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THIRD QUARTERLY MEMORANDUM
HIGH AVERAGE-POWER R-F WINDOW STUDY

Covering the Period
26 July 1961 to 26 October 1961

ELECTRONIC TUBE DIVISION
SPERRY GYROSCOPE COMPANY
Division of Sperry Rand Corporation
GREAT NECK, NEW YORK

CONTRACT NO. AF30(602)-2428

Prepared for
ROME AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
GRIFFISS AIR FORCE BASE
NEW YORK

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CONTRACT NO. AF30(602)-2428
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SECTION I

OBJECTIVES OF PROGRAM

1-1. INTRODUCTION

This quarterly memorandum, covering the period 26 July 1961 to 26 October 1961, describes the program for the investigation and design of output windows for high-power microwave tubes. The Electronic Tube Division, Sperry Gyroscope Company Division of Sperry Rand Corporation, Great Neck, New York, is conducting this program for the Rome Air Development Center, Air Research and Development Command, United States Air Force, under Contract No. AF30(602)-2428 in accordance with RADC Exhibit "A", dated 20 June 1960 and entitled "High Average-Power Radio-Frequency (RF) Window Study".

1-2. OBJECTIVES

A. Study of Dielectric Materials

The first objective of the program is to conduct an investigation of dielectric window materials suitable for use in high-power waveguide windows. The range of materials includes, but is not limited to, the following.

Alumina ceramics

Beryllia ceramics

Pyroceram

Fused silica (amorphous quartz)

Single-crystal alumina (sapphire)

Dielectric fluids that may have application in removing heat.

Selection of the most favorable materials for test window structures is to be based on the results of this investigation.

B. High-Energy Electronic Bombardment of Solid Dielectric Materials

The second objective of the program is to determine the effect of high-energy electronic bombardment on selected samples of solid dielectric window materials. The physical damage, if any, is to be assessed in the light of potential window failure.

C. High-Power Microwave Test Facility

A high-power ring resonator and a suitable r-f driver system are to be constructed for testing and evaluating window structures of improved design. The tests are to be made with c-w r-f power at a frequency of approximately 8.35 kmc. A power level of 200 kw is to be achieved, unless factors presently unknown limit the maximum attainable power in the ring resonator to a lower level; in event of the latter, the limiting factors are to be investigated with the objective of removing them.

D. Design and Evaluation of a High Average-Power Window Structure

The objective of all phases of the program is the development of an optimized X-band window structure capable of handling more than 200 kw of c-w power. If it is possible to extrapolate the point of failure beyond the maximum test power level, a window ultimately capable of transmitting 1 megw of c-w power will be designed.

SECTION II

SUMMARY OF WORK PERFORMED

Initial tests of the completed high-power driver system revealed that certain modifications were required. The arc-detector and protective circuit was modified to achieve a faster response time and positive operation in the event of a waveguide arc; a special test system was developed to measure the response time. A system of automatic attenuation was developed to reduce the high-power drive signal in the presence of a severe load mismatch. A heterodyne arrangement was devised to permit the low-power c-w oscillator signal to be used as a fixed-frequency marker on the swept-frequency response pattern of the ring resonator. This system makes use of a waveguide crystal mixer at the ring-resonator output coupler, and ensures that the ring resonator is accurately tuned before the high-power drive signal is applied.

The first test window structure was tested at high levels of c-w power in the ring resonator. The structure consisted of a compression-sealed disc of sintered beryllia ceramic in a cylindrical waveguide joined by conical mode transducers. The window transmitted 75 kw of power without evidence of breakdown or change of electrical characteristics.

Internal arcing occurred in the ring resonator at the 75 kw level and prevented further high-power operation pending minor repairs. One choke plunger was slightly damaged by an arc, and a joint between two waveguide sections, which was incompletely brazed, suffered some erosion.

A compression sealed double-disc window structure using thin sapphire discs was developed and cold tested. Some modifications were made to the beryllia-disc water load to improve its bandwidth, and to increase the rate of water flow.

SECTION III

SCHEDULE OF PROGRAM

The theoretical study and literature search of the properties of dielectric materials were completed in June 1961. Certain alumina and beryllia ceramics, and crystalline sapphire were selected for further experimental study and high-power tests.

The high-energy electronic bombardment program was completed in July 1961. The first experimental model of a high-power window was tested on the ring resonator at high-power levels in October 1961.

Operation of the ring resonator at power levels up to 200 kw, and tests of alumina, beryllia, and sapphire windows are scheduled for the last quarter of the program. The program will terminate 26 January 1962.

SECTION IV

TECHNICAL PROGRESS OF PROGRAM

4-1. MODIFICATIONS TO HIGH-POWER DRIVER SYSTEM

The high-power driver system has been modified, as discussed in the following paragraphs. The driver console with its associated waveguide circuitry is shown in figure 1. Figure 2 illustrates the block diagram of the modified system.

A. Arc-Detector and Protective Circuit

The manufacturer of the VA-849 klystron amplifier has specified that the r-f drive power must be removed from the tube 5 microseconds or less after an arc strikes at the output window. Because an arc at any point in the waveguide may flash back to the window very rapidly, the arc detector must "look" both toward the window and the load. To accomplish this, a small quartz prism¹ is placed in the side wall of the waveguide. The prism is a short piece of centerless-ground quartz rod. Two faces are inclined at angles of 38.5 degrees with respect to the rod axis, and the third face is perpendicular to the axis. The paths of the light rays are shown in figure 3.

The prism is mounted in a small tube leading from the side wall of the output waveguide at a point 3 inches from the output window, and protrudes 1/8 inch into the waveguide. Light emerging from the prism strikes the cathode of a 1P21 phototube (figure 4), and initiates an electrical impulse that proceeds through the amplifier circuits and causes shut-off of the r-f oscillator tube. The sequence is evident from figure 2. However, there are several features of the circuit that deserve mention.

Shut-off is accomplished by removing the beam voltage of the V-63 klystron oscillator that drives the VA-849 amplifier.

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¹The use of a quartz prism was suggested by R. Dehn of the General Electric Company.

