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SOLAR POWER SATELLITE 50 kW VKS-7773 CW KLYSTRON EVALUATION

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16. Abstract

This program was established to evaluate the electrical characteristics of a cw, 50 kW power output klystron at 2.45 GHz. The tube tested was an 8-cavity klystron, the VKS-7773 which had been in storage for seven years. Tests included preliminary testing of the tube, cold tests of microwave components, tests of the electromagnet, and first and second hot tests of the tube. During the second hot test, the tuner in the fifth cavity went down to air, preventing any further testing. Cause of failure is not known, and recommendations are to repair and modify the tube, then proceed with testing as before to meet program objectives.

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SUMMARY

This program was established to perform specific tests on the VKS-7773 high efficiency 50 kW cw S-band klystron under optimum operation conditions, analyze and evaluate the results of the tests, and recommend design modifications to produce a conceptual design for a flight configuration klystron. The complete Statement of Work is provided as an appendix to the report. The following tests were performed during the program:

- Preliminary Tests of VKS-7773
- Cold Tests of Microwave Components
- First Hot Tests of VKS-7773
- Tests on the VKS-7773 Electromagnet
- Second Hot Tests of VKS-7773

During the second hot tests, the klystron vacuum was lost as the result of failure of the tuner vacuum wall (bellows) in cavity number 5 of the eight-cavity klystron. Because of this, further tests as outlined in the Statement of Work were not completed.

Appendix C to the report discusses possible application of a high-efficiency klystron design stemming from that of the VKS-7773 in a satellite power station.

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I. INTRODUCTION

This program was directed toward evaluation of the electrical characteristics of a 50 kW, cw power output klystron at 2.45 GHz. The program was conducted under NASA Contract NAS 9-15176, and covered the period from 15 January through 15 May 1977.

The vehicle used for the test program was the VKS-7773, an eight-cavity klystron which had been in storage for seven years. After preliminary testing of the tube, additional tests were performed involving cold tests of microwave components, tests on the electromagnet, and first and second hot tests of the VKS-7773 klystron.

A primary objective of the program was to analyze and evaluate the results of the tests, and from those data recommend design modifications to produce a conceptual design for a flight configuration klystron. During the second hot tests, the klystron vacuum was lost as a result of failure of the tuner in cavity number 5. This prevented any further testing of the VKS-7773.

The exact cause of the failure is unknown. Should further effort be desired, it is recommended that the klystron be repaired, modified, and retested in order to meet the requirements for solar energy to microwave conversion.

II. PRELIMINARY TESTS OF VKS-7773

Heater characteristics and outgassing during heater warmup were checked during the month of February 1977. Figure 1 shows VacIon® indication versus time observed. It took approximately five hours for complete cathode outgassing. The heater characteristics shown in Figure 2 are similar to data reported from tests of 1970. The question of cathode emission remained to be answered by application of high voltage in the hot test socket.

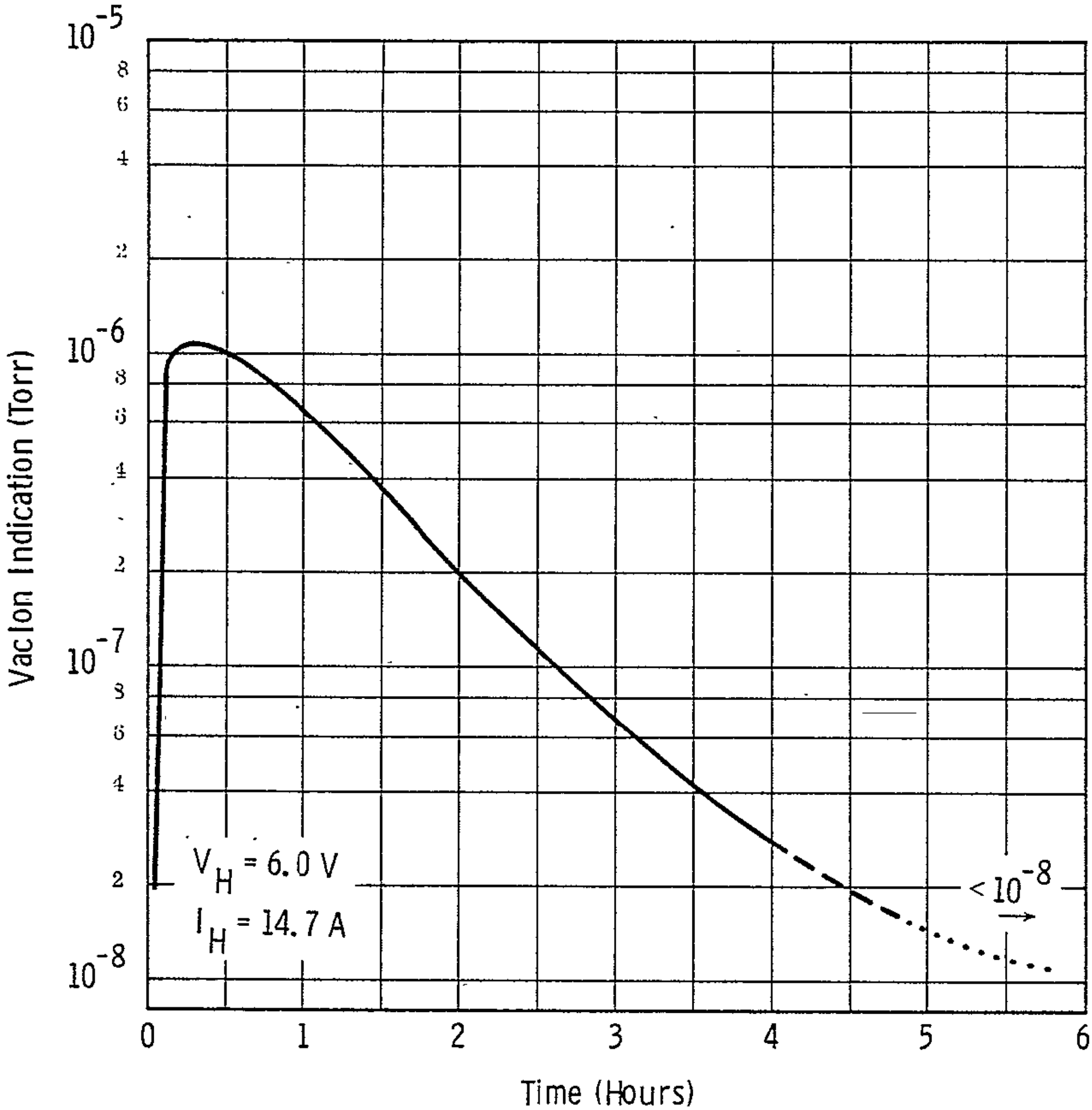

Figure 1. VKS-7773, Cathode Outgassing After Seven Years in Storage

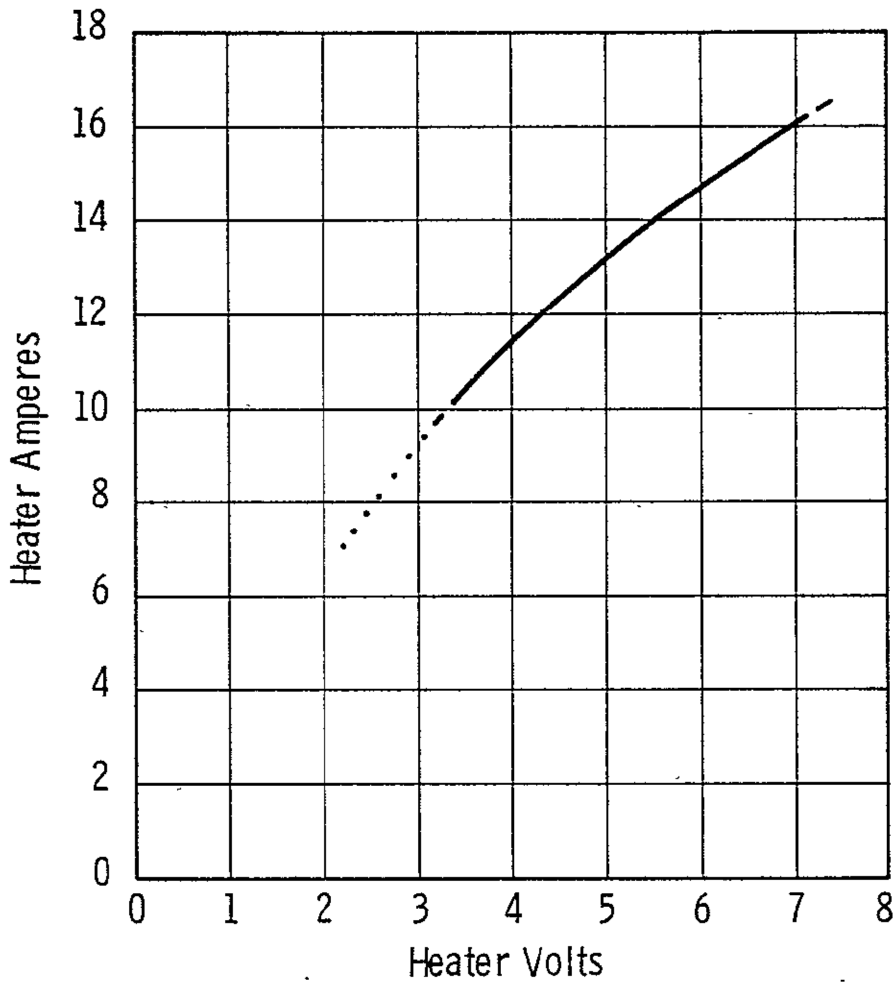

Figure 2. VKS-7773 Cathode Heater Characteristics, Feb. 16, 1977

III. COLD TESTS OF MICROWAVE COMPONENTS

Couplers and waveguide transformers were designed for use in testing the VKS-7773. The couplers permitted sampling rf output at a known ratio down from the level of power transmitted in the main output waveguide transmission line. The waveguide transformers were intended for use in adjusting output load impedance to optimize rf power output and to permit study of tube operating behavior as a function of load impedance.

These units were cold tested prior to use. Cold tests involve the use of WR-340 coax-waveguide transitions and dummy loads of quite low VSWR. One transition was acquired from a terminated microwave heating program. This unit was in WR-340 waveguide S/N66N1007. The first cold test dummy load was fabricated from WR-340 waveguide parts salvaged from another terminated microwave heating program.

The cold test equipment, slotted lines and the like were in WR-430 waveguide. Tapers were used between WR-430 and WR-340 components. Both sizes handle microwave energy at 2450 MHz. Figure 3 shows the results of initial cold tests of coax-waveguide transition S/N66N1007 and dummy load No. 1. It was believed that some improvement might be realized over these data by modifications. An experimental coax-waveguide transition was fabricated in WR-340 waveguide, and it showed a lower VSWR, as seen in Figure 4. Dummy load No. 1 looked reasonable good at 1.03 VSWR.

Cold test work was conducted on several additional microwave components. The high power water load, borrowed from another program, initially showed a moderately high VSWR at 2450 MHz, the test frequency. An inductive post was designed to give the results shown in Figure 4, in which the VSWR was brought down to about 1.04 at 2450 MHz. An additional cold test dummy load was designed and put together in an attempt to lower the VSWR observed with the first unit, S/N 1. The second unit, S/N 1543, showed a VSWR close to 1.01 around 2450 MHz. S/N 1543 was selected because this number appeared on the edge of the coupling flange of the second unit.

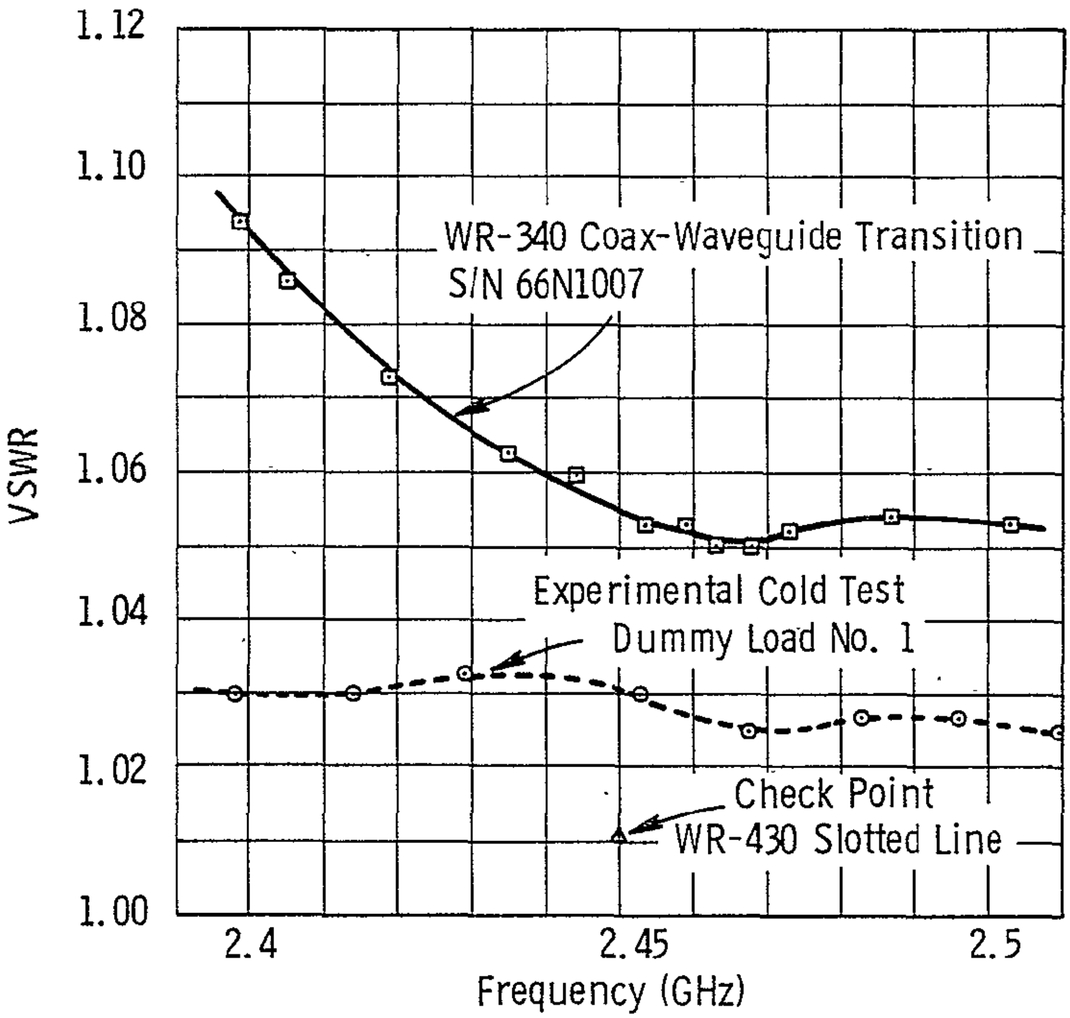

Figure 3. Results of Cold Tests on Coax-Waveguide Transition and Cold Test Dummy Load

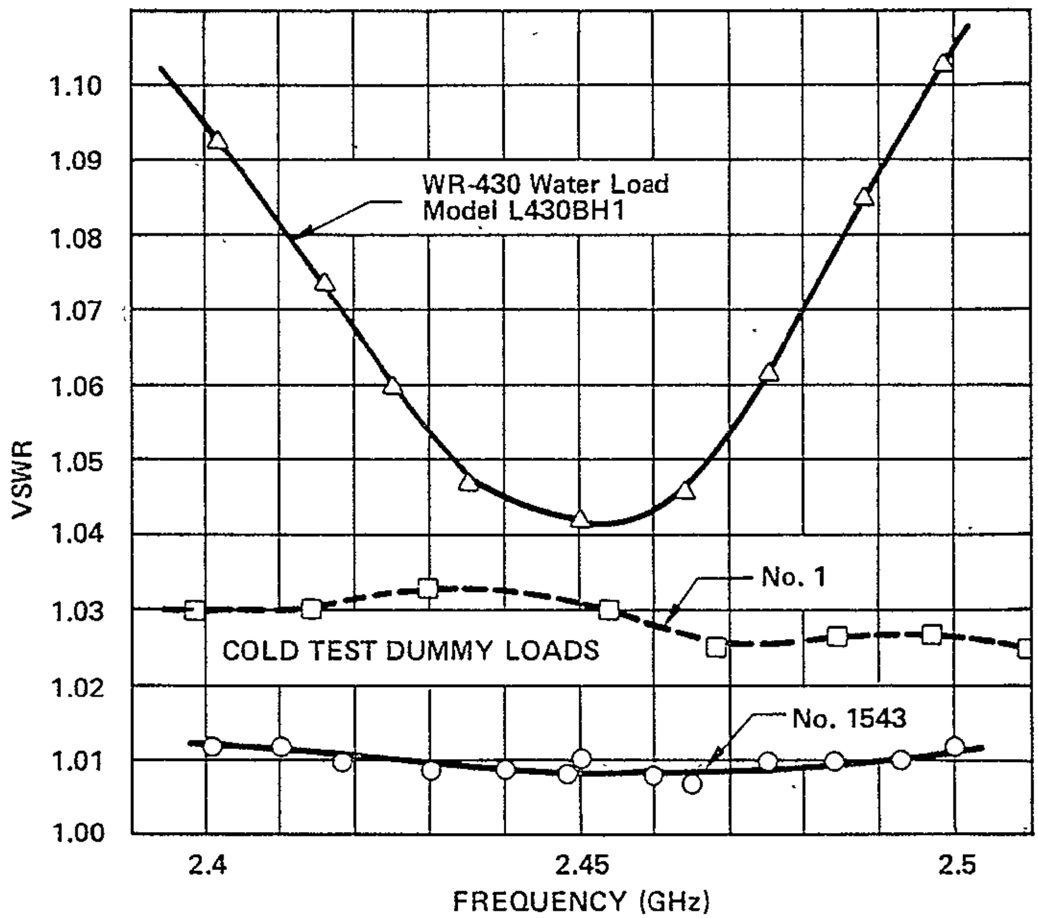

Figure 4. Cold Tests for VSWR of Dummy Loads and of High Power Water Load.

