in Figure 4.

The heating rate is proportional to the power absorbed in the material, which in turn is proportional to the square of the electric field intensity:

$$\Delta T / \Delta t = k_1 P_A = k_2 E^2$$

where: $\Delta T/\Delta t$ is the sample heating rate, k_1, k_2 are the proportionality constants, P_A is the power absorbed, and E is the intensity of the field in the material. The heating profiles along the cavity radius at various points (z) along the cavity axis are shown in Figure 5. The electrical length of the cavity is $\lambda g/2$ (λg - wavelength in the cavity). It can be seen that at $z = \lambda g/8$ from the short circuit metal plate the power deposited in a thin layer of material remains nearly constant for the sample radius $r \leq r_o$, where r_o is the cavity radius. To satisfy this condition a cavity was designed to operate at 2.45 GHz with the dimensions shown in Figure 4, so that the

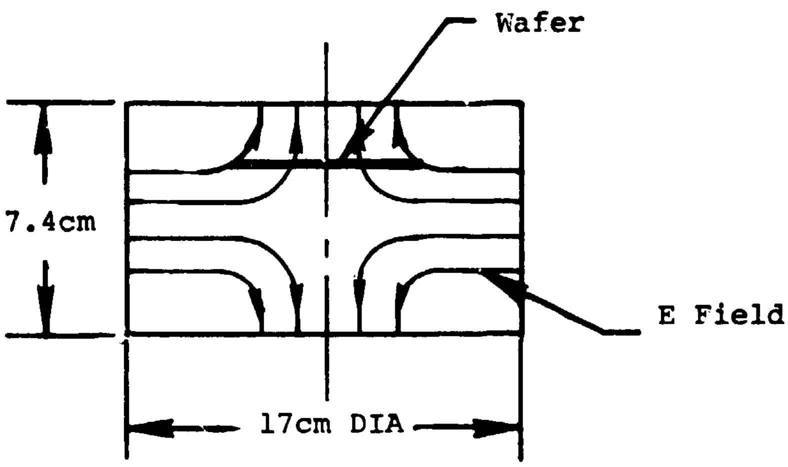


Figure 4: Cylindrical TM_{011} cavity with a single wafer.

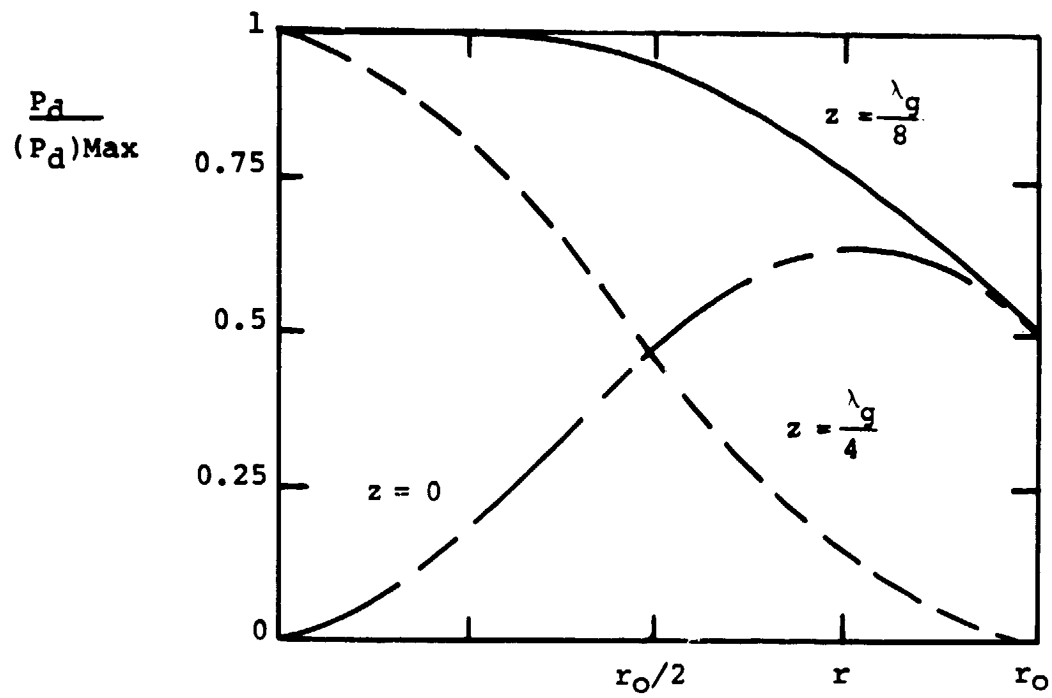


Figure 5: Normalized power distribution along the cylindrical cavity radius, TM_{011} mode.

wafer radius is about half of the cavity radius. The heating power was coupled by a loop located at the end opposite to the wafer. The wafer was located a quarter way from one of the ends (equivalent to $\lambda g/8$).

The empty cavity was tested and adjusted to operate at 2.45 GHz with a proper coupling. When the cavity was tested with a wafer, the electric field losses due to the wafer were too large, thus unacceptable. As a consequence, it became impossible to couple the power from the generator to the cavity.

In conclusion, the resonant TM_{011} configuration cannot be employed for heating of the silicon wafers due to it's poor energy coupling efficiency. The resonant configuration was initally preferred to a waveguide configuration due to its design simplicity.

The waveguide configuration will require special means to eliminate other propagation modes except the desired TM_{011}. However, since the TM_{011} mode provides potential for uniform heating applicators using it should not be excluded from further perusal.

C. Circular Waveguide and Horn Applicators

(Design and Development)

Low power experimental results on the impedance matching and silicon wafer surface heating uniformity for the rectangular waveguide horn applicator were given in Section A. To improve the heating uniformity the following structures were selected for further investigation:

(1) Circular waveguide operating in the TM_{01} mode.

(2) Conical horn excited in the TM_{01} mode.

(3) Circular waveguide operating in the fundamental mode (TE_{11}) withe cross-polarization or circular polarization.

(4) Conical horn excited in the TE_{11} mode; cross-polarized or circularly polarized.

