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DEVELOPMENT PROGRAM FOR A 200 kW, CW, 28 GHz GYROKLYSTRON

H. Jory, S. Evans, J. Moran,
D. Stone, R. Symons, G. Thomas

Quarterly Report No. 17

April through June 1980

Prepared for:

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Operated by:

Union Carbide Corporation for the Department of Energy

Contract No. W-7405-eng-26

Varian Associates, Inc.
Palo Alto Microwave Tube Division
611 Hansen Way
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ABSTRACT

The objective of this program is to develop a microwave oscillator capable of producing 200 kW CW power output at 28 GHz. The use of the gyrotron or cyclotron resonance interaction is being pursued.

During this reporting period, testing of axisymmetric tube 5R2 was continued with various output guide components simulating the EBTS load. This tube was shipped to ORNL and successfully installed and operated.

Miter bend tube 12M installation was completed at ORNL and the tube operated successfully into EBTS.

Axisymmetric tube #6 was delivered to final test and operated to 200 kW at 2% duty.

Work on 5" axisymmetrical tubes, S/N 9 and 10, has been stopped and all effort is being directed to the 2.5" axisymmetrical tubes.

Construction of 2.5" axisymmetrical tubes 8 and 11 is progressing.

A Quality Assurance Report on the failure of the heater in tube 7R1M was completed and sent to ORNL.

Design of a high power mode filter was completed and construction was initiated.

I. INTRODUCTION

The objective of this program is to develop a microwave oscillator capable of producing 200 kW of CW power at a frequency of 28 GHz. In addition, it is intended that the program will serve as the first step toward development of a device to produce a similar power level at a frequency of 60 and 110 GHz. Feasibility for the 60 and 110 GHz designs will be demonstrated, whenever practical, in the design of the 28 GHz device. Tunability or bandwidth is not considered an important parameter in the design, but efficiency is. Mode purity in the output waveguide is not a requirement for the device, but the circular TE mode is considered desirable because of its low loss properties.

With these objectives in mind, the decision was made to pursue an approach based on a cyclotron resonance interaction between an electron beam and microwave fields. The detailed arguments leading to this choice are contained in the final report of the preceding study program[1]. The device configuration of particular interest, called a gyrotron, has been discussed in recent literature.[2,3] It typically employs a hollow electron beam interacting with cylindrical resonators of the TE_{0m1} class.

The optimum beam for the cyclotron resonance interaction is one in which the electrons have most of their energy in velocities perpendicular to the axial magnetic field. Another requirement is that the small component of axial velocity be essentially the same for all electrons. An electron which has a different axial velocity will not interact efficiently. Generation of a beam with high transverse velocity and small axial velocity spread is another important design goal.

The approach chosen to generate the beam is a magnetron type of gun like the one used in the devices described in the Russian literature. With this type of gun, the shaping of the magnetic field in the gun region becomes quite important.

As a result of the excellent performance of the pulsed oscillator producing up to 248 kW of peak power at 28 GHz with good efficiency[4], the

emphasis of the program has been shifted to stress the construction and delivery of CW oscillators.

During the period covered by this report, three tubes, S/N's 5 and 6, both axisymmetric types, and S/N 12M, a miter bend output type, were operated under pulse and CW conditions. A Quality Assurance investigation of S/N 7M's heater failure was made and a report submitted to ORNL. Construction of axisymmetric tubes 6, 8 and 11 was continued. A high power mode filter was designed and construction was initiated.

The following observations on these tubes are reported here in the order in which they were tested or assembled.

II. TECHNICAL DISCUSSION

A. TUBE #12 AT ORNL

The tube was delivered to Oak Ridge on March 19. Difficulty was encountered in attempting to increase beam current and power output due to frequent crowbar activity of the system. After some repairs to the power supply and some aging of the tube the power was increased to the 65 kW range. The tube was successfully operated into EBTS with approximately 60 kW out of the tube and 50 kW into EBTS. After EBTS experiments were satisfied, the tube was removed from the socket to allow alterations to be made to install S/N 5R2.

B. TUBE 5R2

1. Testing

Pulse experiments on the mode filters and miter bends were concluded. The tube was reconnected for CW operation and a series of experiments were conducted. Some delay was incurred due to window arcing which was traced to foreign matter on the window believed to have accumulated during the installation of the load on the tube.

The test set has been plumbed to allow up to 7 gal/min. of water flow through each mode filter to permit power dissipation approaching 18 kW CW; close to the maximum level predicted by the pulse mode filter data.

The following arrangements of tube and rf components were assembled and tested with power dissipations as noted.

1) Gyrotron - Load

   131.5 kW CW Output Power

2) Gyrotron - MF #1 - Load

148 kW CW in Waterload

0.4 kW CW in MF #1

148.4 kW CW Total Output Power

3) Gyrotron - MF #1 - Miterbend - Load

127.4 kW CW in Waterload

3.0 kW CW in MF #1

130.4 kW CW Total Output Power

4) Gyrotron - MF #1 - Miterbend - MF #2 - Load

140 kW CW in Waterload

3.63 kW CW in MF #1

(Power in MF #2 not measured because of instrumentation problem)

143.63 kW CW Total Output Power

5) Gyrotron - MF #1 - MF #2 - Miterbend - Load

Detailed power measurements were not completed due to window failure. This was caused by a cracked alumina disc on the atmosphere side of the window assembly. The vacuum side ceramic disc was intact and no change of tube pressure was noted. The atmosphere side of the window was cracked diametrically across the disc and showed strong circular white rings, which were found to be due to fusing of the alumina. The FC-75 side of the window had a number of cracks. The samples of the material from the window were examined in detail. The FC-75 cooling system and the crowbar firing time were checked and found to be operating correctly. A more detailed discussion of the window failure is contained in section 2.

The external window was replaced, readjusted to the configuration previously employed, and testing of the tube was continued.

The tube was tested again at 200 kW at 4% duty. It was then operated at 140 kW CW for about 1 hour and appeared to operate normally, similar to its performance prior to the breaking of the window.

After consultation with ORNL, the tube was removed from its socket, dressed and packed for shipment to Oak Ridge. Included in the shipping container were three acceleration sensors (Sensory Products, Inc. Model A1-2). They were placed on each axis of the inner box containing the tube. These sensors are designed to record the maximum G's experienced in shipment in the X, Y and Z axes of the container. The results were 8, 10, 17 G's respectively and are judged to be moderate shock, typical of normal handling.

At the request of ORNL, the next gyrotron shipment will contain two additional accelerometers which will permit the recording of X and Y axis maximum shock at each end of the inner box. ORNL has supplied a recording accelerometer, (Impact-O-Graph Model 21C) which will also be installed in the next shipment.

The tube was unpacked, placed in its socket at Oak Ridge and successfully operated there at 122 kW CW into a matched rf load by ORNL and Varian personnel. Testing beyond this power level was not attempted per the request of Oak Ridge. The plan is to perform a series of tests in the 100 kW to 140 kW range and then venture to higher power as determined by Oak Ridge personnel. At the end of the quarter, the waveguide components to be used in the output of the tube were being assembled. It is planned to have the tube followed by a system of mode filters and miter bends terminating in a matched rf waterload which closely simulates the guide system that will be used to connect to EBT-S. Operation of the tube in the new configuration is scheduled to begin July 8 with Varian and Oak Ridge personnel present.

As more data becomes available from tube #5 and subsequent tubes, the effort to better understand the effect on the circular and non-circular mode content of the forward, reflected and mode converted power in the system will continue.

