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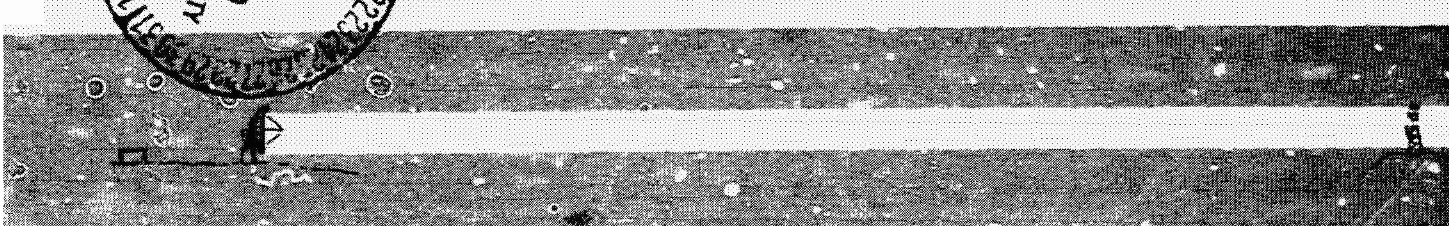
RECEPTION - CONVERSION SUBSYSTEM (RXCV) FOR MICROWAVE POWER TRANSMISSION SYSTEM

FINAL REPORT

PREPARED UNDER JPL CONTRACT NO: 953968
NASA CONTRACT NO: NAS 7-100
(TASK ORDER: RD-151)



PREPARED FOR THE JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
4800 OAK GROVE DRIVE
PASADENA, CALIFORNIA 91103

PREPARED BY RAYTHEON COMPANY
RXCV PROGRAM OFFICE
BOSTON POST ROAD
SUDBURY, MASSACHUSETTS 01776

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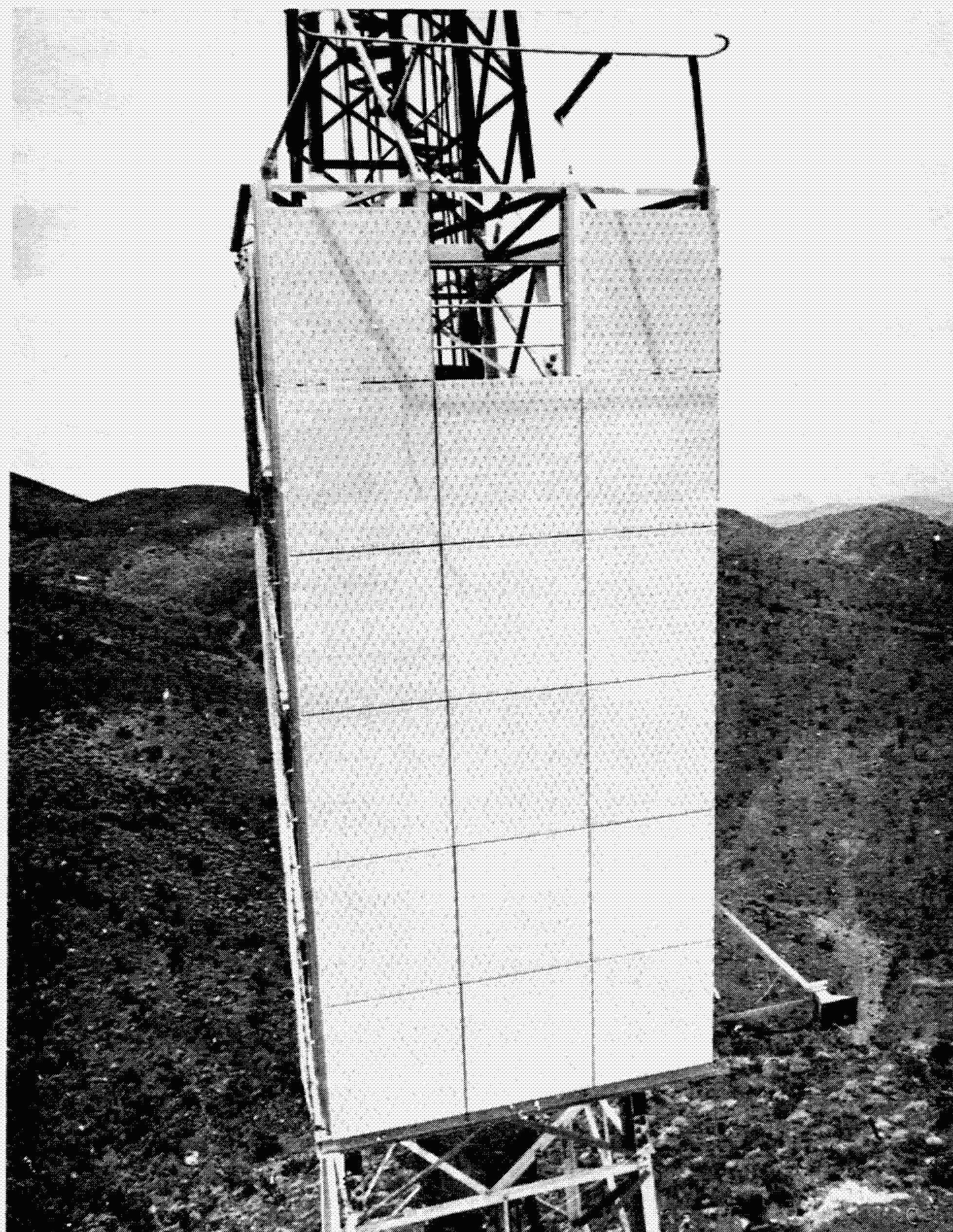
THE JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
4800 Oak Grove Drive
Pasadena, California 91103

Prepared by

RAYTHEON COMPANY
EQUIPMENT DIVISION
RXCV Program Office
Boston Post Road
Sudbury, Massachusetts 01776



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SECTION 1

INTRODUCTION

The National Aeronautics and Space Administration (NASA), Office of Applications, as part of a joint Lewis Research Center/Jet Propulsion Laboratory five year program to demonstrate feasibility of power transmission from space, has included an early ground demonstration of the transmission of a significant amount of RF power over a significant distance with efficient collection and conversion of high RF power to dc.

The California Institute of Technology's Jet Propulsion Laboratory was selected by NASA as prime contractor. They in turn, under a competitive procurement, awarded a cost plus fixed fee contract to the Raytheon Company's Advanced Development Laboratory to undertake the program task as follows:

> "Design, develop, fabricate, verify performance of, ship, receive, assemble on site, align and demonstrate an approximately 25m^2 area device Reception-Conversion Subsystem (RXCV) for collecting high power microwave energy, converting it into dc and dissipating it in an instrumented demonstration load in accordance with the Statement of Work (SOW) and governing documents. Provide the device support structure, perform site modifications, provide demonstration load and instrumentation, provide for the laboratory certification by JPL of high overall dc to dc microwave power transmission efficiency, plan and assist in conducting the demonstration at the JPL Goldstone Venus DSS-13 R&D Station Test Site."

The Raytheon Advanced Development Laboratory was supported by the following elements of the Company:

<u>Microwave and Power Tube Division (MPTD)</u>

- Special Microwave Devices Operation (SMDO)
- Research Division.

Outside subcontractors and major equipment suppliers were:

<u>Subcontractors</u>

- Penn-Tech Inc., West Chester, Pennsylvania
- Plas-Tal Manufacturing Co., Inc., Santa Fe Springs, California
- W.E. Electric Company, Barstow, California
- Kohn Enterprises, Barstow, California

<u>Major Equipment Suppliers</u>

- Interdata Inc., Oceanport, New Jersey
- Texas Instruments, Waltham, Massachusetts

The concept of the system to provide for technology development and engineering experimentation as well as demonstration of microwave power collection and conversion is illustrated in the block diagram Figure 1-1 and in the system artist concept Figure 1-2. The vertically polarized 2388 MHz RF power transmitted over the 1.54 km range results in a near cylindrical power beam having a maximum power density of 0.51 $mW/cm^2/kW$ transmitted power. The half power beamwidth is 0.35 degrees.

The power incident on a single subarray is collected by the 270 halfwave dipoles and converted to dc power at high efficiency with halfwave rectifiers. The dc power is partially dissipated in a fixed resistive load and the remainder in lamps for visual display. The small power losses due to rectification inefficiency are radiated as waste heat from the bus bars in the subarray. A small amount of reflected power occurs and it is known to vary with individual element performance, rectenna element dipole to ground plane spacing and with load impedance. The central element of each subarray is separately instrumented and calibrated through a combination of the hardware and software as an input power reference element. It dissipates its power in a fixed resistance load. The standard gain horn and associated instrumentation provide for an independent incident RF power measurement which through a substitution process transfers the calibration to the instrumented reference elements associated with each subarray.

The support structure and electrical interfaces on the tower are configured to mount 18 subarrays as shown in Figure 1-3.

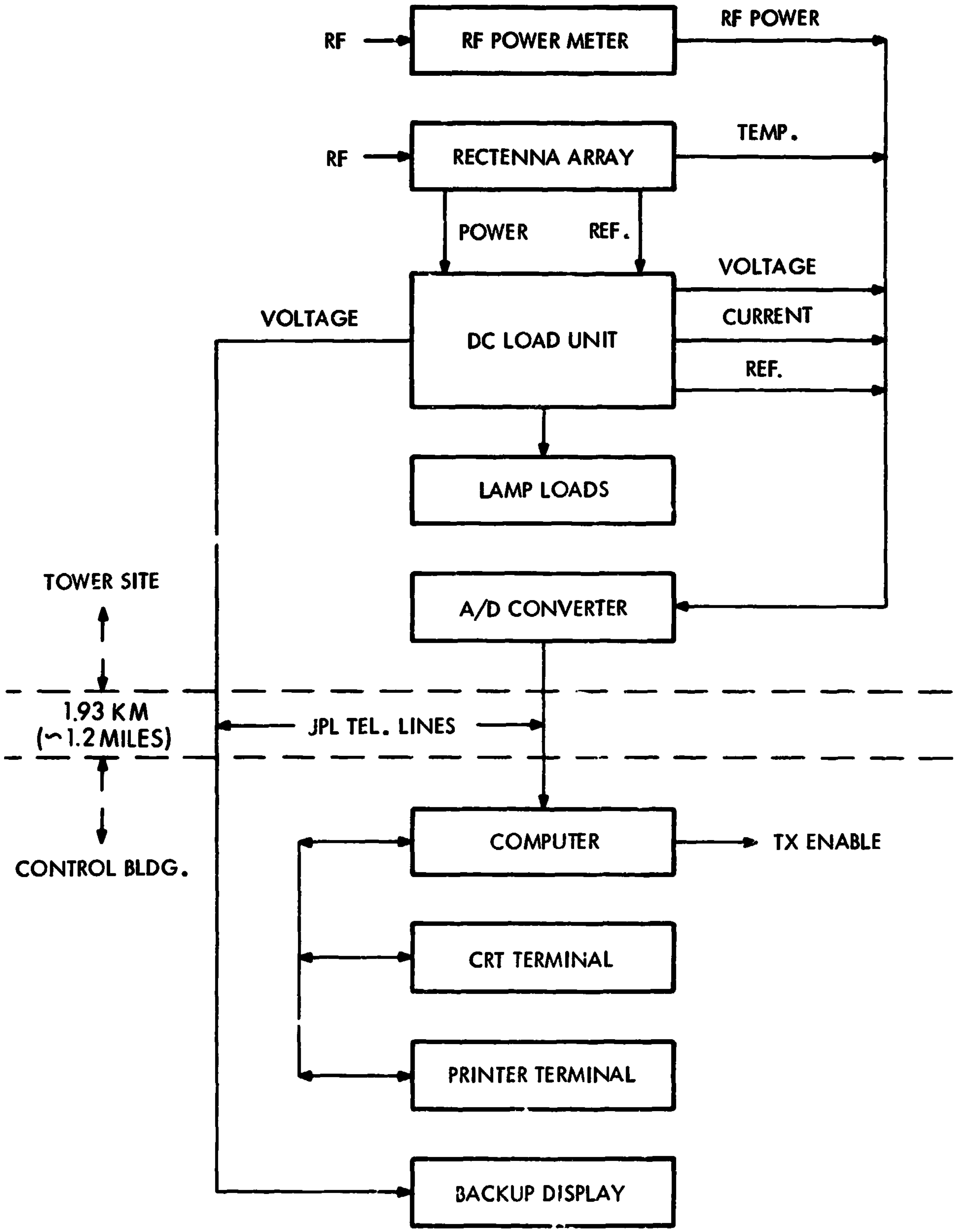
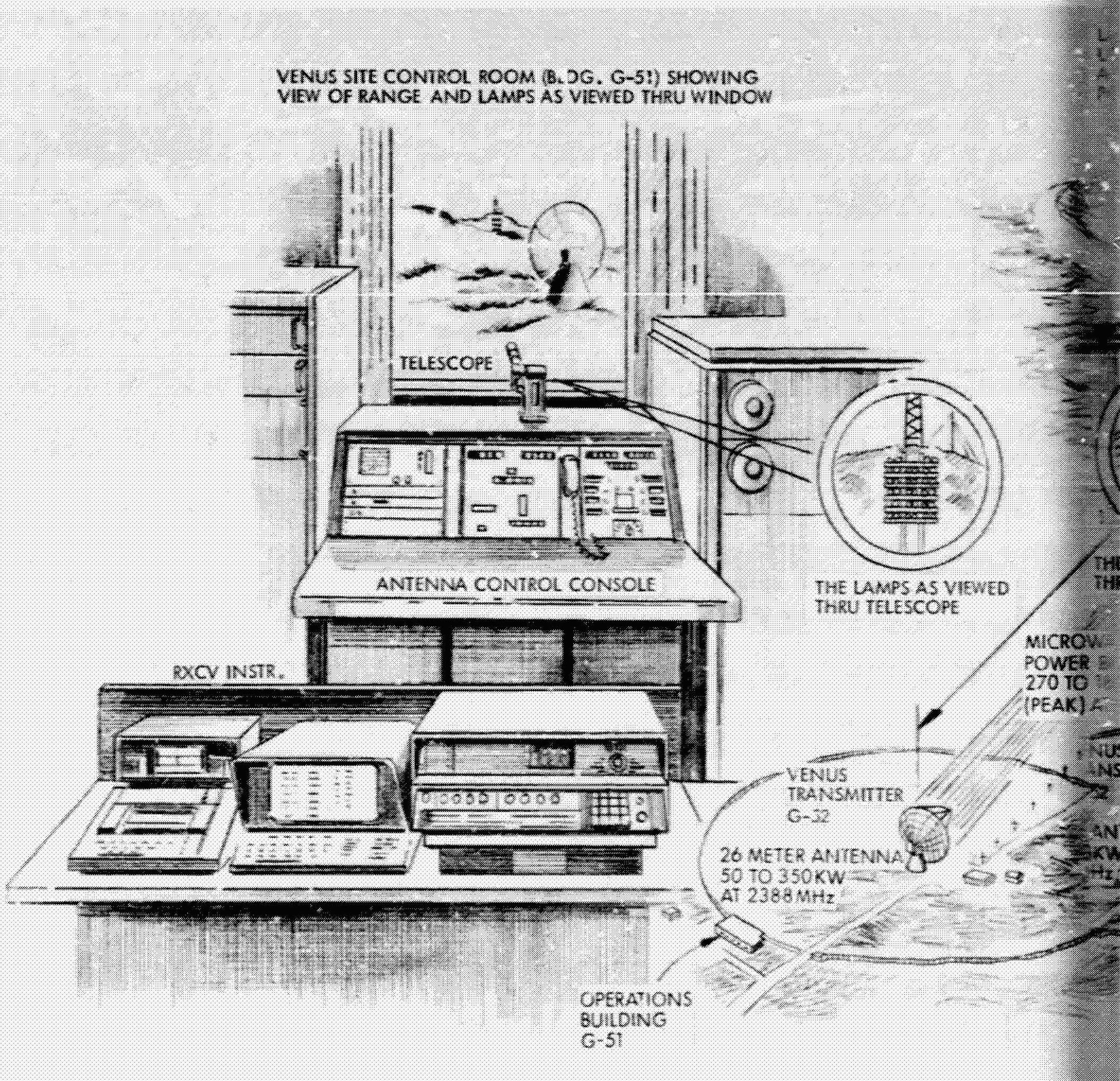


Figure 1-1. RXCV System Block Diagram


VENUS SITE CONTROL ROOM (BLDG. G-51) SHOWING
VIEW OF RANGE AND LAMPS AS VIEWED THRU WINDOW
TELESCOPE
ANTENNA CONTROL CONSOLE
THE LAMPS AS VIEWED
THRU TELESCOPE
RXCV INSTR.
VENUS
TRANSMITTER
G-32
26 METER ANTENNA
50 TO 350KW
AT 2388MHz
OPERATIONS
BUILDING
G-51
MICROW
POWER
270 TO
(PEAK)

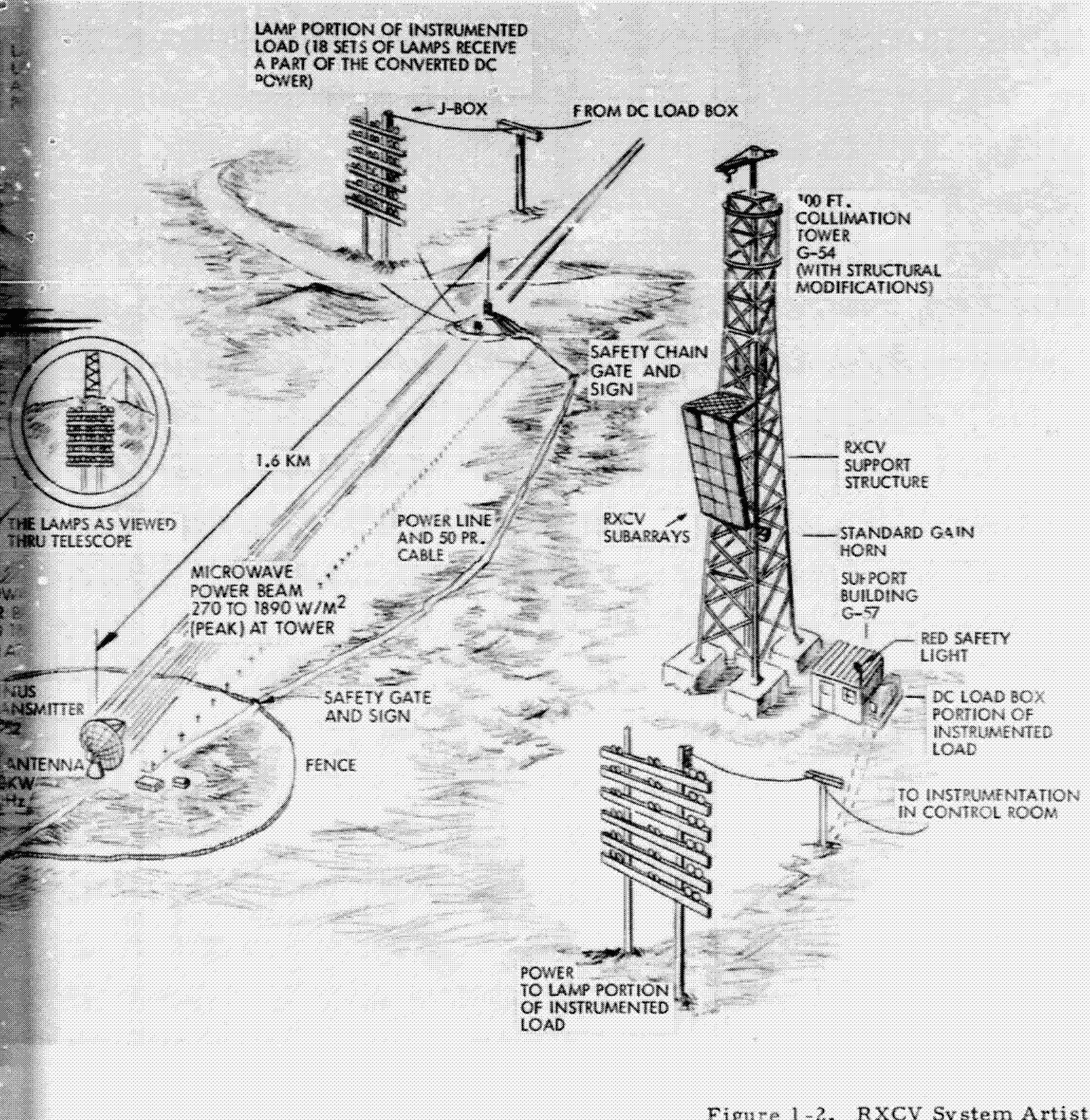


Figure 1-2. RXCV System Artist Concept

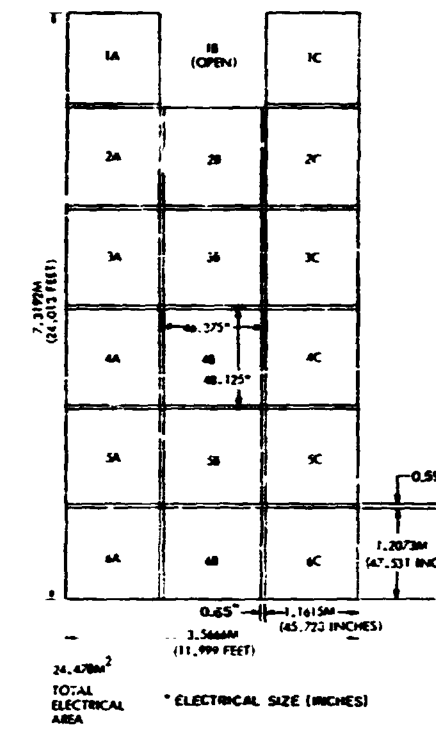


Figure 1-3. Subarray Location Designations in the RXCV Array

The installed configuration is comprised of 17 subarrays with the row one column B location left open. The original proposal specified 18 subarrays, however, as the detailed technical requirements and associated costs were more clearly understood and as the equipment performance confidence increased a decision was made to delete one subarray.

It should be recognized that the configuration of the rectifying antenna for large scale deployments (several square miles) is anticipated to be quite different from the major first production step taken in the RXCV development program. Large scale arrays would be designed for automated production and deployment to reduce the costs of $7,500/M^2$ (\$6203/kW) achieved in the RXCV program perhaps by a factor of 20 or more.

The analog voltage and current measurements from the instrumented loads are converted to digital signals and transmitted by wire to a computer for the primary instrumentation and display in the control room. The computer processes the data and drives the display to present input and output power as well as efficiency for each subarray and for the total array. In addition, a thermistor provides temperature readings for each subarray and the load box.

Furthermore, independent sets of wires provide the analog output voltage data directly to a corresponding set of lights on the backup display panel and to a switchable digital voltmeter. The backup instrumentation is provided for fail-safe indication of the voltage output from the selected subarray.

The requirement to obtain and display data on the receiving subsystem of a high power microwave transmission system in a controlled fashion for technology development, engineering evaluation and demonstration purposes was implemented through the use of the following:

- A telescope in the control room to observe distant details
- Lights configured to correspond with the rectenna subarrays observable from the control room over a large range of power levels
- A dc load operable in two modes, low and high power via a switch provided at the load box
- Protective crowbars installed in each of the subarrays across the primary power buses and a separate crowbar installed in the junction box on the support structure for each reference element
- An interlock to terminate power transmission when preset limits are exceeded
- Azimuth and elevation of the transmitted beam controllable from the control room
- Transmitter power level, calibration and readings controllable from the transmitter building
- Support structure, cables and junction boxes provide for installation and juxtapositioning of subarrays in a safe configuration when the transmitter power is off
- Safety signs and lights to alert personnel to potentially hazardous RF regions.

The program was completed ahead of schedule (11 vs 14 months) and within cost; while exceeding performance requirements as shown in Table 1-1.

Demonstrations were made by Raytheon to interested JPL and NASA personnel, with the final demonstration (5 June 1975) for equipment acceptance being conducted by the JPL Project Manager Mr. Richard M. Dickinson and witnessed by Mr. Samuel Fordyce, Program Manager, NASA Headquarters. Additional demonstrations, maintenance operations, performance measurements, and assessments completed the contracted effort.

Table 1-1 compares the key design requirements with demonstrated performance. More detailed specification requirements are summarized in Table 1-2 while further details and their implementation are discussed in subsequent sections of the report.

TABLE 1-1

COMPARISON OF KEY DESIGN REQUIREMENTS AND DEMONSTRATED PERFORMANCE

	Key Design Requirements	Demonstrated Performance
DC output power	>12,500 watts	30,000 watts
RF to DC efficiency	>70% (goal)	>80%
JPL certified laboratory DC to DC efficiency*	>50%	54%
Cost of construction for subarray production model	<$7,500/kW DC	$6,203/kW DC

*Separate effort from the Goldstone work. Performed at Raytheon MPTD, Waltham, Massachusetts

TABLE 1-2

DESIGN REQUIREMENTS

Scope: Collect incident-free space S-band microwave power, convert it into direct current at high efficiency and dissipate it in an instrumented load that demonstrates microwave power transmission.

Life: Five years minimum in the Goldstone environment.

Material, Parts and Processes: Solid State components shall be used.

Cost: <$7500.00/kW dc for production units

RF Input Frequency Range: 2388 ±5 MHz

Transmission Range: 1.6 km

Transmitter Output Power: Adjustable 20 kW up to 400 kW

Efficiency: 70% (Goal)

Output Power: >12,500 Watts (goal)

Environmental Requirements: The subsystem will be exposed to the Mojave Desert environment (sunshine, preciptation, wind, sand, static charge accumulation, lightning, rodents and dust. In addition the subsystem shall survive:

Wind: 161 km/Hr (100 mph)

Non-Operating Storage Temperature Range: -30°C (-22°F) to 79°C (175°F) without permanent degradation.

Production Approval Ambient Temperature Range: -20°C(-4°F) to 60°C (140°F)

Type Approval Ambient Temperature Range: -30°C (-22°F) to 65°C (150°F). In this range efficiency shall not be less than 60%.

TABLE 1-2 (Cont)

DESIGN REQUIREMENTS

Testing: The prototype subarray shall be subjected to the following tests:

- Rain
- Sand and Dust
- Transportation Vibration
- Transportation Shock
- Sunshine (Ultraviolet)
- High and Low Temperature

Performance Monitoring Instrumentation: At the Goldstone Venus Station Control Room the following functions shall be measured in order to evaluate the subsystem:

Incident Power Density:	Up to 2000 W/M^2 $\pm 5\%$
Output Voltage:	Up to 200V $\pm 5\%$
Output Current:	Up to 20A $\pm 5\%$
Temperature:	-30^oC (-22^oF) to 79^oC (175^oF) $\pm 5\%$ Measured on the common heat sink near the center of the subarray

Modular Element Design: Such that by replicating the RXCV and juxtaposing these elements the subsystem is still efficiently operable over a large area.

Safety: Governed by O.S.H.A. requirements

REPORT ORGANIZATION

This document is organized as follows:

Section 2. Design and Construction of RXCV Subsystems

Describes all of the design and construction details of the RXCV subsystems and its major components.

Section 3. Testing

Describes component and subsystem testing performed and the results of these tests.

Section 4. System Demonstration

Describes the system demonstration used for the JPL acceptance of the RXCV subsystem.

Section 5. Accomplishments and Discussion of Recommendations

Describes the accomplishments relating them to recommendations in each major area of the system.

Section 6. Recommendation Summary

Summarizes recommendations discussed in earlier sections and presents additional integrated recommendations as appropriate.

Section 7. Conclusions

States conclusions and provides supporting discussion.

SECTION 2

DESIGN AND CONSTRUCTION OF RXCV SUBSYSTEM

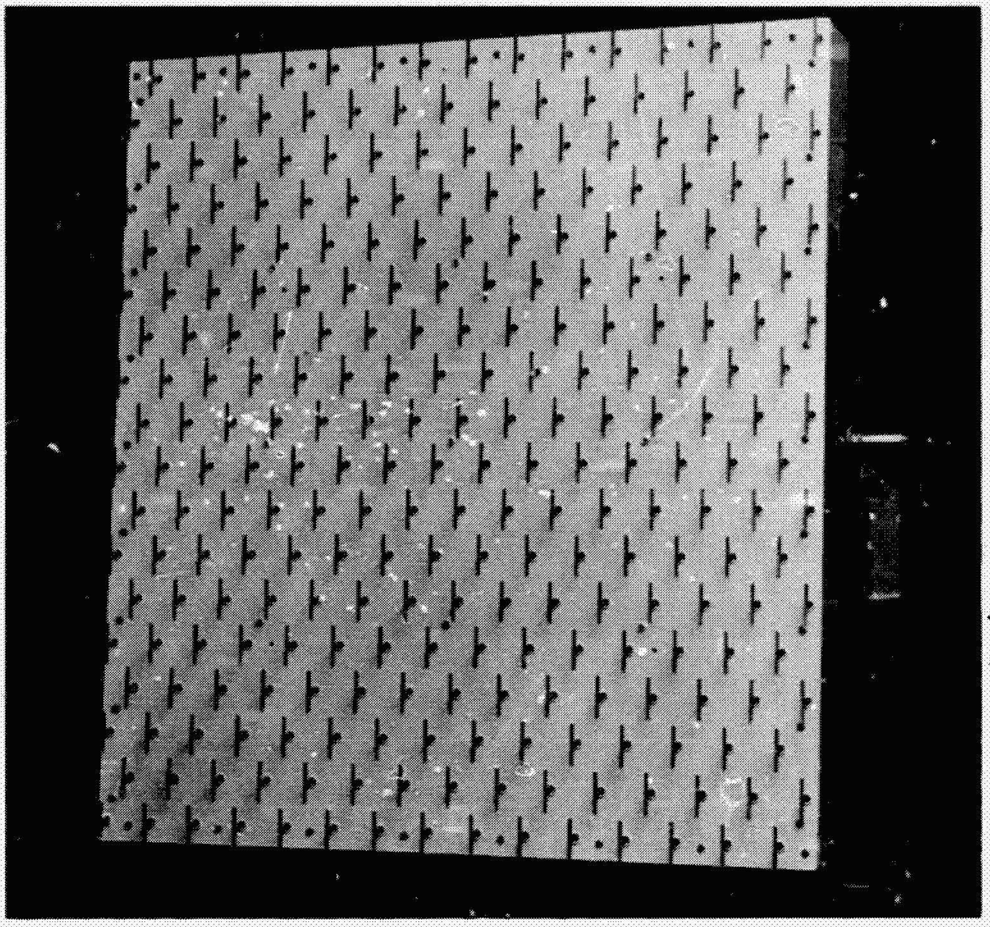
The rectenna subarray is a key development and production item in the RXCV contract. Seventeen of these subarrays, positioned closely together form the complete rectenna which intercepts the microwave beam and converts the microwave power to dc power.

The function of each subarray is dependent upon a quantity of 270 rectenna elements which collect and re[illegible] the incoming microwave power. A key subcomponent in the rectenna ele[illegible] is the gallium-arsenide Schottky barrier diode which is designed for exceptionally high efficiency and high power handling capability. In addition to working out the design of the rectenna element and its rectifying diode and arranging for their manufacture, it was necessary to package them into a subarray in such a format as to insure: reliability and survivability in the field, provide enough instrumentation sensors to interface with the monitoring system, and permit mounting into a total array with a minimum of discontinuity at the interfaces of subarrays.

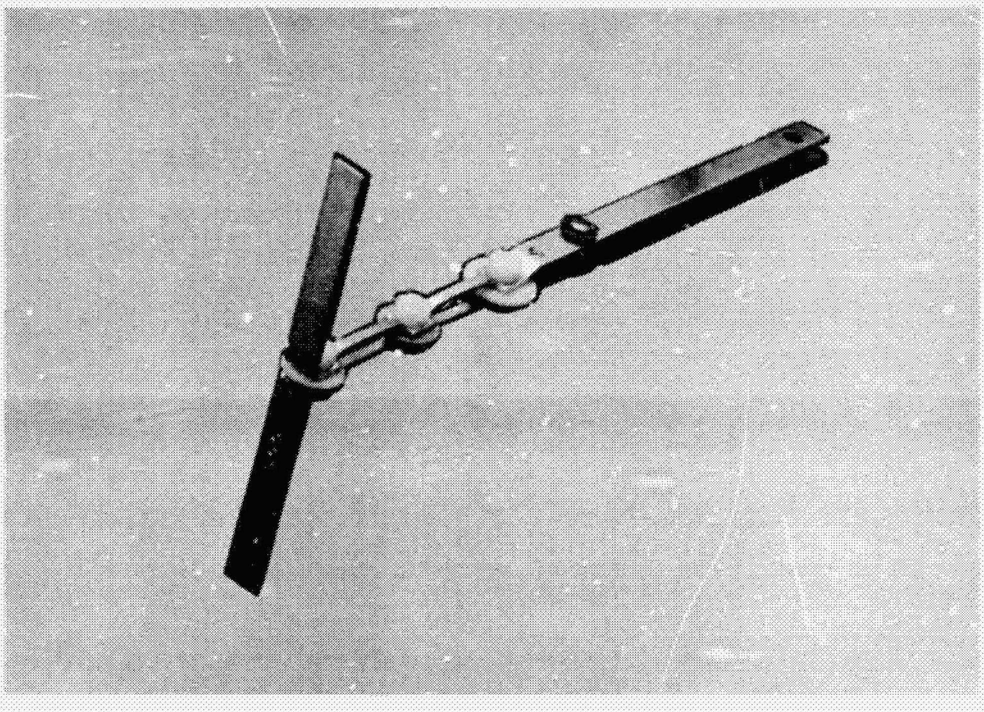
2.1 DESCRIPTION OF THE SUBARRAY

The front and back views of the subarray are shown in Figures 2-1(a) and (c). The subarray is 1.162M (45.73 inches) wide and 1.207M (47.53 inches) high. The depth of the subarray excluding the handles is approximately 13.65 cm (5.375 inches). The rectenna subarray contains 270 rectenna elements which capture and rectify the incident microwave power. Each rectenna element assembly (Figure 2-1(b)) contains a halfwave dipole, a low pass filter section, a rectifier circuit employing a single diode, a dc smoothing filter, and connections for carrying away the dc power. The elements are arrayed in eighteen rows, fifteen elements to the row. The placement of the elements in the subarray is such that the individual subarrays may be interchanged with one another without altering the interface symmetry.

All of the rectenna elements in one row are connected in parallel to a common bus bar. This is made more clear by reference to Figure 2-1(d) which shows the back of the rectenna subarray with cover removed. An electrical circuit diagram, Figure 2-2, shows the parallel connection of these elements.

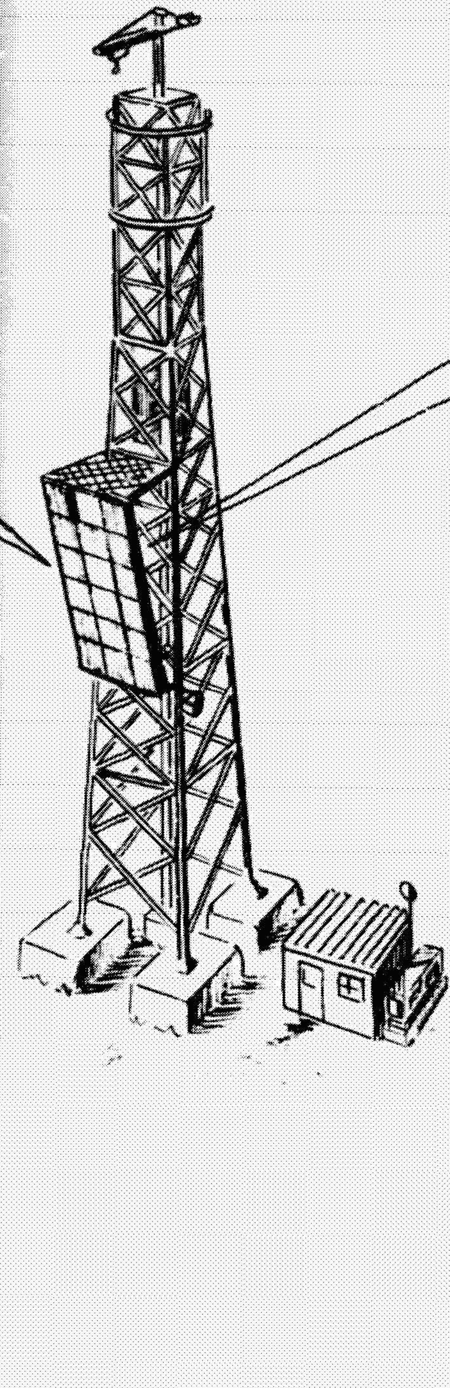


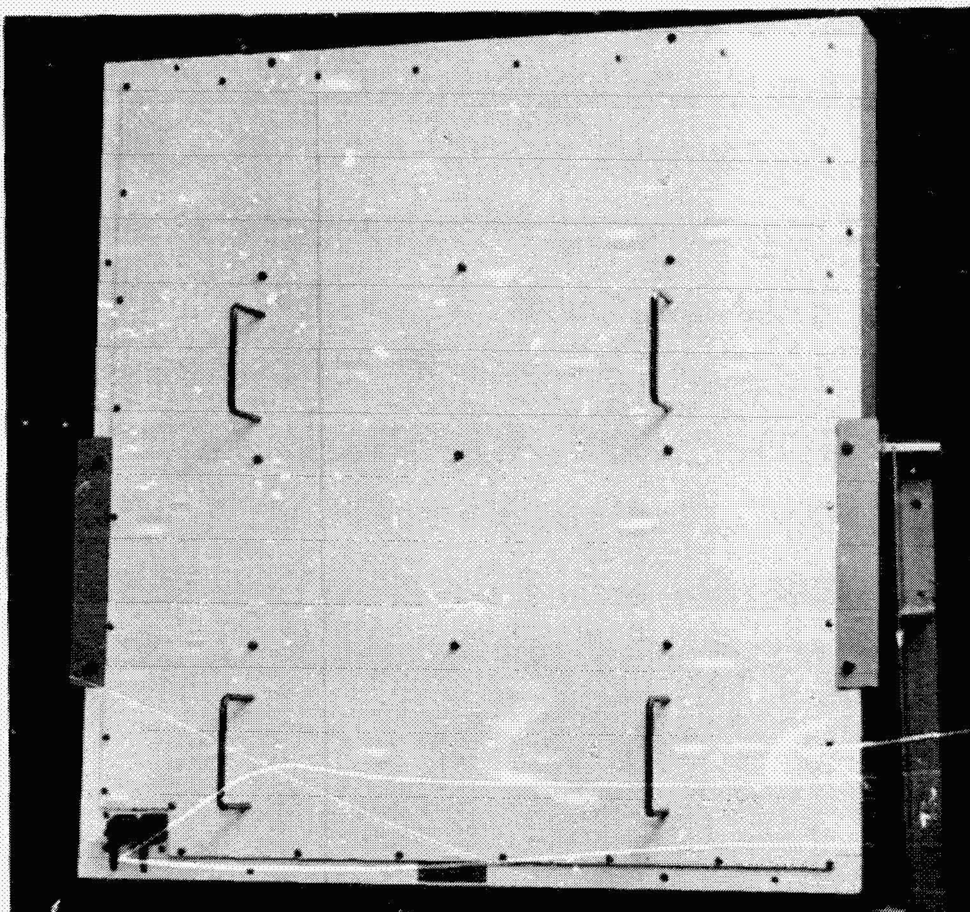
(A) SUBARRAY - FRONT VIEW



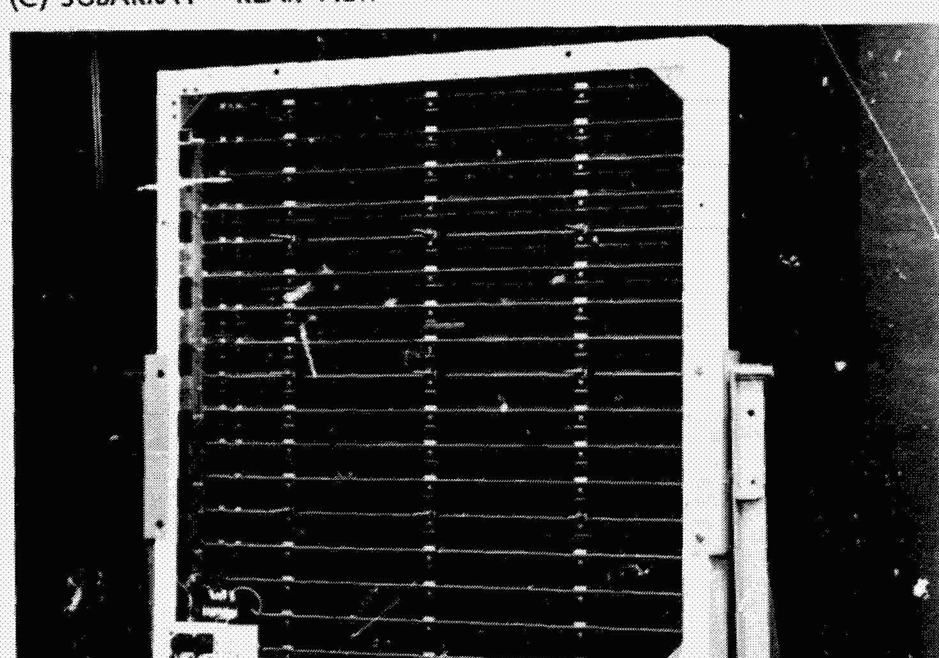
(B) RECTENNA ELEMENT

FOLDOUT FRAME





(C) SUBARRAY - REAR VIEW



(D) SUBARRAY - REAR WITH BACK COVER REMOVED

Figure 2-1. RXCV Subarray Hardware

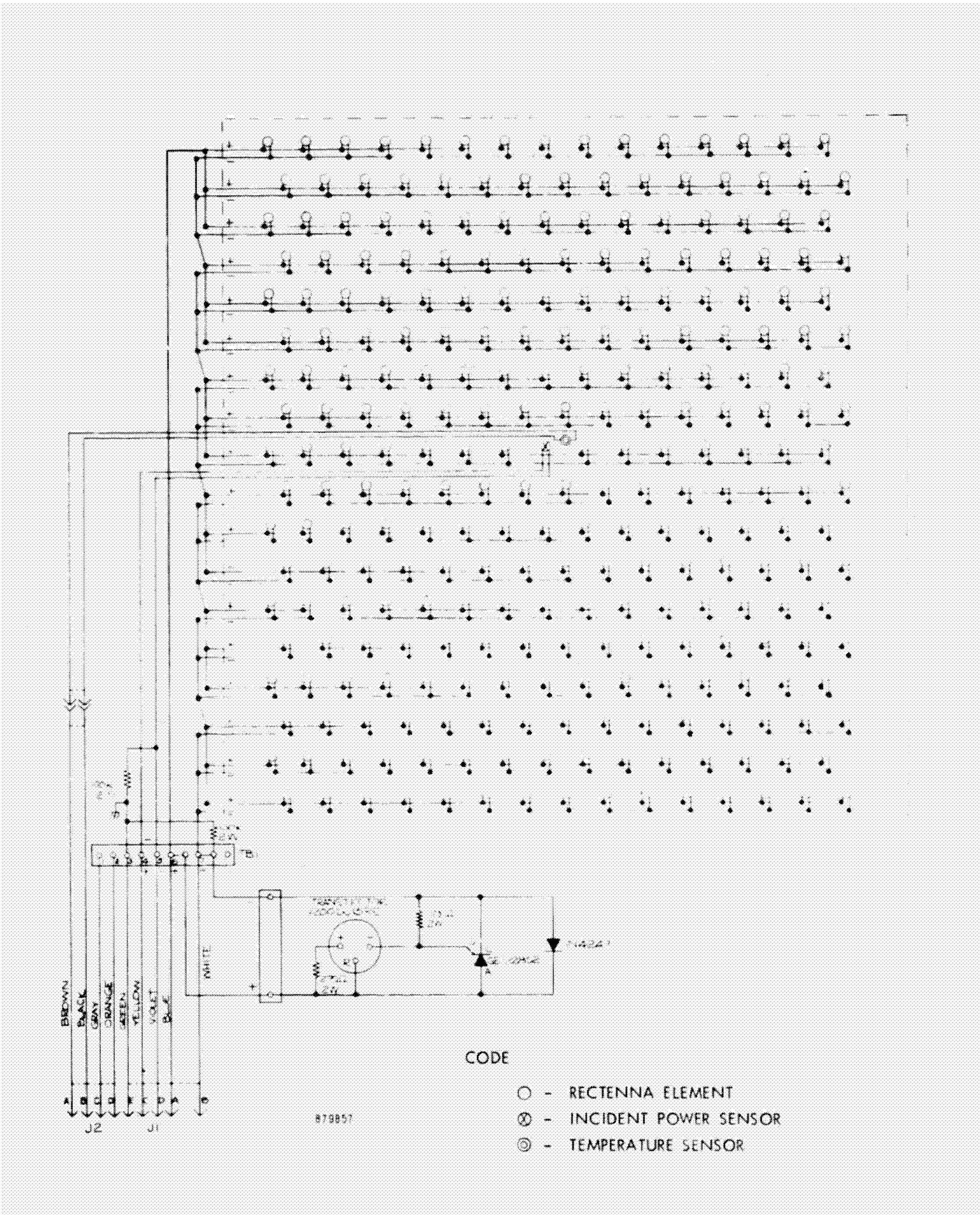


Figure 2-2. Electrical Schematic of Subarray

The connection of the rectenna elements to the bus bars is made by means of a machine screw and nut with appropriate insulating washers which securely clamp the rectenna element to the bus bars as shown in Figure 2-3. As shown in the electrical schematic, three rows of diodes are connected in parallel and six sets of three rows are connected in series to supply a maximum voltage output of 200 volts.

The subarray contains a number of protection and instrumentation features which include crowbar protection for overvoltage, self fusing of the diodes, temperature monitoring, and incident power monitoring.

The crowbar is a protective self-contained feature that comes into play in the event that the voltage across the output terminals of the subarray exceeds a value which would cause damage to the rectifier diode. Its mode of operation is to place a short across the output terminals when a preset value of output voltage is exceeded. The short is automatically removed when the incident microwave power is removed. One common cause of excessive output voltage is removal of the load, either completely or partially as in the case of a burned out electric lamp. A second cause of excessive output voltage is an incident microwave power density level that is too high. The crowbar also provides some protection in the event that an excessively high transient voltage is applied to the output terminals from some external source such as lightning.

The value of voltage at which the crowbar fires was set at 200V. The back cover must be removed to modify this adjustment. The crowbar is mounted inside the subarray as shown in Figure 2-4. The adjusting screw is shown in the photograph.

The self-fusing protective feature of the individual diode as arranged in the subarray immediately removes the diode from the circuit if it should short circuit for any reason. This feature is provided by the one mil diameter gold wires which internally connect the diode chip to the diode cover. In the case of a diode short these wires are burned out because all of the other 44 diodes connected in parallel with the shorted diode are pushing their short circuited currents through the faulted diode. This total current, under even fairly low values

Figure 2-3. Mounting the Rectenna Element to the Bus Bar System

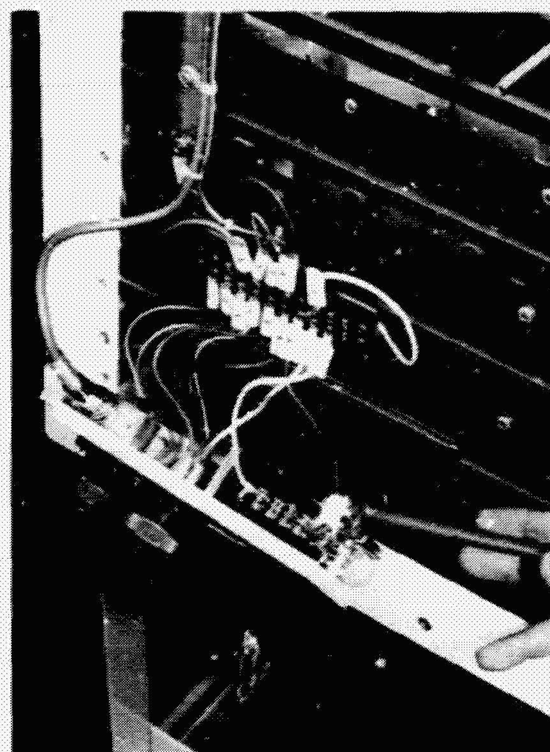


Figure 2-4. Photograph of Output Panel showing Wire Connection and Crowbar. Tip of Pen is Pointing to Crowbar Adjustment.

of incident microwave power, is sufficient to burn out the gold wires. The relationship between the incident microwave power per externally shorted element and the short circuited current is shown in Figure 2-16. Typically the wires burn out at four amperes: eight amperes is the maximum observed. This feature was well tested in the breadboard tests described in paragraph 3.5.

Each subarray contains a thermistor mounted on one of the bus bars as shown in Figure 2-5. This thermistor measures the temperature of the bus bar which also serves as a heat sink for the rectenna element. The thermistor is mounted in an enclosure which prevents stray microwave radiation from heating the thermistor directly and causing an erroneous reading. Such erroneous readings were noted on the breadboard experiment and could be easily identified because of the exceedingly short time constants associated with the microwave heating. No observable false readings have been noted with the shielded design used in the production subarrays.

Figure 2-5. Thermistor Mount and Special Rectenna Element for Instrumentation

Each subarray also contains a separately instrumented rectenna element with an independent load. This element is referred to as the subarray reference element and is shown in Figure 2-5. The reference element output is used in connection with the computer and display unit and, through calibration, in conjunction with the independent reading from the RF Sensor Assembly discussed in paragraph 3.7.4, to measure the incident power density upon the subarray. This measurement of incident power density is then used in the computation of the efficiency of the subarray.

2.1.1 STRATEGY FOR THE DESIGN AND DEVELOPMENT OF THE SUBARRAY FOR THE RXCV AND SUBSEQUENT MODIFICATIONS

The rectenna concept is one which has been in development for over a decade[1,2]. However, there have been periods of low activity and the development is not complete. The most recent support of rectenna development prior to the RXCV contract was provided by NASA's Marshall Space Flight Center. The emphasis in the latter stages of that effort had been to improve the efficiency of both the rectenna and the overall microwave power transmission system. In this context it had been desirable to construct the rectenna in such a manner that the individual rectenna elements could be independently instrumented and physically socketed behind the reflecting plane. This kind of construction was definitely in conflict with that of low cost which had always been one of the major objectives and which necessitates that the active portion of the rectenna and the bus bar system lie in a plane in front of the reflecting plane.

However, it was at this stage of rectenna development that the RFP for the JPL RXCV was formulated. The objectives of this RFP included extensive reliability objectives to encourage the most conservative approach possible to the design and construction of the RXCV, eliminating as much new development as possible. The proposal strategy then was to copy the MSFC structure as closely as possible but to correct any known deficiency of that design.

There was a considerable amount of time overlap between the MSFC contract, the proposal writing for the JPL RXCV and the negotiation of the JPL contract with Raytheon. During this time interval there were findings which impacted the course of the JPL contractual effort. One finding of great importance, from independent development work at Raytheon, was the much greater reliability of the plated-heat sink (PHS) approach to Schottky barrier diode construction than that of the common "flip chip" construction. The MSFC contract

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[1] W.C. Brown, "The Receiving Antenna and Microwave Power Rectification", Journal of Microwave Power, Vol. 5, No. 4, pp 279-292, 1970.

[2] W.C. Brown, "Progress in the Design of Rectennas", Journal of Microwave Power, Vol. 4, No. 5, pp 168-175, 1969.

plan was to use "flip chip" Schottky barrier diodes as manufactured by Raytheon Special Microwave Devices Operation and indeed the initial performance of these devices at the time of acceptance was very good in terms of efficiency and yield. However, in the course of a few months an alarming number of these diodes began to fail - some of them in operation and some on the shelf. Fortunately, because of the insistence of Dr. Chung Kim (Raytheon's Special Microwave Devices Operation) that the PHS diode construction was much superior and because the Equipment Division had become interested in late 1973 in funding a development of the PHS diodes specifically for rectenna purposes, a number of these PHS diodes had become available for evaluation, and were found to be much more reliable. Consequently at the time of the primary design review, a change was made in the type of diode specified for the RXCV construction.

Again at the time of proposal preparation there had been no determination of the collection efficiency of the MSFC rectenna. This was a technical area of prime concern, and was the major consideration in the determination of the nature of the breadboard tests to be made early in the program. By the time of contract negotiation, some initial data from the MSFC rectenna had been obtained. This data indicated that the collection efficiency was over 95 percent. Although the operational frequency of the RXCV was to be 2388 MHz rather than 2450 MHz (used for the MSFC work) leaving the collection efficiency at 2388 MHz to be evaluated. The data indicated that the spacing of the rectenna elements from each other could be carried into the RXCV subarray design.

It was also recognized that the circular format of the bus bars for the collection of the dc power in the MSFC rectenna, which had been specifically designed to receive a microwave beam with Gaussian power distribution, was not suitable for the RXCV. Previous experience on other rectennas provided some indication that a collection of the dc power by a row format should be successful. The row format, because of its mechanical and electrical desirability, was chosen as the design approach. However, a breadboard experiment was determined to be essential to provide the final assurance that this approach was suitable.

In the mechanical design process for the subarray, some unique strategies were implemented to deal with contingencies. Because of the lack of data on the collection efficiency of the design and because it was known that the collection efficiency could be varied within limits by the separation between the dipole and the reflecting plane, a provision was made to adjust this distance in the production model. The adjustment was made possible by the movement of the bus bar system (to which the rectenna elements are supported) with respect to the rest of the subarray. The bus bar system is supported on nine threaded rods with adjustable nuts which are attached to the reflecting plane. Each nut is independently adjustable so that the bus bar system can be accurately positioned from the reflecting plane at nine points. The bus bar system is tied together by three vertical beams to which the individual bus bars are pop riveted. This feature also provides for changing element to reflecting plane spacing in field operations associated with characteristics investigations.

One of the design problems associated with the assembly of the rectenna elements into the bus bar system at the sides, top and bottom was the accessibility problem. This was solved by leaving the frame assembly as one of the final steps. This procedure, of course, means that if a rectenna element in the extreme corner of the subarray had to be replaced, the sides of the frame would probably have to be removed.

Another characteristic of the mechanical design is that the same threaded studs which support the bus bar system from the reflecting plane also extend to and through the rear cover and are clamped to the rear cover by nuts on front and back side. In this way, the reflecting plane and the back cover complement each other in resisting mechanical distortion caused by wind pressure.

In summary it may be stated that the strategy in the design of the subarray and its critical components was to adhere as closely as possible to the MSFC rectenna design, while still meeting the special requirements imposed by the JPL RXCV. Although the original plan was well defined, recognition was given to the probability that new information resulting from the completion of the MSFC contract and from other efforts including the breadboard results would lead to some modification of the original plan.

The original strategy for meeting the environmental requirements of the RXCV Program was to provide each rectenna subarray with its own individual atmosphere by enclosing it in a radome and using a dehumidifier which would be replaced at required intervals. However, due to high anticipated costs as well as complexities of assembly with this arrangement, an effort was made to design the subarray in such a manner that it could cope directly with the environment without the necessity of the radome. A key development in this effort was the development of a conformal coating for the individual elements which prevented corrosion from developing between dissimilar metals used in different parts of the rectenna element. As a result of this effort and confidence produced with the operation of the breadboard without a radome, the radome for the prototype design was abandoned. Substantial cost and time savings were thereby achieved and the simplification of design lead to a more satisfactory arrangement for inspection and maintenance procedures. The unavoidable impact of the radome upon the microwave impedance of the subarray was also eliminated.

There was one known defect in the MSFC rectenna element design for the kind of operation expected in the RXCV application. This defect was identified with the use of nylon machine screws in the assembly. Nylon has a "runaway" characteristic if it is used in a microwave field of sufficient intensity. Its loss tangent increases rapidly with an increase in temperature, leading to increased dissipation and increased heating, and finally melting. The design to eliminate this is discussed in paragraph 2.2.

The physical dimensions of the subarray were largely determined by the availability of raw material and suitable manufacturing equipment for the reflecting plane of the rectenna subarray. These dimensions also coincided with a size that was convenient to assembly and transport. The resulting modularity provides the opportunity, through rearrangement of the subarrays, to investigate characteristic features of this and other designs. The approximately 1.2 x 1.2 meter (4 x 4 ft) configuration is convenient for developing test models of more advanced design, and for permitting their testing in the open 18th subarray location (currently at location at 1B) in the array.

2.2 ELECTRICAL DESIGN AND DEVELOPMENT OF THE RECTENNA ELEMENT

The design of the rectenna element is based closely on that of the rectenna element designed for use in the MSFC rectenna development. In contrast to the design of earlier rectenna elements which made use of four Schottky barrier diodes arranged in a full-wave bridge rectifier format, the MSFC and RXCV rectenna elements use only a single diode in a half-wave rectifier format. It has been found that the half-wave rectifier when combined with suitable wave filters which isolate the rectifier from direct connection to the half-wave dipole input can result in a surprisingly high efficiency for the complete rectenna element (as high as 88 or 89% for selected diodes), see Section 2.3.1 on the diode evaluation. Although a little higher efficiency is anticipated (it has not yet been demonstrated) for a full-wave rectifier, the advantages of the half-wave rectifier from the point of view of reducing the cost of the diodes and the balance of the rectenna element are considerable. A study of the topology of the conventional full-wave rectifier indicates much more complexity of construction. The cost and delivery schedules for the diodes using a full-wave rectifier format would have been much greater. We were fortunate to have the MSFC design well in hand at the time of the interest of JPL in the Goldstone demonstration facility.

The electrical design of the RXCV rectenna element is shown schematically in Figure 2-6. The corresponding mechanical design is shown in Figure 2-7. A photograph of the rectenna element is shown in Figure 2-8.

As shown schematically in Figure 2-6, the rectenna element consists of a half-wave dipole, a two section low pass filter, and a parallel resonant rectifier section consisting of the diode capacitance, and a microwave shorted section of transmission line whose length can be adjusted to provide the proper value of parallel inductance. The sliding microwave short which incorporates a high value of capacitance, also serves as a smoothing filter to remove microwave components from the dc output.

The low pass filter is a most essential part of the rectenna element. It serves to attenuate any harmonic power which propagates toward the half-wave dipole where it would be emitted as RFI and it serves as a storage of energy during the nonconductive portion of the rectification cycle, acting as a buffer

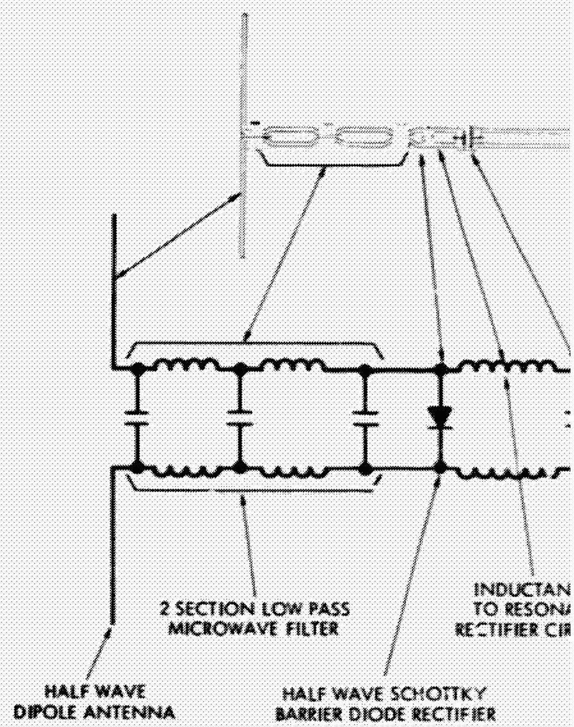
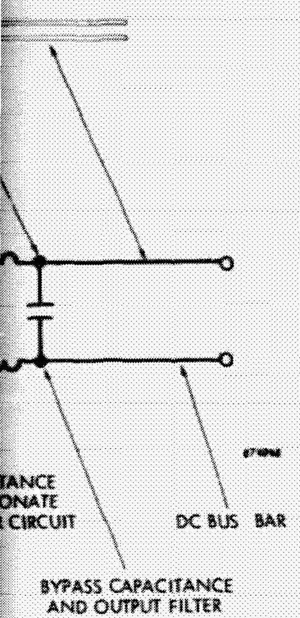


Figure 2-6. Simplified Electrical Schem
Element Used for the JPL R

Figure 2-8.



ematic for the Rectenna
RXCV

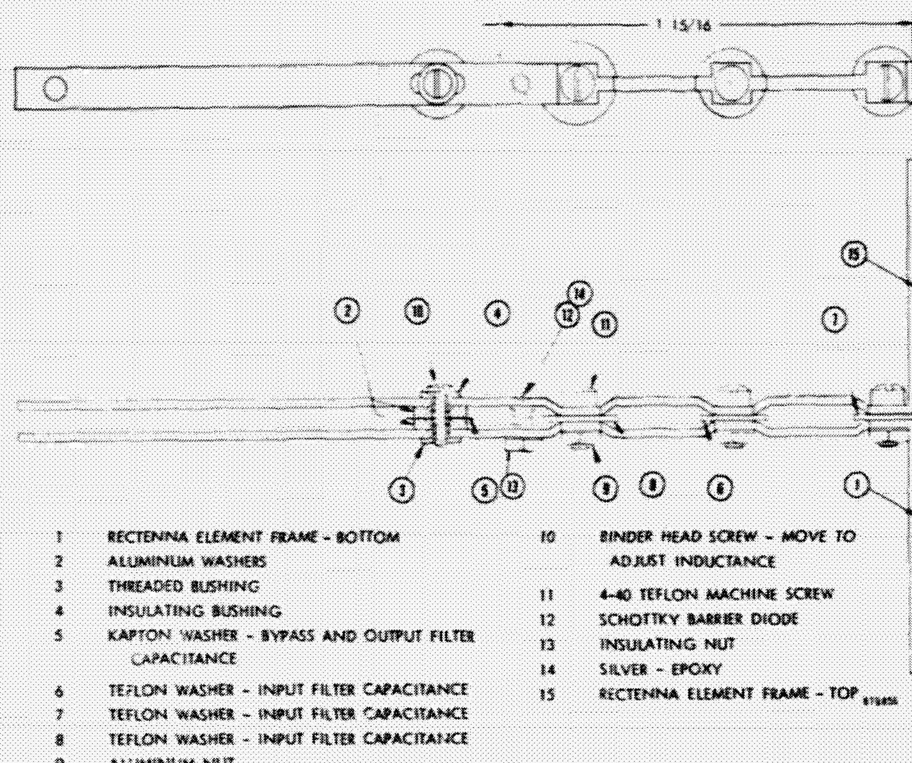
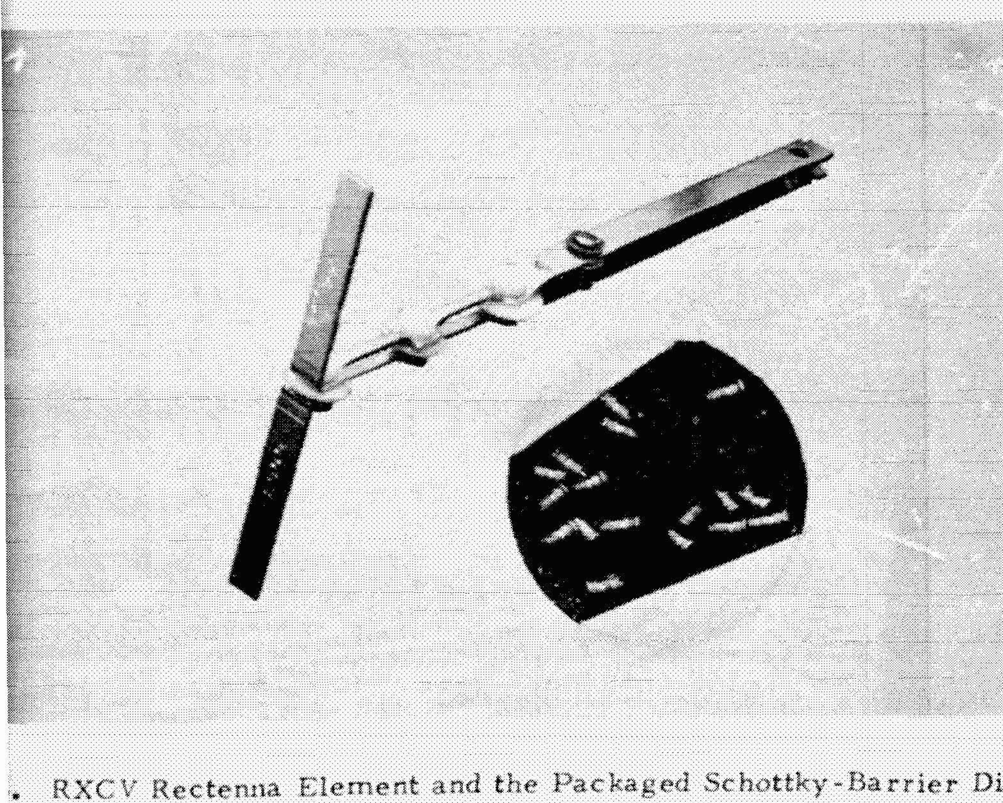


Figure 2-7. Detailed Assembly of the RXCV Rectenna Element



. RXCV Rectenna Element and the Packaged Schottky-Barrier Diodes between the even flow of power into the half-wave dipole and the intermittent flow of power through the rectifier. The characteristic impedance of the filter is matched to the impedance of the half-wave dipole. Both are approximately 120 ohms.