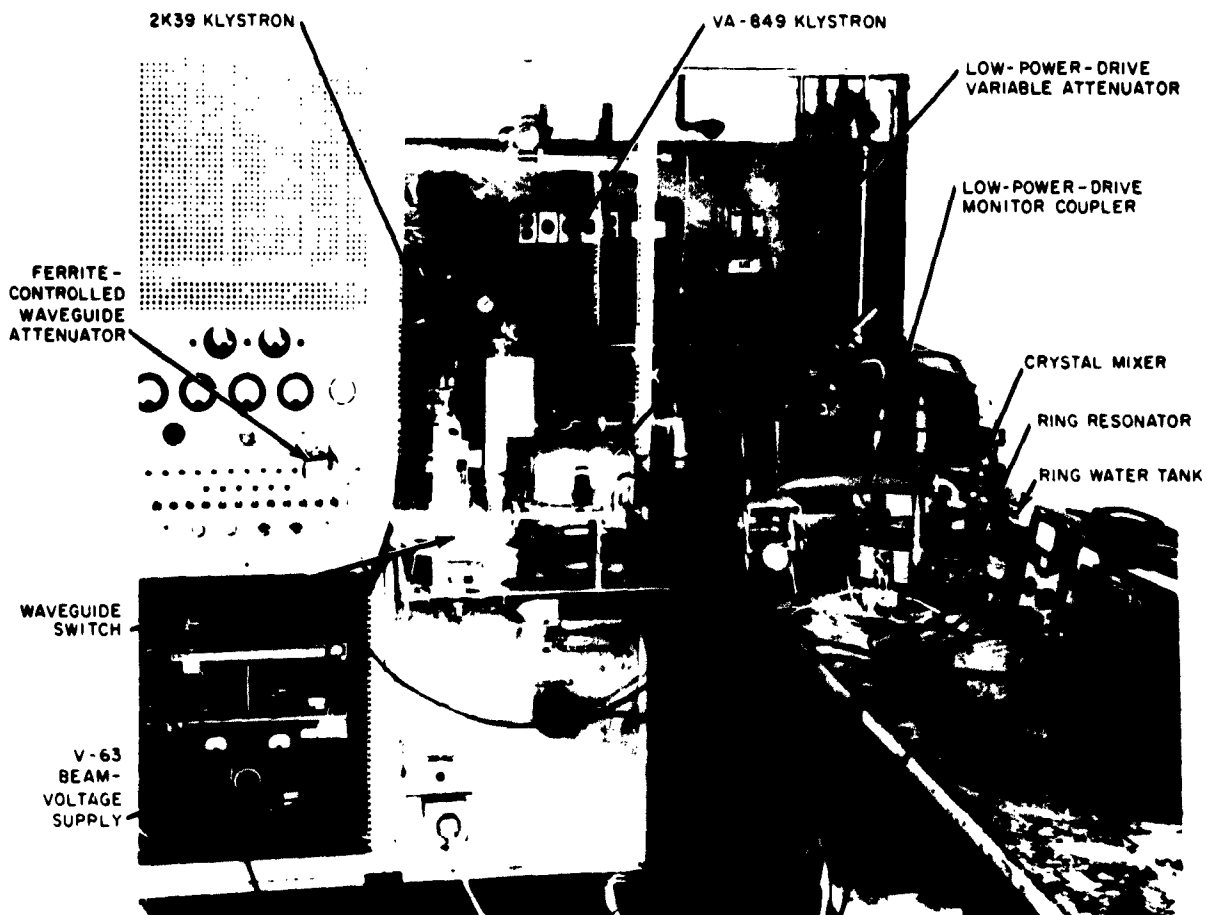


FIGURE 1 DRIVER CONSOLE AND WAVEGUIDE COMPONENTS.