2. Window Failure #5R2

The VGA-8000 S/N 5R2 has been operated intermittently since the fall of 1979. In February it was operated at 212 kW CW and during April and May it was operated pulsed and CW with various output guide configurations. On May 6, 1980 the tube was operated at the 120 kW level CW for approximately 30 minutes and at 140 kW CW for 5 minutes with the test set-up as shown in Figure 1A. The guide configuration was then changed as shown in Figure 1B. The tube would not operate above 25 kW and at this level there were six successive crowbars, each of which turned off the tube. Three or four of these were activated first by the waveguide arc detector. The waveguide was then examined. FC-75 was dripping out of the waveguide indicating a crack in the outer window ceramic (Figure 2).

There was a crack extending to both edges and passing through the center of the outer ceramic. There were also many black specs and white concentric rings on the air side of the window. The ceramic also showed a general brownish color presumably from x-ray discoloration (Figure 3). No damage was apparent on the FC-75 side of the inner (vacuum) window. There were no marks or discolorations on the FC-75 side of the outer (air) window.

A sample of the ceramic window was removed and analyzed utilizing a Scanning Electron Microscope (SEM) and X-ray Emission Spectroscopy (XES). This showed that the white concentric rings were formed from melting and fusing of the alumina. The depth of the fused region is 2.5 to 3 x 10^{-3} inches at the center of the rings. The rings are a single crystal structure which has separated from the multi-crystal alumina ceramic (Figures 4 - 6). The energy required to form the rings is about 400 joules and the temperature necessary to fuse alumina is 2050°C. The only identifiable means of attaining these temperatures is by arcing at the window surface.

The arc detector was operational and has since been tested and found to be operating normally. The time from a light source trigger to crowbar input is 5 microseconds. Assuming all the output power might be coupled into an arc at the window during the 5 microsecond interval, the