A conical horn excited by either of the above two methods is expected to provide a significant improvement over a rectangular waveguide-horn applicator. Conical horn applicators will also be compatible with the high-power experimental arrangement previously designed for the rectangular horn applicator. Only minor mechanical modifications (additions) may be necessary to perform this task.

A transition from a rectangular waveguide to a circular waveguide operating in the TM_{01} mode was performed. The transition requires experimental matching, which includes position of the short circuit plate in the rectangular waveguide and a diaphragm in the rectangular waveguide. Additional mechanical modifications as necessary may be required to eliminate the TE_{11} mode.

A conical horn was designed to be used either with a circular waveguide operating at the TM_{01} mode or the TE_{11} mode with cross or circular polarizations.

The TE_{11} is the fundamental mode in a circular waveguide; the distribution of the electric field in the TE_{11} mode is shown in Figure 6. Unless a wafer sample is much smaller than the waveguide diameter, the heating uniformity will not be very good as shown in Figures 7 and 8. However, the heating uniformity can be substantially improved if the waveguide is excited in the two TE_{11} modes having perpendicular E field vectors (cross-polarization).

Circular polarization also can be used to improve heating uniformity. To introduce a circular polarization of the two cross polarization waves have to have equal amplitudes and a phase difference of 90°.

D. Circular Waveguide and Horn Applicators (Experimental Results - Impedance Matching)

1. Circular Waveguide in the TM_{01} Mode

Experiments were performed to determine the input impedance for the optimum position of the short circuit end plate in the circular waveguide operating in the TM_{01} mode. The best position (several other

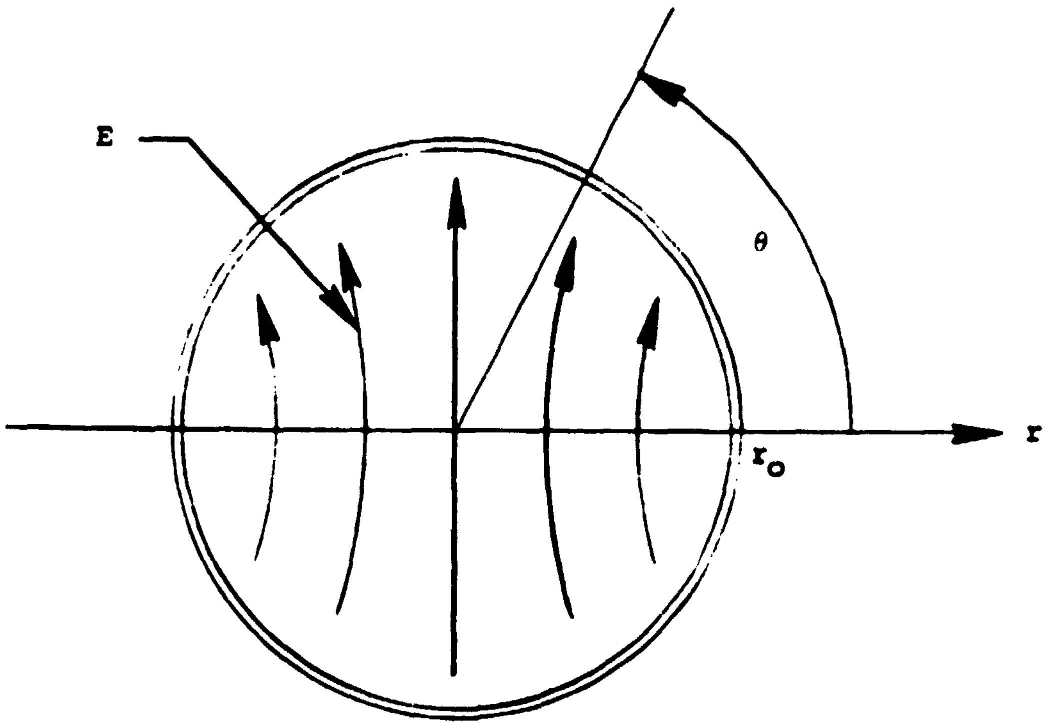


Figure 6: Electric field in a circular waveguide with the TE_{11} mode.

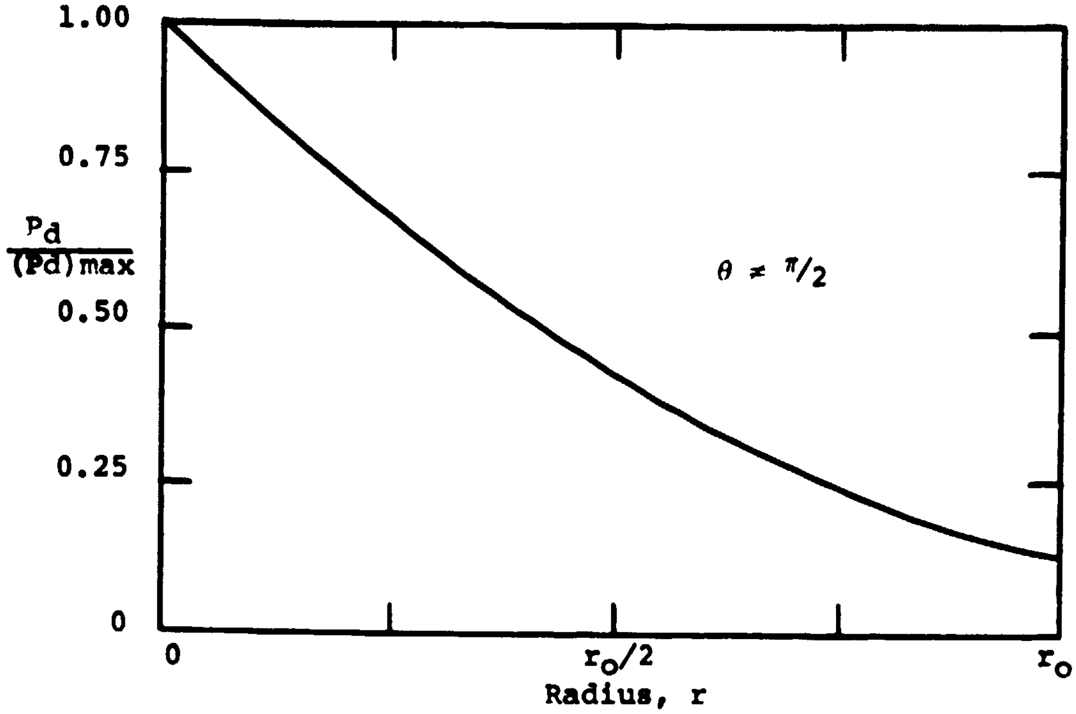


Figure 7: Normalized power dissipated along the radius in a circular waveguide with TE_{11} mode.

