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RESEARCH AND DEVELOPMENT ON L-BAND CROSSED-FIELD AMPLIFIER CHAIN

by
H. L. McDowell

Report No. 6

Quarterly Progress Report

1 March 1964 to 1 June 1964

Contract Nr. AF 30(602)-2533

ARPA Order No. 136.61

Rome Air Development Center
Research and Technology Division
Air Force Systems Command
United States Air Force
Griffiss Air Force Base, New York

S•F•D laboratories, inc.

Union, New Jersey

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RADC-TR-65-79 July 1964

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ABSTRACT

During this quarter, life tests were continued on the Group C SFD-209 tubes. A total of 4411 hours have been accumulated. Tubes L48E and L1E have operated 2150 and 1288 hours, respectively. L1E was damaged by an equipment failure and has been removed from life test for study. Degradation of performance was discontinuous and corresponded to equipment failure. To prevent future failures, the external circuitry has been improved and the final tubes modified.

Tube [illegible]30E was used in an experiment designed to investigate the improvement of efficiency through improved confinement of electrons to the interaction space. A barreling magnetic field was used to improve magnetic confinement but no significant change in efficiency was observed. It is believed that this indicates that the confinement is already quite adequate.

Further tests indicate that V-I characteristics will be quite reproducible from tube to tube. The sources of variations previously noted have been traced down and found to be external to the tube.

On the basis of performance and life tests, the control electrode support and the input window have been redesigned. An attempt will also be made to incorporate preferential π mode damping by means of an absorber located behind the C_{13} couplers.

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PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project, contact Mr. Schneider, EMATE, Extension 4924.

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1.0 INTRODUCTION

During the period of this report, life tests were continued on the Group C design driver tubes and a seventh and eighth tube were completed. The total life test hours accumulated on the program by the end of May 1964 was 6341. Of these, 4411 hours were accumulated on the C design driver. One of the tubes still on life test at the end of May had accumulated 2150 hours of operation. A second tube accumulated 1288 hours of operation during the quarter. End of life for this tube came as a result of an equipment failure which resulted in tube damage. The tubes life tested this quarter operated for a longer period of time before the appearance of starting jitter than was the case with tubes previously tested. Since there is no difference in the tube construction, this is attributed to changes made in the external control electrode circuitry. Success in delaying the onset of jitter by an external circuit change is believed to be an indication that we are on the right track in our analysis of its cause.

After completion of the eighth C design driver tube, we are starting construction of a new group of SFD-216 power tubes. One of these power tubes was partially completed. At this time, discussions with RADC led to a redirection of the program toward emphasis on the driver tube. We therefore halted further construction of power tubes and began planning for a new group of SFD-209 driver tubes. These new driver tubes will incorporate slight design modifications indicated to be desirable by both performance tests and life tests on the Group C design driver tubes. Some specific changes will be improved cooling of the control electrode, a larger input window and some selective π mode absorption behind the C_{13} couplers. The first two of these changes naturally led us in the direction of a higher average power tube. We plan to evaluate the average power capability of this design after the contemplated changes are made.

2.0 GROUP C SFD-209 CONSTRUCTION AND LIFE TEST PROGRAM

During this quarter, life tests were continued on tubes L48E and L1E. By the end of May 1964, L48E had accumulated 2150 hours of operating life and was still on life test. Tube L1E had accumulated 1288 hours at which time the tube was damaged by an equipment failure. Table I presents a summary of Group C SFD-209 tube status and life test results as of the end of May 1964.

During its first 500 hours of life, the cathode current of L48E dropped slightly so that it was necessary to increase the operating voltage to maintain the output power. During this period, there was also a 20% decrease in the bias voltage developed by the control electrode. After this initial change in current, the tube settled down and has operated at approximately the same current for the next 1500 hours. The change in the condition of the control electrode surface may have caused the cathode current change by changing the amount of space charge re-entering the input section of the tube from the drift space. Alternately, the current change may have been caused by changes in the test equipment. This situation will be investigated further. V-I curves for tube L48E taken at the start of life tests and after 500 hours and 2240 hours are shown in Figure 1. No starting delay or starting jitter had appeared by 500 hours. Since such jitter had appeared in previous life tests on J10E-1 and K6E at from 50 hours to 100 hours, this represented a significant improvement. This improvement was all the result of changes in the external control electrode circuitry because tube L48E was essentially identical to tube K6E. The change in circuitry that was made resulted in a lower impedance between control electrode and cathode. As discussed in the last semi-annual report (Report No. 5), the lowering of this impedance lowers the control electrode positive bias developed and thereby lowers the control electrode dissipation. The fact that this circuit change

Tube No.	Serial No.	Seal In Date	Control Electrode Type	Total Life Test Hours	Comments	Present Status
1	H19E	9/13	Notched titanium	--	Voltage breakdown through cracked insulator	Rebuilt as H19E-1 with modified insulator
1a	H19E-1	10/8	Notched titanium	--	Poor starting performance	Rebuilt as H19E-2
2	J10E	10/19	Notched titanium	--	Poor starting performance	Rebuilt as J10E-1
2a	J10E-1	10/28	Notched aluminum	750 End of life	Improved starting but still marginal; removed from life test because of excessive starting jitter	Tested to end of life and opened for analysis
3	K6E	11/15	Stepped	223 End of life	Good performance; damaged by equipment failure on life test; some starting jitter appeared on life test prior to failure	Repumped as K6E-1; now awaiting RF test for analysis of jitter problem
4	L1E	12/12	Stepped aluminum	1288 End of life	Good performance; damaged by equipment failure on life test; some starting jitter appeared on life test prior to failure	Being analyzed
5	L30E	12/19	Stepped aluminum		Performance OK	Awaiting life test
6	L48E	1/2	Stepped aluminum	2150 Continuing	Developed starting delay and jitter of 0.3 μsec	On life test and operating
1b	H19E-2	1/8	Stepped aluminum		Performance OK on quick check	Awaiting RF testing
3a	K6E-1	2/6	Stepped aluminum		Tube removed from life and repumped without opening; initial quick check shows starting jitter	Awaiting testing for analysis of jitter problem
7	D34F		Stepped aluminum "Heat shunts" on support assembly			Awaiting hot test
8	D37F		Stepped aluminum "Heat shunts" on support assembly			Awaiting hot test

SUMMARY OF GROUP C SFD-209 TUBE STATUS AND LIFE TEST RESULTS AS OF 31 MAY 1964

TABLE I

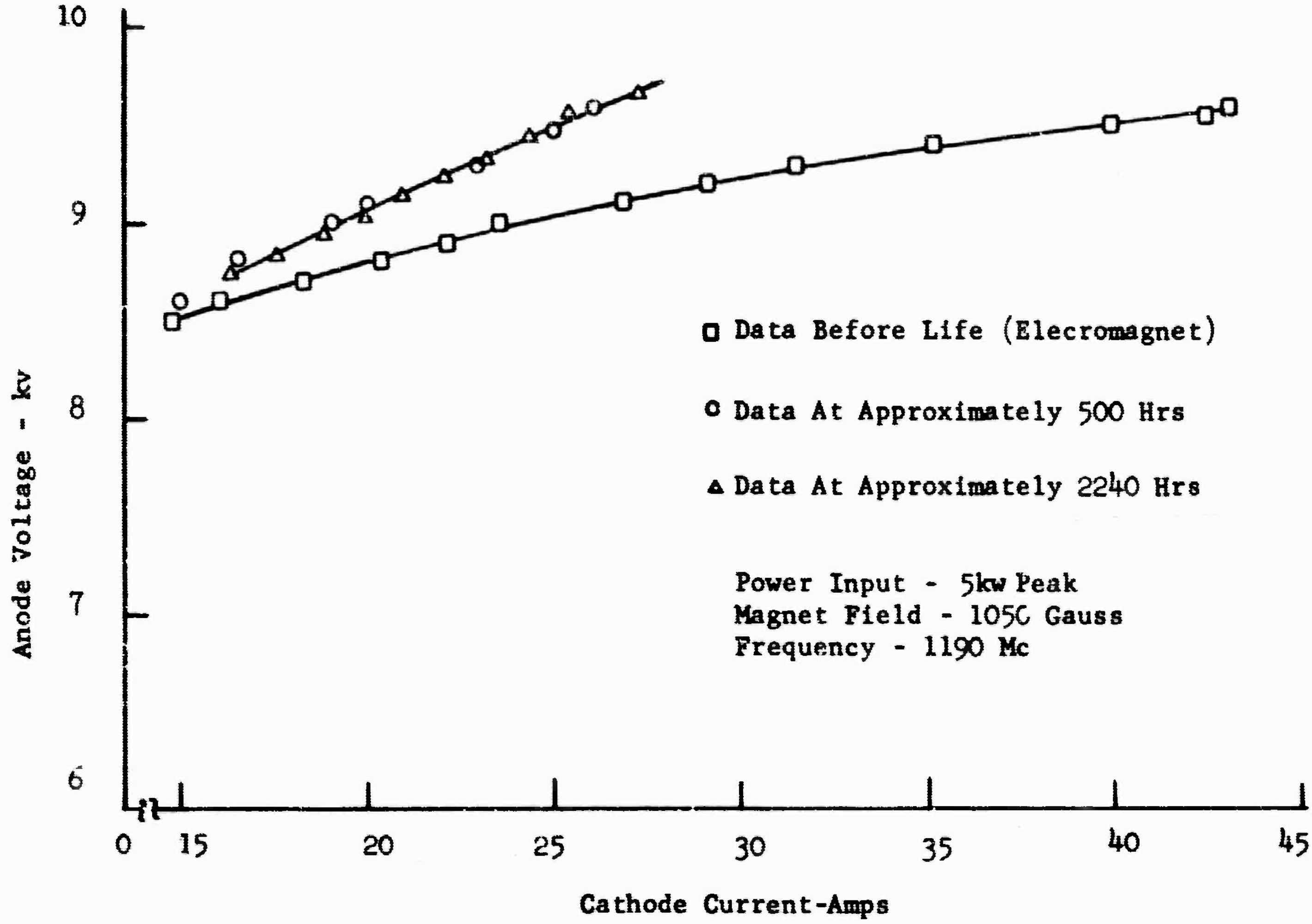

FIGURE 1 V-I CURVES FOR SFD-209 TUBE L48E BEFORE AND DURING LIFE TEST

helped delay the onset of jitter appears to indicate that we are on the right track in our analysis of the cause of this phenomenon.