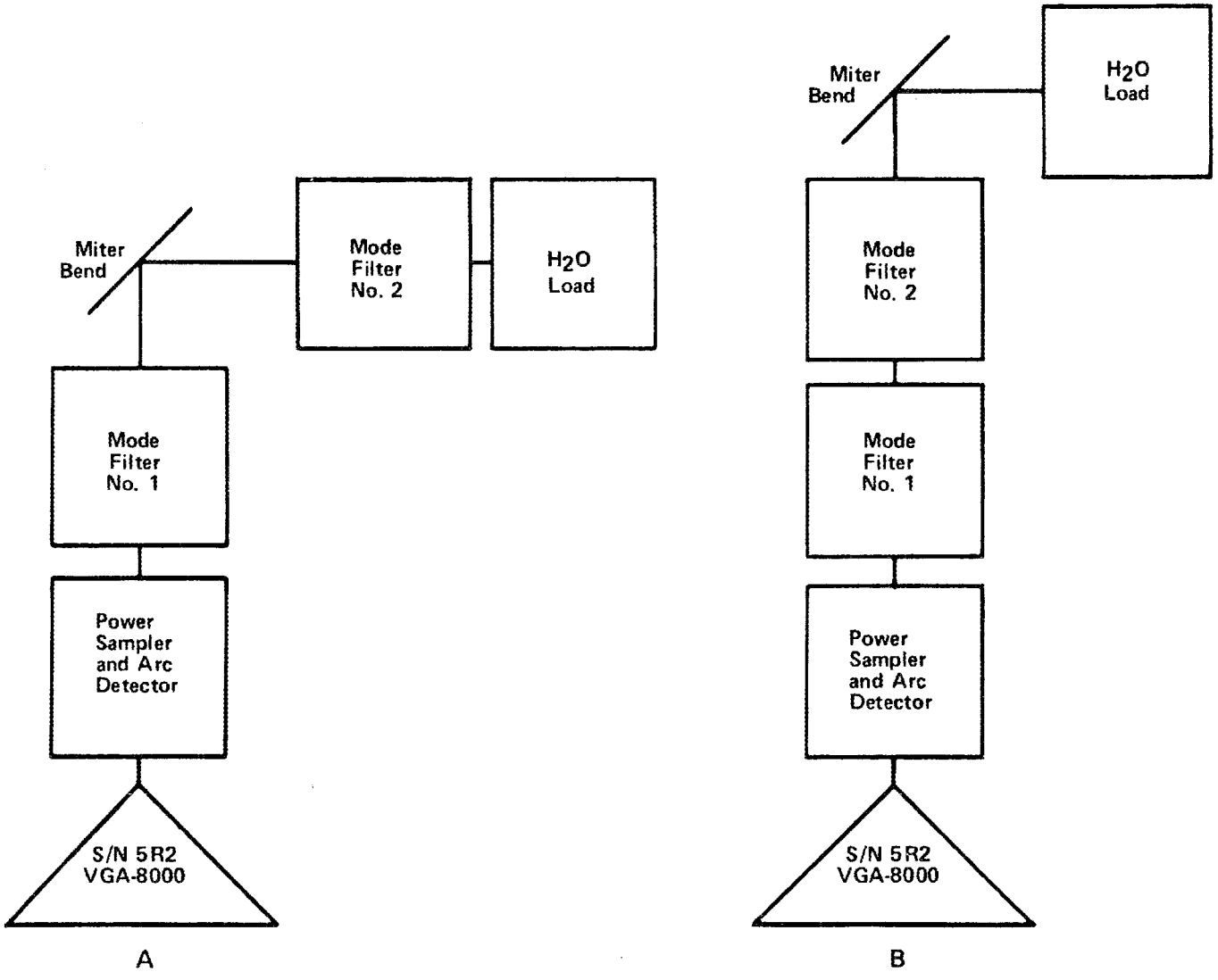

Figure 1. VGA-8000 S/N 5R2 Test Configuration

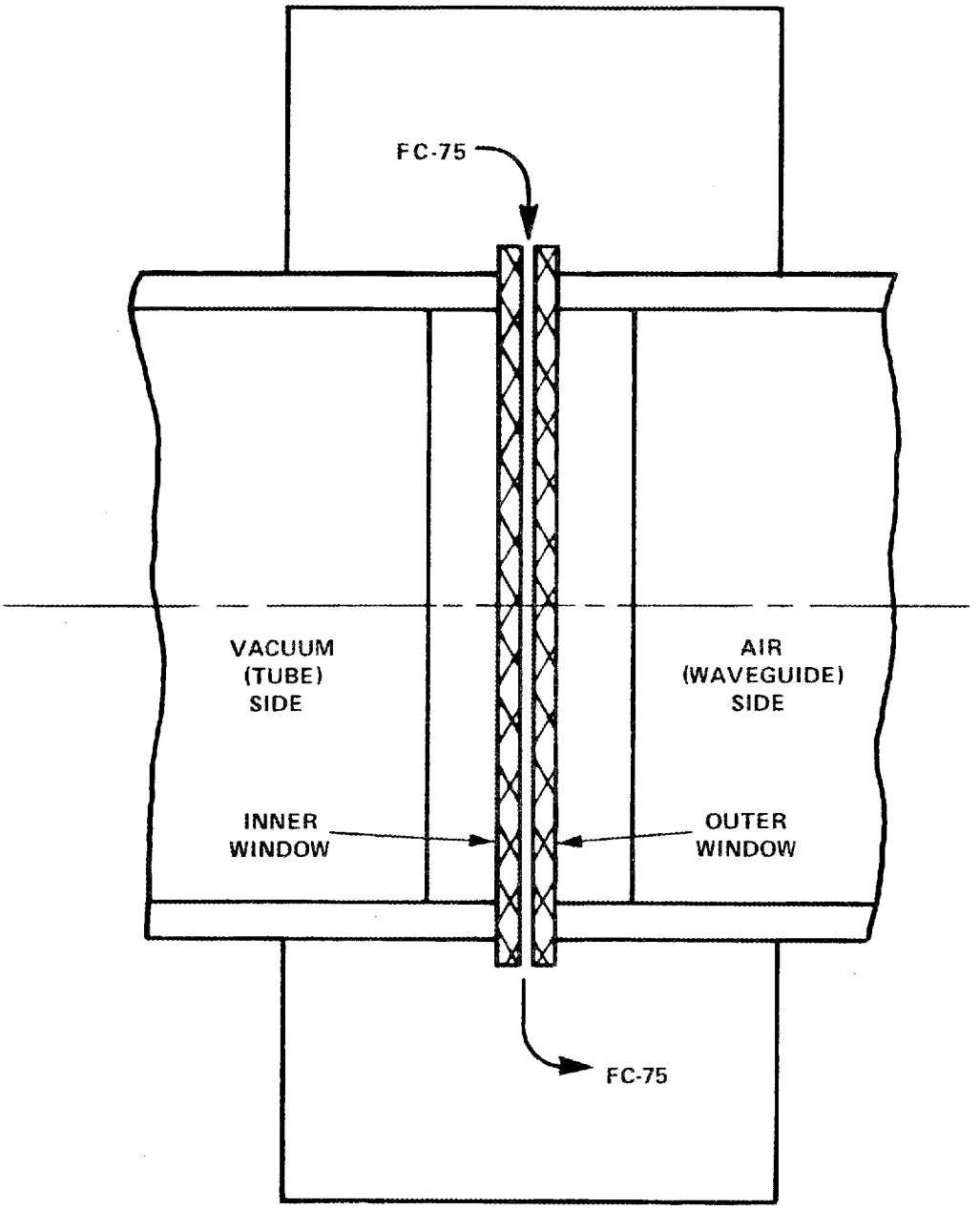

Figure 2. Gyrotron Double Disc Window

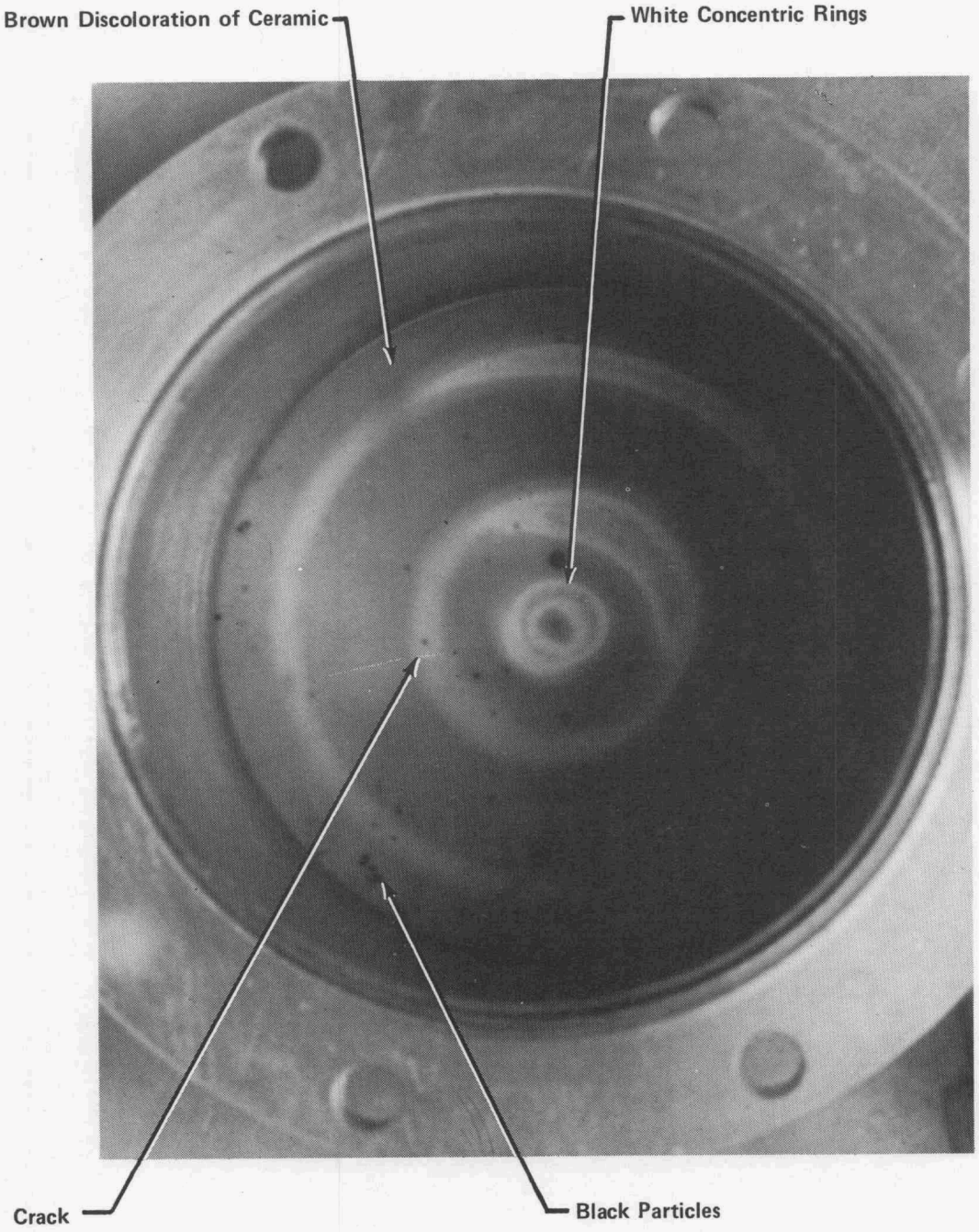

Figure 3. Output Window Assembly (Air Side)

Figure 4. White Ring on Ceramic Fused Area of Window

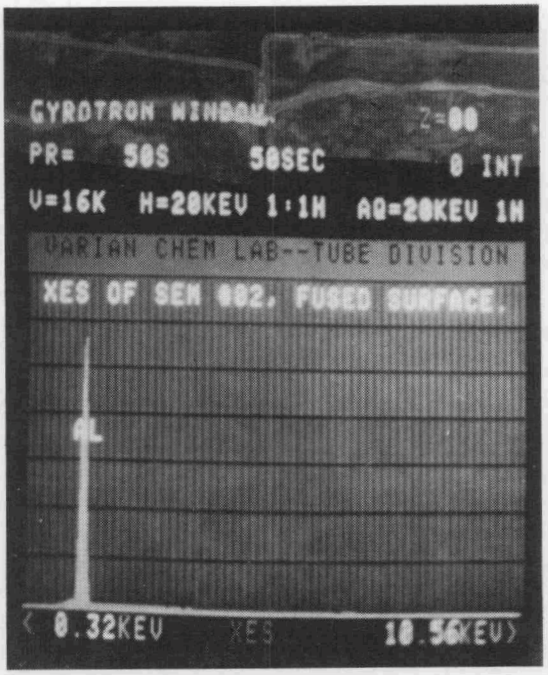

Figure 5. X-Ray Emission Spectrogram of White Ring on Window

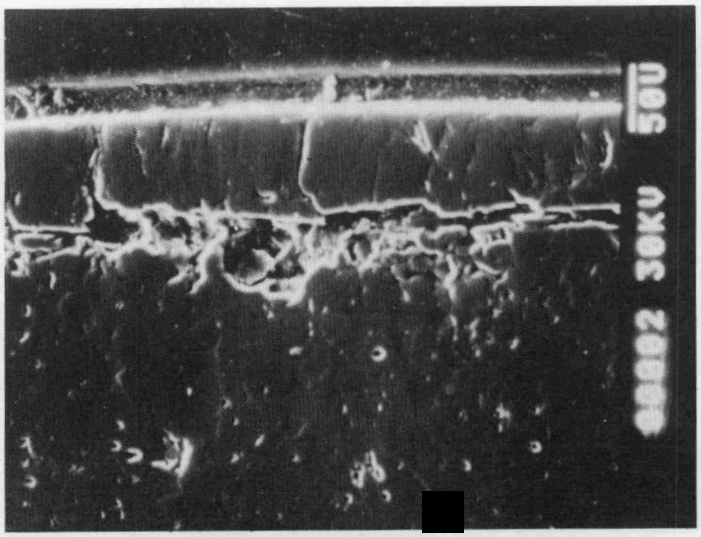

Figure 6. Cross Section of Ceramic in Fused Area of Window

total energy would be 25×10^3 W x 5×10^{-6} s = 0.125 joules; far less than the 400 joules required to fuse the ceramic as described above.