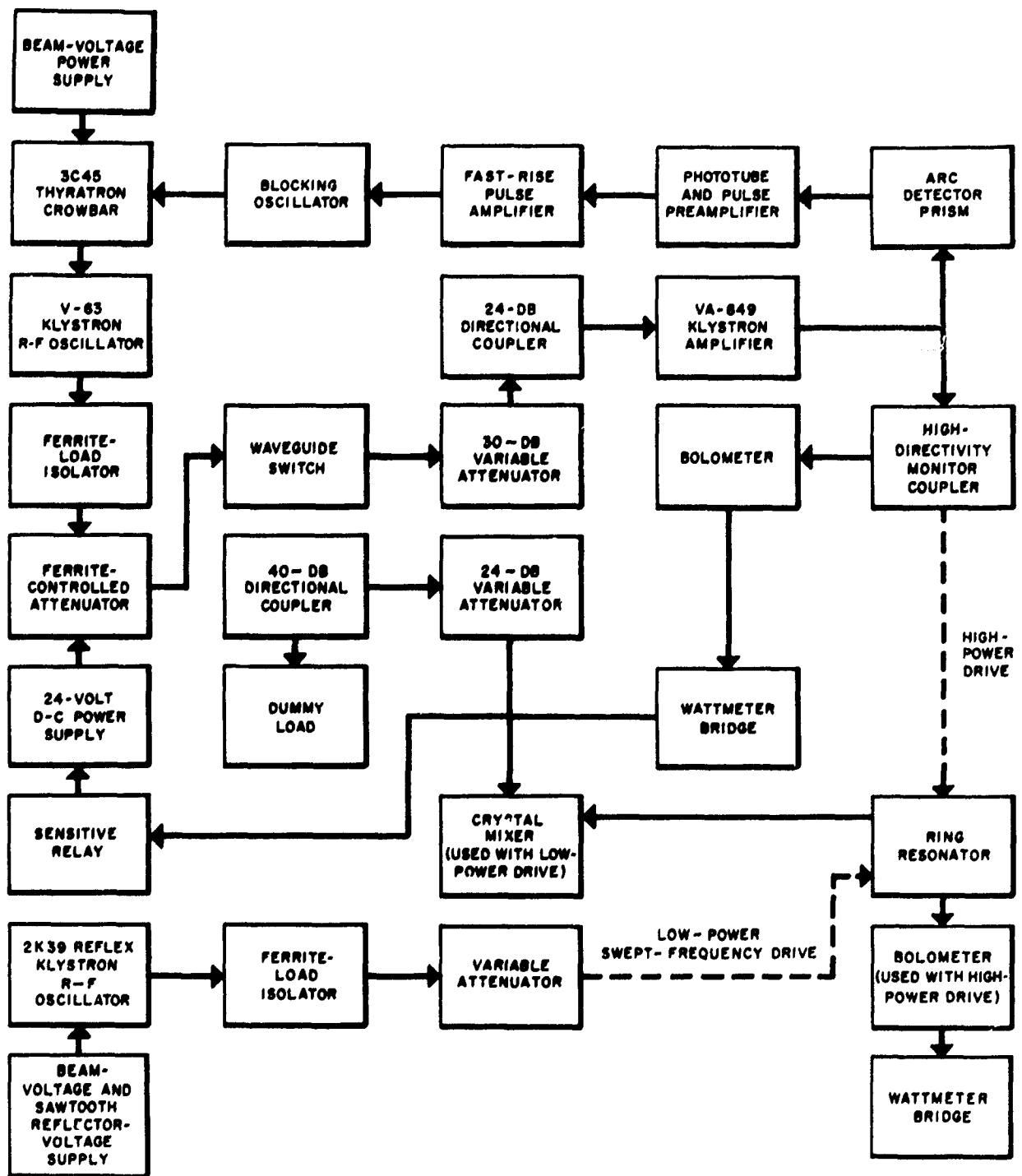


FIGURE 2. MODIFIED HIGH-POWER AND LOW-POWER DRIVE SYSTEM FOR RING RESONATOR, BLOCK DIAGRAM

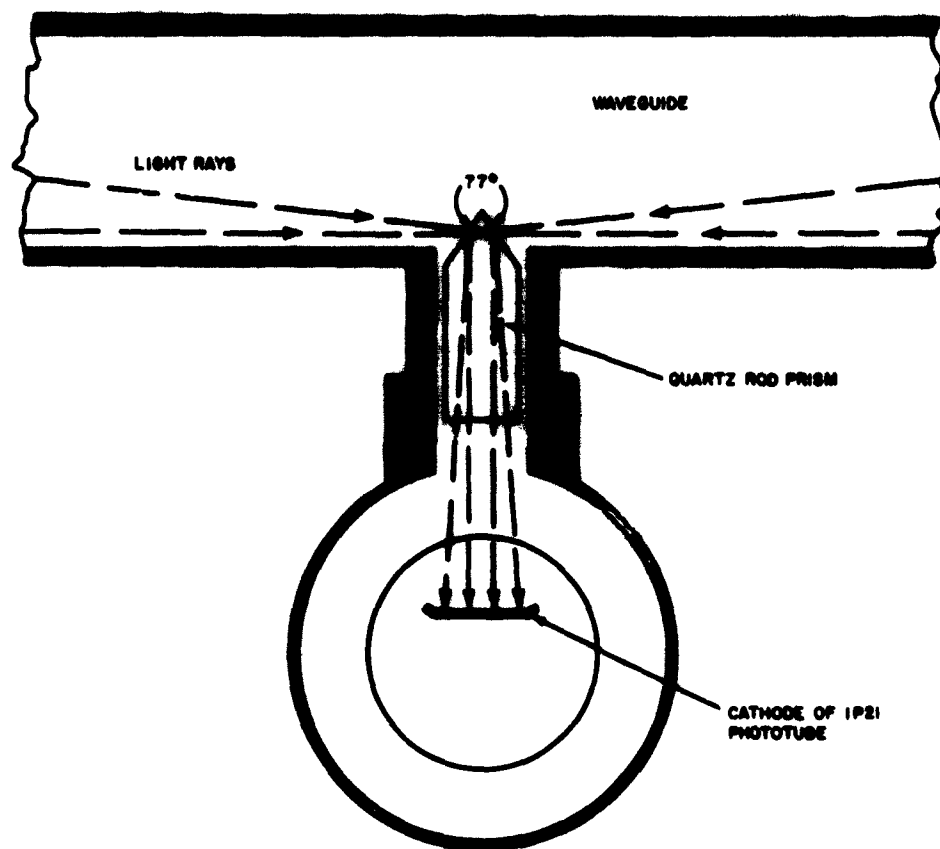


FIGURE 3. PATHS OF LIGHT RAYS THROUGH ARC-DETECTOR PRISM

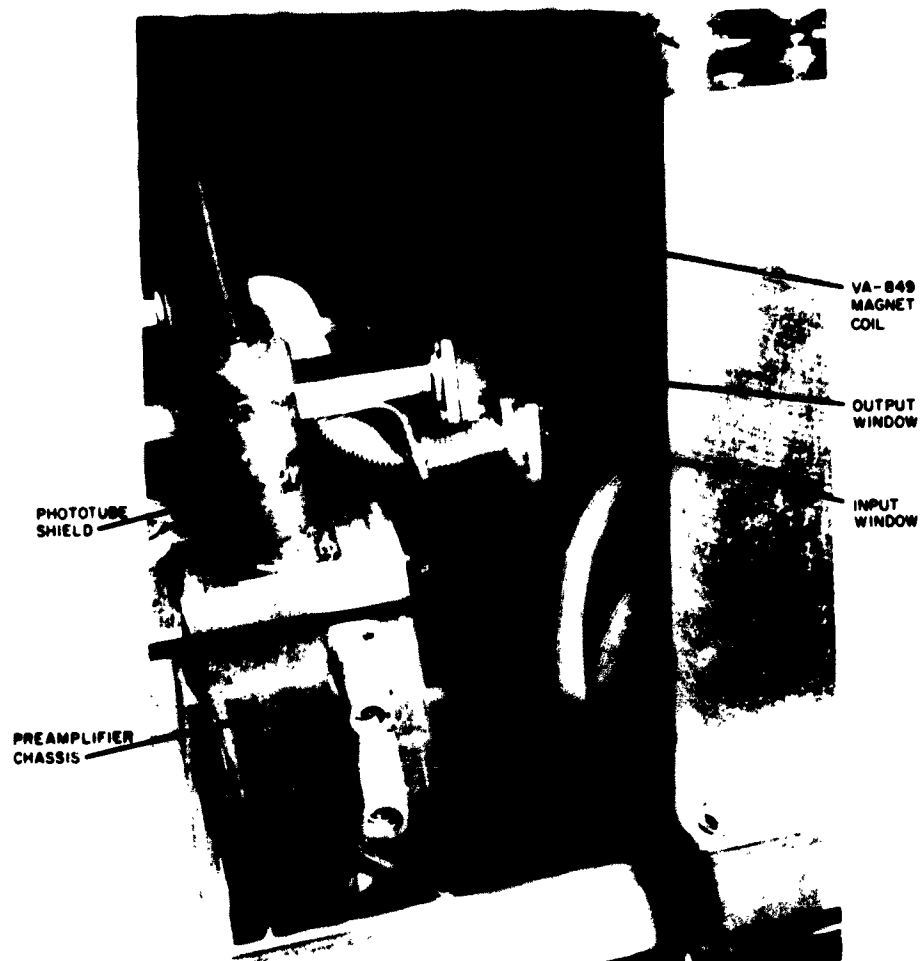


FIGURE 4. PHOTOTUBE AND PREAMPLIFIER CHASSIS

The thyatron circuit that serves this purpose is termed a "crowbar" (figure 5) because it provides a sudden short circuit across the V-63. When the crowbar fires, the V-63 immediately ceases to oscillate, and the heavy current flow causes the overload-relay circuit to trip in the 875-volt beam-power supply. The power supply remains de-energized for 3 minutes. To operate effectively, the cathode voltage of the thyatron must rise rapidly toward ground level when the trigger pulse is applied to the grid. A very large trigger pulse from an inductive circuit (transformer tertiary winding) is used to ensure that the grid rises faster than the cathode. A 50-ohm wire-wound resistor in the negative high-voltage lead serves to limit the thyatron current to a safe value; the inductance of the resistor speeds the rise of the cathode voltage.

Sensitivity and speed of response of the arc-detector and protective circuit were measured using the spark of a capacitor discharged against the waveguide wall, as shown in figure 6. The 1-mfd capacitor was charged to 45 volts and connected through a 10-ohm resistor to the waveguide. The negative lead was fed through an insulating sleeve (that excluded ambient light) to the interior surface of the waveguide. When the spark occurred, the current surge in the resistor produced a positive trigger pulse that initiated a single-sweep trace on a high-speed oscilloscope. Light from the spark, picked up by the prism approximately 22 inches away, initiated an electrical impulse that fired the crowbar. The cathode voltage of the thyatron was sampled by a high-voltage probe and fed to the vertical-deflection signal input terminals of the oscilloscope. A photograph of the single sweep trace, showing the cathode-voltage rise, is reproduced in figure 7. The sweep speed of the trace was 0.1 microsecond per centimeter. Allowing approximately 0.2 microsecond for the internal delay of the horizontal-deflection circuitry of the oscilloscope, the response time of the protective circuit is estimated to be approximately 0.7 microsecond.

A useful property of the phototube is the noise voltage produced by a steady flux of light incident on the cathode. The rms noise-voltage amplitude increases as a function of the light intensity. Therefore, if a steady waveguide arc were to grow to significant proportions without producing a specific light impulse, it would nevertheless de-energize the system by raising the