When L48E had reached the 537-hour level and L1E had simultaneously accumulated 191 hours, we experienced a failure on the control electrode modulator for tube L1E. This appeared to trigger a series of other equipment failures at the same time. After the repairs were made and the tubes were put back into operation, it was found that both L48E and L1E had developed a fixed starting delay of approximately 40 nsec with no obvious jitter. No further change was observed in the operation of the tubes until L48E had reached 902 hours and L1E had simultaneously reached 556 hours. At this point, another equipment failure occurred. After repairs it was found that L48E had developed a starting delay of 80 nsec plus a 100 nsec starting jitter and L1E had developed a starting delay of 200 nsec with a jitter of 150 nsec. No further changes were observed in the operation of L48E until it had reached 1654 hours. The delay on L1E, however, continued to increase until it reached 400 nsec at 1288 hours. At this time the control modulator failed and protective circuitry failed to operate allowing tube L1E to go into continuous conduction and to gas up. This failure is similar to the one which caused end of life for tube K6E. Further work in improving the reliability of the protective circuitry is obviously in order. After the failure of tube L1E, tube L48E was allowed to continue on life test. It operated until at 2011 hours there was a failure of the driver magnetron modulator. When repairs were made and tube L48E was put back into operation, it was found that the starting delay and jitter had further increased to about 300 nsec.

It is noteworthy that the appearance of starting jitter and all of the increases in starting jitter occurred discontinuously at a time of shutdown of the equipment because of some equipment failure. This raises the possibility of high control electrode dissipation associated with the fault condition causing a discontinuous change in the performance of the tubes. This is quite possible even where the equipment which fails is the magnetron driver modulator or a control electrode modulator associated with only one of the two tubes. We have found in the past that whenever arcing occurs anywhere within the life test area, transients are set up in the ground circuits which cause all of the control electrode modulators to trigger falsely and lose control of their associated tubes. Thus it is quite possible that the appearance of starting jitter on the tubes is a result of excessive heating of the control electrodes during these trouble occurrences.

A word of caution concerning the interpretation of the leading edge jitter problem is in order at this point. The starting time of the tube for a given input power and frequency is determined by three factors: the number of initial electrons present in the interaction space when the input RF pulse is applied, the cathode secondary emission ratio which determines the rate of space charge build up and the properties of the drift space and control electrode which determine the fraction of the space charge returned from output to input. The re-entrancy of electrons from output to input is clearly necessary for starting in this tube as may be deduced from the fact that applying a positive bias to the control electrode to interrupt the re-entrancy prevents starting. Thus it is clear that more than a single transit of the electrons around the tube is required for space charge build up. During each transit around the tube, space charge builds up by secondary emission multiplication in the interaction space and decays as a result of impacts of electrons on the control electrode in the drift space. (The effective secondary emission ratio for these impacts is low because the electrons have not gained energy from the RF wave and thus strike the control electrode with low velocity.) Thus changes in either cathode or control electrode properties can have a marked change in starting time. A somewhat lesser effect on starting time is expected as a result of changes in the initial number of electrons present. (A lesser change since the number of electrons present appears only once as a multiplicative factor in the expression for build-up time whereas the secondary emission ratios are raised to the Nth power, where N is the number of impacts per unit time.)

The conclusion that jitter is caused by changes in the control electrode surface is largely a consequence of the examination of tube J10E-1 after life test as reported in the last semi-annual report. The inspection of this tube upon opening after life test showed that the control electrode had been operating at an excessive temperature. This fact was correlated with estimates of the power dissipated on the control electrode and upon the thermal impedance between control electrode and cathode. These estimates showed that the control electrode temperature indeed must have been much higher than originally anticipated. The tentative conclusion that leading edge jitter was caused by changes in control electrode surface was then made on the basis that the changes in the control electrode during life were the most obvious changes to occur in the tube. The fact that changes in the impedance between control electrode and cathode, which reduce dissipation on the control electrode, have succeeded in delaying the appearance of leading edge jitter seems to indicate the correctness of this interpretation. However, this interpretation has not as yet been firmly established and it is still possible that changes either in the cathode surface or in the initial number of electrons present in the interaction space may be involved in the appearance of the leading edge jitter. Attempts to tie down the source of the jitter more definitively are being made through secondary emission measurements to be described in a later section.

Subsequent to its removal from life test and prior to its opening, certain tests have been made on tube L1E to determined if changes have taken place during life test. Measurements of the cold transmission and reflection were recorded and it was found that t' match of the tube had degraded significantly as compared to what it was prior to life test. This is the first time that we have observed a change in the cold circuit properties during life test. In an attempt to evaluate the source of these changes, a number of X-ray pictures of the tube were taken. The only thing visible in these photographs which could conceivably have caused degradation in match was a significant amount of eccentricity in the output coaxial line U-bend and stub support. For comparison purposes, X-ray photographs were taken of tubes with a good match. These photographs showed the same amount of eccentricity in the output coaxial line. We must therefore conclude that the eccentricity is not a source of the degradation in match of tube L1E. It is apparent from the photographs, however, that some additional work on improvement of the output coaxial line sub-assembly may be required at a future date. A typical X-ray photograph of one of these assemblies is shown in Figure 2. We now suspect the possibility of a shift in position of the matching tab as a source of the change in match. Such a change could occur as stresses set up in the tab or the first circuit bar are "relieved" by heating the tube. Another possibility is a deposit found on the input window as a consequence of arcing in the input line. These possibilities will be investigated further when the tube is opened for inspection.

During this quarter the seventh and eighth Group C design driver tubes were completed and sealed in. As discussed in the previous semi-annual report, the thermal impedance between control electrode and cathode in the C-design driver tubes was higher than intended. A large part of this thermal impedance was a consequence of the thin kovar members sealed to the control electrode insulator. A quick improvement in control electrode heat transfer could therefore be made by brazing copper pieces over these kovar details. This change was made in the seventh and eighth Group C tubes. For a given amount of power dissipated on the control electrode, we estimate that this

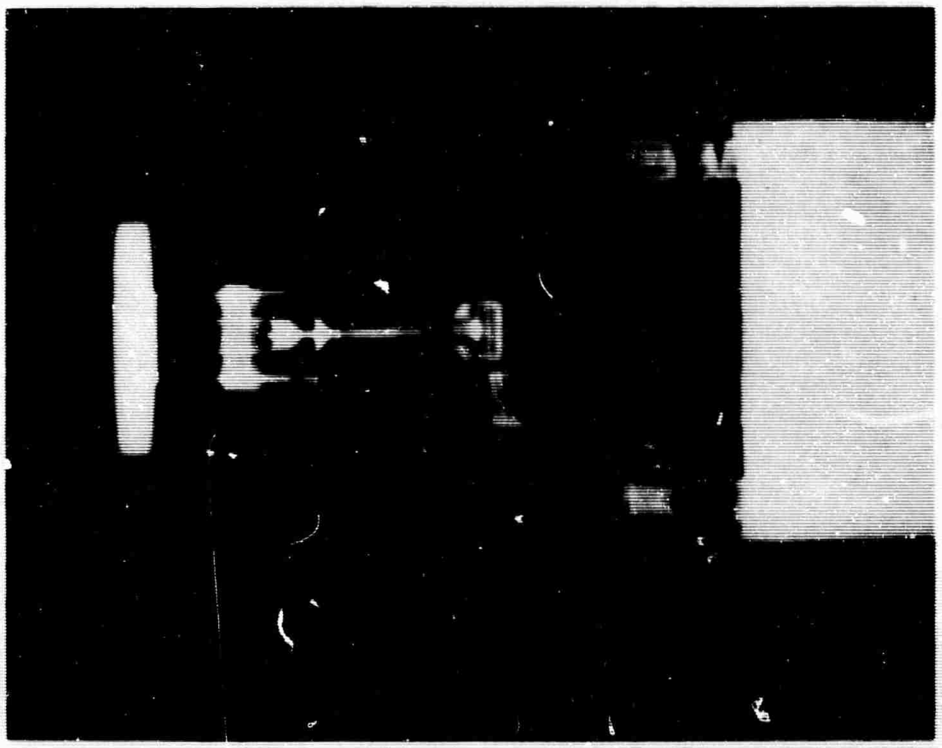

FIGURE 2 X-RAY PHOTOGRAPH SHOWING ECCENTRICITY IN OUTPUT COAXIAL LINE AND POOR CONNECTION AT JUNCTION OF U-BEND ASSEMBLY AND WINDOW

These defects do not cause a serious degradation in match but steps will be taken to correct them will reduce the temperature differential between control electrode and cathode by about a factor of 2. Life tests will show whether this further inhibits the appearance of starting jitter.