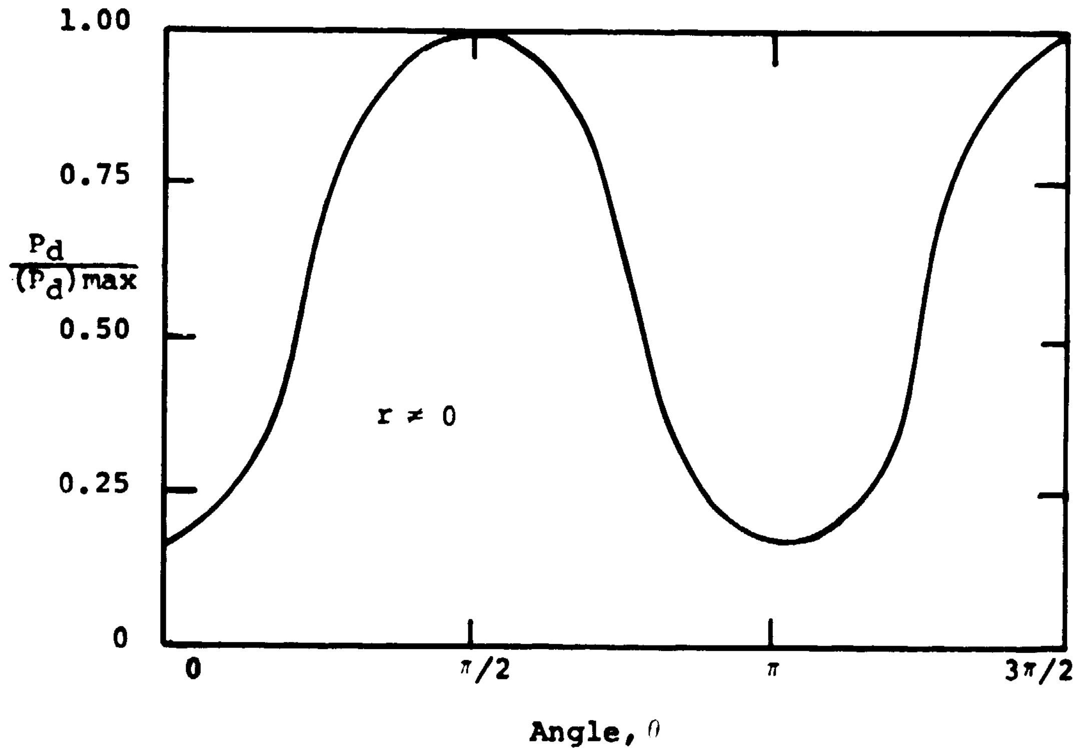


Figure 8: Normalized power dissipated along the angle in a circular waveguide with TE_{11} mode.

positions were tested) gave the input impedance results for wavelengths between 2.4 GHz and 2.5 GHz shown in Figure 9. It can be seen that the matching impedance for transition from the rectangular WR 284 waveguide to the circular TM_{01} waveguide is not as good as was anticipated (The inductive reactance, component is too high). An inductive diaphragm has to be added to the rectangular waveguide to reduce reflections.

2. Circular Waveguide in the TE_{11} Mode

Experiments were performed to determine the input impedance for the optimum position of the short circuit end plate in the circular waveguide operating in the TE_{11} mode. The input impedance is shown in Figure 10. It can be seen that the matching impedance for transition from the rectangular WR 284 waveguide to the circular TE_{11} waveguide transformer port, is well matched, as anticipated, with the reflected power always less than 1% of the incident power for the frequency range of 2.4 GHz to 2.5 GHz.

The input impedance for the branch port operating in the TE_{11} mode is shown in Figure 11. It can be seen that the matching impedance for transition from the rectangular WR 284 to the circular TE_{11} waveguide branch port is not matched well and a diaphragm must be added to reduce the reflections.