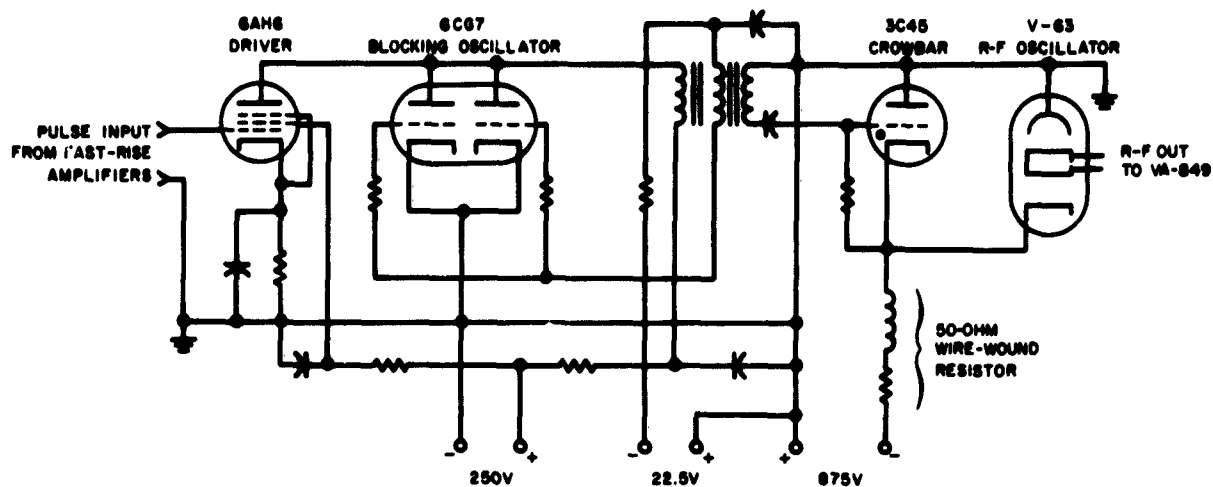


FIGURE 5. BLOCKING OSCILLATOR AND CROWBAR CIRCUITS

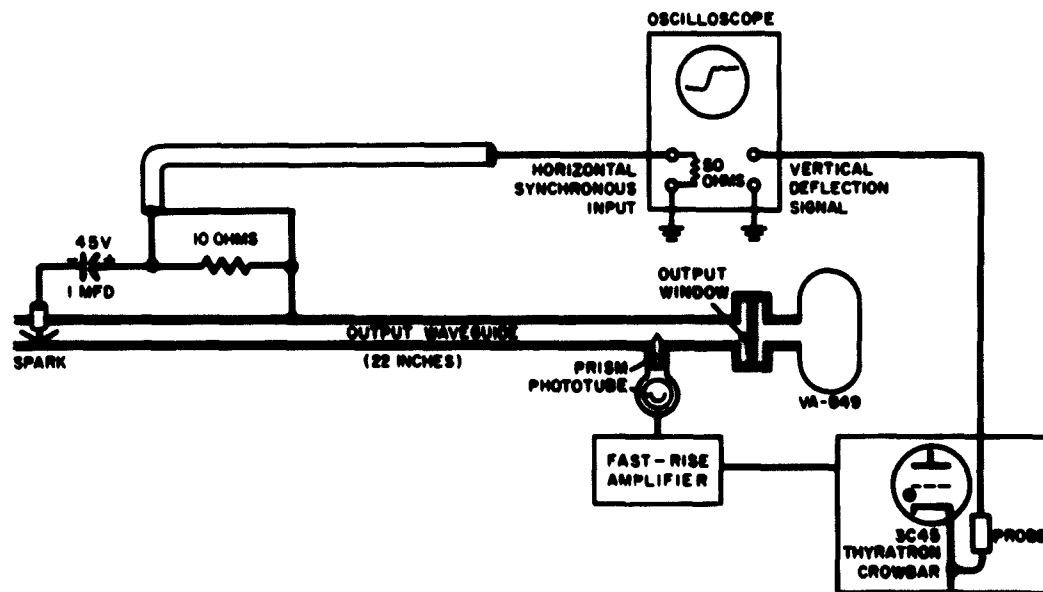


FIGURE 6. ARRANGEMENT FOR MEASURING RESPONSE TIME OF PROTECTIVE CIRCUIT

average noise amplitude until a noise spike served as a trigger pulse. The fast-rise amplifiers are adjusted to place the dark level of the noise voltage just below the trigger threshold.

B. Load-Mismatch Protective Circuit

A second modification was made to prevent damage to the VA-849 klystron amplifier in the event of a severe load mismatch. A load mismatch is likely to occur when the VA-849 drives the ring resonator, because a small phase shift in the ring produces a large change in the load impedance seen by the tube. The manufacturer of the VA-849 has recommended that the voltage reflection coefficient of the load not exceed 0.1. A large reflection coefficient could induce a waveguide arc or increase the beam interception at the output gap.

A high-directivity monitor coupler is used in the output waveguide to sample the forward and reverse waves. Barretter bolometers are used with wattmeter bridges to monitor the c-w power. The bridge indicating the reverse-wave power has been modified to include a sensitive relay that closes at a predetermined power level. When closed, the relay applies direct current to the magnetizing coil of a ferrite waveguide attenuator located in the drive circuit of the VA-849 (figure 1). The current level is preadjusted to produce an attenuation of 23 db. With this reduction of drive power, the output power is reduced to a sufficiently low level so that the danger of damage to the tube by a load mismatch is eliminated. The relay circuit is a lock-in type with manual reset. Full drive power cannot be applied until the operator is satisfied that the load mismatch has been tuned out.

C. Crystal Mixer for Ring-Resonator Tuning

Experience has shown that it is impractical to attempt to tune a high-gain ring resonator with a fixed-frequency drive signal. The ring tuners are so interrelated that the optimum settings are very difficult to find without monitoring the amplitude response over a band of frequencies. The V-63 oscillator in the present driver system is a highly stable, fixed-frequency signal source; the VA-849 is a relatively narrow-band amplifier tube. Consequently, when the ring is tuned with a new component for test, it is disconnected from the VA-849 and connected to a 2K39 sweeping oscillator. The low-power connection is shown in figure 1.

It is important that the ring gain be peaked precisely at the operating frequency of the V-63, which is 8.356 kmc. In the early tests this was done by using an absorption cavity wavemeter in the drive line of the 2K39 oscillator to produce a small notch in the swept-frequency display of the ring signal. The oscilloscope patterns sketched in figures 8 and 9 show the responses produced by a crystal detector monitoring the forward wave of the ring. The pattern of figure 8 indicates that the ring has been tuned to a nearly optimum gain condition, and has a very sharp frequency response. In figure 9, the pattern has been distorted by the wavemeter notch. Because the Q of the ring is comparable to the Q of the wavemeter, the notch is relatively broad, and it is difficult to achieve precise alignment.

The wavemeter method of monitoring the ring frequency has been replaced by a heterodyne method. To use the signal of the V-63 as a frequency marker, a waveguide crystal mixer is used instead of the crystal detector at the ring monitor coupler. A waveguide switch was inserted in the line between the V-63 and the VA-849 to feed the signal into a sampling circuit consisting of a directional coupler and a dummy load. The attenuated sample of the V-63 signal is fed into the mixer together with the forward-wave signal from the ring. When the amplitude of the sample is properly adjusted, the oscilloscope pattern shows a small beat signal superimposed on the normal frequency response signal, as indicated in figure 10. The position of the beat signal in relation to the frequency of the peak response of the ring is clearly discernible.

4-2. HIGH-POWER OPERATION OF RING RESONATOR

The first series of tests of a window structure at high-power levels has been conducted in the ring resonator. An unmetallized disc of beryllia, compression sealed in a copper waveguide section with conical $TE_{11} - TE_{10}$ transition sections, was used as the test window. The cold-test reflectance characteristic of the window is shown in figure 11. Figure 12 illustrates the ring-resonator assembly in its water tank. The maximum power level achieved during the tests was 75 kw of forward-wave power circulating in the ring. This level was sustained for approximately one-half hour before breakdown within the ring occurred. The system was then shut down for repair. The