Impedance transformers required for testing the VKS-7773 with a varying load impedance were fabricated. Cold test results for these are given in Figure 5. Four levels of VSWR are available in all phases: 1.17, 1.29, 1.45, and 1.66. Intermediate levels of VSWR are also possible. Such values are obtainable by simultaneous use of two impedance transformer sections with relative phase adjusted between them. Initial testing of the VKS-7773 was to make use of the simple, single-transformer sections, one at a time.

Preliminary calibration of WR-340 waveguide couplers intended for use in testing the VKS-7773 showed coupling ratios close to those desired as seen in Figures 6 and 7. At 2450 MHz value, close to 59.9 dB down was observed for the first coupler port, while a value close to 61.8 dB down was observed for the second coupler port. This means that with 50 kW flowing in the main waveguide, coupler samples taken at these ports would be 51.2 and 33.0 milliwatts respectively. A small modification in coupler port 2 was later made to increase coupling and the power level of this sample. A number of WR-340 waveguide components, such as dummy loads S/N 1 and S/N 1543, were required in automatic test set calibration prior to actual measurement and calibration of couplers and other microwave devices.

Final calibration tests were later conducted on two couplers. Each of the two couplers had two sampling ports. The WR-340 waveguide coupler had both ports oriented to sample forward power, whereas the WR-435 waveguide coupler had one forward power sampling port and one reflected power sampling port. Figures 8 through 11 show calibrations obtained for the four sampling ports prior to assembly of the waveguide output system. These calibrations were accomplished using a computer-controlled automatic network analyzer. In the 55 to 60 dB level, the equipment is capable of about ± 0.25 dB accuracy. Taking the average values from the curves, the couplings at 2450 MHz were:

WR-430 Port 1	Forward	59.4 dB
WR-430 Port 2	Forward	58.2 dB
WR-435 Port 1	Forward	59.2 dB
WR-435 Port 2	Reflected	59.3 dB

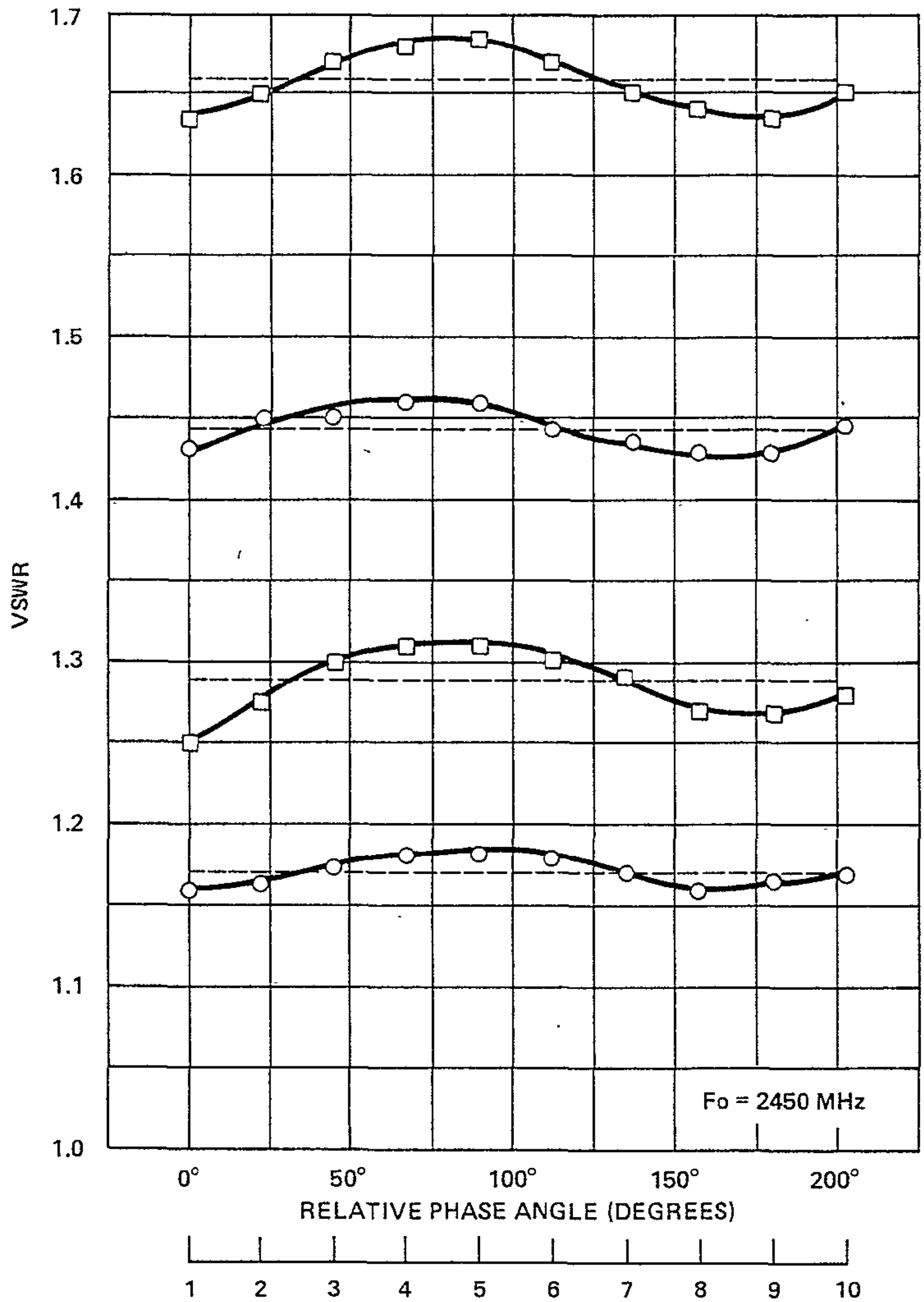

Figure 5. Cold Tests for VSWR of Impedance Transformers for use in Variable Impedance Tests of VKS-7773 Klystron.

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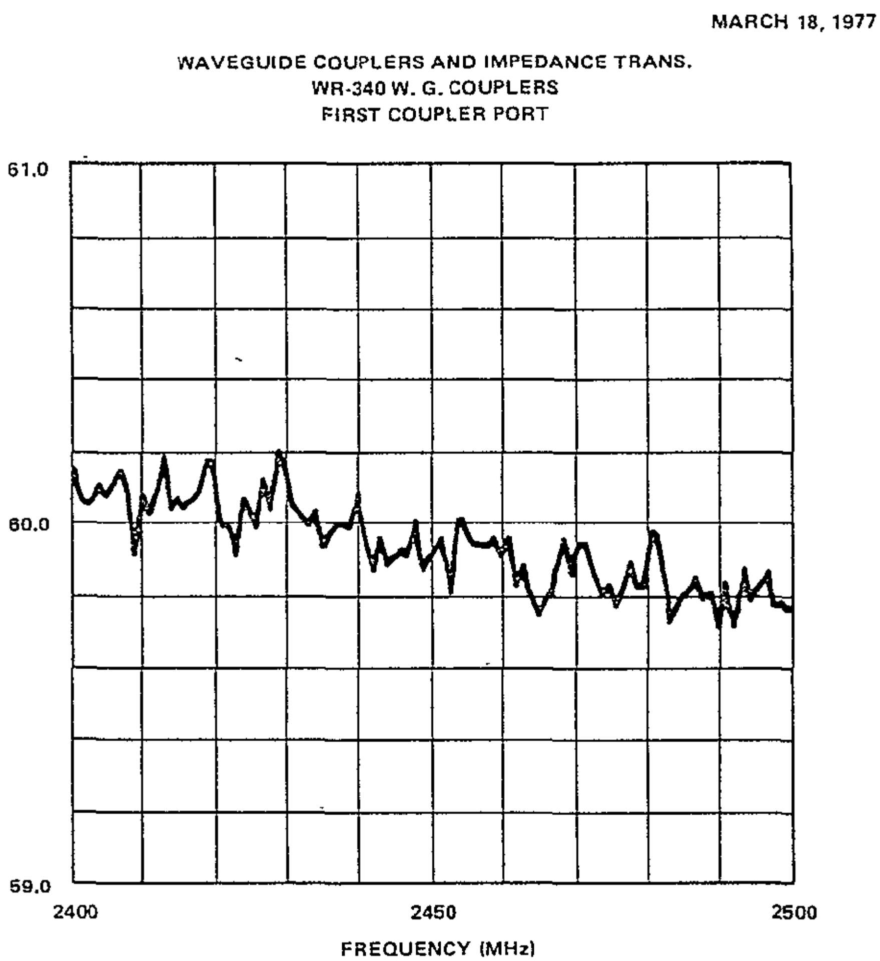

Figure 6. Preliminary Calibration of Coupler Port 1.

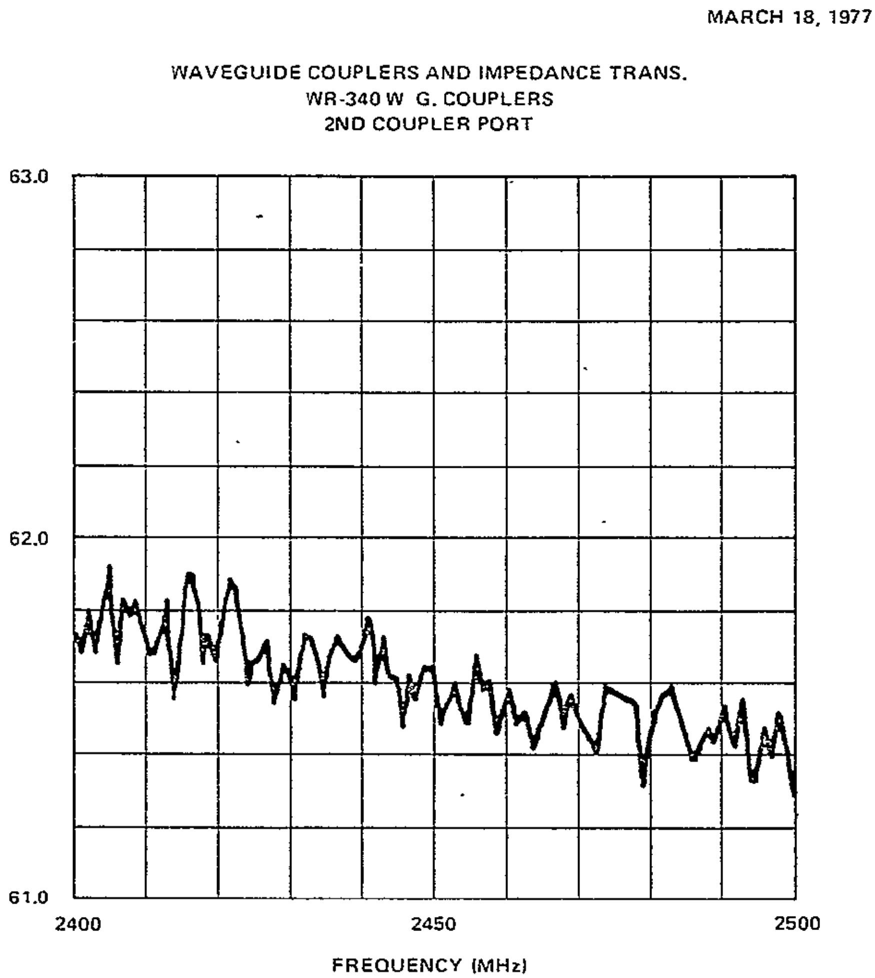

Figure 7. Preliminary Calibration of Coupler Port 2.

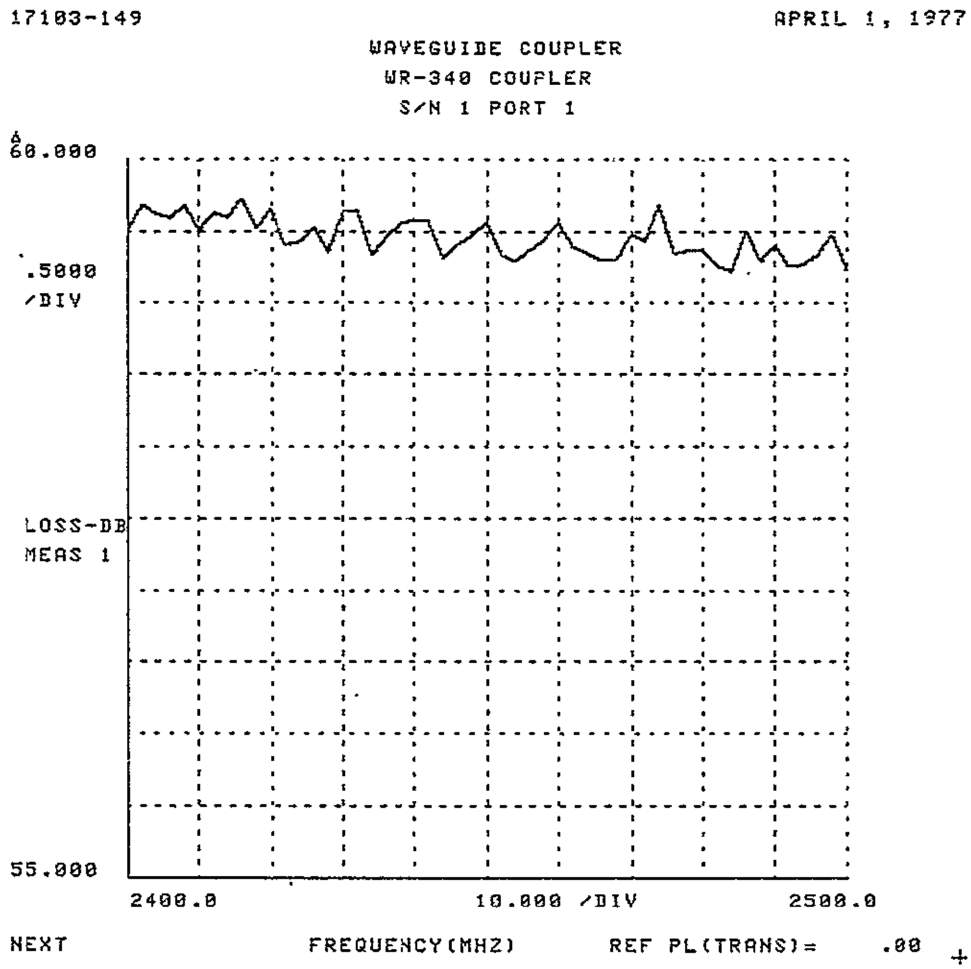

Figure 8. Calibration of WR-340 Waveguide Coupler First Forward Port

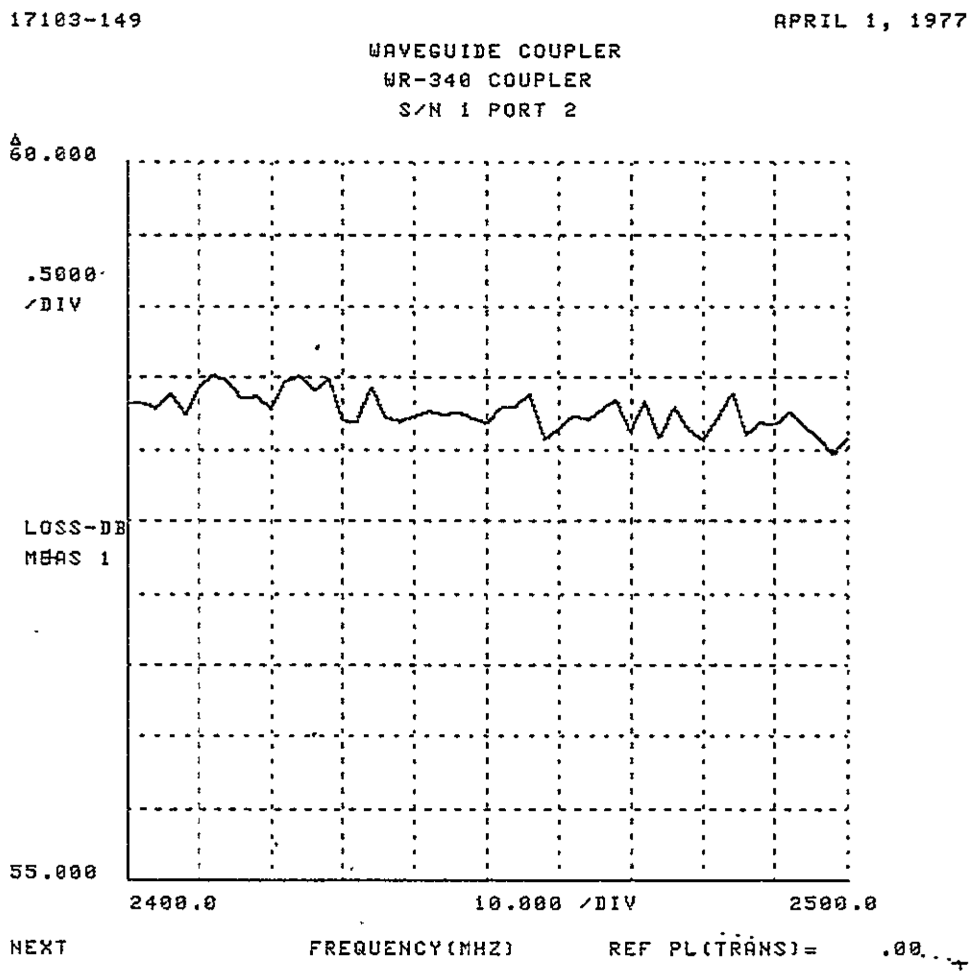

Figure 9. Calibration of WR-340 Waveguide Coupler Second Forward Port

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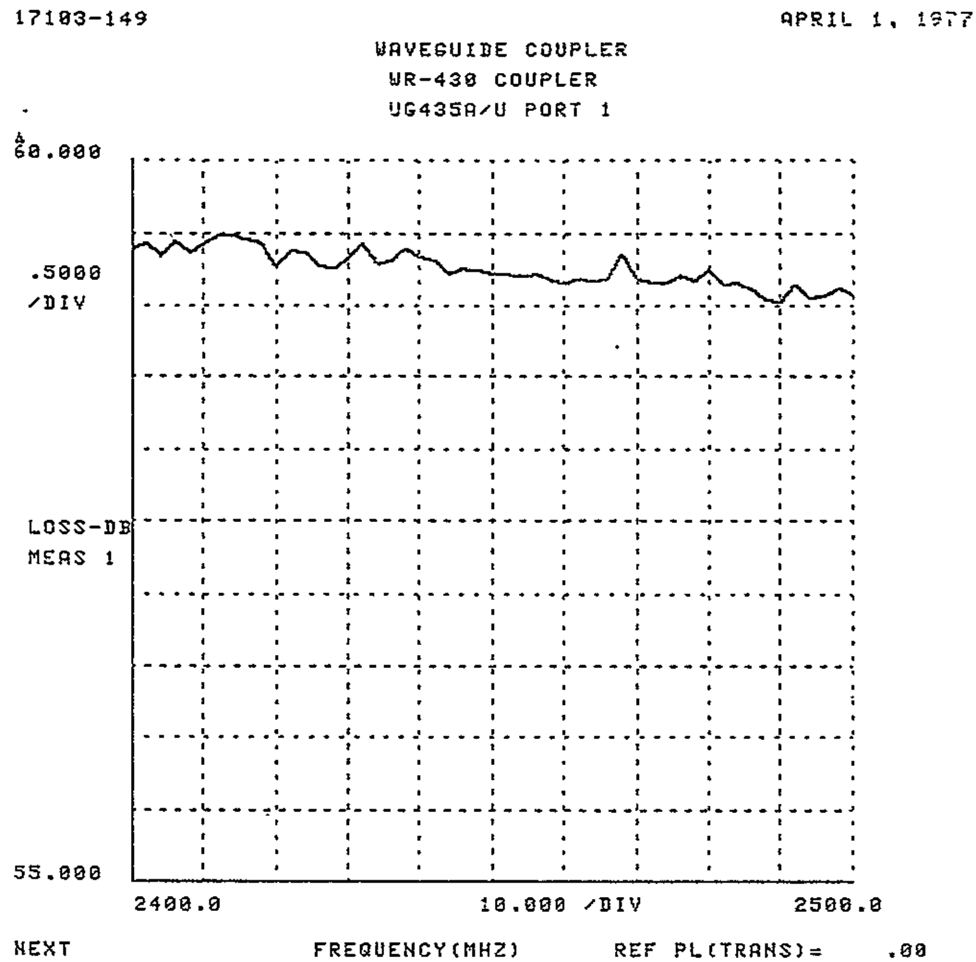