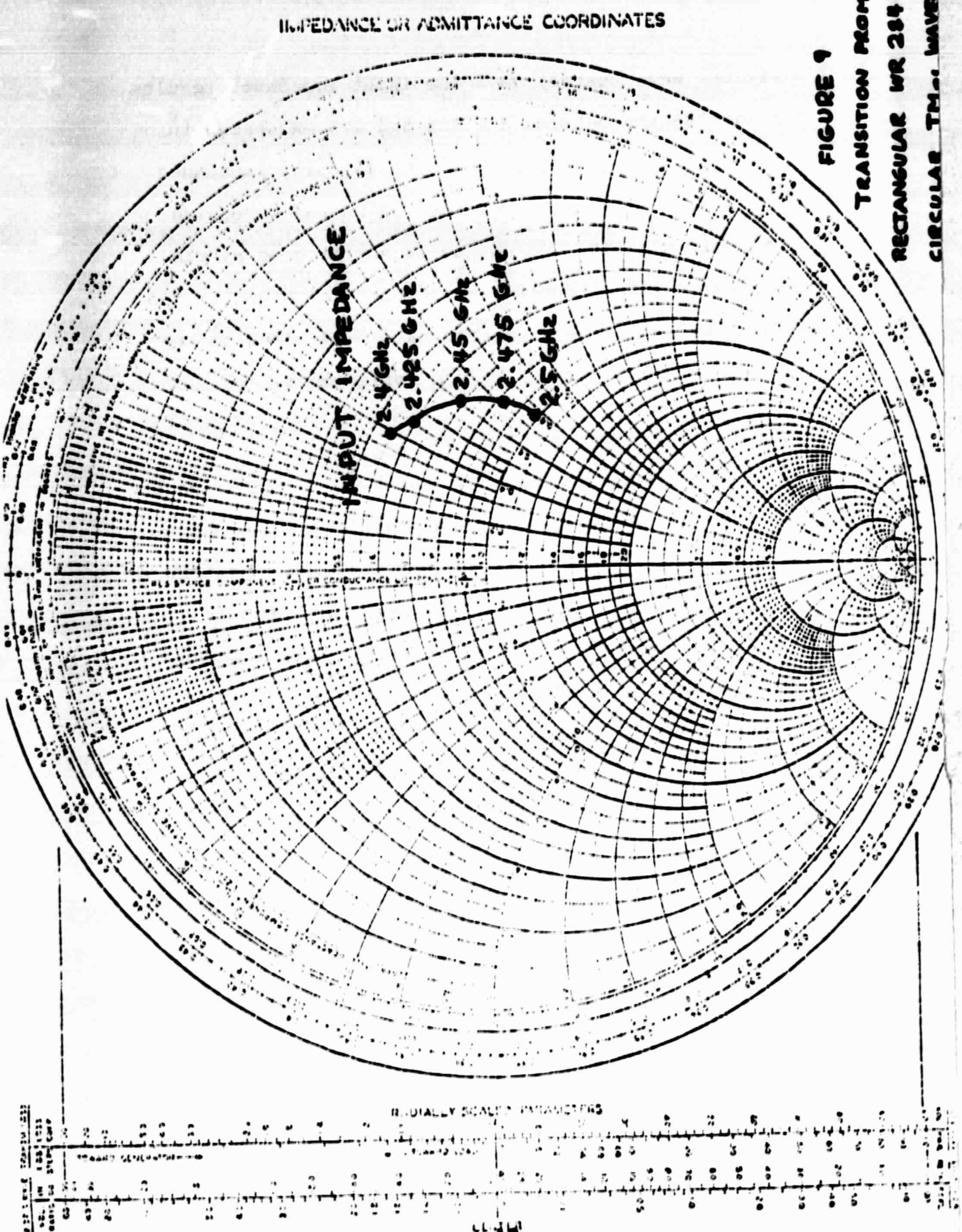


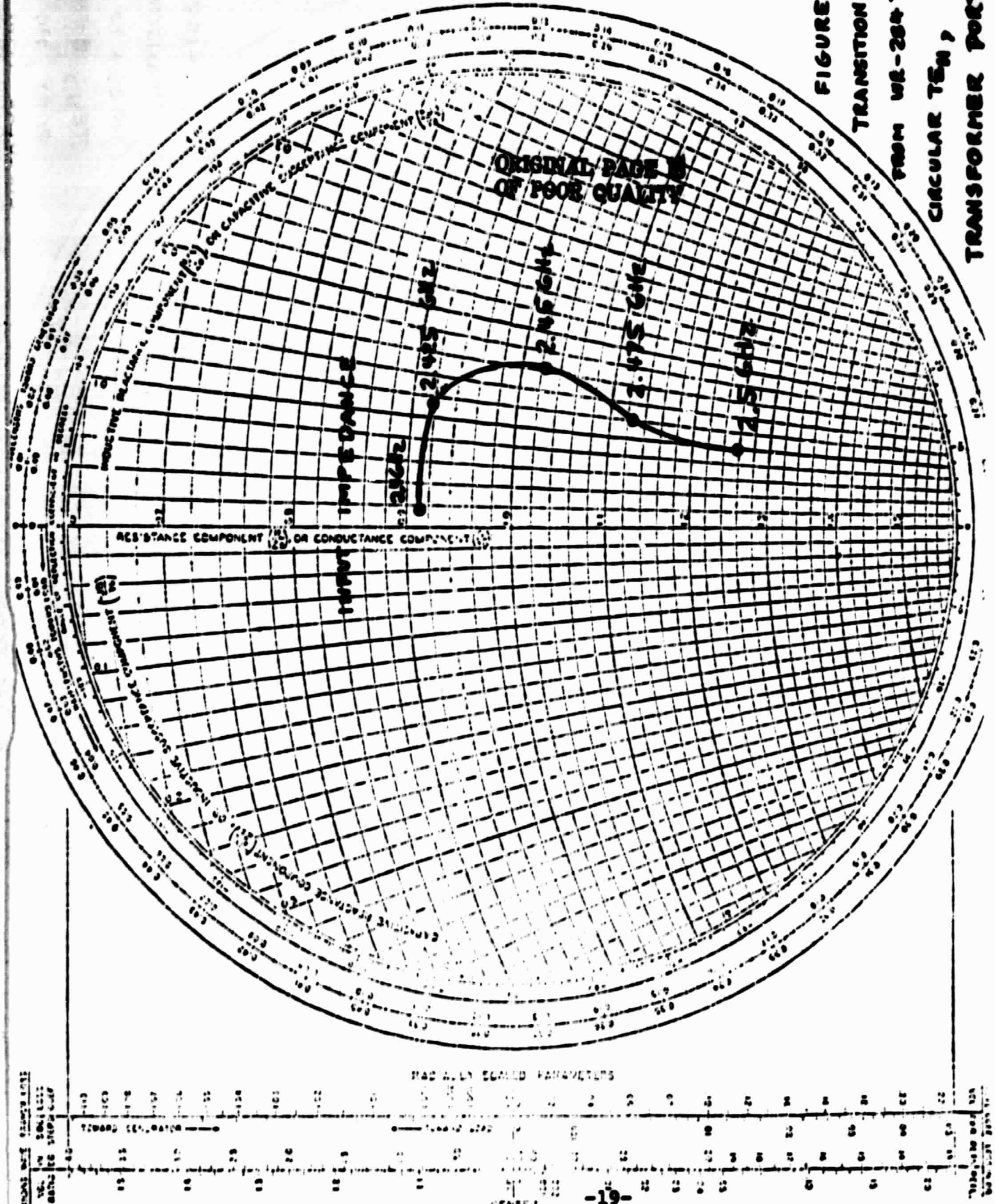
FIGURE 9
TRANSITION FROM
RECTANGULAR WR 284 TO
CIRCULAR TM_{01} WAVEGUIDE

no. GC 195

NAME	TITLE	DWG. NO.
SMITH CHART Form ...	GENERAL RADIO COMPANY, WEST CONCORD, MASSACHUSETTS	DATE

IMPEDANCE OR ADMITTANCE COORDINATES

FIGURE 10
TRANSITION
FROM WR-284 TO
CIRCULAR TE_{11},
TRANSFORMER PORT



IMPEDANCE OR ADMITTANCE COORDINATES

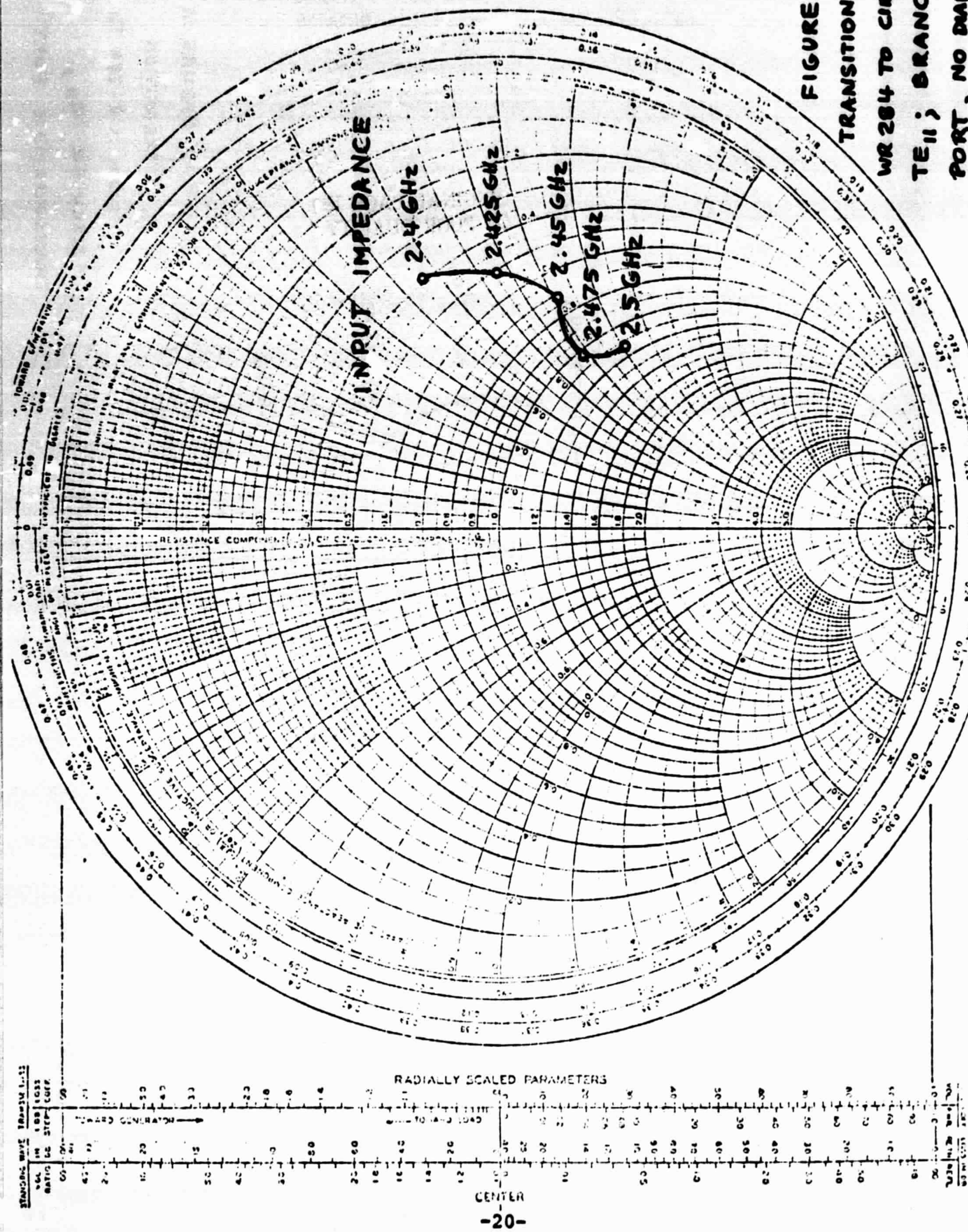


FIGURE 11
TRANSITION FROM WR 284 TO CIRCULAR TE_{11}; BRANCH PORT, NO DIAPHRAGM

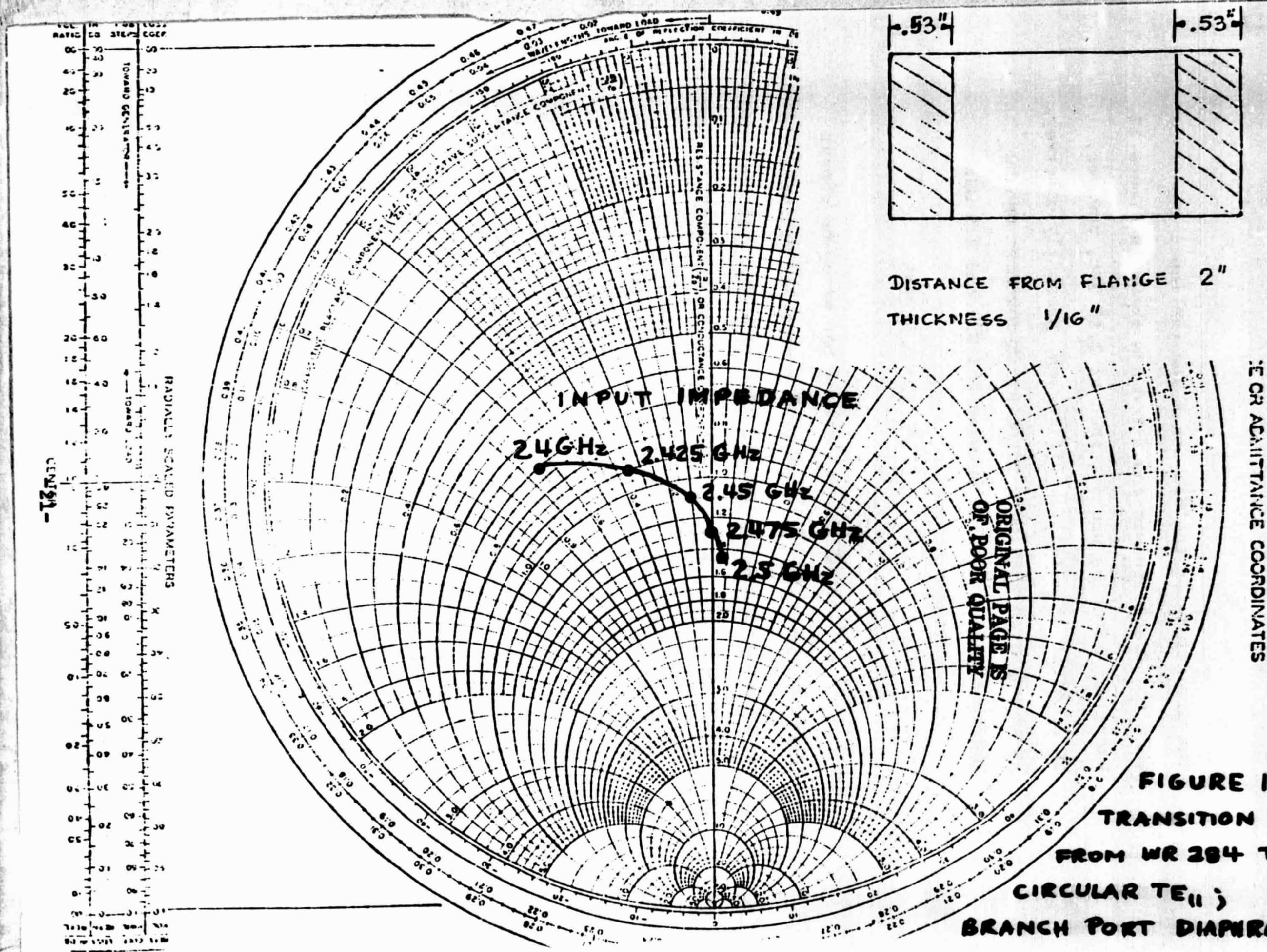


FIGURE 12
TRANSITION FROM WR 284 TO CIRCULAR TE_{11}; BRANCH PORT DIAPHRAGM

The dimensions of the diaphragm and the input impedance when the diaphragm was installed are shown in Figure 12. Excellent matching was obtained at 2.45 GHz, however, as a result of a small modification, presently underway, it is expected that more matching improvement can be achieved at frequencies between 2.4 GHz and 2.5 GHz.

E. Microwave Application to Spray-on Dopant Junction Formation