In the original MSFC rectenna element design, the length of the half-wave dipole and the spacing of the dipole from the reflecting plane was determined by S-curve procedures, utilizing a two bar transmission line consisting of two 1.587 mm (0.0625 inch) x 4.762 mm (0.1875 inch) rectangular bars. A good match was obtained with a spacing of 2.743 mm (0.108 inch) between the bars. In the RXCV element the thickness of the bars were reduced to 1.016 mm (0.040 inch) which would have some impact upon the impedance of the half-wave dipole as well as the wave filters, and a 4.762 mm (0.1875 inch) round sleeve was left off the ends of the antenna. These changes were of a minor nature and were made without rechecking the impedance of the antenna and its match to the transmission line.

The phase shift, attenuation characteristics and the characteristic impedance of a single section of the wave filter are shown as a function of frequency in Figures 2-9 and 2-10. A mid-shunt design of the filter section was used because its increasing characteristic impedance as a function of frequency facilitated the mechanical design of the filter. At the MSFC design frequency of 2450 MHz the phase shift through each filter section was approximately 90 degrees.

Since the initial operation of the JPL RXCV was to be 2388 MHz, but in future years might change to 2450 MHz to be compatible with a phased array transmitter, it was felt important to determine the behavior of the MSFC rectenna element at the two different frequencies. This relative behavior is shown in Figures 2-11 and 2-12. Figure 2-11 indicates the behavior as a function of frequency when the rectenna element is adjusted for minimum power reflection at 2450 MHz, while Figure 2-12 indicates the behavior as a function of frequency when the rectenna element is adjusted for minimum reflection at 2388 MHz. The excessively high efficiency readings at the lower frequencies are probably caused by a change in the coupling characteristics of the directional coupler used

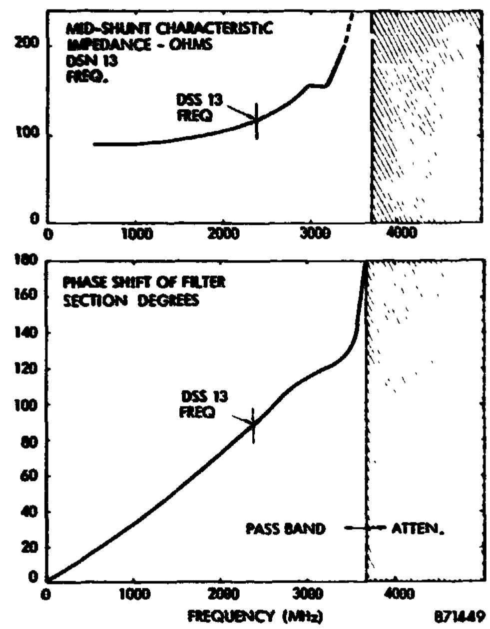


Figure 2-9. Phase Shift and Mid-Shunt Characteristic Impedance of Filter, MSFC Rectenna

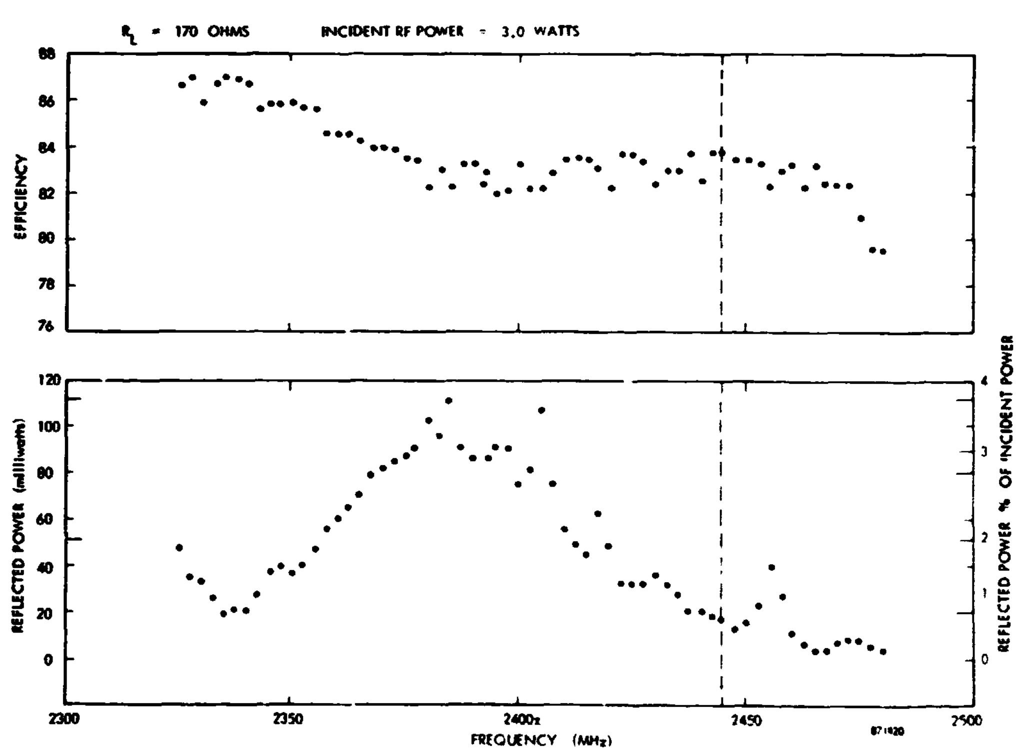


Figure 2-11. Efficiency and Reflected Power as a Function of Frequency, Element Matched at 2445 MHz

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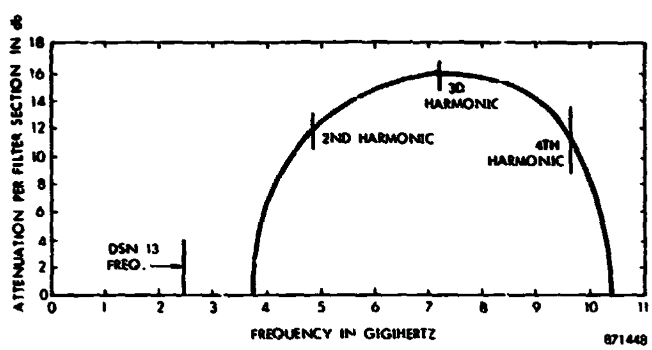

Figure 2-10. Attenuation Characteristic for a Single Section of the Low Pass Filter, MSFC Rectenna Element

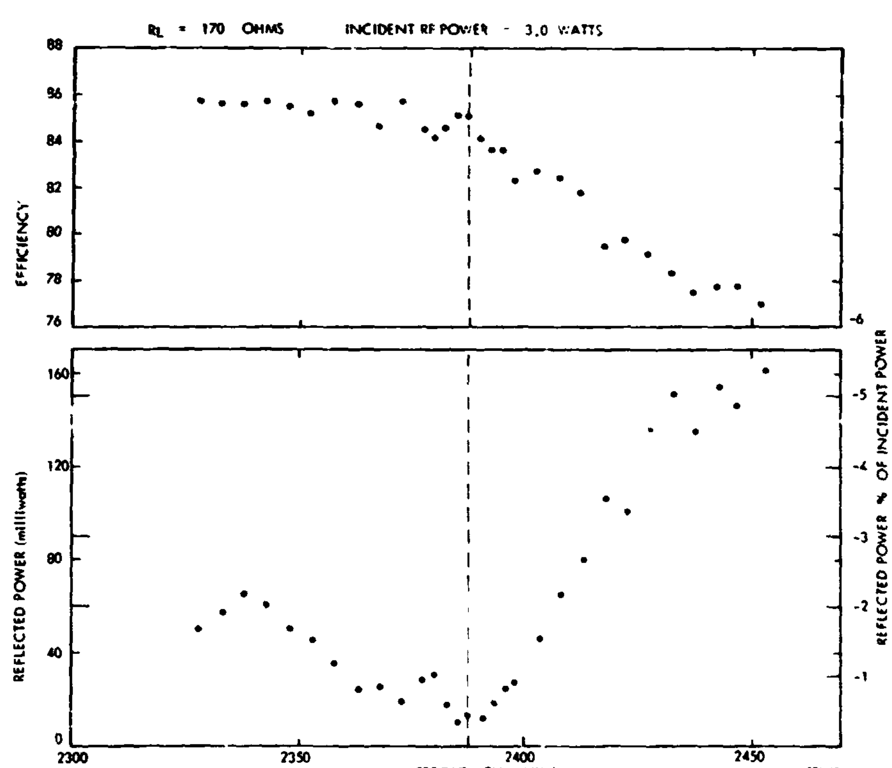

Figure 2-12. Efficiency and Reflected Power as a Function of Frequency, Element Matched at 2388 MHz

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to monitor the power input. Although the RXCV elements are not identical to the MSFC elements, it is probable that good performance could be obtained from the JPL RXCV at 2450 MHz without having to retune the rectenna elements - although that would have to be done if maximum rectenna efficiency were desired. If operation in the future at 2450 MHz is desired the data should be repeated for the actual RXCV element.

Other characteristics of the MSFC rectenna element which are assumed to be similar to the RXCV element are 1) efficiency and reflected power as a function of incident power level, 2) efficiency as a function of load resistance, 3) reflected power as a function of load resistance, and 4) short circuited current and absorbed power as a function of microwave power input. These are given in Figures 2-13 through 2-16 respectively.

2.2.1 MECHANICAL DESIGN OF THE RECTENNA ELEMENT

An important objective in the design of the RXCV rectenna element was to substantially reduce the material and fabrication cost of the rectenna element over that of the MSFC design. Even though the diode cost would remain the principle part of the rectenna element cost, cost savings in terms of parts and assembly labor were important in meeting the overall cost and schedule objectives.

In the mechanical design of the rectenna element as shown in Figure 2-7 it was essential to have a sliding short to compensate for variations in circuit parameters. It was not known in advance whether the short could be preset at a fixed position for all assemblies or whether it would have to be adjusted for each assembly at electrical test. (It turned out that only about 10% of the assemblies with preset positions of the short needed subsequent repositioning.) The sliding short was made possible by slotting both rails of the rectenna element. The physical position of the short was set in the assembly fixture at a point that gave minimum reflected power, established from a sizeable sample of rectenna elements.

One of the major changes sought in the redesign of the rectenna element was another method of holding the assembly together because the nylon machine screws were unsatisfactory from an electrical point of view. Several approaches

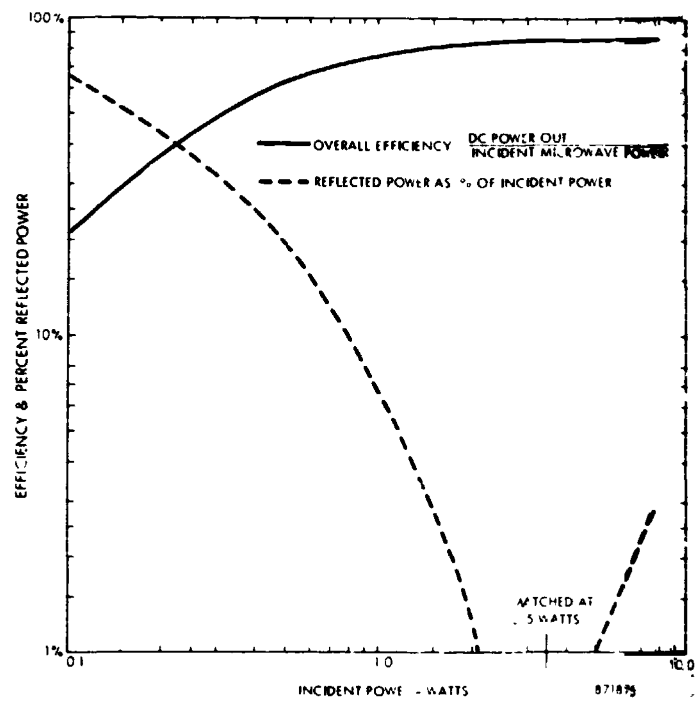

Figure 2-13. Efficiency and Reflected Power as a Function of Incident Power Level

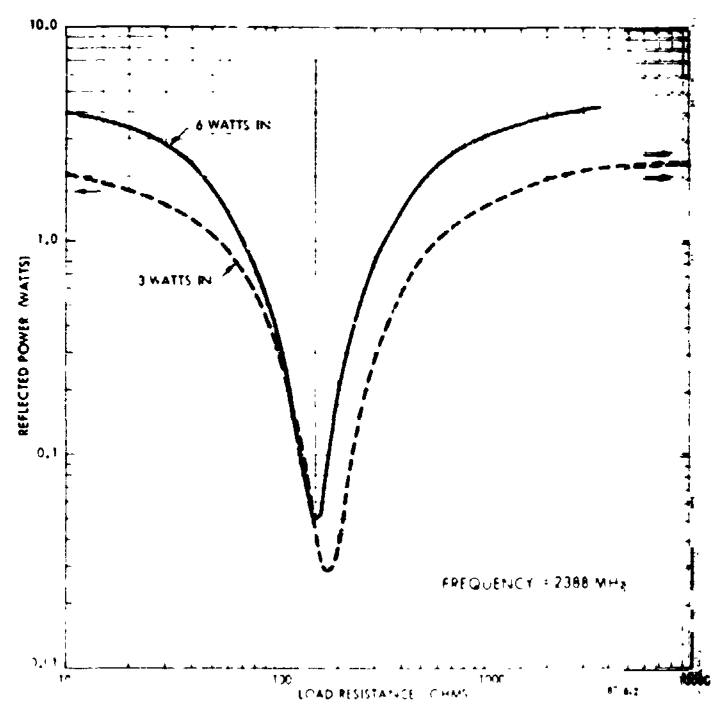

Figure 2-15. Reflected Power as a Function of Load Resistance

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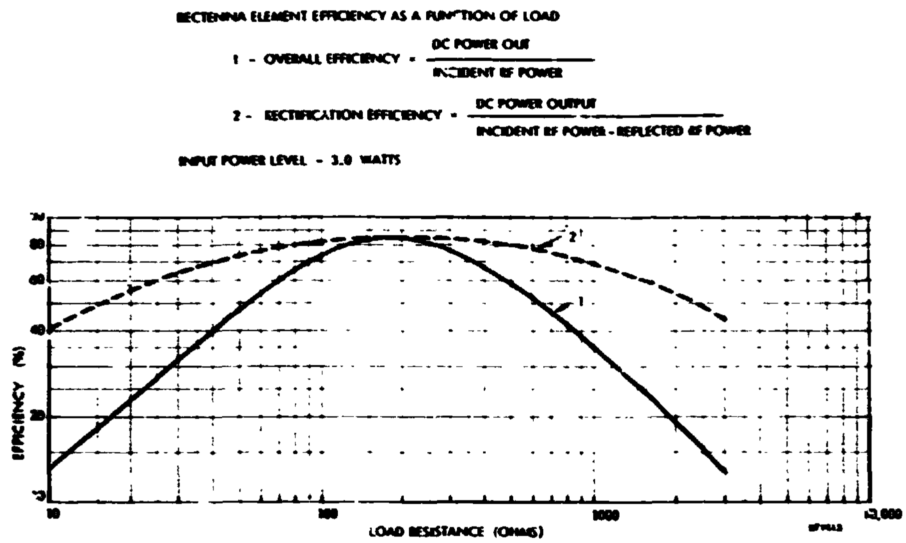

Figure 2-14. Efficiency and Reflected Power as a Function of Load Resistance

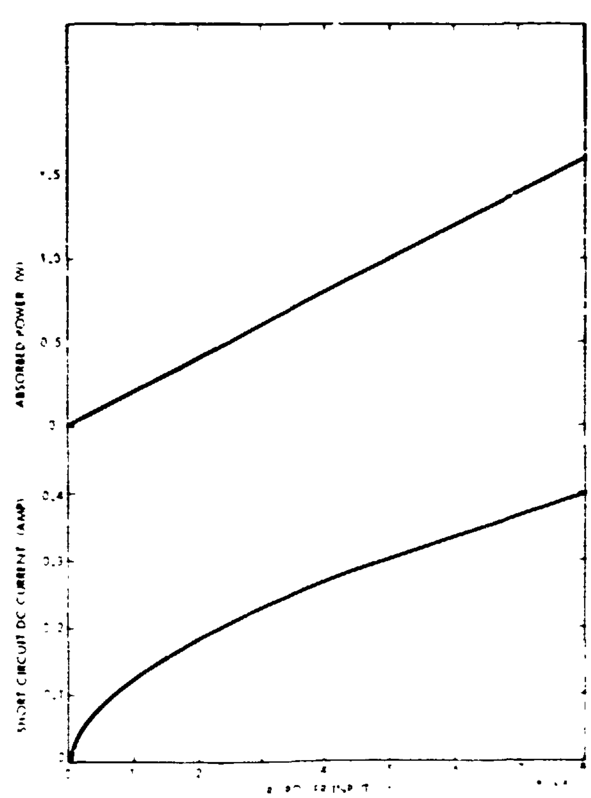

Figure 2-16. Short Circuit Properties of Rectenna Element

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were considered, a metal rivet with insulating washers, an aluminum-oxide ceramic pin, plastic rivets, and the substitution of Teflon machine screws for the nylon screws. The latter solution was adopted, primarily because the approach was straightforward, the parts could be obtained commercially and the substitution would not upset the rather sensitive capacitance parameters in the low pass filter. However, Teflon is mechanically quite weak and tends to flow plastically at relatively low tensile stress. This problem was overcome by using a 4-40 machine screw rather than a 2-56 machine screw, and with the use of torque screwdrivers which prevented over stressing of the teflon.

It is recognized, of course, that in use there are no external forces which tend to pull the siderails apart.

An essential concern in the design of the rectenna element was its reliability under a large number of different environmental conditions. This consideration took on additional significance when the decision to eliminate the radome resulted in exposing the rectenna element to wind and varying humidity conditions. A major concern involved the high contact potential between the gold plate on the diode and the aluminum side rail which could result in rapid corrosion with moisture present. This potential source of difficulty was eliminated through the use of a conformal coating process involving a cleaning operation, a primer (Dow Corning 1203) and the coating (DC3140) itself. However, in testing an early sample of elements that had been conformally coated, an open contact between the top of the diode and the side rail was noted in a small percentage of the samples. This separation could have been caused by the powerful wetting action of the coating permitting it to flow between the diode and the side rail, causing a permanent open circuit. But regardless of the cause, a precaution in insuring a permanent contact in the units was needed. For that reason a change in assembly procedure to include the application of silver epoxy to bind the head of the diode to the side rail prior to the application of the conformal coating was made. This bonding procedure was applied to all elements except the power elements installed in the prototype subarray. This deviation for the prototype unit was considered to provide an opportunity for assessing the performance in field operations without the bonding. As of this writing there has been no noticeable performance changes in the prototype elements after ~65 hours of operation.

With the dipole portion of the rectenna elements now exposed in the final rectenna subarray assembly, ere was some concern that the rectenna elements would vibrate in the wind because of the vortex shedding process whose frequency at some wind velocity might coincide with a mechanical resonance of the rectenna element. This coincidence could cause excessive vibration and an overstressing of the siderails, leading to ultimate failure. To evaluate this possibility further, tests were first made on a shake table to determine natural resonances and mechanical failure modes. This was followed by a check in a wind tunnel with winds up to seventy miles per hour. Although vibration was present as revealed by strain gauges, the maximum stresses induced in the rectenna element were a small fraction of the allowables for the material. Details of these tests are presented in Appendix A.

2.2.2 PRODUCTION OF THE RECTENNA ELEMENTS

The assembly of the rectenna elements was rapidly and effectively carried out by one exceptionally well qualified assembler and a simple but effective assembly jig. The average number assembled in an eight hour day was approximately 80 elements. The use of the assembly jig is shown in Figures 2-17 and 2-18. The securing nut of the sliding short is first placed in position. Then one of the side frames with the diode in position is placed in the jig, followed by the Teflon washers which form the capacitances of the filter. The two metal washers and the Kapton washer are then placed in position using a jig pin, and the other side frame is added. Finally the three Teflon machine screws that hold the side frames together and the machine screw that holds the sliding short together are inserted. The entire assembly is then removed from the jig and hi-potted to make certain that there is adequate dc insulation between the two side rails. The diode is the torqued in to secure contact with the opposing side rail.

The next step in the assembly procedure is the application of the silver epoxy and a baking cycle to cure it. The rectenna elements are then sent through the conformal coating procedure.

The electrical test of the rectenna element is a key activity in quality control. The test set up is shown in Figure 2-19. The element is operated with six watts of incident microwave power in the expanded waveguide fixture and the

Figure 2-17. Assembly of Rectenna Element

Figure 2-18. Assembly of

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Rectenna Element

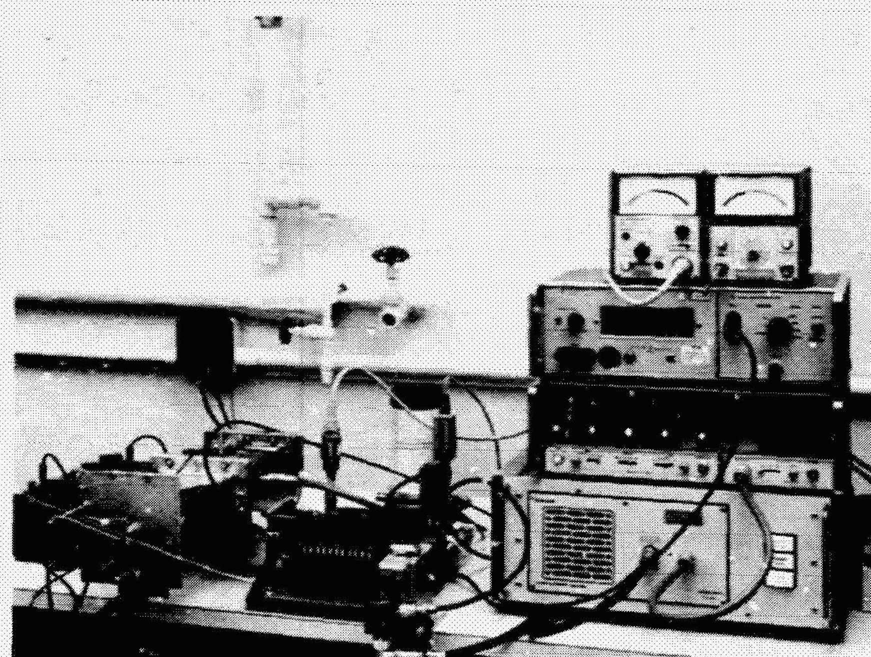

Figure 2-19. Rectenna Element Test Setup

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efficiency as well as the reflected power are noted. Of course any short circuited or open circuited diodes are immediately found with this procedure, as are any shorts or opens from other causes. However, after the final design of the rectenna element and after the processing and assembly procedures had been worked out, no open or shorted elements for reasons other than defects in the diodes were found.

Any rectenna elements in which the reflected power was more than 60 milliwatts were reprocessed to minimize the reflected power by repositioning the microwave short circuit.

2.3 DESIGN OF THE SCHOTTKY BARRIER DIODE

The design of the Schottky barrier diode (shown as a packaged element in Figure 2-8) can be broken down into two parts. The first is the basic construction of the device, including all features designed to promote the reliability of the device. The second is the specifications of the electrical parameters of the diode to optimize the performance of the device in the RXCV rectenna application.

It has been pointed out that based upon the better reliability of the plated heat sink (PHS) diode as compared to the conventional "flip chip" diode, a decision was made to specify the PHS construction. This decision has been more than justified. This type of construction combined with screening procedures for selections of diodes before shipment and 100% testing for microwave properties during the assembly of the diodes into the subarrays has resulted in exceptionally high reliability. No diodes among the 4590 used in the entire rectenna array were found faulty when tested upon arrival of the subarrays at Goldstone. Further, over 360,000 diode hours have been accumulated on a life test at Raytheon with diode failures limited to those associated with infant mortality (see Section 3.3).

It is believed that the RXCV contract provided the first opportunity to formally specify a set of tests that a Schottky-barrier diode would have to pass before being accepted for a high power microwave rectifier application. This was not a trivial exercise in writing procurement specifications because the vendor could not guarantee the microwave efficiency performance of the diode in a rectenna element over whose design he had no control and where the contribution of the diode to inefficiency could not be separated. Further, a microwave screening test at the vendor based upon insertion into a "standard" rectenna element would greatly add to the cost of the procurement. It became evident that any diode tests in the purchase specification should be based upon dc measurements. However, there should be a firm correlation between these screening tests and the microwave performance of the diodes in the actual application. The specification of a set of simple dc measurements was made possible by a good understanding of the relationship between such a set and the microwave efficiency as well as the power handling capacity of the diode. Moreover, the firm establishment of the purchase specification was made contingent upon the evaluation of the first 500 production diodes in the microwave application.

The setting of the diode specifications may be visualized as a two step process. The first step was the establishment of the diode design without reference to dc measurements. The second was the translation of this design into a set of dc measurements which would enable the vendor to properly specify the diode construction parameters.

Although a general design procedure has been worked out for maximizing the efficiency performance of a microwave diode at a specified power handling level, it is enough for our purposes here to point out the principal microwave losses in a diode. These losses consist of the Schottky barrier voltage drop (similar to the brush drop in a generator) and resistive losses which occur in both the forward conduction period and in the non-conduction period. The losses in the non-conduction period occur because of the charging current for the diode capacitance which has to flow through the series resistance in the diode. However, the series resistance and the capacitance becomes less as the applied reverse voltage increases in a manner that makes computation of these losses rather complex. It is this loss in the non-conduction period which distinguishes between high frequency operation of a diode and low frequency operation where these reverse losses can be ignored.

From these microwave loss considerations we can arrive at an optimum design for a given power handling level by specifying the reverse breakdown voltage and the capacitance of the diode at zero bias. The breakdown voltage, V_{br}, in effect specifies the doping density used in the active epitaxial layer of the diode while the capacitance, C_{to}, specifies the active cross sectional areas of the diode. However, these specifications of reverse breakdown voltage and zero bias capacitance must be made contingent upon making the epitaxial layer as thin as possible consistent with the breakdown voltage specification since the series resistance in the active region of the diode is proportional to the thickness of this epitaxial layer. In addition to this series loss there is an almost negligible series loss in the bulk gallium arsenide (GaAs) material and a highly variable and non-negligible loss in the ohmic contact which is made to the bulk material. For all these reasons it is also necessary to specify a test parameter which will insure that the series resistance is not too high. This test parameter has been determined as the voltage required to conduct 200 milliamperes of current through the diode in the forward direction. Actually the specification of the slope of the voltage-current characteristic around the 200 milliampere point would be a more sensitive measure of the series resistance since the Schottky barrier voltage is included in a dc measurement. However, the Schottky barrier voltage is itself a loss and its contribution does get included in this measurement.

The three specifications which were given to Raytheon's Special Microwave Devices Operation (SMDO) were:

Reverse breakdown voltage, V_{br}	55 - 70 volts
Zero bias junction capacitance, C_{to}	3.6 - 3.8 picofarad
Forward voltage for 200 mA of current	1.0 volt dc

The engineering staff in SMDO then used these specifications to order GaAs wafers with the following specifications on the active epitaxial layer:

Doping density	$9.5 \times 10^{15} \pm 20\%$
Thickness of active epitaxial layer:	4.5 micron $\pm 10\%$

In addition an epitaxial buffer film of 1×10^{18} doping density was used.

The zero bias junction capacitance, C_{to}, was obtained during the construction of the diodes after the application of the platinum barrier by an etching process which reduced the cross sectional area of the Schottky-barrier junction to the value which gave the specified value of capacitance.

The three specifications negotiated with the Special Microwave Devices Operation were established on the basis of experience derived from the diodes constructed for the Marshall Space Flight Center contract. They were specifically tailored for a diode that would operate at its maximum efficiency at a power output of five watts. A power output of five watts was considered to be a conservative figure for the RXCV. However, during the execution of the contract a desire developed to operate the subarrays at a considerably higher power level than originally anticipated. For this higher power operation a diode with a higher V_{br} is needed, particularly at the center of the array where the power density is the highest. Therefore, when an opportunity arose to order new wafers for the final manufacturing lots, the V_{br} specification was changed to allow for a higher breakdown voltage.

Traceability of any defective diodes back through the manufacturing process and the wafer quadrant position in the furnace in which the epitaxial layer was deposited was considered of great importance. This traceability was made possible by serial numbering each rectenna element and keeping a record of the diode serial number that went into it. Each diode serial number identified the origin of its semiconductor chip with respect to the furnace where the epitaxial growth was performed, the sequence number of the furnace run, the one position in three that the wafer was in during the furnace run, the dice lot number and the manufacture lot number.

KEY TO DIODE IDENTIFICATION

4 0556 A P X 1 C #12

- #12 → Serial No.
- C → Signifies the third lot made from the dice lot
- 1 → Signifies the first dice lot from the wafer
- X → Signifies PHS construction
- P → Signifies production
- A → Signifies one of three positions of the wafer in the epataxial furnace (A, B, C)
- 0556 → Signifies the number of the furnace run
- 4 → Signifies which furnace

2.3.1 TEST DATA ON THE FIRST 500 DIODES

To be certain that the specifications as given to SMDO and that the diodes they designed and manufactured to these specifications were satisfactory from an RF performance point of view, the first 500 diodes were individually checked for performance in a standard rectenna element into which the individual diodes could be inserted for test. The testing procedure fulfilled that function but in addition a great deal of useful information was obtained concerning the distribution data on diodes and the correlations between dc measurements and RF performance. In fact, the effort of diode design together with data collection, while not meant to represent a development effort, has contributed to progress in upgrading the efficiency of diodes and certainly much to our understanding of their operation and consistency in high power rectifier circuits. Since this report represents the first time such data has been analyzed and published, it is probably worthwhile to discuss it in more detail than would normally be justified.

An important aspect of these measurements is the accuracy of the original calibration of the test setup and the confidence that the calibration remained intact over the time the diodes were tested. The test setup for these measurements was similar to that shown in Figure 2-19 for the production testing of rectenna elements. For an accurate calibration of the equipment, a necessary component is a power standard. For this calibration we used a secondary power standard that had been calibrated at the Bureau of Standards facility at Boulder, Colorado at 2444 MHz. The probable error of the Bureau of Standards calibration is 1%. An estimated probable error in the transfer to our test set is an additional 1%. In addition there is a probable error of 0.5% in transferring this calibration to 2388 MHz. This transfer was done on the basis of the slope of the coupling coefficient versus frequency characteristic of the directional coupler. Thus the probable error on the mean value of any set of measurements is $\pm 1.5\%$. In addition to the probable error of the mean measurement there are items which tend to disperse the data around the mean value. A principal such item is the reflected power which varies considerably, but which was not taken into consideration when computing the efficiency. If the reflected power were considered the efficiency on the average would be a small fraction of a percent higher.

To provide confidence that the original calibration had remained within narrow bounds, a standard rectenna element consisting of one rectenna element with a diode permanently mounted in it was used periodically to assure that no substantial change in the calibration had occurred. In addition an effort was made not to change the physical test set up in anyway so that the original calibration would remain in effect.

The production of the first 500 diodes was broken down into eight lots. The number in the delivered lot reflected the yield derived from a starting lot and the size of the starting lot. Lot numbers are in time sequence. Figure 2-20 summarizes the diode evaluation program, lot by lot, in terms of average efficiency, average voltage for 200 mA of forward current, average breakdown voltage, and average zero-bias capacitance.

The distribution of diodes with efficiency is shown in Figure 2-21 for all lots with the exception of Lot 1. The individual lot contributions are shown. The skewed geometry of the distribution is largely caused by Lot No. 7 whose efficiency was considerably lower than the average of the other lots. Even so there is seen to be a high level of consistency in the efficiency of the diodes; the average deviation is less than 2%. Those few diodes with efficiencies below 82% appear not to be a part of the distribution and are invariably associated with a high value of internal resistance. The average efficiency of the lots (weighted for number of diodes in a lot and with Lot No. 1 eliminated) was 86.12%. With Lot No. 7 and No. 1 excluded, the average efficiency was 86.65%. The average of the deviations of efficiency from the mean was 1.38% (all lots).

The distribution of diodes with forward voltage for 200 mA of current is shown in Figure 2-22. The dispersion here is considerably greater than the distribution of diodes with efficiency indicating that there are other contributions to the inefficiency which tend to reduce the importance of the internal series resistance of the diode upon efficiency consistency. However, there is a high level of correlation between efficiency and forward voltage for 200 mA of current. Figure 2-23 shows this relationship for Lots 2 and 3.

LOT NUMBER	NUMBER IN LOT	YIELD AT SMDO (%)	ELECTRICAL PROPERTIES			
			AVERAGE EFFICIENCY (%)	AVERAGE FORWARD VOLTAGE FOR 200 mA	AVERAGE BREAKDOWN VOLTAGE	AVERAGE CAPACITANCE (pf)
1	14	18.2	87.0*	0.972	66.8	3.71
2	29	23.2	85.6	0.951	66.0	3.77
3	51	30.7	88.1	0.916	59.6	3.65
4	125	56.8	87.4	0.944	63.9	3.75
5	107	53.5	86.2	0.945	67.0	3.73
6	40		84.9	0.959	61.4	3.65
7	95		83.9	0.949	60.5	3.67
8	50		86.3	0.921	63.6	3.70
TOTAL	511	Wt'd Avg.→	86.12			

*DATA FOR LOT 1 EXCLUDED IN WEIGHTED AVERAGE %

879854

Figure 2-20. 500 - Diode Evaluation Program by Lot

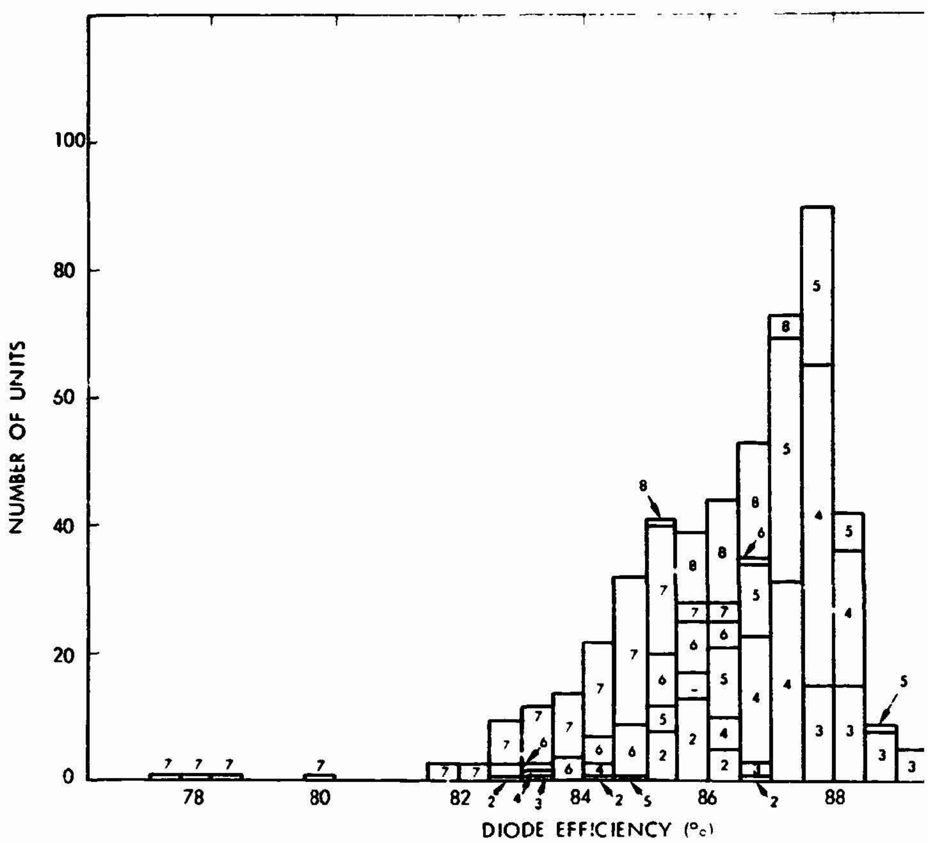

Figure 2-21. Diode Efficiency Distribution

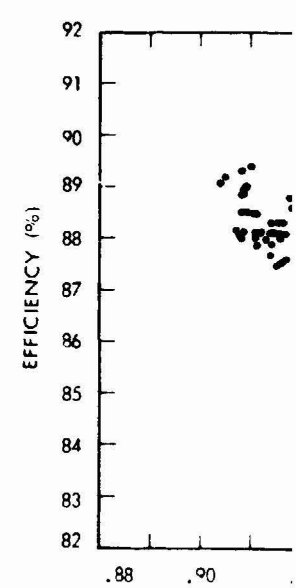

Figure 2-23.

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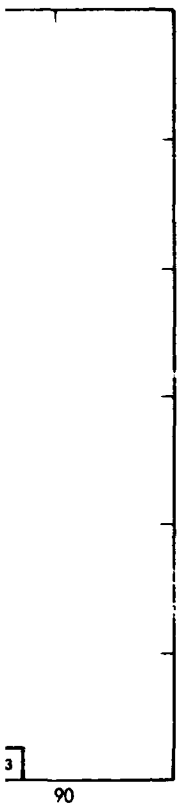


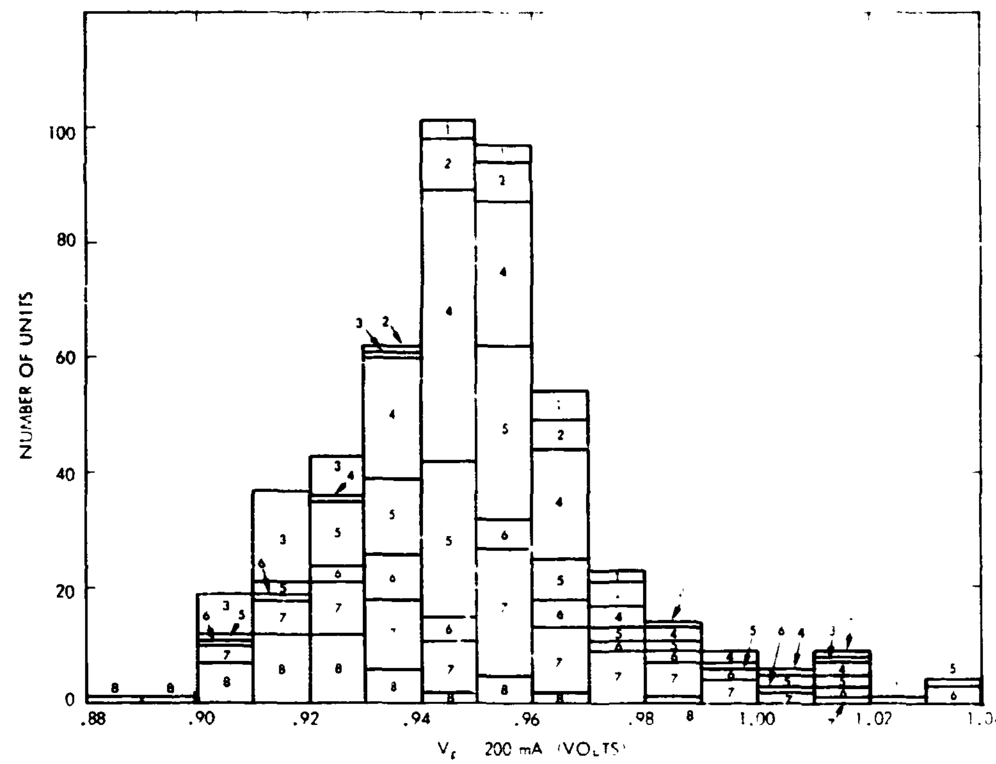
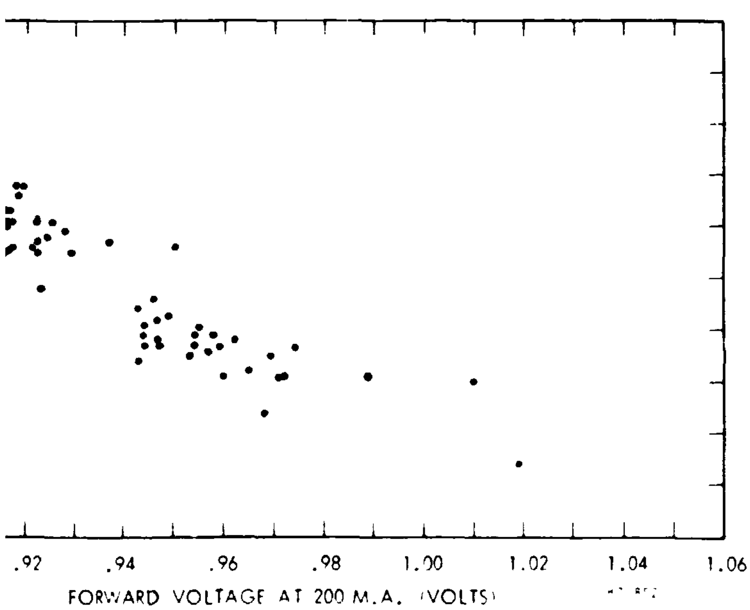


Figure 2-22. Forward Voltage Distribution



Correlation of Efficiency and Forward Voltage

The forward voltage can be considered to consist of the Schottky barrier voltage and the IR drop in the internal resistance of the diode. This relationship is shown graphically in Figure 2-24. If we subtract out the intercept voltage of 0.82V from the forward voltage for 200 mA of current, we can then determine the internal resistance from the slope of the voltage current characteristic. This has been done in Figure 2-25. If the slope of the relationship between efficiency and internal series resistance is extended to intercept the $R_s = 0$ line, the efficiency is seen to be in the 91 to 92% region. Hence, the R_s in the most efficient of the rectenna element diodes is seen to contribute an inefficiency of only about 3% while in the poorer diodes it can run to two or three times that amount.

An inefficiency of 2.9 - 3.0% is contributed by the power drop through the Schottky barrier itself. The inefficiency of the best rectenna elements is 11% (if we assume that the calibration of the test equipment is accurate). Thus the remaining inefficiencies amount to 5%. Of this the circuit losses account for between 2 and 3%, leaving approximately 2% unaccounted for.

In summary it is seen that the efforts associated with the design, production, and testing of the PHS Schottky barrier diodes, procurement and correlation of microwave test results with specifications have resulted in a much better understanding of 1) how to design diodes for high power microwave rectification, 2) how to specify diodes for procurement purposes, and 3) the degree of microwave performance consistency of lots of diodes. This understanding plus the information that is being obtained from the rather massive life test described in Section 3.3 represents a major step forward in the maturation of the design and production of diodes for microwave power transmission purposes.

2.4 DC LOAD

The power output from the RXCV subarrays is dissipated in an instrumented dc load (Figures 2-26 through 2-28) having 18 identical, electrically independent circuits, one for each rectenna subarray position on the collimation tower. Each load circuit includes two incandescent lamps, four power resistors and a two position power range switch. Each load circuit provides independent resistive loads for a subarray main power output and a calibration diode output. Each load circuit has the capacity to dissipate over 2000 watts of subarray main power output when switched to the high power range and over 1100 watts in the low power range.

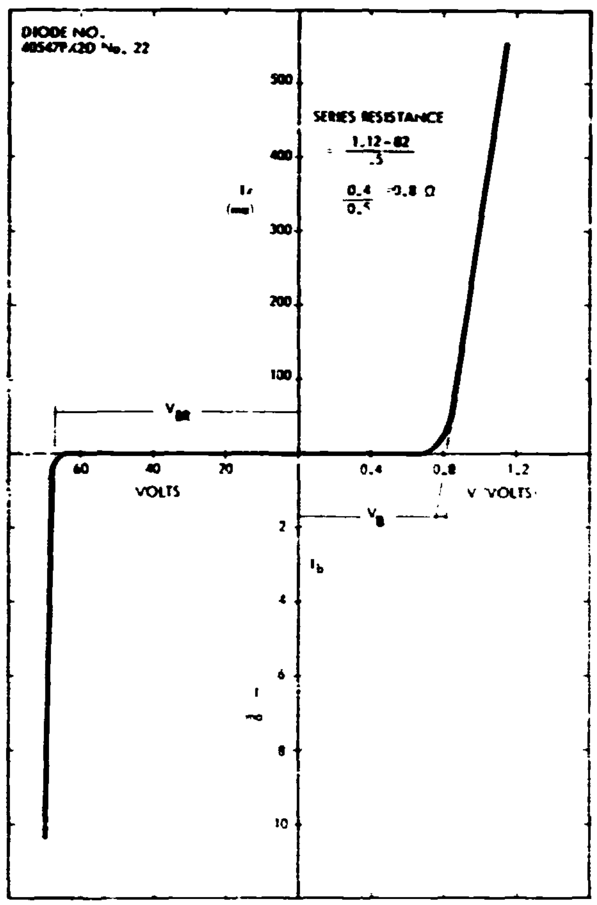


Figure 2-24. Typical Diode Voltage Current Characteristic

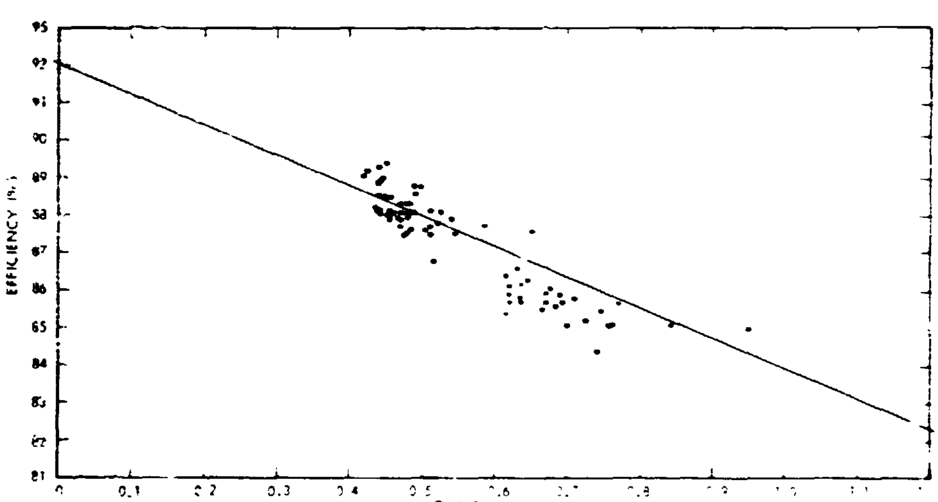
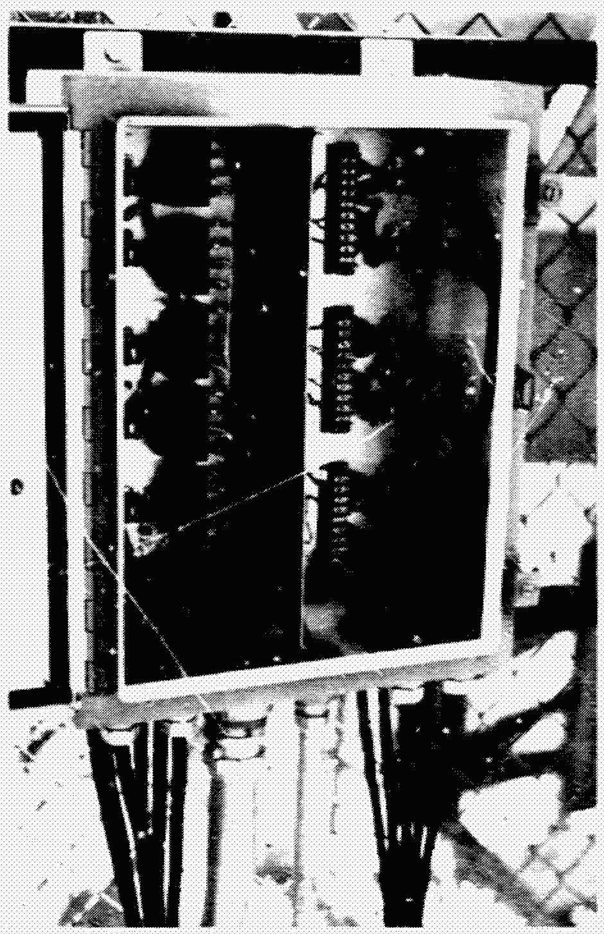
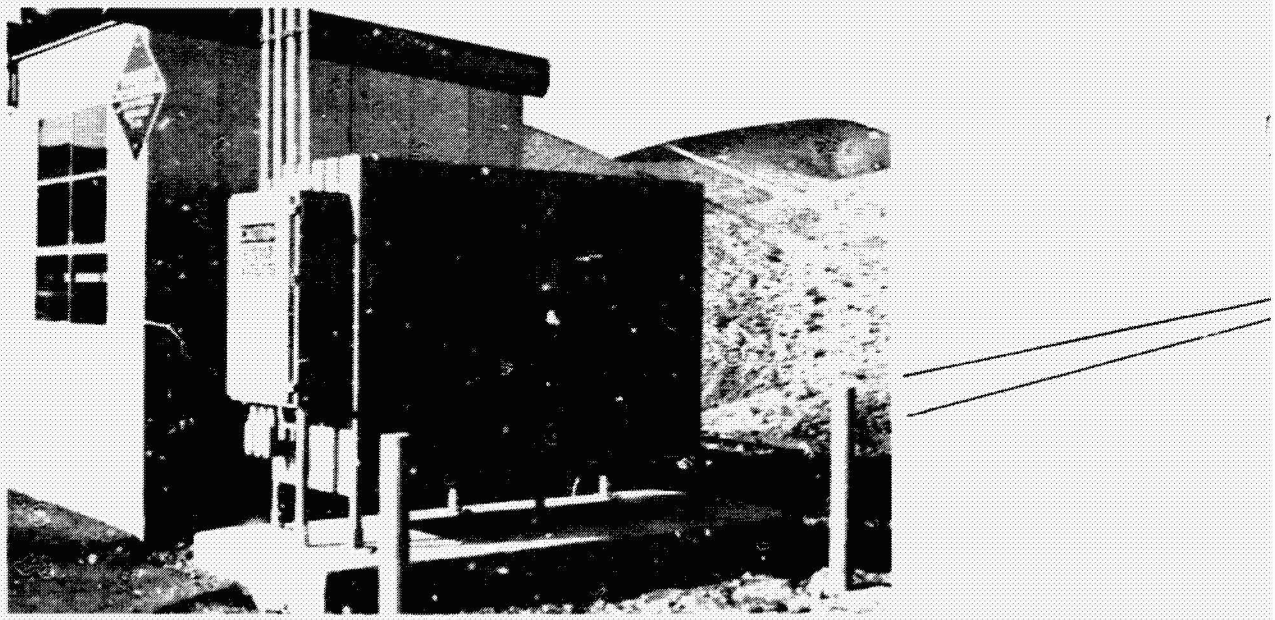


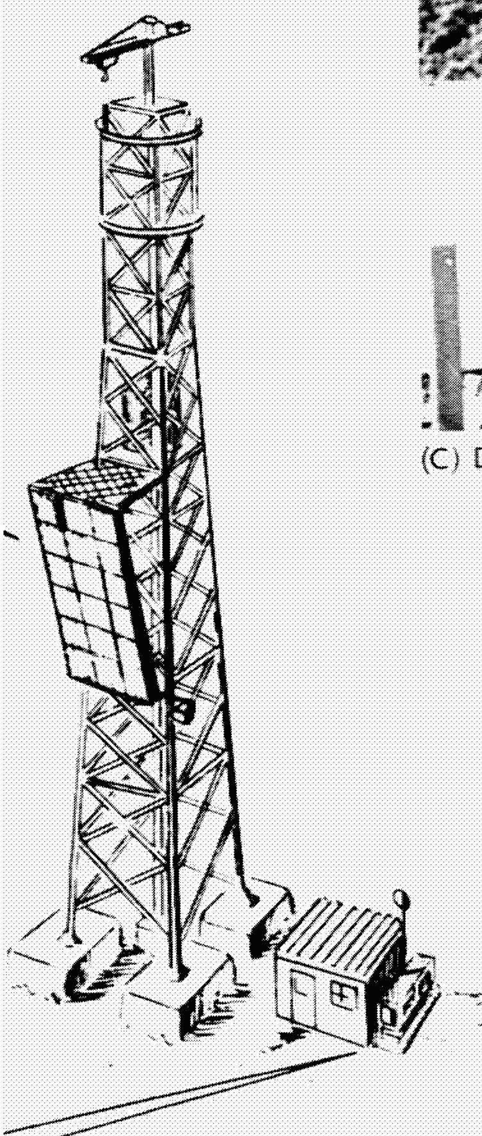
Figure 2-25. Experimentally Derived Internal Diode Series Resistance, Epitaxial Region Undepleted

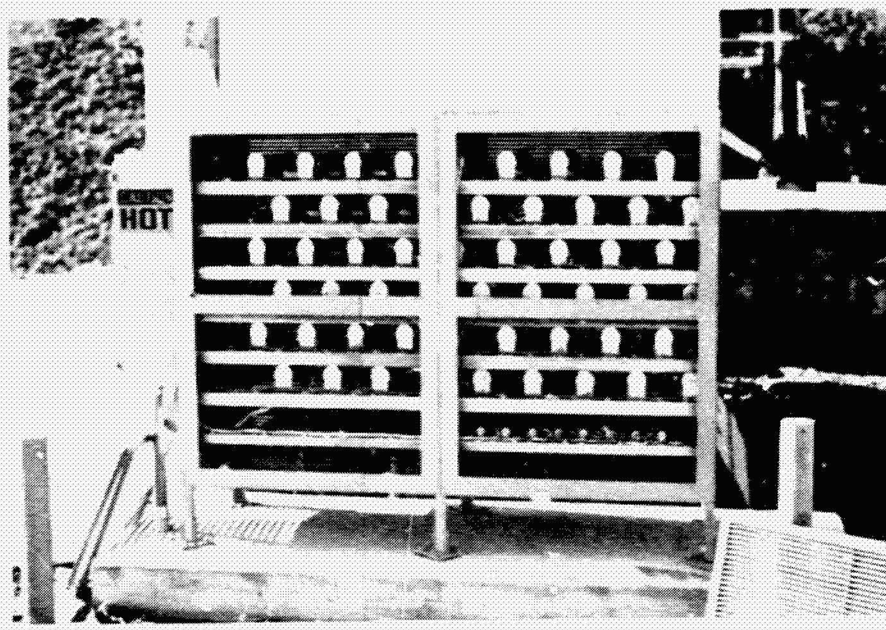


(A) TOWER JUNCTION BOX

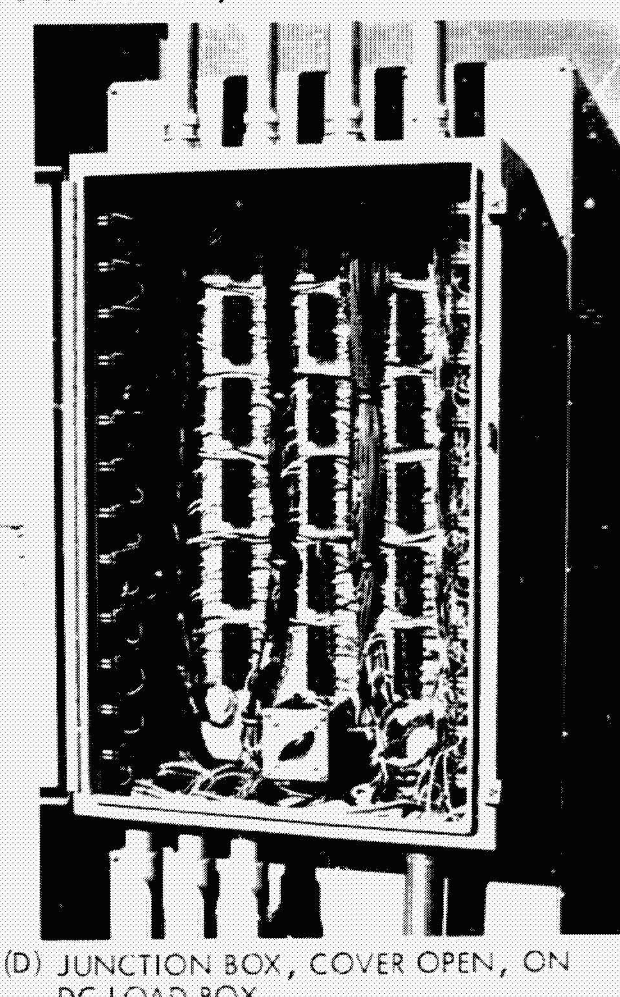


(B) DC LOAD BOX





(C) DC LOAD BOX, SIDE COVER REMOVED



(D) JUNCTION BOX, COVER OPEN, ON DC LOAD BOX

Figure 2-2[illegible]. DC Load Hardware

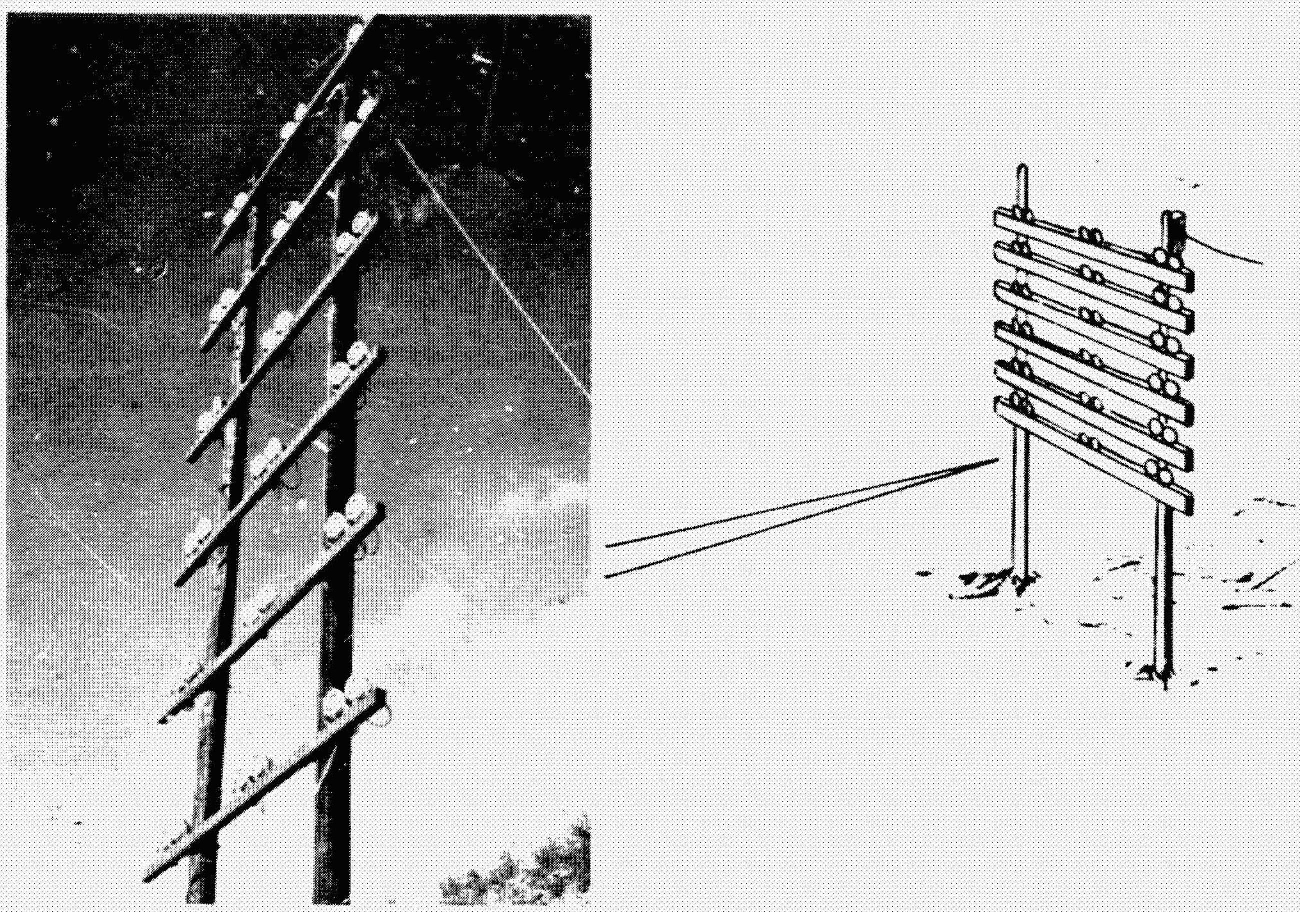
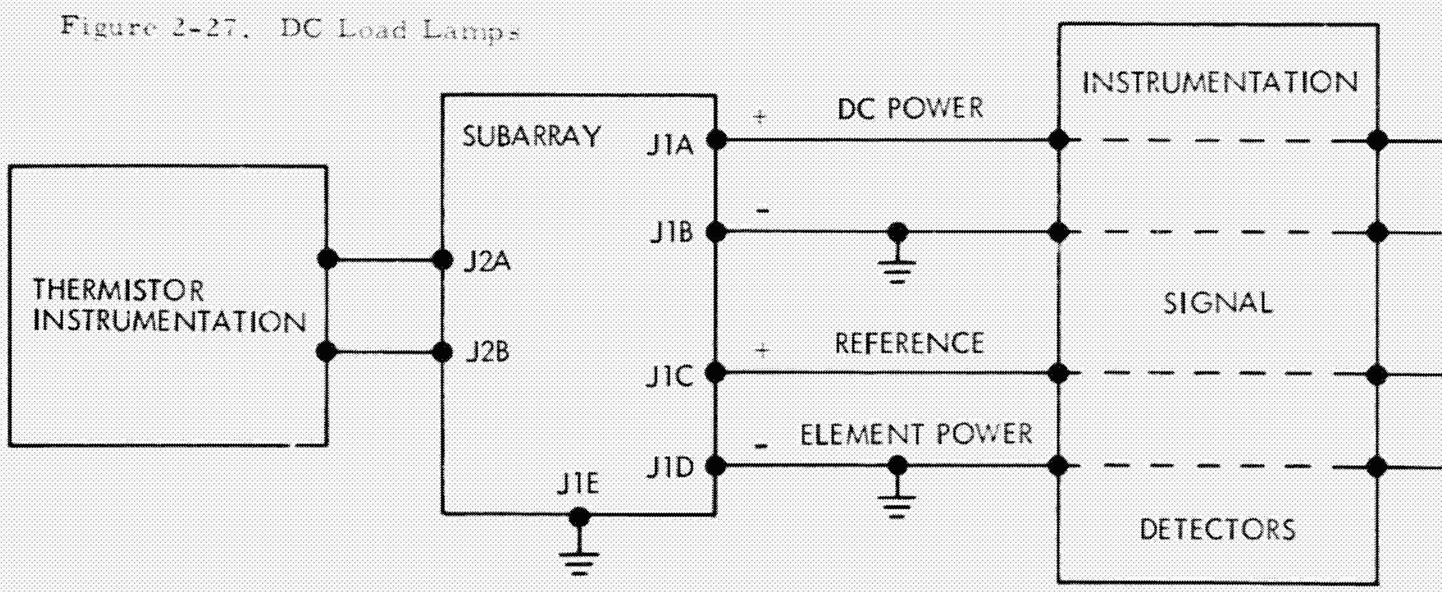


Figure 2-27. DC Load Lamps



FOLDOUT FRAME 1

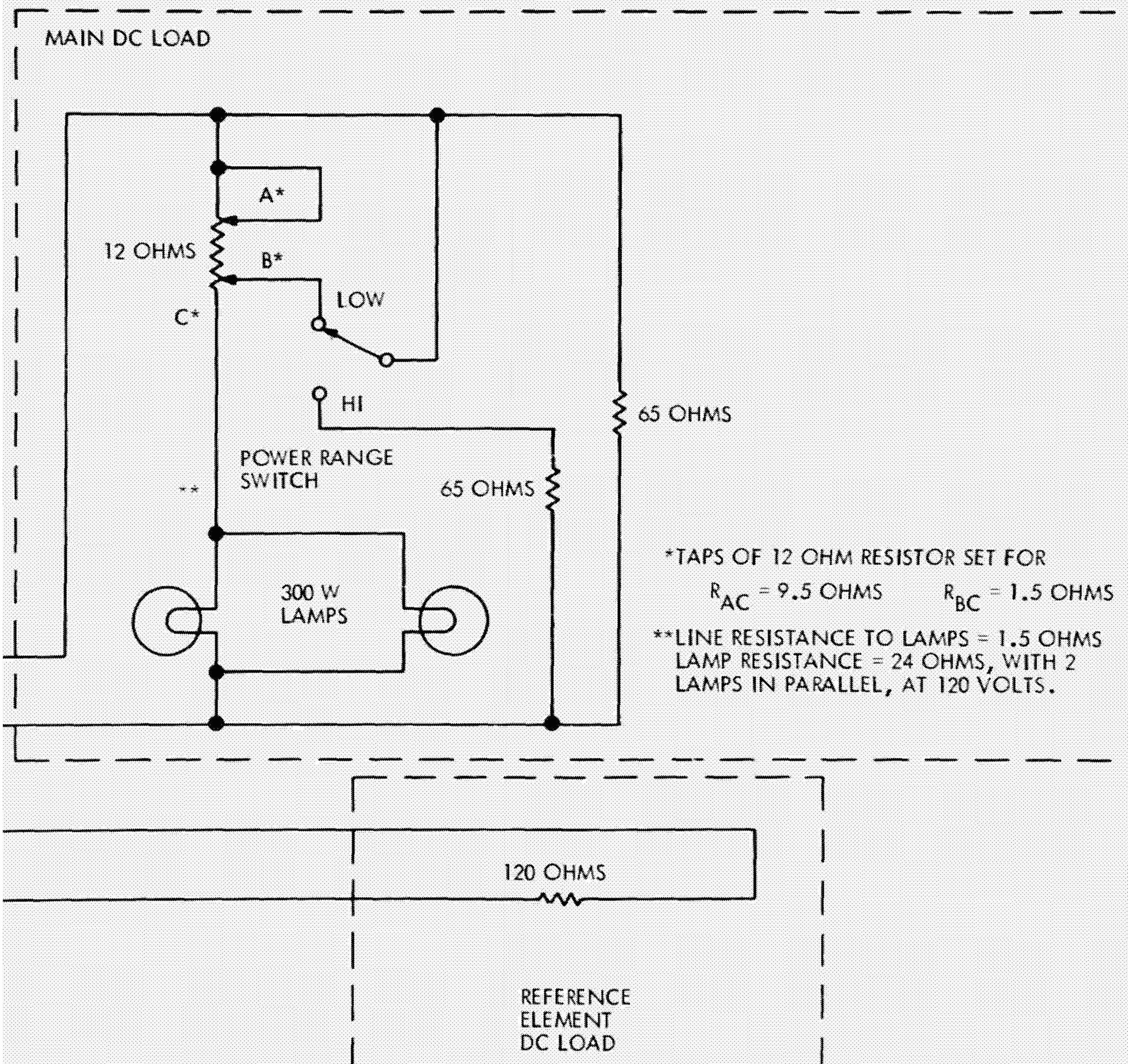


Figure 2-28. DC Load Schematic

Power output from each calibration diode is almost negligible being approximately 0.4% of the main power output. At the 2000 watt level for a subarray, load circuits operate at approximately 185 V and 10.8 amps.