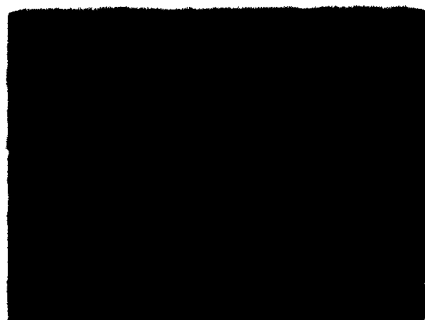


FIGURE 7. OSCILLOSCOPE PATTERN
OF SINGLE-SWEEP TRACE SHOWING
CATHODE-VOLTAGE RISE

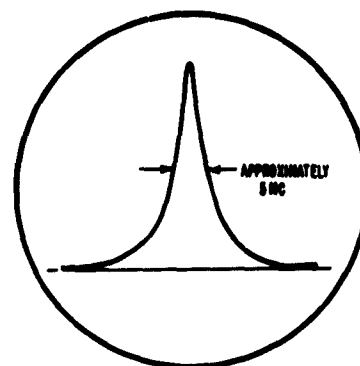


FIGURE 8. SWEPT-FREQUENCY OSCILLOSCOPE
PATTERN OF RING RESPONSE

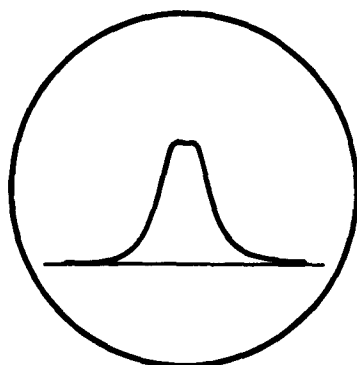


FIGURE 9. PATTERN OF FIGURE 8 DISTORTED
BY FREQUENCY-METER ABSORPTION NOTCH

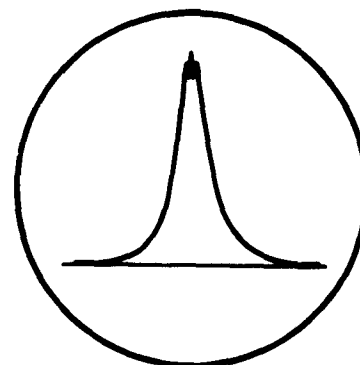


FIGURE 10. PATTERN OF FIGURE 8 WITH
BEAT-SIGNAL FREQUENCY MARKER

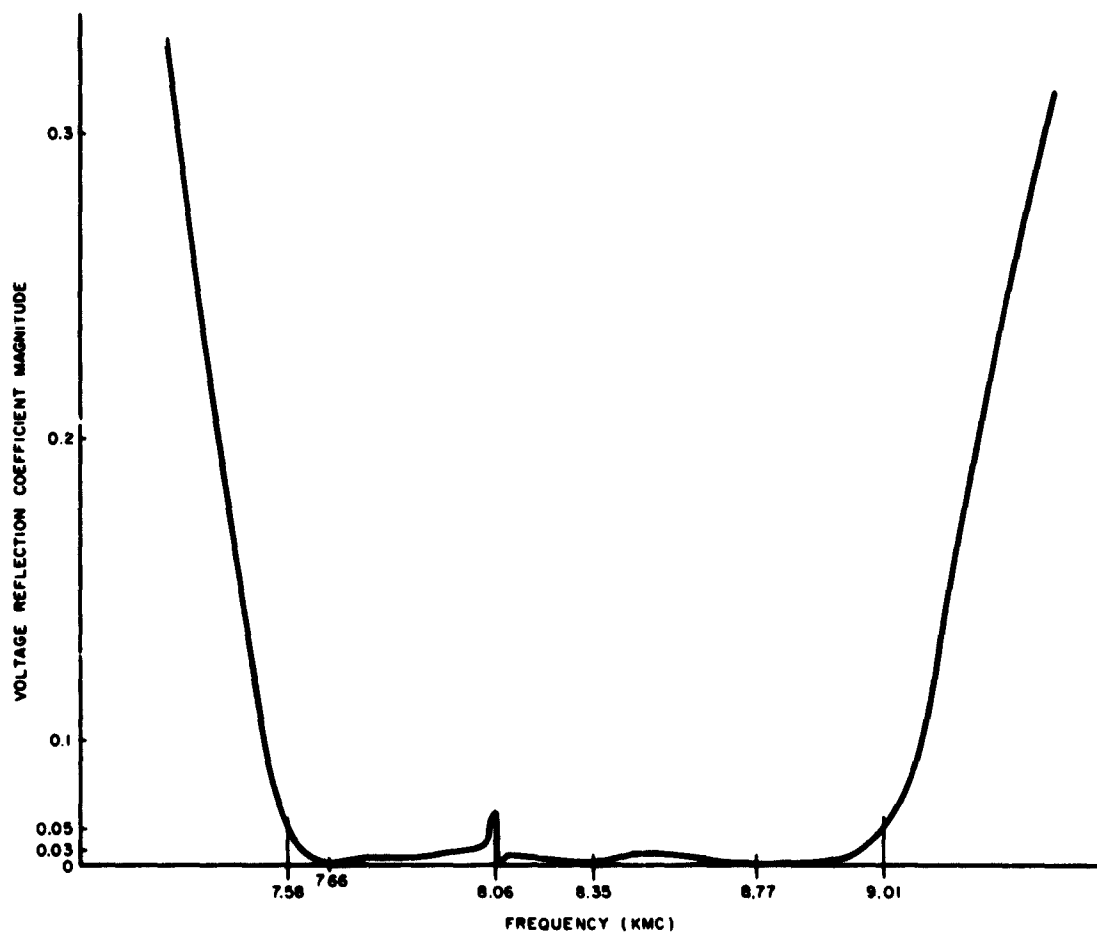
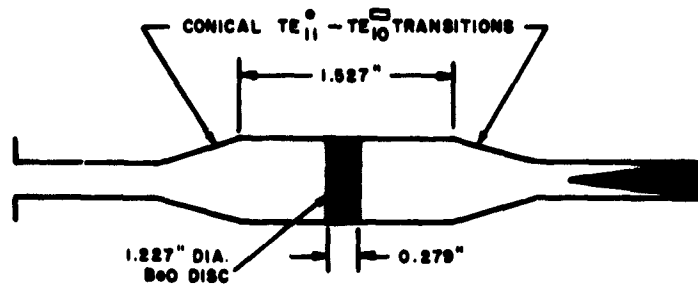


FIGURE 11. MEASURED REFLECTANCE OF COMPRESSION-SEALED BERYLLIA DISC WINDOW

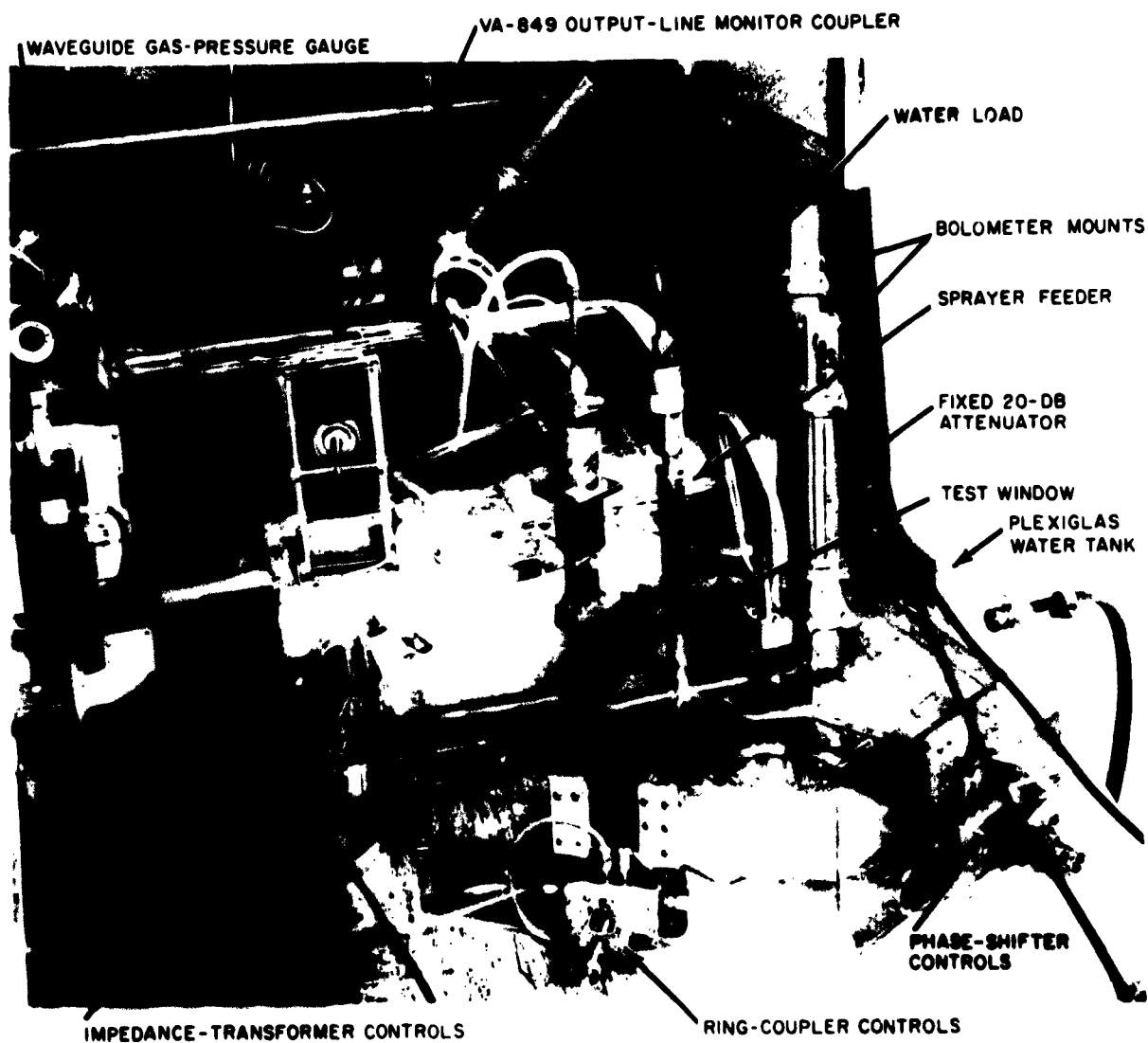


FIGURE 12. RING RESONATOR CONNECTED FOR HIGH POWER OPERATION

window was removed, inspected, and subjected to a cold test. There was no apparent damage, and no change in the reflectance characteristics.