One of the objectives for spray-on dopant junction formation is to achieve controlled minimal penetration of the dopant material into the silicon wafer. Analysis has indicated that complete heat penetration will occur in the thin silicon wafers (0.15 mm to 0.30 mm thickness) when microwave power at frequencies of the order of 2.45 GHz is applied. (See Quarterly Report No. 7).

A microwave fringing field applicator model was considered, for it offered a possibility of control of the microwave energy penetration depth and would, therefore, be suitable for "shallow" heating. Low power test results for this device revealed very difficult problems with impedance matching, efficiency, and field uniformity. Consequently, a new concept is being considered.

The scope of this investigation will include the following: (1) a computer study of the heat transfer through the silicon wafer when cooling is applied to the back surface while microwave heat is applied to the spray-on doped front surface, and (2) experimental verification of the results of the computer study. In this way, the profile of heating through the thickness of the wafer should tend to concentrate heat on the spray-on doped side of the wafer, while the opposite side remains cool. The objective is to achieve a heating profile with minimum penetration depth, with a goal of about .005" or .127 mm.

The system will consist of a microwave heat source for the spray-on doped side of the wafer in the form of a waveguide horn applicator, and cooling for the back wafer surface by either forced air at room temperature, liquid nitrogen expanding against the wafer, or a beryllium oxide heat sink with water cooling. An electrical analog of the heating and cooling system to be studied is shown in Figure 13.

The computer program will be written for equations with independent variable parameters including the microwave power level, the heat sink thermal resistance and temperature, and the wafer thermal resistance and mechanical properties. In addition, the