Each subarray is connected to one of three junction boxes located on the collimation tower via two weathertight connectors and shielded cables. One cable carries the main power and calibration diode outputs and the other provides connections for the thermistor located inside the subarray for internal temperature monitoring. All wires then pass through conduits to their destinations, thermistor wires being routed directly to the collimation tower support building and power output wires being routed to the dc load box.

The lamps (Figure 2-27) dissipate approximately 30% of the subarray output power in the high power range and approximately 60% in the low power range, the balance being dissipated by the power resistors. Power resistors were used in addition to lamps to reduce the voltage applied to the lamps and to provide a more nearly optimal load resistance characteristic to the subarray outputs than would have resulted by using lamps to dissipate all the power. Lamp filament resistance decreases considerably at decreased operating voltage.

The lamps are mounted on a pole supported structure located down hill from the collimation tower toward the control room. The lamps are 300 watt narrow beam PAR-56 spotlamps which are mounted in pairs and grouped to replicate the positions of the subarrays that power each pair. The lamps are aimed at the control room for maximum visibility at that location. The lamps are easily visible in full daylight even at reduced power levels. Each of the 18 pairs of lamps is resolvable at more than a mile with the naked eye.

The DC Load Schematic is shown in Figure 2-28.

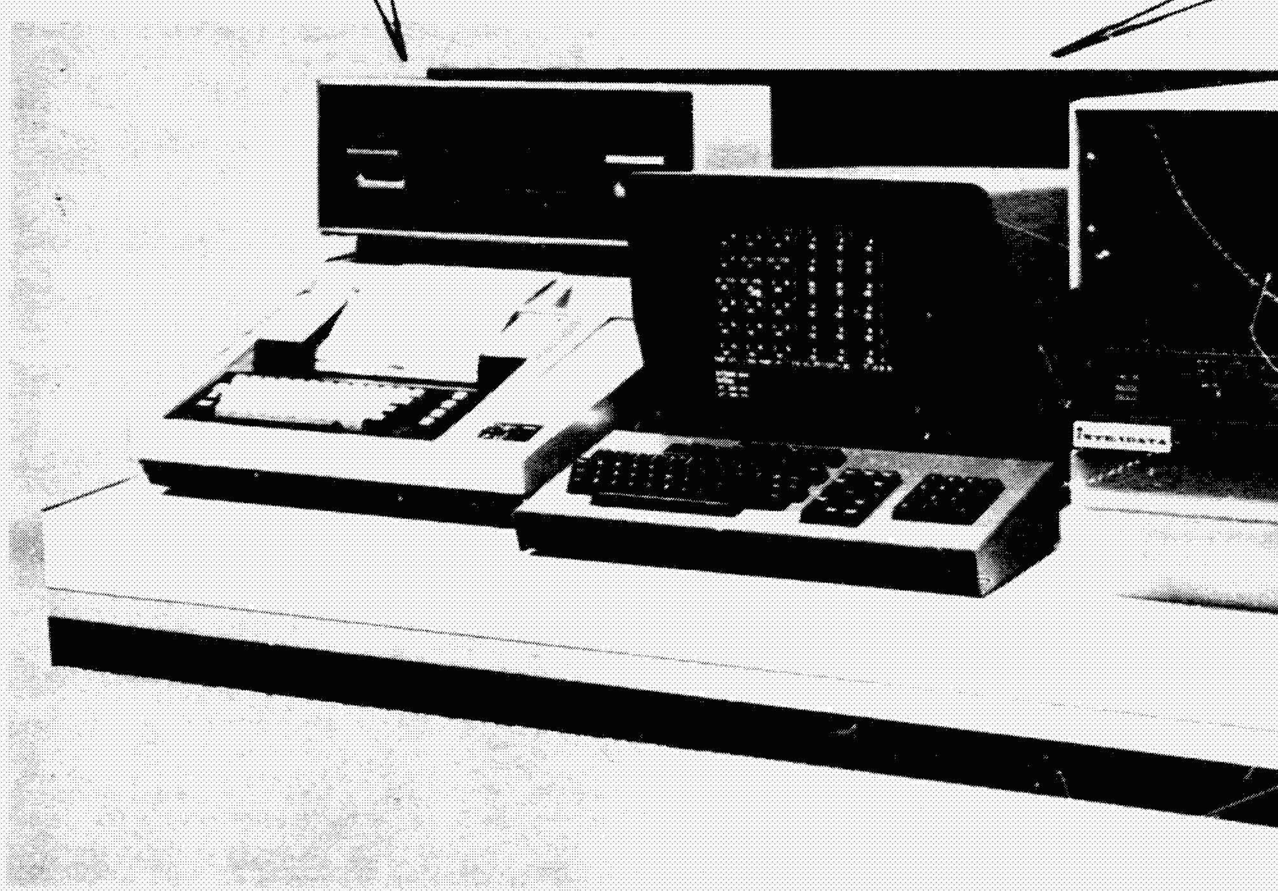
Maintenance philosophy for the dc load is that the RXCV custodian perform preventive and repair maintenance, seeking Raytheon consultation as necessary. Spares of most electrical items have been supplied to JPL.

2.5 INSTRUMENTATION

The RXCV primary instrumentation (Figures 2-29 through 2-31) performs the following functions:

```
PD YC
1375/1722W     0*    0W 1393/1685W  P     153V          0V          155V    V
    80%          NA%         83%          31C          37C          30C

1527/2135W 1765/2178W 1693/2051W         166V         175V         171V
    76%          81%         83%      W   31C          35C          31C     L

1873/2388W 2023/2471W 1928/2298W  E     179V         188V         184V    T
    78%          82%         84%          31C          31C          31C

1927/2318W 2055/2443W 1979/2357W         182V         189V         185V
    83%          84%         84%      -   31C          32C          32C     T

1845/2212W 1911/2287W 1905/2341W  E     177V         181V         181V    E
    83%          84%         81%          31C          34C          31C

1606/1971W 1720/2064W 1625/1995W         166V         172V         167V
    81%          83%         81%      F   30C          31C          31C     P
POWER OUT= 30.251W POWER IN= 36.916W AVG EFFICIENCY= 82% W  157 08:00:26
```

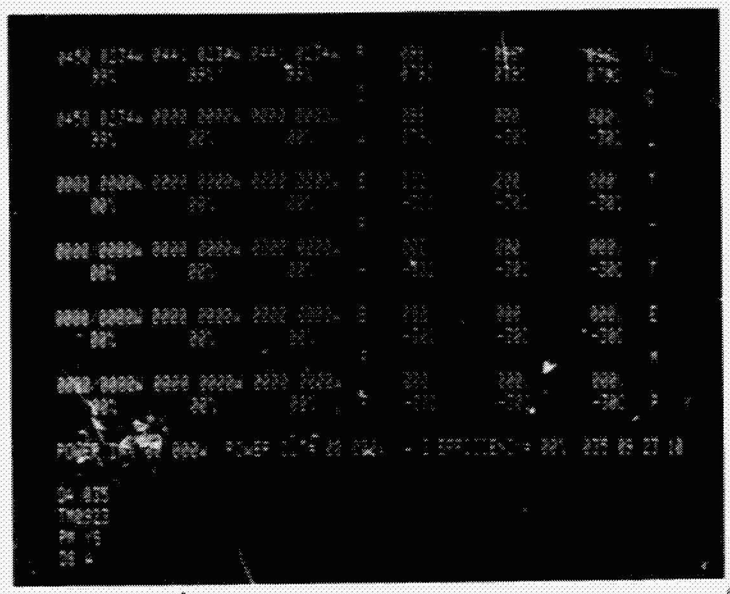
(C) SAMPLE PRINTOUT



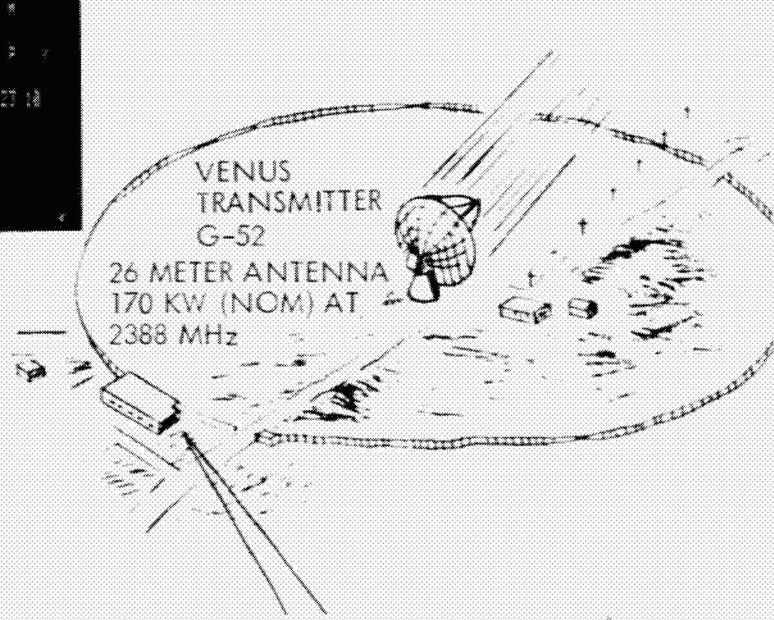
(B) INSTRUMENTATION CONSOLE

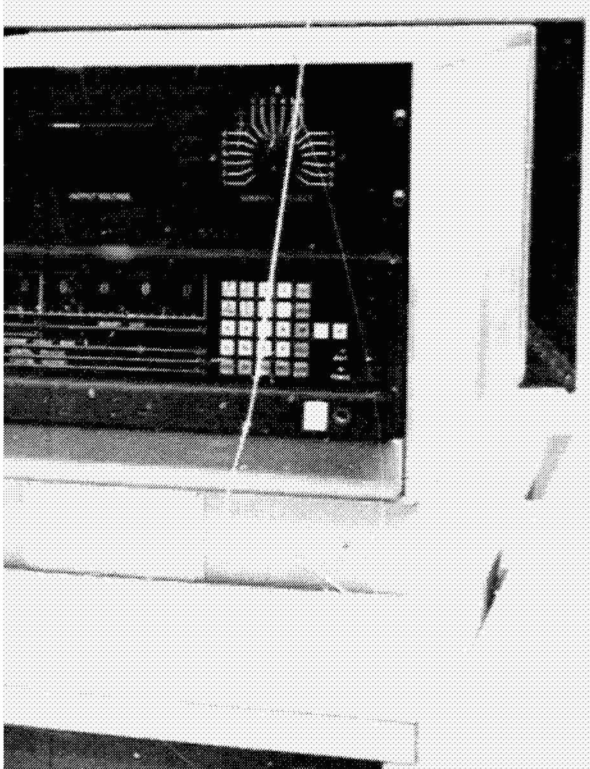
REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

FOLDOUT FRAME



(D) CRT DISPLAY





(A) BUILDING G-51

Figure 2-29. Instrumentation Equipment, Control Room

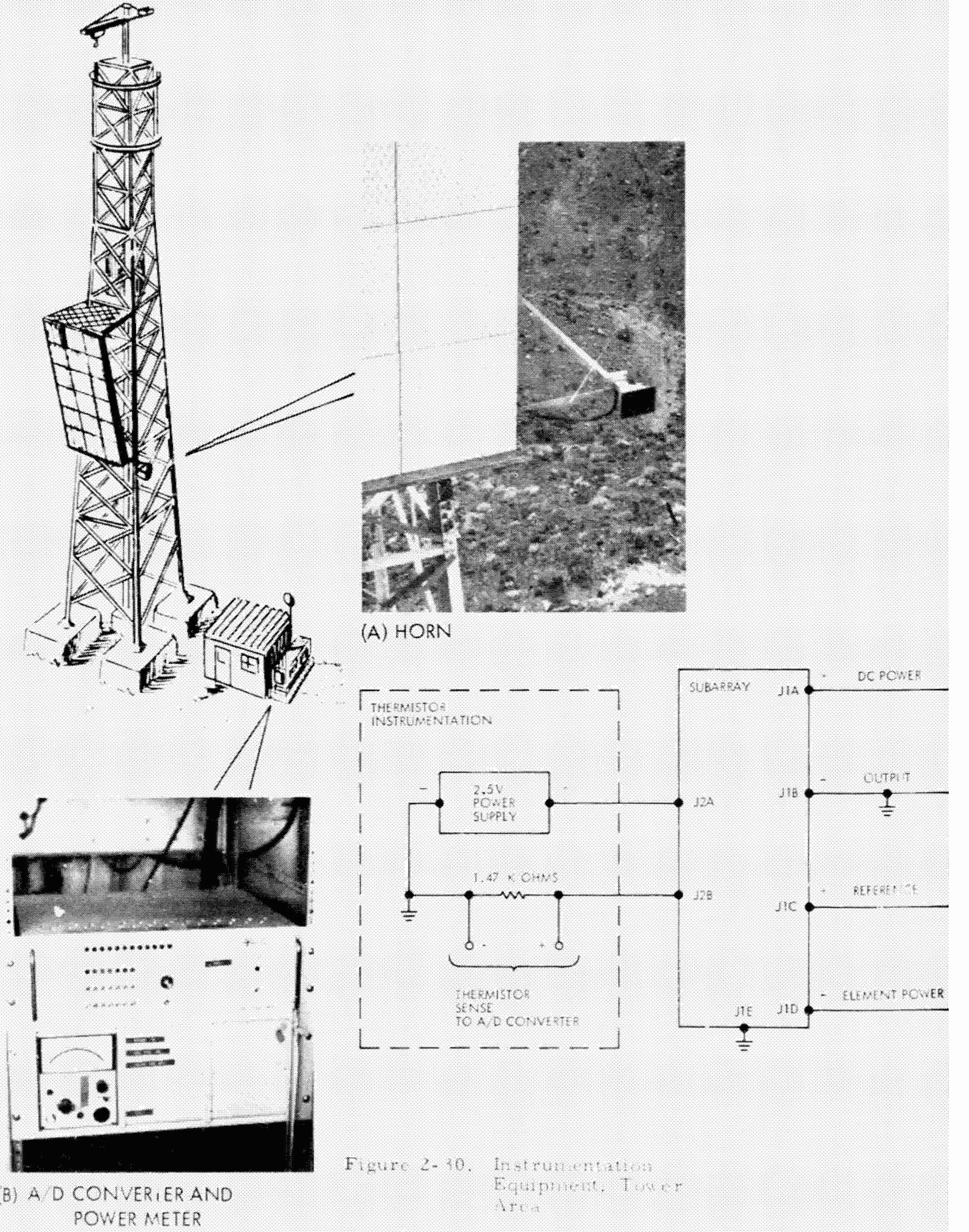


Figure 2-30. Instrumentation Equipment, Tower Area

FOLDOUT FRAME

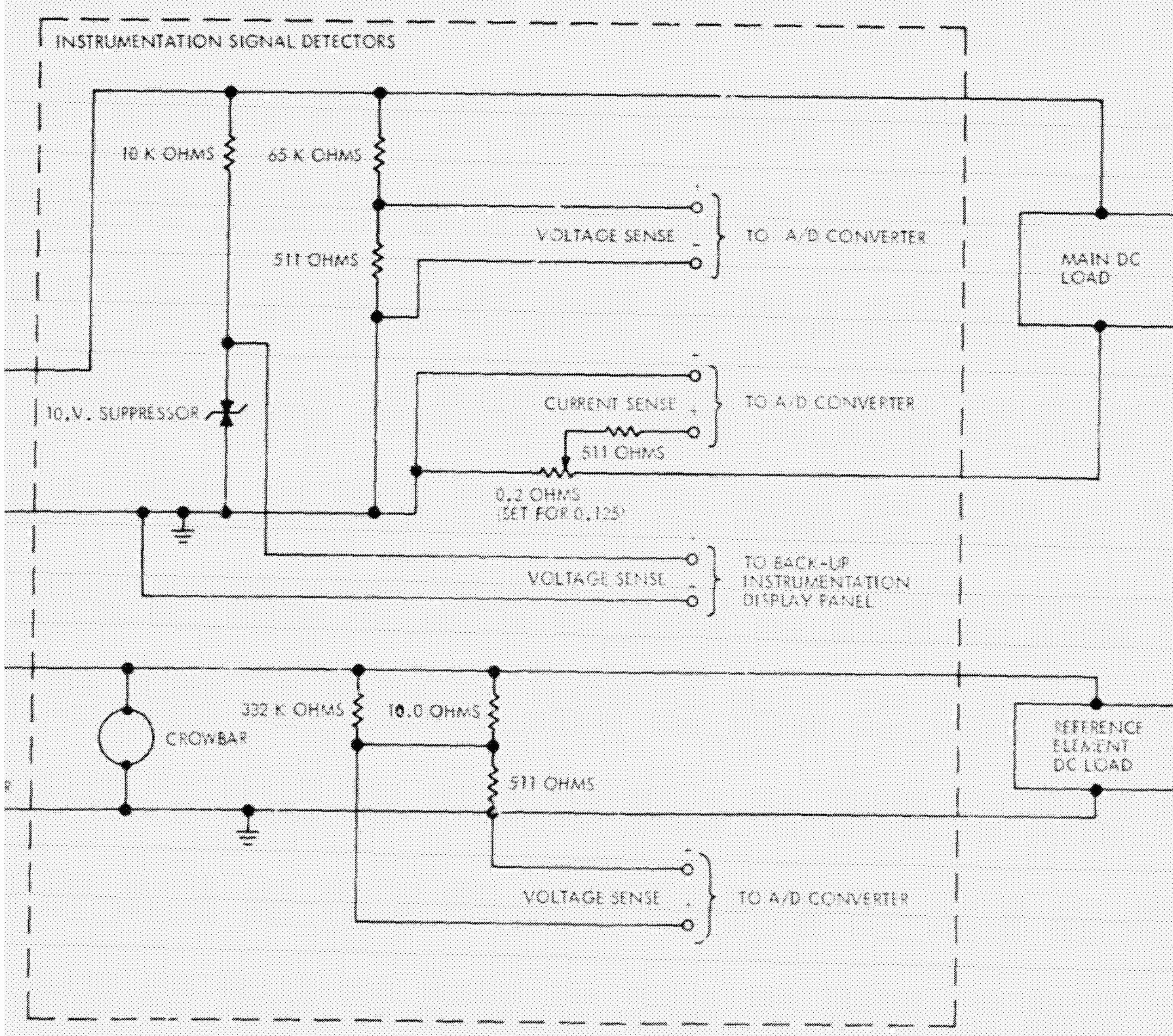


Figure 2-31. Instrumentation Schematic

FOLDOUT FRAME

a. Measures incident RF power, output voltage and current, and the internal temperature of each subarray

b. Transmits these measurements from the collimation tower support building in Digital Form via telephone lines to the computer in the control room

c. Performs data computations including safety limit checks, subarray efficiency and timekeeping

d. Displays, prints and records pertinent data

e. Inhibits the microwave transmitter if critical safety limits are exceeded.

The RXCV backup instrumentation monitors the output voltage from each subarray and transmits that data to the control room in analog form via 18 independent telephone lines. The backup display in the control room includes 18 light emitting diodes (one per subarray location) and a digital panel meter with a subarray select switch. The intensity of each LED is a function of output voltage of the associated subarray. The digital panel meter provides an output voltage reading on any selected subarray. The backup instrumentation is completely independent of the primary instrumentation thus providing redundant monitoring in case of primary system failure.

The dc load box contains the precision resistor voltage dividers and current shunts which provide the primary instrumentation analog to digital converter (ADC) with calibrated signals in the 0 to +2 V range. Thermistors in the subarrays are connected to bridge resistors and a bridge power supply located in the collimation tower support building.

The RF Sensor Assembly which consists of an RF power meter connected to the calibrated horn on the tower is located in the support building.

The outputs of the voltage dividers, current shunts, thermistor bridges and RF power meter are connected to a multiplexed ADC which samples the signals sequentially and converts each sample to a 12 bit binary representation. It is located in the support building at the base of the collimation tower to be as close to the signal sources as possible. The ADC samples each signal 10 times per second with full scale corresponding to the following ranges of the measured parameters:

Subarray output voltage	0 - 256 V
Subarray output current	0 - 16 A
Subarray reference diode voltage output	0 - 40 V
Subarray temperature	-30 to +150°.
Horn RF power	488 watts

The digital data from the ADC is transmitted to the computer system in the control room via approximately 2.4 km (1.5 miles) of 15 twisted pair telephone lines.

The computer system consists of a 16 bit mini-computer interfaced to the telephone data lines, the transmitter interlock circuit and the following peripheral devices:

- Cathode Ray Tube (CRT) Terminal
- Printer/Recorder Terminal
- ASR-33 Terminal

It is programmed to perform the following functions:

- Receive binary data from the ADC
- Scale the 12 bit binary data to engineering units
- Calibrate each subarray input power sensor (rectenna calibration element) to the RF Sensor Assembly
- Compute subarray output power (EXI) and efficiency $\frac{Po}{Pin}$
- Perform limit checks on subarray output voltage, efficiency and temperature
- Take appropriate action if limit thresholds are exceeded, e.g., display warning message and inhibit transmitter as required
- Perform two second data averaging (smoothing)
- Keep time
- Format data for display, printing and recording

- Transfer data to/from the terminals
- Check test data for errors to detect system failures.

The CRT terminal provides data display in two selectable formats: numeric and bar graph. The numeric format (see Figure 2-29(d)) displays the output voltage, output power, input power, temperature and efficiency for each subarray; also total (array) power output, power input and efficiency. Efficiency is the ratio of dc power output to RF power input. A limit warning indication, Julian date and time of day are displayed. Messages also appear on the CRT to echo operator input commands and to help the operator diagnose system problems. The bar graph format contains a 50 segment bar graph for each subarray which graphically displays subarray output power. It also displays (alphanumerically) total power output, total power input, efficiency, limit warning, Julian date and time of day. The display is updated by the computer every two seconds.

The CRT terminal also provides a keyboard by which the operator gives control commands to the computer.

The printer/recorder terminal provides a hard copy capability by which data displayed on the CRT or recorded on tape can be printed for future use. The printer operates at 30 characters per second and uses a thermal (non-impact) print mechanism. A printout is initiated by an operator keystroke. The recorder uses a Phillips type magnetic tape cassette as the storage medium and contains two cassette mechanisms. Each cassette has a data storage capacity of 80 minutes of continuous operation. During normal operation measured data is averaged and recorded on the cassette once per eight seconds thus providing a representative sampling of data for later review. The terminal also has a keyboard which can be used as a backup to the CRT terminal keyboard however, it is not normally used.

An ASR-33 TTY terminal is provided as a computer terminal for loading programs from paper tape and as a backup printer for the printer/recorder terminal. During normal system operation it is not turned on. Program loading is normally performed from the cassette tape but loaded from the paper tape provided. The paper tape punch is not normally used.

The operator and test conductor seated at the console has a direct view of the transmitting antenna, dc load lamp structure and the collimation tower through a large window in the west wall of the control room. He is in visual and voice contact with the transmitting antenna operator and through an intercom is in contact with the transmitter operator.

The RXCV instrumentation requires very little preventive maintenance or adjustment. The RF power meter is the only instrument requiring daily adjustment. Essentially all circuitry is solid state and contained on printed wiring boards. Maintenance philosophy for the RXCV instrumentation is that the RXCV custodian perform preventive maintenance and make necessary minor repair or adjustments with the aid of the supplied equipment manuals. The equipment manufacturers' service organization should be contacted for service and/or repair parts as required.

2.6 LOGISTICS

The major elements of the RXCV, as described in the preceding sections, were designed and built by Raytheon's Equipment and Microwave and Power Tube Divisions. Subcontractors were utilized for Support Structure Analysis and Design, Site Modifications and Construction, as well as general on-site support. The following is a listing of the subcontractors utilized and the areas of work performed by them.

Penn-Tech, Inc., West Chester, Pennsylvania

- Tower and Support Structure Structural Analysis
- Design of the Tower Modifications and Support Structure

Plas-Tal Manufacturing Co., Inc., Santa Fe Springs, California

- Tower Modifications and Support Structure steelwork fabrication and erection.

WE Electric Company, Barstow, California

- Site electrical construction work.
- Miscellaneous site construction work, including concrete pads, chain type gate, sign erection and storage building electrical work.

Kohn Enterprises, Barstow, California

- General support to Raytheon's field operations activities at Goldstone and specifically the rf field mapping.

During all phases of the RXCV contract involving work on-site at Goldstone Raytheon received substantial support from the JPL site personnel (including JPL's O&M contractor, Aeronutronic Ford Corporation). This support was most helpful to Raytheon and beneficial to the successful completion of the program.

2.7 SITE MODIFICATIONS

As an integral part of the RXCV subsystem, modifications to the physical facility at the Venus Station (DSS-13), Goldstone, California, were necessary and were performed by Raytheon. As required by the contract, a detailed plan for all site modification work was prepared by Raytheon and approved by JPL prior to starting the work. In addition, Raytheon prepared detailed specifications, work statements and drawings for all elements of work. Copies of all documents have been provided to JPL. The following is a list of these documents:

a. Site Modification and RXCV Structural Support Plan, including:

   1. Basic Plan, dated October 1974
   2. Revision A, dated 28 January 1975
   3. Supplement #1, Tower G-54 Structural and Foundation Analysis
   4. Supplement #2, Site Survey Report.

b. Specification for RXCV Antenna Support and Tower Modifications, dated 2 January 1975, including Raytheon Drawings 74101, 74103, 74104, 74105 and 74106.

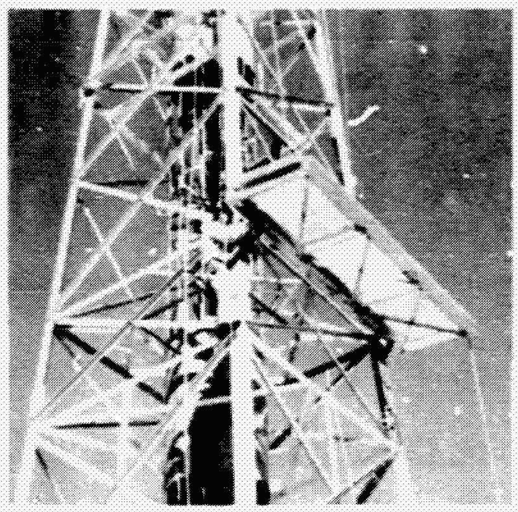
c. Specification for RXCV Antenna Electrical and Miscellaneous Work, dated 7 February 1975, including Raytheon Drawings 75201 and 75202.

The modifications fall into three categories: (1) Tower and Support Structure steelwork, (2) Electrical Installation work, and (3) Miscellaneous work.

The location, at the Venus Station, for the RXCV rectenna array is the 100 foot (~30 meters) tall near-field Collimation Tower (G-54) located about 1.6 km (1 mile) west of the Venus Transmitter. This existing tower was modified to serve as a mount for the subarrays. Figure 2-32 depicts the construction of the Support Structure (views a through d) and the mounting of the RXCV Subarrays on the completed structure (views e through g). The modifications consisted of the support structure itself, additional bracing of the tower from the base to the top of the support structure, and an access ramp from the existing spiral stairway to the support structure work platforms.

Prior to designing the steelwork modifications a stress analysis of the existing tower and foundation was performed and the results of this analysis were used to design the additional tower bracing. See reference document (a)(1), paragraph 2.2, and (a)(3) for the details of this analysis. The details of the steelwork modifications themselves are contained in reference document (b). In addition, two sets of "as-built" detail drawings, prepared by the steelwork contractor, Plas-Tal Manufacturing Co., were delivered to JPL.

The electrical work was the installation of dc load resistors and lamps, instrumentation interconnections, junction boxes, and interconnecting conduits and cables. Four junction boxes are located on the support structure (on the tower). The dc power output and instrumentation connections from the subarrays are connected to three of the J-boxes via flexible cables. The fourth J-box contains RF power sensor instrumentation. A dc load resistor and Junction Box is located adjacent to Building G-57 at the base of the tower (instrumentation equipment is located in this building). Wiring from the tower J-boxes to the dc Load Box and Building G-57 is run in conduit which is run down near the Northeast Tower leg and across the Building G-57 roof. Figure 2-26 shows the dc Load Box, on a concrete pad, and the conduit runs into its J-box. The load lamps are located down the hill from the tower, along side the access road, so that the lamps appear below the tower, with the hillside as a background, when viewed from the Venus Control Room. Figure 2-33 shows the load lamp construction and final configuration. The electrical work is described in detail in reference document (c).



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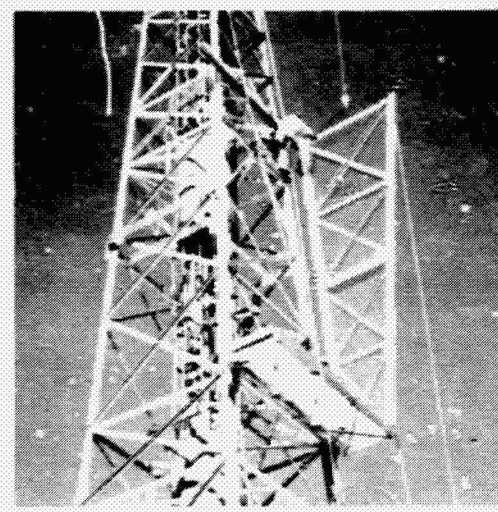

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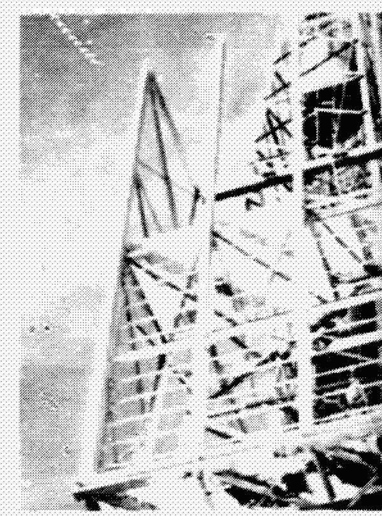
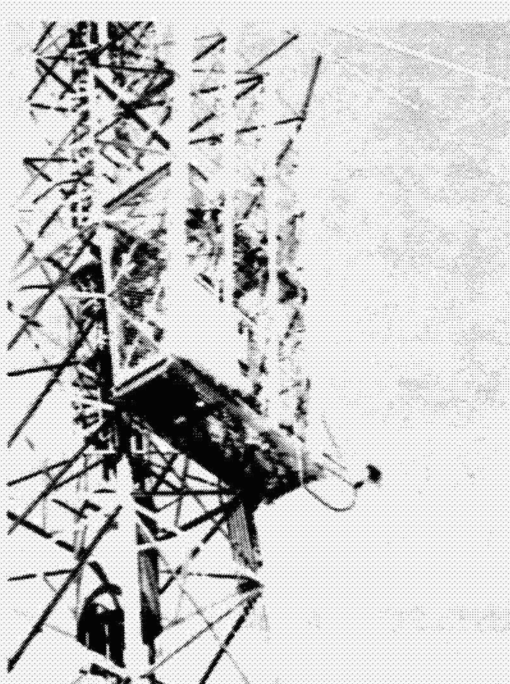


(C)



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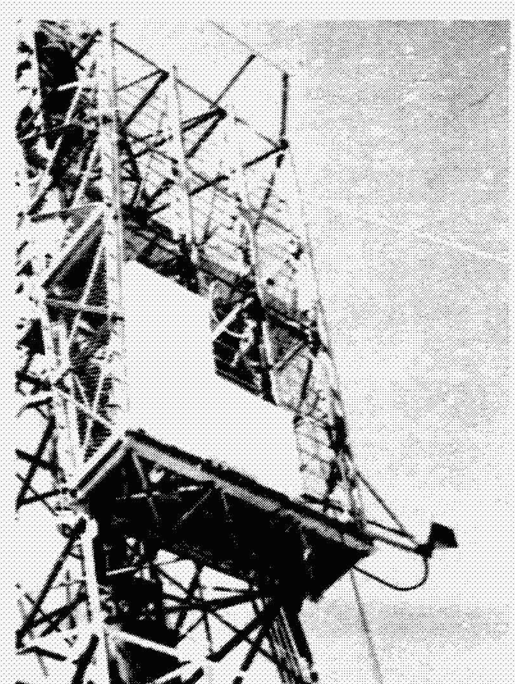


(F)

(G)

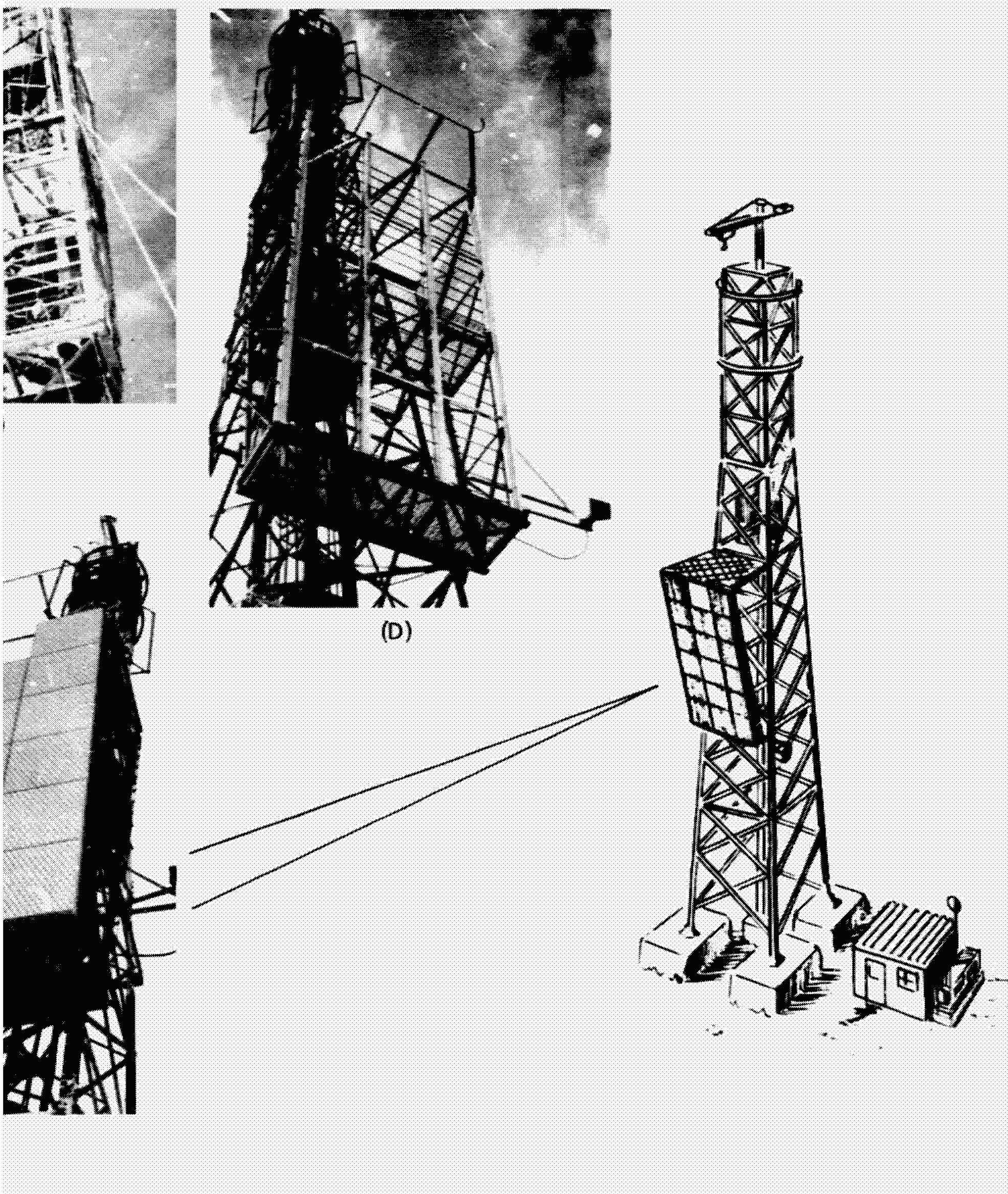
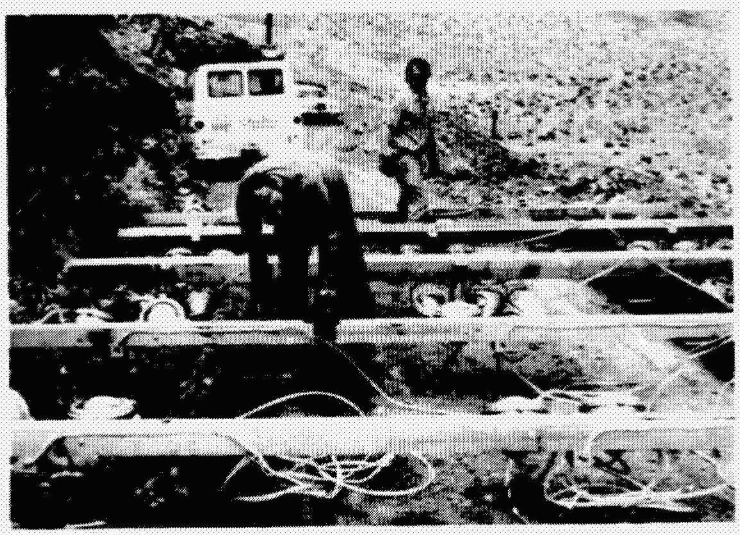


Figure 2-32. Support Structure Construction

FOLDOUT FRAME 2



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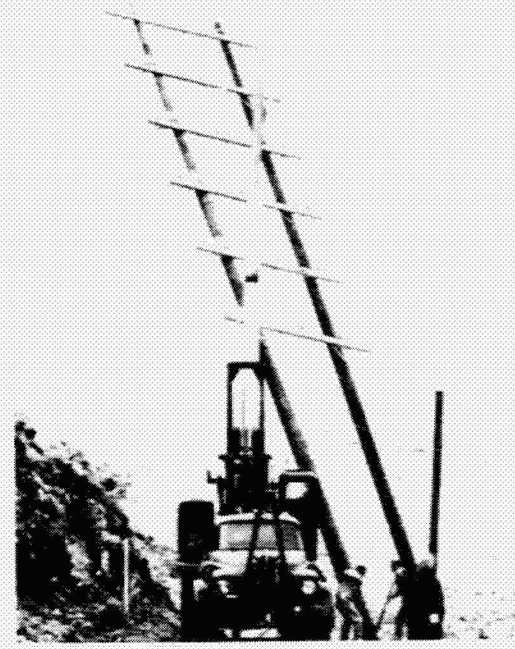
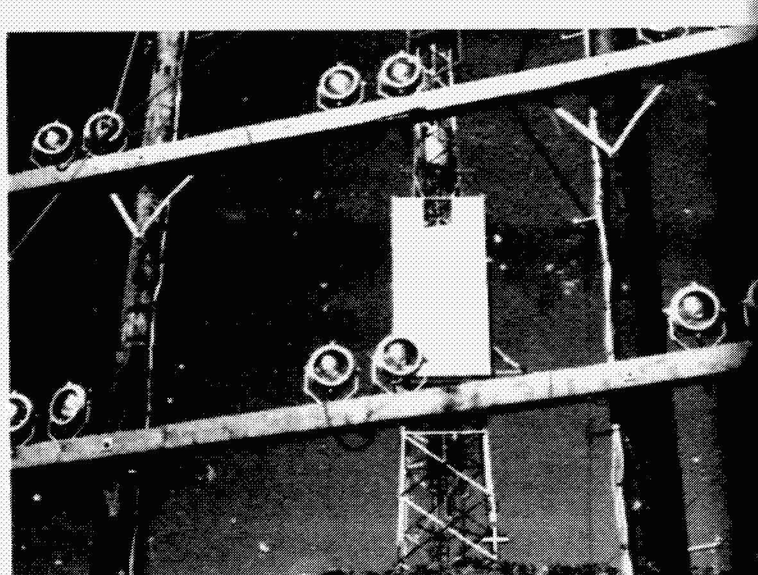


(B)



(D)

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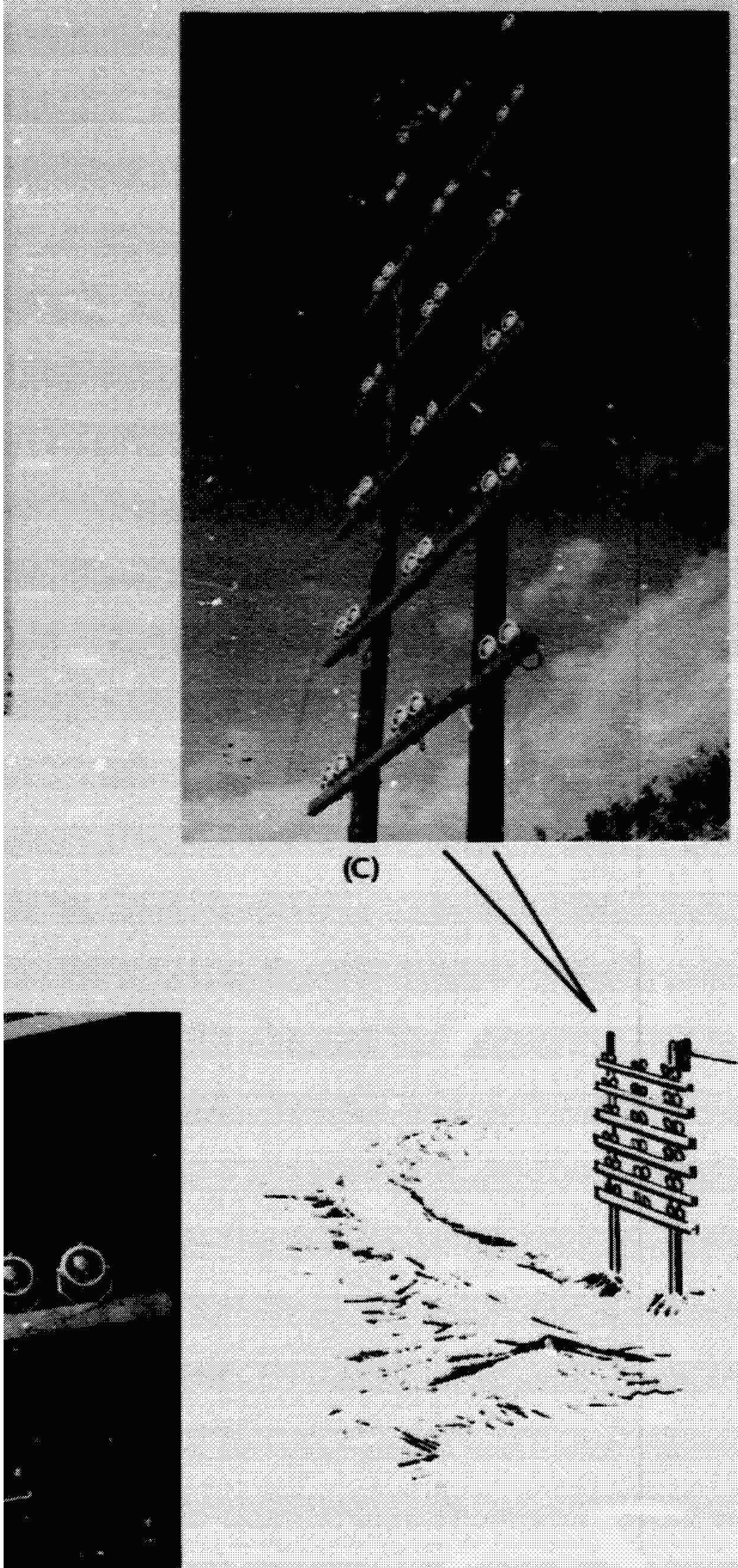


Figure 2-33. DC Load Lamp Construction

FOLDOUT FRAME 2

The miscellaneous construction work consisted of the concrete pad for the Load Box, a post-and-chain type gate at the foot of the tower hill and a number of RF Radiation Hazard Warning Signs. This modification work is described in detail in reference documents (a)(1), (a)(2), (a)(4), and (c).

2.8 SAFETY

Safety was a prime consideration throughout the RXCV program. Following a Safety Plan which was a contract requirement, Raytheon endeavored to conduct the program in a safe manner and to provide a final system with built-in equipment and personnel safety features. A Raytheon Safety Engineer was assigned to the program to monitor equipment design for safety and to assist in identification of on-site personnel hazards.

No significant accidents occurred during the conduct of this program. In fact, only one very minor incident occurred: Bill Brown of Raytheon fell on the hillside, near the tower, at Goldstone-Venus Station (he incurred only minor scratches) during the breadboard testing effort. No incidents of any kind occurred in Raytheon's facilities and no other incidents occurred at Goldstone (including the construction workers). Also, there were no incidents of personnel exposure to harmful RF radiation.

All equipment designs, including site modifications, were reviewed for safety considerations and for compliance with Federal and California OSHA laws and regulations. For example, the DC Load Box is enclosed (but ventilated) to prevent personnel exposure to electrical contacts and to hot components. In addition, Caution signs for both voltage and heat are used on the Load Box. Another example is the Support Structure. Two work platforms are provided, along with permanent ladderwork, so that the rear of all subarrays can be accessed with ease. This rear work area is completely enclosed with cyclone fence wire to provide protection against falling. Access to the area is provided via a connection with appropriate railing, to existing spiral stairs within the tower interior.

The equipment protective devices include the crowbar circuits within the subarrays for the power elements (see paragraph 2.1) and within the junction boxes for the reference elements. The equipment is further protected through a feature built into the instrumentation subsystem which automatically shuts-down the transmitter when certain abnormal conditions are detected (see paragraph 2.5).

In addition to standard protection against electrical shock hazards, the RXCV tower receiving site required personnel protection from RF radiation hazards. During operation of the system under certain conditions of beam pointing and power level, the RF power density level at and around the tower may exceed safe levels for personnel. The tower site, although located in a remote area far from traveled ways, was not protected from unauthorized access by fences or signs and these were deemed necessary for safe RXCV operations. A single road accesses the tower from the Venus 26-meter transmitter site. This road is dirt except for the section going up the hill itself, which is paved. During the site survey, the area to the west of the tower was checked for possible personnel habitation. It was conducted both from the air and on the ground (by truck and on foot). No inhabited areas were found within a region that would be affected by the RF beam when it was on or near the tower. A number of options; fences, signs, lights and audio alarms, were investigated to determine what was required for personnel protection. The configuration selected includes three levels of control and protection. In addition to those normally employed to alert personnel in anticipation of antenna movement and of power transmission. All three levels include RF Radiation Hazard Warning signs designed in accordance with ANSI C95.2-1966 (to comply with Federal and California OSHA specifications). These signs consist of a red isosceles triangle (with a standard Warning phrase) over an inverted black isosceles triangle (with optional special wording).

The first level of control is achieved by gates on the access road. The first gate (Existing) is at the point where the road exits the fence surrounding the transmitter site. A second gate (posts and chain) was added where the paved section of the road begins at the start of the hill. An RF Warning sign, at both gates, advises not to proceed to the tower unless authorized.

The second level consists of a "guard ring" around the hill where the incident RF power density outside of the "guard ring" is less than 1 mW/cm^2 at any azimuth and elevation angles (of the 26-meter Venus Antenna) to be used in normal RXCV testing, and with full transmitter power of 450 kW. The 1 mW/cm^2 limit is a JPL requirement for personnel safety which is well within the 10 mW/cm^2 limit established by OSHA requirements. Normal RXCV testing uses less than

350 kW of transmitter power thus providing an extra margin of safety. This "guard ring" is delineated by a total of 11 RF Warning signs (indicating not to pass, to keep away). The approximate locations of these signs is indicated on Figure 2-34. This sketch also indicates the actual power density reading taken to determine the location of the 1 mW/cm^2 line. This data was taken on 22 May 1975, after all 17 subarrays were installed (so that reflections would be included). Low transmitted power levels were used to obtain the data for personnel protection and it was extrapolated to 450 kW levels. The readings indicated on Figure 2-34 are only representative samples. The measurements were made by personnel on foot and included many other readings not recorded. The 1 mW/cm^2 contour was temporarily marked as the traverse was made and the sign locations, outside the contour, were staked. In some cases the signs are well outside the contour where it was advantageous to do so to improve visibility of the sign by someone approaching the hill. No readings were made on the eastern slope of the hill below the road due to its steep grade which was considered non-climbable. View A of Figure 2-35 shows one of the signs in the foreground with the tower in the background. View B of Figure 2-35 shows the post and chain gate located at the foot of the hill.

The third level of protection is at the tower site itself. A red rotating warning light is mounted above the northeast corner of support building G-57. This light is manually turned on as part of the physical safety survey inside the "guard ring" before a test is to be conducted which will include RF illumination of the tower. Four RF Warning signs indicating that a test is in process when the light is on are mounted near the light facing 90 degrees apart. (Two, back-to-back, facing North-South are on the lamp support post, and one each on the east and west building walls.) View C of Figure 2-35 is a view of the light and signs. Vertical polarization of the power beam and orientation of the rectenna elements was selected to offer the minimum attractive bird perch as a measure of protection for both the birds and the equipment.

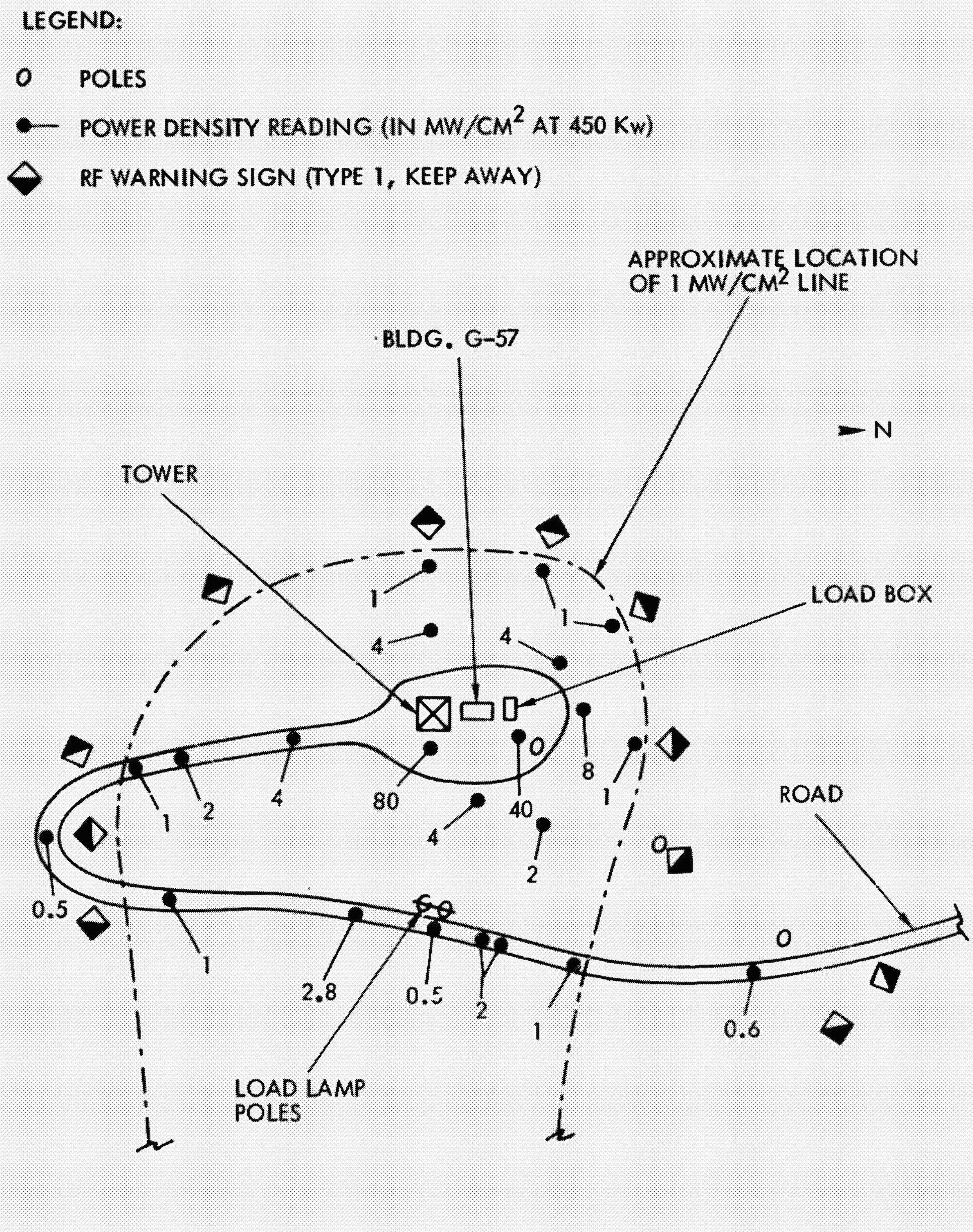
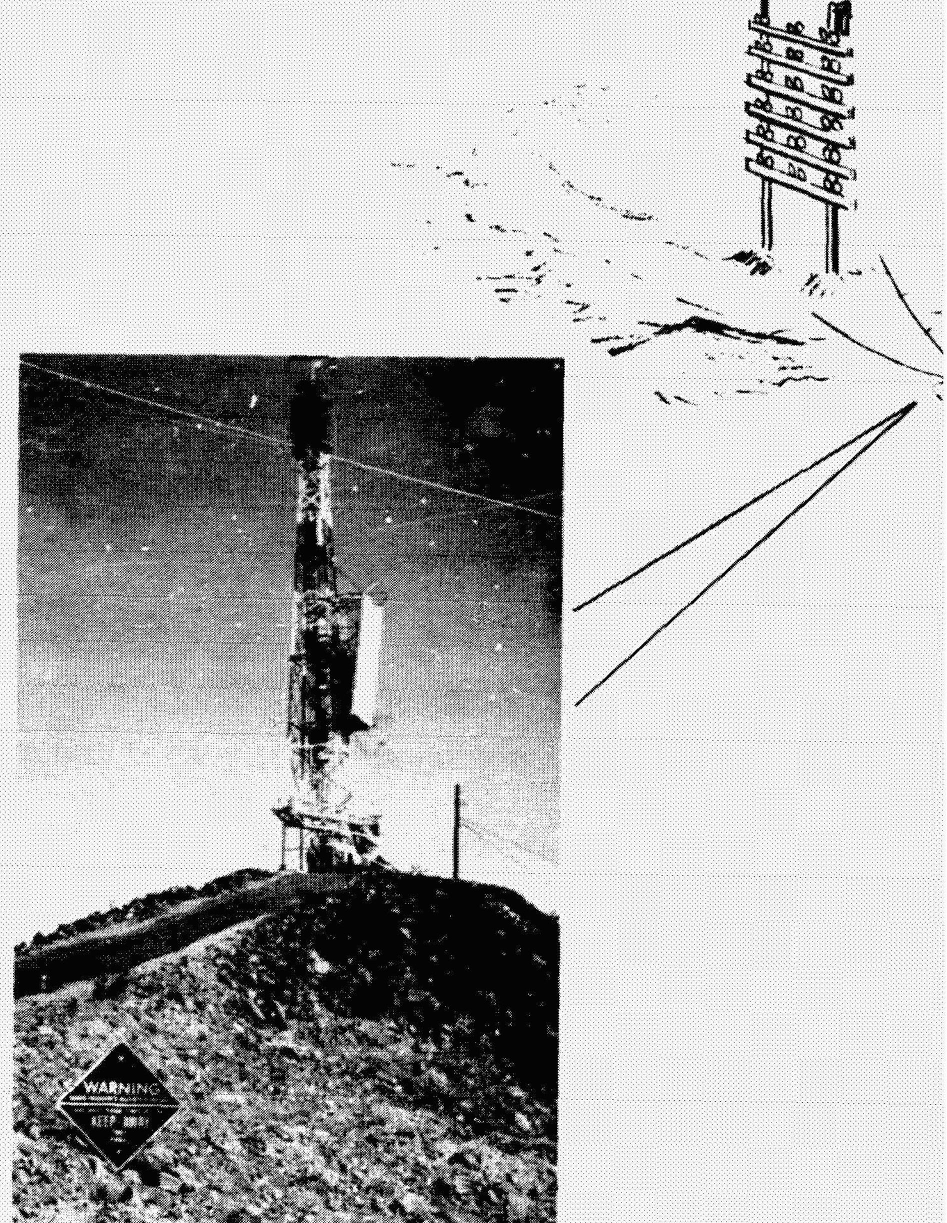


Figure 2-34. Safety Sign Locations



(A)

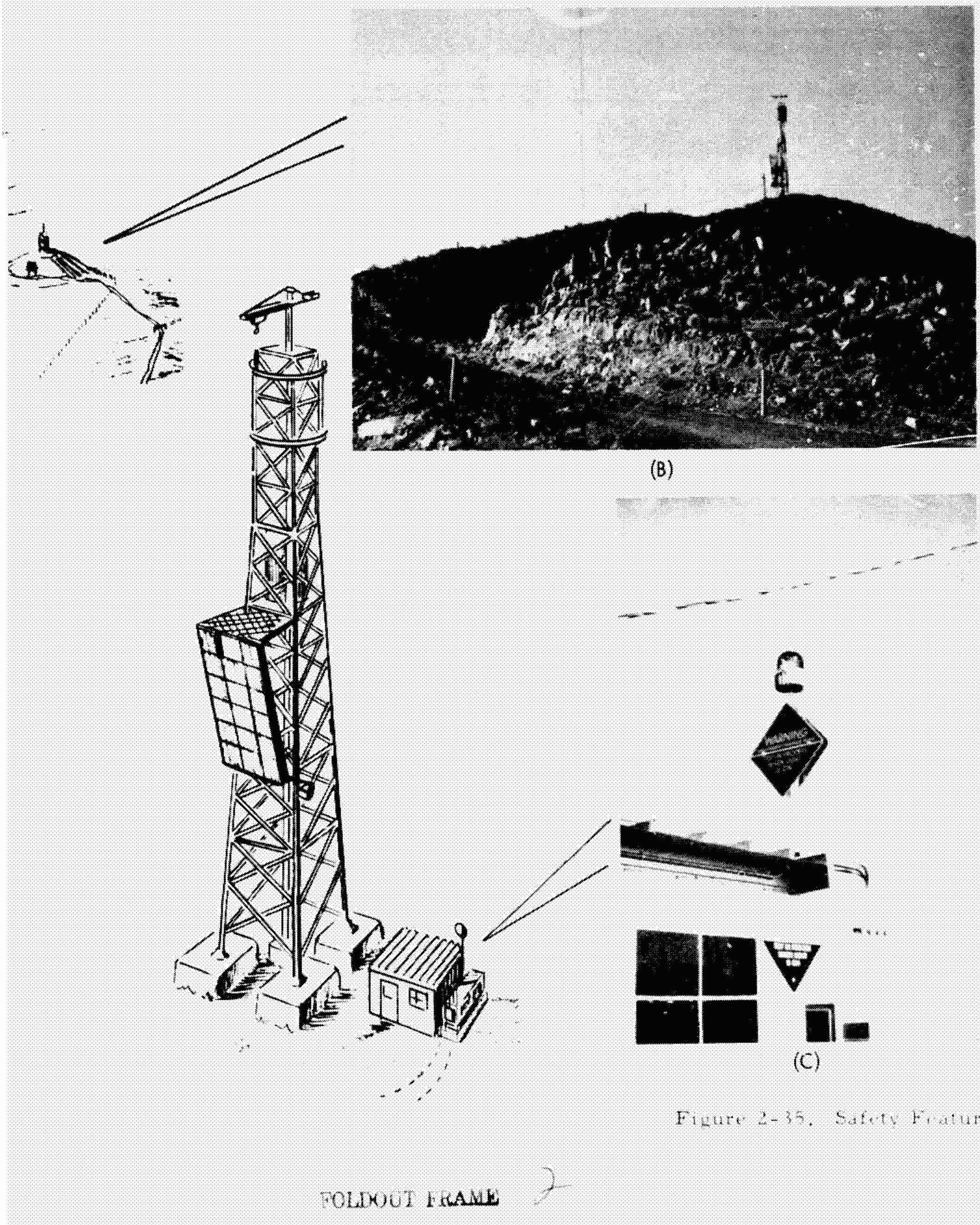


Figure 2-35. Safety Features

SECTION 3

TESTING

3.1 CERTIFIED DEMONSTRATION OF OVER FIFTY PERCENT (DC TO DC) MICROWAVE POWER TRANSMISSION EFFICIENCY

One of the major objectives of the work undertaken by Raytheon Company for NASA's Marshall Space Flight Center was the improvement of overall microwave power transmission efficiency. During May of 1974 efficiency measurements which were confidently felt to be in the region of 48-52 percent, had been achieved and an announcement of 48 percent efficiency had been made at the June Meeting of the IEEE MTT International Microwave Symposium. During June and July some minor improvements to the system were made and measurement accuracy improved to justify confidence that efficiencies in the range of 50 to 52 percent had been achieved.