Another curiosity is the multiplicity of rings. Normally an arc can only be sustained at the innermost ring or line of highest electric field.

The black particles were analyzed with the SEM and XES machines and found to be silicon and silicon with copper. The copper is probably due to the scraping of the flanges while installing the waveguide and changing load configurations. A better support for the output load is being designed to minimize this problem in the future. The silicon is probably from a cleanser paste used to clean the ceramic.

The FC-75 system was also investigated. There were no traces of contaminants in the FC-75 and the system pressure was normal. This is covered in detail in Section 3.

Recommendations have been made in cooperation with Varian QA and these are discussed in the QA report of the window failure.

3. FC-75 System

Some improvements have been initiated in the FC-75 system for cooling the output window. The existing system has a high-pressure pump with marginal flow capability. Therefore, to facilitate more flow, a high-flow, low-pressure pump has been ordered. A pressure relief valve across the pump will keep the absolute pressure set at a low value. There will be a pressure switch at the window which will shut off the tube and the FC-75 unit in the event that there is excessive pressure. This double protection system will guarantee that the pressure is kept low while experimenting with FC-75 flow and tube parameters.

As a further follow-up to the ruptured output window, the FC-75 window cooling system was investigated. An output window model, identical in flow characteristics, but with clear plastic discs, was inserted in place

of the normal window and analyzed for possible bubbles accumulating during operation. It was found that bubbles accumulated in this region when the FC-75 was turned off, but disappeared within 15 seconds after the FC-75 was turned on. It is doubted that this contributed to the window failure described in Section 2.

The following modifications are planned to further improve the FC-75 system:

(1) Raise the reservoir so that the tube window is not the highest point in the system.

(2) Install a pressure interlock switch in the FC-75 line at the window to stop the FC-75 pump and turn off the tube high voltage in the event of a pressure surge.

(3) Add a pressure bypass valve across the pump to limit the maximum pressure in the system.

4. Arc Detector Delay Measurement

The arc detector system was investigated and found to be functioning normally. The delay time (time between light input and crowbar trigger) was measured by injecting a light pulse from a green light emitting diode into the tube's arc detector light pipe and measuring the time delay to the point where the crowbar was triggered. The measurement was made several times and was repeatably 5 microseconds. This corresponds to 200×10^3 W $\times 5 \times 10^{-6}$ s = 1 joule at full CW power; an energy level safely absorbed by the tube.

C. TUBE #6

1. This tube was delivered to test on June 17. It was hi-potted with no difficulty and as of the end of the quarter had been pulse tested at 2% duty up to 200 kW and at 10% duty to 140 kW.

2. Collector Seal

This tube contains a new collector seal which is made entirely of ceramic and metal, unlike that of tube #5. Difficulty was encountered in fabricating this assembly due to cracking in the ceramic caused by excessive differential thermal expansion between the metal and ceramic. After further consultation with our ceramic specialists, the seal was redesigned to reduce thermal stresses. In addition, a longer furnace brazing cycle and electron beam welding were employed. Prior to incorporation in the tube, the completed seal was hydrostatically pressure tested to 180 lbf/in^2 and its pressure-flow characteristic determined.

3. Cooling System Simplification

The pressure-flow characteristic of each cooled assembly was measured and the water cooling system was ultimately reduced to three cooling circuits as shown in Figure 7.

It is possible to incorporate the collector seal circuit with the body and window circuits if cooling were the only issue. However, collector seal power dissipation was found to be a useful and important parameter in adjusting VGA-8000 S/N 5 for optimum operation. For this reason, this circuit will remain independent so that the flow rate can be optimized for accurate calorimetry in conjunction with inlet and outlet thermocouples connected to a differential digital readout.

D. TUBE 7R1 (M)

1. Cathode Heater Failure

After having successfully operated at 55 kW CW at ORNL since December, this tube ceased to operate in March. The problem was traced to an open heater in the gun assembly. The tube was returned to Palo Alto where a Quality Assurance investigation was conducted. A detailed report was prepared and submitted to ORNL in May. The following are highlights taken from this report.

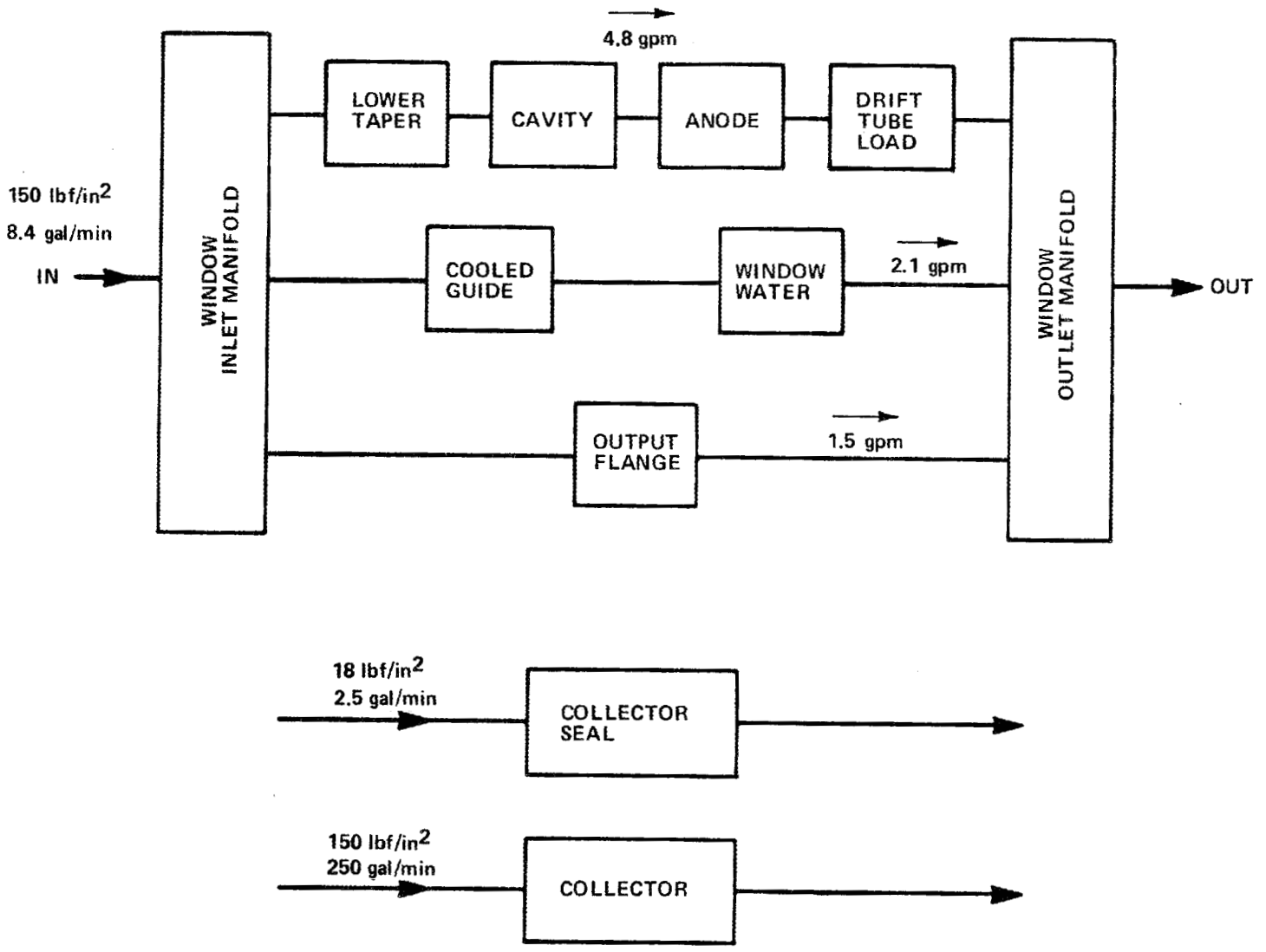

Figure 7. VGA-8000 S/N 6 Water Cooling Circuits

The gun assembly (K-8000) was removed and analyzed (Figures 8, 9, and 10). The following items were noted:

(1) The top focus electrode retaining screw head was eroded due to positive ion bombardment.

(2) The stainless steel modulation anode was spark eroded. The "greening" coating was removed due to arcing.

(3) The high-voltage seal opposite the modulation anode was sputtered with stainless steel which came from the modulation anode and the top focus electrode retaining screw.

(4) A yellowish discoloration of the alumina ceramic immediately below the sputtered metal area of the upper seal was noted. This is normal x-ray discoloration and is not detrimental to the tube's performance.

(5) The lower heater ceramic had a light coating of copper which disappeared after two days (Figure 10). It may have been caused by evaporation of nearby braze during a gas burst or possible rf oscillation due to an unusual combination of tube operating parameters. It should not have effected the tube's operation.

(6) An open circuit was found in the heater lead at the heater tab to heater leg laser weld joint (Figure 10). This was the cause of the tube failure and is believed to be caused by insufficient strain relief being incorporated at the time of assembly.

Microphotography of the moly wire in the weld area revealed a recrystallizaton of the grain structure embrittling the wire. Scanning electron microscopy and electron emission spectroscopy analysis of the area

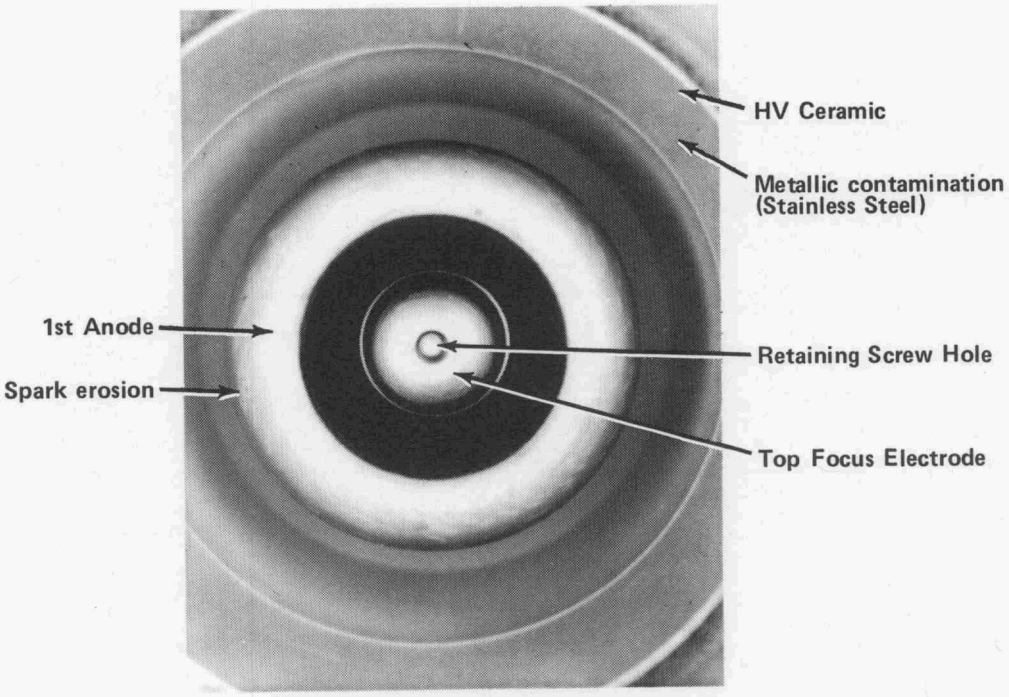

Figure 8. Top View of K-8000 Cathode Assembly

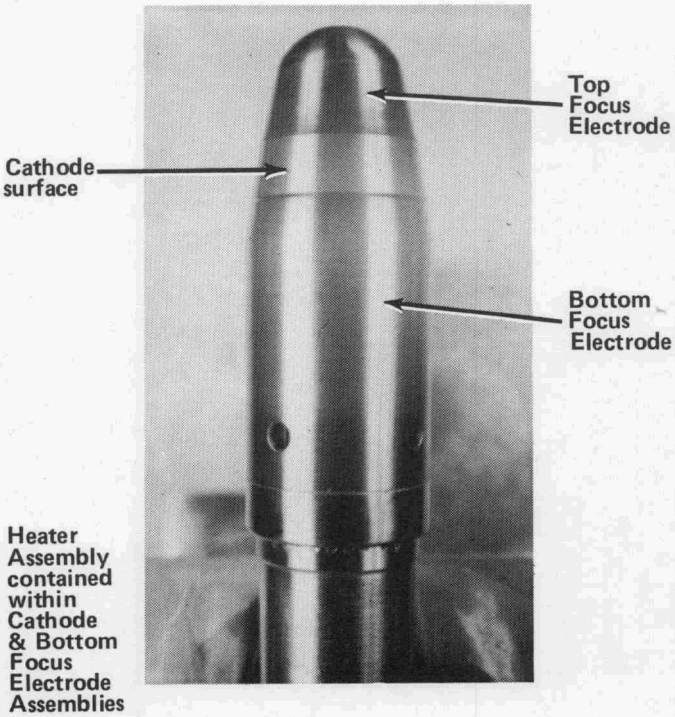

Figure 9. Side View of K-8000 Cathode Assembly

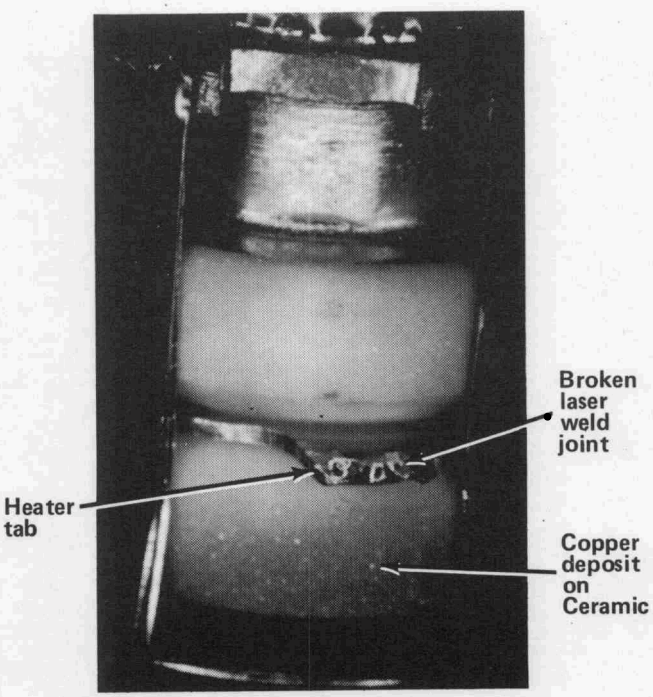

Figure 10. Open Circuit at Heater Tab

revealed distinct patches of moly and cupronickel. Some areas of the cupronickel were rich in nickel.