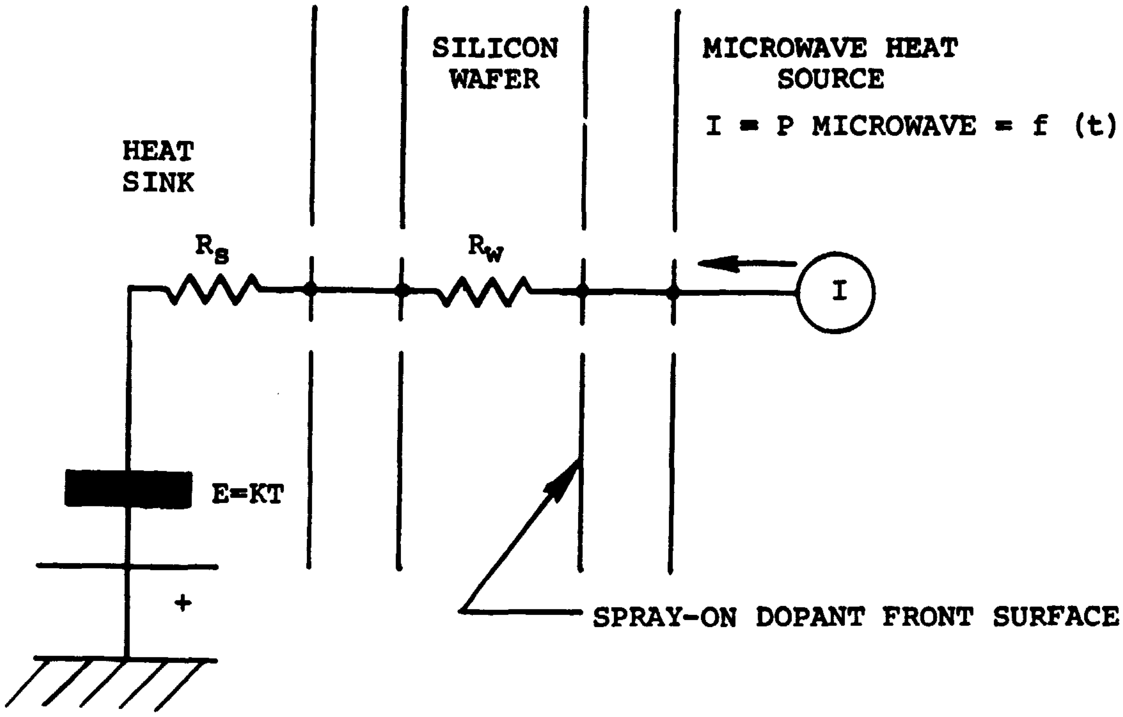


Figure 13: Electrical analog of the microwave wafer heating/cooling system.

time and method of power application may either be continuous or specified by pulse repetition rate and pulse width. If pulsed, the microwave power input level will be a function of time.

As a result of the parameter variations the computer will yield performance parameters, or dependent variables. The dependent variables are the temperature profile versus time for the specified conditions of independent variables. In addition, resultant mechanical stresses in the wafer will be computed. When the computer study has been completed, the results will be experimentally evaluated.

F. Spray-on Aluminum Metallization Equipment

A low cost spray-on technique for applying aluminum to the back surfaces of solar cells is under investigation. Sensor Technology's in-house spray-on system requires several modifications in order to perform this technique. These equipment modifications include the addition of a metallizing spray booth located ahead of the present spray chamber, and an extension of the conveyor. An illustration of the modified spray-on system is depicted in Figure 14. The

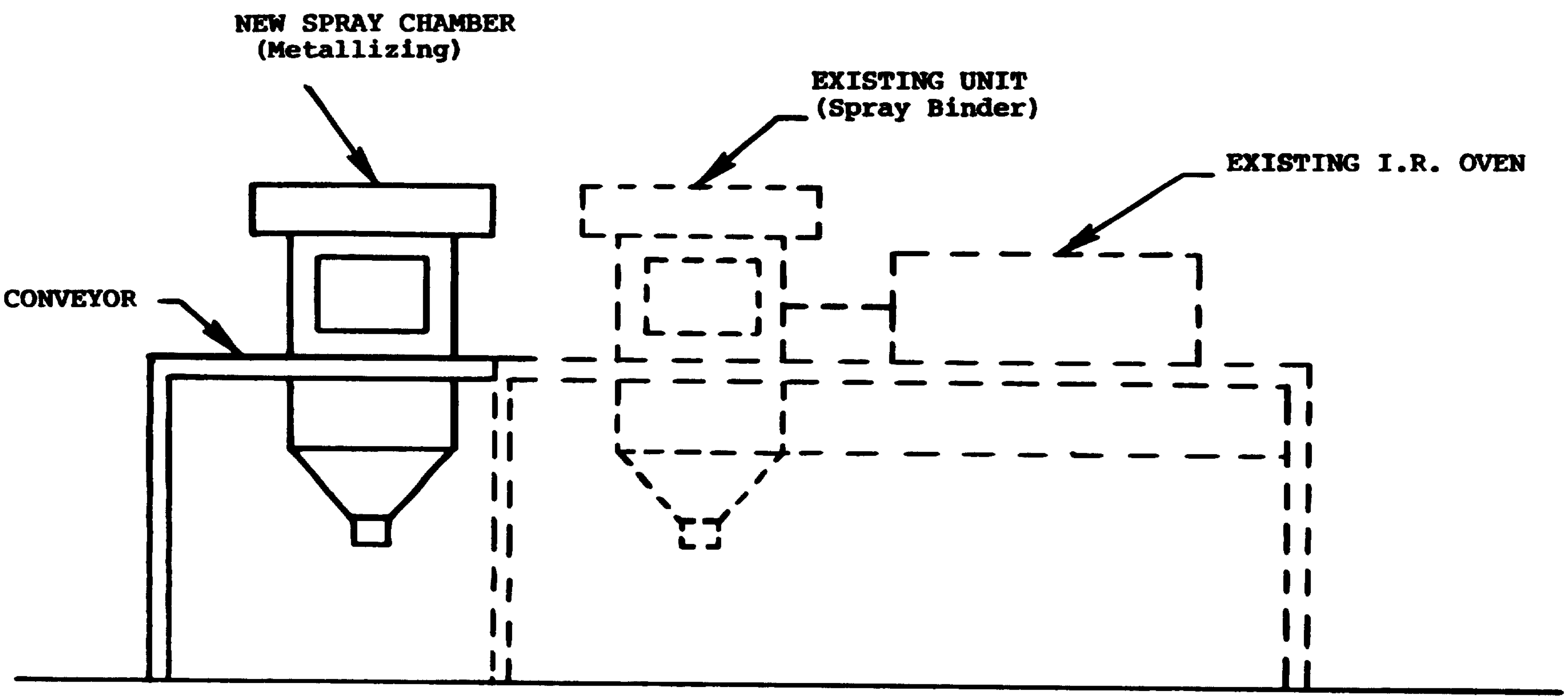


Figure 14: Illustration of the modified spray-on system for applying aluminum to the back surfaces of solar cells.

operation of this system requires manual removal of the pallet from the present booth where the binder solution is applied, and subsequent placement of the pallet ahead of the new booth where the metal will be applied. Advanced Concepts Corporation, of Bristol, Rhode Island, fabricated the equipment and performed initial tests last quarter (see Quarterly Report No. 7). Final equipment adjustments were made this quarter and a new spray nozzle was fabricated. Delivery, installation and final tests at Sensor Technology are planned for next quarter.