It was obvious, however, both to Raytheon and to MSFC, that the measurements should be made with better instrument calibration documentation and that the measurements themselves should be certified by a quality assurance group outside of Raytheon. During the course of the RXCV contract a need for certification of the efficiency measurements arose at NASA headquarters, and it was agreed that these could be made by JPL personnel at Raytheon under an additional task assigned to the contract.

Before these measurements were made and certified, however, the rectenna had been refurbished with the JPL RXCV rectenna elements without conformal coatings which were known to be about two percent more efficient on the average than the MSFC rectenna elements. The test set up was also improved by changing a major portion of the plumbing to a larger waveguide size, eliminating a one percent loss in a 20 dB directional coupler, and installing an improved JPL supplied adaptor between rectangular waveguide and the dual mode horn. The finished test set up is shown in Figure 3-1. From the certified measurements made on 4 March 1975, the ratio of the dc output from the rectenna to the dc power input to the magnetron was computed to be 0.5418 with a

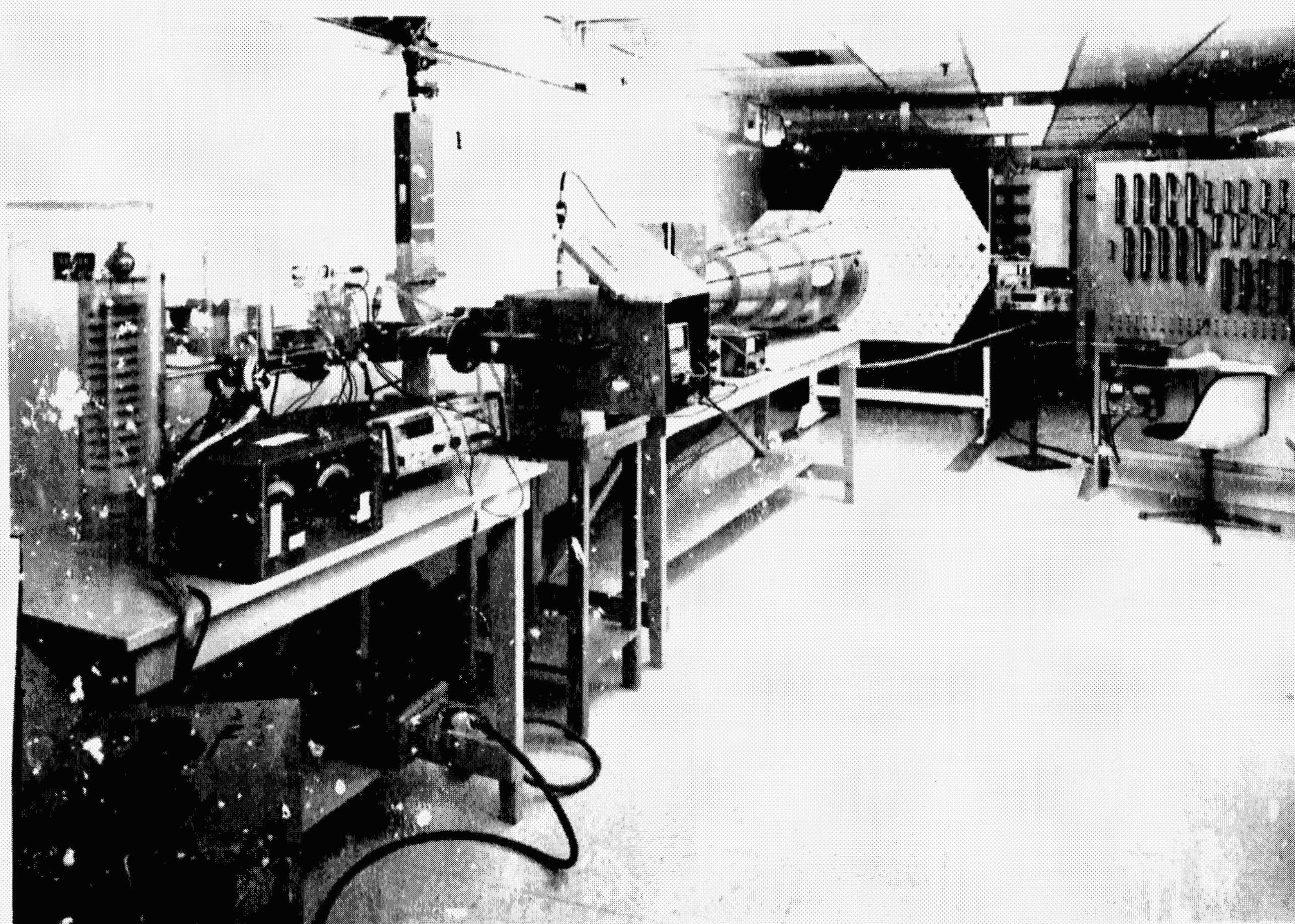


Figure 3-1. Free-Space Microwave Power Transmission System at Raytheon where Certified Overall DC to DC Efficiency Measurements were made.

probable error of ±0.0094. The ratio of the dc power output from the rectenna to the Microwave power input to the dual mode horn was also established as 0.7867 with a probable error of 0.011[3].

It is important to note that significant power levels were involved in the laboratory demonstration. In this test 914 watts of dc power was applied to an off-the-shelf magnetron radiating the RF power through a dual mode horn. This power was transmitted through free space in the laboratory to a rectifying antenna which in turn collected the RF power and converted it to deliver 496 watts of dc power. The dc to dc efficiency of 54 percent was thereby demonstrated. The RF power into the dual mode horn was measured at 630 watts. Figure 14 from Reference 3 is reproduced here as Figure 3-2 to summarize the results.

These certified measurements should serve the two fold purpose of indicating that high overall transmission efficiency is possible with microwaves, and that the published efficiencies are accurate to within relatively small probable errors.

The measurements also confirmed that the largest existing inefficiency is now in the microwave generator, and that the next step in improving overall efficiency is to improve the efficiency of the microwave generator. Based upon a large bank of experimental and theoretical information, there is great confidence that this can be done.

The entire certification procedure including a detailed description of the test set up and the measurement equipment is contained in Reference 3.

3.2 ENVIRONMENTAL AND TYPE APPROVAL TESTS

The following Environmental Type Approval tests were made:

a. Vibration testing of Rectenna Element and Testing Its Interaction with a Wind Stream

b. Static Loading of Subarray to Simulate Wind Loading

c. Rain Test for Entire Subarray

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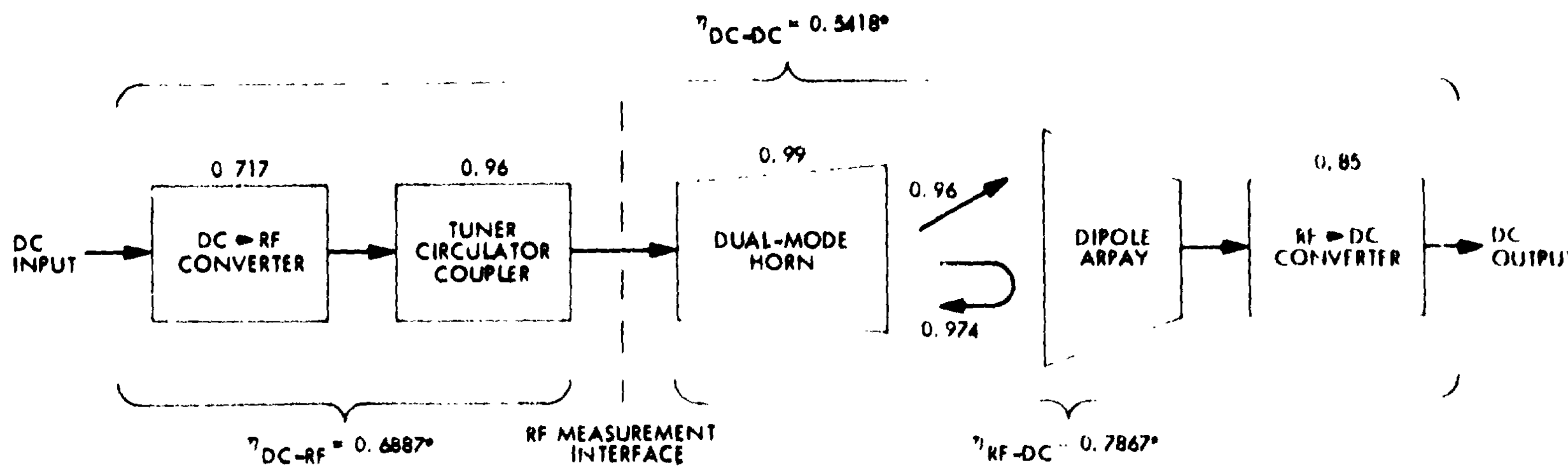
3. R.M. Dickinson, W.C. Brown, JPL Technical Memo 33-727, "Radiated Microwave Power Transmission System Efficiency Measurements," 15 May 1975.



LOSS CONTRIBUTORS

MAGNETRON CONVERSION, CIRCUIT AND REFLECTION LOSSES, HARMONICS, TUNER, CIRCULATOR, COUPLER AND SLOTTED GUIDE I^2R AND REFLECTION LOSSES.

LOSS CONTRIBUTORS

HORN AND ARRAY I^2R, POLARIZATION AND REFLECTION LOSSES. ARRAY SPILLOVER LOSS, DIODE CONVERSION LOSS

ESTIMATED PERCENT LOSSES

MAGNETRON	-28.3
DIODES	-15.0
SPILLOVER	-4.0
CIRCULATOR	-2.6
ARRAY MATCH	-2.6
HORN	-1.0

*MEASURED

Figure 3-2. Distribution of System Efficiencies

d. Survival Under Non-Operating High and Low Temperature

e. Crowbar Performance Test in Simulated RF Environment

f. Check on the Thermistor Unit for Measuring Temperature

g. Measurement of Reflection of Incident Microwave Power from a Subarray

h. Tests on Coupling of Microwave Power into the Cavity Formed by the Back Cover and the Reflecting Plane Plate

i. Wet Test of Rectenna Elements

j. Operating Hot and Cold Tests of Rectenna Elements

k. Drop Test of Subarray in Shipping Container

The above tests are reported upon in the Environmental and Type Approval Test Report PT-4474, included as Appendix A of this Report.

The varied nature of the tests prevent making a general summary with one exception. The water immersion tests on the individual rectenna elements indicated that the operating efficiency would be very poor while the beads of water remained in the transmission line after the elements had been removed from immersion. After evaporation the rectenna elements exhibited normal behavior. There were no substantial design revisions as a result of these tests.

3.3 LIFE TEST ON RECTENNA ELEMENTS AND DIODES

Early in the program it was observed that a life test on the Schottky-barrier diodes would be highly desirable. It was appreciated that the dissipation level in the Schottky barrier diode when used as a microwave rectifier would be considerably below the dissipation level when it is used as an Impatt device and that the dc bias on the diode would be less than half that in an Impatt device. These were factors which would normally enhance the life of the device. Still the microwave power rectification was a new application for the device and there had been no life experience of consequence. Some experimental confirmation was highly desirable.

Fortunately the rectenna designed as part of a complete microwave power transmission system (shown in Figure 3-1) for Marshall Space Flight Center made a natural test rack and panel for the evaluation of diodes used in RXCV rectenna elements. 199 rectenna elements could be inserted into the rectenna test panel. These elements were the same ones used in the certified demonstration discussed in Section 3.1 and it is important to point out here that they did not have the conformal coating applied for environmental protection. Further, the radial Gaussian pattern of illumination made it possible to vary the operating power level of the diodes over a wide range. Finally the rectenna elements were combined into sets, each set being comprised of those elements which had a common radius from the center and therefore similar power illumination. The dc output terminals of all the rectenna elements in a set were connected in parallel across a common load for that set. The arrangement is shown in greater detail in Figure 3-3. If only one diode shorted out, there would be zero voltage across the load which would extinguish a light normally continuously on. In the case of an open diode, a reduction in power output of the set would be found when the total current in a set was periodically checked. Using this equipment a life test was started on 17 March 1975, and with occasional interruptions has been running ever since.

It has been convenient to break the total number of elements down into seven groups depending upon the incident power. The power level and set numbers included in a group is given below.

Group Designation	Set Numbers	Power Range of Group	No. of Units in Group
A	15, 16, 17, 18, 19, 20	0.2-0.5 Watt	78
B	12, 13, 14	0.5-1.0 Watt	30
C	9, 10, 11	1.0-2.0 Watt	30
D	6, 7, 8	2.0-4.0 Watt	24
E	4, 5	4.0-6.0 Watt	18
F	1, 2, 3	6.0-8.0 Watt	18
G	0	8.0-10.0 Watt	1
			199

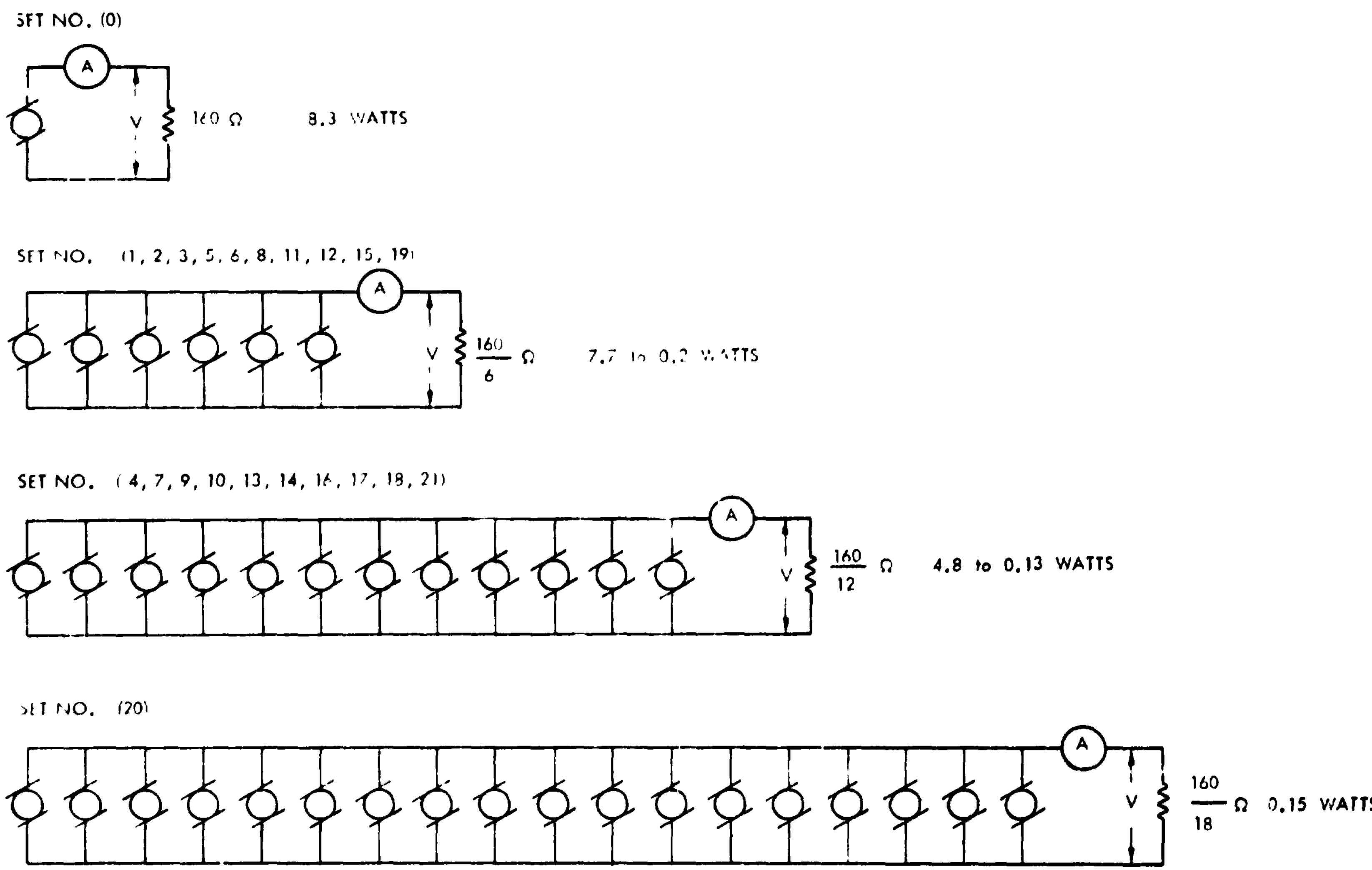


Figure 3-3. Wiring Format for Mark IV MSFC Rectenna

The life test at the time of report writing had reached 2076 hours. During the first 150 hours there were three failures. If we regard these failures as of an infant mortality type, we have since accumulated 1826 hours without a failure or noticeable degradation in efficiency performance. Thus 363,374 diode hours have been accumulated without a failure or noticeable efficiency degradation.

If we apply MTBF tables to this life test data, and request a 90 percent confidence factor, we find that the MTBF is 157,988 hours or 18.1 years. If we relax the confidence factor to 50 percent, an MTBF of 469,285 hours of 59.5 years is obtained.

To date, the variability in efficiency performance has been small and can probably be attributed to measurement error. The efficiency of the diodes in a set is monitored by periodically checking the current which flows into the common load resistor for each set, when the RF power which flows into the illumination horn is precisely set at a pre-established value. The data in Table 3-1 indicates negligible drift in efficiency performance. The average ratio of the last measured currents to the initial measured currents is 0.9982, representing a very small change and one which is easily attributable to measurement error. The average deviation of the ratios from unity is 0.0123.

It is planned to continue this life test as long as possible under the present contract, and then, if possible, to continue it under other sponsorship.

3.4 PRODUCTION LEVEL TESTING

Production level testing consisted of electrically and visually checking each production rectenna element as well as electrically and visually inspecting each finished subarray. Sample test sheets are given in Figures 3-4 and 3-5. The production test set up for the rectenna element is shown in Figure 2-19.

In general, the test procedures were not novel or unusual. However, there was one novel procedure which proved to be a fast and powerful method of checking for non-operational rectenna elements after they were inserted into the subarray. It is a method that was not only used for final checking the subarrays on the production floor but it was used to evaluate any rectenna element failures between the time of production and the time of installation on the tower at Goldstone. With the aid of a cherry picker it can also be used to find any open circuited elements on the finished array.

TABLE 3-1

EFFICIENCY PERFORMANCE

Set #	No. of Elements in Set	Initial Current 151 Hrs	Current 1428 Hrs	Current 1800 Hrs	Ratio of Current (1800 Hrs) to Current (151 Hrs)
0	1	251	251	254	1.0120
1	6	1363	1360	1360	0.9978
2	6	1258	1261	1268	1.0079
3	6	1198	1194	1199	1.0008
4	12	*	*	*	
5	6	1010	1012	1014	1.0040
6	6	939	934	933	0.9936
7	12	1783	1768	1776	0.9961
8	6	792	790	791	0.9987
9	12	1306	1299	1298	0.9939
10	12	1190	1180	1189	0.9992
11	6	547	544	548	1.0018
12	6	524	509	509	0.9714
13	12	935	910	920	0.9840
14	12	818	813	825	1.0085
15	6	362	358	358	0.9890
16	12	654	668	682	1.0428
17	12	639	628	631	0.9875
18	12	558	548	556	0.9964
19	6	220	235	240	0.9600
20	18	678	681	701	1.0339
21	12	431	420	424	0.9838

* Beyond current range of monitor meter.

Average Ratio: 0.9982

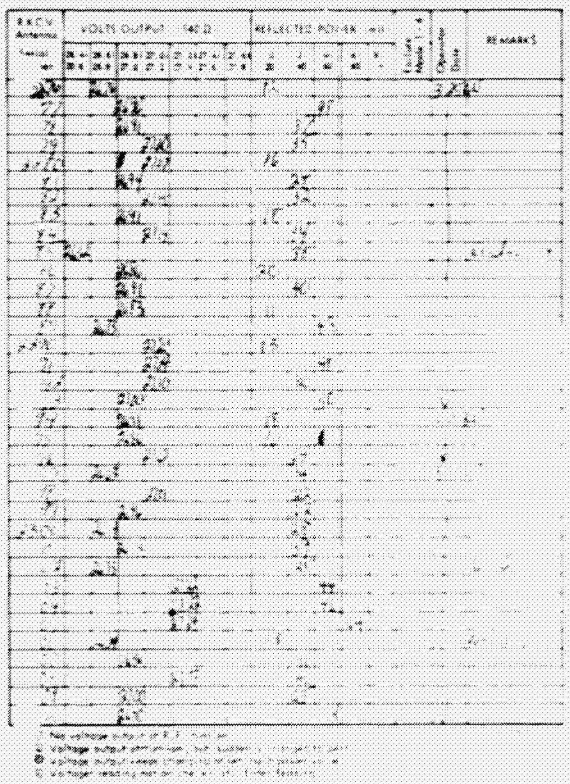


Figure 3-4. Raw Test Sheet

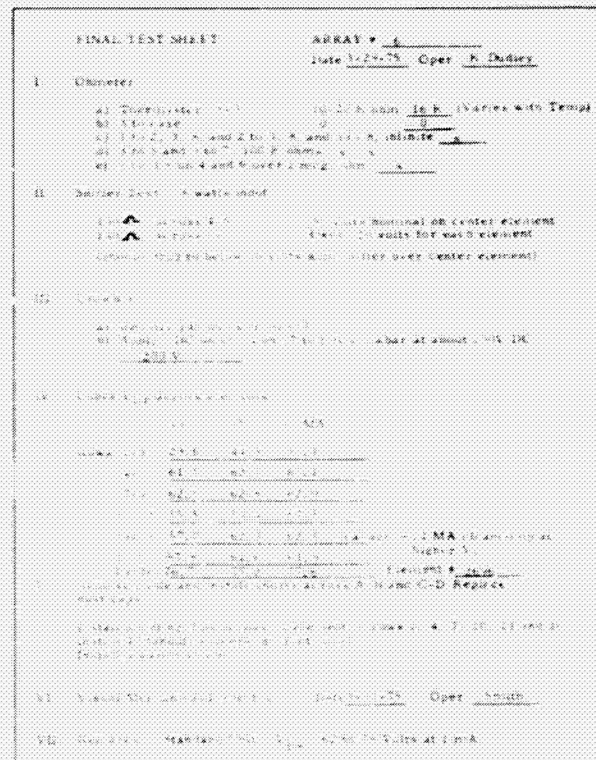


Figure 3-5. Final Test Sheet

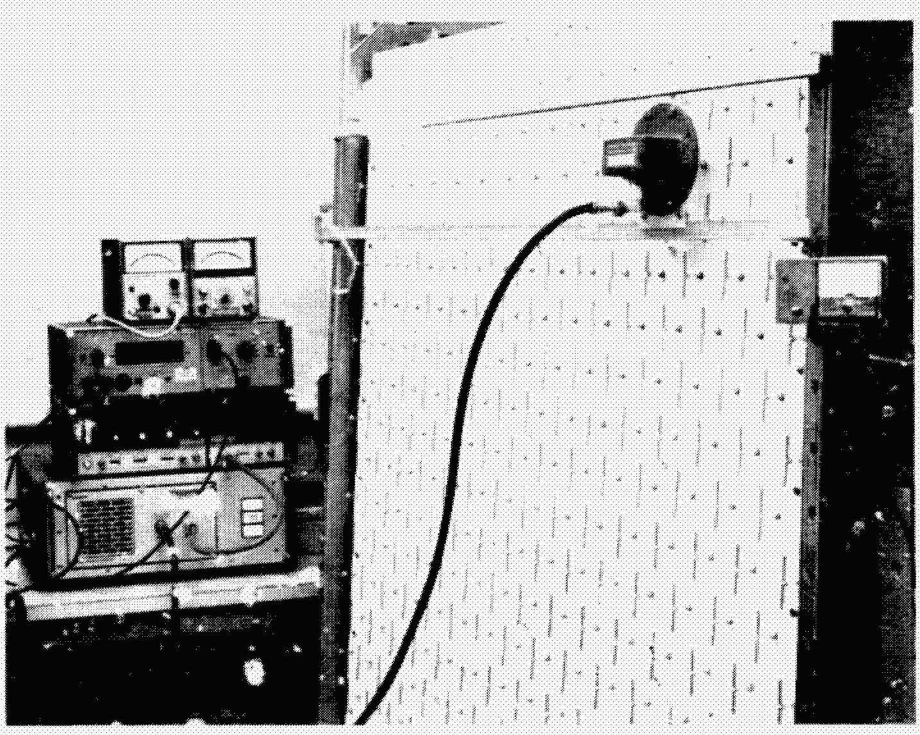


Figure 3-6. Sniffer Test Setup in Raytheon Laboratory

The testing method was known as the "sniffer" test and is shown in Figure 3-6. In this test a localized source of microwave radiation of from six to ten watts is moved across the face of the rectenna. As it passes each rectenna element, it excites that element and the dc power output is monitored by a meter the operator can see at all times. A non-operative element is rapidly located by a pronounced dip in the power as indicated by the monitoring meter.

During the assembly of the subarrays an attempt was made to select rectenna elements going into the various subarrays on the basis of special characteristics. These characteristics were: (1) diodes having low V_{br}, (2) diodes having a high V_{br}, and (3) diodes having a degree of "softness."* There were also the variables of whether the elements were alodine coated or not, whether the back cover was painted black on the inside or not. The prototype also had the bus bars painted black. It was therefore expedient to make a listing of the content of the various subarrays. This was done in conjunction with final testing of the subarrays and is presented in Appendix B.

3.5 BREADBOARD SUBARRAY TEST

The desirability of an early test of a breadboard subarray at the Venus site of the Goldstone Facility was established early in the development of the strategy for the attainment of the RXCV objectives put forth in the RFP. The key to an early test at Goldstone, within three months of the award of the contract, was the use of the rectenna elements developed for the MSFC project. The use of such elements was justified since the strategy was to copy the elements as closely as possible in the design of the RXCV rectenna element. The breadboard in its test position on the collimation tower is shown in Figure 3-7.

The general objectives of the testing were:

a. To confirm the soundness of the basic design approach to the RXCV subarray and to reveal any unexpected weaknesses or aspects that had not been taken into account in the design of the breadboard and in the design of the prototype and production models.

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*"Softness" is a term given to a rounding of the voltage-current characteristic at the V_{br} value of voltage. In Impatt devices such rounding correlates with short operational life.

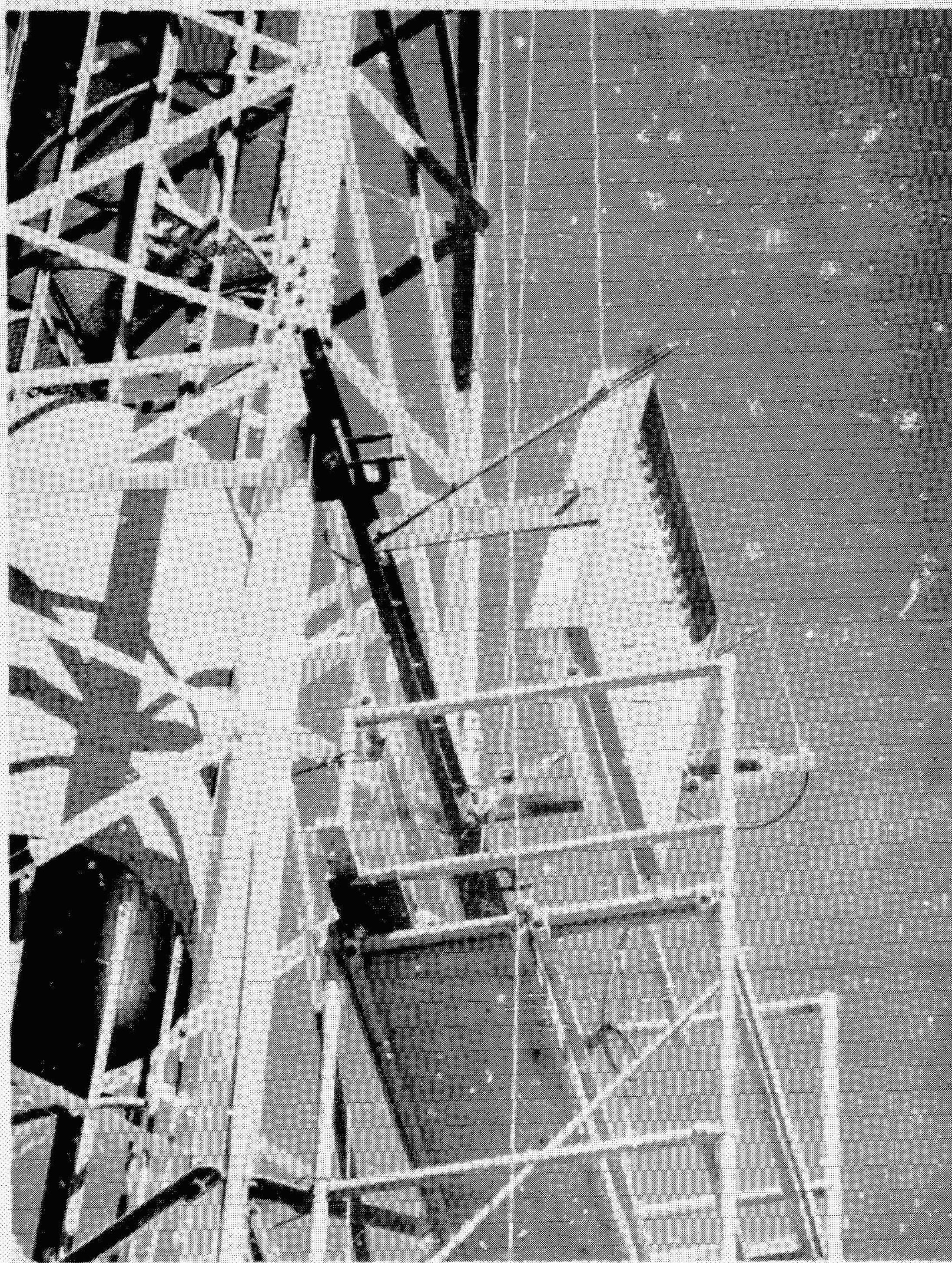

Figure 3-7. The Subarray Breadboard in Position for Test on the Collimation Tower at the Venus Site

b. To provide an opportunity for observance of overall system performance, the system including the high power cw transmitter and 26 meter antenna.

c. Presuming a successful outcome of the testing, to produce early confidence in the success of the major contractual effort.

There were a number of more specific objectives:

a. Evaluation of the efficiency and power handling capabilities of the breadboard.

b. The distribution of dc power output across the 15 rows of rectenna elements.

c. The temperature rise in the heat sinks over ambient temperature.

d. Evaluation of the planned connection of the rows of rectenna elements in a series parallel combination capable of operating successfully into the variable resistive load represented by an incandescent electric lamp.

e. Evaluation under realistic service conditions of the "self healing" capability of the array in the event that one or more of the diodes failed in their usual mode of failure which presents a short across the bus bar into which the rectenna element is operating.

f. Evaluation of the adequacy of the lamp load as a means of demonstrating power transfer by microwave beam, not only from a visual but also from a psychological point of view.

g. Evaluation of the amount of microwave power being reflected from the breadboard subarray.

h. Rectenna efficiency as a function of the spacing between the dipole and the reflecting plane.

The breadboard tests were carried out during the first two weeks of September 1974. The results have been separately documented and reported to JPL. We will confine the discussion in this report to a brief summary.

The general objectives were reached. The basic soundness of the RXCV subarray design approach (with the exception of the five year life requirement, which was not an objective of this test) was amply demonstrated. The overall system, including that portion represented by the high power transmitter was also satisfactorily demonstrated. As a result, a high degree of confidence in the successful outcome of the program was generated among interested NASA, JPL and Raytheon personnel.

Two secondary weaknesses were revealed and a knowledge of their existence was of importance in eliminating them in the final design. The first was the vulnerability of the diodes to the stress caused by instantaneously illuminating the rectenna with microwave power at high intensity. The other was the potential degradation of performance caused by the chance correspondence of the frequency of operation to that of the excitation frequency of a resonant mode of vibration between the back cover and the dipole reflecting plane surface. These two items will be discussed in more detail in the context of additions to the reports and actions taken.

Although the cause of diode failure with a sharply applied pulse has not yet been solved, a step to protect the diodes in the event that the incident power level was too high was taken for the prototype and production units. This step was the insertion of crowbars which close when the output voltage from the subarray was too large. So in the event that a large amount of incident power accompanies the sharply applied pulse, the crowbars would instantaneously close and protect the diodes from overvoltage. It is of interest that most of the crowbars have operated in at least two instances when the transmitter power was suddenly turned on and the antenna was pointed at the completed RXCV array. While the crowbar protected subarrays as a whole appeared not to have been harmed, a number of the reference element diodes had failed which at the time did not have the same crowbar protection. It is true that these reference element diodes are subjected to a higher power level than normal when the rectenna elements around them are short-circuited, but they should be capable of withstanding this higher power level if the transient power level is no higher than the steady state. If we combine these recent experiences with that found and reported upon in the case of the breadboard, where there were no crowbars to confuse the issue, there is a strong indication that when the drive is suddenly applied to the klystron, an excessively high power density at the rectenna results.

The degradation of performance caused by the chance correspondence of the operating frequency with the excitation frequency of a resonant mode of oscillation between the back cover and the reflecting plane surface appeared to have been largely eliminated in the prototype design which was intensively tested and studied for this pennomena. Resonances were found at frequencies below and above 2388 MHz, but when the back cover was distorted sufficiently to make the resonance coincide with 2388 MHz the degradation in output was well within one percent. There are a number of possibilities for the improved performance in this respect, including better balanced and choked rectenna elements which would decrease the amount of power fed back into the back cavity, and changes in mechanical structure which could also impact coupling from the front to the back cover resonance.

3.6 INSTRUMENTATION TESTING

The dc load and instrumentation systems were field tested using a dc power supply as a substitute power source in place of each subarray. The voltage and current at the subarray cable connector was monitored by precision instrumentation calibrated to better than 0.1 percent accuracy. These readings were compared with simultaneous voltage and power readings made by the RXCV primary and backup instrumentation to verify instrumentation accuracy. The design goal was better than 0.1 percent overall dc power measurement accuracy.

Voltage divider resistors were purchased as variable tap power resistors and set to better than 0.2 percent limits using a precision current shunt as the calibration standard. Resistors were purchased to 100 ppm/^{o}C TEMPCO specifications and operate at considerably derated power levels to minimize temperature rise errors. Backup instrumentation resistors were purchased to 0.5 percent tolerance.

All subarray to dc load wiring and instrumentation wiring is shielded and/or run in conduit to minimize EMI effects on instrumentation readings. The ADC was "sprayed" with 2.4 GHz at 10 mW/cm^2 in the laboratory at Raytheon with only minor effect. The installed equipment is believed to encounter considerably lower RF levels. The thermistor bolometer power sensor is protected by an EMI tight enclosure on the collimation tower.

The instrumentation dc field test was performed to secure the following data:

a. Ensure correct subarray location circuit identification wiring including temperature instrumentation circuits

b. Test voltage accuracy of primary and backup instrumentation at 50V and 145V on the dc load low power range and at 100V, 145V and 185V on the high power range

c. Test power accuracy at 50V on the low power range and 145V on the high power range

d. Test the rectenna calibration diode circuits.

A testing problem was encountered in the dc power tests in that the power supply used had enough ripple to cause the primary instrumentation power readings to vary by several percent. Since the sampling rate of the ADC (10 Hz per channel) is a submultiple of the ripple frequency (60 Hz), and since there was a slight asynchronism between the 10 Hz and 60 Hz due to the fact that the 10 Hz is derived from a crystal, ten readings were taken during the time that the sampling point slipped by one period of 60 Hz. These ten readings were taken at uniformly distributed phase angles (multiples of 36^{o}) so that the average of the readings represent the true average of the test function. The averaged readings were repeatable and are believed to be completely valid.

A summary of the test results using averaged readings from the primary instrumentation display is listed in Table 3-2.

The reference element circuits were tested at 30V which represents 7.5 watts of output power into a nominal 120 ohm load. The computer scales this reading to represent equivalent RF input power to the subarray (270 elements) using a predetermined conversion efficiency for that power level. Nominal subarray RF input power level to produce 7.5 watts output from the reference element is approximately 2280 watts. Test readings ranged from 2240 to 2288 watts. This range is satisfactory since the RF calibration procedure used minimizes any residual errors.

TABLE 3-2

LOW AND HIGH POWER LOAD RANGES

● Low Power Load Range, 50V Input			
Subarray	Backup Voltage	Primary Voltage	Primary Power Error
1A	47V	49.8V	-0.3%
1B	46	49.8	-0.5
1C	47	50.0	+3.4
2A	47	50.0	+1.8
2B	48	50.0	-0.4
2C	47	49.7	-0.1
3A	N/A	50.0	+1.3
3B	N/A	50.0	+0.6
3C	46	49.4	+1.3
4A	N/A	49.4	-1.7
4B	N/A	49.9	+0.4
4C	46	50.0	+0.4
5A	47	49.7	+0.7
5B	46	49.8	0
5C	46	50.1	+0.6
6A	46	49.8	+0.9
6B	46	49.8	-0.2
6C	47	49.8	-0.3
Average	46.6	49.8	+0.45

● High Power Load Range, 145V Input			
Subarray	Backup Voltage	Primary Voltage	Primary Power Error
1A	140V	144.9V	-0.5%
1B	139	145.8	-0.2
1C	140	145.4	-0.1
2A	143	145.0	-0.4
2B	144	144.8	-0.8
2C	145	145.2	-0.8
3A	N/A	144.8	+0.7
3B	138	145.3	+0.4
3C	139	145.0	+0.5
4A	137	144.9	+0.1
4B	140	144.7	0
4C	140	145.1	+0.3
5A	141	144.5	-0.2
5B	N/A	144.8	-0.3
5C	140	145.0	+0.6
6A	140	145.1	-0.1
6B	139	145.3	+0.7
6C	141	144.6	0
Average	140.4	145.1	0

3.7 SYSTEM FIELD TESTS

In-plant testing of the RXCV subsystem was limited to unit level testing due to the nature of the subsystem. Full-up testing could only be performed at Goldstone after the complete subsystem was installed at the Venus Station and integrated with the existing equipment to form a complete Microwave Power Transmission System. The system level field testing began on 2 May 1975 and was completed, on schedule, on 6 June 1975. This testing started during the final stages of the instrumentation testing discussed in the preceding paragraphs and the latter stages included the demonstration testing discussed in Section 4.

3.7.1 OBJECTIVES

The objectives of the system field test were to: (1) exercise all elements of the RXCV subsystem in a system configuration including the transmitter, support equipment and the operational environment to assure that they were operational and conformed to the design and (2) to develop data and procedures for conducting demonstrations of the system. Specific objectives, under item (1) were to test each hardware unit and each interface between units to assure proper operation and to test all functions of the system software package. Under item (2) the specific objectives were to obtain the data required to prepare a detailed step-by-step demonstration procedure.

Secondary objectives of this test effort were to collect preliminary engineering data from the subsystem and to validate the RXCV User's Manual.

3.7.2 SUMMARY OF THE RESULTS

All objectives of the system field testing were met and the RXCV was shown to meet or exceed all requirements. The hardware tests identified several minor manufacturing defects, several failures occurred (all were corrected), and one potential problem was identified, the reference elements (one element in each subarray) are subject to diode damage under certain operating conditions. The software testing revealed some small problems. As each problem was identified a corrective program "patch" was made, and upon completion of testing a new program assembly was made. In addition, several operational constraints in the use of the system software were clarified and these items were included in the User's Manual instructions. One hardware/software

procedural problem area was identified. This concerns the method used to measure and calculate RF Input Power (i.e., RF Power incident upon the RXCV subarrays). The User's Manual was validated and corrected and a final version is published as part of this final report effort.

The total series of tests extended over a period of one month. The initial tests, on 2 and 5 May 1975, were conducted with a single subarray (S/N 003) installed (in location 6A). On 7 May 1975 testing was conducted with three subarrays (S/N 003 plus 011 and 014 in locations 5A and 6B). Starting on 8 May 1975 testing was conducted with all 17 subarrays installed. The following table lists the serial numbers versus locations:

ROW	POSITION A	POSITION B	POSITION C
1	007	NONE	013
2	001	002	005
3	006	012	016
4	008	009	010
5	011	017	015
6	003	014	004

EXAMPLE: SUBARRAY SERIAL NUMBER 012 IS LOCATED IN POSITION 3B

Table 3-3 is included to show diode and thermal painting characteristics for each of the subarrays and how they were selected for installation to locate the elements having higher V_{br} near the center of the array and those having lower values were located on the edges.

Most of the hardware was verified in the first few weeks of testing without difficulty and the latter weeks were spent in conducting special tests to evaluate problem areas, refine minor software problems and develop demonstration procedures. Early in the test effort several new records for total power converted were successively established. On 5 May a converted power level of 1891W with one subarray was reached, then on 6 May 5513W was achieved with three subarrays. The first test, on 8 May, with a full complement of 17 subarrays resulted in 12,919W followed by 27.534W on 9 May, and 29,304W on 28 May. During the demonstration testing more than 30 kW were converted (see Section 4).

TABLE 3-3

SUB-ARRAY DIFFERENTIATION

Subarray Number	Diode Construction Breakdown Voltage at 1 MA			Soft	Back Cover Not Painted	Buss Bars Blackened
	55-62	62-75	75+	Soft		
(1) 1.		x				x
2.		x				
3.	x					
4.	x					
5.		x				
6.		x				
7.	x				x	
8.		x				
9.		x				
10.		x				
11.		x				
12.			x			
13.	x					
14.	x	x	x	x		
15.		x				
(2) 16.		x	x			
17.	x	x	x	x		

(1) Prototype. No epoxy on diode, rails not alodined.

(2) Nearly all high voltage diodes, very few with V_{br} below 70 volts.

3.7.3 REFERENCE ELEMENT PROBLEMS

The reference elements, one in each RXCV Subarray, did not have protective devices to prevent damage to them (crowbars for the reference elements have since been installed in the junction boxes). All other elements in the subarray are protected by a crowbar circuit within the subarray which is set to limit output voltage to 200 Vdc, which was calculated to be low enough to protect the diodes. The crowbars were tested during the system field test, both intentionally and by accident (attesting to the need for them). On all occasions the crowbars operated, and there was no evidence to suggest that any of the power diodes had failed, however an RF scan (or sniffer) was identified as essential and was to be conducted at a convenient point to establish status of operability of each element of each subarray.

The RF Scan Test was conducted on 20 August 1975; on the same occasion the opportunity was taken to measure the standoff distance of the dipoles from the ground plane and both are discussed in this section.

Three of the 17 reference element diodes, without protection, did fail (on 4 June). It was not possible to positively identify the cause of these failures, however, the most likely cause is that they were subjected to a high power transie. or were degraded when subjected to earlier power transients associated with power turn on or crowbarring of the neighboring elements. Not only did those diodes see the full effect of the various transmitted power conditions, but, on several occasions, the transmitter was allowed to remain on (for periods of up to about two minutes) with one or more subarrays in a crowbar condition. This applies added stress since with all surrounding elements shorted by the crowbar the reference element captures more input power than its normal share (40 to 50 percent more) resulting in a high output voltage. The three failed reference elements were replaced and normal operation was resumed with more emphasis being placed on the need to operate with the transmitter shutdown interlock in operation. (See also Item 8 on Table 3-5 in paragraph 3.7.5.) The subsequent incorporation of protective crowbars for the reference elements should limit such failures in the future. It is concluded however that the opportunity should be taken at an early time to establish the existence and nature of transients that may overload either the load elements or the reference elements.

3.7.4 RF SCAN TESTING

On Wednesday, 20 August, the subject survey was conducted by means of a "sniffer" test of all 17 subarrays at Goldstone. A HP Signal Generator (at 2388 MHz) and a 10W TWT adjusted for about 7W was utilized. The Venus Site "cherry picker" was employed to access the front of the subarrays. The special test cable, with load resistors, was used as the load and to monitor the output voltage. A total of 18 open circuits was found out of the 4590 elements in the 17 subarrays (i.e., 0.0039 percent defective).

Of the 18 defective elements, ten were located in the prototype subarray (SN001) which utilized development diodes. Two other subarrays each had two defective elements, and four subarrays had one each. The other ten subarrays had no open elements. Table 3-4 lists the 18 open elements found and their locations.

JPL Project Manager decided that corrective action at that time would be limited to installing the three spare elements (on hand at Goldstone) and the outright removal of selected other elements. It was also decided to limit actions to three subarrays (SN's 001, 012, and 017). A total of five defective elements were removed and returned to Raytheon for analysis. In addition, two normal functioning elements selected as control samples were removed and returned to Raytheon for comparison testing. Table 3-5 details this corrective action taken.

3.7.5 GROUNDPLANE SPACING

Measurements of the groundplane (i.e., front cover panel) to diode antenna element spacing were made on 21 August 1975. The design spacing is 2.54 cm (1.00 inch) nominal. The first set of measurements were taken near the nine studs that support the bus bar assembly (to which the elements are attached) and determine the spacing. Figure 3-8 indicates the results of this set of measurements. As shown the lowest reading (on any subarray) was 2.44 cm (0.96 inches) and the highest was 2.66 cm (1.03 inches). The largest difference within a single subarray was 1.5 mm (0.06 inches) on 2A and 6A and the smallest was 0.25 mm (0.01 inches) on 3B and 3C. The average spread was 0.76 mm (0.03 inches).

A second set of measurements was taken at the edges, four corners plus top and bottom center. Figure 3-9 indicates these results. Much higher variations

TABLE 3-4

LISTING OF DEFECTIVE ELEMENTS

Subarray		Defective Elements		
SN	Location	Row*	Number*	SN
001	2A	4	10	00239
		6	8	0297
		7	5	0316
		11	2	0390
		11	4	0387
		11	6	0386
		11	14	0377
		12	3	0404
		18	7	0493
004	6C	1	5	01671
007	1A	11	7	01020
010	4C	2	12	02942
012	3B	9**	8	0530
014	6B	16	4	04617
		16	6	04824
017	5B	9	11	04554
		11	14	04760

* Row 1 is the top, Row 18 is the bottom. Elements numbered left to right from the rear (right to left from the front).

** Reference Element.

TABLE 3-5

RECTENNA ELEMENT CORRECTIVE ACTIONS

Subarray		Element			Action Taken
SN	Location	Row	Number*	SN	
001	2A	12	3	0404	Removed and returned to Raytheon.
		12	3	04958	Spare installed.
		11	2	0390	Removed and returned to Raytheon. No replacement.
		11	4	0387	Removed and returned to Raytheon.
		13	13	0409	Removed. No replacement.
		11	4	0409	Installed.
		3	3	00228	Removed and returned to Raytheon. No replacement. Good element (control sample) for comparison to failed units.
004	6C				No action taken.
007	1A				No action taken.
010	4C				No action taken.
012	3B	9	8	0530	Reference element. Removed and returned to Raytheon.
		3	3	02793	Removed.
		9	8	02793	Installed.
		3	3	04917	Spare installed.
014	6B				No action taken.
017	5B	9	11	04554	Removed and returned to Raytheon.
		9	11	04938	Spare installed.
		17	4	03587	Removed and returned to Raytheon. No replacement. Good element (control sample) for comparison to failed units.

*Row 1 is the top, row 18 is the bottom. Elements numbered left to right from the rear (right to left from the front).

	A			B			C		
	0.99	1.00	1.00				1.01	1.00	1.00
1	1.00	1.00	1.00				1.00	1.00	1.01
	1.02	1.02	1.00				1.02	1.01	1.00
	0.98	1.02	0.96	1.01	0.99	1.00	1.01	0.99	1.00
2	1.02	0.99	1.01	1.01	0.98	0.98	1.00	1.01	1.02
	0.99	1.00	1.00	1.01	0.99	0.99	1.02	1.01	1.02
	1.01	1.01	0.99	1.00	1.00	1.00	1.00	1.00	1.01
3	1.00	1.00	1.02	1.01	1.00	1.01	1.00	1.00	1.01
	1.01	1.01	1.00	1.00	1.00	1.00	1.01	1.00	1.00
	0.98	1.00	1.02	1.01	1.01	0.98	1.02	1.00	1.01
4	1.00	0.99	1.01	1.01	0.99	1.00	1.00	0.98	1.01
	1.03	1.01	1.00	1.00	1.00	1.00	1.02	0.99	1.01
	0.99	0.99	1.00	1.00	1.01	0.99	1.01	1.03	1.00
5	1.01	1.01	1.00	1.03	1.01	1.02	1.00	0.98	1.02
	0.99	1.00	1.01	1.00	1.01	0.99	1.03	1.00	1.02
	0.99	1.02	1.02	1.00	1.00	1.01	1.01	1.01	1.00
6	1.01	0.96	0.99	1.01	0.98	1.01	0.99	0.98	0.98
	1.01	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00

Inches	0.96	0.97	0.98	0.99	1.00	1.01	1.02	0.03
cm	2.44	2.46	2.49	2.51	2.54	2.57	2.59	2.62

Conversion Inches to Centimeters

Figure 3-8. Ground Plane Spacing Inventory Near Nine Studs (Inches)

	A	B	C
1	1.03 1.02 1.03		0.99 1.00 1.04
	1.07 1.07 1.06		1.05 1.01 1.07
2	0.93 0.88 0.90	1.01 0.98 0.94	1.05 1.03 1.02
	0.99 1.04 1.08	1.05 1.02 1.00	1.08 1.04 1.01
3	0.97 0.96 1.01	1.00 1.01 1.04	1.05 1.02 1.02
	0.94 1.02 1.11	1.02 1.03 1.03	0.98 1.02 1.06
4	1.09 1.02 1.03	0.97 1.02 1.07	0.97 0.98 1.01
	0.97 1.06 1.13	1.07 1.02 1.01	1.02 1.03 1.06
5	1.05 1.05 1.05	0.96 1.03 1.06	0.98 0.98 1.93
	1.00 1.00 1.02	1.00 1.06 1.11	1.00 1.04 1.10
6	1.02 1.03 1.07	0.98 1.00 1.02	0.97 0.98 1.01
	1.08 1.05 1.10	1.00 1.03 1.03	0.99 1.03 1.06

Inches	Centimeters
0.93	2.36
0.94	2.39
0.95	2.41
0.96	2.44
0.97	2.46
0.98	2.49
0.99	2.51
1.00	2.54
1.01	2.57
1.02	2.59
1.03	2.62
1.04	2.64
1.05	2.67
1.06	2.69
1.07	2.72
1.08	2.74

Figure 3-9. Ground Plane Spacing Inventory Corners and Edge Centers (Inches)

in spacing is indicated by these measurements. The lowest reading was 2.29 cm (0.90 inches) and the highest was 2.74 cm (1.08 inches) both occurring on subarray 2A, a spread of 4.6 mm (0.18 inches). The smallest spread of any subarray was 1.0 mm (0.04 inches) (on 3B). The average spread over the individual subarrays was 2.3 mm (0.09 inches).

It appears that some small amount of twisting of the subarray sides (or frames, they are 15.0 cm (six inch) channels) has taken place, possibly as a result of irregularities in the supporting I beams to which the subarrays are bolted. No corrective action was taken relative to this groundplane spacing.

3.7.6 RF INPUT POWER MEASUREMENTS

This section discusses the RF input power measurements to be used in determination of RF to dc efficiency. The method of calculation used in the software along with the associated field test experience is discussed first. Three independent determinations of incident RF power are also discussed:

a. Theoretical estimates at a range of 1.54 km from the 26 meter dish as a function of transmitted power.

b. Incident RF power measurements by a standard gain horn in the plane of the rectifyi..g antenna.

c. Laboratory measurements of rectenna element efficiencies in converting received RF power to dc, laboratory measurements of Voltage Standing Wave Ratio (VSWR) to determine reflected power, field measurements of subarray output dc power.

Approach a. uses transmitted RF power as the basic measurement along with assumptions about geometry and aperture illumination efficiency. Approaches b. and c. give measurements of incident RF power directly and its reference back to the transmitted RF power is for purposes of comparison. Approaches b. and c. should then have less uncertainty than Approach a. given nominal instrumentation accuracies. The JPL estimates for transmitted power uncertainty at the power meter is between ±6 percent and ±12 percent with the smaller value applying when an instrumented water load is used to measure RF power and calibrate the meter.

The results of the three independent approaches are then discussed in order to determine what the computer software should use to compute the incident RF power for calculation of RF to dc efficiency and for display purposes.

The actual steps taken in the computation and display of efficiency are then discussed at some length. Recommendations are made for instrumentation technology development and for engineering experiments to determine efficiencies most accurately.

3.7.6.1 Input Power Measurements Methodology

Section 3.6 described the instrumentation measurement accuracies. The methodology of calculating RF input power was investigated in significant detail during the system field test. In the early phases of testing the results were poor indicating the possibility of a problem in the hardware or software used to measure and calculate input power. As testing progressed several problems were solved (Horn Alignment, 26M antenna pointing and software operating procedures) and acceptable measurements were obtained.

In brief, the method of measuring RF input power is as follows. In each RXCV Subarray a single element is dedicated to RF power measurements. The dc output of this reference element is wired separately and is connected to a 120 ohm fixed load resistor. An instrumentation circuit monitors the output voltage (across the load resistor) and this voltage is processed in the computer system. The software converts this voltage into input power by means of a curve representing power in VS. voltage out and the "Raw" reading from the curve is multiplied by a "calibration factor". The curve was developed, in the laboratory expanded waveguide fixture, by detailed measurement of the element performance.

It was subsequently det rmined that the reference element "share" of power pickup is a function of the resistive load associated with the neighboring elements. This will effectively modify the calibration curve and is discussed further in this section.

The reference elements used in the system are ones which had high breakdown voltage and were identified as a double blue dot type. The calibration factor is determined by means of a measurement of the actual RF power as measured by the standard gain horn and an HP 432A power meter. The transmitting antenna is aimed to boresite on the horn and the computer notes the power reading.

The boresite is then moved to each subarray, in turn, and the calibration factor is calculated from the difference between the "raw" reading from the curve and the horn reading converted to the effective area of a subarray.

The original version of the software performed the "Horn reading conversion to the effective area of a subarray" calculation as follows. The "Raw" reading on the power meter, 10 mW scale, is equal to 242 mW/m^2 full scale or 24.2 mW/cm^2 per mW indicated on the meter.* The effective area of the subarray is 1.4399 m^2. (This effective area assumes the gap between subarrays is actually part of the area, i.e., the array is continuous.) Therefore the power density over the effective area is 348.4 watts per subarray, per mW indicated in the power meter. (Due to a computation error the original software used 346.5W.)

3.7.6.2 Incident Power Theoretical Estimate

Two theoretical estimates are made for RF power incident on a subarray at a range of 1.54 km from the 26 meter dish as a function of transmitted power. The first estimate is based on a JPL report and the second one is based on Hansen's equations. They both use the following theoretical expression and differ only in the estimates of the efficiency factor.

- Theoretical Expression for Received Power

Let the transmitter power be P, the transmitter gain be G_t, the range to the receiver be R, and the effective area of the receiving antenna be A_{eff}.

Then the power density at the range of the receiver, if true far-field conditions exist, is

$$\sigma = PG_T/(4\pi R^2)$$

* This number is based on the gain of the horn 16.92 dB, the insertion loss of the sensor assembly, 41.74 dB and the frequency of 2388 MHz.

and the actual received power is

$$\rho = \sigma \cdot A$$

However, in the present case the range is insufficiently great for far-field conditions, and the expression for received power must be modified by an efficiency factor, η. Thus the final expression for the theoretical received power is

$$\rho = \sigma \cdot A \cdot \eta$$

- The "Efficiency Factor", η

There are two sources from which the value of η can be derived. The first of these is a graph of power density as a function of range for various Goldstone antennas, supplied by JPL. The principal disadvantage for this source is that it is clearly stated in the associated test [4] that the error in the graph may be as much as 1 dB (over 25 percent) in the region of interest. The value of η at 1.54 km range is found from the graph to be 0.703.

A second source for η is the theoretical expression given by Hansen[5] for antennas with an aperture distribution of the form $(1 - \rho^2)$:

$$\eta_H = \frac{4}{\theta^2}\left[1 - \frac{2}{\theta}\sin\theta + \frac{2}{\theta^2}(1 - \cos\theta)\right]$$

where θ is an abbreviation for $\pi D^2/(4R\lambda)$, and D is the diameter of the aperture. Although the aperture distribution of the DSS-13 antenna is effectively not unlike a $(1 - \rho^2)$ distribution, it is possibly different enough to invalidate the use of this expression for η.

- Theoretical Calculations

For comparison with previously published quantities, take a value for transmitted power of P = 1 kW.

In several instances information from the JPL Project Manager was solicited and is identified by the symbol (Ex JPL).

4. Unpublished JPL report.
5. R.C. Hansen, Editor, "Microwave Scanning Antennas," Academic Press, 1964, Volume 1, Chapter 1, pp. 33-40.

Now C_t = (54.3 $\pm$0.2) dB (ex JPL)

= 2.6915 $\pm$4.71%

Also R = 5047.8 feet (ex JPL, using data from angle servos)

or R = 5056.6 feet (ex JPL, using data from geodetic survey)

from which R = 5052.2 $\pm$4.4 feet

= 1539.9 meters $\pm$0.09%

therefore σ = 9.0323 W/m^2 $\pm$4.71% $\pm$0.18%

Next, D = 85 feet $\pm$1/2 inch (ex JPL)

= 25.908 meters $\pm$0.05%

At the operating frequency of 2388 MHz

λ = 0.12554 meters $\pm$0.04%

Hence, in the expression for η_H,

θ = 2.7270 radians $\pm$0.10% $\pm$0.09%

and thus

η_H = 0.6560 $\pm$0.09% $\pm$0.08% $\pm$0.03%

Alternatively, as indicated above, the value of η deduced from the JPL graph is

η_J = 0.703 $\pm$25.9%

There are two cases to be considered for the receiving antenna: the standard gain horn and the rectenna subarray. For the horn, the effective area must be calculated from the measured gain, G_H, using the relation

$$A = G_H \lambda^2 / 4\pi$$

Since we have[6]

G_H = (16.917 $\pm$0.017 $\pm$0.08) dB

6. J.C. Parr, Raytheon Memo JCP-91, "RXCV RF Field Measurements-Final Results of Calibration," 14 January 1975.

then

$$A_H = 0.061667\ m^2 \pm 0.39\% \pm 2.05\% \pm 0.08\%$$

For the rectenna, the effective subarray dimensions are stated as 1.222 x 1.177 meters (48.125 x 46.375 inches) with a tolerance of 1.578 mm (0.0625 inch) hence, assuming no reflection, the effective receiving area is

$$A_R = 2231.8 \pm 3.9 \text{ sq. inches}$$

or

$$A_R = 1.4399\ m^2 \pm 0.26\%$$

However, the rectenna subarray, unlike the horn, is large enough for the non-uniform power density at the peak of the transmitted beam to have a noticeable effect. Using the known dimensions of the subarray and the polynomial approximation to the power density (Appendix C), simple double integration, (left as an exercise for the reader), leads to a reduction of 0.71 percent in the value of average incident power, thus providing a new effective area to be associated with peak power density of

$$A_R = 1.42975\ m^2 \pm 0.026\%$$

- Theoretical Results

Substituting the various values obtained above in the expression for received power, and specifying the estimated accuracy as the RSS (root-sum-squares) of the individual uncertainties, we have:

(a) for the standard gain horn:

$$P_H = 0.3916 \text{ W/kW} \pm 26.4\% = {0.4950 \atop 0.3098} \text{ W/kW}$$ --- Using the JPL graph

$$P_H = 0.3654 \text{ W/kW} \pm 5.16\% = {0.3843 \atop 0.3475} \text{ W/kW}$$ --- Using Hansen's formula for τ.