Tube 7R1 (M) has been placed in storage. There is no plan at this time to rebuild it.

E. TUBE #8

1. Collector Seal

This tube will have a collector seal similar to the one in tube #6 but somewhat improved. The outer rings will be made from monel replacing the stainless steel used previously. This was done to better match the temperature coefficients of the metals and ceramic and to further minimize differential expansion and the risk of cracking the ceramic.

2. Window

Work has been done using new parameters to achieve a better match for the double disc output FC-75 window. Cold test of the new window indicates a better match at 28 GHz and a lower VSWR at the frequencies above and below 28 GHz. The computer plots show that both beryllia windows (Figures 11 and 12) are better than the alumina windows (Figure 13) as far as bandwidth is concerned. The new BeO window has a thickness of ceramic and FC-75 which combine to be 2.599 wavelengths which yields a bandwidth, defined as VSWR less than 1.2, of 0.8 GHz. This is a 20% wider bandwidth than previous windows. From the figures it is also apparent that the VSWR above and below 28 GHz is comparatively lower for the new BeO window which will improve performance by loading unwanted frequencies out of the tube.

The BeO window, incorporating new ceramic and FC-75 dimensions was successfully cold tested and indicated a 20% improvement in bandwidth. The final assembly for tube #8 has been completed.

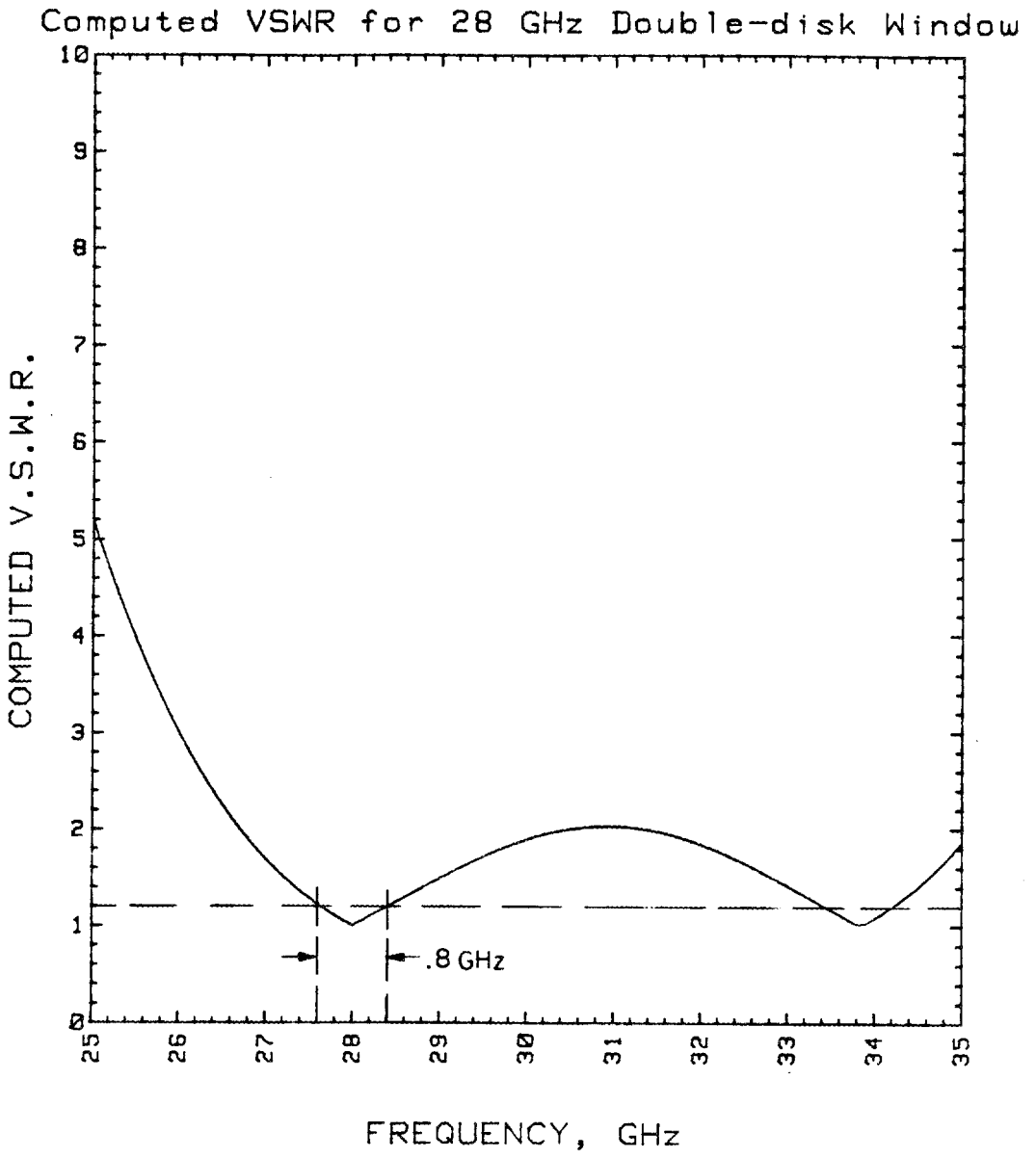

Figure 11. Tube No. 8 Beryllia Window

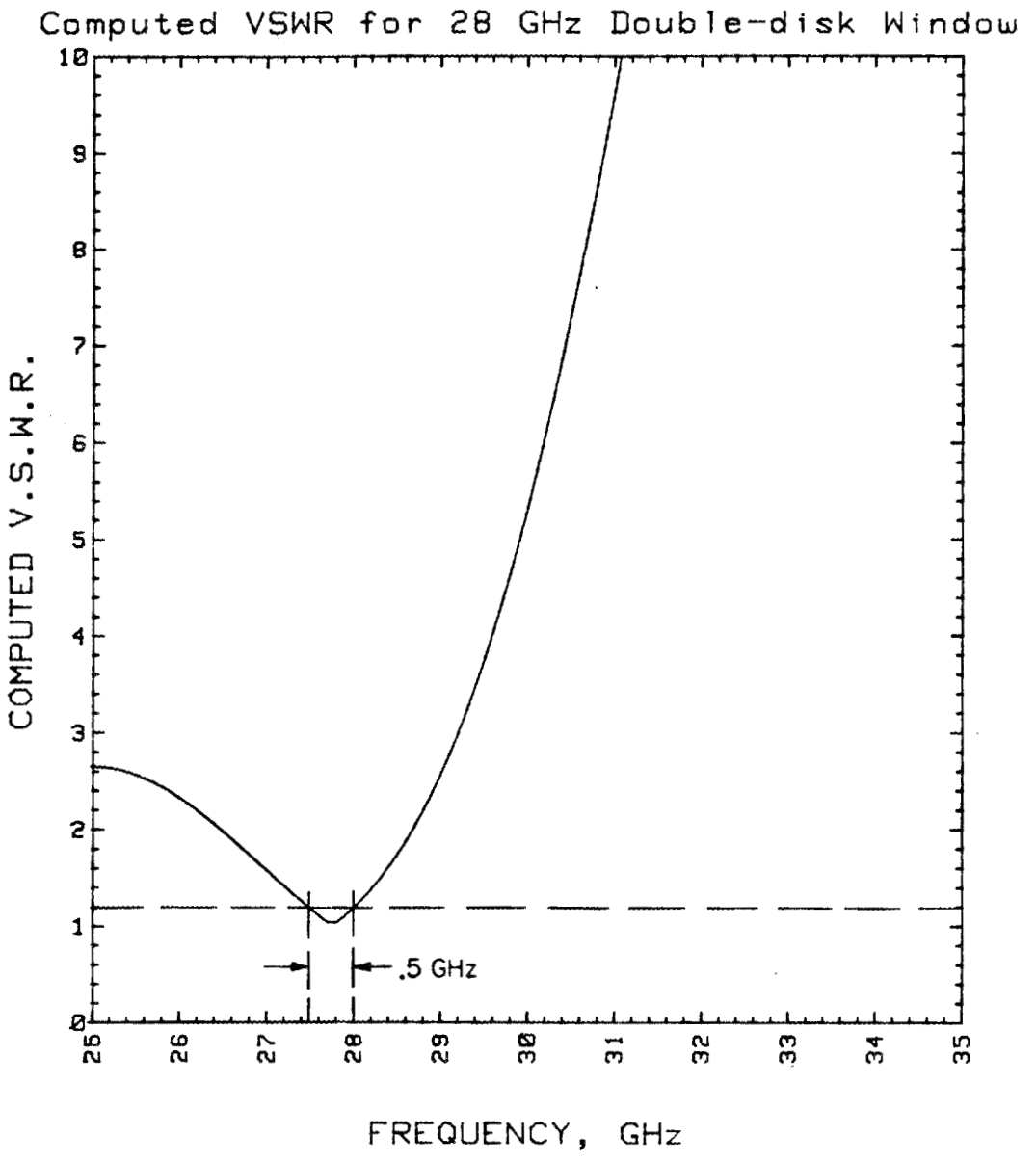

Figure 12. Tube No. 6 Beryllia Window

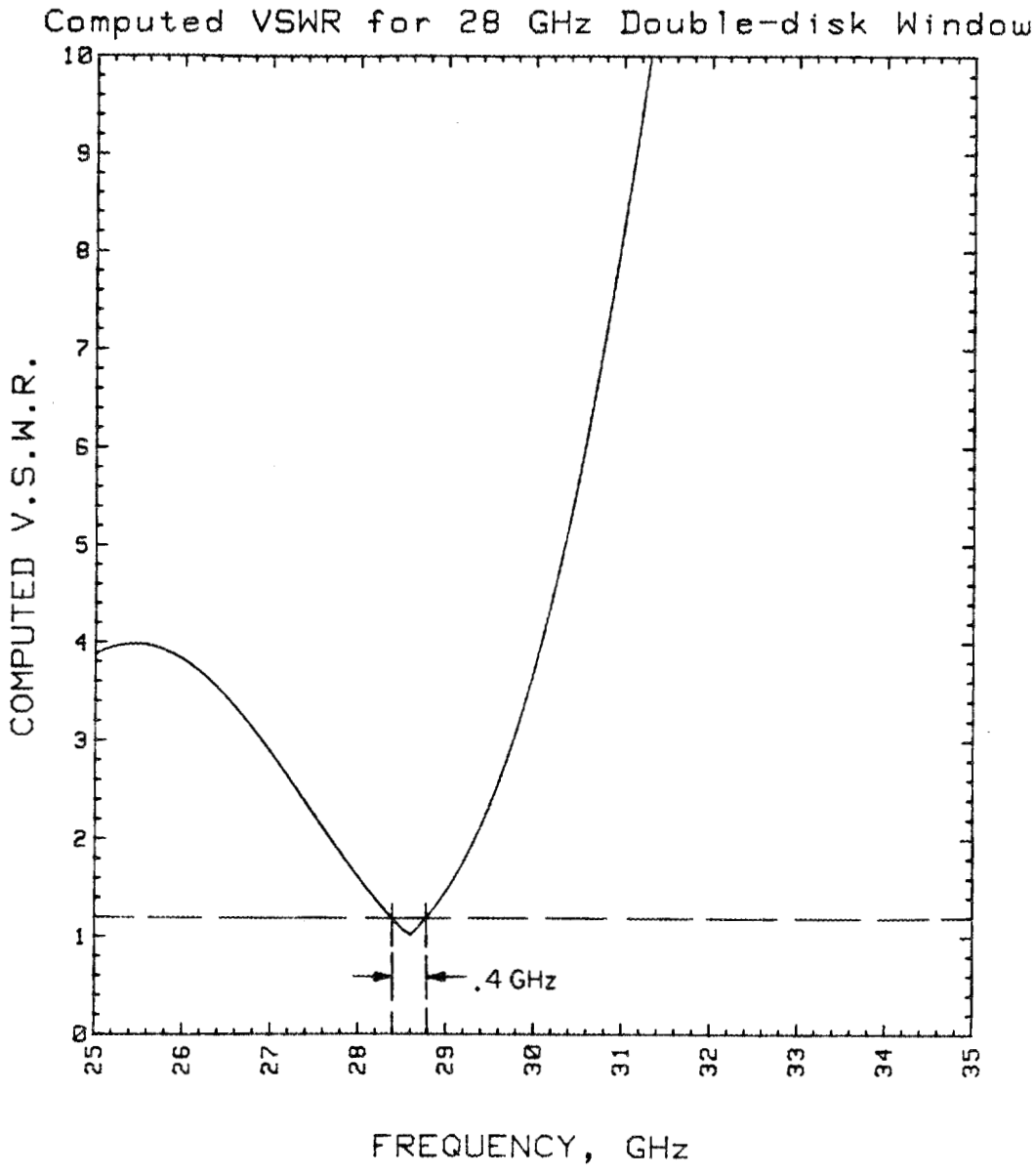

Figure 13. Tube No. 5 Alumina Window

F. TUBE #11

This tube is intended to be identical to tube #8 except for a possible cavity modification.