3.0 HOT TEST MEASUREMENTS

During this quarter, additional hot testing was done on tube L30E. Figure 3 shows frequency response characteristics for this tube at two different values of dc operating voltage. Figure 4 shows a performance chart taken near mid-band frequency.

An experiment was then made to see if improved confinement of the electrons to the interaction space would improve the efficiency. A change was made in the electromagnet-pole piece configuration so as to provide a more barreling magnetic field and therefore more magnetic confinement of electrons near the ends of the cathode. The magnetic field configurations for the original measurements of Figure 4 and for the changed pole piece configuration are shown in Figures 5 and 6, respectively. Figure 7 shows a performance chart taken under the same conditions as Figure 4 but with the new magnetic field configuration. It is seen that the results are essentially the same as those obtained in Figure 4. From these results, we tentatively conclude that leakage of electrons from the interaction space is not a factor limiting efficiency in the present design.

A study was also made of possible reasons for variations in the V-I curves of the Group C tubes. Figure 8 shows an assembly of V-I curves on these tubes for a magnetic field strength of 1100 gauss. It is not surprising that tube L1E differs from the remainder of the group. A repair had been necessary in the can of tube L1E and as a consequence the dimension from C_{13} couplers to the back wall of the envelope was not held as well as it was in the remainder of the tubes. A change in this dimension shifts the ω-β curve along the frequency axis thus changing the circuit synchronous voltage and consequently the operating voltage for a given magnetic field. A major part of the variation between the remainder of the group of tubes was traced to problems with calibration of the electromagnet. At least 300 volts of spread along the voltage axis was found to be due to this cause.