(b) for the rectenna subarray:

$$P_R = 9.0785 \text{ W/kW} \pm 26.3\% = {11.466 \atop 7.188} \text{ W/kW}$$ --- Using the JPL graph

$$P_R = 8.4715 \text{ W/kW} \pm 4.72\% = {8.871 \atop 8.090} \text{ W/kW}$$ --- Using Hansen's formula for τ

For 250 kW transmitted power therefore

P = 2270 ±597 watts (using JPL Report No. 890-24)

P = 2118 ±100 watts (using Hansen's Formula for η)

3.7.6.3 Incident Power Measured by a Standard Gain Horn

During the field probing operations measurements were made of the RF power density profiles close to the rectifying antenna range, from the 26 meter dish. The peak power densities obtained are discussed and related back to transmitted RF power for purposes of comparison. These measurements were made at low RF power output from the 26 meter antenna and due to the inability to use the water load to calibrate the RF output power meter as is done in the high power cases, the extrapolation from the low power situation to the high power situation is not as accurate for the high power case as one would expect using measurements taken when the transmitter is operations at high power.

Measurements taken at high power on the RXCV installed configuration of the standard gain horn are also discussed and results are presented in Figure 3-10 for comparison purposes.

- Standard Gain Horn at Low Power Situation

During the field probing operations the following values were obtained while operating at low power:

Transmitted Power	= 8.5 ±0.1 dBW
	= 7.079W ±2.33%
Received Power	= (3.65 ±0.06 ±0.015) dBm (including meter calibration data from [7])
	= 2.317 mW ±1.39% ±0.35%

Thus for 1 kW transmitted power, the power received by the horn should be

$$P_H = 0.3273 \text{ W/kW} \pm 2.74\% = {0.3363 \atop 0.3186} \text{ W/kW}$$

and scaling for the rectenna subarray using the values quoted previously,

$$P_R = 7.5880 \text{ W/kW} \pm 3.45\% = {7.850 \atop 7.335} \text{ W/kW}$$

(7) J.C. Parr, Raytheon Memo JCP-82, "RXCV Power Meter Calibration", dated 19 November 1974.

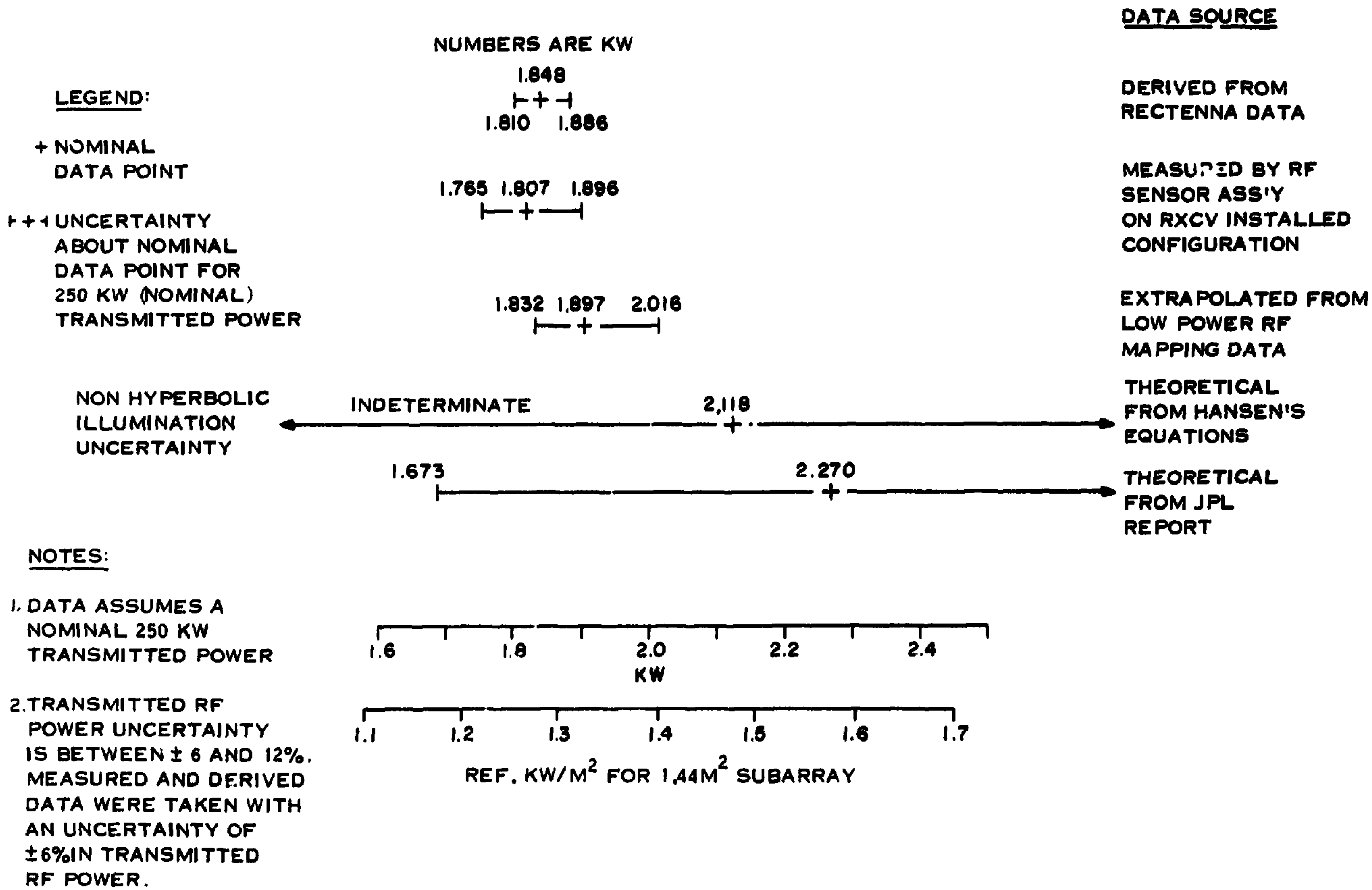

Figure 3-10. Subarray Incident RF Power Determined from Available Sources

Monitor Horn Misalignment

The Monitor Horn misalignment has been estimated to be less than 2^{o}. For monitor horn misalignment of 2^{o} in either principal plane or in orientation with the vertical, the indicated received power can be less than the actual received power by up to 2.80 percent. (This is the only unilateral source of error known.)

Extrapolation to 250 kW

Combining all the previous results and extrapolating to the case of 250 kW transmitted power and to the effective area of the rectenna subarray, at the beam center, being the receiver, we have:

$P = 1897\,^{+119}_{-65}$ watts (extrapolation from low power RF mapping experimental results)

Transmitted Power Uncertainty

The JPL estimates for transmitted power uncertainty at the power meter is between ± 6 percent and ± 12 percent with the smaller value applying when an instrumented water load is used to measure RF power and calibrate the meter.

- Data at High Power RXCV Installed Configuration of Standard Gain Horn

In order to compare the actual readings from the RF Sensor Assembly (gain horn, power meter and interconnections) with the calculated data three separate tests were conducted, on three days, to obtain a meaningful average. For each test run the Venus transmitter was calibrated (via the water load) at an output power level of 250 kW just prior to RXCV data taking. The transmitting antenna was then boresited on the gain horn and a series of readings were taken. Table 3-4 is the data from the three test runs. As shown the overall average is 1807 watts, and the total range of the readings on all three days was 1765 watts to 1842 watts, i.e., 1807 + 35W - 42W. Again the tolerance on the 250 kW output of the transmitter is less than ± 12 percent possibly as low as ± 6 percent. These data are included in Figure 3-10 as "Measured by RF Sensor Assembly on RXCV Installed Configuration."

TABLE 3-6

RF SENSOR TEST DATA

Watts Per Subarray		
MIN	MAX	AVG
1765	1802	1781
1793	1837	1817
1811	1842	1822
	Overall Average	1807

*Reference Data Sheet by D.A. Salmond on May 22, 28, and 29, 1975.

An additional ±2.8 percent should be added for monitor horn misalignment previously discussed. This would result in nominal 1807, minimum 1765 and maximum 1896 watts per subarray.

* Derived from Figure 13 of Memo JCP-78A, "RXCV RF Field Measurements," included in this report as Appendix C.

3.7.6.4 Input Power Based on Rectifying Antenna Efficiency and Reflected Power

The efficiency can be calculated on the basis of efficiency of the rectenna element and the measurement of reflected power. Overall capture and rectification efficiency of the rectenna subarray can be accurately estimated on the basis of the average efficiency of the rectenna element when measured in the expanded waveguide fixture and a standing wave ratio probe measurement made in front of the subarray. The standing wave ratio measurements must then be compensated for the difference in resistance of the load in the laboratory case compared to that of the field site installation.

The reliability of the measurement of average efficiency of the rectenna element depends upon the accuracy of the reference microwave power standard and upon the errors made in transferring the standard reference to the rectenna element measurement test set. The probable error of these two items is plus or minus 1.5 percent. The carefully measured average efficiency of the first 500 diodes when they had no conformal coating was 86.12 percent. The distribution of the rectenna element efficiency is shown in Figure 2-21. Specific tests were not conducted to determine the loss due to the thin conformal coating, however, tests on particularly thick coatings showed losses less than one percent. It has been observed that some accumulation of particles on the coating has occurred in the field installation and for the purposes of this calculation the loss due to both the thin coating and any particles is assumed to be 0.5 percent. The rectification average efficiency of the elements in the prototype should therefore be 85.6 percent ± 1.5 percent.

The probe measurement for standing wave ratio can be very accurate if a power meter is used with the probe. This accuracy, combined with the fact that the reflected power loss is very low for low values of standing wave ratio, makes the measurement of the reflected power extremely accurate at low VSWR. It would be highly desirable to validate the VSWR measurement for the finished rectenna array in the nearly uniform power density field at Goldstone.

The VSWR measurements which have been used in our calculations are laboratory measurements made upon the RXCV elements in a circular format excited with a microwave beam having a gaussian distribution. The elements were matched out in the expanded waveguide fixture into a 140 ohm load at the power level that they encounter in the gaussian array. However, the actual load on the elements in the gaussian array was 160 ohms because of the high temperature coefficient of the load resistors which were set to 140 ohms at room temperature. Based upon VSWR measurements into the gaussian array the reflected power was only 0.3 percent of the incident power.

These measurements do not directly correspond to the rectenna array at Goldstone because the load resistance at the characteristic 250 kW transmitter operating point is 128 ohms. Based upon measurements on the rectenna element in the expanded waveguide fixture, a change in load from the match point of 160 ohms to 128 ohms would cause a reflection of 1.2 percent as indicated in Figure 2-15 and from mismatch theory. It is expected that the subarray matched into 160 ohms but operated into 128 ohms would behave the same way. However, this is partly conjecture.

If we assume the most probable value of reflected power to be 1.2 percent the most probable value of collection efficiency is 98.8 percent with an assumed uncertainty of +0.2 percent - 0.7 percent.

If we multiply the most probable collection efficiency by the most probable rectification efficiency we obtain a figure of 84.6 percent for a subarray with conformal coating (the prototype). If we then add (RSS) the probable errors we arrive at an efficiency of 84.6 percent + 1.6 percent - 1.9 percent.

In conclusion it is noted that if the VSWR measurements are in doubt, the validity could be established by making arrangements for these measurements to be made on the finished rectenna array at the Venus site as suggested.

A test data printout from the RXCV at the Venus site on 9 May 1975 at 10:40 a.m. is presented in Figure 3-11. At 11:05 a water load calibration of the transmitter was performed at 250 kW. The results were 246 kW actual with 250 kW indicated as recorded on the data sheet by W.C. Brown, 9 May 1975.

As shown in Figure 3-8 the dc power output of subarray 3B was 1521 $\pm$0.4 percent watts at 246 kW with the $\pm$0.4 percent being output power measurement instrumentation uncertainty. The equivalent dc output for 250 kW would then be 1546 $\pm$0.4 percent watts. The boresite was located between subarrays 3B and 4B

Subarray 3B Output Power

```
1073/1185W     0*     0W 1045/1329W  P     135V        0V        136V   V
    91%        NA%           79%            28C       46C         27C

1262/1624W 1359/1669W 1292/1526W           145V      153V        149V
    78%        91%           95%      W     28C       31C         29C   L

1414/1641W 1521/1709W 1441/1669W     E     155V      161V        157V   T
    86%        89%           96%            30C       30C         29C

1420/1654W 1516/1871W 1444/1653W           154V      160V        156V
    86%        81%           97%      -     30C       31C         30C   T

1338/1558W 1389/1664W 1361/1517W     E     149V      152V        151V   E
    86%        93%           90%            30C       32C         29C

1140/1265W 1216/1458W 1144/1366W           139V      143V        138V
    90%        93%           94%      F     29C       29C         28C   P
POWER OUT= 22.380W POWER IN= 26.358W AVG EFFICIENCY= 85%.    129 10:40:02
```

Figure 3-11. May 9, 1975, 10:40 a.m. Data Printout

(AZ 260.578°, EL 7.104°). Based on the RF mapping data the difference in dc power output of a subarray with the beam boresited on the center of a subarray from boresiting on the edge is 1.11 percent*. The dc output for subarray location 3B at 250 kW from the transmitter boresited on 3B would be 1546 x 1.011 or 1563 ±0.4 percent watts. Assuming the 84.6 percent with an uncertainty of +1.6 percent - 1.9 percent for the subarray efficiency, the incident RF power would be a nominal of 1848, minimum 1810, and maximum 1886 watts per subarray.

The tolerance on the 250 kW output of the transmitter is less than ±12 percent possibly as low as ±6 percent. These points are then referred to on Figure 3-11 as "Derived from Rectenna Data." From these data it is also clear that the maximum RF to dc efficiency to be displayed for a subarray at 250 kW transmitter output boresited on the subarray during calibration should not exceed 85 percent to assure credibility.

*Derived from Figure 13 of Memo JCP-78A, "RXCV RF Field Measurements" Appendix C of this report.

3.7.6.5 Results of Three Independent Approaches to Determine Incident RF Power

The following summarizes the results of the three independent approaches assuming 250 kW of RF power is transmitted from the 26 meter dish 1.54 km from a 1.44 M^2 subarray.

a. Theoretical Estimates

$P = 2270 \pm 597$ watts (using JPL Report #890-24)

$P = 2118 \pm 100 \pm$ indeterminate watts (using Hansen's Formula)

b. Based on Measurements using Standard Gain Horn

$P = 1897^{+119}_{-65}$ Extrapolated from measurement at 7W transmitted power

$P = 1807^{+89}_{-42}$ Measured at 250 kW transmitted power

c. Based on Measurements of Rectenna Efficiency and Reflected Power.

$p = 1848 \pm 38$ watts

The theoretical estimates of nominal peak power at the rectenna subarray location are about 20 percent higher than the measured values. The uncertainties are also higher for the theoretical estimates. This may be accounted for as being due to uncertainty in efficiency η. From Figure 3-10 a range of values between 1.83 and 1.87 kW of incident RF power for a nominal 250 kW transmitted is within the region of uncertainty for all of the cases investigated. The data with the least uncertainty is associated with measurements taken on the rectenna test article itself or on its development hardware and its nominal data point is close to the most probable value. The independent data having the least uncertainty is taken by the RF sensor assembly using the standard gain horn in the RXCV installed configuration. Its nominal value is slightly less than that from the rectenna itself and when used in the efficiency calculation it would lead to a higher efficiency than is considered to be justified. It is because of this that for computation and display purposes the nominal value from the RF sensor assembly should be biased to the high side. A factor of $\frac{1.896}{1.807} = 1.049$ should be applied to the independent RF sensor assembly derived input power measurement. This will result in the maximum values of displayed efficiencies being credible with a penalty, in some instances, of displaying efficiencies that are two low.

3.7.6.6 Computation and Display of Efficiency

The software in the primary instrumentation and display system computer divides the dc output power for a subarray by the input power to determine and display efficiency.

The output power is calculated by multiplying measured output voltage by measured output current for the dc load coming from the 269 rectifying antenna elements uniformly distributed over the subarray.

The input power is calculated by utilizing the measured output voltage from the single central reference element dissipated across its calibrated (120 ohm) resistive load. The computer software converts is voltage to watts of input power by means of an efficiency curve (Figure 3-3 of the Users Manual) then multiplies this wattage by 270 to approximate the power input over the entire subarray and finally this result is multiplied by a calibration factor which is the ratio of gain horn power meter (RF Sensor Assembly) reading adjusted to correspond to the effective area (1.4399 m^2) of a subarray (270 x reference element output power).

The original software used during checkout contained an error in the value of effective area of the subarray 1.432 m^2 instead of 1.4399 m^2, however, the foregoing data has been corrected in recognition of this error. This would have resulted in a nominal efficiency of 86.5% (displayed as 87%) at 250 kW output from the transmitter boresited on the subarray. This is based on the adjusted measured output subarray 3B (1,563 w) defined above and the measured average RF power input (1,807 w) also discussed above.

A factor of 1.047 was applied to the measured input RF power calculation in the delivered software package rather than the previously discussed 1.049 which should reduce the nominal displayed efficiency from 87% to 82%.

Should the RF sensor assembly measured value be on the low side 1.765 kW) with the factor of 1.047 bringing it to 1.848 Kw the calculated and efficiency would be 1.563/1.848 = 84.6% or 85% displayed efficiency.

Similarly the high value of 1.896 kW with the factor of 1.047 would make the calculated efficiency 1.563/(1.047 x 1.896) = 78.7 percent or 79 percent displayed efficiency.

Another possible error in the power input measurement as determined by the centrally located reference element is the sensitivity of the coupling of incident power into this element to the load resistance into which the surrounding elements are operating. The load resistance is in turn a function of the incident power level. Thus if the reference element is calibrated when the incident power level corresponds to that of a 250 kW output of the transmitter it will see a disproportionate power input at other operating levels. This effect has been measured in the laboratory and a correction factor on the incident power as read by the reference element has been established. The incident power as read by the reference element when it is calibrated at a transmitter power output of 250 kW should be corrected downward by 0.0235 percent for each kilowatt of transmitter power below 250 kW and corrected upward by 0.0235 percent for each kW of transmitter power above 250 kW.

Referring to the demonstration test data printout in Section 4, Figure 4-10, observe that displayed efficiencies range between 77 and 85 percent with the overall efficiency being 82 percent.

It should be noted however that the best estimate for efficiency of a centrally located subarray is 84.6% + 1.6% -1.9% as derived in paragraph 3.7.6.4, so that the displayed efficiencies are most probably accurate to ±2% when the output power from a centrally located subarray near the power beam boresite is approximately 1600 watts. For power levels different from the point of calibration the input power is modified in the software according to the calibration curve (Figure 3-3 of the Users Manual).

Where efficiencies are observed to be significantly less than 83 percent or more than 87 percent further investigation of element operability, reflected power and edge effect should be conducted.

One of the further investigations that should be undertaken is to measure the incident power with the RF Sensor Assembly at each of the subarray azimuth and elevation locations with respect to the boresite being directed at the array center of area. This should be done by pointing the transmitting antenna boresite such that the standard gain horn is located in relative azimuth and elevation with respect to the boresite to coincide with the location of each of the subarrays in turn. Conducting this experiment at say 250 kW transmitted power and comparing the RF Sensor Assembly measured incident power with that recorded for each subarray when the boresite is pointed at the array center would be a good check on the calibration process for transferring input power indication to the reference element of each subarray.

3.7.6.7 Recommendations

The following recommendations are made for instrumentation technology development and for engineering experiments to determine efficiencies most accurately.

- VSWR Measuring Instrumentation

Instrumentation including sensors should be developed to measure the VSWR in front of the subarrays for the purposes of obtaining the most accurate understanding of reflected power in the field installation and from that improving the understanding of RF to dc conversion efficiency.

- Most Accurate Overall Efficiency

Due to the errors introduced as the incident power is increased or decreased from the point of calibration for a particular subarray the following procedure is recommended.

As a first approximation, determine the incident power for each subarray with the boresite at the array center in the manner previously described.

Then conduct the calibration process for each subarray at the particular power level determined by the initial approximation.

With the new calibration for each subarray record the values of input power for each subarray with the boresite at the array center. Successive approximations of incident power and subsequent calibration should lead to the most accurate set of measurements of input and output power at the transmitted power level desired.

3.7.7 MISCELLANEOUS PROBLEM AREAS

The other minor problems experienced and corrected during the system field tests are listed in Table 3-7 (Hardware) and Table 3-8 (Software) along with the resolutions to these problems.

TABLE 3-7

HARDWARE

Abnormal Condition:	Resolution:
1. No power output from subarray S/N 017, location 5B.	1. Cable W-271-B5 defective (Power output cable). Connector J1 incorrectly wired at the factory. Rewired connector.
2. Power reading on subarray location 1C is 4% low.	2. Value of current shunt resistor (R9 in the load box) incorrect. Resistor replaced.
3. Back-up display subarray voltage reading are 6 to 8 V low, and read -5 V with subarray power off.	3. Modified back-up display meter circuit: (1) changed meter shunt resistor from 10 ohms to 10.5 ohms to improve reading, and (2) changed meter common from ground to phone line common to resolve -5V condition.
4. Subarray S/N 010 (Location 4C) developed low output voltage and power (about 50% power, 68% voltage at all input power levels).	4. Found short between a bus bar and a vertical support bracket. Removed insulating rivet and placed additional insulating material between bus bar and support.
5. Subarrays outputs crowbared during normal operation.	5. Found problem occurred, with about 50% probability, whenever the RXCV transmitter interlock relay was opened with the following conditions: The RXCV relay was connected to the transmitted drive voltage unit, however, it was partially disconnected to preclude interrupting the drive and shutting down the transmitter (done intentionally). Site personnel suggested that this may change transmitter output characteristics however specifics were not pursued. Problem resolved by totally disconnecting RXCV relay from drive voltage unit when automatic transmitter shutdown is not desired. The operational configuration has the RXCV transmitter interlock relay fully connected and operating.

TABLE 3-7 (Continued)

HARDWARE

Abnormal Condition:	Resolution:
6. Load Lamp for 6A does not light.	6. Lamp burned out. Replaced.
7. Load lamps dim on various subarrays	7. Lamp fixtures rotated by high winds. Realigned fixtures and tightened mounting hardware.
8. Three subarrays do not read input power: S/N 001, location 2A S/N 006, location 3A S/N 012, location 3B	8. Diodes in reference elements shorted in all 3 subarrays. Replaced reference elements. Install protective crowbars for reference elements at an early opportunity.

TABLE 3-8

SOFTWARE

Abnormal Condition:	Resolution:
1. During power up or power down false crowbar alarms were generated.	1. Modified data timing (to assure input and output power are read close together) and changed criteria for alarm (New criteria is efficiency of 2.5% or less, old was 10% or less, both with input power of 100 w or more)
2. During power up or power down divide overflows occur in efficiency calculation routine.	2. Modified routine so that output power must be 32 w or more for individual subarrays and 64 w for total efficiency before division is attempted.
3. No capability in program to read data not normally on CRT display.	3. Added new routine to read any memory location and display contents on the CRT.
4. Calibration routine will accept input commands for rows 7, 8 and 9 (non-existent).	4. Routine modified to accept only valid subarray locations.

SECTION 4

SYSTEM DEMONSTRATION

4.1 INTRODUCTION

Raytheon Company prepared a "Demonstration Plan" for the RXCV Subsystem. This plan was submitted to JPL for approval and was approved on 15 October 1974. Demonstration Objectives, Equipment Descriptions, and Demonstration Scenarios are included in the plan. The preparation of the plan, during the design phase of the program, allowed Raytheon to consider the demonstration requirements in the RXCV design.

During the final phase of the Raytheon operations at Goldstone, an "RXCV Acceptance Test Demonstration" step-by-step procedure was prepared in accordance with the requirements of the Demonstration Plan. Demonstrations were conducted, per this procedure, and the system was shown to be fully operational and shown to exceed the contractural requirements with respect to performance. Details of the demonstration are included in the following paragraphs of this section.

4.2 DEMONSTRATION OBJECTIVES

The primary objective of the RXCV demonstration was to collect incident free-space S-band microwave power, convert it into direct current at high efficiency and dissipate it in an instrumented load that demonstrates microwave power transmission. Specifically this demonstration utilized input power from the Goldstone Venus DSS-13 26 m antenna at a distance of approximately 1.6 km, at a frequency of 2388 $\pm$ 5 MHz and with Klystron output power adjusted between a range of 50 to 350 kW. The RXCV output power was demonstrated to be more than 12.5 kW and the ratio of dc output at the load (load input voltage times load input current) to available incident RF power (the integrated incident power density at the input the converter aperture times the collector area) was demonstrated to be more than 0.7. Thus, reception and conversion of kilowatts of power over kilometers of distance with an efficiency of 70 percent or better was demonstrated.

The secondary objective of the RXCV Demonstration was to collect and provide engineering data on the operation of the RXCV rectenna under variable levels of incident RF power, variable load conditions and variable environmental conditions.

The Acceptance Test Demonstration was conducted, at Goldstone-Venus Station on 3 and 5 June 1975 and it met the objectives of the test.

4.3 DEMONSTRATION PROCEDURE

Raytheon prepared a step-by-step procedure for the demonstration. This procedure includes steps to exercise and test all aspects of the RXCV. It provides for: testing using both the low and high range of the dc load; testing at various transmitter power levels; routines for "sweeping" the transmit antenna boresite across the rectenna to provide the varying visual load lamp indications; routines for demonstrating all of the hardware and software features of the RXCV Instrumentation. The original version of the procedure was utilized on 3 June for a "dry run". Several minor changes were made to improve the readability and general flow of the steps. The final version, identified as the 6-3-75 revision, was then used for the final run of the demonstration on 5 June 1975. Appendix D contains this demonstration procedure.

4.4 DEMONSTRATION RESULTS

The demonstration was successful. The RXCV subsystem was shown to exceed contractual requirements by a large margin. The maximum converted RXCV output dc power was over 30 kW against a requirement of 12.5 kW. Efficiencies of 78 percent to 84 percent were obtained (at various normal operating levels) against a 70 percent or better requirement.

The dry run of the demonstration was conducted, on 3 June 1975, by Mr. David A. Salmond of Raytheon and Mr. Richard M. Dickinson of JPL, and the final run was conducted, on 7 June 1975, by Mr. Dickinson with assistance from Mr. Salmond. The testing was witnessed by Mr. Owen E. Maynard of Raytheon (both days) and on 5 June by Mr. Samuel Fordyce of NASA Headquarters.

During the dry run, the system equipment was fully operational and the procedure was run in its entirely, with no problems. Between the dry run and

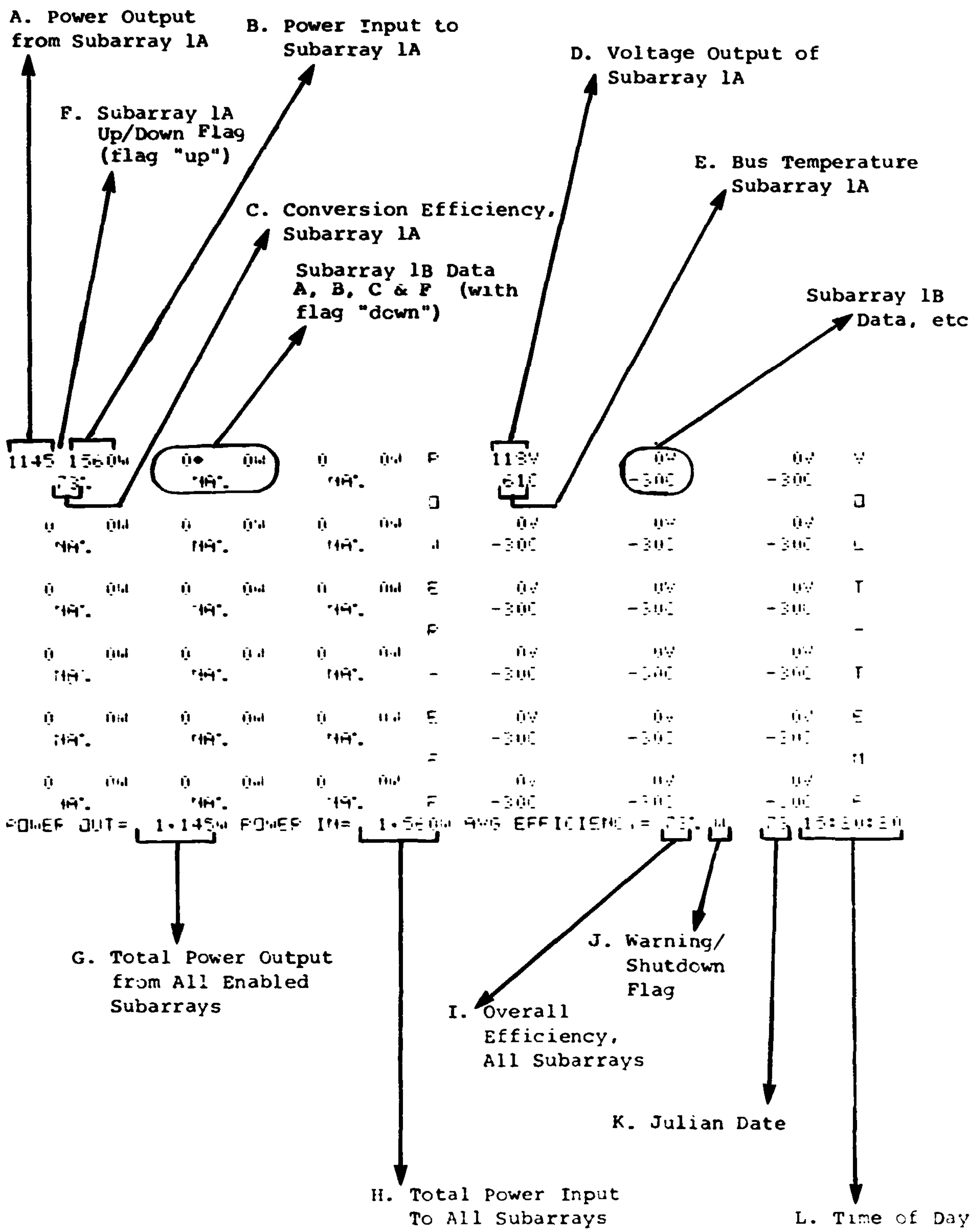

Figure 4-1. Alphanumeric Data Printout Format

the final run, on 4 June, three reference elements failed (in subarrays 2A, 3A and 3B). This failure is discussed in detail in paragraph 3.7.3. By agreement between JPL and Raytheon, the final run of the Acceptance Test Demonstration was conducted without replacement of the elements; therefore, no input power nor efficiency was obtained, during the 5 June final run, from subarrays 2A, 3A and 3B. Also, at the discretion of Mr. Dickinson, certain steps were omitted on 5 June. (These steps exercised features of the instrumentation hardware and software and were not essential to the main objective of the demonstration.)

The results of the demonstration tests are recorded on the printouts from the RXCV instrumentation equipment to illustrate the data obtained. The following material is included to permit the reader to interpret these data printouts.

The alphanumeric data printout provides a picture of the power in, power out, efficiency, output voltage and bus temperature for each subarray, plus an overall system power in, power out and efficiency, and is shown in Figure 4-1. The following items are provided:

a. Power output by subarray. This is output voltage times current, corrected for lead losses. It is displayed to a resolution of 1 watt.

b. Power input by subarray. This is input power as measured by calibrated reference diode. It is displayed to a resolution of 1 watt.

c. Conversion efficiency. This is power out divided by power in for each subarray, rounded to the hearest percent, and set to NA if the input is zero, or ** if the value is over 99 (due to some malfunction).

d. Voltage output by subarray. This is the subarray output voltage corrected for lead loss and displayed to the nearest volt. This displayed value will blink if it exceeds the preset warning threshold.

e. Bus temperature by subarray. This is the measured bus temperature, displayed to the nearest degree centigrade. This displayed value will blink if it exceeds the preset temperature threshold.

f. Subarray up/down flag. If a subarray has been deleted from error checking and overall computations, it will be flagged by '*' rather than a '/' between the power out and power in values.

g. Total power output. All subarray outputs not "down" are summed and displayed to a resolution of 1 watt.

h. Total power input. All subarray inputs not "down" are summed and displayed to a resolution of 1 watt.

i. Overall efficiency. Total power output is divided by total power input and displayed to the nearest percent.

j. Warning/shutdown flag. A single character is displayed to reflect the system state. The values are:

Character	Meaning
Blank	Normal state
Blinking W	Warning threshold exceeded
Blinking S	System has shutdown due to threshold exceeded

k. Julian Date. The day of the year (1 to 365 or 366) is displayed.

l. Time of day. The standard 24 hour clock is displayed.

The bar graph data printout is a bar graph of relative output power. It relates output power for each subarray to a prechosen threshold. A 50 segment double bar is displayed (25 segments in each bar) with each segment representing 2 percent of the reference value. These are in a 3 by 6 matrix, in the same relative positions as the actual subarrays. Items g through l above are also displayed in this format.

The following paragraphs discuss the results of the demonstration testing on a section-by-section basis (refer to the procedure in Appendix D). Data from both the dry run (3 June, Julian Day 154) and the final run (5 June, Julian Day 156) is included in the analysis of the results.

Sections 1A and 1B of the procedure concern setup procedures and were completed for both runs without incident.

Section 2 was also completed without problems. This section includes loading of the operational program into the computer memory from tape cassette, transmitter turn-on, and RXCV computer initialization. Figure 4-2 is a sample of the instrumentation data printouts, from the TI Silent 700 terminal. The message printouts from steps 2.7 through 2.11 are shown in this figure.

Section 3 is the first half of the actual test itself. The dc load is operated in the "low" power mode, and transmitter power output in the 50 to 150 kW range is used. Steps 3.1 through 3.12 are initial turn-on and verification steps. Figure 4-3 is the step 3.6 dry run printout and Figure 4-4 is the same step in the final run. This data is used in step 3.7 to verify normal system operation before proceeding with the test. In Figure 4-4 the total power in and average efficiency are not valid due to the lack of input power from subarrays 2A, 3A and 3B. Subsequent to step 3.7, during the final run, the software was configured to omit these 3 subarrays from the total power and efficiency calculations.

The next activity is an input power calibration routine (i.e., calibration of the reference elements in each subarray against the standard gain horn). The calibration (step 3.13) is performed at the 100 kW transmitter output level. Figure 4-5 is the before calibration reading and Figure 4-6 is the after calibration reading (steps 3.12 and 3.13(h) from the dry run). Observe that the Power Out is about the same before and after; but after calibration, the input power is higher and the efficiency is lower. At this low power level, efficiencies in the seventies are to be expected, based on the laboratory data.

Figure 4-7 is an example of the Bar Graph Display printout (step 3.17 of the dry run). This printout indicates power output as a percentage of a

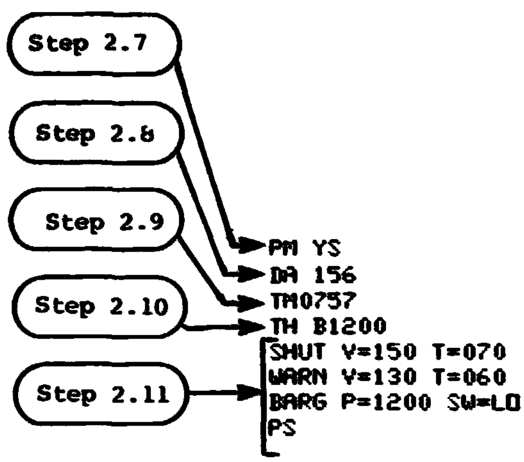

Figure 4-2. Printout Steps 2.7 through 2.11 (Final Run)

```
PD YS
 191/ 256W    0*    0W  193/ 292W  P      53V          0V
    75%         NA%        66%            22C          18C

 223/ 355W  249/ 332W  232/ 311W          57V          62V
    63%        75%        75%      W      21C          22C

 251/ 346W  272/ 349W  256/ 339W   E      62V          65V
    73%        78%        76%             21C          21C

 248/ 352W  267/ 388W  256/ 331W          61V          64V
    70%        69%        77%      -      21C          21C

 226/ 303W  239/ 349W  229/ 286W   E      58V          59V
    75%        68%        80%             21C          21C

 184/ 256W  202/ 295W  187/ 276W          52V          54V
    72%        68%        68%      F      21C          21C
POWER OUT=  3,905W POWER IN=  5,416W AVG EFFICIENCY= 72%
```

Figure 4-3. Printout Step 3.6 (Dry Run)

```
PD YS
 429/ 490W    0*    0W  423/ 541W  P     87V          0V         86V   V
    88%         NA%        78%           23C   [illegible]C         22C

 500/ 681W  536/ 646W  502/ 588W         93V         99V         95V
    73%        83%        85%      W     22C         23C         22C   L

 553/ 655W  593/ 670W  556/ 653W   E     99V        103V        100V   T
    84%        89%        85%            22C         22C         22C

 550/ 669W  583/ 743W  555/ 635W         98V        102V         99V
    82%        78%        87%      -     22C         22C         22C   T

 508/ 587W  522/ 666W  508/ 560W   E     94V         95V         94V   E
    87%        78%        91%            22C         22C         22C

 421/ 500W  452/ 560W  418/ 525W         85V         88V         85V
    84%        81%        80%      F     22C         21C         22C   P
POWER OUT=  8,609W POWER IN= 10,369W AVG EFFICIENCY= 83%    154 08:57:36
```

Figure 4-5. Printout Step 3.12 (Dry Run)

FOLDOUT FRAME

```
                     PD YS
 54V    V             191/ 256W    0*   0W  188/ 286W  P     53V          0V          53V   V
 21C                     75%       NA%         66%           27C         23C          26C

 60V                  227/   6W  249/ 343W  230/ 321W        58V         62V          59V
 22C    L                NA%       73%         72%     W     26C         26C          26C   L

 63V    T             259/   3W  276/   1W  258/ 349W  E     63V         65V          63V   T
 21C                     NA%       NA%         74%           26C         26C          26C

 62V                  259/ 362W  276/ 401W  262/ 346W        63V         65V          63V
 21C    T                72%       69%         76%     -     26C         26C          26C   T

 58V    E             240/ 326W  249/ 359W  238/ 292W  E     60V         61V          59V   E
 21C                     74%       69%         82%           26C         26C          26C

 52V                  199/ 274W  216/ 315W  198/ 283W        54V         56V          54V
 21C    P                73%       69%         70%     F     26C         26C          26C   P
154 08:51:42         POWER OUT=  4,015W POWER IN=  4,523W AVG EFFICIENCY= 89%    156 08:05:20
```

Figure 4-4. Printout Step 3.6 (Final Run)

```
PD YS
 427/ 569W   0*   0W  425/ 562W  P     86V          0V          86V   V
    75%       NA%        76%           26C         21C          25C

 496/ 669W  535/ 669W  503/ 635W       93V         98V          95V
    74%       80%        79%     W     25C         27C          26C   L

 547/ 704W  588/ 727W  554/ 694W  E    98V        102V         100V   T
    78%       81%        80%           25C         25C          25C

 541/ 703W  576/ 723W  551/ 694W       97V        101V          98V
    77%       80%        79%     -     26C         26C          26C   T

 497/ 653W  514/ 667W  502/ 650W  E    92V         94V          93V   E
    76%       77%        77%           26C         26C          25C

 411/ 548W  444/ 583W  411/ 580W       83V         87V          84V
    75%       76%        71%     F     25C         25C          26C   P
POWER OUT=  8,522W POWER IN= 11,030W AVG EFFICIENCY= 77%     154 09:18:38
```

Figure 4-6. Printout Step 3.13 (h) (Dry Run)

FOLDOUT FRAME 2

predetermined value. In this case, 100 percent was set to 1200W. Each asterisk on the bar equals 2 percent; for example, subarray 1A (upper left corner) has 28 asterisks indicating 56 percent of 1200W or 672W. This is verified by the printout of the engineering unit (alphanumeric) display of about the same data taken 14 seconds later (during the dry run) as shown in Figure 4-8 (step 3.19 printout) which indicates 668W power out for subarray 1A.

Section 3 of the test procedure continues with a test of the automatic system shutdown feature incorporated into the instrumentation software (steps 3.20 through 3.35). Several other instrumentation features are tested (steps 3.36 and 3.40 through 3.56) and steps 3.38 and 3.39 provides for a visual demonstration of the load lamp by means of "sweeping" the transmit antenna (the Venus 26m antenna) on and off the rectenna array which results in the corresponding lamps turning on glowing brighter or decreasing in intensity in sequence as the transmit beam moves on and off the individual rectenna subarrays.

Section 4 reconfigures the RXCV DC Load into the "high" power mode. Section 5 is the initialization for the second half of the active test (Section 6) which is run at higher transmitter output power levels, up to 350 kW.

Section 6 starts with a turn-on sequence and verification check similar to the first steps in Section 3 (steps 6.1 through 6.8). The transmitter output power level is increased to 150 kW, then 250 kW (steps 6.9 through 2.21). At the 250 kW level, the input power calibration routine is repeated (step 6.22). Figure 4-9 is the before calibration data (step 6.21) during the dry run. Note that this is not completely uncalibrated data; the calibration performed in step 3.13 at the 100 kW level is still being used by the software to calculate input power. Figure 4-10 is the after calibration data (step 6.22(h) of the dry run).

The transmitter output power is increased to 300 kW to obtain higher RXCV output power (steps 6.23 through 6.28). During the dry run, the highest level of converted power achieved was 28,662W as shown in Figure 4-11. During the final run, optional step 6.30 was utilized and over 30 kW of power was converted to dc by the RXCV subsystem. Figure 4-12 is a copy of this data.

Figure 4-13 is a view as seen through the telescope of the lighted lamps.

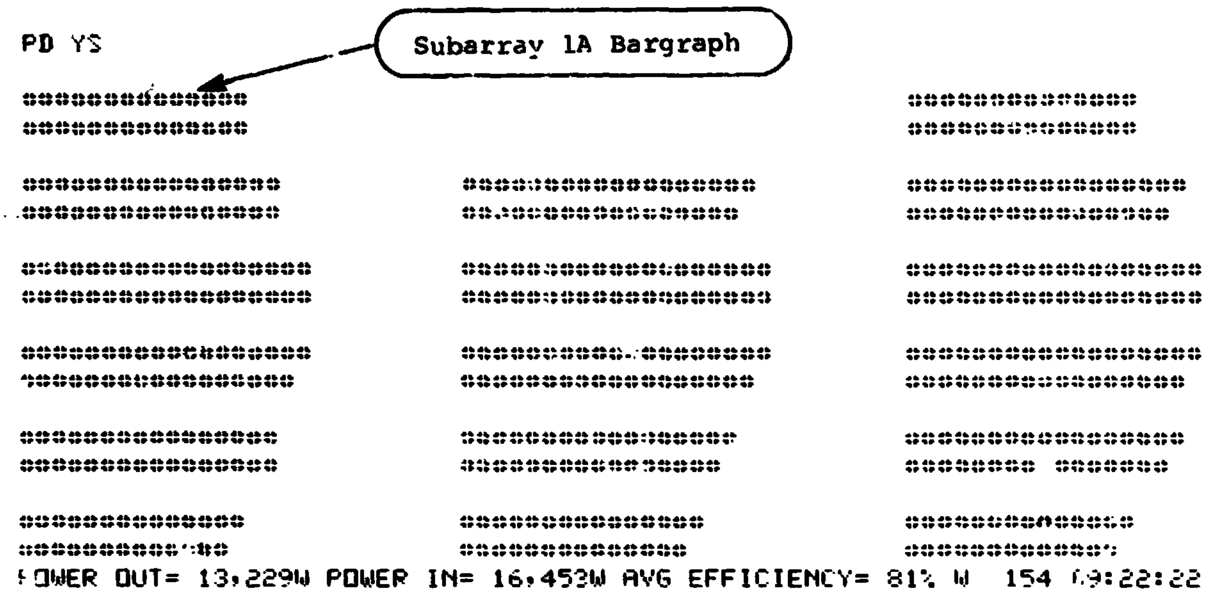

Figure 4-7. Printout Step 3.17 (Dry Run)

```
PD YS
1188/1488W      0*    0W 1173/1457W  P     141V         1V        141V   V
    80%        NA%         81%              28C        40C         28C

1351/1750W 1439/1820W 1356/1716W           150V       157V        152V
    77%        79%         79%       W      28C        30C         28C   L

1472/1804W 1569/1939W 1474/1817W  E        157V       163V        158V   T
    82%        81%         81%              28C        23C         28C

1451/1802W 1525/1859W 1447/1822W           156V       160V        155V
    81%        82%         79%       -      29C        28C         29C   T

1327/1705W 1358/1656W 132./1670W  E        148V       149V        148V   E
    78%        82%         79%              28C        29C         28C

1107/1391W 1174/1491W 1087/1422W           136V       139V        134V
    80%        79%         76%       F      28C        28C         28C   R
POWER OUT= ..,822W POWER IN= 28,609W AVG EFFICIENCY= 80%.     154 12:52:46

CL NAL
```

Figure 4-9. Printout Step 6.21 (Dry Run)

FOLDOUT FRAME 1

Subarray 1A Power Out

```
668/ 833W    0*    0W  667/ 825W  P    112V        0V       112V   V
  80%          NA%        81%          26C        21C        25C

774/ 987W  826/1002W  793/ 945W        120V       126V       122V
  78%         82%         83%      W   26C        28C        26C   L

848/1030W  912/1077W  861/1040W   E    126V       132V       125V   T
  82%         85%         83%          26C        26C        26C

840/1030W  891/1072W  853/1033W        125V       130V       126V
  82%         83%         83%      -   25C        27C        26C   T

774/ 965W  797/ 933W  784/ 982W   E    119V       121V       120V   E
  80%         81%         80%          26C        27C        26C

642/ 806W  689/ 847W  642/ 853W        108V       112V       108V
  80%         81%         75%      F   26C        26C        26C   P
POWER OUT= 13.251W POWER IN= 16.310W AVG EFFICIENCY= 81% W  154 09:22:36
```

Figure 4-8. Printout Step 3.19 (Dry Run)

```
PD YS
1174/1459W    0*    0W 1172/1463W  P    141V         1V       142V   V
  81%          NA%        80%           33C        45C        32C

1332/1719W 1428/1763W 1352/1678W        149V       157V       152V
  77%         81%         81%       W   33C        37C        34C   L

1463/1764W 1564/1863W 1477/1760W   E    153V       164V       159V   T
  83%         84%         84%           34C        34C        34C

1434/1727W 1526/1792W 1450/1711..       155V       160V       156V
  83%         85%         85%       -   34C        35C        35C   T

1312/1591W 1358/1609W 1326/1573W   E    148V       150V       149V   E
  82%         84%         84%           34C        37C        34C

1098/1365W 1164/1424W 1090/1374W        136V       139V       135V
  80%         82%         79%       F   34C        34C        34C   P
POWER OUT= 22.720W POWER IN= 27.634W AVG EFFICIENCY= 82%    154 13:15:14
```

Figure 4-10. Printout Step 6.22(h) (Dry Run)

```
PD YS
1477/1823W     0*    0W 1465/1815W  P     159V          1V         159V   V
    81%         NA%        81%             34C         44C          33C

1685/2133W 1797/2202W 1699/2094W           169V        177V         172V
    79%         82%        81%        W    33C         37C          34C   L

1846/2193W 1968/2319W 1852/2184W  E        178V        186V         179V   T
    84%         85%        85%             34C         34C          34C

1319/2157W 1316/2245W 1822/2124W           176V        183V         177V
    84%         85%        86%        -    34C         35C          34C   T

1665/1997W 1715/2009W 1680/1973W  E        168V        170V         169V   E
    83%         85%        85%             34C         37C          34C

1400/1709W 1476/1784W 1381/1711W           155V        158V         153V
    82%         83%        81%        F    34C         34C          34C   P
POWER OUT= 28,663W POWER IN= 34,472W AVG EFFICIENCY= 83% W  154 13:28:02
```

Figure 4-11. Printout Step 6.27 (Dry Run)

```
PD YS
1401/1781W     0*    0W 1408/1713W  F     155V          0V         156V   V
    79%         NA%        82%             37C         62C          37C

1656/  13W 1777/2218W 1697/2071W           168V        176V         172V
    NA%         90%        82%        W    38C         44C          40C   L

1888/   9W 2024/    1W 1921/2312W  E       191V        189V         184V   T
    NA%         NA%        83%             41C         41C          40C

1934/2315W 2049/2443W 1963/2338W           193V        189V         185V
    84%         84%        84%        -    41C         42C          41C   T

1347 2240W 1903/2283W 1881/2250W  E        178V        181V         180V   E
    82%         83%        84%             40C         44C          39C

1604/1951W 1707/2028W 1605/1996W           167V        171V         166V
    82%         81%        80%        F    38C         40C          38C   P
POWER OUT= 30,265W POWER IN= 29,962W AVG EFFICIENCY= **% W  156 13:47:22
```

Figure 4-12. Printout Step 6.30(d) (Final Run)

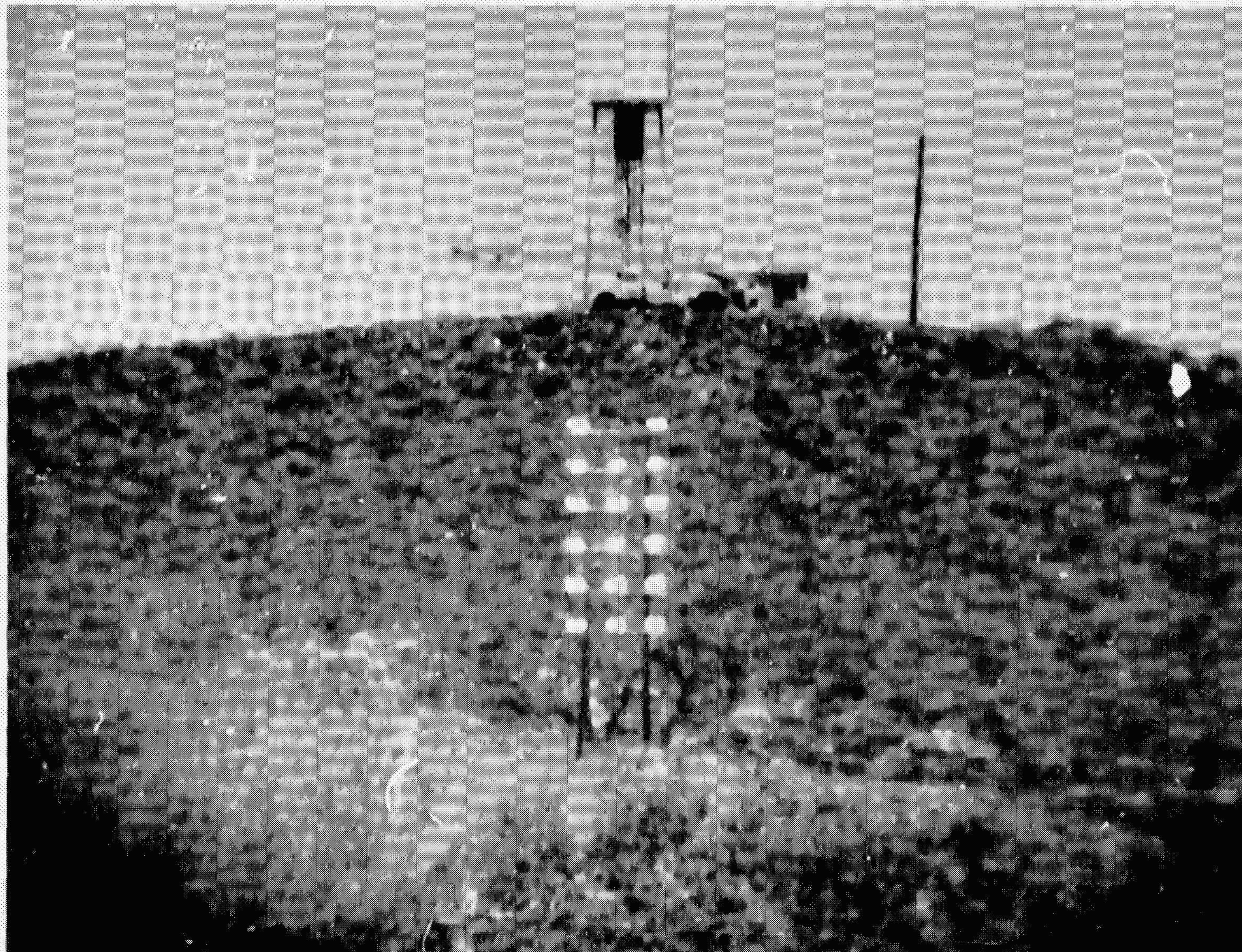

Figure 4-13. Lighted Load Lamps (Viewed Through Telescope)

Section 7 of the test procedure is limited to exercising the data recording and playback features of the instrumentation hardware and software. No live testing is performed by this section. Section 7 was performed during the dry run only.

SECTION 5

ACCOMPLISHMENTS AND DISCUSSION OF RECOMMENDATIONS

There were several lessons learned during the conduct of the JPL RXCV program. It is expected that considerably more will be learned over the time period when JPL will be conducting the technology development, engineering experimentation and demonstration program. The following summarizes the lessons learned from both the management and technical points of view with the emphasis being in those areas where subsequent development and operational programs would most benefit.

5.1 PROGRAM OBJECTIVES, THEIR MANAGEMENT AND IMPLEMENTATION

The establishment and understanding of program objectives between the customer and the contractor is essential to the meaningful conduct of the program and in particular to the understanding of the many detailed considerations and decisions to be made to achieve desired management cost and technical goals. This was achieved in this program through a spirit of cooperation at all levels brought about by an awareness by those concerned of the possible importance of the effort to the solution of energy problems anticipated in the not-too-distant future.

Responsible clarification and modification of detailed objectives was achieved from the time of contract negotiations by essentially daily communication between the customer and contractor project managers. They were focussed into major decision points at the time of contract negotiations, primary design review and final design review. In addition, program management and technical reviews with senior personnel not normally working on the program were introduced. This was found to not adversely impact the program rather to enhance it and to make it possible to achieve the cost and schedule objectives.

The following management recommendations are suggested to be applied to similar technology development and feasibility demonstration programs:

a. In addition to the normal review points, a Program Management Review between the customer and contractor be conducted at both the contractor and customer facilities to exercise the objectives in detail.

b. Daily contact be established between the customer and contractor Project Managers. It is also recommended that contact by telephone between counterpart task managers be reinforced by face to face meetings early in the program and as often thereafter as is deemed highly desirable.

c. Highly detailed technical reviews, presented by the task managers, be conducted with experienced personnel outside the program structure to bring their objectivity and special knowledge to bear on the program.

d. Early negotiations provide for the above activities and for the rational decision making process between designated project managers, required to assure effective reconsideration and implementation.

5.2 TECHNICAL ACCOMPLISHMENTS AND RECOMMENDATIONS

The activities undertaken to achieve the technical requirements of the program (see Section 1, Table 1-2), keeping in mind the stated and implied objectives, afforded the opportunity to approach the technology developments, design, fabrication, installation and field operations in a manner to be most beneficial to the NASA Office of Applications five year program to demonstrate feasibility of power transmission from space. Targets of opportunity were continually sought to be most beneficial and the following discussion of accomplishments as well as recommendations reflect the spirit of those activities.

5.2.1 RECTIFYING ANTENNA TECHNOLOGY, DESIGN AND DEVELOPMENT

5.2.1.1 Accomplishments

The plated heat sink (PHS) Schottky barrier diode, its integration into the half-wave rectifying element and that element's incorporation into the RXCV subarray are second steps in rectifying antenna technology development. The first steps were made under the Marshall Space Flight Center's contract NAS 8-25374 (Raytheon Report PT-4594) to the Microwave and Power Tube Division of Raytheon Company. The advances made in the RXCV program for this area of technology are discussed in Sections 2.1 through 2.8 of this report.

The development of specifications for the diode supplier such that large quantity deliveries could be made was of vital significance. These are high quality devices specified in terms of dc performance parameters that will subsequently perform in the RF to dc conversion environment. The development of their specifications, plans, procedures and processes was the most crucial and significant accomplishment. Their fabrication, quality control and testing throughout the development and production phases was recognized as the highest technical risk activity.

The design and development of the rectifying antenna element to achieve the required level of production, to operate with high performance in the operational environment and to understand its capabilities through laboratory investigations as well as those in the field was most significant.

A sliding adjustable microwave short which incorporates a high value of capacitance was included in the element design. This serves as a smoothing filter to remove microwave components from the dc output.

A low pass filter was included in the element design to attenuate any harmonic power which propagates toward the half-wave dipole where it would be emitted as RFI.

The design and development associated with the incorporation of the rectenna elements into the subarray and the integration of the subarray into the total array for collection of RF power with its conversion to dc with low RF relfected power was most significant in the effort to achieve high overall RF to dc performance at high power levels.

The above accomplishments provided the necessary background to develop the detailed technology program for the range of power levels of interest to concepts requiring large scale RF power transmission and efficient conversion to dc as identified in the Microwave Power Transmission System Studies by Raytheon's Advanced Development Laboratory under contract NAS 3-17835 to NASA Lewis Research Center as a part of NASA's Office of Application's five year program to demonstrate feasibility of power from space. These accomplishments permitted further detailed definition of the technology development effort undertaken by Raytheon's Advanced Development Laboratory in the contract NAS 3-19722 RF to dc Collector/Converter Technology Development from NASA Lewis Research Center.

5.2.1.2 Recommendations

It is recommended that:

a. The Rectenna Technology Development Program be continued to improve efficiency of RF to dc conversion for the range of power densities of interest to large scale rectifying antennas (1 to 185 mW/cm^2).

b. The rectenna technology development program be continued to include the development of low cost approaches to the fabrication of diodes, rectenna elements and their incorporation in field installations.

c. The technology for low cost structural support of the rectenna in large scale field installations in several geographic locations of interest with their associated terrain and environments be developed at an early opportunity.

d. The RXCV equipment installation and facility be considered for utilization in developing and demonstrating the low cost technology.

e. The technology for dc power collection and conversion to ac as required for transmission and distribution to the user network be developed and demonstrated at an early opportunity.

f. Equipment and procedures be developed to determine the presence of harmonic originated and other RFI from normal and malfunctioning rectenna elements (see paragraph 2.2).

g. Advantage be taken of the targets of opportunity to observe effects of the microwave power transmission reception and conversion on free life forms such as birds to begin to understand biological effects technology for microwave power transmission systems.

h. Advantage be taken of targets of opportunity to observe effects of free life forms, such as birds, on the microwave power transmission system equipment.

i. Techniques be developed for the field measurement of VSWR with a view to ascertaining the amount of RF power that is reflected under various conditions of rectifying antenna configurations and load.

5.2.2 INSTRUMENTATION

5.2.2.1 Accomplishments

The instrumentation, including displays and interfacing with the transmitter operations, was conceived and developed to provide the flexibility desired for detailed engineering experimentation with the RXCV as configured and as other configurations might require. It is discussed at length in paragraph 2.10. The primary instrumentation and display along with the visual observation of antenna movement and lamp illumination as seen from the control room were configured to impart the information pertinent to demonstrations to a range of observers from those not previously familiar with the technology to those interested in advancing the technology in detail. The primary instrumentation provided is in general non-redundant and although it is expected to perform on demand it was believed prudent to provide a less sophisticated backup that would permit continuation of demonstrations in the event of malfunctions requiring long maintenance time. The backup instrumentation alone should provide for the display of minimum data that is believed to be acceptable to certain observers who would otherwise spend excessive time at the remote site as well as for real time backup essential information.

The standard gain horn and RF power meter which comprise the RF sensor assembly is provided as the independent source of incident RF power. Through the computer software it is employed to calibrate the reference elements on each subarray which in turn provide the data to the computer for input power. The computer provides for the data handling computations and inputs to the CRT display as well as to the storage tapes.

A Raytheon supplied probe was employed to measure the VSWR on the breadboard installed at the Venus Site and for measurements taken in the Raytheon laboratory.

5.2.2.2 Recommendations

The following recommendations are discussed in more detail in paragraphs 3.7.6.7. However, in that they are instrumentation related they are included here:

a. A series of engineering experiments are recommended to determine the extent of uncertainties in incident power measured by the reference element as the power level changes from the calibrated value.

b. A probe with associated equipment is recommended to be developed to measure the VSWR in desired locations as the incident power interacts with the rectifying antenna. This probe should be compatible with the environment of field operations and should provide for installation in locations of interest.

5.2.3 DC LOAD INTERFACING TECHNOLOGY AND DEVELOPMENT

The dc load and its associated interfacing for the RXCV was developed to begin understanding the considerations to be made for the effective utilization of the output power from rectifying antennas and for the circuit protection provisions that should be applied to the rectifying antenna elements, the load and the associated instrumentation.

5.2.3.1 Accomplishments

The dc load, as discussed in paragraph 2.8, was conceived to offer a level of flexibility to operate into both fixed resistance and resistance that varied with load (lamps). Both low and high power modes were provided to change the proportions delivered to the fixed and varying resistance and to provide a significant visual representation of the output power in each mode. The lamp loads have a finite probability of failure and the associated loss of resistance affects the performance of the rectifying antenna elements. This creates undesirable characteristics while operating close to the breakdown voltage for the diodes. Rather than unduly limiting the transmitted power level, protective circuitry (crowbars) were provided for the rectenna subarrays.

The reference elements were operated without the protection of crowbars and were on several occasions subjected to excessive power levels which, in several cases, resulted in diode burn-out. This led to laboratory investigations into load sharing between elements as a function of the relative resistance of their loads and to the definition of a clear need for such protective devices for the reference elements which were subsequently installed.

The configuration of the load box including the integral junction box as well as the junction boxes on the platforms behind the subarrays provide access for further changes of configuration as the technology and engineering experimentation programs are developed.

The dc load, cables, lightning protection, and associated grounding provided the opportunity to address some of the issues associated with the environment and with operating into useful loads.