Cold test work has been done on shifting cavity resonances away from the desired frequency at 28 GHz. Some interference from other modes has been seen during tube operation. Of particular note are the TE_{221} down from 26.6 GHz to 26.0 GHz and the TE_{321} from 31.7 GHz up to greater than 32.0 GHz by changing the cavity geometry. In so doing, a new mode has been trapped in the tapered section of the cavity which appears to interact well with the beam. It is of very high Q and is easily loaded by a small load ring 0.030" long in the wall of the cavity. A continuing problem is that quite often when one mode is detuned out of the frequency range, another is detuned into the frequency range because of the large cavity size.

G. MODE FILTERS

A new mode filter (VFA-8000-A3) (Figure 14) has been designed and a prototype is under construction. It is similar to the mode filters described in earlier reports, except that it has an increased water flow capability which will permit higher rf power dissipation. The previous model VGA-8000-A2 has been tested to 14.5 kW CW with a maximum flow rate of 5.6 gal/min. The power handling capability of the VFA-8000-A3 will be determined on tube #6.

The VFA-8000-A3, as the previous A2 version, has a 2.5" inside diameter which mates directly to the waveguide flanges. There are eleven concentric slots in the inner conductor which are open to a ceramic cylinder behind which cooling water is circulated. Circular modes are propagated with negligible loss while non-circular modes are attenuated by approximately 4.7 dB.

Figure 14. VFA-8000-A3 Mode Filter

III. PROGRAM SCHEDULE AND PLANS

With the shipment of axisymmetrical tube #5R2, the remaining effort will be devoted to the completion of axisymmetrical tubes, numbers 6, 8 and 11 described earlier in this report.