Figure 10. Calibration of WR-435A/U Waveguide Coupler First Forward Port

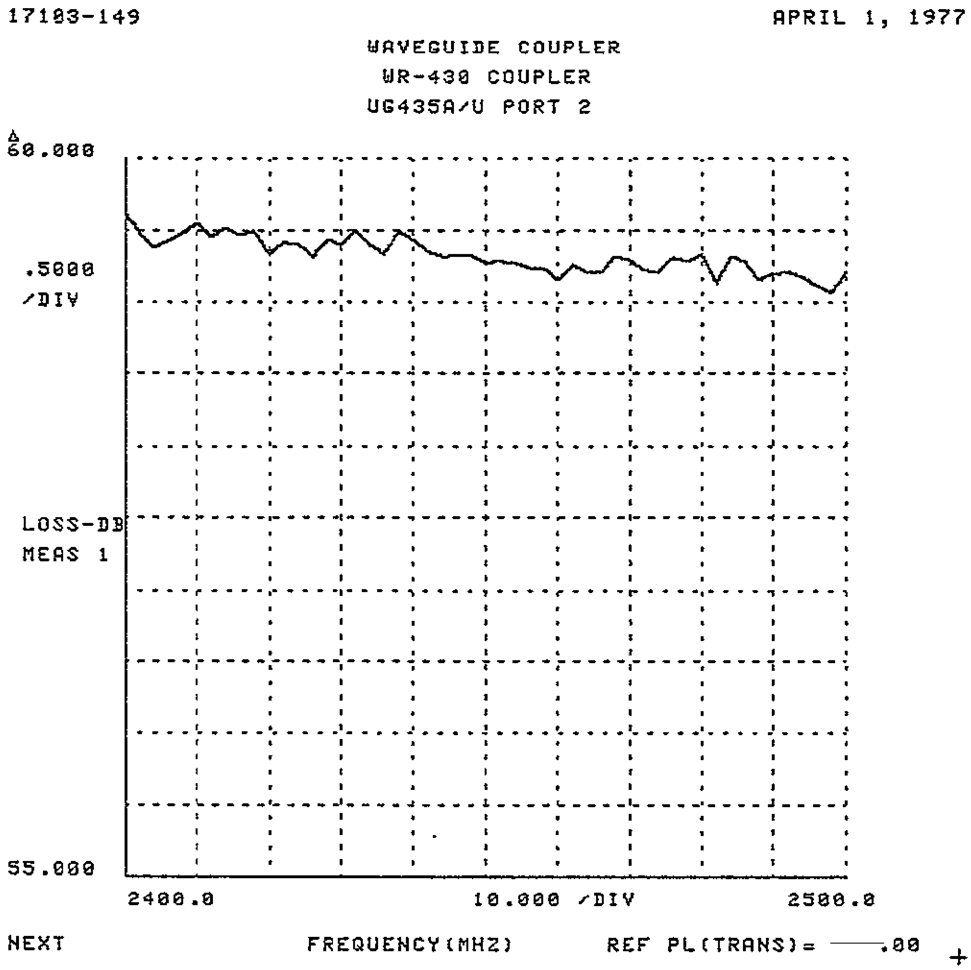

Figure 11. Calibration of WR-435A/U Waveguide Coupler Second Reflected Port

There were thus three sampling ports for observing forward power and one for observing reflected power from the klystron water load. Power in the water load was also available through inlet and outlet water temperature and water-flow measurements.

Figure 12 shows the results of additional cold test measurements to determine phase (post position) vs VSWR magnitude for several possible post position arrangements in an impedance transformer to be used immediately outside the klystron output flange.

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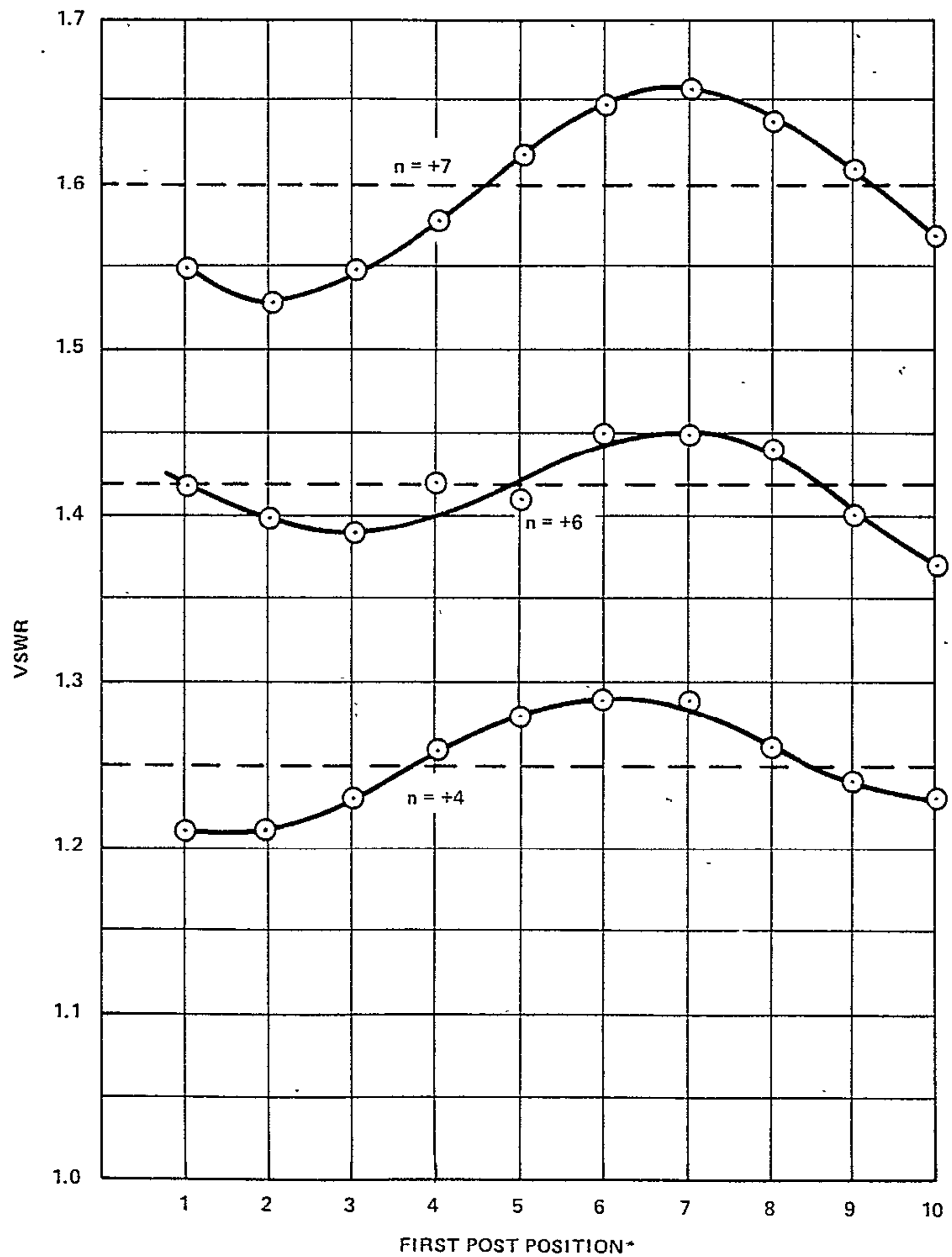

Figure 12. VKS-7773 Klystron, Dual Post Mismatch vs First Post Position. The second post is placed n positions beyond the first post on the opposite side.

*Post positions 1 and 10 approximately correspond.

IV. FIRST HOT TESTS OF VKS-7773

The VKS-7773 klystron was installed in the test socket during the first week in April and modification of the test facility was undertaken to provide the necessary magnetic focusing field, electromagnet power supplies and water cooling circuits for the experimental klystron.

On April 7, the VKS-7773 klystron was first turned on. Processing and testing continued for about one week. After some adjustment of the electromagnet coil, good beam transmission was obtained with no rf drive, and the tube was dc aged slowly and carefully up to 37 kV at 3 A beam current. Body current was 0.003 A at this operating point. However, body current had shown cyclic behavior. Figure 13 shows the results of careful dc measurements made of beam voltage, beam current, and body current in the range 10 to 30 kV. Checks were made every half kV in the range. The electromagnet currents used were those employed during the last recorded tests of the klystron seven years earlier.

Figure 14 shows the electron beam microperveance computed from the data of Figure 13. In the operating region, considered to be in the range of 20 to 35 kV in the present instance, the microperveance was quite close to 0.5 μperv, the original design value.

Figure 15 shows the results of one preliminary test involving adjustment for proper rf performance of the impedance transformer immediately following the klystron output flange. With the rf drive at a constant low level and with constant dc input, the phase position (post position) of the mismatch was varied through all phases. At each position, the klystron rf output cavity was tuned for maximum relative power output. Body current was noted. Then relative power output, rf output cavity tuning, and body current were plotted against mismatch post position, as shown. The horizontal dashed line crossing at an output cavity tuning position of about 39.7 represents the tuning without mismatch. Where the mismatch tuning curve crosses the horizontal dashed line, the load impedance is resistive. There are two such positions of the mismatch post. With a near-correctly coupled output cavity, klystron