5.2.3.2 Recommendations

a. It is essential to investigate a range of load characteristis beyond that currently configured, to understand how they might affect the rectenna and how they might in turn be affected by the characteristics of the power source.

b. Power conditioning requirements for general and specific users as well as requirements for power protection from general and specific users must be addressed and associated technologies developed.

5.2.4 CERTIFIED DEMONSTRATION OF OVER 50 PERCENT (DC TO DC) MICROWAVE POWER TRANSMISSION EFFICIENCY

5.2.4.1 Accomplishments

The demonstration as discussed in paragraph 3.1 was accomplished and was reported on in JPL TM 33-727. This was a most meaningful demonstration and certification in that it established a level of credibility for the feasibility of highly efficient overall microwave power generation transmission, reception and conversion. A value of 54 percent was achieved with an existing off the shelf magnetron as the RF generator which was the major contributor of losses.

5.2.4.2 Recommendations

As the technology of RF generators is developed, similar certified demonstrations should be conducted to continue to raise the credible efficiency to approximately 70 percent which is considered vital to large scale microwave power transmission systems.

5.2.5 SITE MODIFICATIONS

5.2.5.1 Accomplishments

The site was modified as described in Section 2. This critical activity centered around the tower structural analysis and modifications as well as the foundation analysis. In addition the dc loads with associated power cables were installed. Safety provisions were incorporated as required.

The capacity of the tower and its foundation to support the array is as described in Supplement #1 of the Site Modification and RXCV Structural Support Plan. The tower modifications and foundation are such as to support a full complement of 18 subarrays under most extreme wind conditions of 49 m/sec (95 knots) assuming no ice loading.

In the foundation analysis three methods were investigated to determine the capacity of the foundation. The acceptable approach used considered foundations, (typically for retaining walls which consist of either one slab, or slabs so tied together by either strap beams or superstructure that they can be considered to act as one slab), to be safe if they comply with a set of constraints associated with soil pressures, resultant force intersection within the base, differential settlement, and prevention of sliding. This is discussed in Supplement #1 of the Site Modification and RXCV Support Plan where a comfortable margin was indicated.

5.2.5.2 Recommendations

Should it become desirable to test more than 18 subarrays or otherwise increase the wind load, it should be done only after detailed review of the reports (Supplement #1, "Tower G-54 Structural and Foundation Analysis", to The RXCV Structural Support Plan) and analysis of the desired changes. As a first step, additional areas should be confined to the ~1.2M x 1.2M (4 ft x 4 ft) open section making a total of 18 subarrays.

5.2.6 ENVIRONMENTAL AND TYPE APPROVAL TESTS

5.2.6.1 Accomplishments

The subject eleven tests were conducted as described in paragraph 3.2. They were successful and required no substantial design revisions.

5.2.6.2 Recommendations

Periodic inspection and detail testing of the rectenna elements in particular should be conducted and malfunctions or degradations should be reported for evaluation as to impact on future technology developments.

5.2.7 LIFE TEST OF RECTENNA ELEMENTS AND DIODES

5.2.7.1 Accomplishments

The subject test has and is being conducted as described in paragraph 3.3 with 199 elements being subjected to a range of power densities. More than 2000 hours of applied power has been accumulated with only three failures occurring in the first 150 hours and none thereafter.

5.2.7.2 Recommendations

The life test be continued to the extent permitted by equipment needs in support of element technology development.

5.2.8 PRODUCTION LEVEL TESTING

5.2.8.1 Accomplishments

Production level testing techniques were developed at the rectenna element level and at the subarray level of assembly as discussed in paragraph 3.4.

Tests at the rectenna element level, along with production data from the diode supplier (breakdown voltage and their performance efficiency) provided for categorization of the elements as to their capacity to withstand a range of power levels. This categorization was then considered in selection of elements for the reference elements (high breakdown voltage) and for subarrays having particularly high potential with respect to performance (efficiency). Unexpected weaknesses were identified and the design or processes were modified to correct the weakness or explicit decisions were made to incorporate, in known locations, elements of questionable performance namely some soft diodes were incorporated in subarrays 14 and 17 and the elements for the prototype (#1) did not incorporate alodining of side rails or bonding of the diode to the side rail.

Tests at the subarray level were developed as follows. The prototype was illuminated with the near Gausian beam from a dual mode horn and the results were compared with those from the JPL computer program. This test did not assure operability of each element but did address certain aspects of the integrated effect. A technique was then developed to illuminate each of the elements in sequence. This technique (Sniffing) was then employed on all of the elements of each of the subarrays as a part of production level testing before shipment. It was again employed as Goldstone on each subarray before installation on the tower with no malfunctions identified that might be attributed to shipping and handling. It was again performed from the cherry picker bucket on each subarray after 65 hours of operation with 18 elements identified as open.

5.2.8.2 Recommendations

The "RF Sniffer test" should be conducted on each element in place again after approximately 650 hours of field operation.

5.2.9 BREADBOARD SUBARRAY TEST

Breadboard Subarray field tests were conducted as discussed in paragraph 3.5. These tests employed diodes of the "flip chip" type and a few of the plated heat sink (PHS) type. They were conducted three months after contract award to confirm the soundness of the basic design approach to be taken.

Two important weaknesses were revealed in developing the demonstration which resulted in design and/or process changes to the prototype and production models. Constraints for operational procedures were also identified.

a. Instantaneous illuminating of the rectenna resulted in several flip chip diode failures.

   Action - Procedure developed to preclude instantaneous illumination, protective crowbars were incorporated and the less susceptible PHS diode was employed throughout.

b. Degradation of performance was observed to be related to resonant mode operation between the back cover and the reflecting plane surface.

Action - In-depth laboratory investigation including testing t. ,sure that the resonant condition did not exist.

Attempts were made to conduct field tests, using Raytheon supplied laboratory equipment, to determine reflected power which were deemed invalid and led to laboratory investigations which are discussed in the Environment and Type Approval test report. (Appendix A of this report.) Lessons learned will be beneficial to the development of field operational equipment.

Recommendations are as follows:

a. Early field tests on breadboard configurations should be considered as a planned part of technology development programs to confirm the soundness of the basic design approach to be used in future rectifying antenna development programs.

b. As indicated in Section 5.3.3, field testing techniques and equipment should be developed to investigate reflected power.

5.2.10 INSTRUMENTATION TESTING

Instrumentation field testing was conducted to establish operability and to determine uncertainties associated with the various measurements as discussed in paragraph 3.6.

5.2.11 SYSTEM FIELD TESTS

System field tests were conducted to exercise all elements of the RXCV subsystem in a system configuration including the transmitter, support equipment and the operational environment to assure that they were operational and conformed to the design. Data and procedures were developed to be used in the conduct of system demonstrations. Problems were identified and resolved as discussed in paragraph 3.7.

RF input power measurements and their use in determining RF to dc efficiency are discussed at length in paragraph 3.7.6.

Recommendations are discussed in paragraph 3.7.6.7.

5.2.12 SYSTEM DEMONSTRATION

The demonstration plan, a requirement of the contract, was submitted and approved. Demonstrations were conducted per the established step-by-step procedures. The system was shown to be fully operational and to exceed the contractural requirements with respect to performance by a large margin.

The maximum converted RXCV output dc power was over 30 kW against a requirement of 12.5 kW. Efficiencies of 78 percent to 84 percent were demonstrated (at various normal operating levels of power) against a 70 percent or better requirement.

Recommendations for future demonstrations are incorporated in Section 6 - Recommendation Summary.

SECTION 6

RECOMMENDATION SUMMARY

The following recommendations are made in recognition of accomplishments and lessons learned in the RXCV program as well as other related work and objectives of the NASA Office of Applications five year program to demonstrate feasibility of power transmission from space. They are largely associated directly with rectifying antenna technology development and associated demonstrations. However, important recommendations are included for microwave power transmission technology, end to end power transmission demonstrations and program management in general. Biological and ecological effects studies are recommended where appropriate.

6.1 RECTIFYING ANTENNA TECHNOLOGY (ITEM A)

1. Determine the effects of and develop the protective hardware for transient RF power levels from microwave power transmission system equipments.

2. Perform a series of engineering experiments to determine the extent of uncertainties in incident power measured by the reference elements as the power level changes from the calibrated value.

3. Develop a VSWR probe to measure voltage standing wave ratios to determine the reflected power from sections of rectifying antennas.

4. Conduct periodic inspection of the rectenna elements, reporting malfunctions or degradations for evaluation as to impact on future technology developments.

5. Conduct "RF Sniffer Test" after approximately 650 hours of field operation on each element in place.

6. Continue life tests on the subarray of rectenna elements at the Raytheon facilities.

7. Determine the performance effects of changing the dipole to reflecting plane spacing for a centrally located subarray in the field installation.

8. Improve efficiency of RF to dc conversion for RF power densities between 1 and 185 mW/cm^2.

9. Develop low cost approaches to the fabrication of diodes, rectenna elements and their incorporation in large scale field installations.

10. Develop and demonstrate the technology for low cost structural support of the rectenna in large scale field installations.

11. Consider the RXCV installation and facility for utilization in developing and demonstrating the improved efficiency and low cost technology.

12. Should it become desirable to test more than 18 subarrays or otherwise increase the wind load, it should be done only after detailed review of the structural and foundation reports (Supplement 1, "Tower G-54 Structural and Foundation Analysis", to the RXCV Structural Support Plan) and analysis of the desired changes. As a first step, additional areas should be confined to the ~1.2M x 1.2M (4 ft x 4 ft) open section making a total of 18 subarrays.

13. Develop and demonstrate the technology for dc power collection and conversion to ac as required for transmission and distribution to the user network.

14. Investigate a range of load characteristics to understand how they might affect the rectenna and how they might in turn be affected by the characteristics of the power source.

15. Determine the power conditioning requirements for specific users and determine the associated protection requirements for the rectenna equipments.

16. Develop test equipment and procedures to determine the presence of harmonic originated and other RFI from normal and malfunctioning rectenna elements.

17. As targets of opportunity, observe the effects of free life forms, such as birds, on the microwave power transmission system equipments.

18. Conduct biological and ecological studies for large scale rectenna installations receiving essentially continuous microwave power over protracted time periods possibly as high as 30 years.

6.2 MICROWAVE POWER TRANSMISSION TECHNOLOGY (ITEM B)

1. Measure the characteristic starting and operating transients of microwave power transmission system equipments as they affect the incident RF power levels at a rectifying antenna.

2. As targets of opportunity, observe the biological effects of microwave power transmission systems on free life forms such as birds.

3. Conduct certifiable demonstrations of end-to-end dc to dc power transmission, efficiency including reception and conversion as improved equipment becomes available.

6.3 PROGRAM MANAGEMENT (ITEM C)

1. In addition to the normal review points, a Program Management Review between the customer and contractor should be conducted at both the contractor and customer facilities to exercise the objectives in detail.

2. Daily contact should be established between the customer and contractor Project Managers. It is also recommended that contact by telephone between counterpart task managers be reinforced by face to face meetings early in the program and as often thereafter as is deemed highly desirable.

3. Highly detailed technical reviews, presented by the task managers, should be conducted with experienced personnel outside the program structure to bring their objectivity and special knowledge to bear on the program.

4. Early field tests on breadboard configurations should be considered as a planned part of technology development programs to confirm the soundness of the basic design approach to be used in future rectifying antenna development programs.

5. Early negotiations should provide for the above activities and for the rational decision making process between designated project managers, required to assure effective reconsideration and implementation.

SECTION 7

CONCLUSIONS

The most important conclusion to be drawn is associated with the field demonstration of a significant amount of useful dc power (30 kW) which has been efficiently converted from RF power (82 percent) which in turn has been transmitted through free space (wireless power transmission) over a long distance (1.54 km).

Review of work done to date in the RXCV program and an awareness of related programs leads to the conclusion that considerable advancement has been made in the understanding of both the technology development and program management areas of (wireless) microwave power transmission, reception and conversion to useful dc power.

The RXCV field demonstrations in conjunction with the JPL certified laboratory demonstration of the MSFC developed technology at Raytheon for end to end microwave power transmission efficiency permits the following statements to be made and conclusions to be drawn.

a. Significant amounts of power can be transmitted through free space over long distances and converted to useful dc power in field installations.

b. Reliable, fault tolerant, efficient (82 percent) high power rectifying antennas have been built utilizing large numbers of identical solid state components for predictable costs ($<$ $7500/kW dc output). As equipment performance and low cost production technologies are investigated over a range of power densities (1 to 185 mW/cm^2), reliability is expected to remain high and costs are expected to decrease markedly.

c. Efficient (54 percent) microwave power generation, (wireless) transmission, reception and conversion to dc has been demonstrated in the laboratory. As equipment technology is advanced, significant increases in efficiency are anticipated.

d. A safe field installation using an existing transmitter to beam power over 1.54 kM (a mile) to a rectifying antenna (rectenna) has been established. This facility can be used for advanced rectenna development and demonstrations over the power density range of interest to large scale rectennas.

e. No adverse biological effects have been observed due to the limited microwave power transmission demonstrations conducted to date. (Detailed pretesting inventory of the wildlife forms was not conducted.) See Section 6, Items A(17), A(18), and B(2) for recommended biological and ecological effects studies.

f. The basic design approach to the rectenna is such as to have no known life limits for its components operating in the environment at the Goldstone Venus Station RXCV facility on standby or at steady power densities up to 185 mW/cm^2. Diode short term failures and performance degradation have been identified in a limited number of instances. Performance degradation has been associated with contamination in the diode chips in a limited number of cases. Power densities above 185 mW/cm^2 will trigger crowbars that protect the elements. Power densities above 185 mW/cm^2 may damage diodes of unprotected elements. It is expected that a few malfunctions of elements will continue to occur but that overall performance will not degrade significantly in five years or more of operation.

g. With the major increases in RF generation efficiency and with the increases in rectenna efficiency expected from their technology development programs, large amounts of power can be transmitted over long distances with end to end efficiencies in excess of 54 percent, perhaps as high as 70 percent.

h. Microwave power transmission demonstration programs can be accomplished within estimated cost and schedule at the same time achieving significant advances in technology and pointing the way for meaningful future activities.

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APPENDIX A

RAYTHEON COMPANY
Microwave and Power Tube Division
Waltham, Massachusetts

ENVIRONMENTAL AND TYPE APPROVAL TESTS ON THE RXCV PROTOTYPE SUBARRAY

PT-4474
25 February 1975
5 August 1975

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VIBRATION TESTING OF RECTENNA ELEMENT AND TESTING ITS INTERACTION WITH A WIND STREAM

Introduction

Fatigue failure is a common form of failure in many systems exposed to vibration. The vibration frequency may be close to some mechanical resonance in a component and the normal strains and stresses are greatly amplified by the interaction which takes place between the driving force and the resonant system in the component.

In the Goldstone environment there are really only two possible sources of vibration. One of these is an earthquake and the other is oscillations of the exposed rectenna element caused by the wind. The frequency components of an earthquake may interact with the tower but not with the rectenna elements. Howeven, an interaction may be possible between the wind and the rectenna element. The mechanism here is vortex shedding which is wind velocity dependent and which may reinforce a natural resonant frequency of the rectenna element.

In considering wind vibration we must consider the rectenna elements individually since there is no mechanical coupling between them. In considering the individual rectenna element, we note that it is firmly mounted at the DC output end by a machine screw which is tightened to place the joint under the proper compression. The point of support toward the dipole end is the teflon washer which has an interference fit in the "choke" which in turn is securely mounted to the reflector plate. The teflon material in the washer has a high damping coefficient and would tend to eliminate any vibration of the complete rectenna element. Likewise the presence of the teflon washers between the two side frames of the rectenna element would tend to dampen out any oscillation at this point.

We therefore proposed a test procedure which would first locate the frequency of the mechanical resonances with the aid of a mechanical shake table. We would also find out from the theoretical considerations if an interaction could occur with such a mechanical resonance at wind velocities sufficiently high to carry appreciable energy content. If it were found that such an interaction could occur then we would measure the amount of mechanical stress induced in the rectenna element by the use of strain gauges and a controlled flow of air - perhaps in a wind tunnel.

Mechanical Vibration Test Results

It was determined that the mode of vibration to which the vortex shedding process would couple would be in the plane of the rectenna element - that is the plane passes through the center of both arms of the dipole and through the low-pass filter and rectifier circuit. The mode is highly damped by the teflon washer which is an interference fit in the metal sleeve insert into the reflecting plane.

To determine the frequency of any mechanical resonances in this plane and then to identify where mechanical failure might occur in such a mode, tests were made on a shake table. Prior to being vibrated, the rectenna element was mounted in the same manner in which it would be mounted in the rectenna. Therefore, it was supported at the bus bar point and also by a hollow metallic sleeve which ma contact with the largest diameter teflon washer at the proper point.

The shake table was operated at 20G for 45 minutes until failure occurred. As the test proceeded the resonant frequency was lowered from 222 to 170 cycles, primarily, it is believed, because the edges of the teflon washer wore and allowed a larger portion of the rectenna element, which was supported as a cantilever from the bus bar to become involved in the mode of vibration. The frequency of the shake table was tracked with the mechanical resonant frequency. Failure actually occurred by a fracture in the upper and lower side rails of the rectenna element at the point of the inboard capacitance section of the low pass filter after 45 minutes of operation. An examination of the teflon washer which was supported by the metal sleeve insert showed that it was highly worn and permitted undamped vibration after the test had been run a while.

There was no tendency of machine screws, nuts, teflon washers, and rectifying diode to loosen as a result of the shake table test even though there was no conformal coating or other adhesive or locking element involved. All of these parts were tight at the conclusion of the test.

Aerodynamic Loading on Rectenna Elements Due to Vortex Shedding

Both theoretical and experimental aspects of aerodynamic loading on rectenna elements due to Vortex Shedding more handled and supervised by Norman Ham, Professor of Engineering at M.I.T., whom we employed as a consultant. Tests were run in the "low speed" wind tunnel at M.I.T. The maximum wind speed used was 64 miles per hour.

There was not room to get the entire subarray into the wind tunnel; yet the tests would not be highly valid unless a substantial area and number of rectenna elements were involved. Therefore a small section of the rectenna was constructed and mounted in the wind tunnel as shown in Figures 6 and 7.

The strain gauges used in the test were applied to the side members of the rectenna element just in front of the point of failure that was determined by the shake table tests. It is estimated that the stresses indicated by these strain gauges would be about one third of those actually occurring at the point of failure because of the wider separation between the side members, at the point of attachment of the strain gauges.

The maximum stress that was found in the location of the strain gauges occurred at a wind speed of 64 miles per hour and amounted to 125 lbs per square inch in tension and compression, or a peak to peak stress of 250 lbs per square inch. The maximum compression or tensile stress at the point of fracture is estimated to be from 250 to 400 lbs/sq. in. The frequency of vibration was approximately 225 cycles at all wind velocities but showed large amounts of modulation at high wind velocities which would be expected when the natural mechanical resonance does not coincide with the natural frequency of the driving force.

The theory of the phenomenon and results of the test were written up by Professor Ham and are included as a immediate continuation of this write-up.

1. Critical Wind Angle

Consider the general case of the wind approaching the rectenna mounting board at angle θ as shown in Figure 1. Following Reference 1, Page 104, it can be shown that the component of local velocity at the board center, and perpendicular to the board, is of magnitude

$$\frac{v}{V} = \left(\frac{h}{r_o}\right)^{\frac{\pi}{\theta} - 1} \sin\theta$$

where v = component of local velocity perpendicular to mounting board.
V = wind speed
h = height of rectenna element
r_o = arbitrary reference length

This results is plotted in Figure 2 for r_o = 6 ft. It is seen that v reaches a masimum at an angle θ of approximately 150 degrees (board angle of attack of 30 degrees).

2. Critical Wind Speed

Following the References 2 and 3, the vortex shedding frequency is given by the Strouhal number

$$S = \frac{fc}{v} \approx 0.2$$

where f = frequency of vortex shedding from one edge of the rectenna element

c = width of rectenna element.

Since the vortices are shed alternately from each edge, the frequency of vortex-induced bending of a rectenna element is 2f cps. Therefore at the critical board angle

$$2f \approx 0.4 \frac{v}{c} = \frac{0.4}{c} \frac{v}{V} V$$

$$= 8.2 \; V \text{ cps}$$

This result is plotted in Figure 3. Note that for the measured rectenna first mode bending frequency of 225 cps, the critical wind speed is about 30 mph.

3. <u>Evaluation of Wind Tunnel Test</u>

The variation of measured bending stress at the critical section of a rectenna element mounted at the board center is shown in Figure 4 for various board angles and a constant wind speed of 64 mph. Note that the maximum stress occurs at a board angle of attack of 15 degrees, somewhat lower than the angle of attack of 30 degrees for maximum normal velocity predicted theoretically.

The measured bending stress is less for rectenna elements mounted at the forward or aft edges of the board, as shown in Figure 4.

The variation of measured bending stress with wind speed at the critical board angle of attack of 15 degrees is shown in Figure 5 for a centrally mounted rectenna element. Though a clear trace of frequency 225 cps occurred around 30 mph, indicating resonance of the rectenna element with the unsteady aerodynamic loading, the bending stress did not peak at resonance, but continued to increase almost linearly with wind speed.

Clipping the mounting washer to permit slop of the rectenna element in its mounting did not increase the bending stress, as shown in Figures 4 and 5.

4. <u>Conclusions</u>

From the results of this investigation it is concluded that the peak-to-peak bending stresses induced in rectenna elements by unsteady aerodynamic loading are low, increasing to a maximum value of 250 psi. at a wind speed of 65 mph and a board angle of attack of 15 degrees.

Bending stresses vary substantially with board angle of attack; the critical angle was found to be about 15 degrees.

Resonance of the rectenna element at a wind speed around 30 mph did not cause a large increase in bending stress.

The bending stresses increased nearly linearly with wind speed.

Slop in the mounting of the rectenna element did not affect the bending stresses.

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2. Hoerner, S., "Fluid Dynamic Drag" published by the author, 1965.
3. Fage, A. and Johansen, F.C., "On the Flow of Air Behind an Inclined Flat Plate of Infinite Span", ARC R. and M. No. 1104, February 1927.

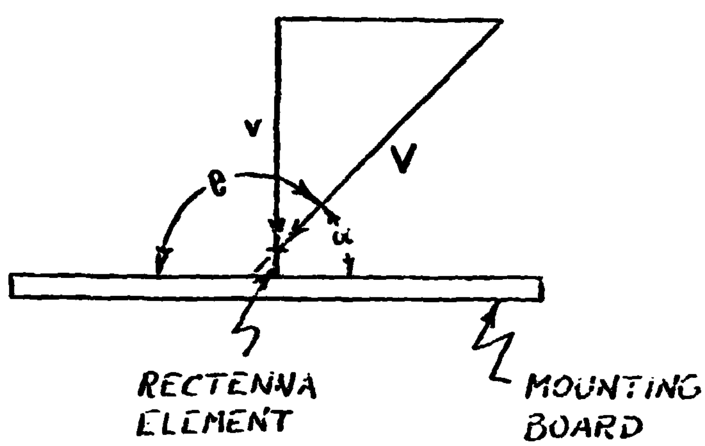


FIGURE 1

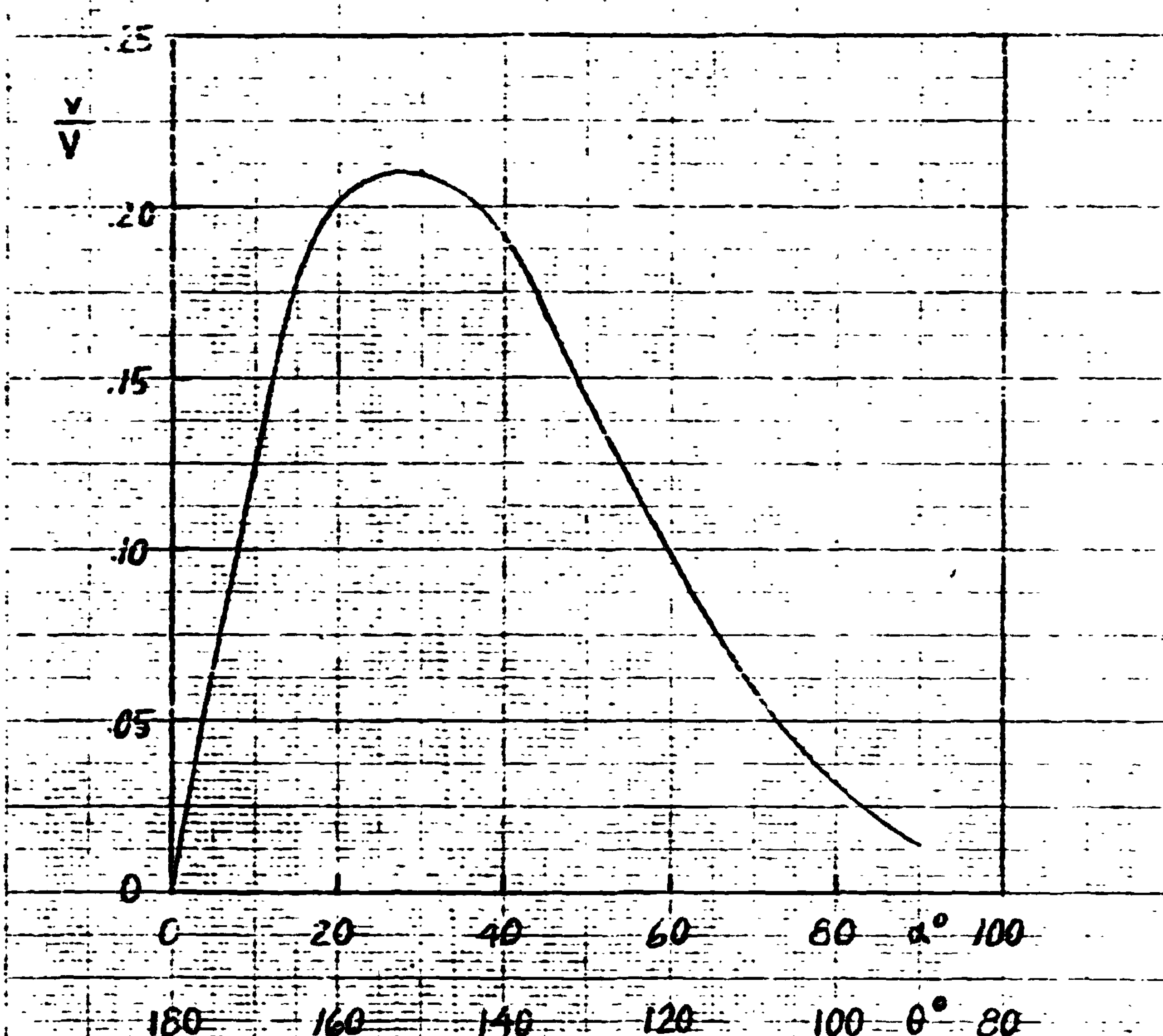


FIGURE 2

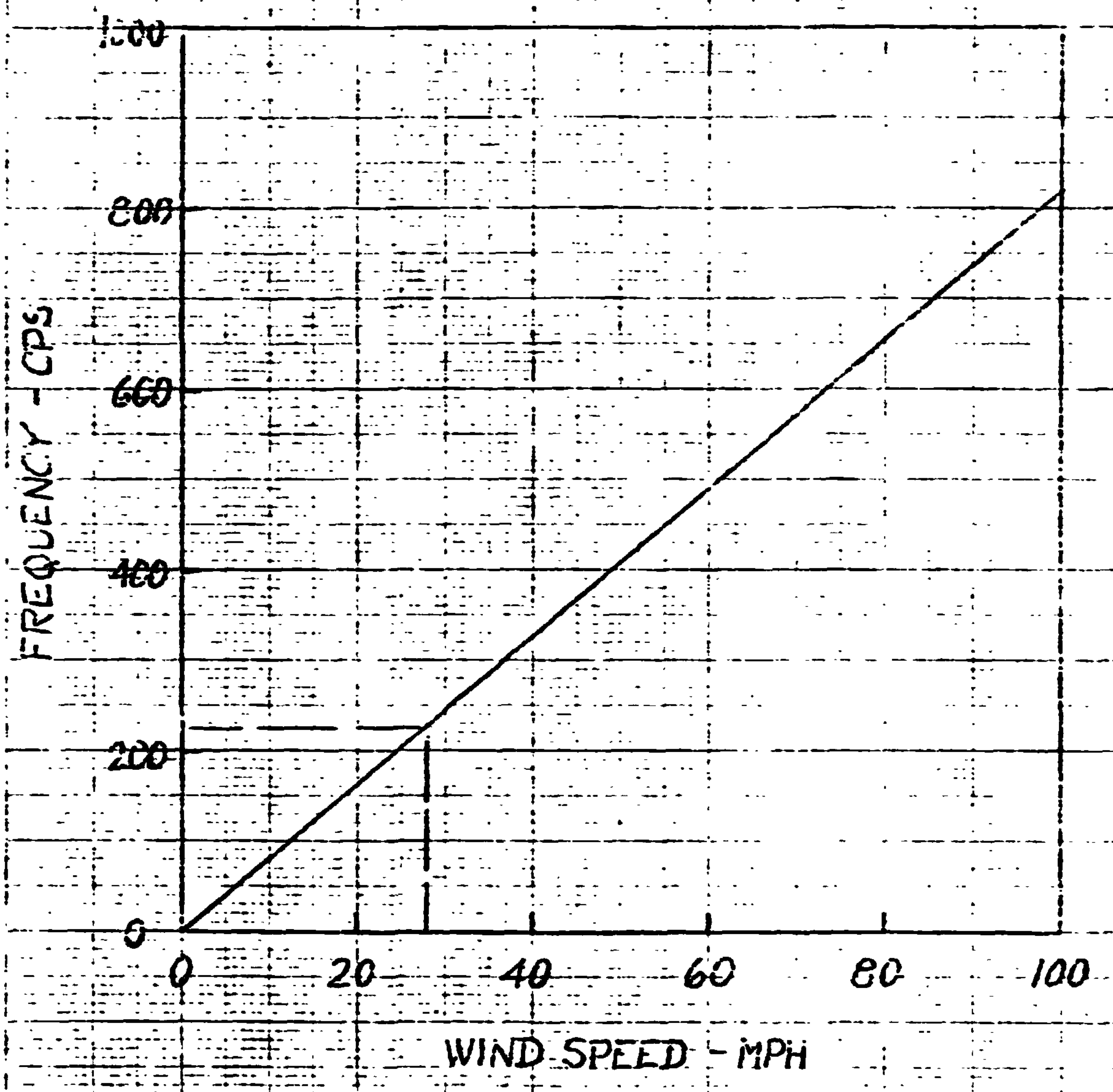

FREQUENCY - CPS
1000
800
600
400
200
0
0
20
40
60
80
100
WIND SPEED - MPH

FIGURE 3

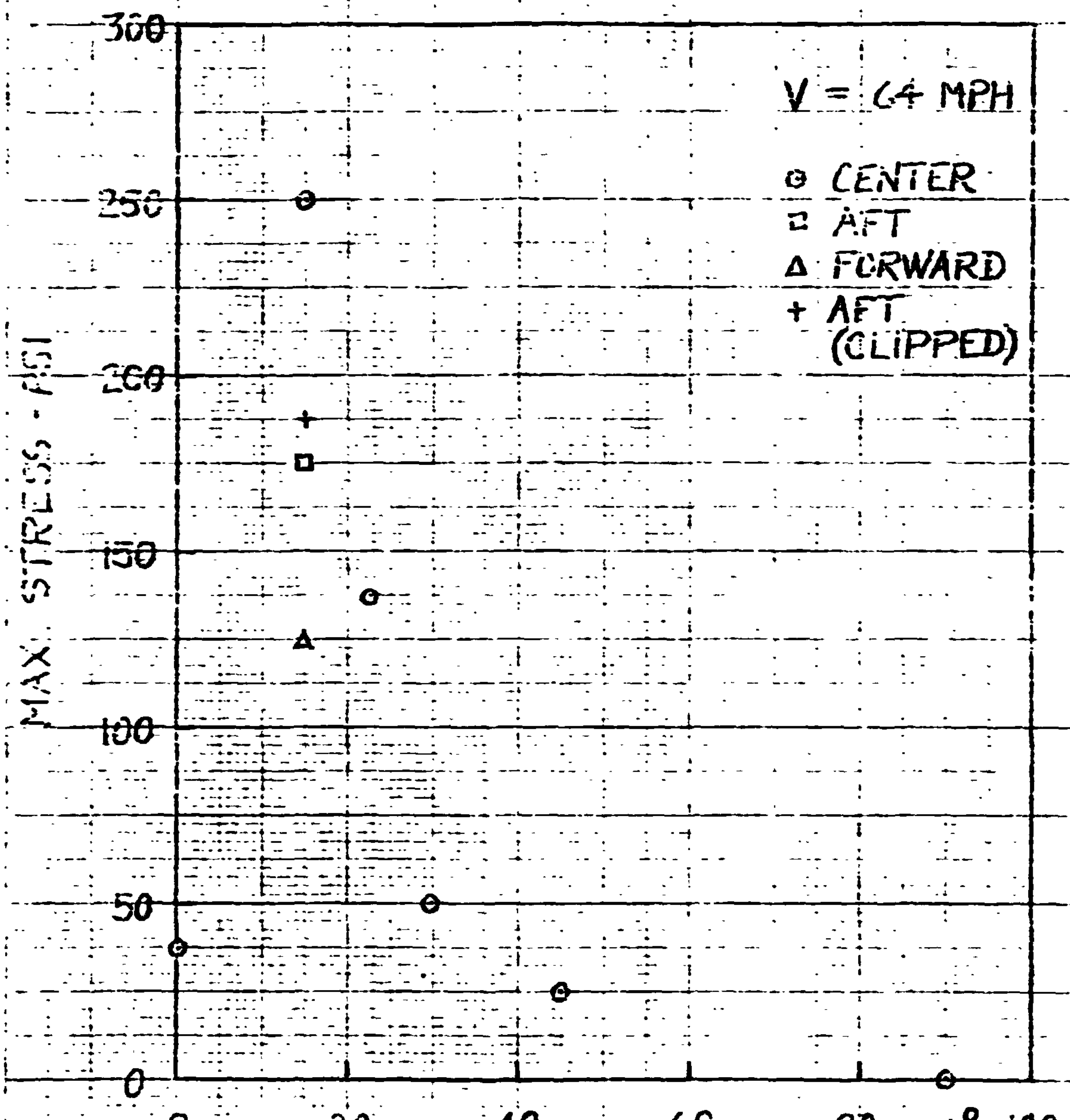

V = 64 MPH
CENTER
AFT
FORWARD
AFT (CLIPPED)
MAX. STRESS - PSI
300
250
200
150
100
50
0
0
20
40
60
80
α°
100

FIGURE 4

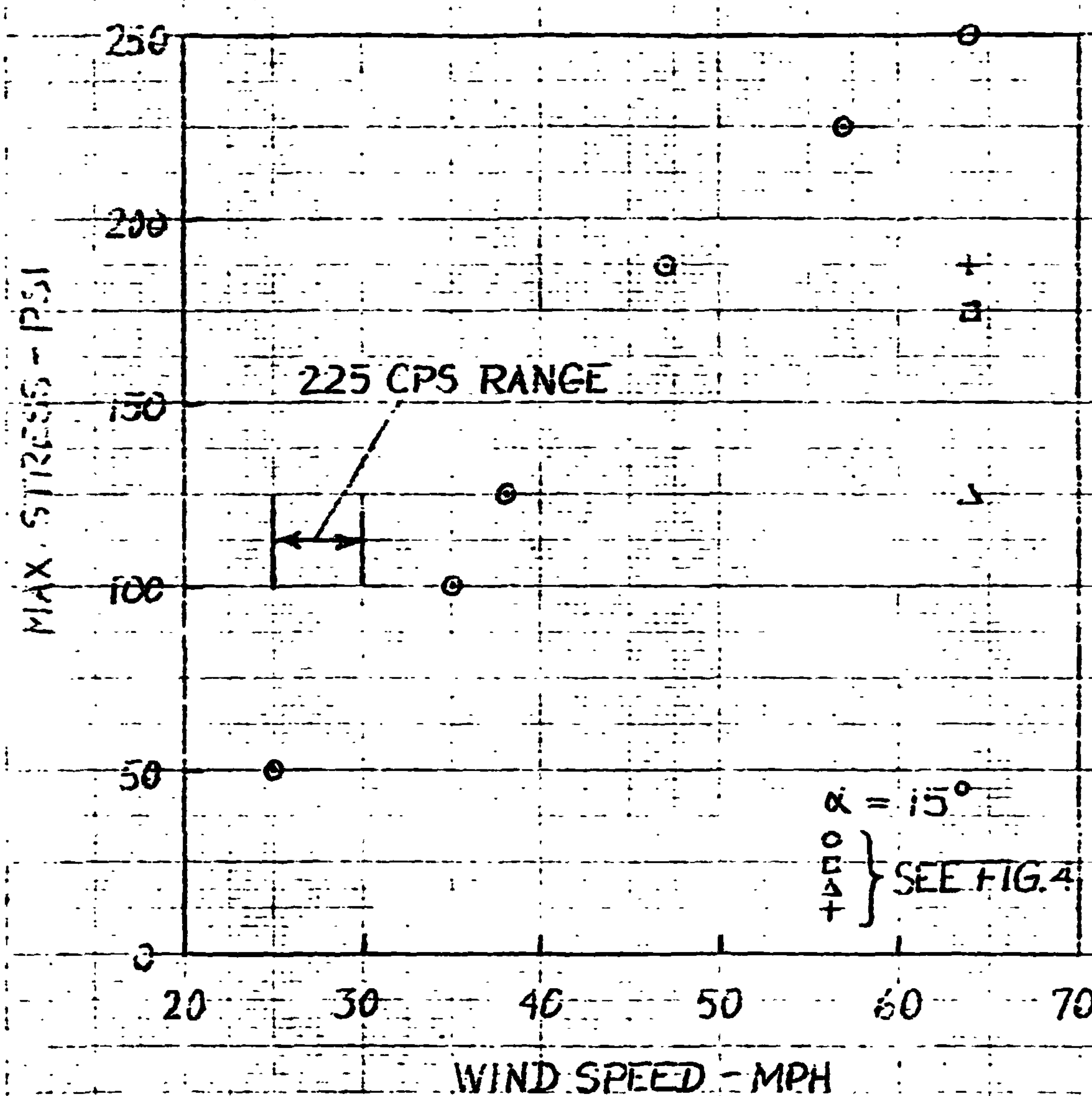

250
200
150
100
50
0
MAX. STRESS - PSI
225 CPS RANGE
α = 15°
SEE FIG.4
20
30
40
50
60
70
WIND SPEED - MPH

FIGURE 5

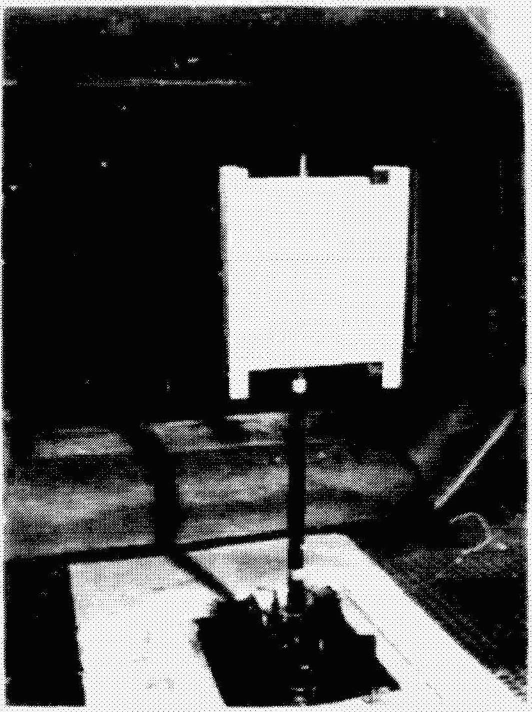


Figure 6.

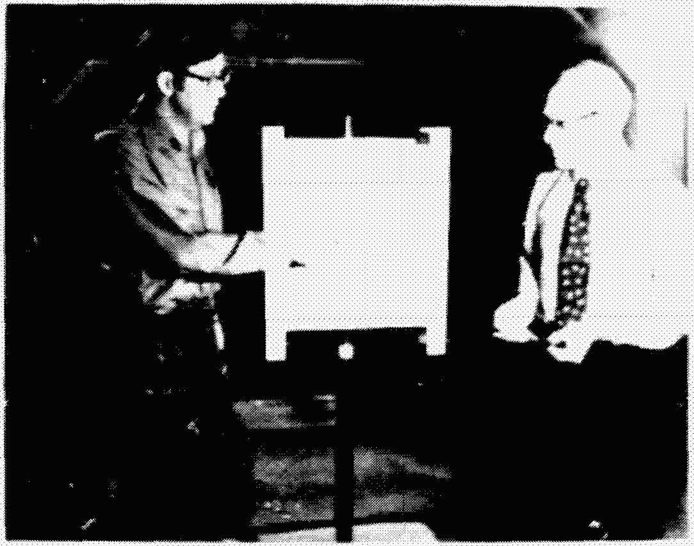


Figure 7.

STATIC LOADING OF SUBARRAY TO SIMULATE WIND LOADING

Introduction

The back cover and the reflecting plane of the subarray are tied together by nine 1/4-20 threaded rods and act together to resist bending stresses caused by the wind. If the deflection caused by these stresses is too large, damage to the rectenna subarray could occur with winds of high speed with the most damaging velocity vector. It is therefore desirable to determine how much deflection could occur. This is normally done by statically loading the array in some way with a distributed load corresponding to the pressure effects of a high speed wind.

A distributed load was applied in the following manner: The rectenna subarray was placed upon the floor facing down with the back cover facing up. The rectenna was supported from the floor by two aluminum angles which were attached to the rectenna subarray at the regular support points at which the subarray is supported by the rectenna framework on the tower. (Six 3/8 inch bolts and nuts.) Pails of water were then placed upon the rear cover up to a distributed loading of 36.7 lbs/square ft. The deflection was then measured at the center of the rear cover by means of feeler gauges which were inserted under a reference bar which had been checked for straightness.

Test Results

The deflection which occurred with the distributed loading of 36.7 lbs/sq. ft. was 0.116 in.

The deflection was further reduced with the use of an aluminum beam with a cross section of a hollow square. The dimensions were 1-1/2 x 1-1/2 by 1/8 in. wall. The beam was attached at the center point only and hence the longitudinal stresses in the beam were minimal and the beam was acting with a minimum moment of area. Under these circumstances the deflection was reduced to 0.026 in.

Following these deflection tests the rectenna subarray was visually examined for any signs of damage. None were found.

As a result of the relatively small deflection of 0.026 in. at the distributed loading of 36.7 lbs/sq.ft., a decision was made not to reinforce the back cover.

RAIN TEST FOR ENTIRE SUBARRAY

Introduction

Since there is no radome on the front of the subarray, a considerable amount of water could get into the subarray in the event of a driving rain storm impinging upon the front of the rectenna. Although the rectenna would not normally be in operation during such a storm, and in fact would not operate well if drops of rain were retained in the wave filter sections of the elements, it is necessary that the subarray perform properly after exposure to such a storm and after it has dried out from the storm.

It was decided to make a severe test with respect to survival after having been exposed to large amounts of water. The test took the form of removing the back cover and then hosing down both the front and the back of the structure with large amounts of water and letting it dry out. The determination of whether it had been damaged was made by means of the "sniffer test" in which each rectenna element is tested separately before and after the dousing by radiating it with microwave energy and noting the DC output of the unit. A visual inspection was also made after it had dried out.

Test Results

All of the rectenna elements were operational. There was no visual damage.

SURVIVAL OF NON-OPERATING HIGH AND LOW TEMPERATURE

Introduction

The subarray may encounter non-operating high and low temperatures when it is exposed in the rectenna array on the tower or when it is in storage. Although the design of the subarray has taken into account high temperatures during operation, which may be considerably higher than those encountered during non-operation, and used materials compatible with both high and low temperatures, the tests for non-operating high and low temperature are relatively easy to perform and could reveal unanticipated faults in design or assembly.

A particular concern in the testing of the prototype was whether or not any of the contacts between the Schottky barrier diodes and the siderail of the rectenna element might open up as the result of the expansion of the conformal coating material which was known to have occupied much of the area between the diode and the siderail and remain open. (The production model eliminates this potential difficulty by using a silver based epoxy to fill in the voids in the contact between diode and side-rail before the conformal coating is applied.) The "sniffer test" in which each element is independently radiated in time sequence with a small amount of microwave power is an excellent test for an open circuited diode as well as a short circuited diode.

The test routine adopted was as follows.

1. Check all of the rectenna elements with a sniffer before delivery of subarray to Acton testing laboratories.

2. Place the rectenna subarray prototype in a chamber whose temperature is 170°F for a period of 48 hours. Bring the temperature back to room temperature.

3. Test each rectenna element with the "sniffer" for shorts or opens; check the resistance of the thermistor; check the array with an ohmeter to double check the "sniffer" finding of no short circuits; check the reference rectenna element. Make a thorough visual check for loose joints.

4. Reinsert the rectenna subarray into the test chamber, reduce the temperature to -30°C and let the subarray remain at that temperature for not less than 18 hours.

5. Remove the rectenna subarray from the test chamber at Acton test laboratories and repeat the "sniffer" tests on the elements and the continuity check on the thermistor, and the ohmmeter tests for open and short circuits of the array and of the reference rectenna element. Make a thorough visual check for loose joints.

Test Results

There were no defects, as tested for in item 3 above, found after the 48 hour high temperature exposure and similarly after the low temperature exposure. All of the elements were operational and there were no irregularities found in the other checks. No loose joints were discovered.

CROWBAR PERFORMANCE TEST IN SIMULATED RF ENVIRONMENT

Introduction

These tests were performed by H.R. Riggert. In summary the RXCV operated properly and there was little if any noticeable effect of the microwave ambient environment. Mr. Riggert's detailed report follows.

Test Procedure and Test Results

On 20 January the prototype crowbar assembly was tested for functional operation and for susceptibility to temperature change and EMI. A Nobatron 225-400B high voltage, low current power supply (225 V at 100 ma) was used to fire the crowbar. Once it was fired a Nobatron ORC 40-30 power supply (40 V at 30 a) was connected in parallel with the 225-100B to provide test current up to 20 a. A simpson 460 digital voltmeter was used to monitor the crowbar terminal voltage.

The crowbar trip voltage was adjustable over the range of 179 to 230 volts (spec is 180 to 220 V). The adjustment setability or resolution was within 1 [illegible]. The trip point changed less than 1 V when the temperature was raised from room temperature to an estimated 60°C using a heat gun on the assembly for approximately 10 minutes.

EMI conditions were created using an HP616 A signal generator driving an Alfred 6868 klystron amplifier (10 W at 2 GHz-4 GHz) driving a gain horn. This system was operated at 2.4 GHz and produced a power density of about 10 mW per cm^2 at the mouth of the horn. When the crowbar assembly was "sprayed" at a distance of about 12 in. from the horn the trip point appeared to increase slightly, from 200 V (no EMI) to about 202 V and returned to 200 V when the field was removed. There is some uncertainty about the actual test conditions since the Simpson 460 voltmeter reading decreased several volts while the EMI was being applied. This is possibly due to the EMI effect on the voltmeter or the power supply regulator, the latter being directly exposed to the EMI while the voltmeter was several feet away from the exposed area. It is believed that the voltmeter reading was valid and since the effect of EMI appeared to be so slight no further attempt was made to validate the test condition.

The crowbar assembly was operated in free air in the conducting state at 16 amps until the heatsink temperature stabilized (15 minutes). The heatsink stabilized at 51.5°C and the SCR stud at 61°C as measured using a thermocouple instrument. (On production models the paint should be removed on the heat transfer surface under the SCR and thermal compound applied to minimize the thermal resistance.) At 16 amps the forward drop of the SCR was 1.00 V. Raising the current momentarily to 20 amps increased this to 1.06 V.

It is concluded that the crowbar's susceptibility to temperature and EMI are negligible and that temperature rise at the SCR stud was acceptable. However, the reasonable measures should be taken to minimize thermal resistance in the SCR mount since SCR dissipation could be as high as 25 W (125 V x 20 a) and the stud temperature should be kept below 75°C.

CHECK ON THE THERMISTOR UNIT FOR MEASURING TEMPERATURE

A check of the thermistor unit in the prototype was made by measuring its resistance. The shielding appears to be adequate in that there was no transient change in resistance reading when the microwave power was turned on or off. One run was made on the time-temperature (resistance) response to a step function of microwave power. The DC power output was allowed to stabilize at a level of 290 watts. Then the illumination was abruptly turned off. The time constant for the temperature decay for this pattern of illumination was 18 minutes and the total temperature drop in 120 minutes was 6 Fahrenheit degrees. Optimum conditions for low temperature change prevailed. The bus bars were painted black and the inside of the back cover was also painted black.

A plot of the response of the thermistor resistance to a step function in the applied power is shown in Figure 1.

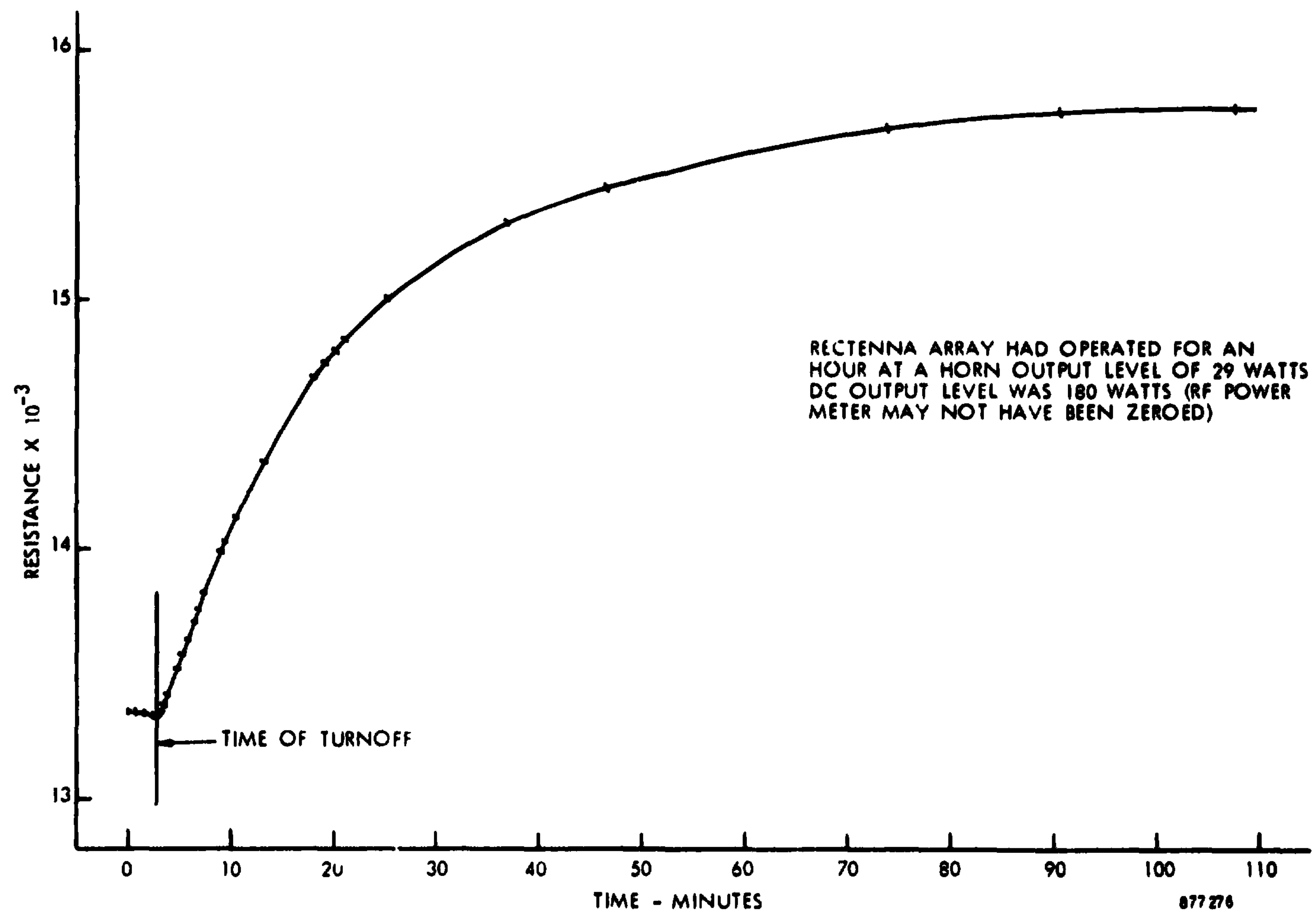


Figure 1. Response of Thermistor to Step Function of Microwave Power Illumination of Rectenna

MEASUREMENT OF REFLECTION OF INCIDENT MICROWAVE POWER FROM A SUBARRAY

Introduction

The collection efficiency of the RXCV subarray rectenna design has been of concern since the beginning of the project and was not resolved at the Goldstone testing as had been hoped. Confidence that the reflection would be low improved as the result of resetting the individual MSFC rectenna elements to the power levels at which they would be used in an illumination mode characterized by an incident gaussian beam with a high ratio of center to edge illumination density and then running a VSWR test with such a beam. This type of illumination and proper matching of the individual elements to the density of the beam while making VSWR tests is desirable since the reflected power tends to have a gaussian illumination as well. Hence the VSWR probe measures the interference pattern between two gaussian beams which tend to remain gaussian irrespective of position along the beams, and the validity of the measurements is greatly enhanced. The validity of the measurement is further enhanced by low VSWR ratios since the pattern of the reflected power becomes of relative importance.

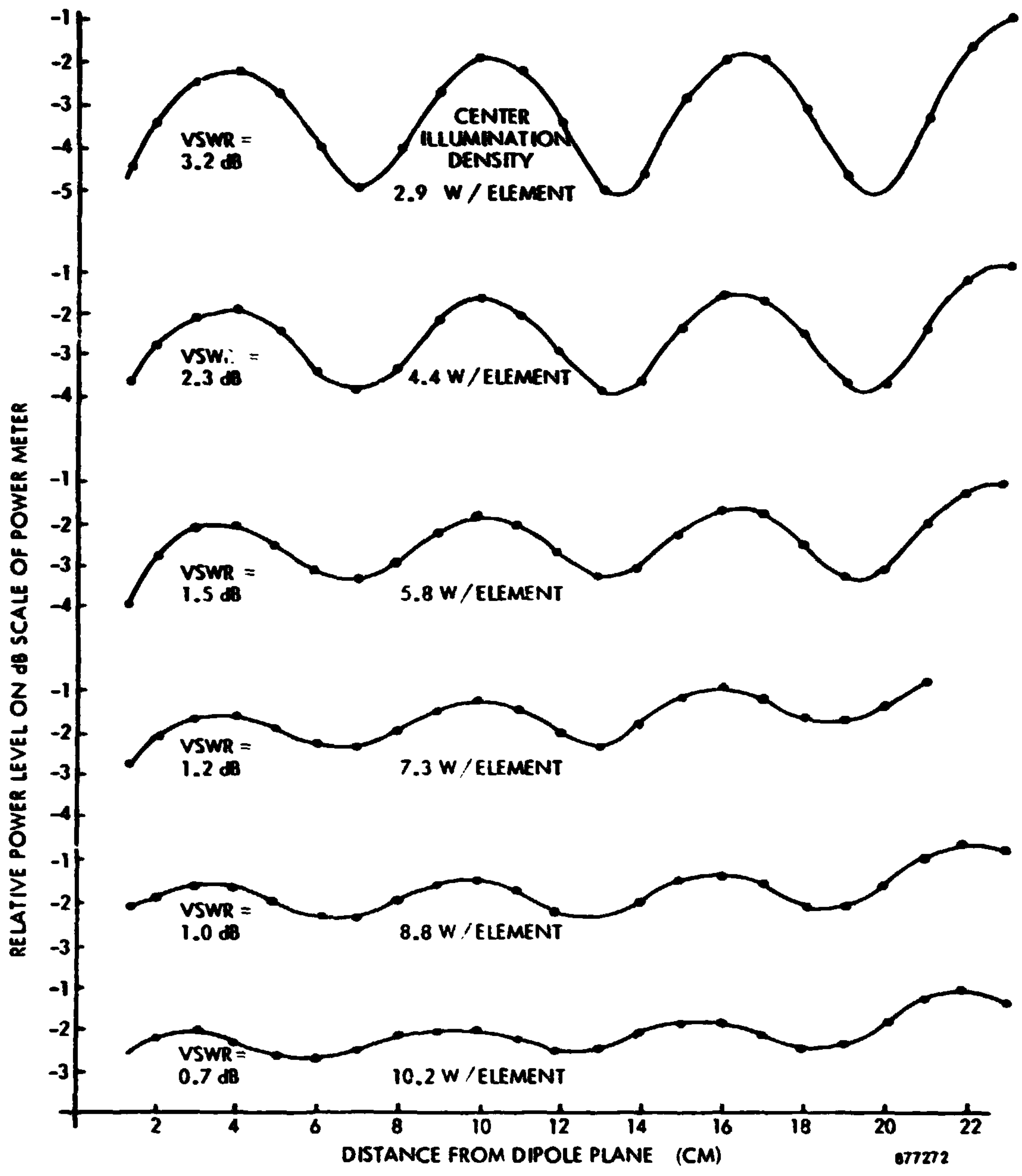
In these tests a ratio of as low as 2.0 db was achieved with a spacing of 2.0 cm between the half-wave diopoles and the reflecting plane. However, the new RXCV rectenna elements are sufficiently different from the MSFC elements to have left an element of doubt.

VSWR Tests on the Final RXCV Rectenna Element and Subarray Format

During the month of February a set of VSWR measurements was made on the new RXCV elements tuned for a gaussian illumination in the MSFC rectenna configuration. The elements were tuned for a gaussian beam having an intensity of illumination at the middle of 9.4 watts per rectenna element and tapering to an illumination of 0.39 watts at the edge of the 4 feet diameter rectenna array. The separation between the half-wave dipoles and the reflecting plane was 2.5 cm. The test distance between the mouth of the horn and the array was 67 inches.

The VSWR measurements were made as a function of the illumination level starting at a low level and working up to the power level for which the elements had been tuned. The lowest dual mode horn input level was 170 watts corresponding to a center illumination of approximately 2.9 watts per rectenna element, and the highest was 599 watts corresponding to a center illumination level of approximately 10.2 watts per rectenna element. The VSWR gradually improved as the power levels were increased from 3.2 db at the lowest power level to 0.7 db at the highest power level. The collection efficiencies which correspond to these VSWR ratios are 96.6% and 99.8% respectively. (As defined, collection efficiency includes only the energy impinging on the receiving array). The VSWR signatures were of excellent quality up to a distance of 20 cm from the rectenna. Data was not taken beyond this point. The spacing between the half-wave dipole and the reflecting plane was not varied.

The VSWR signatures for the six sets of measurements that were made are shown in Figure 1. The behavior of the rectenna as a microwave load with a variation in incident power density is shown in Figure 2.



Rectenna Edge to Horn Mouth Spacing 67 Inches, Frequency 2382 MHz, Center Rectenna Element Matched at 9.4 Watts in Expanded Waveguide Fixture

Figure 1. VSWR and Minimum Position as Function of Power Level

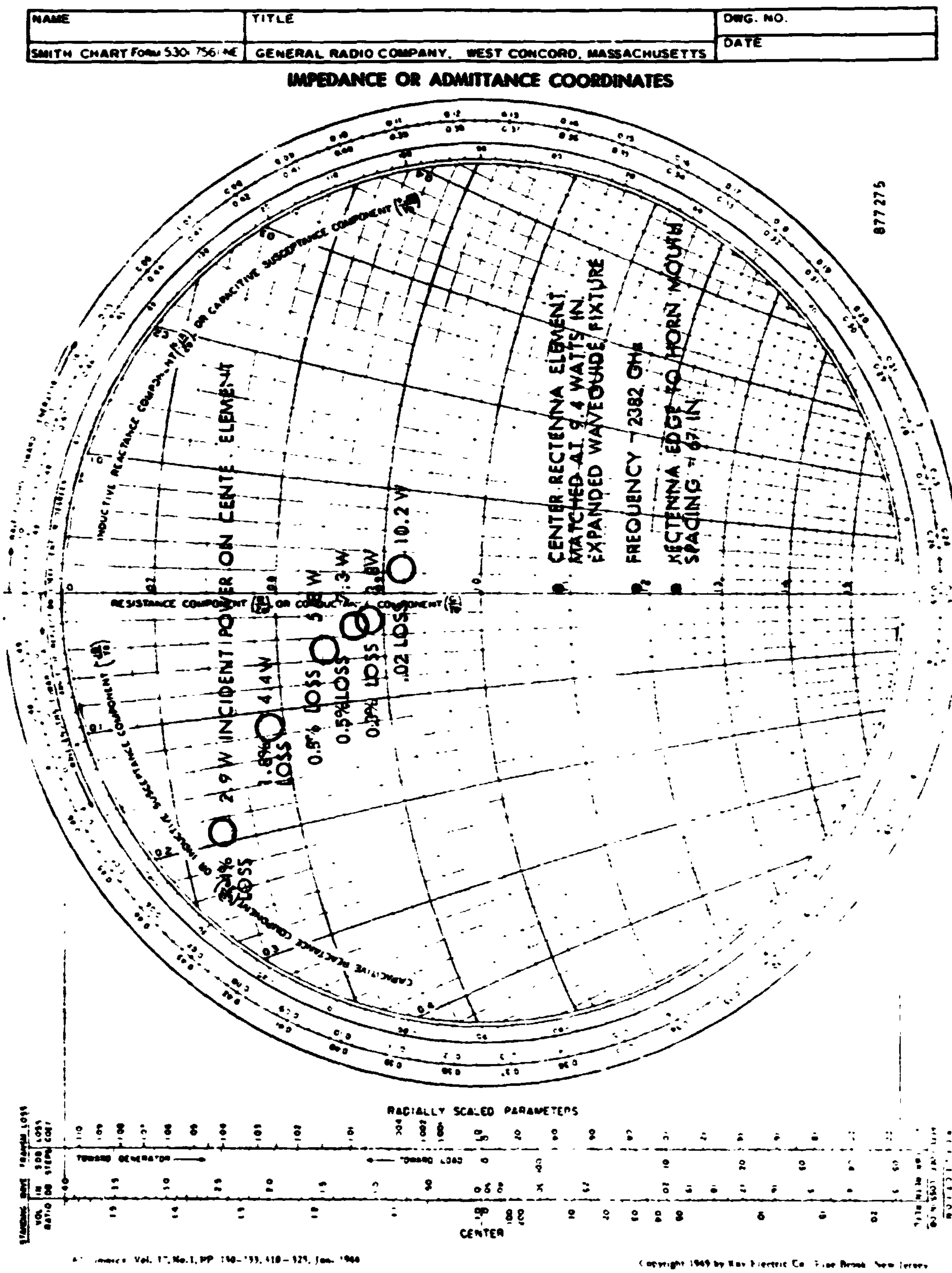


Figure 2. Behavior of Rectenna as a Microwave Load

TESTS ON COUPLING OF MICROWAVE POWER INTO THE CAVITY FORMED BY THE BACK COVER AND THE REFLECTING PLANE PLATE

Introduction

At the test of the breadboard rectenna subarray at Goldstone it was found that the efficiency of the breadboard was sensitive to the spacing between the back cover and the reflecting plane plate. Later, laboratory tests indicated that the efficiency of the center row of elements (and therefore presumably the rest) could drop by a factor of .40 when a resonant cavity was formed between the two pieces of metal. (See monthly RXCV report for October.) There was therefore concern as to the behavior of the prototype in this respect although the new design is different from a cavity point of view and metal sleeves were placed around the elements.