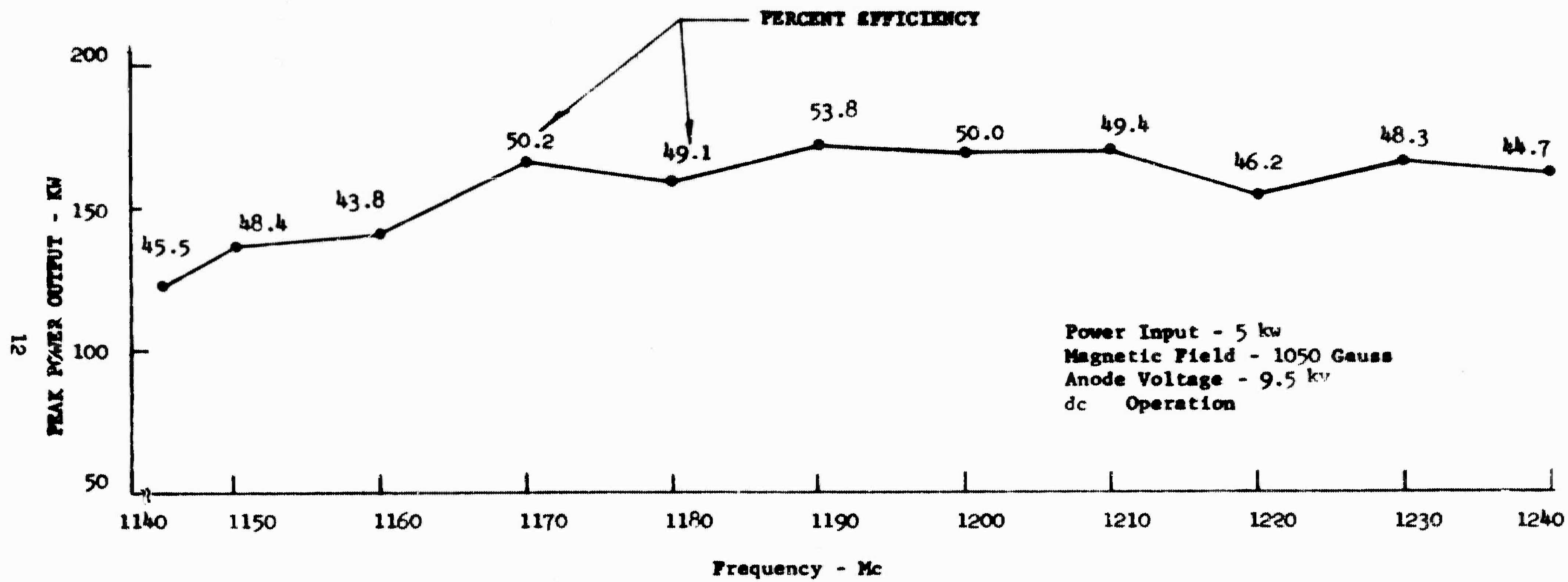

FIGURE 3 SFD-209 TUBE L30E FREQUENCY RESPONSE

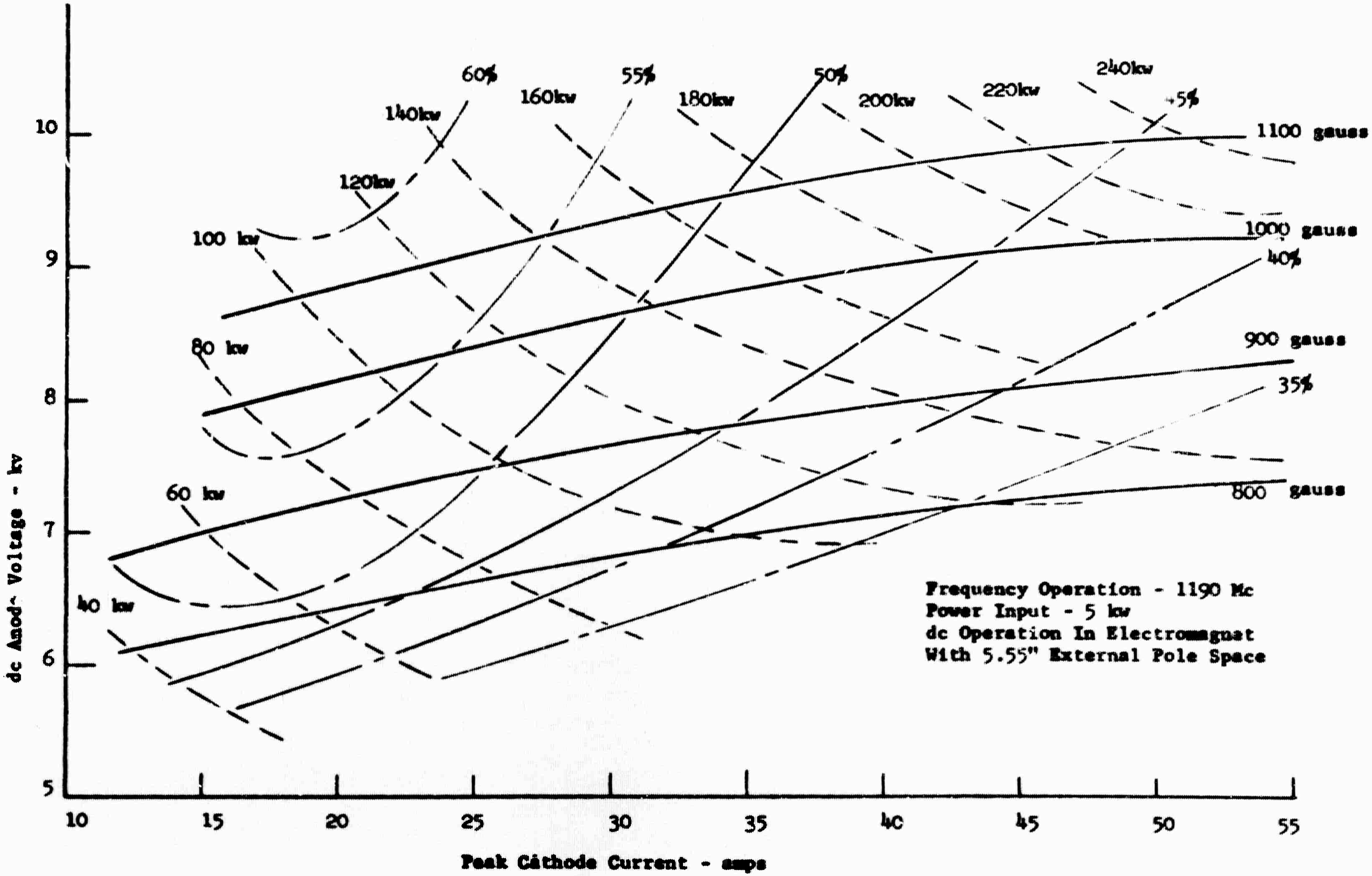

FIGURE 4 PERFORMANCE CHART SFD-209 TUBE L30E

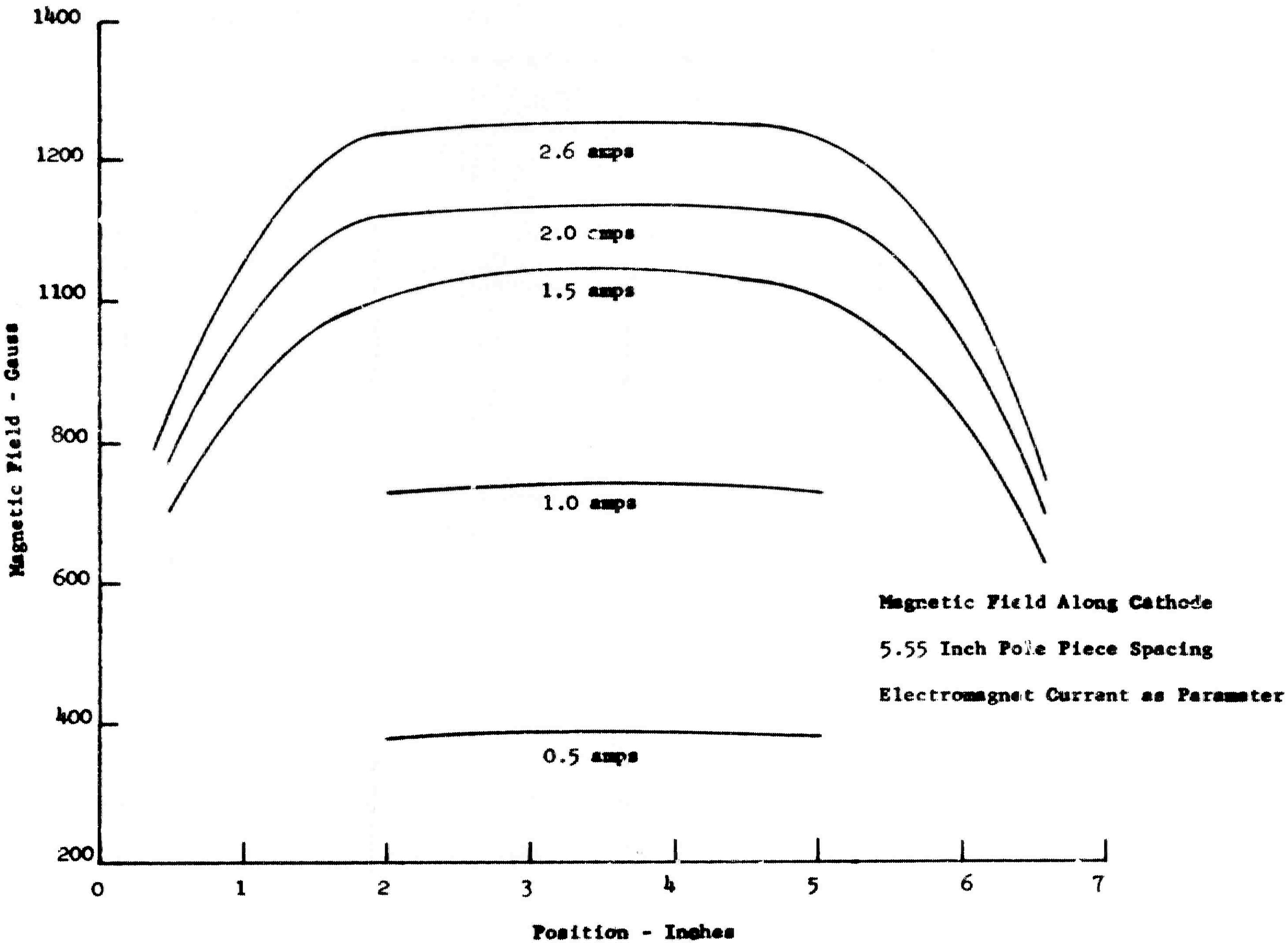

FIGURE 5 MEASUREMENTS ON HOT TEST ELECTROMAGNET

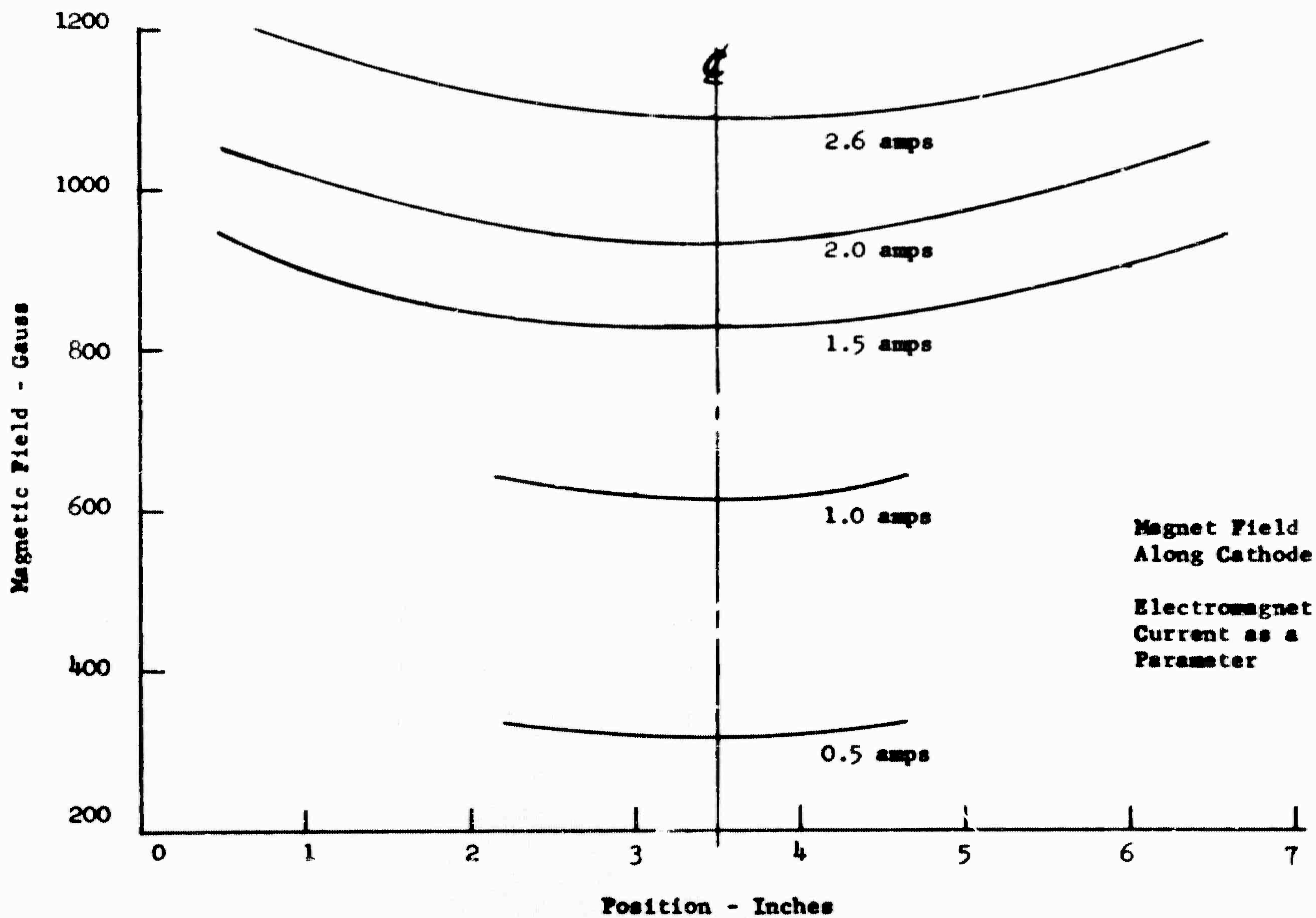

FIGURE 6 MEASUREMENTS ON HOT TEST ELECTROMAGNET

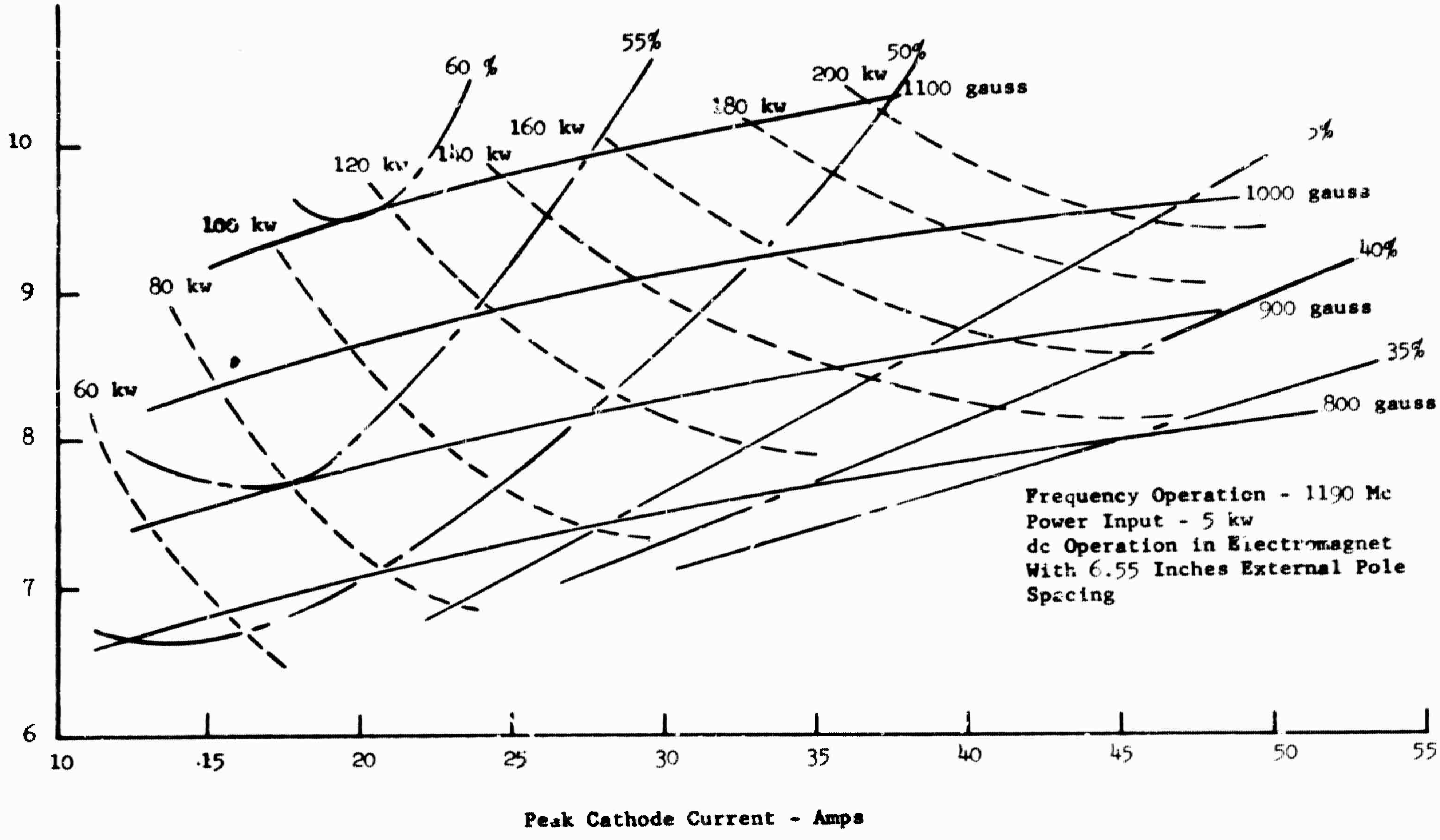

Figure 7 **PERFORMANCE CHART SFD-209 TUBE L30E**

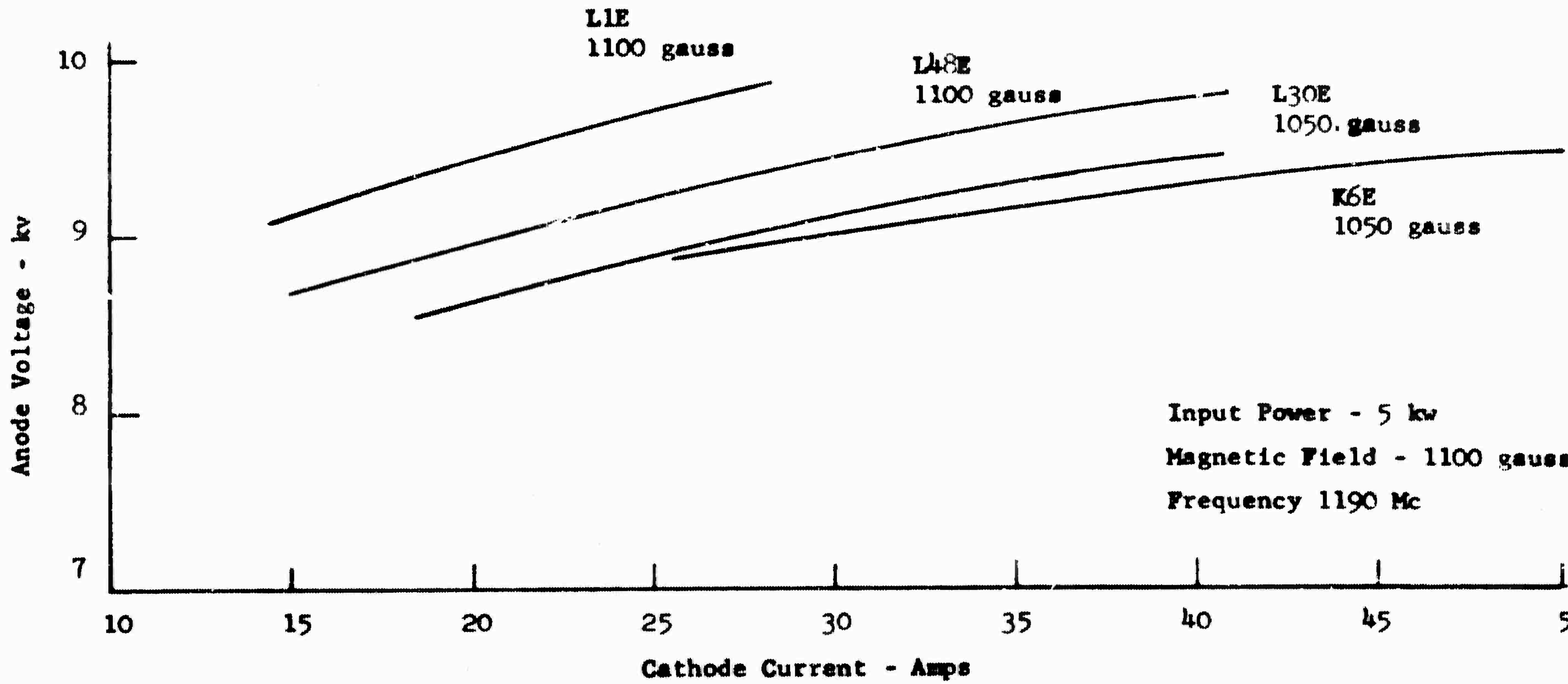

FIGURE 8 V-I CURVES FOR A GROUP OF SFD-209 TUBES

This problem has been resolved and will not occur in future measurements. The results of Figure 8 appear to indicate that when this source of variability is eliminated, the V-I curves will be quite reproducible from tube to tube.

4.0 SFD-209 REDESIGN PROGRAM

Performance tests and life tests on the SFD-209 have shown the desirability of several design changes. From the life tests, we have learned that the control electrode operates at an excessive temperature. A first quick fix was made on the seventh and eighth Group C tubes by brazing copper heat shunts over the kovar support members for the control electrode insulator. However, it was evident that a more thorough-going improvement of the control electrode support design was required. We are therefore changing the supporting structure to the design shown in Figure 9. This design incorporates a beryllia insulator which has a high thermal conductivity, in place of the alumina insulator used in the previous design. The cross-section of the insulator is further increased considerably as compared with the previous design. Finally, the method of mounting the insulator avoids the use of the thin kovar members of the previous design. As a net result, we expect a considerably improved heat transfer from this new control electrode support.

Another change shown to be necessary by the life testing involves the input window. Examination of the input window of the tubes removed from life test indicates that there has been considerable sparking between the center conductor and the outer conductor of the window on the atmospheric side. This has resulted in a black deposit covering the input windows of tubes after several hundred hours of operation. This deposit does not seem to have interfered with the cold transmission or reflection through the tube, but nevertheless it is evidence of a marginal design and could very well cause difficulty as the average power level of the tube is increased. The window coating may possibly be a reason for the change in match observed on tube L1E. We have therefore decided to change the input window to a 7/8 coaxial line size, the same as is currently used for the output window. This may result in an input window somewhat larger than