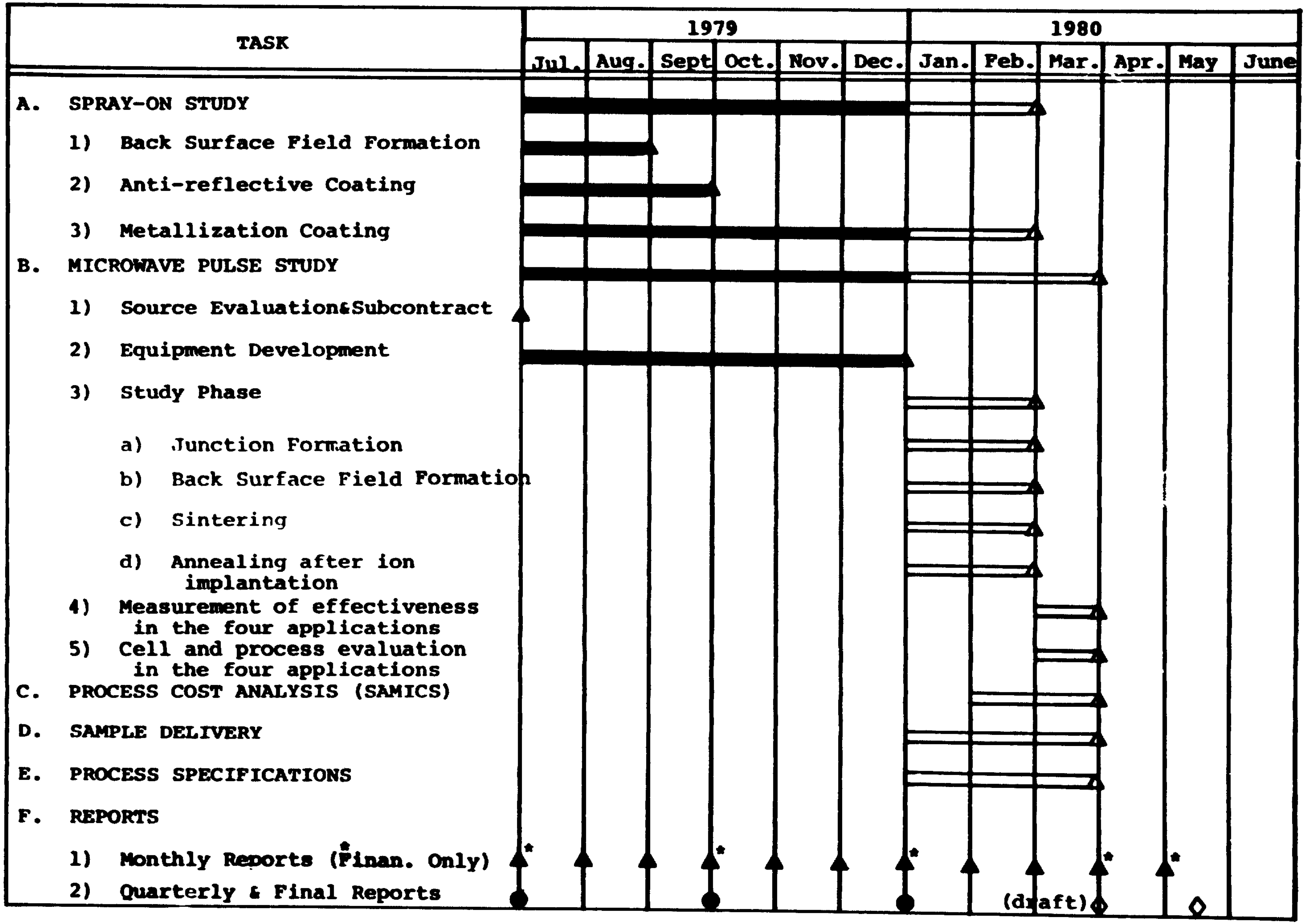
CONCLUSIONS AND RECOMMENDATIONS

Work performed this quarter on microwave heating experiments led to a number of conclusions. The low power experimental results on the impedance matching and wafer surface heating uniformity for the standing wave rectangular waveguide horn applicator are satisfactory. Further experiments with the rectangular waveguide horn applicator at high power will be performed. The particular resonant TM_{011} cylindrical cavity configuration studies this quarter cannot be employed for heating silicon wafers due to its poor energy coupling efficiency. However, since the TM_{011} mode provides potential for uniform heating applications, using it should not be totally excluded from further perusal. Utilization of two cylindrical waveguides operating in the TE_{11} mode with circular polarization appears to be suitable for producing good wafer surface heating uniformity. Excellent impedance matching was obtained at low power. A microwave fringing field applicator model was found to have difficult problems with impedance matching, efficiency, and field uniformity. At the present time this method for controlling the depth of wafer heating has been discontinued in favor of a study involving heat transfer through a silicon wafer when cooling is applied to the back surface while microwave heat is applied to the front surface.

PROGRESS SUMMARY AND PROGRAM PLAN

The progress summary and program plan for the add-on study of Phase 2 of the Array Automated Assembly Program is presented in the Milestone Chart in Table 1. Delivery, installation and tests are planned next quarter for the microwave equipment and spray-on aluminum equipment.

Table 1: Milestone Chart For Phase 2 Array Automated Assembly Task - (Second Part)



<u>LIST OF REFERENCES</u>

1. S. S. Rhee, K. L. Allison, and G. T. Jones; DOE/JPL 954865-79/6; Phase 2 Array Automated Assembly Task; Quarterly Technical Report No. 6; JPL Contract 954865; LSA Project; Automated Array Assembly Task; June 1979; Sensor Technology, Inc.

2. S. S. Rhee, K. L. Allison, and G. T. Jones; DOE/JPL 954865-79/7; Phase 2 Array Automated Assembly Task; Quarterly Technical Report No. 7; JPL Contract 954865; LSA Project; Automated Array Assembly Task; September 1979; Sensor Technology, Inc.