MILESTONE CHART AND STATUS REPORT

○ ORIGINAL START □ REVISED START △ MAJOR MILESTONE
▽ INTERMEDIATE OR DECISION POINT ◇ PROPOSED SCHEDULED DEVIATION FOR A MAJOR MILESTONE
STATUS REPORT TIME — ACTIVITY SCHEDULED ▬ ACTIVITY COMPLETED

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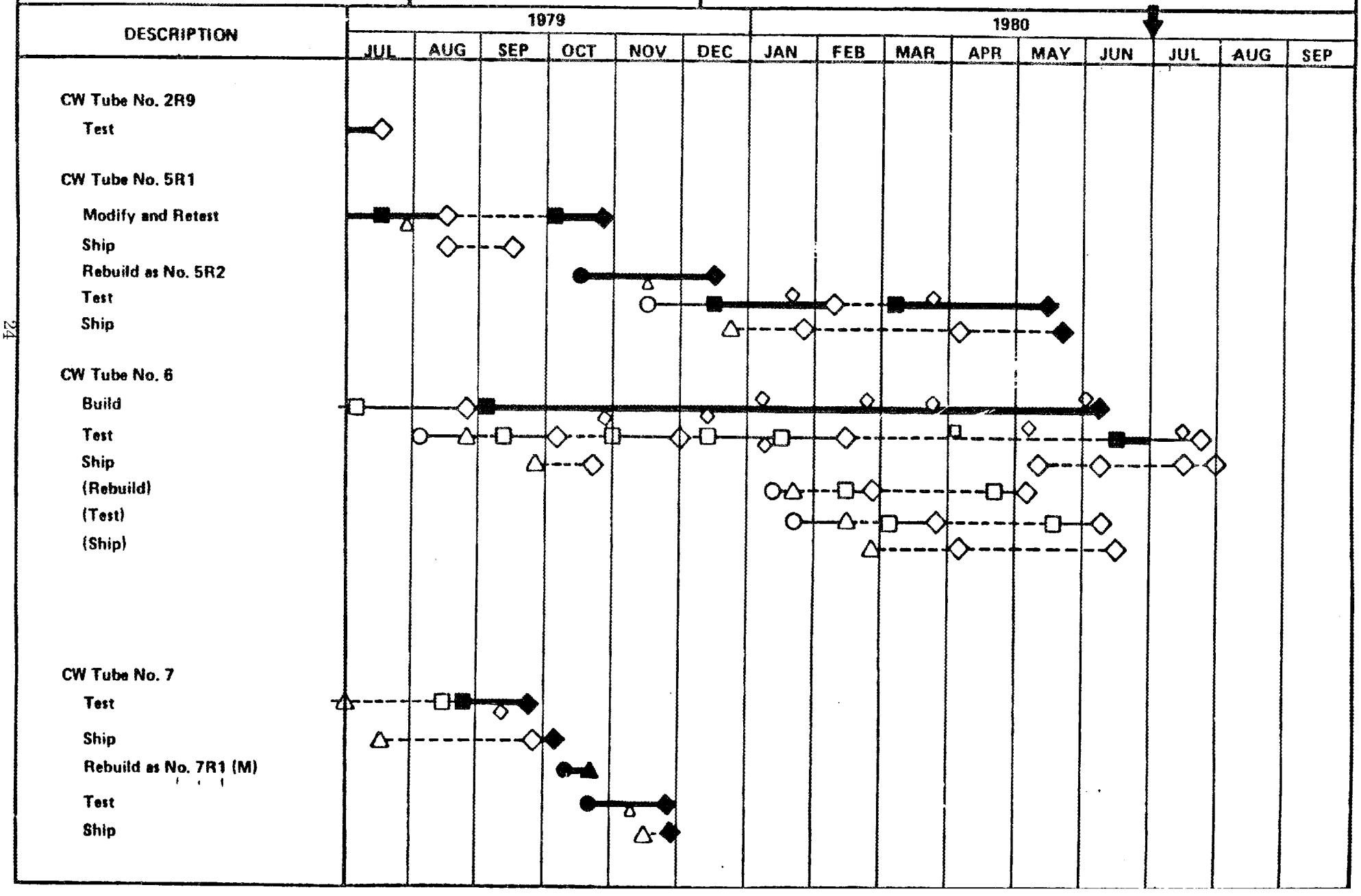

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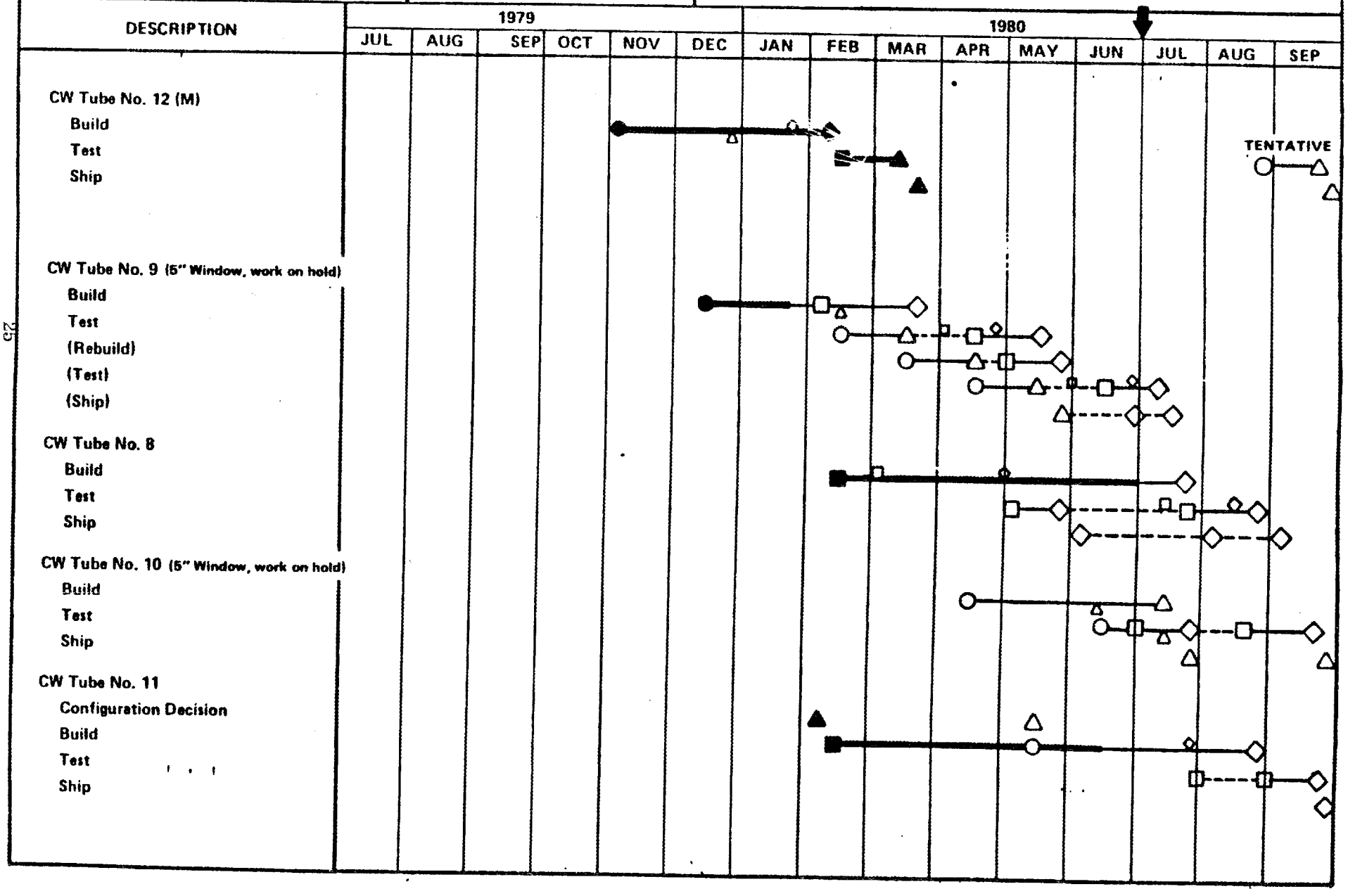

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