As a result of operating at the 75-kw level, the ring resonator was damaged in two places. A joint at one of the hybrid coupler sections, which evidently was incompletely brazed, arced internally and opened sufficiently to cause a heavy leakage of gas from the pressurized ring. Also, one of the sliding choke plungers showed evidence of arcing. In both cases, steps have been taken to repair the damage.

It will not be possible to pass the hybrid assembly through the oven again to rebraze the damaged joint. Other brazes were made with lower-melting alloys after the gold brazes were made in the oven. Consequently, when the opening has been thoroughly cleaned, an attempt will be made to flow silver-bearing solder into the joint. This will be a difficult undertaking, and great care will be exercised to avoid a flow of excess solder inside the waveguide. Otherwise, the performance of the ring could be degraded.

It is believed that the choke plunger that showed evidence of arcing may have been incorrectly positioned, and either touched the waveguide wall or moved too close to it. The choke and waveguide surface have been polished to remove the corrosion caused by the decomposition products of sulfur hexafluoride gas. The alignment of all the chokes will be checked very carefully before the ring is reassembled for further tests. Provision will be made to rinse the entire ring with clean alcohol, and then blow through it with dry nitrogen, just prior to inserting the choke plungers and connecting the drive and load lines. The purpose of this cleaning is to remove all traces of dust and particles of metal which might induce arcing in the waveguide.

4-3. DEVELOPMENT OF COMPONENTS AND TEST STRUCTURES

A. Rectangular Block Window

For high average-power applications, the rectangular block window has one advantage over the circular disc window: the internal sources of heat are more uniformly distributed throughout the volume of the material, making it possible to

remove more heat by surface cooling with a specified peripheral temperature. The disadvantage the rectangular block has been the difficulty of making an effective seal. Many attempts were made to insert a metallized block in a waveguide and seal the four sides by an oven braze. The results were unsatisfactory for two reasons. First, the waveguide deformed at elevated temperatures, causing voids between the mating surfaces that did not fill with brazing alloy. Secondly, the brazing alloy was extruded from the seal region before solidifying, with the result that large fillets were formed in the corners. Both of these circumstances degraded the electrical performance of the window.

The sealing problem has been approached in a different manner in the present program. Instead of sealing the block in a waveguide, the waveguide was constructed around the block², as shown in figure 13. The rectangular sharp-cornered block of AD-995 sintered alumina was sealed in three steps by the titanium-shim method. In the first braze, the two broad walls were sealed under uniform pressure applied by a weight. The edges overlapping the ends were then machined flush with the ceramic. The two narrow walls were then sealed by the same method, and brazing material was flowed into the crevices at the junctions of the four metal members. The brazes were made in a vacuum bell jar. Despite the number of operations, the process was straightforward and presented no unusual difficulties. This window is presently undergoing cold tests for broadbanding purposes, and will be prepared for high-power tests in the near future.

B. Double Sapphire Disc Window

A high-power window consisting of two thin sapphire discs compression sealed in sections of cylindrical waveguide has been developed. The elements of the window are shown in figure 14, and the completed assembly is shown in figure 15.

The discs are 1.227 inches in diameter by 0.039 inch thick, and are sealed into copper cylinders having a nominal

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²Second Quarterly Memorandum, High Average-Power R-F Window Study, furnished by Sperry Gyroscope Company to U. S. Air Force under Contract No. AF30(602)-2428, p. 18.

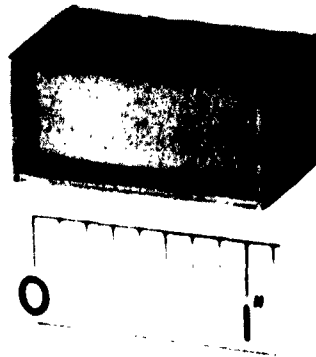


FIGURE 13. ALUMINA BLOCK WINDOW SEALED BY TITANIUM-SHIM METHOD

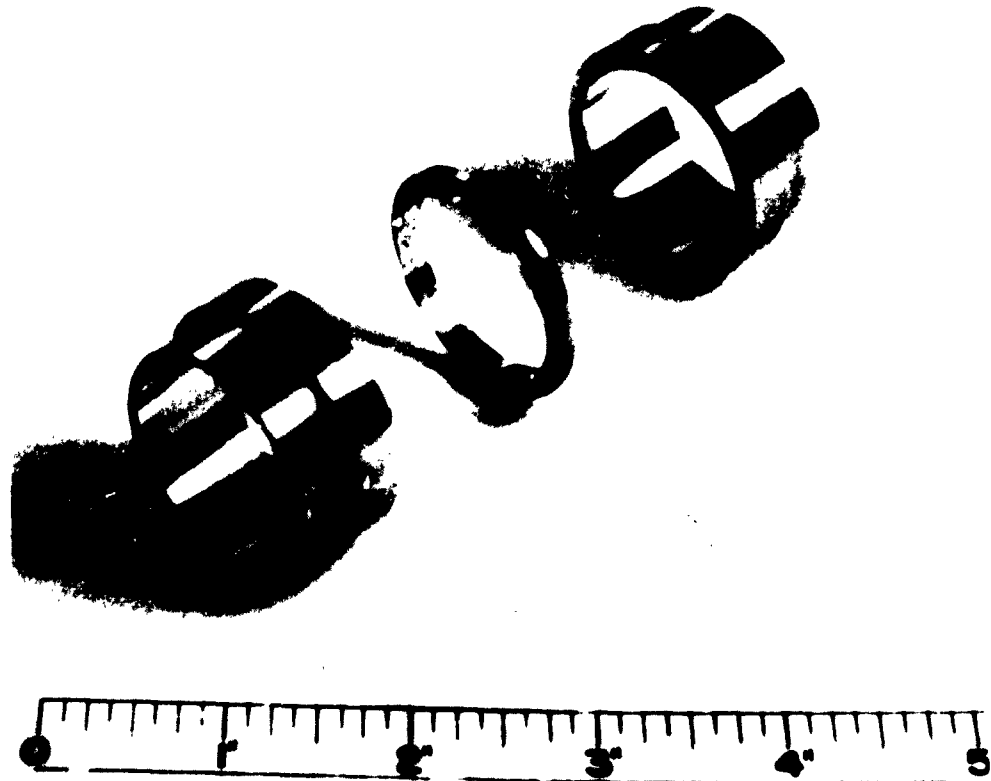


FIGURE 14. COMPONENTS OF SAPPHIRE DISC WINDOW ASSEMBLY

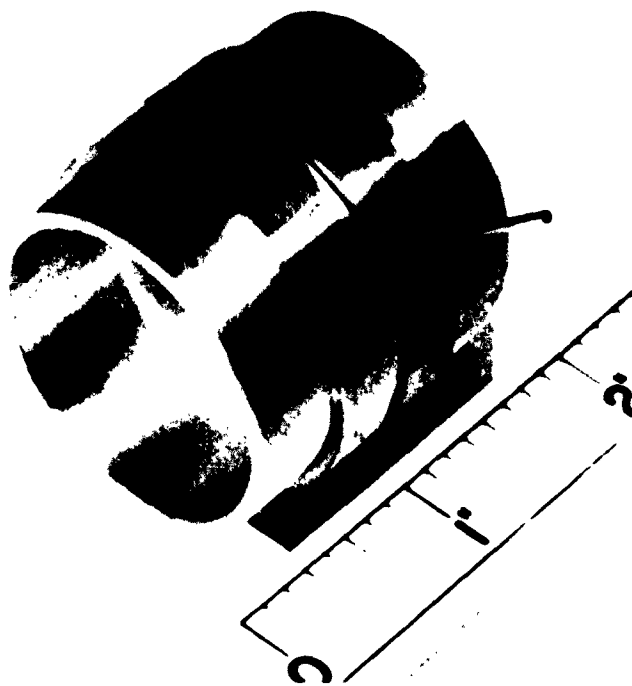


FIGURE 15. SAPPHIRE DISC WINDOW ASSEMBLY WITH PRESSURIZING TUBULATION

diameter of 1.224 inches. Each seal is made by inductively heating the cylinder in a hydrogen bell jar. When the cylinder has expanded sufficiently to remove the dimensional interference, the disc is placed in position by means of an alignment tool.