The method used to explore the cavity resonance phenomena consisted of putting a probe in the center of the back cover and connecting this to a power meter so that absolute as well as accurate relative readings of power picked up by the probe could be monitored.

There were two general classes of tests; those in which the cavity spacing was varied by using a nut on the center 1/4-20 threaded rod which holds the reflecting panel and the back cover together to both depress and raise the center of the back cover, and those in which the frequency of the gaussian beam was varied at the 10 watt level.

Test Results

The variation of the probe pick up as a function of the position of the back cover is shown in Figure 1.

The variation of the probe pick up as a function of the variation of frequency of the illuminating beam is shown in Figure 2.

From these figures and other sources of data certain observations and conclusions follow:

1. There is a cavity resonance very close to 2388 MHz in the prototype and the energy coupled through the cavity to a probe in the back is highly sensitive to small changes in the separation of the back cover from the reflecting plane. A total change of .030 inch covers the half power points of the resonance.

2. Coincident with the maximum power into the probe as the spacing is varied there is a maximum drop in efficiency of about 1%. This contrasts sharply to the drop in efficiency of nearly 40% which was obtained in the laboratory for the center row of elements in the breadboard rectenna. This power drop is so low that it is difficult to detect on an analog type DC watt meter, but can be detected with a digital instrument.

3. The frequency sensitivity of the phenomonon was investigated. There are a number of resonances. These occur at 2380, 2398, 2415, 2330 and 2336. The measured Q values with the coupling of the probe reduced to the point where it has no impact on the Q are 400 to 800. Thus the solution of putting in a false back on the cover to change the resonant frequency is not necessarily simple. On the prototype the 2398 and 2380 MHz peaks are located almost equidistant from the operating frequency of 2388 MHz.

4. It was found that the probe in the back cover was excited by an electric field which was perpendicular to the back cover. This observation would seem to confirm that the excitation is caused by a mode in which both sides of the rectenna elements are at the same microwave potential and that this potential is moving up and down with respect to the reflecting plane at a microwave frequency rate.

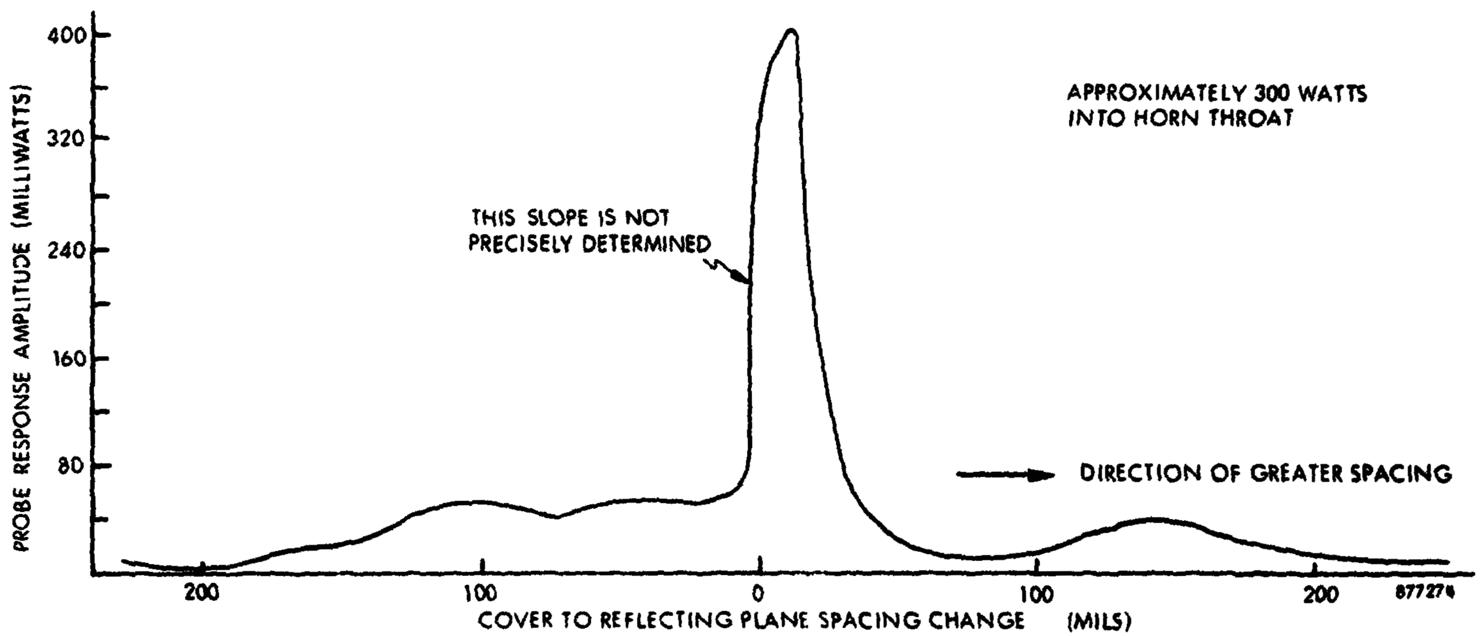


Figure 1. Tuning of Cavity by Changing Spacing Between Center of Reflecting Plane and Back Cover

WET TEST OF RECTENNA ELEMENTS

In addition to wetting down the entire subarray with the back cover removed as described in section 3, wet tests were made on the individual rectenna elements. In this test the entire rectenna element, completely finished including the conformal coating, was immersed in a pan of water and then inserted into the expanded waveguide fixture and operated at normal power input of six watts to see if (1) destructive phenomena such as arcing might occur during the drying out stage, and (2) if any permanent degradation could be noted after the element had completely dried out, both with and without the application of 6 watts of incident microwave energy during the drying out stage. These tests are consistent with the situation in which the rectenna might be operated during a driving rain storm, operated before being completely dried out, or operated after completely drying out.

Complete immersion of the element inevitably resulted in large beads of water accumulating between the two side frames of the rectenna in the microwave region as well as the DC bus bar region. When first put on test, the resulting efficiency would be low but the resulting microwave dissipation in the beads of water would heat up the water and it would evaporate within a relatively short period of time. The efficiency would be back to normal within typical time periods of 10 to 15 minutes. In one case the element did not come back to normal until after an additional four hours of air drying.

A total of three conformally coated elements were checked; one non-coated element was also checked. In no case was there any evidence of arcing during or after the drying out period.

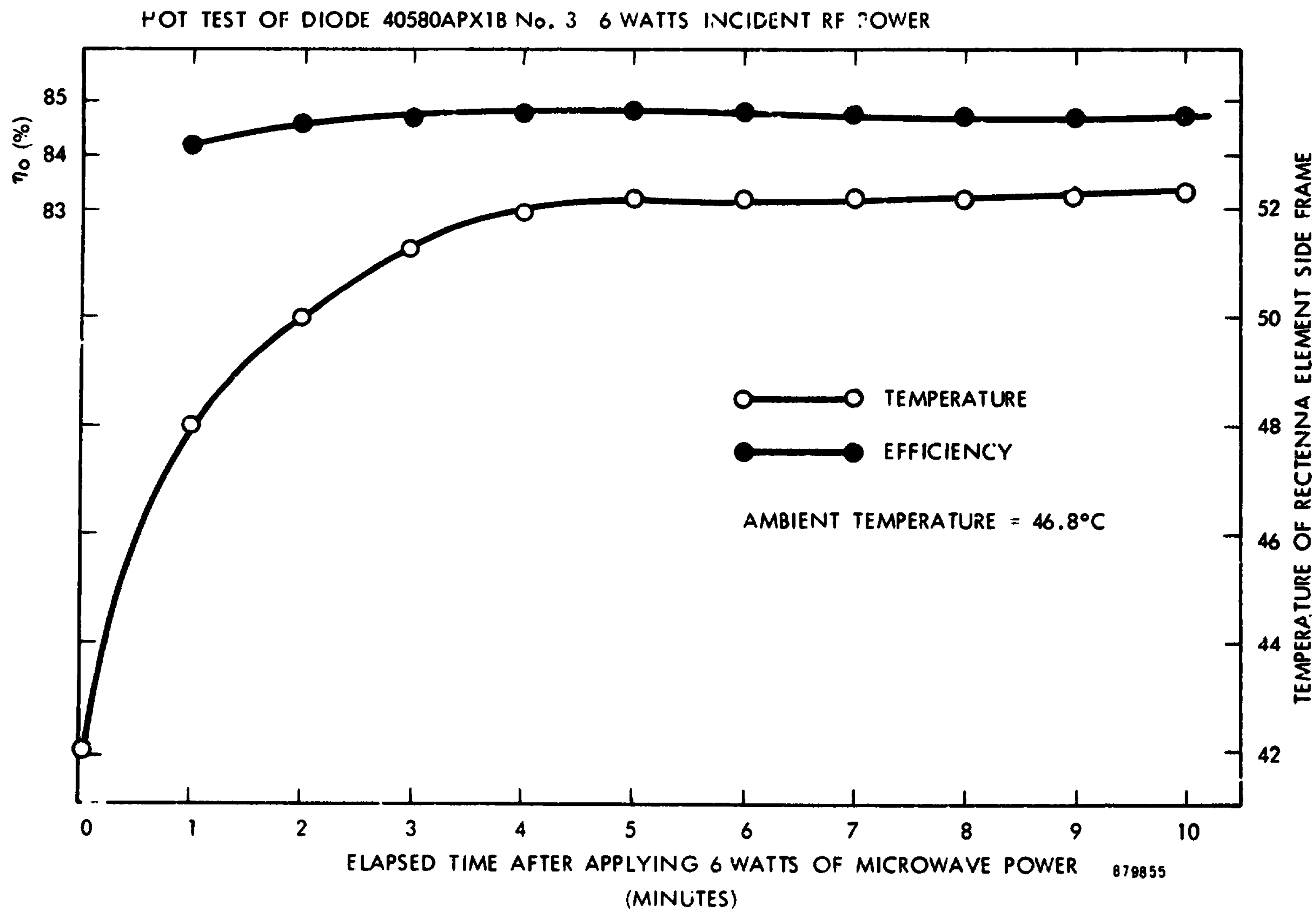
OPERATING HOT TEST OF RECTENNA ELEMENT

The ambient temperature of the desert environment is at times quite high. It was desired to know if there were any difficulties to be uncovered by operating the rectenna element in a high ambient temperature environment.

To simulate such an environment one of the rectenna elements was placed in the wave guide test fixture and the entire assembly surrounded with a heating tape and a thermal blanket. Thermometers in the form of thermistors were placed at two points. One point was on the waveguide itself to measure the ambient temperature surrounding the rectenna element. The other thermistor was mounted to one of the side frames of the rectenna element itself on the DC bus side of the adjustable microwave short. The whole assembly was heated to a stabilized temperature of 46.8° Centigrade (116° F) and then six watts of incident microwave power was applied to the rectenna element. The rectenna element was then operated for ten minutes and any changes in efficiency noted over this period of time. The temperature of the side frame of the rectenna element was monitored as a function of time as well.

The efficiency plotted as a function of time is shown in Figure 1. There was a slight improvement in efficiency during the first minute or two, a commonly observed phenomena during normal test. Then the efficiency stabilized at a high value. The change in the temperature of the side rail of the rectenna element is also plotted as a function of time. It is noted that the temperature rises and tends to stabilize at a temperature about 10 Centigrade degrees higher.

At the conclusion of this run, the microwave power was removed for one minute and then recycled several times to note if there was a change of efficiency caused by the turn-on turn-off cycle. There was no observable change.



HOT TEST OF DIODE 40580APX1B No. 3 6 WATTS INCIDENT RF POWER
η_o (%)
85
84
83
TEMPERATURE OF RECTENNA ELEMENT SIDE FRAME
52
50
48
46
44
42
TEMPERATURE
EFFICIENCY
AMBIENT TEMPERATURE = 46.8°C
0
1
2
3
4
5
6
7
8
9
10
ELAPSED TIME AFTER APPLYING 6 WATTS OF MICROWAVE POWER
(MINUTES)
879855

Figure 1.

DROP TEST OF SUBARRAY IN SHIPPING CONTAINER

In this test the prototype model of the subarray was inserted into the container and supported to simulate the support that it would receive if the full complement of five subarrays were in the container. The test was supervised by the packaging engineer for the Microwave Power Tube Operation and by a representative from the Quality Assurance Department.

The tests that were made were standard ones for a large container. An accelerometer of the type used in shipping tests was attached securely to the back cover of the rectenna subarray.

Six edge drops were made, all from a distance of 18 inches above the floor. The drops included (1) edge drop, front end, (2) corner drop, left front corner, (3) left side drop, (4) right side drop, (5) corner drop, back right corner, and (6) edge drop, back end. The maximum acceleration recorded under these conditions was 13.5 G, a resulting vector acceleration composed of vertical and horizontal components. This is a relatively small acceleration for a drop test.

The subarray was inspected by the QA representative after the drop tests. There was no damage.

APPENDIX B

RXCV SUBARRAY DIFFERENTIATION

AND

FINAL TEST DATA

<u>SUB ARRAY DIFFERENTIATION</u>

Subarray #	Diode Construction Breakdown Voltage at 1 MA: 55-62	62-75	75+	Soft	Back Cover Not Painted	Buss Bars Blackened
(1) 1.		x				x
2.		x				
3.	x					
4.	x					
5.		x				
6.		x				
7.	x				x	
8.		x				
9.		x				
10.		x				
11.		x				
12.			x			
13.	x					
14.	x	x	x	x		
15.		x				
(2) 16.		x	x			
17.	x	x	x	x		

(1) Prototype. no epoxy on diode, rails not alodined.

(2) Nearly all high voltage diodes, very few with V_{Br} below 70 volts

FINAL TEST SHEET ARRAY # 1

Date 4/22/75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 15 (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite X
d) 3 to 5 and 3 to 7, 100 K ohms X X
e) - on 3 + on 4 and 6, over 1 meg. ohm X, 15 MEG.

II. Sniffer Test 8 watts input

139 Ω across 4-5 30 volts nominal on center element
140 Ω across 6-7 Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
200 Volts .

IV. Check V_{Br} across elements

	.1	.5	1. MA	5.0	10.0mA
Rows 1-3	30.3	44.5	51.2	54.3	55.2
4-6	21.3	33.9	41.0	54.3	54.8
7-9	31.7	45.0	50.7	65.1	55.6
10-12	31.0	42.5	48.5	55.5	56.4
13-15	38.3	55.0	60.5	62.5	62.8
16-18	26.0	40.5	48.2	60.8	62.0
Center	74.7	75.1	75.4		

Element # 4522

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4/16/75 Oper. Smith

VII. Remarks: Prototype V_{Br} over 55 Volts

Diodes Not Epoxied

Rails Not Alodined

Buss Bars Blackened

FINAL TEST SHEET ARRAY # 2

Date 3-28-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 16 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite x
d) 3 to 5 and 3 to 7, 100 K ohms x x
e) - on 3 + on 4 and 6, over 1 meg. ohm 20 meg Ω+

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply +DC on #6, - on #7 to fire crowbar at about 200V DC
200 V.

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	39.7	56.7	61.8
4-6	58.0	62.5	62.8
7-9	42.3	58.8	61.0
10-12	45.7	60.1	61.7
13-15	45.9	59.0	61.6
16-18	34.0	56.1	63.0
Center	75.0	75.5	75.9

Element # 2684

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 3-31-75 Oper. Smith

VII. Remarks: Standard Array V_{Br} = 62 to 75 Volts at 1 mA

FINAL TEST SHEET **ARRAY #** 3

Date 3-29-75 **Oper.** K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 16 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
d) 3 to 5 and 3 to 7, 100 K ohms x x
e) - on 3 + on 4 and 6, over 1 meg. ohm x

II. Sniffer Test 8 watts input

130Ω across 4-5 — 30 volts nominal on center element
140Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
200 .

IV. Check V_{Br} across elements

Rows	.1	.5	1. MA
1-3	52.2	54.4	54.
4-6	43.0	57.0	57.7
7-9	42.0	53.7	56.6
10-12	52.0	56.6	56.8
13-15	51.3	55.5	55.7
16-18	56.0	56.3	56.5
Center	77.4	78.0	78.3

Element # 2695

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 3-31-75 Oper. Smith

VII. Remarks: Low breakdown diodes (V_{Br} = 55 to 62 Volts)

FINAL TEST SHEET ARRAY # 4

Date 3-29-75 Oper. K. Dudley

I. Ohmmeter

3

30k a) Thermistor 8-9 10-20 K ohm 16 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
100 d) 3 to 5 and 3 to 7, 100 K ohms 100 K
e) - on 3 + on 4 and 6, over 1 meg. ohm ∞

II. Sniffer Test 8 watts input

OK 130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply +DC on #6, - on #7 to fire crowbar at about 200V DC
About 200 V .

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	54.7	55.5	55.7
4-6	51.8	55.6	55.8
7-9	46.7	57.9	58.3
10-12	44.7	56.9	58.3
13-15	47.7	57.4	58.2
16-18	43.7	55.3	58.2
Center	76.1	76.6	76.8

Element # 2656

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 3-31-75 Oper. Smith

VII. Remarks: All low breakdown diodes (V_{Br} = 55 to 62 volts)

FINAL TEST SHEET **ARRAY # 5**

Date 3-29-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 16 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
d) 3 to 5 and 3 to 7, 100 K ohms
e) - on 3 + on 4 and 6, over 1 meg. ohm 20 meg. +

II. Sniffer Test 8 watts input

130 Ω across 4-5 30 volts nominal on center element
140 Ω across 6-7 Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
about 200 V .

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	62.5	62.9	63.1
4-6	56.5	66.8	67.2
7-9	55.5	62.7	62.9
10-12	61.7	63.1	63.4
13-15	54.8	63.5	63.8
16-18	56.9	63.0	63.2
Center	76.1	76.5	76.8

Element # 2661

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 3-31-75 Oper. Smith

VII. Remarks: Standard unit (V_{Br} = 62 to 75 Volts)

FINAL TEST SHEET **ARRAY # 6**

Date 3 29-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 16 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite x
d) 3 to 5 and 3 to 7, 100 K ohms x x
e) - on 3 + on 4 and 6, over 1 meg. ohm x

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
200 V.

IV. Check V_{Br} across elements

	.1	.5	1. MA	
Rows 1-3	29.6	44.8	53.3	
4-6	61.3	62.3	63.1	
7-9	62.5	62.8	62.9	
10-12	33.5	50.4	57.1	
13-15	57.0	62.0	62.3	leakage ~ .1 MA cleaned up at higher V.
16-18	57.8	61.6	61.0	
Center	76.7	77.2	77.6	Element # 2696

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 3-31-75 Oper. Smith

VII. Remarks: Standard Unit. V_{Br} = 62 to 75 Volts at 1 mA.

FINAL TEST SHEET — ARRAY # 7

Date 3-28-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 — 10-20 K ohm 15 K (Varies with Temp)
b) 3 to case — 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite x
d) 3 to 5 and 3 to 7, 100 K ohms ✓ ✓
e) - on 3 + on 4 and 6, over 1 meg. ohm 1 meg +, 20 meg.

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
200 V .

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	38.1	54.5	55.2
4-6	54.5	54.8	55.1
7-9	47.1	55.8	56.3
10-12	51.5	54.8	55.4
13-15	40.0	52.6	56.7
16-18	43.8	53.8	56.5
Center	-	-	-

Element # 2671

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection — Date 3-27-75 Oper. Smith

VII. Remarks: All low voltage diodes in this array. (V_{Br} = 55 to 62 Volts at 1 MA).
No paint on inside cover.

FINAL TEST SHEET ARRAY # 8

Date 4-9-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 16 (Varies with Temp)
b) 3 to case 0. ____
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
d) 3 to 5 and 3 to 7, 100 K ohms
e) - on 3 + on 4 and 6, over 1 meg. ohm x

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
199

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	48.9	61.2	63.1
4-6	47.5	56.0	56.3
7-9	50.6	59.6	60.1
10-12	54.0	62.1	62.3
13-15	56.8	63.6	63.9
16-18	46.2	60.0	60.7
Center	75.6	76.2	76.7

Element # 2697

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-7-75 Oper. Smith

VII. Remarks: Standard Unit (V_{Br} = 62 to 75 Volts at 1 mA)

FINAL TEST SHEET — ARRAY # 9

Date 4-9-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 16 (Varies with Temp)
b) 3 to case 0. x
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite x
d) 3 to 5 and 3 to 7, 100 K ohms
e) - on 3 + on 4 and 6, over 1 meg. ohm x

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
200.

IV. Check V_{Br} across elements

Rows	.1	.5	1. MA
1-3	56.4	57.0	57.2
4-6	61.5	61.8	62.0
7-9	49.5	62.7	63.2
10-12	61.6	62.8	63.0
13-15	57.9	60.3	60.6
16-18	40.8	55.5	56.3
Center	76.3	77.3	77.7

Element # 2700

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-7-75 Oper. Smith

VII. Remarks: Standard Unit (V_{Br} = 62 to 7[illegible] volts at 1 mA)

FINAL TEST SHEET

ARRAY # 10

Date 4-9-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 16 K (Varies with Temp)
b) 3 to case 0. x
c) 1 to 2, 3. 8; and 2 to 3, 8; and 3 to 8; infinite x
d) 3 to 5 and 3 to 7, 100 K ohms
e) - on 3 + on 4 and 6, over 1 meg. ohm x

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply +DC on #6, - on #7 to fire crowbar at about 200V DC
199 .

IV. Check V_{Br} across elements

	.1	.5	1. MA	10 mA	20 mA
Rows 1-3	39.0	58.1	62.2		
4-6	44.5	59.9	62.6		
7-9	42.2	59.5	59.9		
10-12	10.9	50.0	63.8	68.8	71.9
13-15	10.9	45.5	67.0	72.7	73.2
16-18	11.0	48.1	65.0	68.9	70.1
Center	76.2	76.8	77.2		

Element # 02930

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10. 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-7-75 Oper. Smith

VII. Remarks: Standard Unit (V_{Br} = 62 to 75 Volts at 1 mA)

FINAL TEST SHEET **ARRAY # 11**

Date 4-9-75 **Oper. K. Dudley**

I. Ohmmeter

25 a) Thermistor 8-9 10-20 K ohm 16 (Varies with Temp)
0 b) 3 to case 0. 0
∞ c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ✓
100k d) 3 to 5 and 3 to 7, 100 K ohms 100 K
e) - on 3 + on 4 and 6, over 1 meg. ohm #4 ∞ #6 6 meg. Ω

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
198 .

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	62.1	69.3	69.6
4-6	63.7	64.3	64.6
7-9	55.2	56.6	56.8
10-12	55.8	69.3	70.2
13-15	64.7	70.7	71.2
16-18	65.2	70.8	71.1
Center	77.0	77.5	77.8

Element # 2688

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-7-75 Oper. Smith

VII. Remarks: Standard Unit (V_{Br} = 62 to 75 Volts at 1 mA)

FINAL TEST SHEET | **ARRAY #** 12

Date 4-17-75 **Oper.** K. Dudley

I. Ohmmeter

a) Thermistor 8-9 | 10-20 K ohm 15 K (Varies with Temp)
b) 3 to case | 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
d) 3 to 5 and 3 to 7, 100 K ohms ✓✓
e) - on 3 + on 4 and 6, over 1 meg. ohm ∞,20 meg. ohm

II. Sniffer Test 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
198 .

IV. Check V_{Br} across elements

	.1	.5	1. MA	1 µa	5 µA	25 µA	50 mA
Rows 1-3	74.4	74.9	75.0	7.0	39.8	74.1	74.2
4-6	66.9	75.1	75.3	7.6	29.	52 0	60.2
7-9	68.3	74.6	74.9	7.5	32.	56.0	63.0
10-12	70.0	74.5	74.[illegible]	8.6	32	56.7	64
13-15	68.9	74.7	74.9	7.8	39	54.1	64.9
16-18	63.4	72.7	73.2	7.0	28.9	48 0	55.7
Center	75.0	75.9	76.5	10.1	48.1	74.8	74.9

Element # 2933

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-16-75 Oper. Smith

VII. Remarks: All high voltage diodes. V_{Br} over 75 volts at 1 mA

FINAL TEST SHEET ARRAY # 13

Date 4-17-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 10-20 K ohm 15 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
d) 3 to 5 and 3 to 7, 100 K ohms
e) - on 3 + on 4 and 6, over 1 meg. ohm ∞, 20 meg ohm

II. Sniffer Test 8 watts input

130Ω across 4-5 — 30 volts nominal on center element
140Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC 198.

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	52.3	54.0	54.2
4-6	43	53.5	54.0
7-9	49.0	55.1	55.4
10-12	35.4	49.4	54.5
13-15	35.4	50.1	56.1
16-18	47	58.6	59.0
Center	76.0	77.0	77.3

Element #2698

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-16-75 Oper. Smith

VII. Remarks: All low breakdown voltage diodes (V_{Br} = 55 to 62 volts at 1 mA)

FINAL TEST SHEET ARRAY # 14

Date 4-17-75 Oper. K. Dudley

I. **Ohmmeter**

a) Thermistor 8-9 10-20 K ohm 15 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
d) 3 to 5 and 3 to 7, 100 K ohms ✓
e) - on 3 + on 4 and 6, over 1 meg. ohm ∞, 15 meg.

II. **Sniffer Test** 8 watts input

130 Ω across 4-5 — 30 volts nominal on center element
140 Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. **Crowbar**

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
199 .

IV. Check V_{Br} across elements

	.1	.5	1. MA	5 MA
Rows 1-3	28.1	45.8	53.6	60.7
4-6	24.9	38.2	44.4	55.2
7-9	25.0	35.0	42.0	55.0
10-12	29.5	44.7	50.1	56.1
13-15	31.9	45.1	51.0	61.5
16-18	25.3	39.6	46.2	53.9
Center	76.7	77.7	78.0	Element # 2678

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-17-75 Oper. Smith

VII. Remarks: ARRAY 14 — This array contains mostly soft diodes. The V_{Br} 1 mA is normal (over 55 volts) but drops to as low as 31 volts at 5 μA. About two thirds are from the lot of soft diodes (S23). The others are diodes found to be soft when installed in other arrays.

FINAL TEST SHEET **ARRAY # 15**

Date 4-17-75 Oper. K. Dudley

I. **Ohmmeter**

a) Thermistor 8-9 10-20 K ohm 15 K (Varies with Temp)
b) 3 to case 0. 0
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite ∞
d) 3 to 5 and 3 to 7, 100 K ohms
e) - on 3 + on 4 and 6, over 1 meg. ohm ∞, 5 meg. Ω

II. **Sniffer Test** 8 watts input

130 Ω across 4-5 30 volts nominal on center element
140 Ω across 6-7 Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
198 .

IV. Check V_{Br} across elements

		.1	.5	1. MA
Rows	1-3	53.6	64.4	68.4
	4-6	54.7	62.7	63.0
	7-9	63.6	64.1	64.3
	10-12	62.7	63.2	63.6
	13-15	62.2	62.5	62.7
	16-18	50.0	62.9	63.4
	Center	77.7	78.1	78.4

Element # 2699

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-16-75 Oper. Smith

VII. Remarks: Standard Unit V_{Br} = 62 to 75 Volts

FINAL TEST SHEET **ARRAY # 16**

Date 4-22-75 Oper. K. Dudley

I. Ohmmeter

a) Thermistor 8-9 - 10-20 K ohm 15 KΩ (Varies with Temp)
b) 3 to case 0. x
c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite x
d) 3 to 5 and 3 to 7, 100 K ohms " "
e) - on 3 + on 4 and 6, over 1 meg. ohm ∞, 10 Meg.

II. Sniffer Test 8 watts input

130Ω across 4-5 — 30 volts nominal on center element
140Ω across 6-7 — Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply +DC on #6, - on #7 to fire crowbar at about 200V DC
199 .

IV. Check V_{Br} across elements

	.1	.5	1. MA
Rows 1-3	72.2	74.1	74.3
4-6	56.2	72.2	74.6
7-9	72.1	74.1	74.3
10-12	59.6	74.1	74.5
13-15	60.2	62.1	62.3
16-18	62.9	63.1	63.3
Center	74.4	75.1	75.5

Element # 4197

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-16-75 Oper. Smith

VII. Remarks: High voltage diodes rows 1-12, $V_{Br} > 75$ volts
Rows 13-18 Reg. and High voltage diodes, $V_{Br} > 62$ volts

FINAL TEST SHEET ARRAY # 17

Date 4-18-75 Oper. F. Dudley

I. Ohmmeter

30' a) Thermistor 8-9 10-20 K ohm 15 (Varies with Temp)
0 b) 3 to case 0. 0
∞ c) 1 to 2, 3, 8; and 2 to 3, 8; and 3 to 8; infinite x
d) 3 to 5 and 3 to 7, 100 K ohms
e) - on 3 + on 4 and 6, over 1 meg. ohm ∞, #3-6 2.5 Meg.

II. Sniffer Test 8 watts input

150 Ω across 4-5 30 volts nominal on center element
140 Ω across 6-7 Over 20 volts for each element

(should drop to below 10 volts with sniffer over center element)

III. Crowbar

a) Remove 140 ohms from 6-7
b) Apply + DC on #6, - on #7 to fire crowbar at about 200V DC
197.

IV. Check V_{Br} across elements

	.1	.5	1. MA	5 MA	10 MA
Rows 1-3	17.2	28.7	34.3	49.8	56.2
4-6	17.2	29.4	36.0	52.1	59.0
7-9	13.3	26.5	33.4	50.7	56.8
10-12	13.1	25.2	31.5	50.0	55.5
13-15	16.5	30.2	37.8	54.5	56.1
16-18	6.7	17.4	23.1	39.7	47.4
Center	74.1	75.0	75.4		

Element # 4199

V. Remove cable and install shorts across A-B and C-D. Replace dust caps.

Install shorting clips across 1 element in rows 1, 4, 7, 10, 13 and 16.
Install 4 standoff spacers on front panel.
Install plywood shield.

VI. Visual Mechanical Inspection Date 4-22-75 Oper. Smith

VII. Remarks: All soft diodes

Rows #16-18 worst. V_{Br} at 0.1 MA 30 to 40 volts.

APPENDIX C

RXCV RF FIELD MEASUREMENTS

J. C. Parr
Raytheon Company
Memo #JCP-78A
5 August 1975

System Parameters

The DSS-13 antenna (transmitter) is an 85 ft. (25.9 m) Cassegrain antenna operating at 2388 MHz. The gain, determined by various measurements made over several years, is stated to be 54.3 ± 0.2 dB. The receiver is located nominally 48'6" above the base of the collimation tower which is at a slant range of approximately 5200 feet (see Appendix A). For the purpose of field measurement the receiver was a standard-gain horn with 16.92 dB gain. The nominal received power on boresight with linear polarization is 0.397 mW per watt transmitted (see Appendix B).

Two fundamental types of measurement were made: either the receiver was fixed in position and the transmitter was scanned in azimuth and elevation, or the transmitter was fixed in direction and the receiver was traversed vertically and horizontally. The results of these and other measurements are detailed below in chronological order, followed by a discussion of their significance.

It should be noted that 'cw' and 'ccw' refer to the direction of the transmitting antenna as seen from above; 'left' and 'right' refer to the position of the receiving antenna as seen from the transmitting antenna.

Chronological History of Measurements

In order to verify that the transmitter was correctly aligned on the collimation tower, the receiving horn was stationed 48'6" above the tower base (at the nominal center of the rectenna location) and the transmitter was scanned over a small arc in both azimuth and elevation. The transmitter was initially aligned on the horn by means of the TV camera affixed to the upper edge of the main reflector. The radiated power was 7.08 watts, circularly polarized.

Figure 1 shows the graphs of received power as a function of scan angle. It was noted that the optical boresight was considerably different from the RF boresight in elevation (but virtually coincident in azimuth); at the time, a rapid estimate of the misalignment was made, the estimate being 0.07°; later a more accurate value of 0.0645° was calculated from the graph. This corresponds to almost 6' displacement at the receiver. The peak power received was 1.27 mW, compared with a calculated value of 1.41 ± 0.02 mW The measured 3 dB beamwidths were 0.379° (elevation) and C ° (azimuth). The transmitter position read out was to the nearest 0.002°, which is equivalent to about 2" at the receiver.

The transmitter was then fixed in direction 0.07° above the previously determined optical boresight, and the receiving horn was traversed vertically up the centerline of the tower. At heights of 36', 48'6" and 61', corresponding to the bottom edge, centerline and top edge of the rectenna, horizontal traverses of ±7' were also made.

Because of the structural configuration of the collimation tower, it proved extremely difficult to determine the exact height of the horn over certain ranges at certain locations. Conversely, at other locations the horn height could be accurately determined; at three of these locations the horn was traversed vertically in fine increments in order to ascertain if there was any fine-structured ripple in the field density. Figure 2 shows the measured RF power as a function of receiver height, while Figure 3 shows the power as a function of horizontal displacement at the three above-mentioned heights. The peak measured power was 1.31 mW.

It was observed that there was considerable apparently random scatter of the measured points which did not appear during the first set of measurements when the transmitter was scanned and the receiver was stationary. As an experiment, the receiver was traversed from 45' to 53' height in small increments, the results being shown in Figure 4, with a pseudo-random ripple that could not possibly be due to reflections.

An on-site brainstorming session led to the belated appreciation that these ripples were caused by the structure of the collimation tower forcing the horn support beam to yaw as it was traversed vertically. The rollers at each end of the beam were sometimes in contact with the legs of the tower - as intended - and were sometimes forced outwards by angle members used to cross-brace the tower legs. This unwanted displacement could be at either or both ends of the beam, and was variable in amount; as the horn yawed, the received power decreased owing to the horn's boresight swinging away from the transmitter. At a later date an attempt was made to assess the magnitude of this effect, but for the present it was decided to annotate the measured results to indicate whether the left or right hand end of the beam was displaced from the tower leg. The following cases were distinguished:

"O.K."	if both rollers were in contact with the tower legs, or both were equally displaced outwards;
"LHO"	if the left-hand roller was displaced and the right-hand roller was in contact;
"RHO"	if the converse of "LHO" obtained;
"LH $\frac{1}{2}$ O"	if the left-hand roller was displaced to the maximum extent and the right-hand roller was only partially displaced;
"RH $\frac{1}{2}$ O"	if the converse of "LH $\frac{1}{2}$ O" obtained.

It should be noted that maximum power received (the "O.K." state) corresponded to a valid measurement, and hence a curve drawn through the maximum points in Figure 2 is likely to represent the true power variation.

The azimuth and elevation scans of the transmitter were then repeated in order to obtain a better antenna pattern over a wider angular range. A linear vertical polarization was provided. The results of these measurements are shown in Figures 5 and 6, and expanded plots of the peaks are shown in Figure 7. The agreement with Figure 1 is good, although there are minor discrepancies: the azimuth beamwidths are 0.324° and 0.336°, a difference of 0.012°; the elevation beamwidths are 0.379° and 0.373°, a difference of 0.006°. The azimuth boresight errors are 0.0055° and 0.0027° CW, a difference of 0.0028° to be associated with position read-out tolerances, and the associated elevation boresight errors are 0.0645° and 0.0135°, a difference of 0.051° rather than the re-alignment figure of 0.07°. The peak power level was 2.22 mW, compared with the calculated value of 2.80 ± 0.03 mW, but the horn was displaced ("RH 1/2 O") by the tower structure and therefore the measured level is expected to be less than the calculated value.

The measurements were taken in the transition region between the near and far field so the beam shape and sidelobe structure are understandably different from those at the aperture. It would be instructive to attempt to calculate the pattern at this range, but unfortunately this task is not within the scope of the program.

The next measurement, chronologically, was of received power at the geometrical center of each rectenna subarray. The results are shown in Figure 8, which are self explanatory. One additional location was measured, corresponding to a downward vertical displacement of one subarray height. Generally, the left and right hand subarrays receive about 0.2 dB less power density at their centers than the central subarrays.

Now that the cause of the "random ripples" had been determined, the vertical centerline traverse was repeated, with suitable annotations. The three horizontal traverses at the positions of the bottom, center and top of the rectenna were also repeated. The results are shown in Figure 9 (where the "O.K." condition is distinguished) and Figure 10; these should be compared with Figures 2 and 3 respectively. The peak power was 2.30 mW, which is nearer the calculated value of 2.81 ± 0.3 mW, but is not twice the peak power level with circular polarization. The peak occurs at 47.0' instead of 49.1'; the value at 49.1' is in precise agreement with the value calculated from the known optical boresight misalignment and the deliberate 0.07° offset. Finally, the 3 dB width is 0.373° in both cases, which agrees well (0.379°, 0.373°) with the values obtained by scanning the transmitter.

This last measurement concluded the planned work necessary to establish the field density over the projected position of the rectenna. However, in recognition of the possibility of a slight advantage to be gained if the rectenna were to be located further down the tower, it was decided that it was worthwhile repeating field density measurements with the transmitter RF boresight at 36' height. The transmitting antenna was therefore depressed by 0.115°, the value calculated to aim the beam peak at 36' height at the tower.

A vertical traverse was started but only a few measurements had been made before an accident with the equipment caused the destruction of the thermistor mount - it took the full impact of the horn support beam against the tower, when the rollers caught temporarily on the cross-bracing. Using the Venus Site laboratory facilities, the thermistor was disassembled, reshaped, resoldered and generally restored. A check, using laboratory equipment, showed that the sensitivity of the thermistor mount was close to the nominal value, but there is now no way of knowing whether the calibration changed due to the damage and repair operations. Only seven measurements were made before the accident, which can be correlated with the same measurements after the accident; comparison indicates that the thermistor sensitivity appears to have increased by 0.62 ± 0.20 dB, but other effects (e.g. transmitter re-alignment - the measurements were on a steep part of the curve) may be responsible.

The next measurement was a repeat of the vertical traverse, with the transmitter aimed at the 36' height (by calculation); the results are shown in Figure 11. Superimposition of Figures 9 and 11, theoretically taken under identical conditions except for the transmitter elevation, indicates that the received power level has increased by 0.12 dB. This is considered to be a more reliable value than the 0.62 dB mentioned above. Horizontal traverses at receiver heights of 36', 48-1/2' and 61' were again made, and the results are shown in Figure 12.

Finally, some miscellaneous measurements were made. The elevation angle of the receiving horn was varied, and it was confirmed that the horn tilt was exactly correct to obtain maximum power. Similarly, the horn polarization angle was varied and found to be correct -- vertical polarization gave maximum received power. The yaw angle (rotation of the horn about a vertical axis, simulating the effect of the tower structure) was varied, indicating a variation of about 0.1 dB if the horn was at "RHO" or "LHO". Lastly, the transmitting antenna was changed back to RH circular polarization, and the polarization ellipse at the receiver was determined. The results were as follows:

1. Transmitter vertically polarized;
   Receiver vertically polarized (maximum power): 1.88 mW

2. Transmitter circularly polarized;
   Receiver vertically polarized (maximum power): 1.10 mW
   Receiver horizontally polarized (minimum power): 0.85 mW
   Total CP power: 1.39 mW

Discrepancy: 1.88 - 1.39 mW = 1.31 dB.

VP Difference: 1.88 - 1.10 mW = 2.33 dB.

The rationale for the difference was not immediately apparent.

Summary and Conclusions

If the following assumptions are made:

1. Peak readings are more realistic than readings made from a smooth curve.

2. The relation between received vertically-polarized power readings with circularly and vertically polarized transmission is as measured, not 2:1 in ratio.

3. The thermistor underwent a sensitivity change of 0.12 dB as a result of mechanical damage and subsequent repair.

Then the five peak power readings which are strictly comparable are as follows:

3.60 dBm from Figure 2,
3.59 dBm from Figure 7,
3.68 dBm from Figure 8,
3.72 dBm from Figure 9,
3.70 dBm from Figure 11,

where these figures have been modified where necessary to reflect the present thermistor sensitivity.

The mean value of the peak level is 3.66 ± 0.06 dBm (2.32 + 0.035 mW), which may be compared with the predicted value of 4.49 ± 0.20 dBm (2.81 ± 0.03 mW). It can be assumed, subject to confirmation after calibration, that the peak received power is 34.42 dB below the transmitted power.

In order to facilitate future work involving power density, the previous results have been combined into a composite graph and then normalized to a basis of milliwatts per square centimeter per kilowatt transmitted. This composite is shown in Figure 13 and applies to both horizontal and vertical displacement from the peak of the beam.

It is immediately possible to deduce the power density at the center of each rectenna subarray; this has been done, and the results are shown in Figure 14. Also, using a polynomial curve-fitting program, an expression for power density as a function of distance from boresight can be derived(*), and simple double integration leads to the total power incident on each subarray; these values are also shown in Figure 14. Agreement with Figure 8 is good.

The only significant topic remaining is that of field reflections, or other source of ripple. In general, the power meter could be read to an accuracy of better than ±0.05 dB; a good idea of this accuracy can be obtained by inspection of Figures 1 and 7, where the horn was stationary and the transmitter was moving. It can be assumed that variations of more than ±0.05 dB should not be ascribed to meter-reading errors. (Care was taken to ensure that zero drift was negligible, and periodic amplitude checks were made at the peak of the beam.)

As can be seen from Figures 3, 10, 12, there appears to be a random fluctuation of ±0.07 dB RMS when the horn was traversed horizontally and comparison of these Figures indicates that the fluctuation is truly random. The only plausible explanation is that there were reflections from the horn support structure and from the collimation tower, producing local variations in the RF field.

Similarly, as can be seen from Figures 9 and 11, there is a random fluctuation of ±0.07 dB RMS when the horn is traversed vertically and both rollers are in contact with the legs of the tower. Expanded plots of received power in these areas show <u>random</u> scatter again, with no trace of <u>periodic</u> fluctuations.

It can be concluded that there is no evidence of periodic ripple, within the limits of measurement accuracy, and therefore ground reflections are negligible.

Power Meter Calibration

The technique is based on substitution of accurately measured DC power for the unknown RF power, with correction for system mismatches, as detailed in "Microwave Power Measurement", Hewlett-Packard Application Note No. 64, and Operating and Service Manual for Hewlett-Packard Power Meter 432A. Calibration accuracy is limited by the following parameters:

(*) $p = 0.525609 - 0.00134043R^2 + 0.00000151259R^4 - 0.0000000006812R^6$

(a) the ± 0.5 μW inherent meter error;

(b) the ± 10 mV inherent analog voltage output error;

(c) the scale reading error, estimated as ± 0.02 dB at full scale (and greater elsewhere);

(d) the ± 1 count error in the DVM used for the calibration measurements.

In practice, this implies that calibration of meter scale reading vs. RF input power cannot meaningfully be carried out below about 100 μW, and calibration of analog voltage vs. RF input power has a possible error of about ± 0.5 mV at all scale readings.

Table 1 shows the meter scale reading error for various RF power levels, with the estimated calibration accuracy; for these measurements, the meter pointer was set at the appropriate scale division, which is very different from <u>reading</u> the pointer position. It appears then that the calibration accuracy is generally better than 0.3%.

Table 2 shows the analog output voltage error for various RF power levels; the overall picture is essentially the same as the scale error variation.

Taking into account the power meter error at the signal levels obtained during the RF field measurements, it can be concluded that the peak power at the receiver was actually 35.00 ± 0.11 dB below the transmitted power; the possible error value was derived by taking the RSS of the individual measurement and calibration errors.

<u>Final Calibration Factors</u>

For the permanent field monitor the signal received by the horn is attenuated by a directional coupler, a coaxial pad, and a length of coaxial cable with sundry coaxial adaptors. The insertion loss of this assembly, including mismatch effects, was measured using a Hewlett-Packard Automatic Network Analyzer, as 41.74 ± 0.05 dB.

J. C. Parr, Group Leader
Microwave Antenna Section

cc: D. A. Salmond

APPENDIX A

Slant Range From Transmitter To Receiver

There are two ways in which slant range can be calculated, and the results differ by 0.1%; the average, 5052.2 ft., was used in calculations.

1. Range Via Geodetic Coordinates

Information supplied by JPL stated that the coordinates of the transmitter vertex are 35° 14' 51.788" N by 116° 47' 38.427" W, and of the tower base are 35° 14' 43.492" N by 116° 48' 38.253" W. Ploughing through the necessary spherical geometry (e.g. via "Reference Data for Radio Engineers", pp. 732-734) leads to an angular separation of 49.558". or, assuming a mean sea-level radius of 20898950.0 ft.* and a transmitter elevation of 3600.3 ft., a ground-level separation of 5022.13 ft.

The difference in elevation between transmitter vertex and receiver (48'6" above tower base) is nominally 626.2 ft. and the horn is approximately 5 ft. from the tower centerline, hence the slant range is 5056.06 ft.

2. Range By Angular Measurement

Using the TV camera (with zoom lens) attached to the DSS-13 antenna, the elevation angles of the base and top of the collimation tower were measured as 6.536° and 7.760° respectively. The height of the tower was 113' 3-1/2". The resulting calculated value of slant range, allowing for camera height, distance between antenna axes, etc., is 5047.80 ft.

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*This value supplied by W.W. Shrader, 29 August 1974.

APPENDIX B

Calculation of Received Power

Transmitter Gain: 54.3 ± 0.2 dB

Receiver Gain: 16.92 ± 0.09 dB (including transition loss)

Wavelength: 0.41188 feet

Range: 5052.2 ± 4.4 feet

Hence $(4\pi R/\lambda)^2 = 103.76 \pm 0.008$ dB*

Beam-Broadening Loss: 1.47 dB (nominal parameters)

Hence received power is nominally 34.01 ± 0.10 dB below transmitted power, a factor of $3.97 \times 10^{-4} \pm 2\%$.

For the RF field measurement exercise, the transmitted power was 38.5 ± 0.1 dBm, or 7.08 W; the nominal received power was therefore 4.49 ± 0.20 dBm, or 2.81 ± 0.03 mW with linear polarization.

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*The value actually used at Venus Site was stated to be 104.4 dB.

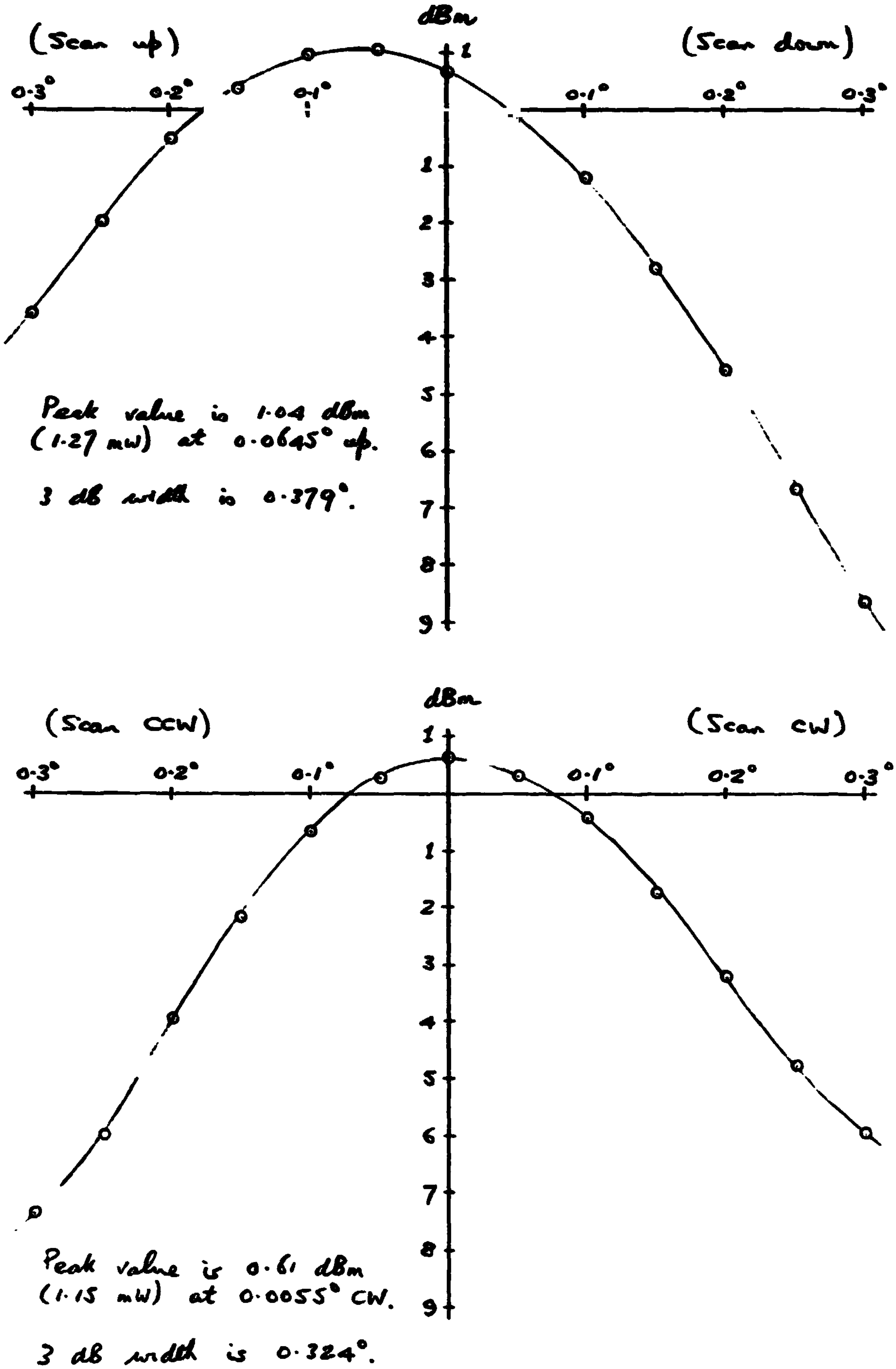
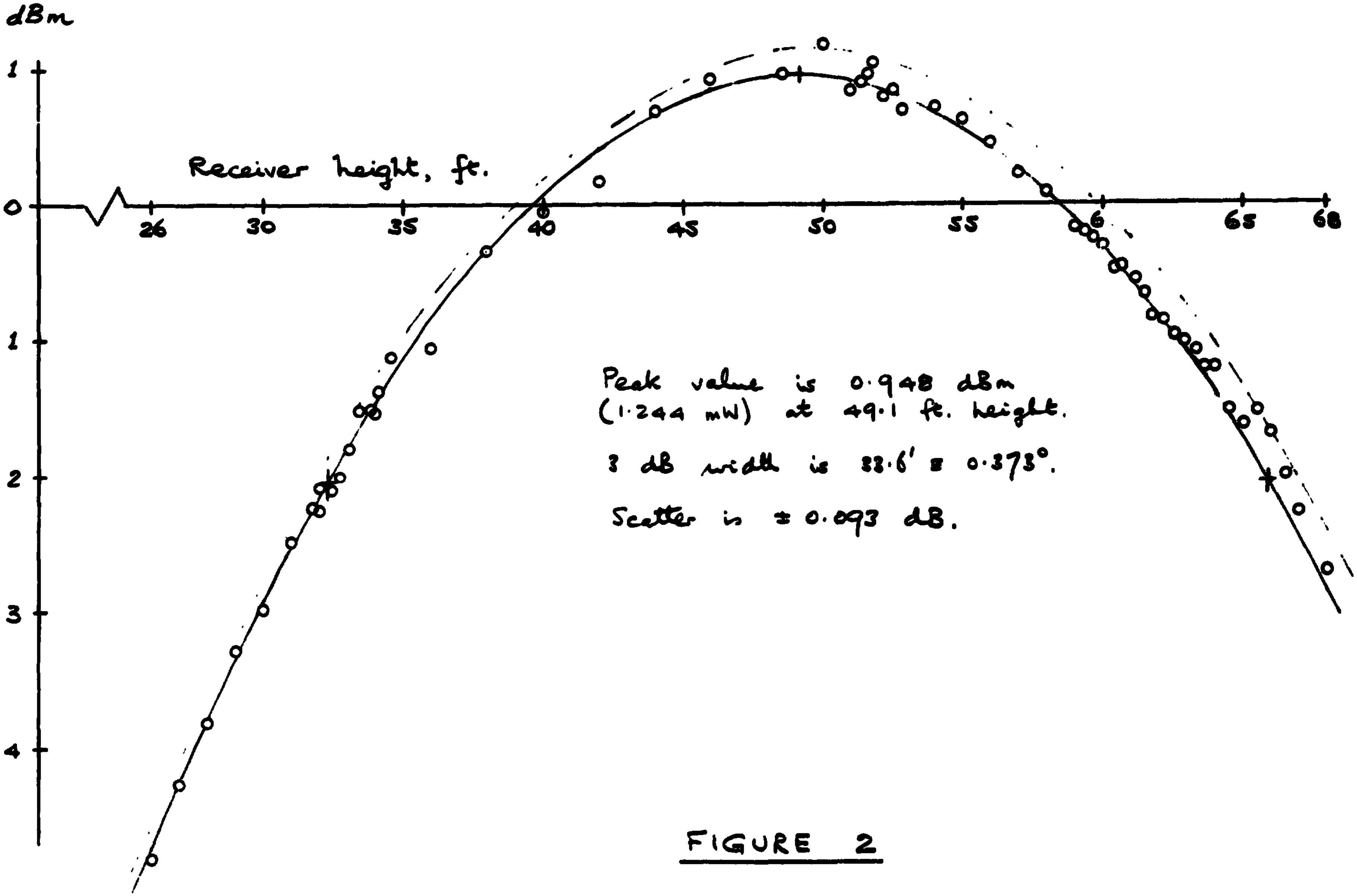

dBm
(Scan up)
(Scan down)
0·3°
0·2°
0·1°
0·1°
0·2°
0·3°
1
1
2
3
4
5
6
7
8
9
Peak value is 1·04 dBm (1·27 mW) at 0·0645° up.
3 dB width is 0·379°.
dBm
(Scan CCW)
(Scan CW)
0·3°
0·2°
0·1°
0·1°
0·2°
0·3°
1
1
2
3
4
5
6
7
8
9
Peak value is 0·61 dBm (1·15 mW) at 0·0055° CW.
3 dB width is 0·324°.

FIGURE 1



dBm
1
0
1
2
3
4
Receiver height, ft.
26
30
35
40
45
50
55
60
65
68
Peak value is 0.948 dBm (1.244 mW) at 49.1 ft. height.
3 dB width is 33.6' = 0.373°.
Scatter is ± 0.093 dB.

FIGURE 2

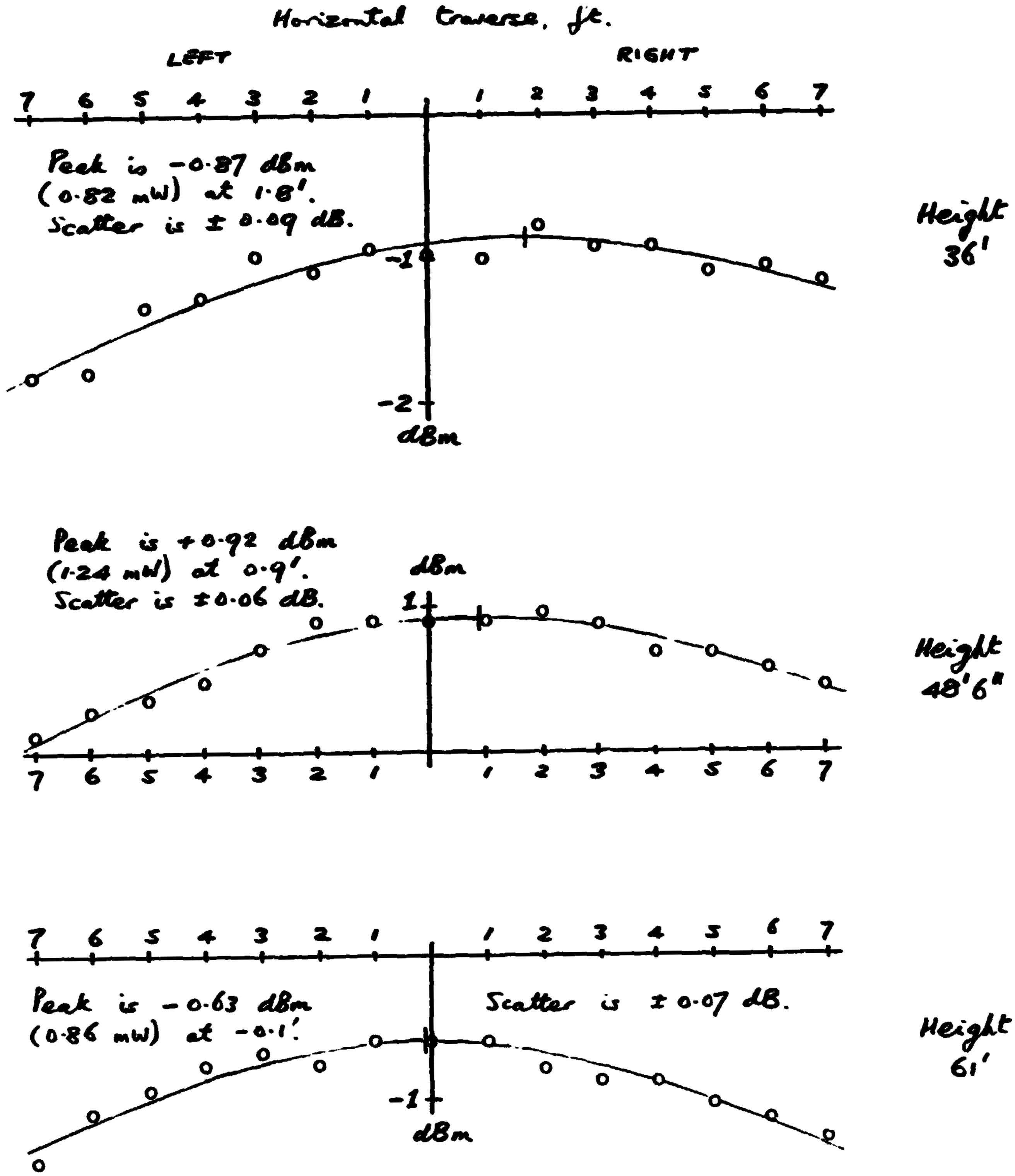

Horizontal traverse, ft.
LEFT
RIGHT
7 6 5 4 3 2 1 1 2 3 4 5 6 7
Peak is -0.87 dBm
(0.82 mW) at 1.8'.
Scatter is ± 0.09 dB.
-1
-2
dBm
Height
36'
Peak is +0.92 dBm
(1.24 mW) at 0.9'.
Scatter is ±0.06 dB.
dBm
1
Height
48'6"
7 6 5 4 3 2 1 1 2 3 4 5 6 7
7 6 5 4 3 2 1 1 2 3 4 5 6 7
Peak is -0.63 dBm
(0.86 mW) at -0.1'.
Scatter is ± 0.07 dB.
-1
dBm
Height
61'

FIGURE 3

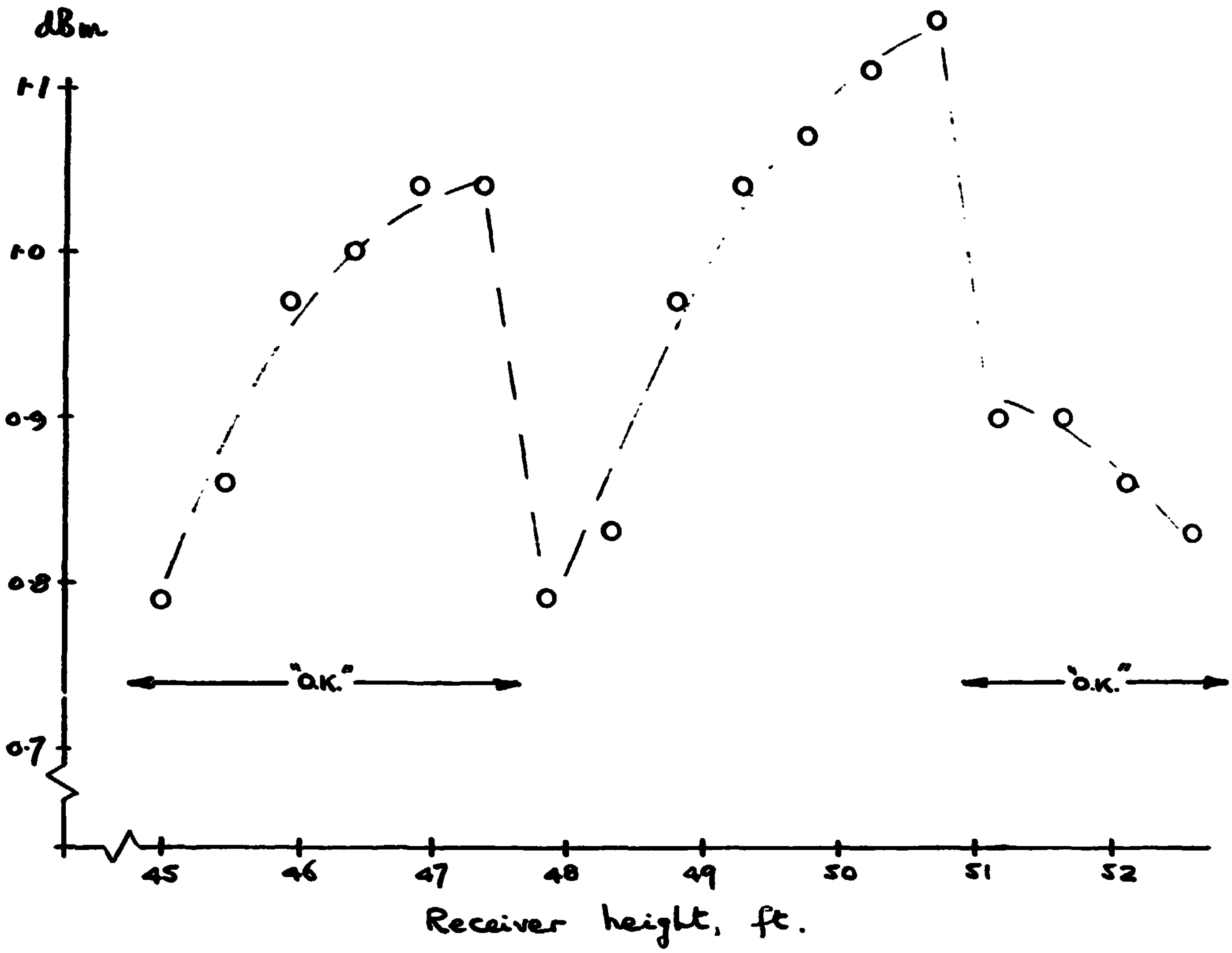


FIGURE 4

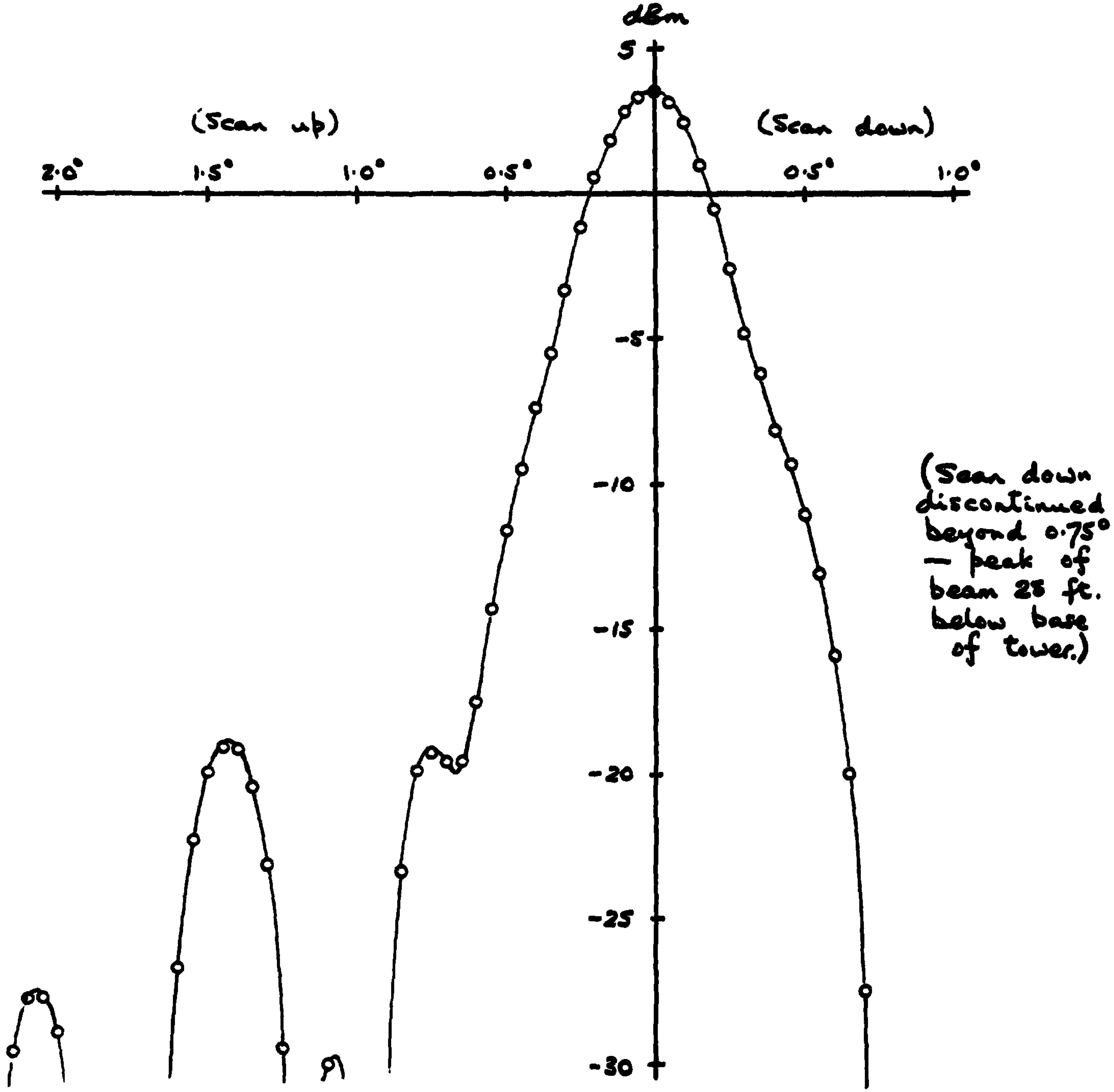

dBm
5
(Scan up)
(Scan down)
2.0°
1.5°
1.0°
0.5°
0.5°
1.0°
-5
-10
-15
-20
-25
-30
(Scan down discontinued beyond 0.75° — peak of beam 25 ft. below base of tower.)