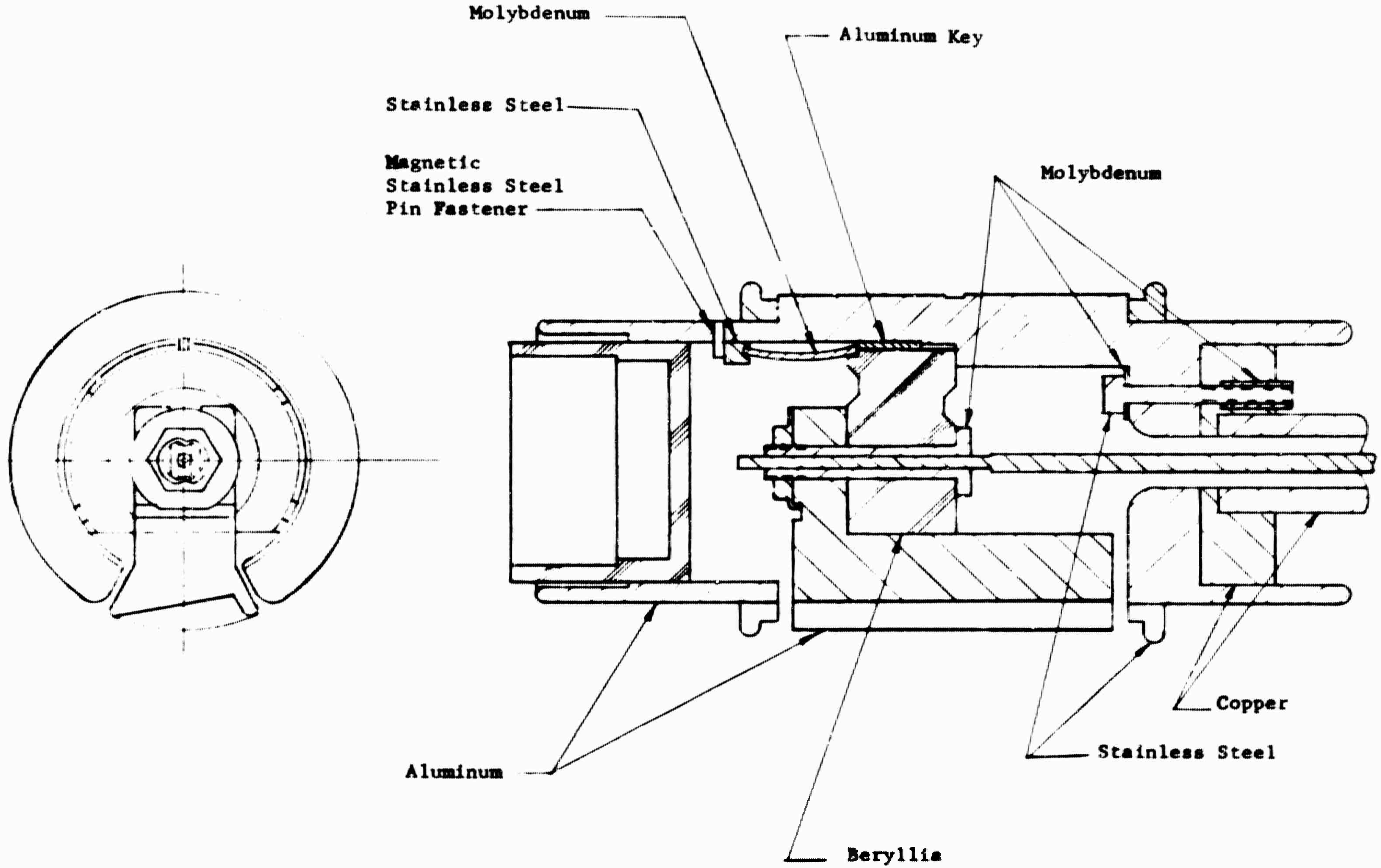

FIGURE 9 REVISED CONTROL ELECTRODE SUPPORT FOR SFD-209

absolutely necessary, but it will certainly represent a conservative design which has been proven out in practice.

Another area where performance measurements have indicated that improvement may be desirable is in the further suppression of the region of π mode oscillations. Such oscillations have not been present during any of the RF performance measurements presented in this report or in the preceding semi-annual report. However, we know that there is a region of π mode oscillation at lower drive power levels and at low operating voltages; i.e., on the left-hand side of the performance chart. To increase the gain of the tube, it is necessary to further suppress these oscillations. If this can be accomplished, the input drive power to the tube can be reduced with little change in output power. Even if the tube is to be operated with approximately 5 kw of input drive as we have done for the RF testing, it would be advantageous to decrease the required input power for satisfactory locking and thereby provide a greater degree of insensitivity to effects of antenna VSWR. (The effective reduction of input power by signals reflected from the antenna and re-reflected from the tube input was discussed in Section 6 of the last semi-annual report.) It is known that attenuation located between the C_{13} couplers and the vacuum envelope will introduce differential attenuation at the band edges. An example of such attenuation obtained on cold test was shown in Figure 9 of the semi-annual report covering February to September 1963 (Report No. 4). To further suppress the π mode, we decided to attempt the incorporation of such attenuation in the new tube design.

As an experimental vehicle for differential attenuation, we decided to use a linear version of the slow wave circuit for the SFD-209. Parts for such a linear circuit had been ordered previously in 1963 for use on ferrite studies. These studies were however discontinued before the circuit was assembled. During this quarter, the linear circuit was assembled, matched and used for studies of differential attenuation. Such attenuation was obtained. Figures 10 and 11 show the results of cold transmission and reflection measurements from the linear cold test circuit, with and without an Eccosorb absorber located between C_{13} couplers and the back wall of the tube. It is seen that the absorber introduces differential attenuation at both band edges. Indications are that the attenuation at the π mode frequency may be quite large. It is believed that a smaller amount of attenuation will be satisfactory, with a consequent reduction in the amount of attenuation introduced at the band center. We are currently in the process of working out a mounting procedure for locating a porous ceramic absorber in the actual tube to reproduce results somewhat as shown in Figure 11.

In the course of measurement on the linear cold test circuit, some interesting results on the effect of back wall spacing on the dispersion curves were obtained. Figure 12 shows dispersion curves as a function of spacing between the C_{13} coupler rings and a smooth back wall. Figure 13 shows dispersion curves as a function of spacing between a 2 inch high ridge behind the C_{13} coupler rings and a smooth back wall. In both cases it is seen that bringing a metal wall close to the C_{13} couplers depresses the entire dispersion curve but at the same time depresses the π mode frequency by more than it depresses the band-center frequency. This is an indication of the fact that more energy is stored in this region at the π mode frequency than at band center. This selective π mode depression helps to remove the π mode from synchronism in the Group C design. This effect is also illustrated in Figure 14 which shows the percentage depression of various points on the dispersion curve, as the spacing of the C_{13} couplers to the back wall is varied. These data show how the back wall spacing may be used as a vernier adjustment on the location of the pass band.