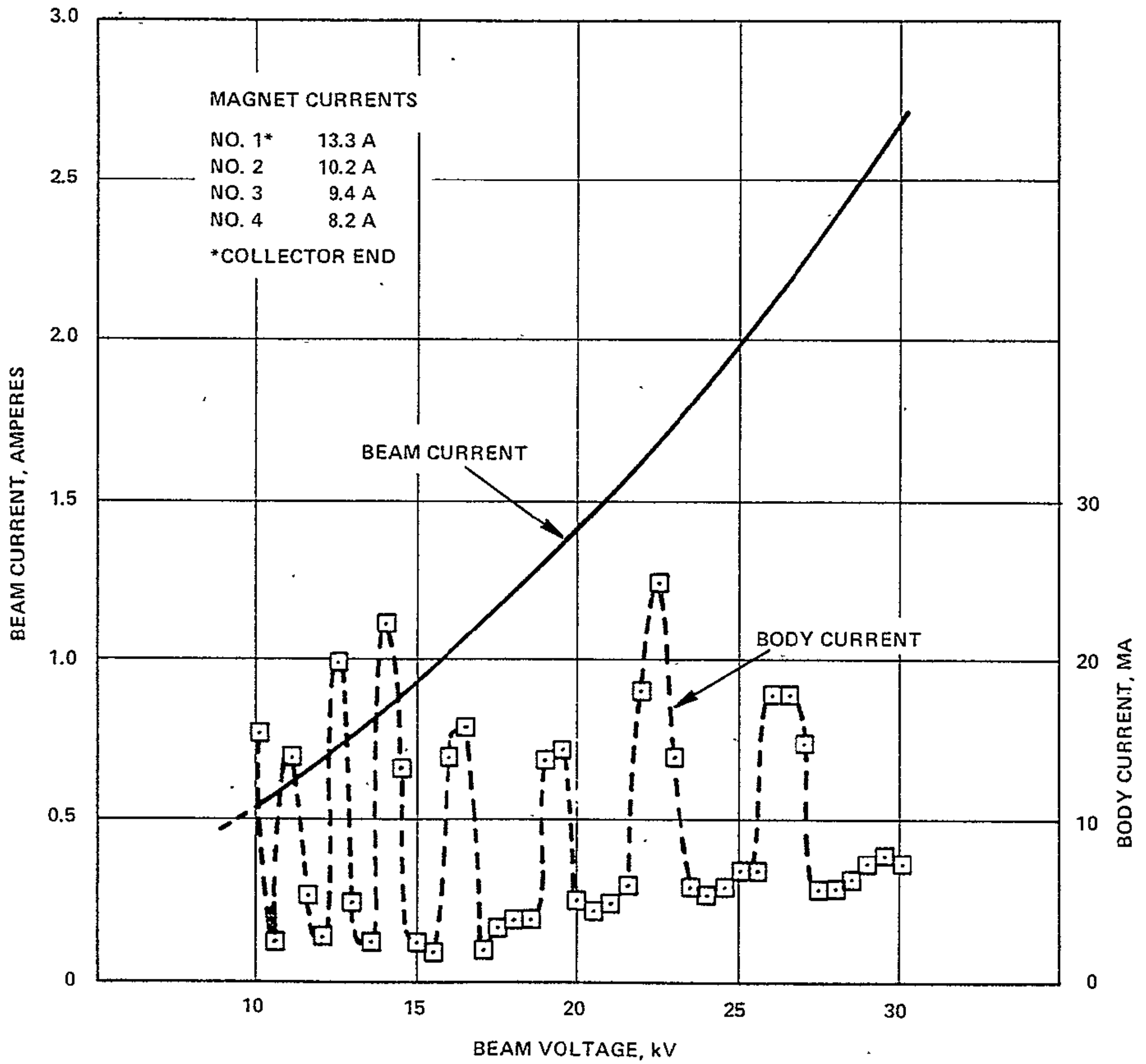

Figure 13. VKS-7773 Klystron, Beam Characteristics, No RF Drive

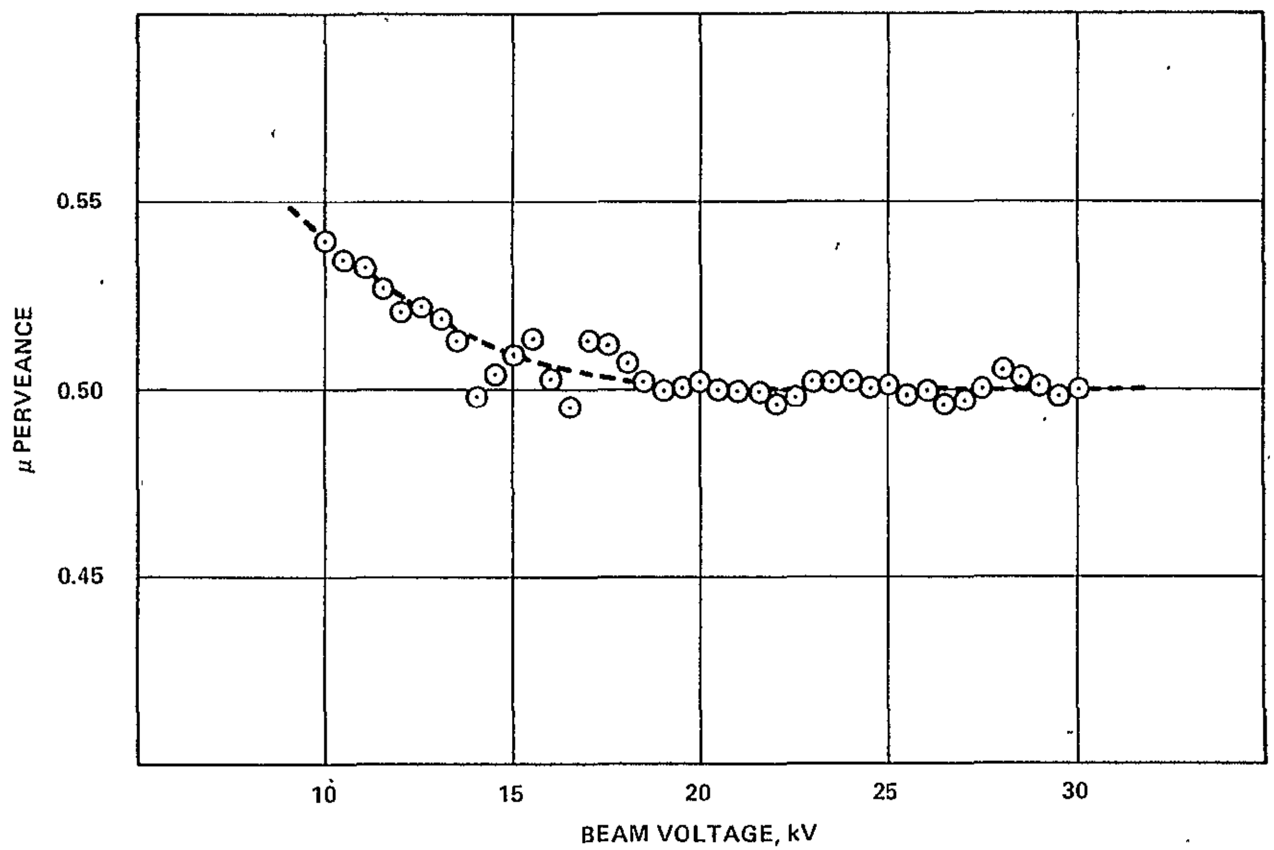

Figure 14. VKS-7773 Klystron, Electron Gun μperv vs Beam Voltage

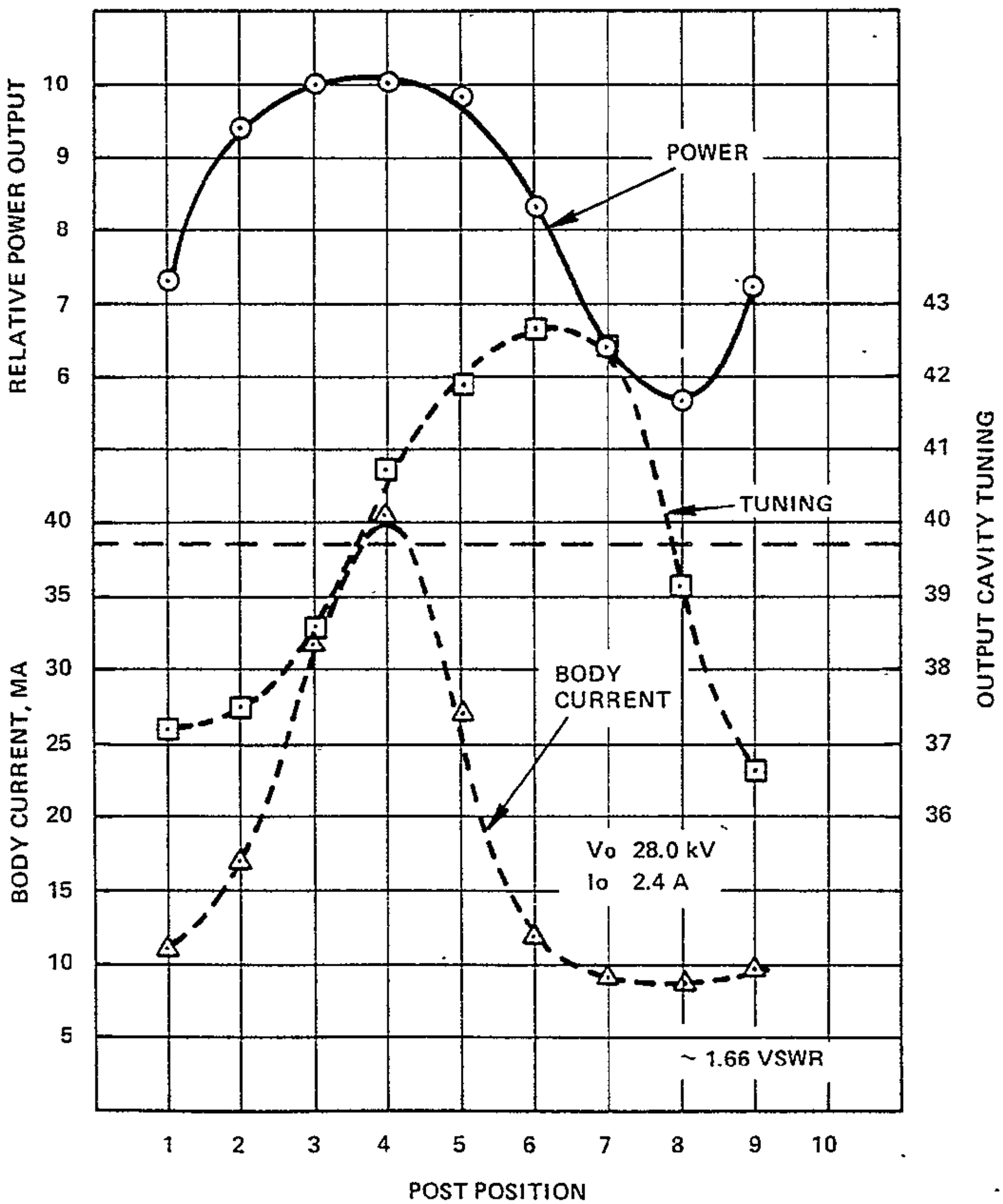

Figure 15. VKS-7773 Klystron, Relative Power Output, Output Cavity Tuning, and Body Current vs Reactive Post Position in Impedance Transformer

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gain tends to increase at one post position because of higher resonant gap voltage. Body current is higher because this increased gap voltage causes beam interception. At the other position resonant gap voltage is lower, gain is lower, and body current interception is lower. This position represents increased output cavity coupling.

With electromagnet currents set at values employed during recorded tests of seven years earlier, attempts to increase rf drive into the saturation and high power region were thwarted by excessive body current. Body current must be limited to about 0.1 A in the tube to avoid damage to the tip of the output drift tube. The tube could be saturated with other adjustments of the electromagnet currents, but these merely "squeezed" the electron beam at the output gap, avoiding excessive body current, but also restricting power output. The maximum power observed in one of these checks was 27.6 kW at an efficiency of 43 percent, far below anticipated performance.

One other departure from normal conditions evident from rf tests was the tuner dial reading for the output cavity at resonance. If differed substantially from hot test values recorded in the tests of seven years ago, although it agreed closely, evidently coincidentally, with cold test values of that period. It is possible that the output cavity drift tubes may have been damaged since the original tests, as it now appears that the tube has been used at least once or twice in the interim, possibly as a dc load. Inadvertent misadjustment of the magnetic fields employed could have caused damage. An unsuccessful attempt was made to x-ray the output cavity interaction gap to check the drift tubes, but the photos obtained did not show sufficient detail to be definitive. Apparently the question could be settled only by tube disassembly, and this was not contemplated unless further attempts at testing, with the best possible electromagnet configuration, were unsuccessful.

V. TESTS ON THE VKS-7773 ELECTROMAGNET

The behavior of the electromagnet became suspect during first hot tests of the klystron. The tube was removed, and the electromagnet was disassembled for examination. Interior weldments made during assembly of the electromagnet appeared to have caused superficial damage to the exterior of the coil windings in a number of places. The lower coil (nearest the electron gun) was found to be separated from the top coils, so that a common axis of magnetic field did not exist. It is not known at this time whether this feature was intended in original electromagnet manufacture or not. If the coils were originally fastened together in one unit by epoxy, for example, they are separated now. The weldments protruding toward the exterior of the coils were filed down and made smooth. It is not known whether or not the external coil damage had actually caused partial shorts in windings. Hopefully it had not. Consultation with the Varian electromagnet group elicited the information that such damage is extremely difficult to detect by any known electrical tests, short of magnetic field measurements.

It was decided to obtain suitable fixtures for making magnetic tests on the electromagnet. Reoperations were made to permit alignment of the bottom loose coil and the top coil assembly on a common axis. Magnetic parts duplicating those in the VKS-7773 klystron magnetic circuit were obtained in order to duplicate the tube. A precision measuring instrument was made available to the effort in May. Parts were obtained to permit use of this machine in the proposed tests.

The object of the test was to determine both the axial and transverse magnetic fields provided by the electromagnet and to optimize magnetic behavior by proper adjustments. During the tests, an attempt was to be made to adjust for a transverse magnetic field no greater than 0.2 percent of the axial. Whatever the outcome, magnetic field conditions would be known and useful for subsequent klystron testing.

Figure 16 is a photograph showing the magnetic circuit assembly simulating that of the VKS-7773 klystron (on the right) and the magnetic probe guide tube (on the left). The former assembly makes use of a strong aluminum center tube to support the

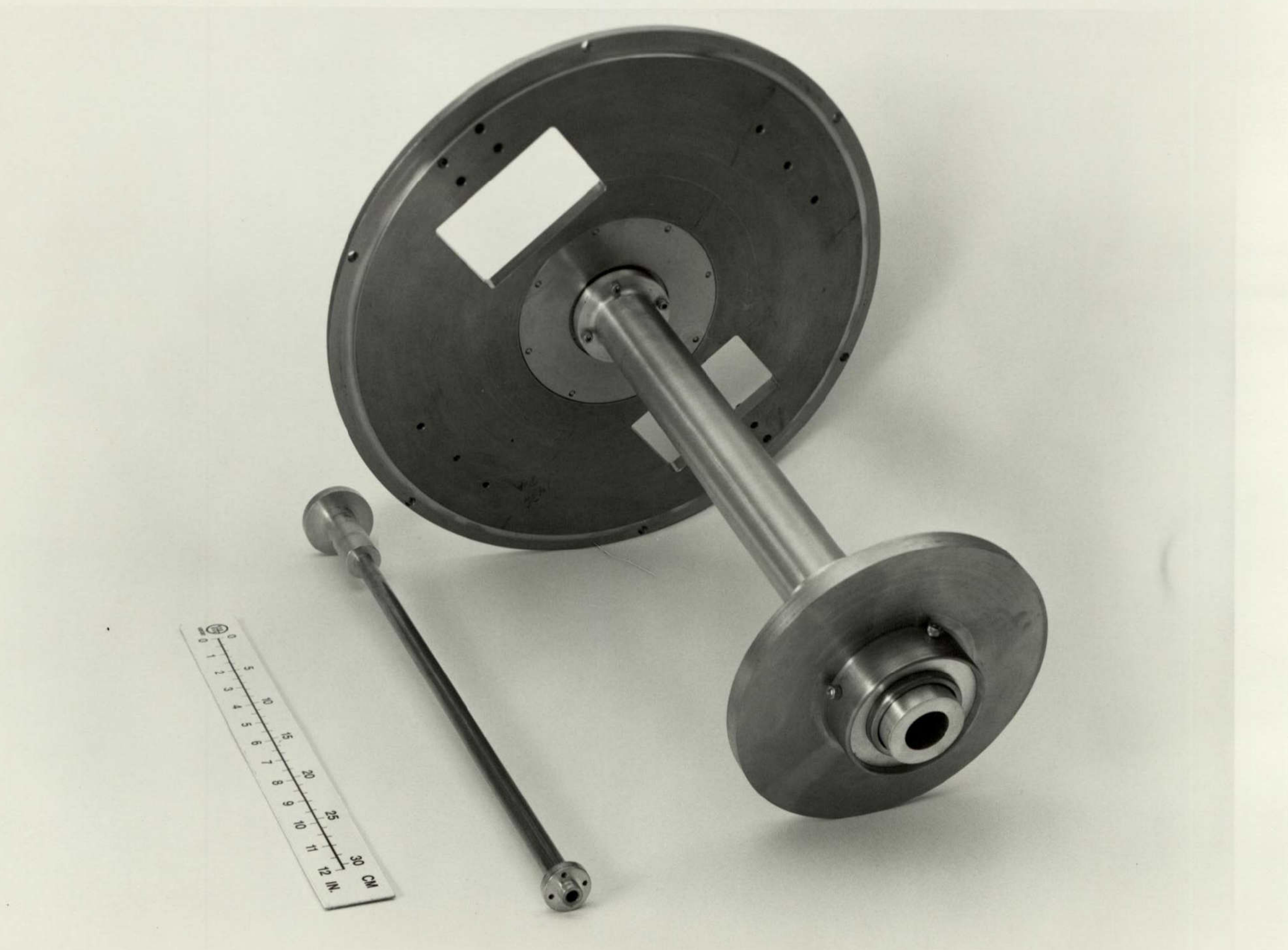


Figure 16. Photograph of Magnet Parts

large diameter collector magnetic pole at the one end and the several magnetic parts making up the electron gun magnetic circuit at the other end. The magnetic probe guide tube fits snugly inside the aluminum support tube and confines the magnetic probe to the region corresponding to the electron beam drift tunnel.

Figure 17 shows the test position. The electromagnet support table is in the right foreground with the electromagnet mounted underneath the top surface and the precision probe travel device mounted on top. A travel dial gives vertical probe position readout to within 0.001 inch. A Bell 620 Hall effect Gaussmeter and axial and transverse magnetic field probes were available for the measurements. The normal electromagnet power supplies and water cooling circuits available at the test position were employed.

The VKS-7773 electromagnet uses six coils. Five coils form one coil assembly starting with number one at the collector end. A single separate coil at the electron gun end completes the windings. The top coil assembly and the separate coil may be moved under control with respect to each other and the center axis of the electromagnet shell assembly.

The coil currents used during high power, high efficiency operation of the VKS-7773 klystron seven years ago and employed during first rf hot tests were:

Electromagnet
Coil Currents

I1 = 13.3 A (Collector end)

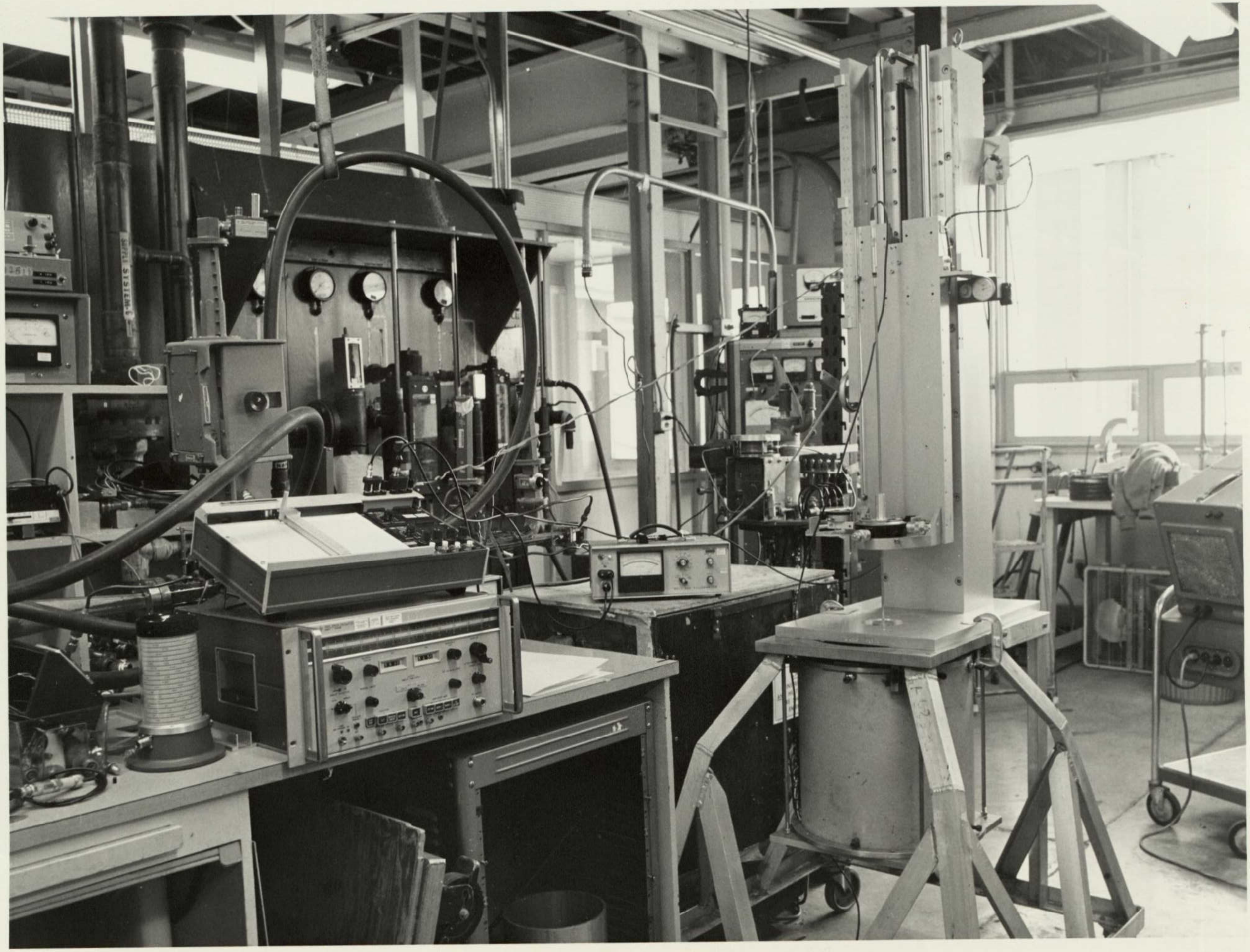
I2 = 10.2 A

I3 = 9.4 A

I4 = 10.2 A

I5 = 8.2 A

I6 = 8.2 A (Gun end)