Each copper cylinder has a stainless-steel ring shrunk-fit over a portion of the outer wall. The steel ring adds compression to the seal, and ensures that the copper cylinder does not go out of round when heated. After the seals are made, the two cylinders are tin-soldered to the central ring, which provides the correct separation between the discs and supports the pressurizing tubes. The nickel-alloy pressurizing tubes are brazed to the ring before assembly.

This not a bakable window, but it is pressure-tight at normal operating temperatures. To achieve broadband performance, conical transducers are used to join the window section to the input and output rectangular waveguides. The measured reflectance of the assembly is shown in figure 16. High-power tests will be made on this window during the next quarter. Plans have been made to fabricate a double-disc window with sapphire discs brazed by the titanium-shim method. This will result in a bakable window with slightly greater losses due to the higher resistivity of the metallized edges of the discs.

C. High-Power Water Load

The high-power water load serves two purposes. First, it uses a beryllia disc window, and is studied as a special window application. Secondly, it is an essential component of the high-power test facility.

Two modifications have been made to improve the performance of the water load since the first model was tested (reference 2, p. 17). The water tubulation was changed to increase the flow, and irises were incorporated to improve the bandwidth. The modified load is shown in figure 17, and its measured reflectance is shown in figure 18.

In the first model, the inlet water stream was directed axially at the center of the beryllia disc. With a flow of 1 gpm, the load was able to dissipate approximately 6 kw with a good match. Beyond this power level, the match was erratically poorer because of vapor-bubble formation at the ceramic surface.

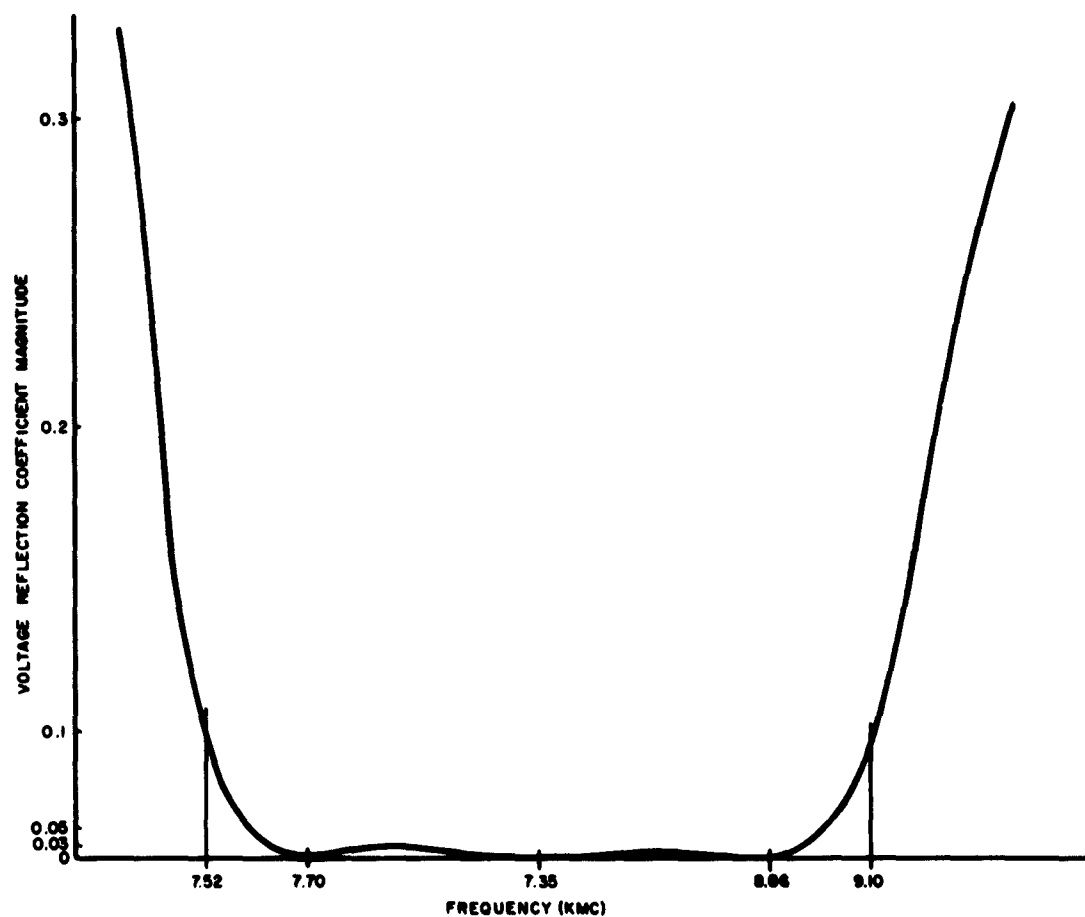
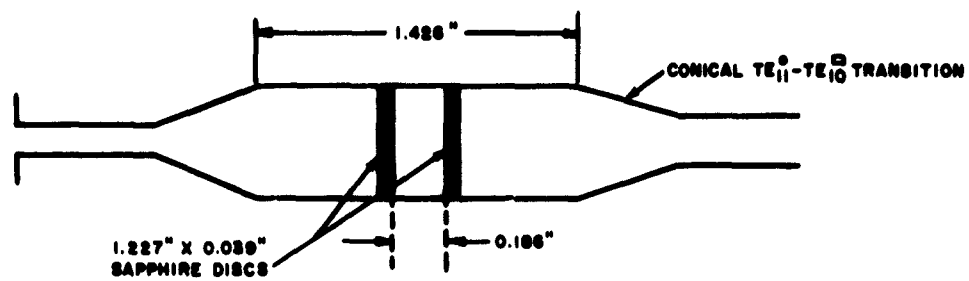