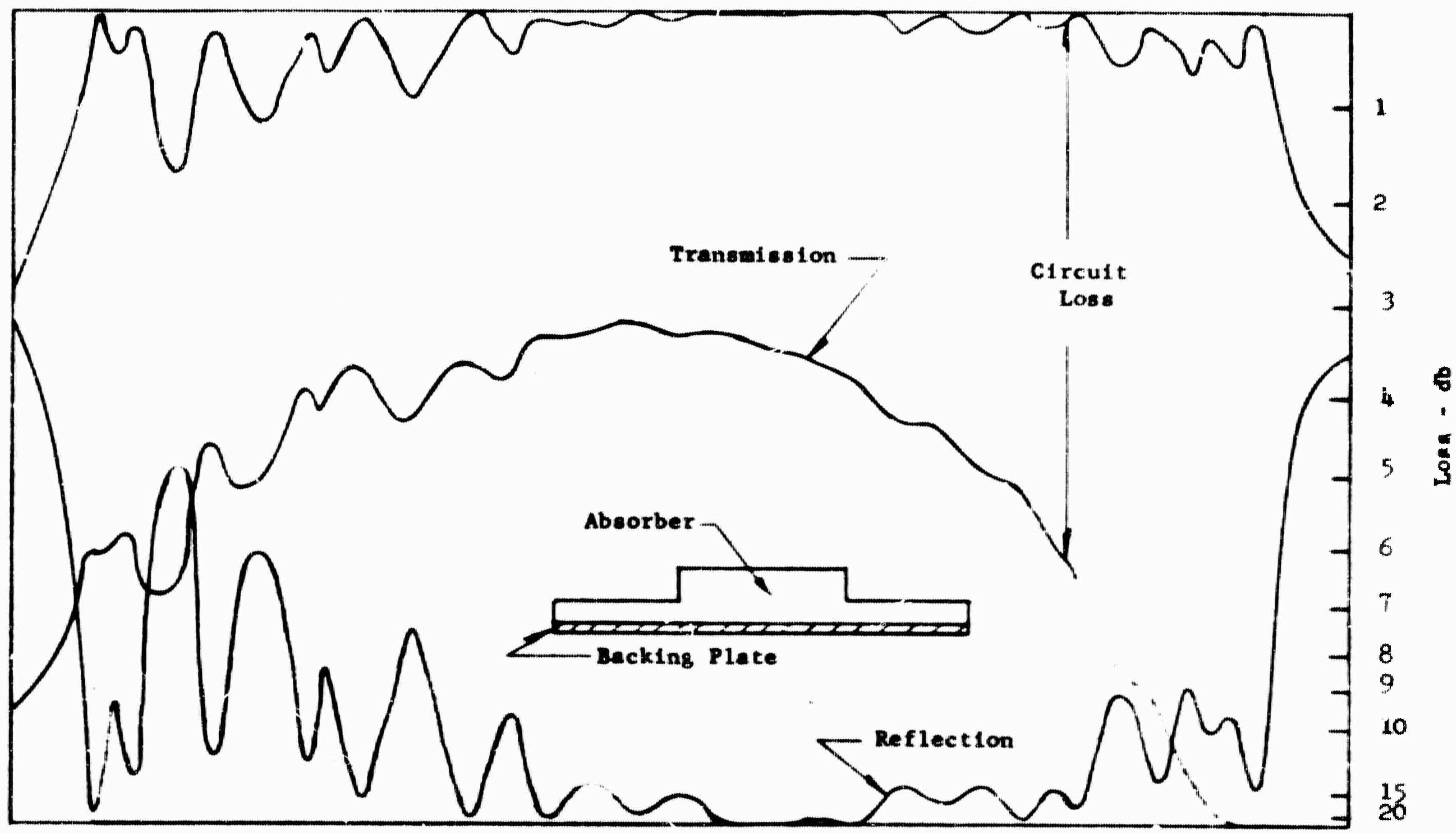

FIGURE 10 CIRCUIT LOSS INTRODUCED BY PLACING ABSORBER BETWEEN CIRCUIT AND ENVELOPE

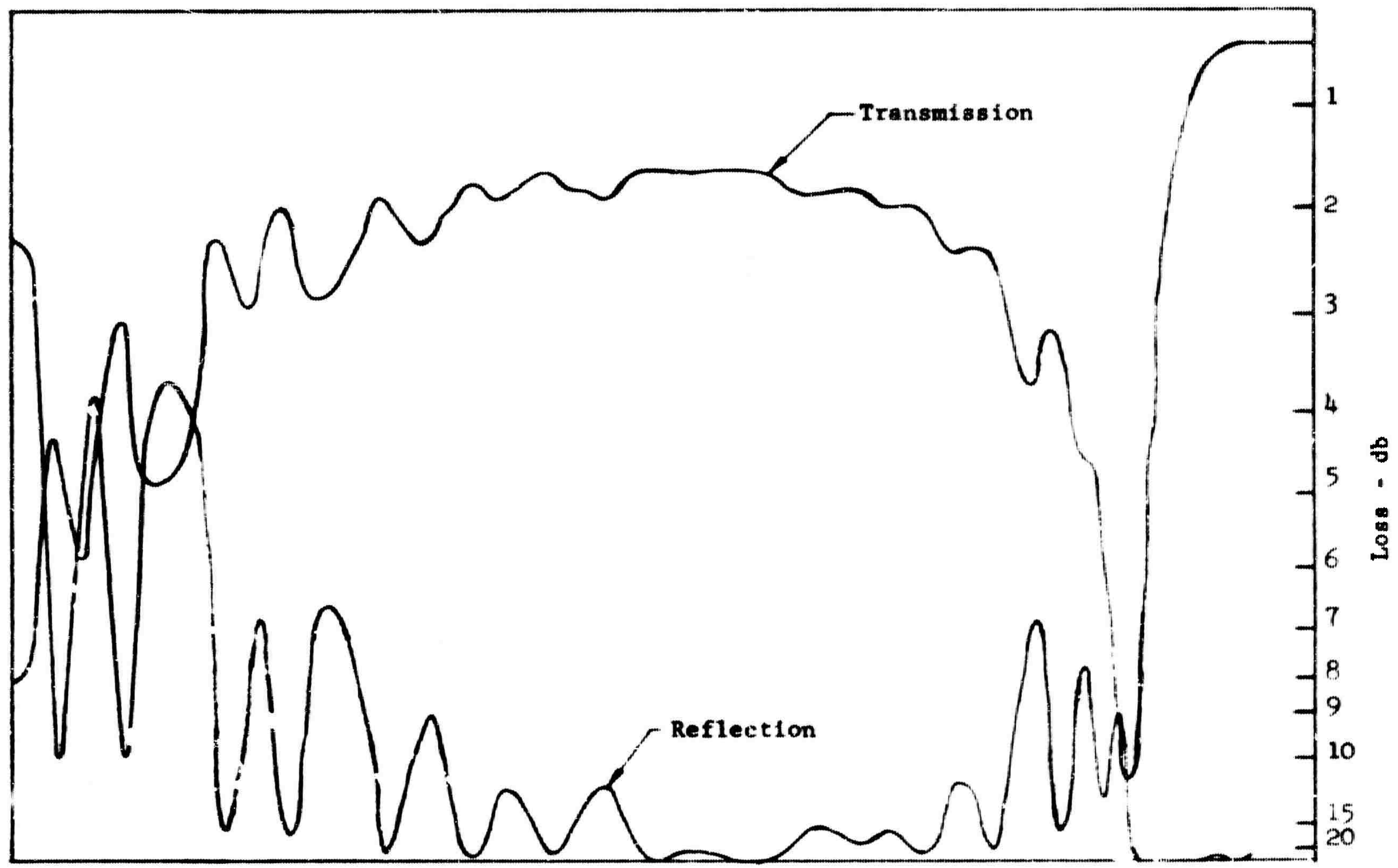

FIGURE 11 INSERTION LOSS OF CIRCUIT WITHOUT ABSORBER

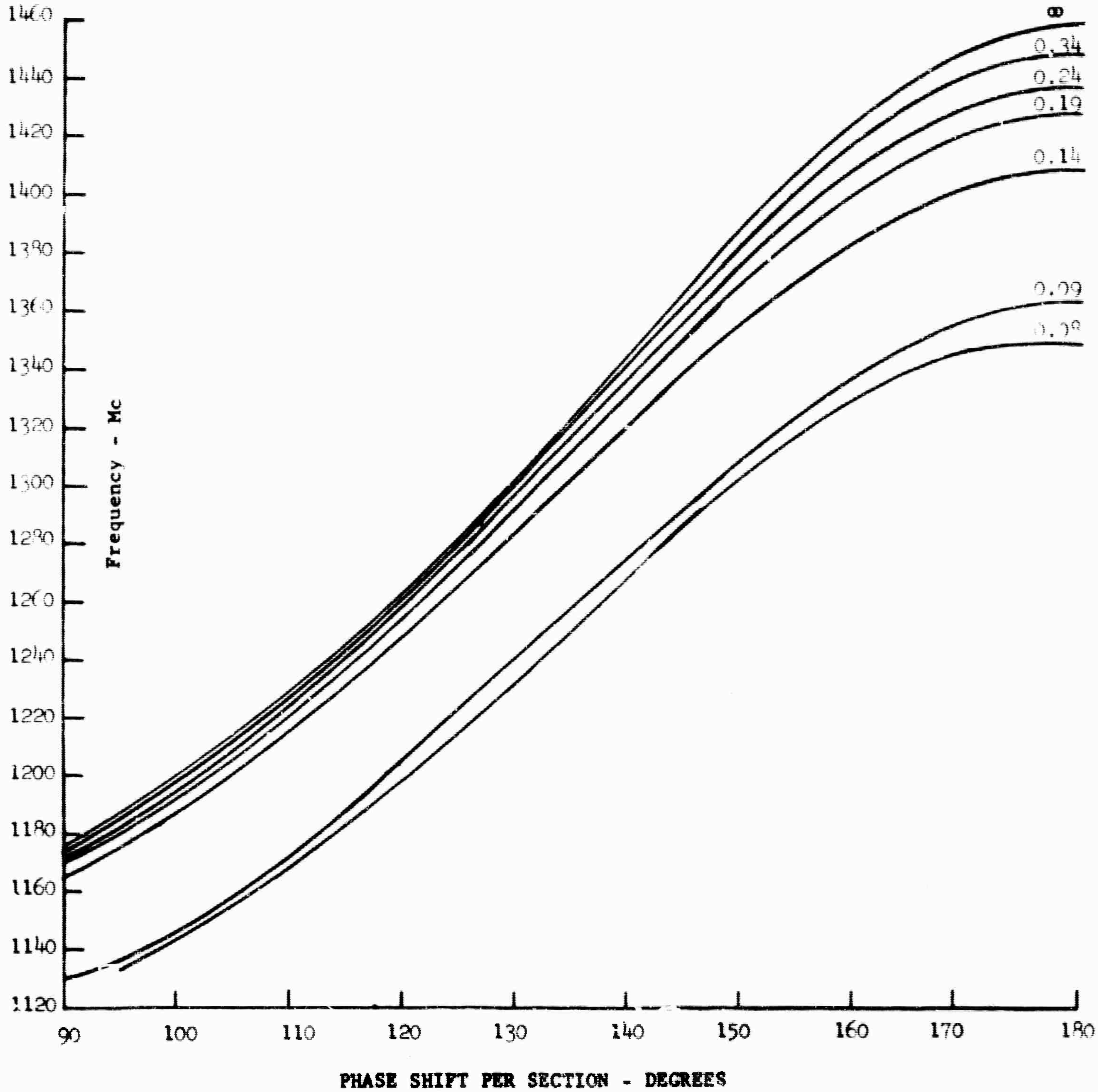

FIGURE 12 ω-β CURVES AS A FUNCTION OF SPACING BETWEEN BACK WALL AND C_{13} COUPLER RINGS FOR L-BAND LINEAR CIRCUIT

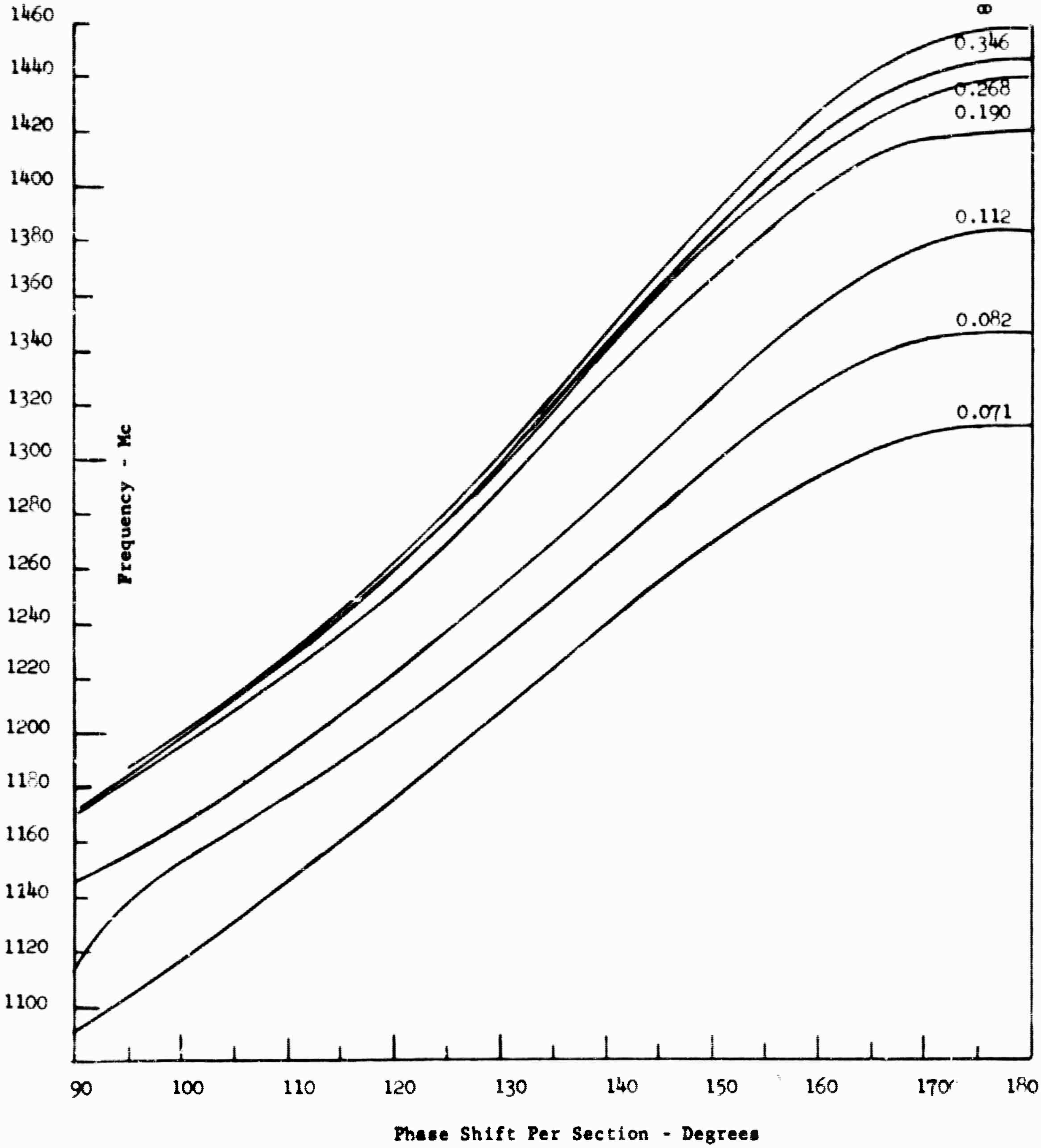

FIGURE 13 ω-β CURVES AS A FUNCTION OF SPACING BETWEEN 2 INCH RIDGE AND C_{13} COUPLER RING FOR L-BAND LINEAR CIRCUIT

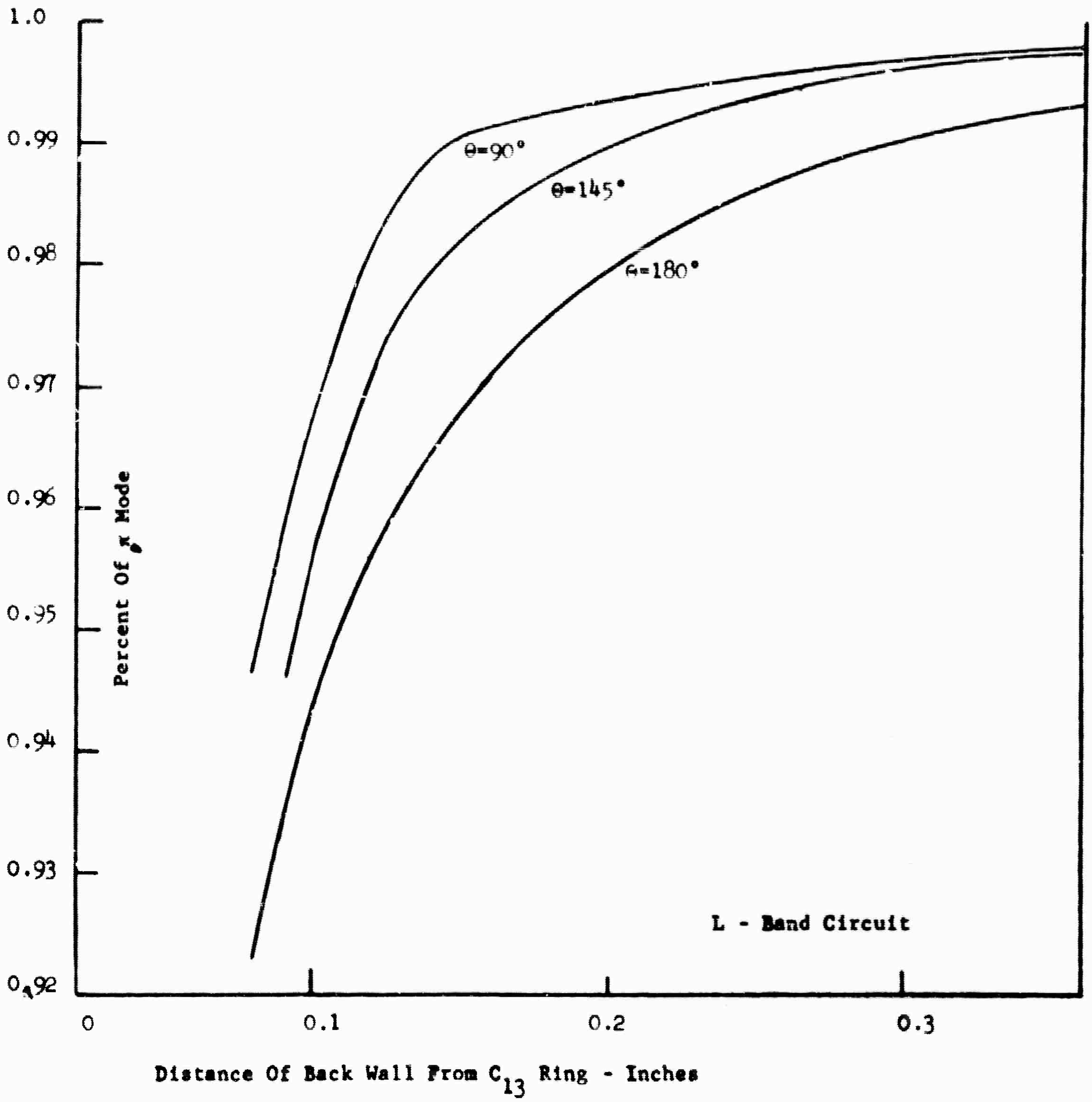

FIGURE 14 RELATIVE EFFECT OF BACK WALL SPACING ON FREQUENCY AT THREE DIFFERENT PHASE SHIFTS PER SECTION

5.0 SECONDARY EMISSION EXPERIMENTS

When tube J10E-1 was removed from life test, an experiment was performed on it in which the tubulation was opened and the tube let down to air. The tube was then repumped and tested again. It was found that this procedure did not change the starting jitter phenomenon which had developed by the end of life. The fact that the tube surfaces could be exposed to air without changing the nature of the jitter problem led to the conclusion that significant secondary emission measurements could be made on the cathode and control electrode parts removed from the tube. A secondary emission tester was set up in a bell jar with an arrangement which would permit various actual tube parts to be used as the target electrode to evaluate changes which had taken place during life. To first validate the performance of the secondary emission tester, it was tried on a molybdenum target. In a succession of experiments, there was continual difficulty in obtaining the proper results for a molybdenum target. Tests have been made to assure that spurious current is not getting to the collector electrode of the secondary emission tester. Improvements in accuracy have been obtained by reduction in the current density on the target but the values obtained for the secondary emission of molybdenum have still been too high. In recent experiments, approximately the correct values were obtained on the first run over the target but successively higher values occur on later runs. The targets have also shown discoloration in some of these experiments. It is the opinion now that the test surfaces are being contaminated by some substance present in the bell jar. Thus the secondary emission tester is being mounted into a demountable metal envelope. On a previous program this tester has given satisfactory results for a molybdenum target in such surroundings. Once such measurements have been repeated, test pieces will be cut from the electrodes removed from tube J10E-1 for evaluation as targets in this secondary emission tester.