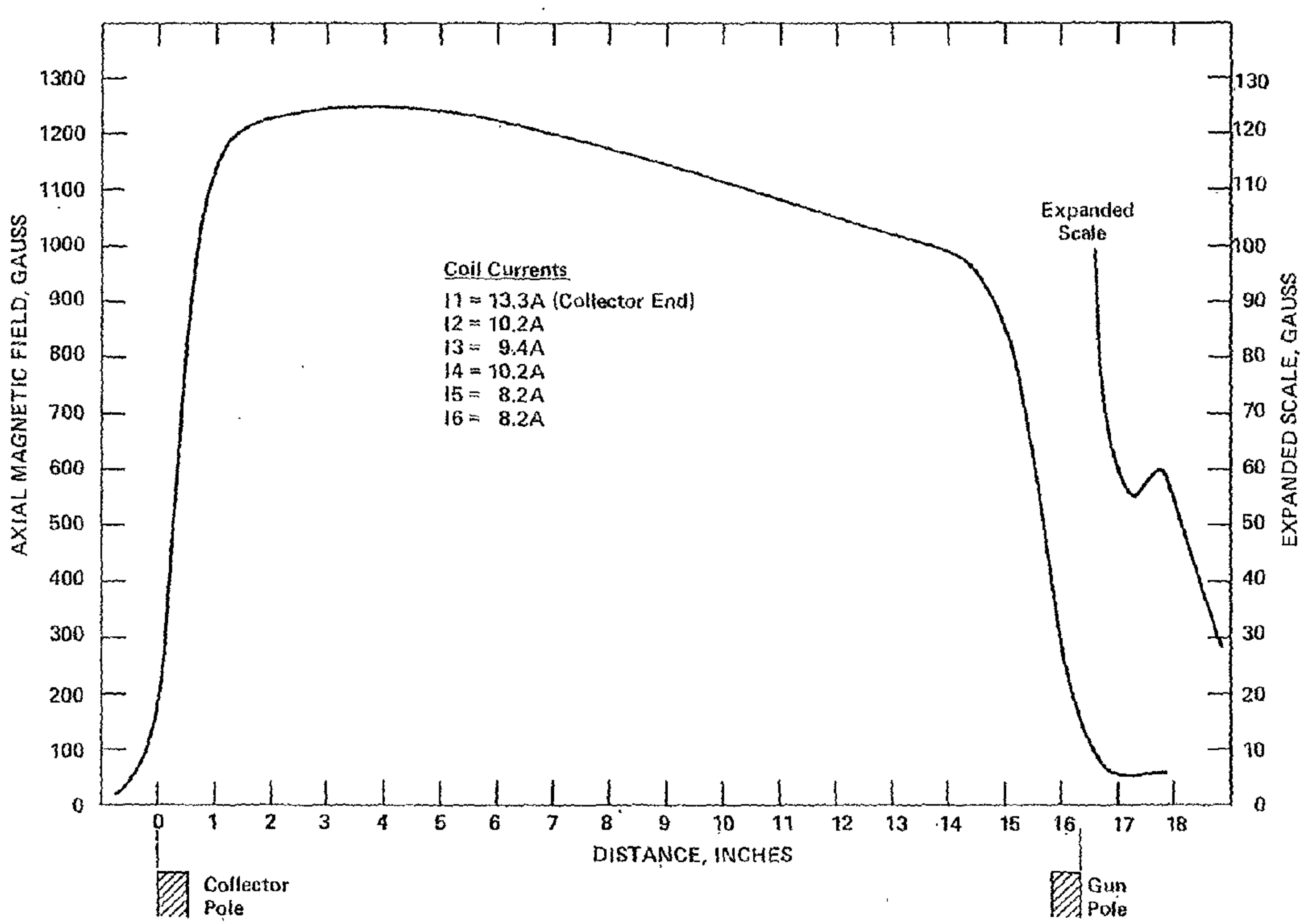


Figure 18. VKS-7773 Electromagnet, Axial Magnetic Focusing Field

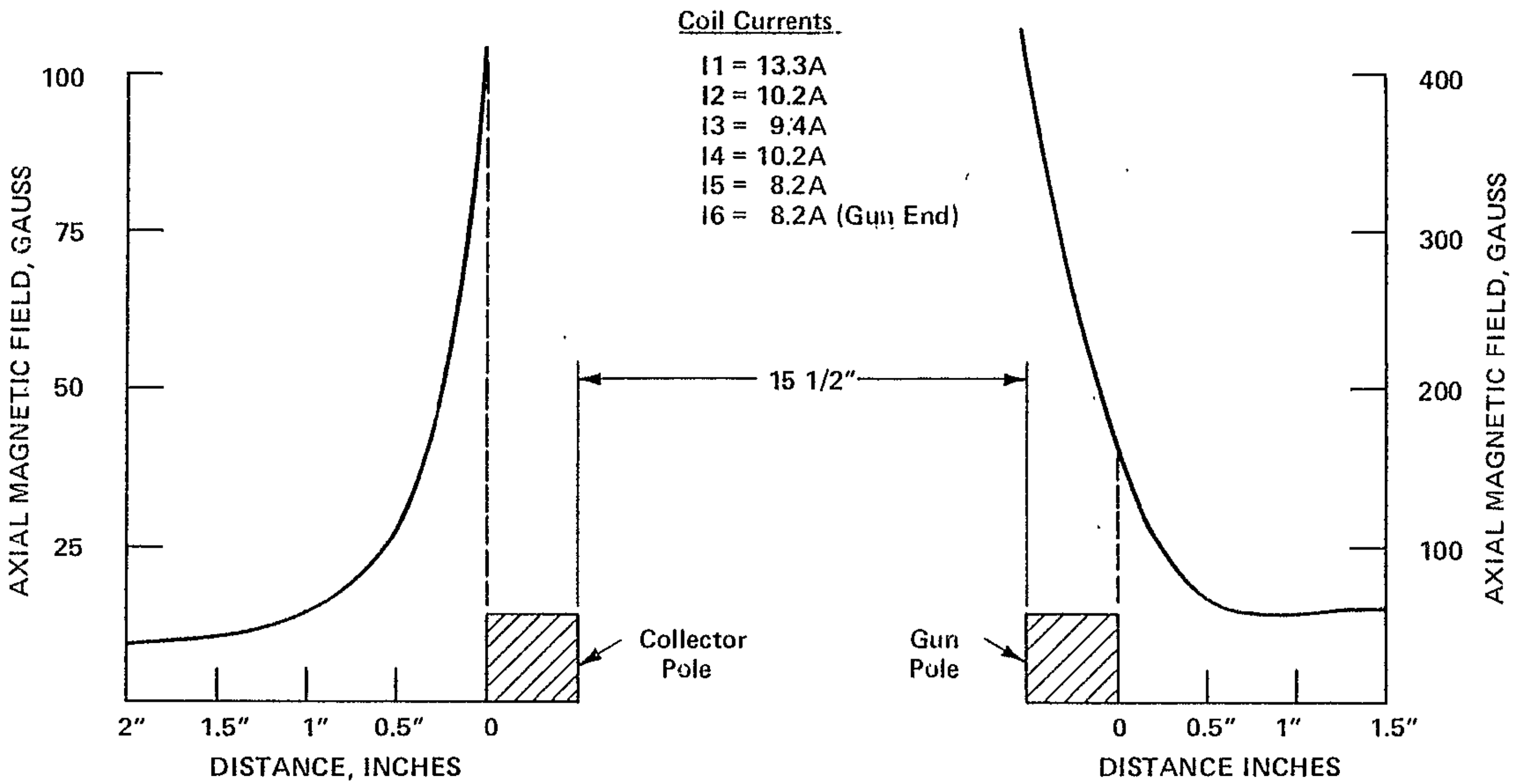


Figure 19. VKS-7773 Electromagnet, Axial Magnetic Fields Observed at Ends

In this case, $\bar{A}$ is the vector component caused by axial field effects, while $\bar{B}$ is the desired transverse component. The technique works reasonably well when the transverse magnetic field observations are relatively large and the rotational angle well defined.

The data in Figure 20 were obtained by this method. This was an initial test with the top coil assembly and the bottom coil geometrically centered on the axis of the electromagnet by physical measurement. Observations were made every inch along the electromagnet axis. A few measurements were also made at half-inch positions. The relative angles of the maximum measurements are shown for each measurement. The length of each vector indicates magnitude of transverse magnetic field component, the vector $\bar{B}$ described earlier. It is plain that a strong transverse magnetic field exists in one direction between the magnetic polepieces.

The transverse probe was centered within the electromagnet coil structure for adjustments to minimize transverse magnetic field components. The procedure involved small motions of the top coil assembly and of the bottom coil, one at a time, and rotation of the transverse probe to determine results. The optimum adjustment would be one in which the maximum observation were reduced and the minimum observation increased. With no transverse magnetic field, in other words, the probe should show a uniform response in all directions. This happy condition could not be realized, though an important reduction in transverse magnetic field was achieved. Figure 21 shows the results of the exercise. The top curve of Figure 21 shows the data of Figure 20 with only transverse magnetic field magnitude shown. The bottom curve shows similar data for the condition minimizing transverse magnetic field. It was not possible to eliminate transverse magnetic field all along the electromagnetic axis. The general contour of vector components varied first in one region, then in another, as the coils were shifted about. The lower illustration of Figure 21 shows the compromise situation arrived at after several hours of coil adjustment and measurement. It may be mentioned that the rotational angles of the vectors of the lower data showed more or less random direction from one to the next.

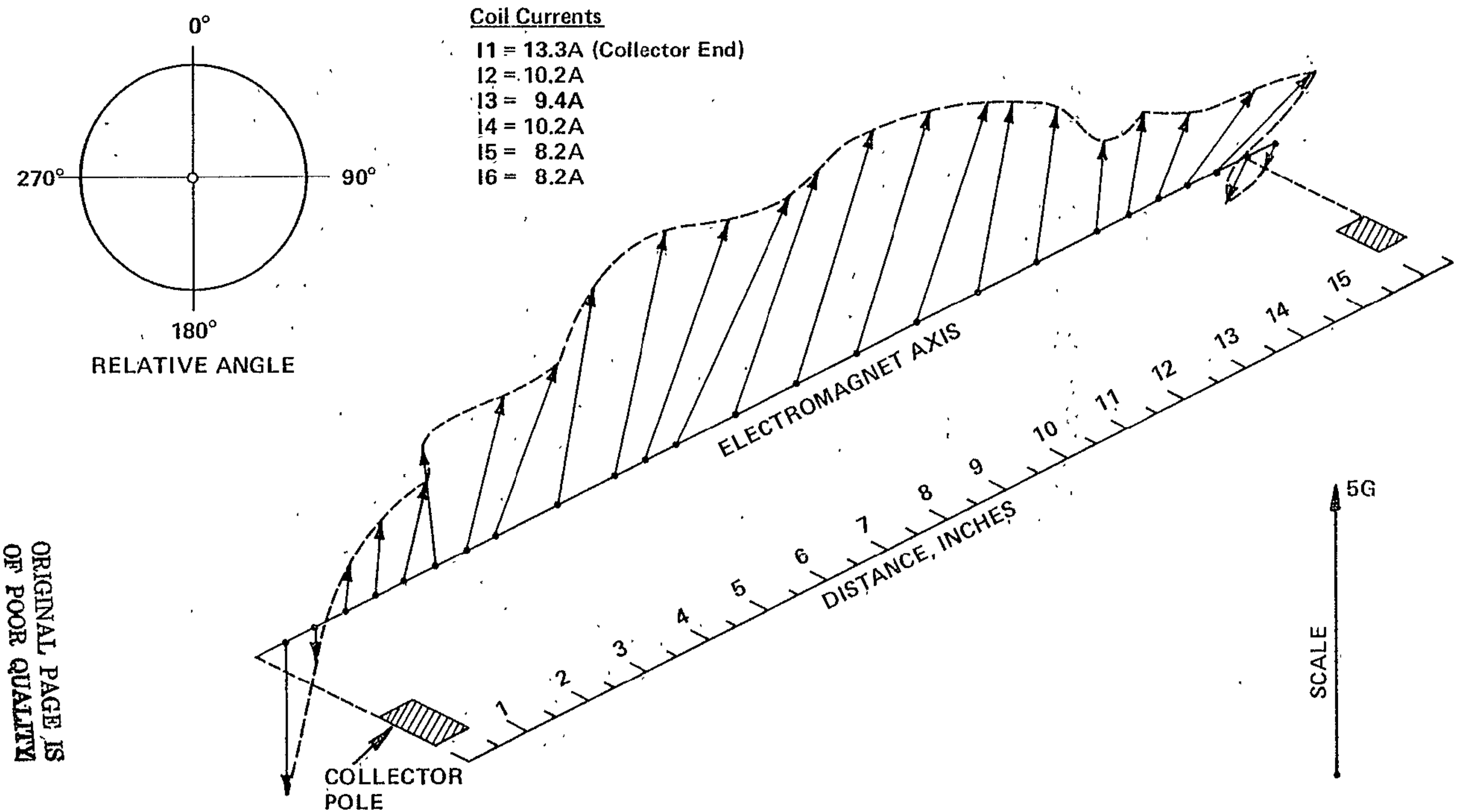


Figure 20. VKS-7773 Electromagnet, Transverse Magnetic Field Observed With Bottom Coil and Top Coil Assembly Geometrically Centered on Axis.

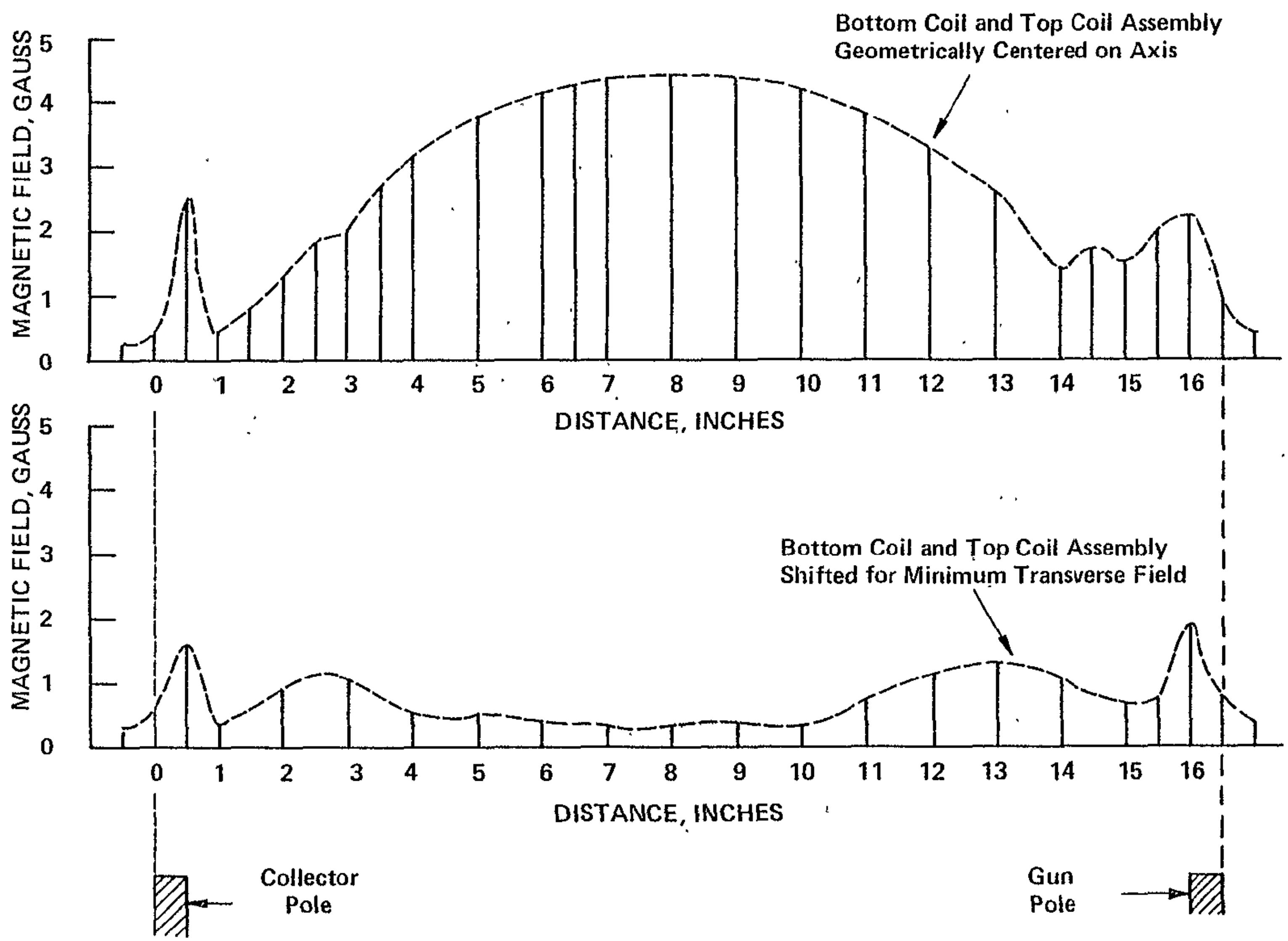


Figure 21. VKS-7773 Electromagnet, Observations of Magnitude of Transverse Magnetic Field for Two Adjustments of Coil Positions.

Relatively precise measurements of transverse magnetic field may be made by taking measurements along four rotational angles 90° apart. Such data may be resolved, for example, by determining the vector associated with each of the pairs of reciprocal angles, then taking the results of these two. Measurements of this type were obtained using an X-Y plotter operating from X output from the precision probe motion device and Y output from the Gauss-meter. These data are shown in Figures 22 and 23.

The ballistic trajectory of an electron may be computed in the presence of the transverse magnetic field indicated by these measurements if certain simplifying conditions are assumed. These are that the axial magnetic field be taken as constant, a reasonable approximation in the high magnetic field region, and that the electron be injected at full beam voltage along the axis at the electron gun end. A Varian computer program is set up to make this calculation. The output is given in terms of X and Y coordinates and in distance off the axis that the electron moves in traveling along the axis under the influence of the axial and transverse magnetic fields. The computation was made for the case represented by Figures 22 and 23 with the simplifying assumptions. The data are shown in Appendix B. The results indicate a relatively minor effect on electron trajectory by the transverse magnetic fields in the central portion of the distance between magnetic polepieces, thirteen inches out of a total of fifteen and one-half inches from electron gun pole to collector pole.

However, the plots of Figures 22 and 23 do indicate stronger transverse magnetic fields at the ends, close to the magnetic poles. These might be important, especially in the region near the electron gun.

It was felt that approximately the best possible magnetic field arrangement had been obtained with the VKS-7773 electromagnet, and it remained to retest the tube.