FIGURE 16. MEASURED REFLECTANCE OF DOUBLE SAPPHIRE DISC WINDOW

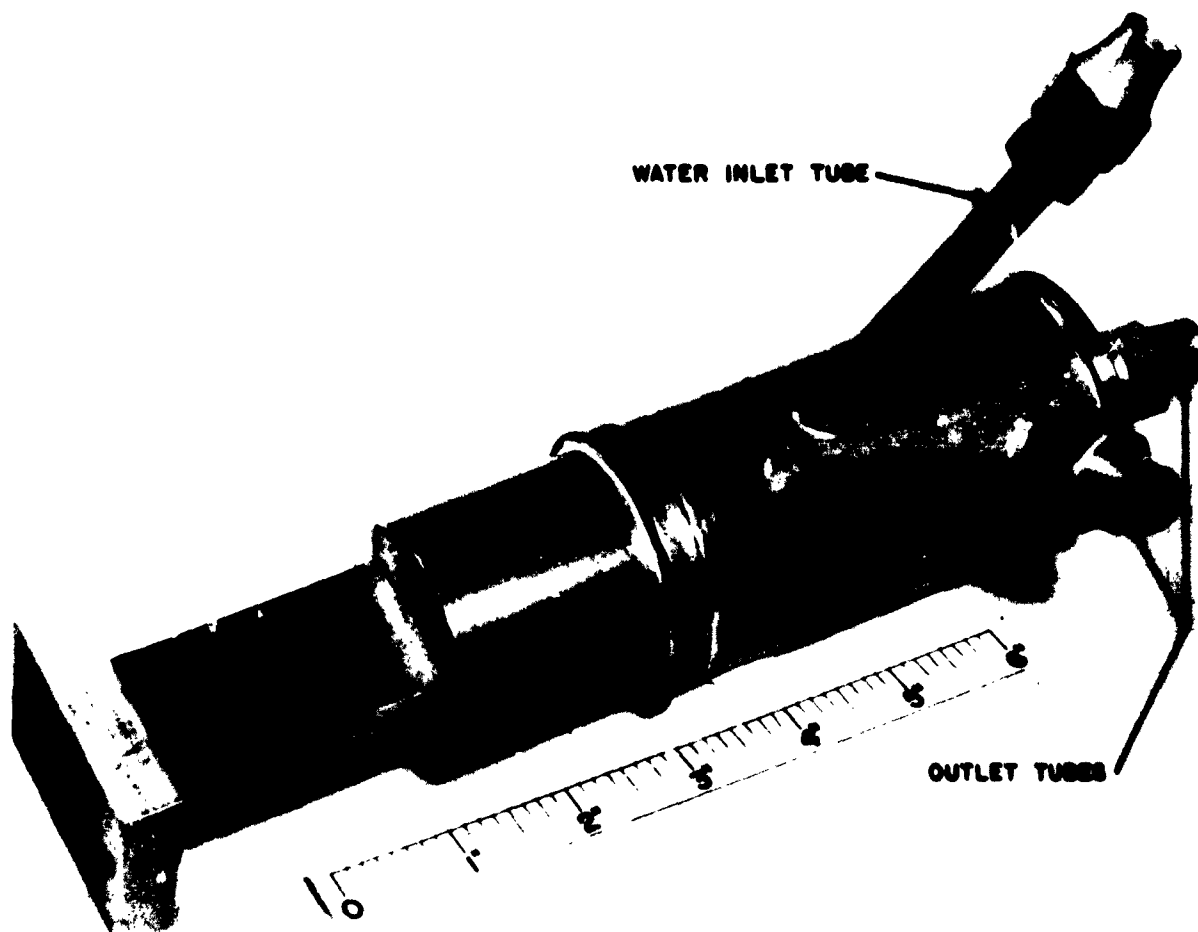


FIGURE 17. HIGH POWER WATER LOAD WITH NEW WATER TUBULATION

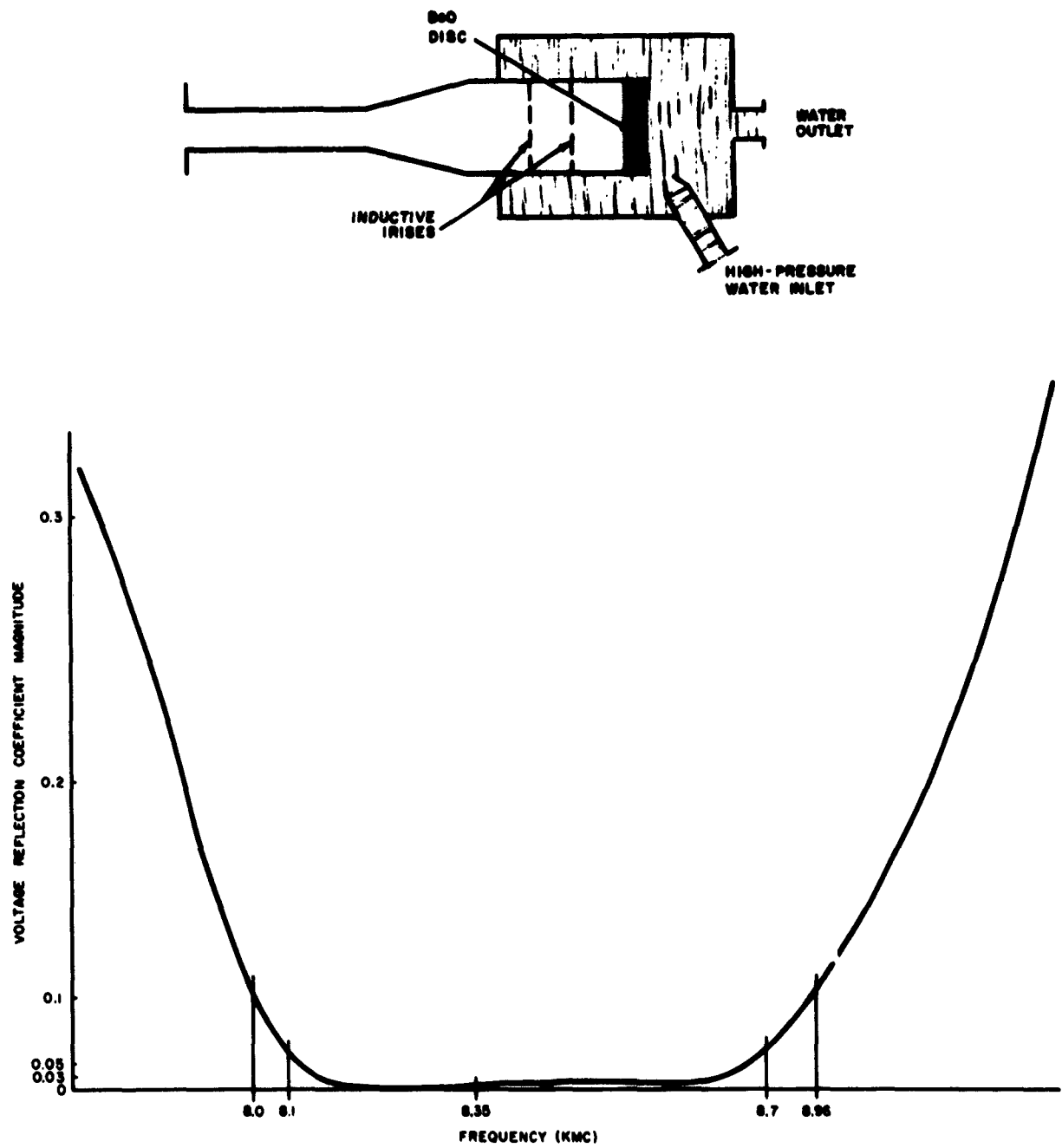


FIGURE 18. MEASURED REFLECTANCE OF MODIFIED HIGH-POWER WATER LOAD

The dissipation factor of water is so high that more than 60 percent of the power is dissipated within 0.07 inch of the ceramic-water interface. Consequently, an extremely rapid flow over the surface is essential.

It was believed that the axial flow caused a static region at the center of the window. Thus, the inlet tube was inserted through the side of the chamber at an angle of 45 degrees, and a larger tube was used to increase the flow. With a flow of approximately 1.5 gpm, the load operates satisfactorily up to a level of 15 kw. In the present arrangement, the flow is limited by the diameter of the temporary supply-line tubing, which will soon be replaced with a permanent line of larger capacity. It is expected that the new load will handle 20 kw with a good match when the flow is increased to 2 or 3 gpm.

SECTION V
FISCAL STATUS OF PROGRAM

The current rate of expenditure is approximately
\$12,000 per month. This rate will apply during the remainder
of the program. The schedule and the budget are compatible.

SECTION VI

PROGRAM FOR NEXT INTERVAL

The next period is the last quarter of the present program, the contract terminating 26 January 1962. The final report covering the entire program will be prepared during the period.

Further tests of window structures at high-power levels will be conducted using the ring resonator. Unless unforeseen difficulties limit the tests to lower levels, a power of 200 kw will be achieved. The operating characteristics of the test window structures at this level will be analyzed in an effort to predict their performance at power levels as high as 1 megw c-w, at X-band frequencies.

To find αl , Tomiyasu's curves giving power gain as a function of one-way ring attenuation are useful⁶. When the coupling coefficient is optimized, as it must be for maximum gain, the one-way ring attenuation is given by the asymptote of the coupling coefficient curves. The asymptote was replotted for clarity in the Second Quarterly Memorandum (reference 2, figure A-4). By Tomiyasu's unfortunate choice of nomenclature, " α " is also used to designate the one-way ring attenuation in db. This quantity is equal to $8.686 \alpha l$.

The ring resonator used in the present program has a maximum power gain of 13.7 db. From figure A-4 of reference 2, the one-way attenuation is approximately 0.4 db. Therefore, $\alpha l = 0.046$. At 8.35 kmc, there are approximately 28 guide wavelengths around the ring, and the quantity $(\lambda / \lambda_g)^2 = 0.6$. These values yield an unloaded Q of 3200 and a bandwidth of 5.2 mc.

It should be noted that the equation in footnote 10 on page 23 of the Second Quarterly Memorandum is in error. The correct equation is " α " = $8.686 \alpha l$. Also, the ring-resonator gain equation on the same page should be clarified. The factor k multiplies the square root in the denominator, and should appear adjacent to the radical sign rather than separated from it.

⁶K. Tomiyasu, "Attenuation in a Resonant Ring Circuit",
IRE Trans. MTT-8, March 1960, p. 253.