6.0 CONCLUSIONS

Some of the conclusions to be drawn from the effort during this quarter are

1. the appearance of leading edge jitter during life test has been delayed by a change in the external control electrode circuitry. The circuit change allows the control electrode to operate cooler by lowering the dissipation. Thus it appears that the analysis of a cause of the jitter as excessive heating and a change in the surface properties of the control electrode is the correct one. It is believed that this effect will be eliminated by an improvement currently being made in the method of supporting the control electrode.

2. Life test results to date indicate that tube life well in excess of 2000 hours will be obtained with the SFD-209.

3. Life tests have shown the desirability of changing the input window from its present 3/8 size to a 7/8 coaxial window.

4. An evaluation of the hot test data has shown that some of the variability in the operating voltage for a given current has been a result of a calibration problem. It now appears as if the voltage-current characteristics at a given magnetic field will be quite reproducible from tube to tube.

5. Cold test measurements have indicated the feasibility of including an absorber behind the C_{13} couplers to provide differential attenuation of the band edge frequencies. This will result in an extension of the range of parameters over which the tube will operate without the presence of π mode oscillations. As a consequence, it will permit either the increase of the gain of the tube or increased tolerance of the tube to poor antenna VSWR.

7.0 PROGRAM FOR NEXT QUARTER

During the next quarter, we expect to

1. construct additional SFD-209 tubes with the new control electrode mounting design, with a 7/8 coaxial input window and possibly also with a porous ceramic absorber located behind the C_{13} couplers to damp the π mode;
2. continue life testing of the present Group C design driver tubes;
3. evaluate life test failures of the Group C design tubes. This will include an investigation of the properties of surfaces removed from life test tubes using the secondary emission tester.
4. set up and commence phase measurements on the SFD-209.

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