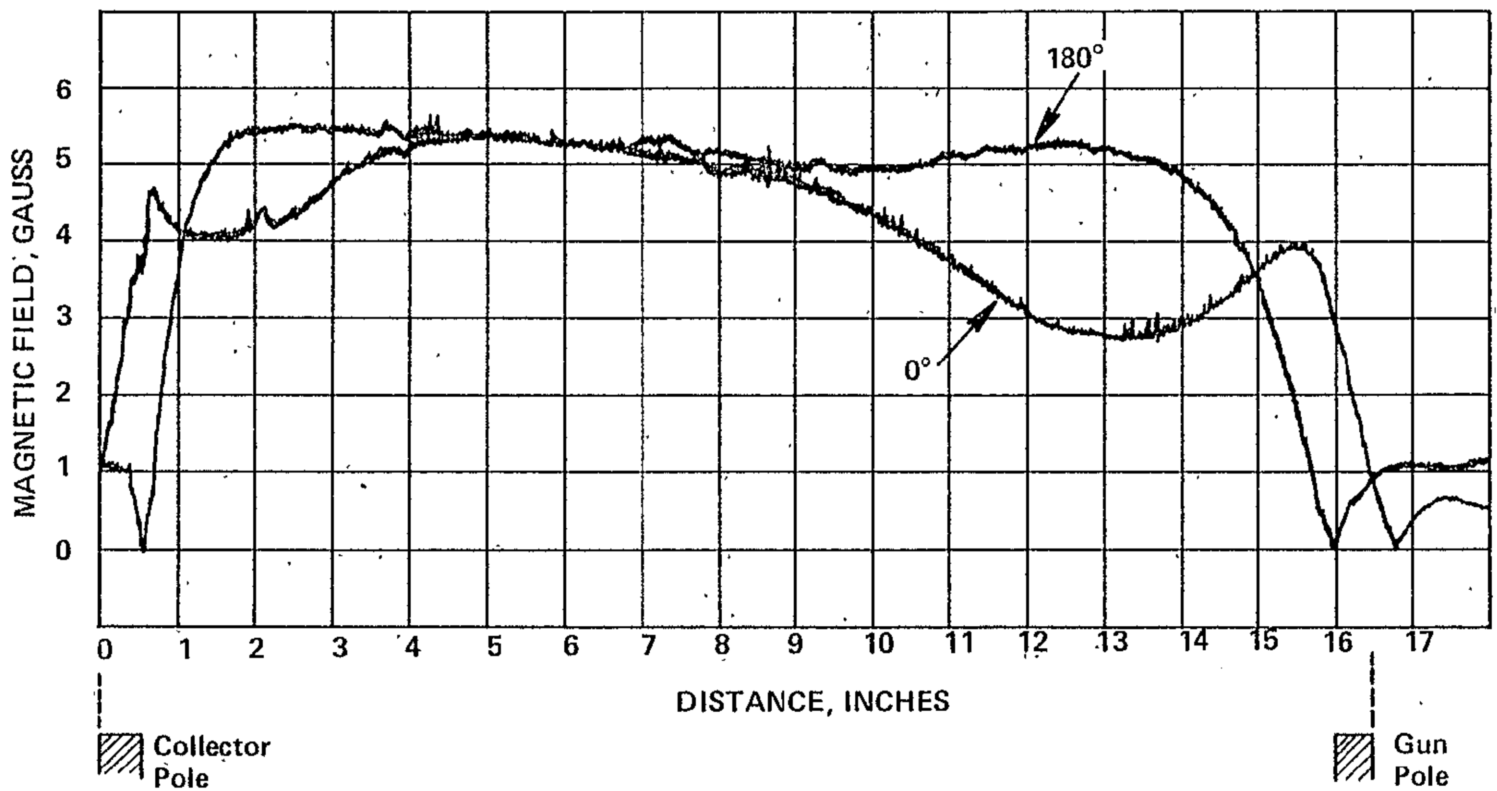


Figure 22. VKS-7773 Electromagnet, Transverse Magnetic Field Measurements.

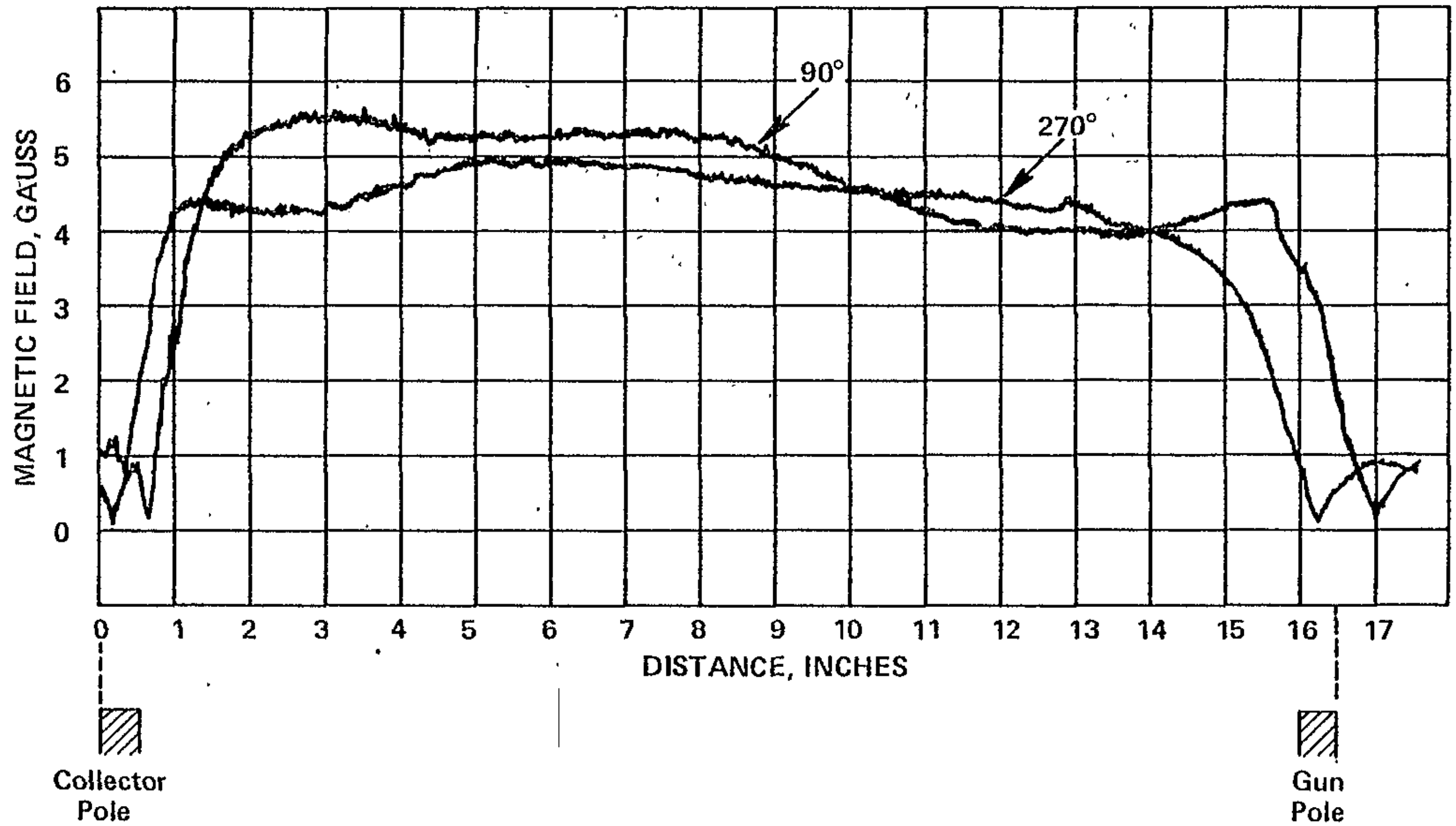


Figure 23. VKS-7773 Electromagnet, Transverse Magnetic Field Measurements.

VI. SECOND HOT TESTS OF VKS-7773

The VKS-7773 50 kW cw high efficiency klystron was placed in the test socket for a second round of hot tests on May 27, and turned on June 6. DC beam tests without rf were conducted first. Beam current and electron beam μperveance were noted at intervals of one-half kV over the voltage range from 5 to 30 kV.

Figure 24 shows the results of observations of electron beam current and μperveance. A beam current meter of 0.5% accuracy was installed in series with the regular 2% accuracy meter mounted on the test set control panel. Readings from the more accurate meter were used. The data of Figure 24 indicate an electron beam μperveance slightly under 0.5, close to the anticipated value and adequate for the contemplated tests.

Figure 25 shows observations of body current as a function of electron beam voltage. The data may be compared to that of Figure 14. The cyclical nature of body current vs beam voltage is similar. The maximum excursions of current are approximately double those observed during the first tests, while the minimum values are about the same. The minimum values occur at close to the same beam voltages in each case.

DC body current was close to a minimum of 5 milliamperes in the beam voltage ranges 23-24 kV and 27-28 kV. A beam voltage of 23.8 kV was selected for rf tests and adjustment of load coupling.

RF was first applied at small signal level, and the impedance transformer was adjusted in steps to determine optimum coupling for a beam voltage of 23.8 kV. In several instances, rf power output either jumped sporadically to values 2 to 3 dB higher than levels under observation or sometimes sagged from the higher levels toward the lower over a period of several minutes. Data obtained during the tests were considered questionable, and it was decided to increase rf drive to a level of the order of 0.5 watt. Except for two instances of unexplained arcing and momentary surges of VacIon indication to about 10^{-6} Torr, the tube operated quite stably

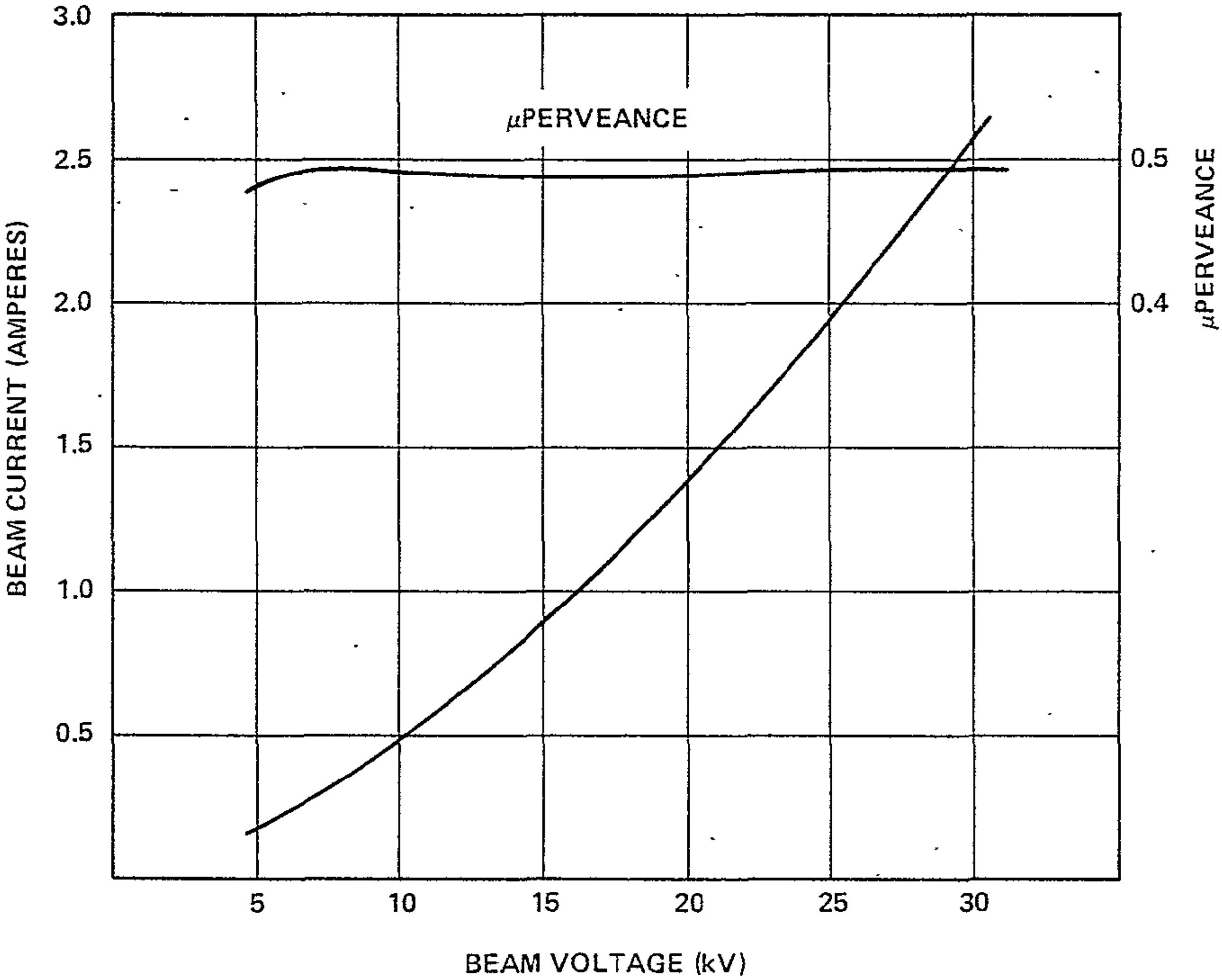


Figure 24. VKS-7773 Beam Current and μperveance vs Beam Voltage During Second Hot Tests

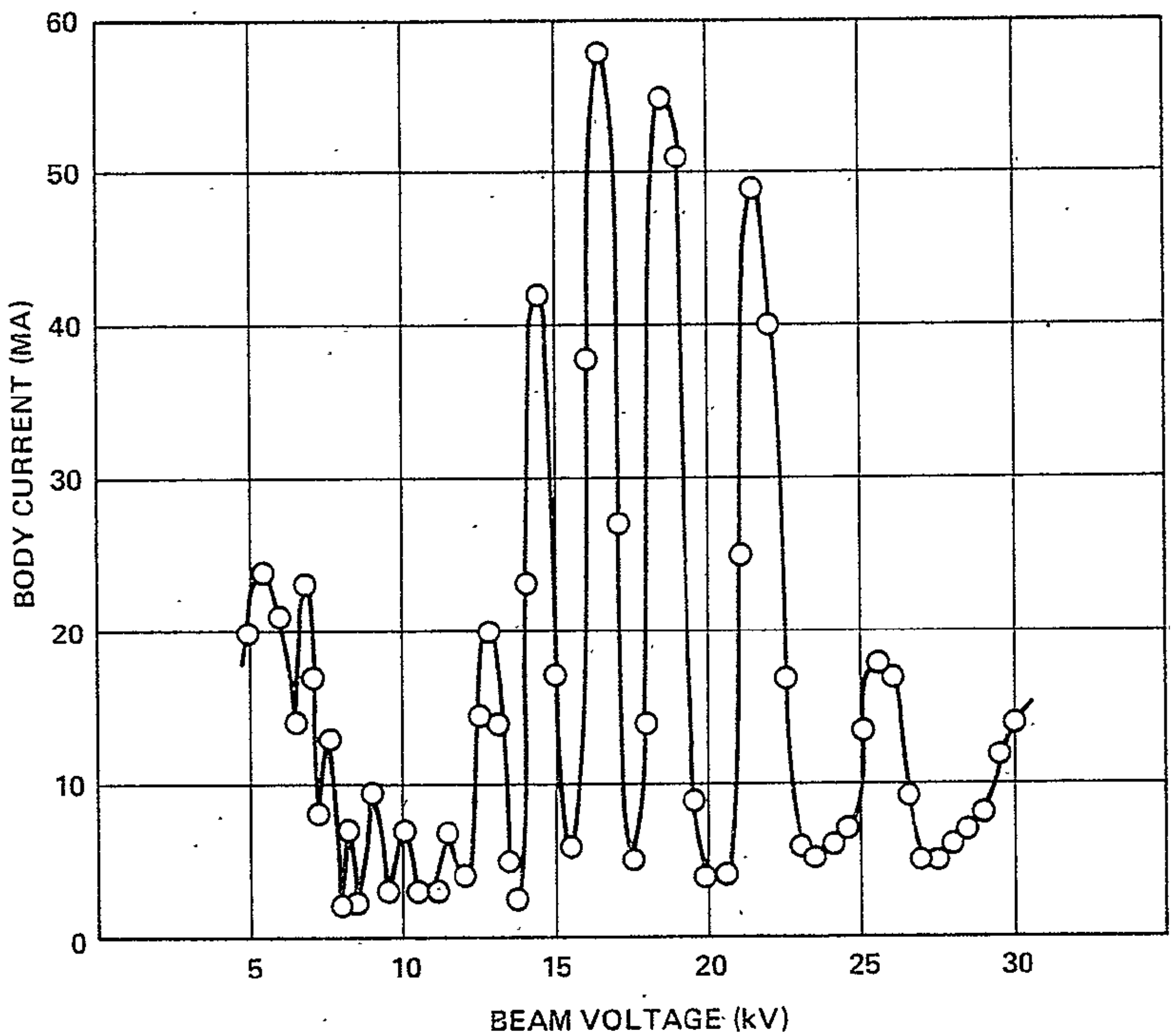


Figure 25. VKS-7773 Body Current vs Beam Voltage During Second Hot Tests

at higher rf drive level and power output. During further tests under these conditions the output impedance transformer adjustment for proper coupling, as indicated by minimum body current at high rf drive, was determined with the 1.45 VSWR impedance transformer in use at the time. With incorrect adjustment, for example, body current read about 85 milliamperes at 0.5 watt rf drive; whereas with correct adjustment the same rf drive level resulted in about 20 milliamperes body current. Thus, it appeared that rf drive saturation and maximum power output capability might now be possible.

In anticipation of saturation rf drive tests, the seven rf driver cavities were adjusted to their proper tuner settings. Then, the eighth or output cavity was tuned for maximum power output. While this adjustment was being made, klystron power output suddenly dropped to zero, and the VacIon indication increased from $< 10^{-8}$ to about 10^{-4} Torr. The tube had gone down to air.