FIGURE 5

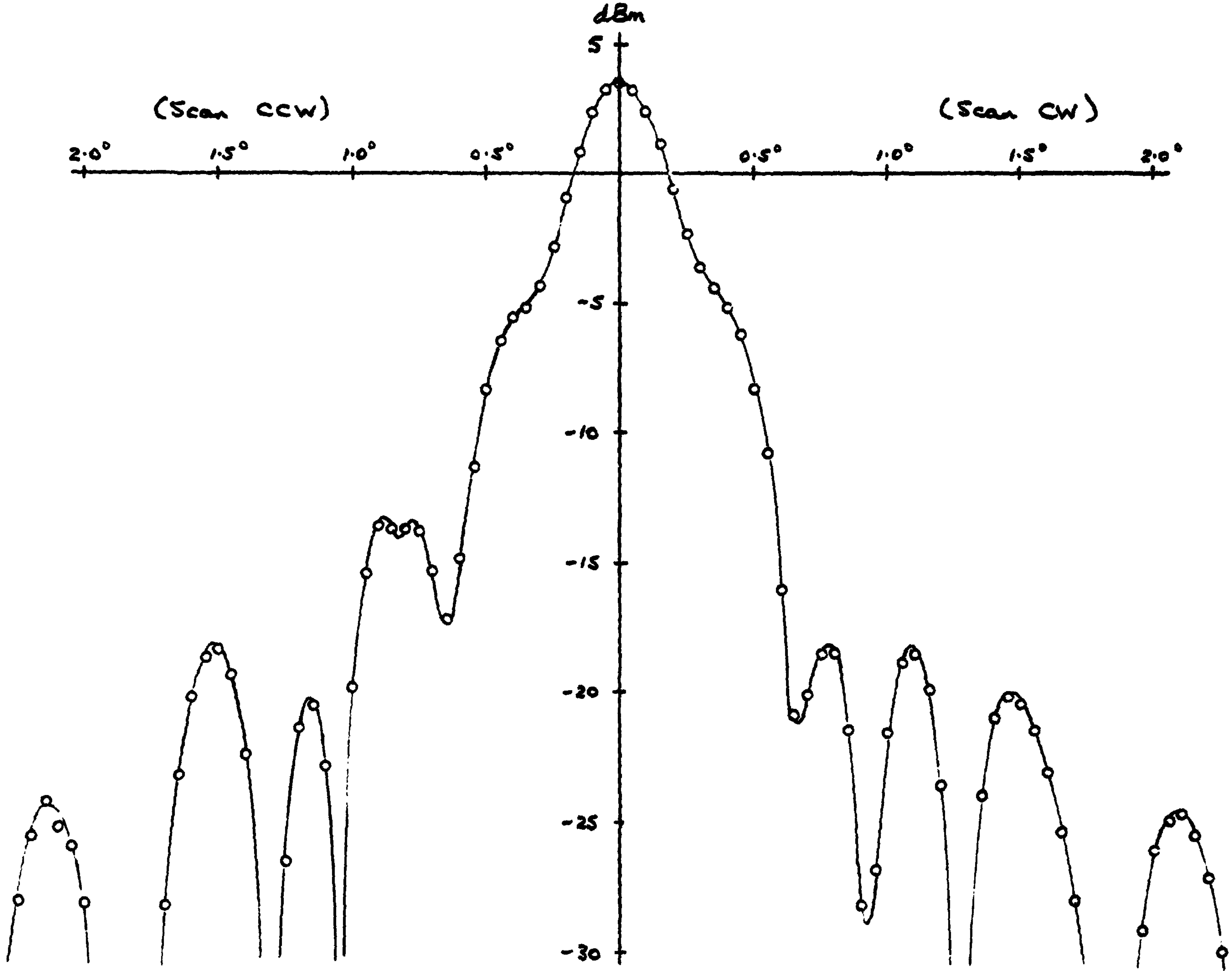
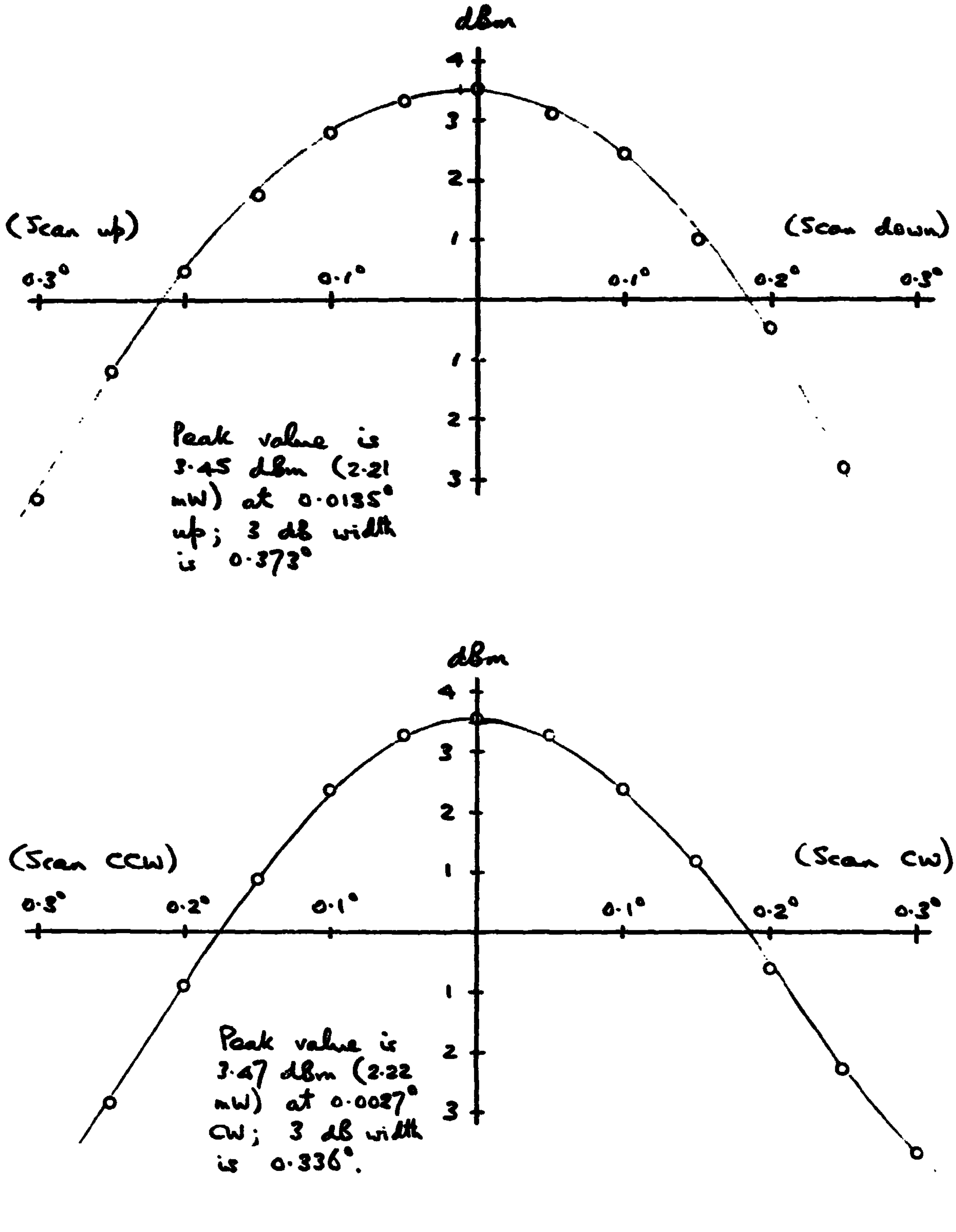


FIGURE 6



dBm
(Scan up)
(Scan down)
0.3°
0.1°
0.1°
0.2°
0.3°
4
3
2
1
1
2
3
Peak value is 3.45 dBm (2.21 mW) at 0.0135° up; 3 dB width is 0.373°
dBm
(Scan CCW)
(Scan CW)
0.3°
0.2°
0.1°
0.1°
0.2°
0.3°
4
3
2
1
1
2
3
Peak value is 3.47 dBm (2.22 mW) at 0.0027° CW; 3 dB width is 0.336°.

FIGURE 7

Yaw	Height	Lateral Displacement (Left or CCW) 4'0"	℄	(Right or CW) 4'0"
RHO	58' 11"	1·48 mW 1·70 dBm	1·50 mW 1·76 dBm	1·42 mW 1·52 dBm
LHO	54' 9"	1·83 mW 2·62 dBm	1·83 mW 2·62 dBm	1·84 mW 2·65 dBm
LHO	50' 7"	2·04 mW 3·10 dBm	2·21 mW 3·44 dBm	2·02 mW 3·05 dBm
O.K.	46' 5"	2·11 mW 3·24 dBm	2·27 mW 3·56 dBm	2·14 mW 3·30 dBm
RHO	42' 3"	1·99 mW 2·99 dBm	2·08 mW 3·18 dBm	2·00 mW 3·01 dBm
LHO	38' 1"	1·77 mW 2·48 dBm	1·85 mW 2·67 dBm	1·80 mW 2·55 dBm
O.K. (Extra subarrays)	33' 11"	1·41 mW 1·49 dBm	1·47 mW 1·67 dBm	1·41 mW 1·49 dBm

FIGURE 8

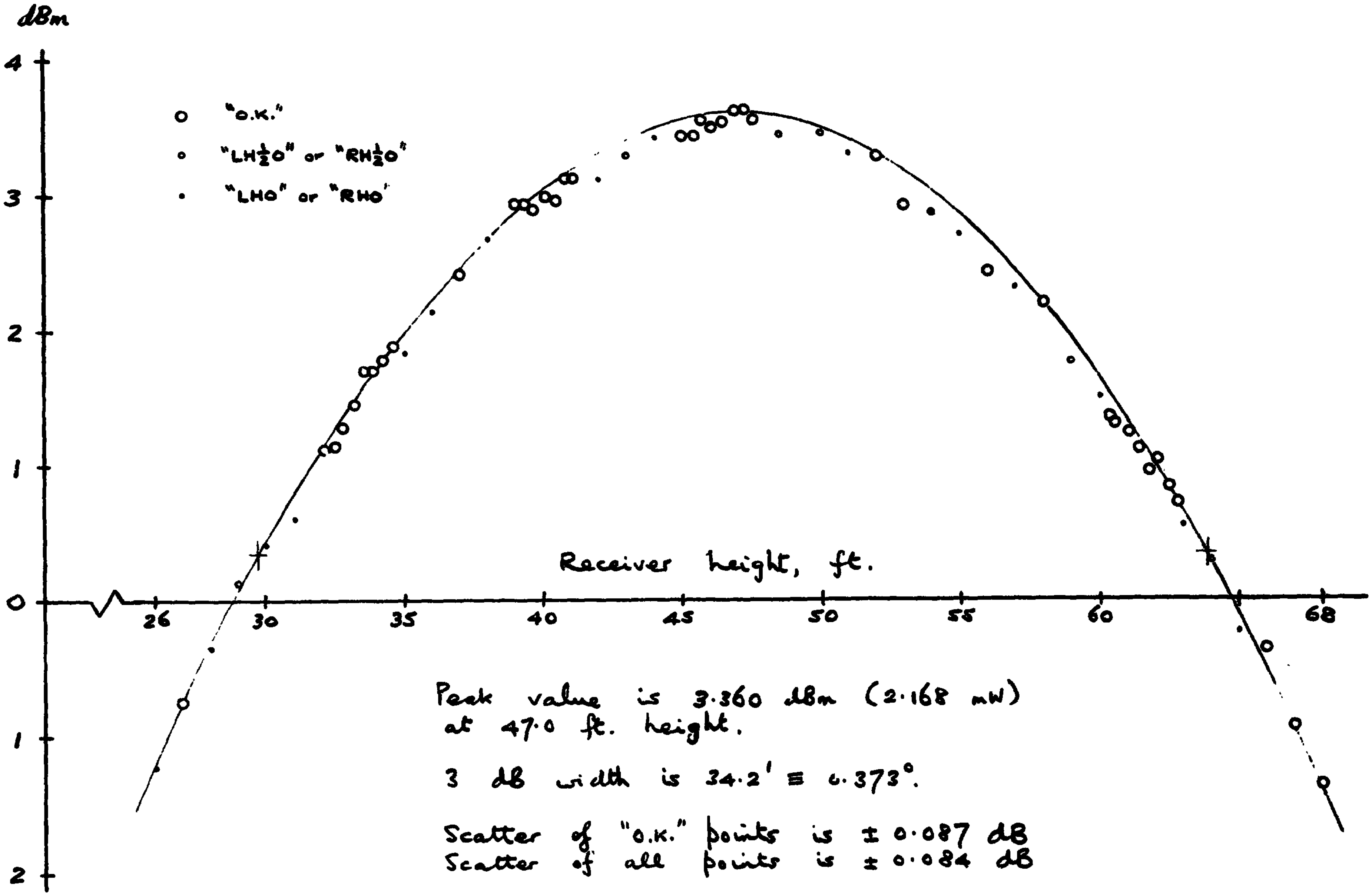

dBm
4
3
2
1
0
1
2
"O.K."
"LH½O" or "RH½O"
"LHO" or "RHO"
Receiver height, ft.
26
30
35
40
45
50
55
60
68
Peak value is 3.360 dBm (2.168 mW)
at 47.0 ft. height.
3 dB width is 34.2' ≡ 0.373°.
Scatter of "O.K." points is ± 0.087 dB
Scatter of all points is ± 0.084 dB

FIGURE 9

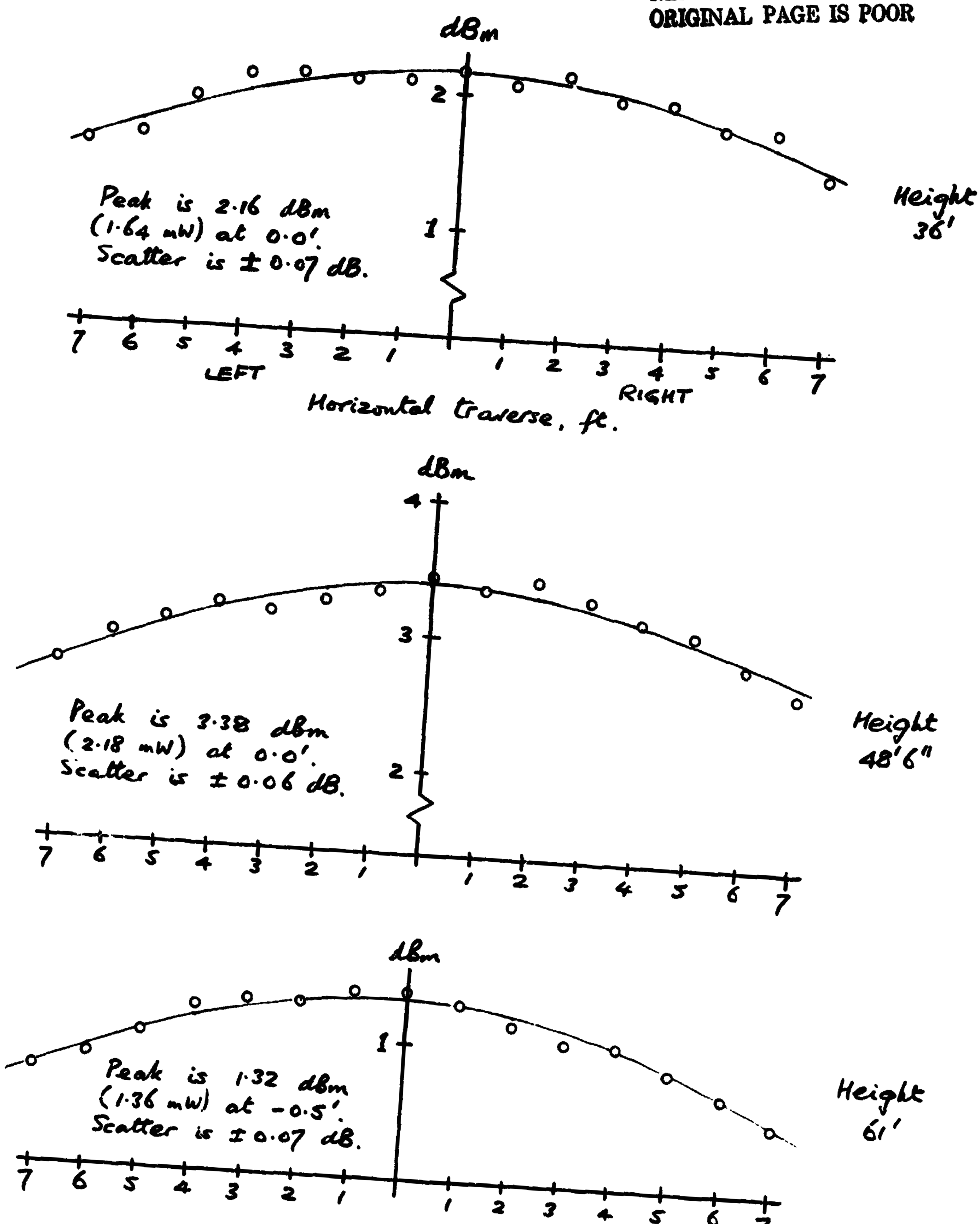

dBm
2
1
Peak is 2.16 dBm
(1.64 mW) at 0.0'.
Scatter is ± 0.07 dB.
Height
36'
7 6 5 4 3 2 1
LEFT
1 2 3 4 5 6 7
RIGHT
Horizontal traverse, ft.
dBm
4
3
2
Peak is 3.38 dBm
(2.18 mW) at 0.0'.
Scatter is ± 0.06 dB.
Height
48'6"
7 6 5 4 3 2 1
1 2 3 4 5 6 7
dBm
1
Peak is 1.32 dBm
(1.36 mW) at -0.5'.
Scatter is ± 0.07 dB.
Height
61'
7 6 5 4 3 2 1
1 2 3 4 5 6 7

FIGURE 10

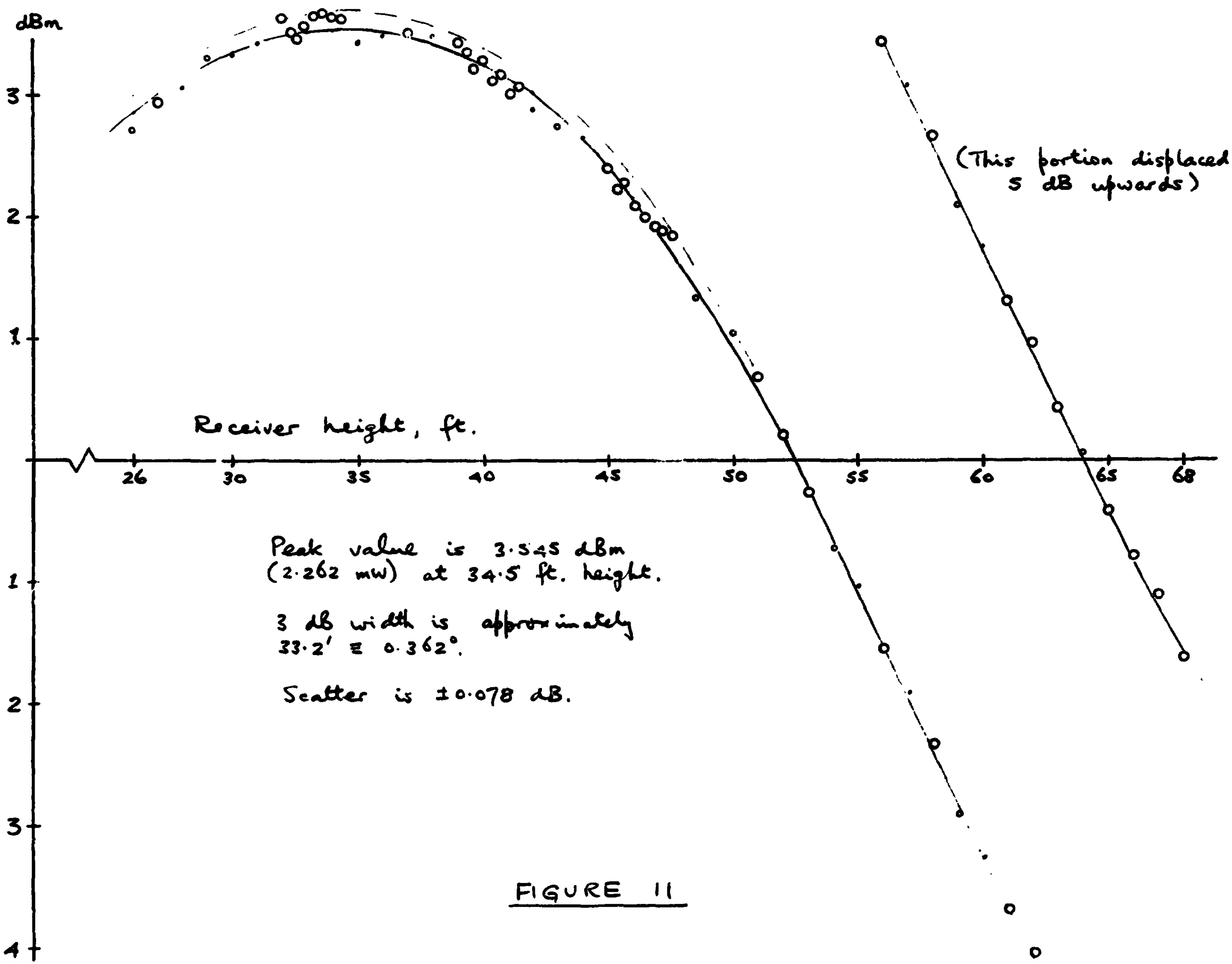

dBm
Receiver height, ft.
(This portion displaced 5 dB upwards)
Peak value is 3.545 dBm (2.262 mW) at 34.5 ft. height.
3 dB width is approximately 33.2' ≡ 0.362°.
Scatter is ±0.078 dB.
26
30
35
40
45
50
55
60
65
68
3
2
1
1
2
3
4

FIGURE 11

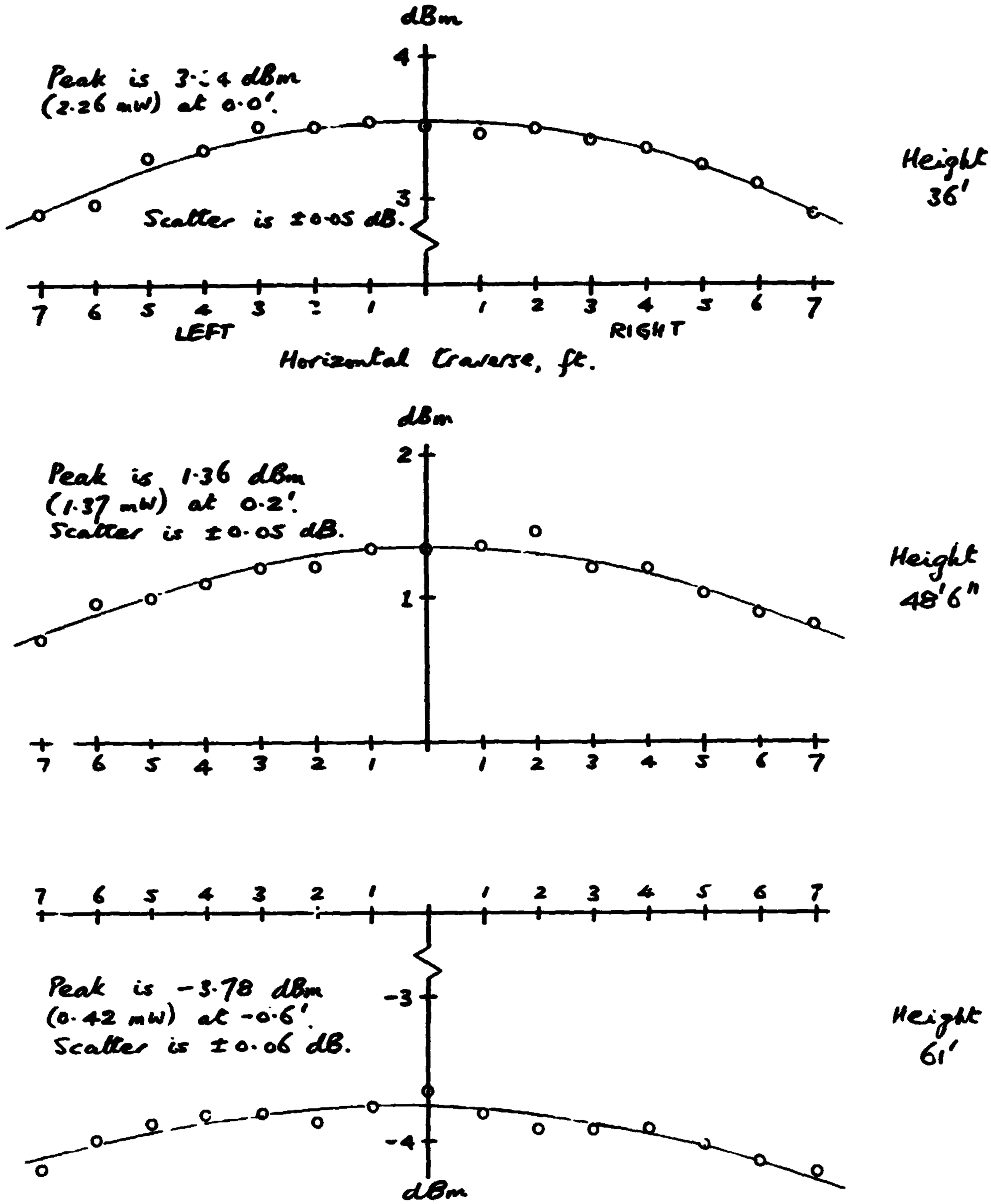
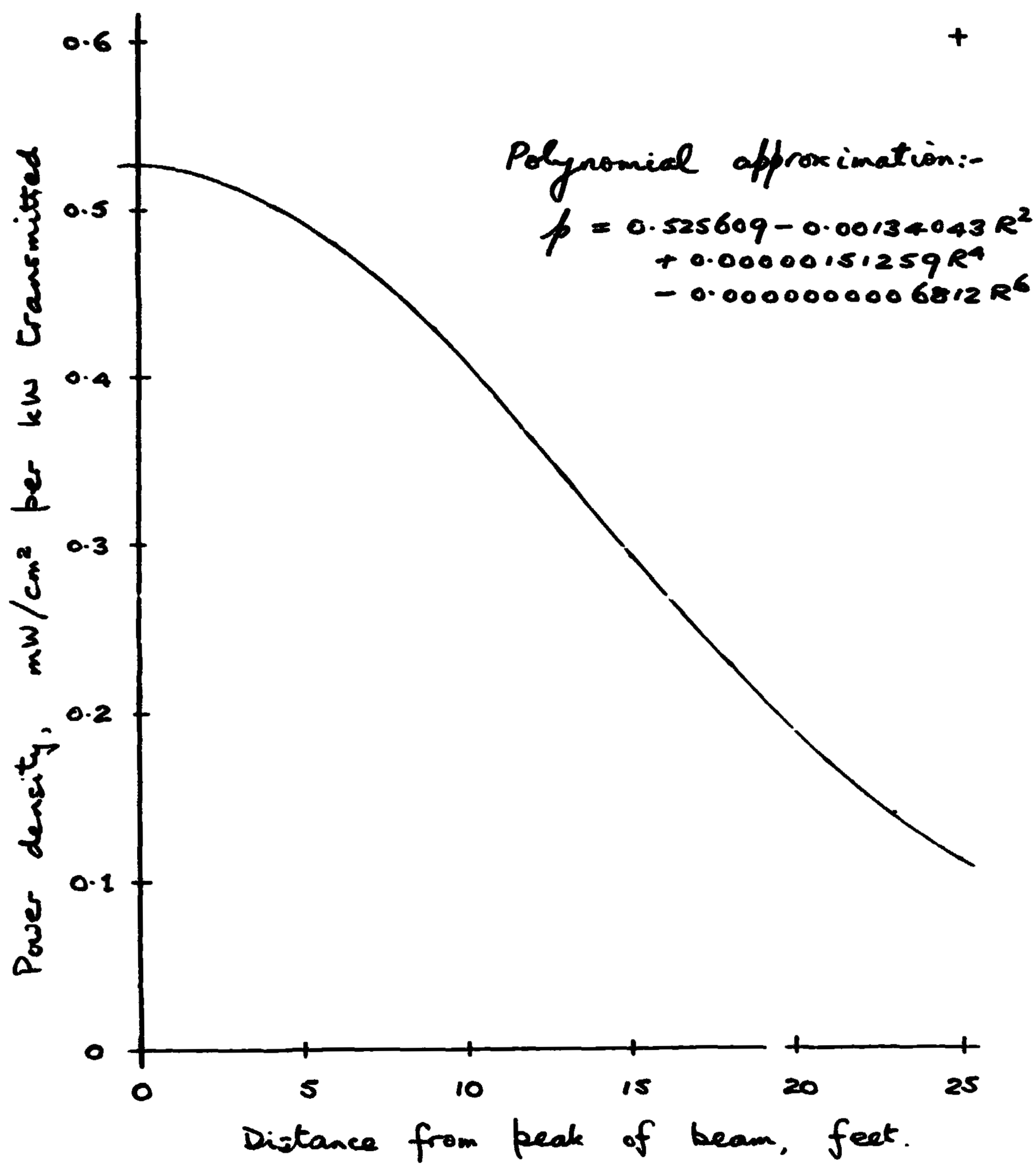

dBm
Peak is 3·54 dBm
(2·26 mW) at 0·0′.
Scatter is ±0·05 dB.
Height 36′
LEFT
RIGHT
Horizontal traverse, ft.
dBm
Peak is 1·36 dBm
(1·37 mW) at 0·2′.
Scatter is ±0·05 dB.
Height 48′6″
Peak is −3·78 dBm
(0·42 mW) at −0·6′.
Scatter is ±0·06 dB.
Height 61′
dBm

FIGURE 12



0·6
0·5
0·4
0·3
0·2
0·1
0
Power density, mW/cm² per kW transmitted
Polynomial approximation:-
p = 0·525609 − 0·00134043 R²
+ 0·00000151259 R⁴
− 0·0000000006812 R⁶
0
5
10
15
20
25
Distance from peak of beam, feet.

FIGURE 13

Predicted power levels at rectenna subarrays.

Upper figure: power density at subarray center per kilowatt transmitted.

Center figure: ditto, dBm.

Lower figure: total power incident on subarray.

0·398 mW/cm² −4·01 dBm 5·63 W/kW	0·415 mW/cm² −3·83 dBm 5·87 W/kW	0·398 mW/cm² −4·01 dBm 5·63 W/kW
0·464 mW/cm² −3·34 dBm 6·55 W/kW	0·484 mW/cm² −3·16 dBm 6·82 W/kW	0·464 mW/cm² −3·34 dBm 6·55 W/kW
0·500 mW/cm² −3·02 dBm 7·06 W/kW	0·522 mW/cm² −2·82 dBm 7·35 W/kW	0·500 mW/cm² −3·02 dBm 7·06 W/kW
0·500 mW/cm² −3·02 dBm 7·06 W/kW	0·522 mW/cm² −2·82 dBm 7·35 W/kW	0·500 mW/cm² −3·02 dBm 7·06 W/kW
0·464 mW/cm² −3·34 dBm 6·55 W/kW	0·484 mW/cm² −3·16 dBm 6·82 W/kW	0·464 mW/cm² −3·34 dBm 6·55 W/kW
0·398 mW/cm² −4·01 dBm 5·63 W/kW	0·415 mW/cm² −3·83 dBm 5·87 W/kW	0·398 mW/cm² −4·01 dBm 5·63 W/kW

FIGURE 14

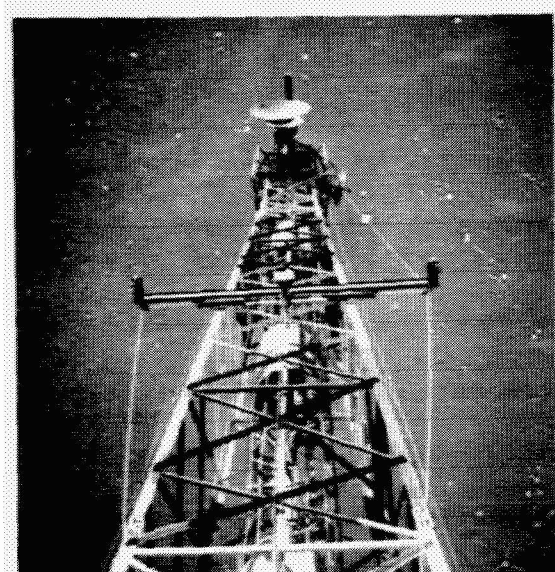
Table 1

Meter Range, dBm	RF Input, mW	Scale Error %	Scale Error dB	Cal. Accuracy %	Cal. Accuracy dB
+10	10	+.11	+.005	.07	.003
	6	-.04	-.002	.12	.005
	3	0	0	.23	.010
+5	3	0	0	.23	.010
	2	+.27	+.012	.35	.015
	1	-.26	-.011	.06	.003
0	1	-.21	-.009	.06	.003
	.6	-.65	-.028	.10	.004
	.3	-.93	-.041	.20	.009
-5	.3	-.67	-.029	.20	.009
	.2	-.81	-.035	.29	.012
	.1	-1.9	-.079	.51	.022

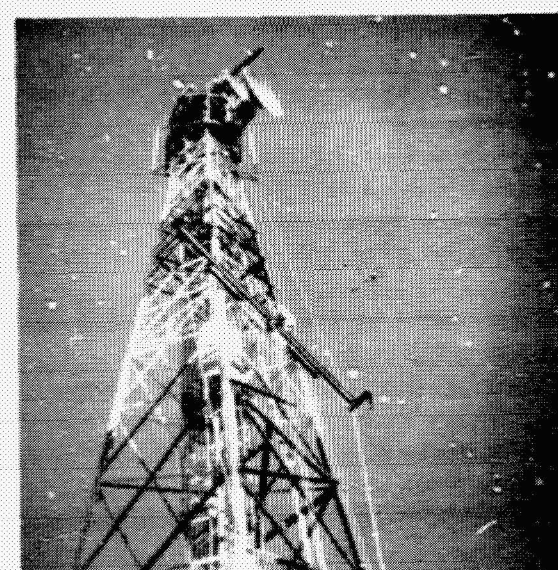
Table 2

Meter Range, dbm	RF Input, mw	Analog Voltage Output	Calculated Analog Voltage	Analog Voltage Error
+10	9.9892	1.000	.9989	+.0011
	6.0025	.602	.6002	+.0018
	3.0001	.301	.3000	+.0010
+5	3.0001	.950	.9487	+.0013
	1.9946	.635	.6307	+.0043
	1.0026	.317	.3170	0
0	1.0021	1.001	1.0021	-.0011
	.60393	.602	.6039	-.0019
	.30278	.302	.3028	-.0008
-5	.30200	.950	.9550	-0.0050
	.20163	.634	.6376	-.0036
	.10187	.318	.3221	-.0041
(ALL)	0	-.001	0	-.0010

(All error values have ± 0.0005 estimated accuracy.)

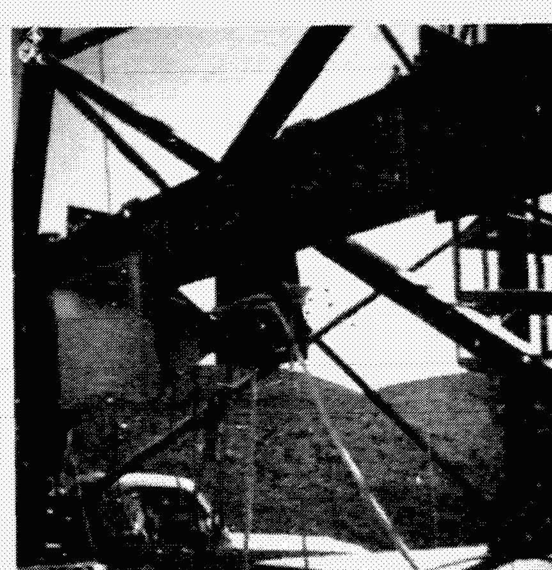


(A)



(B)

RIGGING USED DURING RF MAPPING



(C)

Photographs of Standard Gain Horn and Rigging used during "RF Mapping"

APPENDIX D

RXCV

ACCEPTANCE TEST DEMONSTRATION

PROCEDURE

Revised 6-3-75

CONTENTS

SECTION 1A

PRE-TEST ANTENNA/TRANSMITTER SETUP

1A.1 The Venus 450 kW, 2388 MHz transmitter should be activated, checked and warmed-up, as required, in accordance with established Venus site procedures, prior to the start of RXCV testing. Site personnel should also verify that the polarization is linear and that the RXCV interlock (transmitter drive) is connected.

1A.2 The Venus 26 M antenna drive and servo system should be activated, checked and aligned as required in accordance with established Venus site procedures, prior to the start of RXCV testing.

SECTION 1B

RXCV SYSTEM PRE-TEST SETUP

NOTE: Perform the following at the Tower RXCV Receiving Site.

1B.1 Verify that all RXCV equipment at the tower RXCV receiving site is connected and turned on. In addition, perform the following:

(a) Verify A/D converter switches are set in accordance with Para. 2.1.1 of the User's Manual.

(b) Perform course and fine zero adjustment of the HP 435 power meter, and set the scale to "10".

(c) Place the load range switch (in the DC load unit J-box) to the "LOW" position.

1B.2 Perform the following safety checks:

(a) Turn on red warning light on Building G-57 at the tower site.

(b) Verify that no other personnel are at or near the tower site area.

1B.3 Return to the control room, and on the way back:

(a) Secure the chain across the tower access road.

(b) Secure the "rear gate" in the transmitter fence.

(c) Notify the Venus Crew Supervisor that the tower area is closed for testing.

1B.4 Start testing per Section 2.

SECTION 2

LOW POWER TEST INITIALIZATION

RECORD: **DATE:** ______________________________

START TIME: ______________________ **PDT**

STOP TIME: ______________________ **PDT**

COMPUTER COMMANDS:

Throughout this procedure the "commands" column indicates RXCV computer software input commands. C) indicates that the command is to be typed on the CRT keyboard. TI) indicates the command is to be typed on the TI Silent 700 keyboard. All commands are completed with a "carriage return", i.e., the RETURN key is depressed.

STEP **INSTRUCTIONS**

2.1 Verify that all RXCV equipment in the control room is connected, turned on, and that all switches and controls are set in accordance with Para. 2.1 of the User's Manual (except for tape controls which will be set in steps following).

2.2 Load the RXCV Operation Program (4 June 1975 Revision) into the computer in accordance with Para. 2.2 of the User's Manual. (With this program revision location X'50' in the "bootstrap" should contain X'2640'.)

2.3 Request that the transmitter (xmtr) personnel perform the following (proceed with step 2.4 while this xmtr cal is in progress):

(a) Place the transmitter in the water load configuration and perform a "water load calibration" at an output power of 100 kW, and with the power meter range set to monitor from 50 kW to 150 kW.

(b) When the calibration is completed the output power level should then be adjusted to 50 kW (with the xmtr still in the water load).

STEP	INSTRUCTION	COMMAND
2.4	Obtain a blank tape cassette and mark it as "Demo Test Data" plus the date.	None
2.5	Place the above tape cassette on the TI Silent 700 (either tape holder) and set selected cassette unit to "Playback", then rewind and load. Verify tape "ready" light comes on.	None
2.6	Restart computer program.	C):ST
2.7	Select "Print Messages" on Silent 700	C):PM YS
2.8	Set correct day and time into computer, if required.	C):DAbddd :TMhhmm as req'd
2.9	Verify Up/Down status of all subarrays (see Fig. 3-1 of User's Manual), 1B should be down, other up.	C):DNbysa, as req'd
2.10	Set bargraph 100% = 1200 W	C):TH B1200
2.11	Read system status and verify (on CRT and printout): SHUT V = 150 T = 070 WARN V = 130 T = 060 BARG P = 1200 SW = LO PS	C):PS
2.12	Verify that Step 2.3 has been completed by the xmtr personnel.	None
2.13	Make PA safety announcements (antenna movement and RF power out-the-horn, etc.).	None
2.14	Proceed to Section 3.	None

SECTION 3

LOW POWER TEST

RECORD: DATE: ______________________________

START TIME: ______________________ PDT

STOP TIME: ______________________ PDT

Record start times for the indicated steps in the "Time" column.

STEP	INSTRUCTION	COMMAND	TIME
3.1	With the xmtr still in the water load, position antenna to: AZ 260.524° EL about 10°	None	____
3.2	Print CRT display	C):PD YS	____
3.3	Start data recording	C):RC YS	____
3.4	Request xmtr personnel to switch the transmitter output from the water load to the feed horn, and to output RF power, and to readjust power level, as required, to 50 kW.	None	____
3.5	Position antenna to: EL 7.104° (maintain AZ 260.524°)	None	____
3.6	Print CRT display, after printout starts restart recording. Verify that recording starts after printout is completed.	TI):PD YS TI):RC YS	____

STEP | **INSTRUCTION** | **COMMAND** | **TIME**

3.7 Verify normal operation of the system as follows: — COMMAND: None — TIME: ____

(a) On the printout from Step 3.6 check (for each subarray):

Voltage: 50 to 70 V
Power Out: 180 to 295 W
Power In:* 270 to 435 W
Temperature: not more than 2° above Step 3.2 temp. reading

(*If no previous cal has been done, input power may vary beyond limits.)

<u>Note</u>: The center subarrays (3B, 4B) should be near max, the outside corners (1A, 1C, 6A, 6C) near the min, and the others in between.

(b) Observe that all load lamps are on (dim), using spyglass.

(c) Observe that all LEDs (on back-up display) are on (dim).

(d) Check all back-up voltage readings against CRT voltage reading (within ± 4 V).

(e) Set back-up selector switch to 3B position.

3.8 Select Display B. — COMMAND: C):DS B — TIME: ____

3.9 Increase xmtr power to 100 kW. — COMMAND: None — TIME: ____

3.10 Select Display A. — COMMAND: TI):DS A — TIME: ____

3.11 Observe load lamps and LEDs (for increased brightness). — COMMAND: None — TIME: ____

STEP	INSTRUCTION	COMMAND	TIME
3.12	Print CRT display.	C)PRINT	____
3.13	Perform reference diode calibration as follows:		____
	(a) Clear old cal data.	C):CL NAL	
	(b) Position antenna to the horn: AZ 260.636° EL 6.968°		
	(c) Enter horn ref data.	C):BL	
	(d) Read horn ref data (answer will print on Silent 700).	C):RDOC94	
	(e) Position antenna to subarray 6C: AZ 260.566° EL 6.974°, then enter cal reading.	C):CL Y6C	
	(f) Position antenna to all other subarrays (in a zig-zag order, i.e., 6B, 6A, 5A, 5B, 5C, 4C,..., 2A, 1A, 1C) and enter cal reading at each one (use table of coordinates)	*): CLbysa (*Use both KBs at random)	
	(g) Position antenna to: AZ 260.524° EL 7.104°		
	(h) Print CRT display	TI):PD YS	
	(i) Read cal factors (answers will print on Silent 700)	C):RDOC96 :RDOC98 :RDOC9A :RDOC9C :RDOC9E :RDOCA0 :RDOCA2 :RDOCA4 :RDOCA6 :RDOCA8	:RDOCAA :RDOCAC :RDOCAE :RDOCB0 :RDOCB2 :RDOCB4 :RDOCB6 :RDOCB8

STEP	INSTRUCTION	COMMAND	TIME
3.14	Start recording.	TI):RC YS	____
3.15	Select Display B.	TI):DS B	____
3.16	Increase xmtr power to 150 kW.	None	____
3.17	Print CRT display.	C)PRINT	____
3.18	Select Display A.	C):DS A	____
3.19	Print CRT Display.	C)PRINT	____
3.20	Decrease xmtr power to 100 kW.	None	____
3.21	Reset voltage warning threshold to 95 V, then observe all readings 95 V or more flash and 94 V or less do not.	C):TH V095	____
3.22	Reset voltage shutdown threshold to 120 V (computer will output "check request" after first input).	C):TH*V120 :TH*V120	____
3.23	Print status, verify readings: SHUT V = 120 T = 070 WARN V = 095 T = C60 BARG P = 1200 SW = LO	C):PS	____
3.24	Start recording.	C):RC YS	____
3.25	Increase xmtr power towards 150 kW. Shutdown will occur. Observe: (a) Shutdown indicated on CRT. (b) Load lamps and back-up LEDs go out.	None	____

STEP	INSTRUCTION	COMMAND	TIME
	(c) Xmtr is shut down by drive voltage removal.		
	(d) Silent 700 tape recorder continues to run for about 90 seconds after shutdown, then stops.		
3.26	Position antenna EL to about 10° (maintain AZ 260.524°).	None	____
3.27	Enter instant replay mode.	C):IR	____
3.28	Replay the 12 sec data buffer. Enter all 3 types of CR commands at random.	C):EOT C):CR TI):CR	____
3.29	Restart program. Observe:	C):ST	____
	(a) CRT display is updated and time is still correct.		
	(b) Xmtr drive is restored.		
3.30	Adjust xmtr power to 150 kW.	None	____
3.31	Print system status, verify: SHUT V = 150 T = 070 WARN V = 130 T = 060 BARG P = 1200 SW = LO PS	C):PS	____
3.32	Start recording.	C):RC YS	____
3.33	Position antenna EL to 7.104° (maintain AZ 260.524°).	None	____
3.34	Print CRT display.	C)PRINT	____

STEP	INSTRUCTION	COMMAND	TIME
3.35	Start recording.	C):RC YS	____
3.36	Test "Kill Print" option as follows:		____
	(a) Start CRT display printout.	C)PRINT	
	(b) Allow printer to print a few lines then "kill print". Observe print stops (wherever it is) and recording starts.	C):KP	
3.37	Select Display B.	TI):DS B	____
3.38	Sweep antenna on and off the subarrays in azimuth at a rate of about .05°/sec (sweep between about 260° to 261°, maintaining EL 7.104°). Observe CRT, load lamps and LEDs. When several sweeps have been completed, reposition to AZ 260.524°.	None	____
3.39	Sweep antenna on and off the subarrays in elevation at a rate of about .05°/sec (sweep between about 7° to 7.8°, maintaining AZ 260.524°). Observe CRT, load lamps and LEDs. When several sweeps have been completed, reposition to EL 7.104°.	None	____
3.40	Select Display A.	C):DS A	____
3.41	Stop recording.	C):RC N	____
3.42	On Teletype (TTY):	None	____
	(a) Place power switch to "LOCAL".		
	(b) Push "ON" tape punch.		
	(c) Depress "LINE FEED" about 12-15 times, verify tape is punched.		
	(d) Place power switch to "LINE".		

STEP	INSTRUCTION	COMMAND	TIME
3.43	Print messages on TTY.	C):PM YT	____
3.44	Print status (and verify TTY prints).	TI):PS	____
3.45	Print CRT display on TTY.	C):PD YT	____
3.46	Push tape punch "ON" on TTY.	None	____
3.47	Record data on TTY paper tape. Observe tape is punched. (Note: Printout will occur also.)	C):RC YT	____
3.48	After at least 5 records have been punched and printed, stop recording and verify block being recorded completes, then tape punching stops.	C):RC N	____
3.49	Verify "kill print" option, on TTY as follows:		____
	(a) Start recording.	C):RC YT	
	(b) Start CRT display printout. Verify block being recorded completes, the tape stops punching, and display print starts.	C):PD YT	
	(c) Allow printer to print a few lines, then "kill print" and verify that display printout stops at once and recording restarts (tape punching, etc.).	C):KP	
3.50	Allow at least one data block to be punched, then stop recording (block in process will complete).	TI):RC N	____
3.51	Change message print location to Silent 700.	C):PM YS	____

STEP	INSTRUCTION	COMMAND	TIME
3.52	Place TTY power switch to "LOCAL", then advance printout and punched tape with "LINE FEED". Remove and retain printout and punched tape. Place TTY power switch in "OFF" position.	None	____
3.53	Position antenna EL to about 10°.	None	____
3.54	Turn off xmtr output (remove drive).	None	____
3.55	Position antenna to elevation zenith.	None	____
3.56	Proceed to Section 4.		

SECTION 4

RXCV LOAD RECONFIGURATION

NOTE: Perform the following at the Tower RXCV Receiving Site.

4.1 At the tower site:

(a) Place the load range switch in the "HIGH" position.

(b) Perform coarse and fine zero adjustment of the HP 435 and reset scale to "10".

(c) Verify warning light is on.

4.2 Perform the following safety checks:

(a) Verify that no other personnel are at or near the tower site area.

(b) On returning to the control room secure both the chain across the tower access road and the "rear gate" in the transmitter fence.

4.3 Proceed to Section 5.

SECTION 5

HIGH POWER TEST INITIALIZATION

STEP	INSTRUCTION	COMMAND
5.1	Request that the transmitter personnel perform the following procedures: (Note: Go on to Steps 5.1 thru 5.3 while this step is in progress.) (a) Place the transmitter in the water load configuration and perform a "water load calibration" at an output level of 250 kW, and with the power meter range set to monitor from 50 kW to 350 kW. (b) When the calibration is completed the output power level should then be readjusted to 50 kW (with the xmtr still in the water load).	
5.2	Read system status and verify (on CRT and printout): SHUT V = 195 T = 070 WARN V = 170 T = 060 BARG P = 1200 SW = HI PS	C):PS
5.3	Verify that the transmitter personnel have completed Step 5.1.	None
5.4	Make PA Safety Announcements.	None
5.5	Proceed to Section 6.	

SECTION 6

HIGH POWER TEST

RECORD: DATE: ______________________________

START TIME: ______________________ PDT

STOP TIME: ______________________ PDT

Record start times for the indicated steps in the "Time" Column.

STEP	INSTRUCTION	COMMAND	TIME
6.1	With the xmtr in the water load position antenna to: AZ 260.524° EL about 10°	None	_____
6.2	Print CRT display.	C)PRINT	_____
6.3	Start data recording.	C):RC YS	_____
6.4	Request xmtr personnel to switch the transmitter output from the water load to the feed horn, and to output RF power, and to readjust power level, as required, to 50 kW.	None	_____
6.5	Position antenna to: EL 7.104° (maintain AZ 260.524°)	None	_____
6.6	Print CRT display.	C)PRINT	_____
6.7	Start data recording.	C):RC YS	_____

STEP	INSTRUCTION	COMMAND	TIME
6.8	Verify normal operation of the system as follows: (a) On the printout from Step 6.7 check (for each subarray): Voltage: 45 to 65 V Power Out: 160 to 280 W Power In: 270 to 435 W Temperature: NMT 2° above Step 6.2 temp. readings Note: The center subarrays (3B, 4B) should be near max, the outside corners (1A, 1C, 6A, 6C) near the min, with other in between. (b) Observe that all load lamps are on (dim) using spyglass. (c) Observe that all LEDs (on back-up display panel) are on (dim). (d) Check all back-up voltage reading against CRT reading (within ± 4 V). (e) Set back-up switch to 3B.	None	_____
6.9	Select Display B.	C):DS B	_____
6.10	Increase xmtr power to 150 kW.	None	_____
6.11	Select Display A.	C):DS A	_____
6.12	Print CRT Display.	C)PRINT	_____
6.13	Set bargraph 100% to 2 kW.	C):TH B2000	_____
6.14	Print status.	C):PS	_____

STEP	INSTRUCTION	COMMAND	TIME
6.15	Verify status: SHUT V = 195 T = 070 WARN V = 170 T = 060 BARG P = 2000 SW = HI PS	None	_____
6.16	Start data recording.	C):RC YS	_____
6.17	Select Display B.	C):DS B	_____
61.8	Increase xmtr power to 250 kW.	None	_____
6.19	Observe load lamps and LEDs (for increase brightness).	None	_____
6.20	Select Display A.	C):DS A	_____
6.21	Print CRT display.	C)PRINT	_____
6.22	Perform reference diode calibration as follows:		_____
	(a) Clear old cal data.	C):CL NAL	
	(b) Position antenna to the horn: AL 260.636° EL 6.968°		
	(c) Enter horn ref data.	C):BL	
	(d) Read horn ref data (answer will print on Silent 700).	C):RDOC94	
	(e) Position antenna to Subarray 6C: AL 260.566° EL 6.974° then enter cal reading.	C':CL Y6C	

STEP	INSTRUCTION	COMMAND	TIME
	(f) Position antenna to all other sub-arrays (in a zig-zag order, 6B, 6A, 5A, 5B, 5C, 4C,..., 2A, 1A, 1C) and enter cal data at each one (use table of coordinates).	*):CLbysa (*Use either KB)	
	(g) Position antenna to: AZ 260.524° EL 7.104°		
	(h) Print CRT display.	C)PRINT	
	(i) Read cal factors (answers will print on Silent 700).	C):RDOC96 :RDOC98 :RDOC9A :RDOC9C :RDOC9E :RDOCA0 :RDOCA2 :RDOCA4 :RDOCA6 :RDOCA8 :RDOCAA :RDOCAC :RDOCAE :RDOCB0 :RDOCB2 :RDOCB4 :RDOCB6 :RDOCB8	
6.23	Start recording.	C):RC YS	_____
6.24	Select display B.	C):DS B	_____
6.25	Increase xmtr power to 300 kW.	None	_____
6.26	Select Display A.	C):DS A	_____
6.27	Print CRT Display.	C)PRINT	_____

STEP	INSTRUCTION	COMMAND	TIME
6.28	Start recording.	C):RC YS	____
6.29	OPTIONAL Antenna "sweeps" may be performed at this time by repeating Steps 3.38, 3.39 and 3.40 of Section 3.		____
6.30	OPTIONAL Additional power may be transmitted and converted at this time by the following steps:		____
	(a) Verify Display A and recording on.		
	(b) Increase xmtr power to 310 kW.		____
	(c) Observe display, lamps, etc.		
	(d) Print CRT display.	C)PRINT	____
	(e) Start recording.	C):RC YS	____
	(f) Repeat sub-steps (b) thru (e) above, using 10 kW xmtr power steps as desired. (Note: Shutdown will occur if any subarray voltage reaches 195 V.)		
6.31	Position antenna EL to about 10°.	None	____
6.32	Turn off xmtr output and secure transmitter operations.	None	____
6.33	Secure antenna operations.	None	____
6.34	Stop recording.	C):RCN	____
6.35	Proceed to tower RXCV receiving site and turn off red warning light.		
6.36	Proceed to Section 7.		

SECTION 7

POST TEST DATA PLAYBACK

This section uses tapes recorded in Sections 3 and 6.

RECORD: DATE: ______________________________

START TIME: ________________________ PDT

STOP TIME: ________________________ PDT

STEP	INSTRUCTION	COMMAND
7.1	On TI Silent 700 depress "RECORD CONTROL" OFF, rewind data tape recorded in Sections 3 and 6, then advance tape to "ready" and set to playback.	None
7.2	On TI set "playback" and "printer" local/line controls to "LOCAL".	None
7.3	On TI Playback Control Panel depress "CONT START" and verify "ON" lamp comes on and printing starts. (Note: If "ERROR" lamp lights, depress "STOP", then "ON", and repeat as required.)	None
7.4	Observe printout (format should be IAW Section 3.2 of User's Manual).	None
7.5	On TI Playback Control Panel depress "STOP".	None
7.6	Search tape until the data from Step 3.24 is located. (Use FF and rewind to move tape, and Playback Control "CONT START" and "STOP" to read tape. Read time on the printout.)	
7.7	On TI set "playback" and "printer" local/line controls to "LINE".	None

STEP	INSTRUCTION	COMMAND
7.8	Start computer tape replay.	TI):TR YS
7.9	Observe CRT display: (a) Replay will begin after about 8 seconds. CRT display will change to data from the tape. (b) CRT will update every 8 to 9 seconds, with a data sample 8 to 9 seconds apart until about 10 seconds prior to the Step 3.25 shutdown. The 12 second buffer data will then be replayed.	None
7.10	When the shutdown data replay is completed the next data is from Step 3.33, when this data begins to replay select display B on CRT.	C):DS B
7.11	Observe CRT until Step 3.35 replay occurs, then stop replay. (Wait for the data display to complete and tape to stop.)	C):TR N
7.12	Restart real-time program.	C):ST
7.13	Observe time on CRT, verify that the clock returned to present local time.	None
7.14	Rewind tape and remove cassette from TI Silent 700.	None
7.15	On TTY verify power switch is off.	None
7.16	Select "print message" on TTY, and verify CRT message is: PM YT DEVICE NOT RDY	C):PM YT

STEP	INSTRUCTION	COMMAND
7.17	On TTY, place power switch to "LINE".	None
7.18	Select "print messages" on TTY and verify: (a) CRT message que display: PM YT DEVICE NOT RDY PM YT (b) TTY Printout: PM YT PM YT	C):PM YT
7.19	Request system status and verify CRT status display and status printout on TTY.	C):PS
7.20	Place punched paper tape retained from Step 3.52 on TTY tape reader.	None
7.21	Start tape replay from TTY, then observe the following: (a) Tape reader starts. (b) CRT time stops updating. (c) Within about 1 minute CRT displays replay data. (d) CRT is updated about every 25 seconds.	C):TR YT
7.22	After several updates, stop replay (wait for tape to stop and for CRT to update with final data read).	C):TR N
7.23	On TTY, place power switch to LOCAL, then push "MANUAL START" on tape recorder. Verify tape starts and observe printout. (Format is IAW Section 3.2 of the User's Manual, except that the last 7 characters overprint.)	None

STEP	INSTRUCTION	COMMAND
7.24	After at least one full printout, stop print-out by pushing "MANUAL STOP" on TTY tape reader.	None
7.25	Remove paper tape and printout paper from TTY.	None
7.26	On TTY, place power switch to "LINE".	None
7.27	On Computer Control Panel, stop program by depressing "SGL" then "INI" controls.	None
7.28	On TI Silent 700 place power switch "OFF".	None
7.29	Restart Program; on Computer Control Panel depress: DTA, 8, 0, ADD, RUN	None
7.30	Select "print messages" on TTY, then verify: (a) On CRT: PM YT (b) On TTY Printout: PM YT	C):PM YT
7.31	Select "print messages" on Silent 700, then verify: (a) On CRT: PM YT PM YS DEVICE NOT RDY (b) No printouts on TTY or TI.	C):PM YS
7.32	On TI push on power switch.	None

STEP	INSTRUCTION	COMMAND
7.33	Select "print messages" on TI Silent 700, then verify: (a) On CRT: PM YT PM YS DEVICE NOT RDY PM YS (b) On TI printout: PM YS PM YS (c) No printout on TTY.	C):PM YS
7.34	Remove printout from Silent 700.	None
7.35	Place TTY power switch to "OFF".	None
7.36	Correct time on CRT display as required.	C):TMhhmm
7.37	Restart program.	C):ST

- END OF TEST -