It was thought that the output cavity tuner bellows, which provides the vacuum wall around the movable tuner drive plunger, had failed, since failure had occurred during output cavity tuning. A leak check conducted on June 8, however, showed that the leak had developed in the number 5 cavity tuner. This unfortunate circumstance prevented further testing of the tube.

The exact cause of failure in the number 5 cavity tuner is not known. Possibly the somewhat erratic behavior of the power output observed with low levels of rf drive is a clue to malfunction. Eventual scrap analysis and repair of the VKS-7773 may reveal the problem. The tube is begin held at present for further effort in this direction should it finally be desired.

VII. RECOMMENDATIONS

The VKS-7773 would be the starting point for any development work on the ultimate space power satellite klystron.

Repair, modification, and retest might be the first steps in such a program. Recommendations for such an initial effort might include:

1. Construction of a new and zero transverse field electromagnet.
2. Modifications to optimize output coupling.
3. Check of all cavities and changes to modern design where indicated.

A conceptual design for a space power satellite tube based on the VKS-7773 klystron was presented at the 1976 IEDM. A reprint of this presentation is included as Appendix C.

APPENDIX A

EXHIBIT "B"

STATEMENT OF WORK

FOR

50 kW VKS-7773 CW KLYSTRON EVALUATION

CONTENTS

1.0 PURPOSE

1.1 OBJECTIVE

The objective of this statement of work (SOW) is to describe the efforts required to determine and evaluate the optimum electrical characteristics of a cw 50 kW power output klystron at 2.45 GHz. The effort includes the evaluation of the current status of this klystron including power efficiency, temperatures, effects of tuning at a single frequency, effects of increase of beam voltage, etc.

1.2 END PRODUCTS

The end product shall be a final report which documents:

a. The procedures to optimize the tuning, the gain, the efficiency and all other necessary steps to evaluate the current state of the VKS-7773 high efficiency klystron cw amplifier, having a minimum of 74% efficiency.

b. The testing of the VKS-7773 50 kW power amplifier at voltages up to 35-40 kilovolts to determine the optimum efficiency performance as a function of:
   (1) electron beam voltage
   (2) magnetic field
   (3) cavity tuning
   (4) variations in load impedance
   (5) RF drive level
   (6) current

c. Measure the following parameters:
   (1) Temperature of cathode and anode while tube is in various cw power operations.
   (2) Noise spectrum as a function of input current. Magnetic field and RF drive level for well-matched input and output conditions.
   (3) Noise spectrum as a function of transient conditions at start-up and shut-down.
   (4) Under optimum conditions as determined from 1.2-b, above, measure AM noise and estimate PM noise in a narrow bandwidth (1-3 KHz) for various frequency displacements from the carrier frequency (in dB per MHz below the nominal power output).
   (5) Gain and bandwidth and all operational DC and RF parameters for this tube.

d. Analyze the results of the tests described and prepare a comprehensive report on these results and their implications regarding design of a high efficiency (85-90%) klystron for ultimate space use. From the data gathered in paragraphs above, contractor shall recommend design modifications to further optimize efficiency and reduce noise. The contractor shall identify primary sources of noise in the klystron and recommend possible solutions to such problems. Contractor shall provide a conceptual design of the flight configuration klystron.

1.3 BACKGROUND

A solar power station will convert solar energy into electrical energy; this energy is then transmitted from the solar satellite station in geosynchronous orbit to the earth via an S-band microwave system. The tentative operating frequency for the microwave beam is 2.45 GHz.

One essential link in the conversion of solar energy into electrical energy is the DC-microwave converter. One of the possible DC-microwave converters under consideration is the 50 kilowatt power output high efficiency klystron operating at cw. One laboratory model has been designed and fabricated to operate under these conditions for another industrial use and for terrestrial applications. This laboratory model can be altered to meet some of the basic requirements for the solar energy to microwave conversion.

This work is intended to clarify what detailed testing of the VKS-7773 klystron is needed, define the equipment and facilities required and perform those specified tests with existing equipment. Finally, evaluation of the data and recommendations for design modifications will result.

2.0 TECHNICAL REQUIREMENTS

2.1 STUDY REQUIREMENTS

The contractor will be required to develop approaches or concepts that are applicable to the fulfillment of the technical objectives set forth in this statement of work. These will be results of concept and feasibility requirements, tradeoff analyses, engineering assessments, and/or other specified identified investigations.

2.2 TASK DESCRIPTION

The contractor shall perform the following tasks to determine the current status of the VKS-7773 high efficiency cw klystron after it has been tuned to optimum operating conditions.

a. Record the procedures for testing the VKS-7773 klystron. Test it at 2.45 GHz frequency for optimum efficiency and minimal noise while recording variations in applied voltage,magnetic field, load impedance and RF drive level.

b. Record temperatures, noise values, gain and bandwidth during these tests.

c. Analyze and evaluate the results and recommend design modifications to maximize efficiency, minimize noise, lower weight, improve heat removal to produce a conceptual design for a flight configuration klystron.

3.0 PROGRAM MANAGEMENT REQUIREMENTS

3.1 CONFERENCE REQUIREMENTS

The contractor shall support formal reviews. These reviews shall be at NASA-JSC, and the contractor will prepare and make available to the attendees all documentation necessary to accomplish the objective of the review.

3.2 CONTRACTOR DATA MANAGEMENT

The contractor will maintain as a ready reference for NASA-JSC a complete listing of all source documents utilized during the contract period of performance. (This listing shall be included in the final report.)

3.3 DOCUMENTATION REQUIREMENTS

The contractor will furnish all data items identified and described on the DRL (Data Requirements List), JSC form 2323, and in supplemental DRL's to be subsequently furnished to or developed by the contractor for additional data which the Government requests. The data items will be prepared in accordance with the DRD (Data Requirements Description), NASA form 9, attached to the DRL and referenced on the DRL for each line of data specified thereon. Where practical, the contractor's own internal documents will be utilized to meet and/or supplement the requirements specified herein. Internal documents need not be retyped and/or duplicated by a printing process prior to submission.

APPENDIX B

COMPUTER-CALCULATED ELECTRON BEAM IN A TRANSVERSE MAGNETIC FIELD

EETMF 11:29 05/26/77 THURSDAY 101

ELECTRON BEAM IN TRANSVERSE MAGNETIC FIELDS

V0= 28.00 KV BZ= 1180.0 GAUSS
DZ=0.0100 IN L= 1.1367 IN

Z(IN)	R MILS	X MILS	Y MILS	VX(IN/SEC)	VY(IN/SEC)	BX	BY
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
0.100	0.010	0.010	0.003	6.970E+05	2.916E+05	-0.1	0.4
0.200	0.039	0.034	0.020	1.015E+06	1.051E+06	-0.2	0.4
0.300	0.084	0.059	0.060	7.637E+05	2.010E+06	-0.3	0.3
0.400	0.143	0.069	0.126	-7.583E+04	2.841E+06	-0.4	0.3
0.500	0.214	0.051	0.208	-1.349E+06	3.253E+06	-0.5	0.2
0.600	0.294	-0.004	0.294	-2.771E+06	3.081E+06	-0.6	0.2
0.700	0.379	-0.095	0.367	-4.014E+06	2.333E+06	-0.7	0.1
0.800	0.466	-0.214	0.414	-4.802E+06	1.191E+06	-0.8	0.1
0.900	0.551	-0.346	0.429	-4.995E+06	-4.957E+04	-0.9	0.0
1.000	0.630	-0.475	0.414	-4.631E+06	-1.061E+06	-1.0	0.0
1.100	0.699	-0.589	0.377	-3.879E+06	-1.650E+06	-1.0	-0.0
1.200	0.756	-0.680	0.330	-2.972E+06	-1.732E+06	-1.0	-0.0
1.300	0.802	-0.748	0.289	-2.200E+06	-1.303E+06	-1.1	-0.1
1.400	0.843	-0.801	0.264	-1.811E+06	-5.077E+05	-1.1	-0.1
1.500	0.889	-0.850	0.263	-1.941E+06	3.969E+05	-1.1	-0.1
1.600	0.952	-0.909	0.284	-2.569E+06	1.123E+06	-1.1	-0.1
1.700	1.039	-0.989	0.319	-3.527E+06	1.435E+06	-1.1	-0.1
1.800	1.153	-1.097	0.356	-4.549E+06	1.222E+06	-1.2	-0.2
1.900	1.287	-1.230	0.380	-5.351E+06	5.277E+05	-1.2	-0.2
2.000	1.430	-1.378	0.381	-5.711E+06	-4.599E+05	-1.2	-0.2
2.100	1.570	-1.529	0.355	-5.519E+06	-1.492E+06	-1.2	-0.2
2.200	1.695	-1.667	0.304	-4.807E+06	-2.296E+06	-1.2	-0.2
2.300	1.798	-1.782	0.237	-3.772E+06	-2.631E+06	-1.2	-0.2
2.400	1.876	-1.868	0.169	-2.708E+06	-2.398E+06	-1.1	-0.2
2.500	1.932	-1.929	0.114	-1.918E+06	-1.666E+06	-1.1	-0.2
2.600	1.976	-1.975	0.082	-1.622E+06	-6.538E+05	-1.1	-0.2
2.700	2.022	-2.020	0.079	-1.895E+06	3.383E+05	-1.1	-0.2
2.800	2.082	-2.080	0.098	-2.641E+06	1.014E+06	-1.1	-0.2
2.900	2.167	-2.163	0.128	-3.623E+06	1.173E+06	-1.1	-0.2
3.000	2.278	-2.272	0.155	-4.536E+06	7.680E+05	-1.0	-0.2
3.100	2.407	-2.401	0.165	-5.085E+06	-9.749E+04	-1.0	-0.2
3.200	2.542	-2.538	0.148	-5.074E+06	-1.179E+06	-1.0	-0.2
3.300	2.668	-2.666	0.103	-4.471E+06	-2.149E+06	-0.9	-0.2
3.400	2.772	-2.772	0.037	-3.425E+06	-2.715E+06	-0.9	-0.2
3.500	2.848	-2.847	-0.036	-2.212E+06	-2.703E+06	-0.9	-0.2
3.600	2.893	-2.892	-0.102	-1.161E+06	-2.112E+06	-0.8	-0.2
3.700	2.917	-2.913	-0.145	-5.512E+05	-1.114E+06	-0.8	-0.2
3.800	2.931	-2.926	-0.160	-5.316E+05	4.548E+01	-0.8	-0.2
3.900	2.950	-2.946	-0.147	-1.075E+06	9.021E+05	-0.7	-0.2
4.000	2.989	-2.987	-0.116	-1.985E+06	1.329E+06	-0.7	-0.2
4.100	3.054	-3.053	-0.082	-2.950E+06	1.155E+06	-0.7	-0.1
4.200	3.142	-3.141	-0.060	-3.636E+06	4.413E+05	-0.6	-0.1
4.300	3.242	-3.242	-0.061	-3.801E+06	-5.862E+05	-0.6	-0.1
4.400	3.340	-3.338	-0.091	-3.359E+06	-1.607E+06	-0.5	-0.1
4.500	3.419	-3.416	-0.144	-2.402E+06	-2.303E+06	-0.5	-0.1
4.600	3.470	-3.464	-0.208	-1.178E+06	-2.454E+06	-0.5	-0.1
4.700	3.490	-3.479	-0.269	-1.366E+04	-1.999E+06	-0.4	-0.0

4.800	3.482	-3.468	-0.311	7.827E+05	-1.060E+06	-0.4	-0.0
4.900	3.458	-3.443	-0.324	1.012E+06	9.715E+04	-0.3	-0.0
5.000	3.433	-3.419	-0.306	6.434E+05	1.143E+06	-0.3	0.0
5.100	3.423	-3.412	-0.266	-1.747E+05	1.802E+06	-0.3	0.0
5.200	3.437	-3.430	-0.215	-1.177E+06	1.918E+06	-0.3	0.0
5.300	3.478	-3.474	-0.169	-2.050E+06	1.475E+06	-0.3	0.1
5.400	3.539	-3.536	-0.140	-2.520E+06	6.243E+05	-0.2	0.1
5.500	3.606	-3.603	-0.137	-2.433E+06	-3.622E+05	-0.2	0.1
5.600	3.664	-3.661	-0.158	-1.801E+06	-1.172E+06	-0.2	0.1
5.700	3.701	-3.696	-0.195	-7.970E+05	-1.545E+06	-0.2	0.1
5.800	3.710	-3.702	-0.235	2.934E+05	-1.351E+06	-0.2	0.2
5.900	3.691	-3.682	-0.263	1.160E+06	-6.289E+05	-0.2	0.2
6.000	3.654	-3.645	-0.266	1.560E+06	4.249E+05	-0.2	0.2
6.100	3.612	-3.604	-0.240	1.372E+06	1.526E+06	-0.2	0.2
6.200	3.581	-3.576	-0.187	6.419E+05	2.368E+06	-0.2	0.2
6.300	3.575	-3.573	-0.118	-4.124E+05	2.703E+06	-0.2	0.2
6.400	3.599	-3.598	-0.048	-1.478E+06	2.437E+06	-0.2	0.2
6.500	3.649	-3.649	0.007	-2.236E+06	1.654E+06	-0.2	0.2
6.600	3.713	-3.713	0.037	-2.463E+06	5.923E+05	-0.2	0.2
6.700	3.775	-3.775	0.039	-2.090E+06	-4.284E+05	-0.2	0.2
6.800	3.820	-3.820	0.018	-1.228E+06	-1.099E+06	-0.2	0.2
6.900	3.838	-3.838	-0.014	-1.344E+05	-1.215E+06	-0.2	0.2
7.000	3.828	-3.828	-0.042	8.658E+05	-7.373E+05	-0.2	0.2
7.100	3.796	-3.796	-0.050	1.467E+06	1.908E+05	-0.1	0.2
7.200	3.755	-3.755	-0.030	1.486E+06	1.286E+06	-0.1	0.2
7.300	3.722	-3.722	0.017	9.207E+05	2.216E+06	-0.1	0.2
7.400	3.710	-3.709	0.084	-5.466E+04	2.701E+06	-0.1	0.2
7.500	3.729	-3.726	0.156	-1.145E+06	2.592E+06	-0.1	0.2
7.600	3.775	-3.769	0.217	-2.022E+06	1.915E+06	-0.1	0.2
7.700	3.837	-3.829	0.255	-2.419E+06	8.679E+05	-0.1	0.2
7.800	3.901	-3.892	0.263	-2.213E+06	-2.423E+05	-0.1	0.2
7.900	3.949	-3.942	0.244	-1.462E+06	-1.090E+06	-0.1	0.2
8.000	3.972	-3.967	0.209	-3.828E+05	-1.428E+06	-0.1	0.2
8.100	3.966	-3.962	0.173	7.076E+05	-1.164E+06	-0.1	0.2
8.200	3.935	-3.932	0.152	1.493E+06	-3.857E+05	-0.1	0.2
8.300	3.891	-3.887	0.155	1.750E+06	6.698E+05	-0.1	0.2
8.400	3.849	-3.844	0.187	1.411E+06	1.684E+06	-0.1	0.2
8.500	3.824	-3.817	0.242	5.869E+05	2.350E+06	-0.0	0.2
8.600	3.827	-3.815	0.307	-4.683E+05	2.466E+06	-0.0	0.2
8.700	3.858	-3.841	0.368	-1.431E+06	1.991E+06	-0.0	0.2
8.800	3.909	-3.888	0.409	-2.004E+06	1.062E+06	-0.0	0.2
8.900	3.965	-3.942	0.423	-2.008E+06	-4.773E+04	-0.0	0.2
9.000	4.010	-3.989	0.408	-1.433E+06	-1.014E+06	0.0	0.2
9.100	4.032	-4.015	0.373	-4.367E+05	-1.544E+06	0.0	0.2
9.200	4.025	-4.011	0.331	6.893E+05	-1.472E+06	0.0	0.2
9.300	3.991	-3.980	0.300	1.610E+06	-8.204E+05	0.0	0.2
9.400	3.941	-3.930	0.291	2.052E+06	2.180E+05	0.0	0.2
9.500	3.889	-3.876	0.312	1.882E+06	1.333E+06	0.0	0.2
9.600	3.852	-3.835	0.360	1.153E+06	2.194E+06	0.0	0.2
9.700	3.841	-3.818	0.424	8.001E+04	2.544E+06	0.0	0.2
9.800	3.862	-3.831	0.490	-1.017E+06	2.278E+06	0.0	0.2
9.900	3.907	-3.869	0.541	-1.810E+06	1.476E+06	0.0	0.2
10.000	3.963	-3.922	0.566	-2.065E+06	3.774E+05	0.0	0.2
10.100	4.013	-3.974	0.561	-1.686E+06	-6.794E+05	-0.0	0.2
10.200	4.042	-4.007	0.533	-7.709E+05	-1.351E+06	-0.0	0.2
10.300	4.043	-4.012	0.495	3.974E+05	-1.414E+06	-0.0	0.2
10.400	4.014	-3.987	0.463	1.462E+06	-8.255E+05	-0.0	0.3
10.500	3.965	-3.938	0.455	2.096E+06	2.624E+05	-0.1	0.3

10.600	3.910	-3.881	0.479	2.102E+06	1.550E+06	-0.1	0.3
10.700	3.870	-3.832	0.536	1.468E+06	2.677E+06	-0.1	0.3
10.800	3.857	-3.807	0.618	3.735E+05	3.333E+06	-0.1	0.3
10.900	3.879	-3.814	0.708	-8.649E+05	3.344E+06	-0.1	0.4
11.000	3.931	-3.851	0.790	-1.888E+06	2.733E+06	-0.1	0.4
11.100	4.001	-3.910	0.850	-2.407E+06	1.712E+06	-0.1	0.4
11.200	4.070	-3.974	0.881	-2.289E+06	6.133E+05	-0.1	0.4
11.300	4.122	-4.026	0.885	-1.588E+06	-2.169E+05	-0.2	0.5
11.400	4.148	-4.055	0.874	-5.311E+05	-5.125E+05	-0.2	0.5
11.500	4.145	-4.054	0.863	5.474E+05	-1.667E+05	-0.2	0.5
11.600	4.121	-4.029	0.870	1.308E+06	7.367E+05	-0.2	0.5
11.700	4.091	-3.990	0.905	1.505E+06	1.948E+06	-0.2	0.5
11.800	4.072	-3.954	0.973	1.061E+06	3.124E+06	-0.3	0.6
11.900	4.080	-3.938	1.069	8.881E+04	3.936E+06	-0.3	0.6
12.000	4.124	-3.952	1.178	-1.140E+06	4.159E+06	-0.3	0.6
12.100	4.199	-3.998	1.284	-2.306E+06	3.747E+06	-0.3	0.6
12.200	4.297	-4.071	1.373	-3.111E+06	2.820E+06	-0.3	0.6
12.300	4.398	-4.159	1.432	-3.338E+06	1.647E+06	-0.4	0.6
12.400	4.488	-4.244	1.461	-2.944E+06	5.658E+05	-0.4	0.6
12.500	4.554	-4.311	1.466	-2.069E+06	-1.104E+05	-0.4	0.5
12.600	4.591	-4.352	1.461	-9.984E+05	-1.899E+05	-0.4	0.5
12.700	4.604	-4.366	1.462	-7.391E+04	3.414E+05	-0.5	0.5
12.800	4.605	-4.360	1.483	4.055E+05	1.316E+06	-0.5	0.5
12.900	4.612	-4.350	1.533	2.735E+05	2.434E+06	-0.5	0.5
13.000	4.639	-4.351	1.611	-4.543E+05	3.354E+06	-0.5	0.5

MAXIMUM RADIAL EXCURSION = 4.639 MILS

STOP
PROCESSING 15 UNITS

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX C

HIGH-EFFICIENCY KLYSTRON CW AMPLIFIER FOR SPACE POWER APPLICATIONS

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ABSTRACT

This presentation concerns concepts and computer-aided design analyses of a high efficiency klystron cw amplifier for space power applications. It derives from experience with the Varian VKS-7773 50 kW S-band cw klystron amplifier, a 28 kV 2.4 A 50 dB gain tube operating at 2450 MHz with 74.4% efficiency.

INTRODUCTION

Proposed satellite power stations, where solar energy is converted to microwave energy and beamed to earth to be converted to ac power, require high-efficiency microwave devices. Large numbers of microwave tubes are planned. It is estimated that one percentage point in efficiency is roughly equivalent to two hundred million dollars in installation costs for a single satellite power station. Total tube operating efficiency of 85% is often mentioned as the acceptable minimum.

One investigation of the proposed system has been completed (1). Another may be undertaken shortly. Study of the completed report and discussion of the microwave device with various interested groups indicates desirability of the following characteristics:

High efficiency	Radiant cooling
High power	Long life
High gain	Light weight
Low noise	Low cost
Low harmonic output	Ease of manufacture
Low voltage	Repeatability in manufacture
Signal stability	Acceptable packing density
Ease of phase control	Site repairability

The tube will operate in outer space. An "open" tube construction is advocated by many so that the high vacuum may inhibit HV arcing and give virtual freedom from internal ion bombardment. While no known existing microwave device can satisfy all of the requirements of the space application, the klystron is outstanding in areas of high power, high gain, low noise, ease of phase control, and long life.

This paper concerns design concepts and computer-aided analyses of a high-efficiency klystron cw amplifier deriving from experience with the Varian VKS-7773 S-band cw klystron amplifier in 1970. Calculations indicate that a new tube of modified design will produce 50 kW of S-band cw power at 85% or higher total efficiency. A tube base efficiency in the range 78% to 81% may be realized by reduction of electron beam perveance and by other changes. A total efficiency of 85% or more may be achieved through use of collector depression. In the practical SPS klystron, the paramount requirements are: a suitable depressed collector; and with radiant cooling, waste heat removal at the output cavity. A detailed study of the possible role of the klystron in the space power application is available in a NASA technical report by MacGregor and Rowe (2). Results discussed herein are similar, though reached by somewhat different methods. The use of a mod-anode in the electron gun design is proposed for tube protection and control and to reduce the voltage appearing between adjacent electrodes.

THE VKS-7773 KLYSTRON

The VKS-7773 2450 MHz klystron cw amplifier has an output of 50 kW at 74.4% tube base efficiency when operated at 28 kV, 2.44 A beam current, and efficiency remains high even for reduced beam voltage. Higher power output and somewhat higher efficiency should be possible at higher beam voltage. With a depressed collector, a total efficiency of 86% could be obtained for a collector recovery efficiency of 55%. Data on the klystron were presented at the International Conference on Microwaves and Optical Generation and Amplification in Amsterdam by Erling Lien (3)(4) of Varian in 1970. Eight tunable cavities are employed, two of these being second harmonic cavities. These help optimize electron beam bunching at the output, at the same time reducing the required circuit length. Tuning provides a ± 25 MHz tuning range, at the same time permitting cavity frequency adjustment for experimentation and efficiency optimization.

The VKS-7773 is an experimental klystron primarily intended for use in industrial heating. Its potential with respect to possible space application has not been explored. It uses liquid cooling and is designed to fit a large existing electromagnet, features that would be changed in a space version of the design.

Table 1 summarizes the operating characteristics of the VKS-7773, and those of a new design operating at a tube base efficiency of 77.5% and a total efficiency of 87.5%. Improved tube efficiency will be obtained by increasing the electronic conversion efficiency and using a depressed collector having 55% recovery efficiency.

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Table 1. Klystron CW Amplifier Operating Characteristics

	VKS-7773	NEW DESIGN
Frequency, GHz	2.45	2 45
Tuning, MHz	±25	Fixed
Beam Voltage, kV	28	36 5
Beam Current, A	2 4	1.74
Beam Microperveance	0 5	0.25
Power Output, kW	50	50
Base Efficiency, η_b, %	74 4	77 5
*Total Efficiency, η_t, %	...	87 5
Saturated Gain, dB	50	50

*With depressed collector

TOTAL EFFICIENCY, η_t

In the space power satellite application, the relative importance of each percentage point in efficiency necessitates optimization of the product of electronic conversion efficiency, η_e, and output cavity circuit efficiency, η_{ckt}. This product represents tube base efficiency, η_b.

$$\eta_b = \eta_e \eta_{ckt} \qquad 1)$$

As it turns out, as electron beam microperveance is decreased and electronic conversion efficiency increased, beam conductance is reduced and circuit efficiency decreased. The optimum η_t relationship sought is modified somewhat by collector recovery efficiency, η_c. Considering only the power associated with the electron beam for the moment, total klystron efficiency, η_t, may be expressed as

$$\eta_t = \frac{\eta_e \eta_{ckt}}{1 + \eta_c (\eta_e - 1)} \qquad 2)$$

Heater, beam intercept, and electromagnet power are considered separately.

First determining electronic conversion efficiency and circuit efficiency, Equation 2 is used in design calculations of klystron operating characteristics.

Electronic Conversion Efficiency

Figure 1 shows data curves for electronic conversion efficiency as a function of beam microperveance in the range of interest. The dotted curve is extrapolated from a linear approximation of computer calculations for microperveances of 2.0, 1.0, and 0.5, optimized at each point for output cavity gap electron beam bunching. The solid curve was obtained by reducing drift tunnel radius γa as microperveance was decreased. Space charge density in the drift tunnel was maintained close to that of the VKS-7773, and the calculated beam focusing magnetic field was kept less than that of the existing tube. Beam voltage was allowed to increase with reduced microperveance to maintain microwave power output at 50 kW. The linear relationship resulting from these conditions is given by the expression:

$$K_o = 5.53 - 6.67 \eta_e \qquad 3)$$

The main argument made here is that extrapolation of a linear data approximation obtained for higher microperveances gives acceptable estimates for electronic conversion efficiency in the region. This thesis pivots on the known value for the VKS-7773 klystron. The data may be quite conservative. At 0.25 microperveance, the electronic conversion is 0.793. By way of comparison, an independent computer calculation reported by Kosmahl and Albers (5), using axially and radially deformable rings of electron charge, gives an efficiency of 0.83 for a case similar to the VKS-7773 at this microperveance.

Circuit Efficiency

Output cavity circuit efficiency may be derived in terms of the normalized load conductance, G_L/G_o; cavity R/Q, unloaded Q, Q_o; electron beam microperveance, K_o; and beam voltage, V_o.

$$\eta_{ckt} = \frac{1}{1 - \frac{1}{(G_L/G_o)(R/Q)(Q_o)\sqrt{V_o}\, 10^{-6} K_o}} \qquad 4)$$

For maximum circuit efficiency, the variable terms should be as large as feasible.

In the space power application, radiant cooling will require that the output cavity operate at an elevated temperature. Copper, the usual material of an output cavity, shows increased resistivity at higher temperatures, and Q_o decreases. In a typical case, with Q_o = 6500 at 20°C, an operating temperature of 300°C would lower Q_o to about 4400 and circuit efficiency from 0.978 to 0.968.

Collector Recovery Efficiency

Few attempts have been made to design depressed collectors for high efficiency, high power klystrons. A NASA report by Neugebauer and Mihran (6) discusses the application of an electrostatic reflex collector to a 1 to 2 kW 750 MHz cw klystron, achieving a collector recovery efficiency of 57% in one test, and raising operating efficiency from a normal undepressed value of 54.3% to 70.9% with collector depression. Collector recovery efficiency may be optimized by first refocusing the electron beam between output cavity and collector entrance. The subject is discussed in a NASA report by Branch and Neugebauer (7). A tapered magnetic field distribution, for example, gives good beam refocusing characteristics for both high and low-efficiency klystrons.

In the proposed SPS klystron development, design of the depressed collector is critical in order to realize maximum possible total efficiency. Computer programs are available for designing both the electron beam refocusing section and the reflex electrostatic collector. A highly informative exercise might be the design of these components and their application to the VKS-7773 klystron. It is anticipated this work would result in a collector having a recovery efficiency of at least 0.55. This figure was used in calculations that follow.

DESIGN CURVES

Figure 2 shows klystron design curves generated by solving Equation 2 for various electron beam microperveances derived from Equation 3, for suitable circuit efficiency variables in Equation 4, and for a collector recovery efficiency of 0.55. The total efficiency curve is quite broad, and good klystron performance is indicated over a wide range of beam microperveances. If beam voltage is limited to 40 kV or less, the desirable range is evidently from about 0.2 to 0.35 microperveance. Consideration has been given to a microperveance 0.3 tube, operating at 34 kV 1.85 A. The 0.25 microperveance design point shows the somewhat higher tube base efficiency of 0.775, with a beam input of 36.5 kV 1.74 A. This point was selected for further discussion. Electronic efficiency was 0.793. If it were as high as 0.83, tube base efficiency would be 0.812 and total efficiency 0.896.

KLYSTRON MOD-ANODE

Figure 3 is a simplified diagram illustrating the klystron mod-anode. As proposed here, the electrode provides several advantages. The maximum voltage appearing between any two adjacent electrodes is halved, 18.25 kV in the arrangement shown, as opposed to the 36.5 kV electron beam voltage employed. Two low current power supplies furnish the small body intercept current, while a higher capacity supply furnishes the main beam and collector current.

The mod-anode conducts no current and is isolated by the resistance R. The two 18.25 kV 0.07 A power supplies provide means for protection and control of the klystron. In the event of an arc between cathode and mod-anode, for example, the small capacitance C1 discharges and the mod-anode shifts briefly to cathode potential, shutting off the electron beam. With the arc extinguished, the klystron returns to normal operation in tens of microseconds. System logic circuitry, sensing various malfunctions such as loss of rf drive, waveguide load mismatch, and the like may control the two low energy power supplies to effect klystron protection from faults. The two 18.25 kV 0.07 A power supplies are regulated to stabilize phase and power output. The collector power supply may vary as much as 10% with little effect on tube performance.

NOISE

Most of the noise power present at the klystron output will be amplified rf driver input noise. The best available estimates give the contribution of the 50 dB gain klystron as -140 dB/kHz for AM and -130 dB/kHz for PM noise within the passband referenced to rf power output. An independent study (2) suggests that the use of a second harmonic cavity may lower noise output significantly from the normal level. Noise tests of the VKS-7773, which has two second harmonic cavities, would be useful in exploring this possibility.

WASTE HEAT

It is assumed that proximity of other tubes and equipment will require heat disposal in the general direction of the sun. However, some advantage may be realized if the radiating surfaces are disposed at an angle to the sun direction to reduce solar heating. Waste heat at the klystron collector will amount to about 5 kW, which may be radiated from a relatively small refractory metal collector element at 700°C or more. Body heat, including heater, rf, and interception loss, will amount to about 2.65 kW but must be disposed of at 300°C or less at the tube body if use of samarium cobalt magnets is contemplated. The tube body heat radiator must also radiate heat received from the sun at about 1.3 kW/m^2. The calculated total body radiator heat for one arrangement is 4.12 kW. A system of heat pipes will move heat from the klystron circuit to the body radiator. With a radiating area of 1.6 m^2, the unit would operate at close to 200°C, neglecting electromagnet heat. The addition of 750 W for electromagnet power would increase radiator operating temperature to about 223°C. Heat shields would be used as necessary to direct radiation in the desired direction.

Heat pipe technology is still "new," though life guarantees of five and even ten years are now given in some cases. A cursory look at the klystron body heat problem by an engineer from a local heat pipe company yielded the comment that the problem "does not look too difficult on the surface." Additional study and appropriate experimentation are certainly necessary.

BEAM FOCUSING

The importance of each percentage efficiency point indicates the desirability of developing an alternate method of beam focusing using lightweight samarium cobalt magnets. Several possible schemes, other than simple PPM, are known and should be investigated.

CONCLUSIONS

The use of 0.25 electron beam microperveance and reduced drift tunnel radius γa will almost certainly yield an electronic conversion efficiency close to 80%, possibly higher. A high Q toroidal output cavity should give a circuit efficiency clost to 97% or higher at 300°C. Collector recovery efficiency of 55% in an electrostatic

Table 2. High Efficiency SPS Klystron CW Amplifier

Beam Voltage, kV	36 5
Beam Current, A	1.74
RF Power Output, kW	48.2
Gain, dB	50
Collector Recovered Power, kW	7.1
Electromagnet Power, kW	0 75
Heater Power, W	50
Max Circuit (Body) Temperature, °C	300
AM Noise dB/kHz	-140
PM Noise, dB/kHz	-130
Harmonics, Typical dB	-30 to -40
Tube Base Efficiency, %	76 8
Total Efficiency, %	85 8

reflex depressed collector appears technically feasible with electron beam refocusing. Preliminary study of klystron body waste heat and the use of heat pipes looks promising. Including all losses and assuming 300°C maximum body temperature, the successful klystron design would have the characteristics listed in Table 2.

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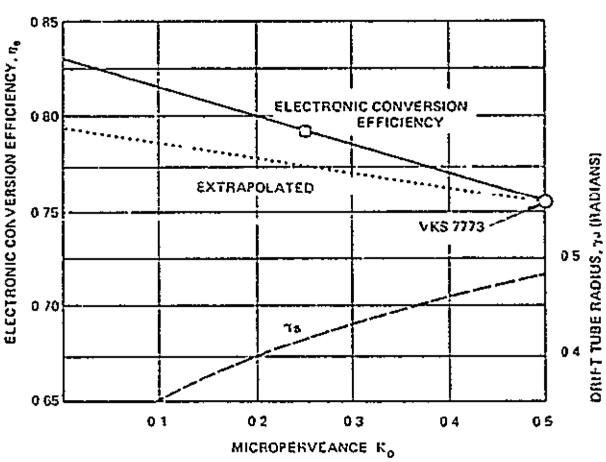

Figure 1. Electronic Conversion Efficiency vs Electron Beam Microperveance

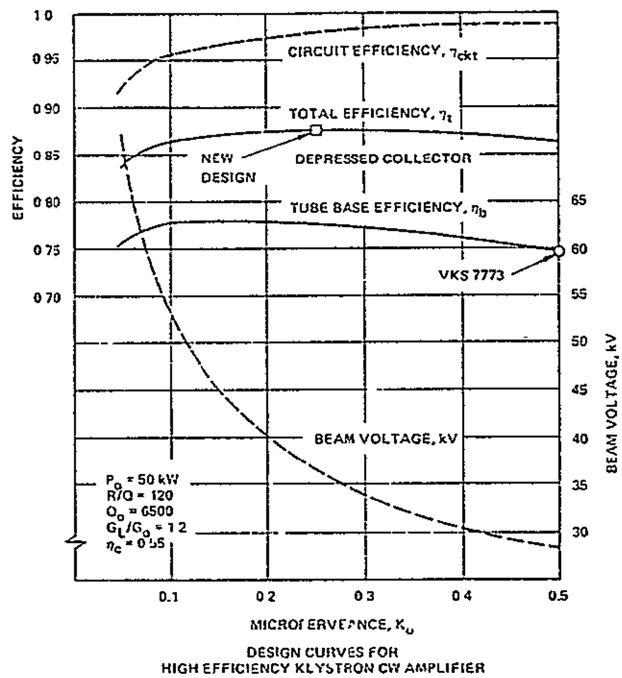

Figure 2. Design Curves for High Efficiency Klystron CW Amplifier

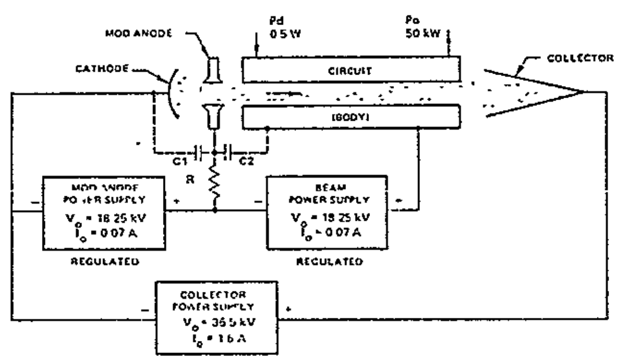

Figure 3. Simplified Diagram Illustrating the Klystron Mod-Anode