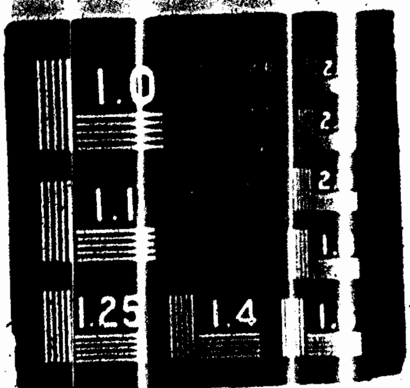
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HIGH POWER MAGNETICALLY CONFINED PLASMA DUPLEXER

Report No. 8 Contract No. DA 36-039-AMC-02364 (E)

8th Quarterly Report (1 March 1965 to 31 May 1965)

Army Task No. 7900-21-223-01-00

for

PROJECT DEFENDER

and

U.S. Army Electronics Command

Fort Monmouth, New Jersey

Submitted by:

ELCON LABORATORY, INC.

Subsidiary of Metcom, Inc.

119 Foster Street

Peabody, Mass.

HIGH POWER MAGNETICALLY CONFINED PLASMA DUPLEXER

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This research is part of Project Defender. The work prepared under this contract was made possible by the support of the Advanced Research Projects Agency under Order No. 426, through the U.S. Army Electronics Command.

Submitted to:

U.S. Army Electronics Command
Fort Monmouth, New Jersey

Purpose:

Research work to determine the feasibility of utilizing a plasma confined by magnetic fields to improve high power duplexer performance in accordance with the U. S. Army Electronics Command, Electron Tube Division, Technical Guidelines No. MW-5A, dated 6 March 1964.

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ILLUSTRATIONS

1. Purpose of Contractual Effort

The objective of this contractual effort is to determine the feasibility of improved high power duplexer performance using a plasma which is confined by a magnetic field. Specifically, the objective is the reduction and direction of heat losses, decrease of sputtering and gas clean-up of a plasma by magnetic confinement. The program aims toward the development of a stable and controllable magnetic plasma confinement scheme. The following tasks will be carried out in a period of twelve months beginning June 1, 1964.

1.1 A study of the properties of high power microwave plasmas in a magnetic field.

1.2 Determination of the characteristics of various Penning type gas mixtures in a confining magnetic field.

1.3 Investigation of the following properties of magnetically confined plasmas.

- 1.3.1 Thermal Properties
- 1.3.2 Arc Loss
- 1.3.3 Recovery Time
- 1.3.4 Gas Clean-up
- 1.3.5 Noise
- 1.3.6 Leakage Energy

1.4 Determination of High power limitations of the magnetically confined plasma duplexer.

1.5 Experiments to check the results of the analytical program.

1.6 Design of an exploratory development model duplexer utilizing the results of the feasibility study.

1.7 Consideration of methods of size, weight and power consumption reduction in the prototype duplexer.

2. Abstract

Three methods of reducing the recovery time of the magnetically confined plasma duplexer are investigated. One method, the use of a plasma tuned cavity, is partially successful, but is too complicated to be practical. A second method using d.c. sweeping electric fields is unsuccessful. A third method, using thin dielectric fibers to reduce the average ambipolar diffusion distance in the plasma is a satisfactory compromise solution to the problem of achieving an acceptable recovery time and having a very effective confining magnetic field.

3. <u>Conferences, Lectures, Reports and Publications</u>

3.1 Conference on 25 March 1965 at Elcon Laboratory, Inc.

3.1.1 Present: Maurice Weiner, USAECOM - Louis W. Roberts, Dr. Edwin Langberg, William Ghen, Elcon.

3.1.2 Experimental Program: Discussed the multiple recovery phenomenon and the objective of using partially deionized plasma for microwave tuning of an oversize cavity. Demonstrated recovery of an oversize cavity.

3.1.3 Conclusions: Preliminary results using an oversize cavity indicate that it may be possible to achieve a useful recovery by this method. Investigation of this approach to be continued.

3.2 Conference on 15 April 1965 at Elcon Laboratory, Inc.

3.2.1 Present: John Carter, USAECOM - Louis Roberts, Dr. Edwin Langberg, William Ghen, Elcon.

3.2.2 Experimental Program: Results of attempts to achieve a useful recovery time using the oversize cavity approach, Contract status discussed.

3.2.3 Conclusions: The oversize cavity approach to recovery time control shows some promise, but other methods should be investigated before design of the exploratory model duplexer is completed. A 60 or 90 day no-cost contract extension should be considered to allow time to complete the investigation of recovery time control, and to allow adequate time for delivery of long lead-time components.

3.3 Conference of 4 May 1965 at Elcon Laboratory, Inc.

3.3.1 Present: Maurice Weiner, USAECOM - Louis W. Roberts, Dr. Edwin Langberg, William Ghen, Elcon.

3.3.2 Experimental Program: Discussed the results of the attempts to control recovery time by means of the oversize cavity. Design of exploratory model duplexer discussed. Plans to attempt to control recovery time by means of d.c. "sweeping" fields discussed.

3.3.3 Conclusions: The oversize cavity method of recovery time control is probably not feasible, and other methods should be evaluated before finalizing the design of the duplexer.

3.4 Paper presented at the Hexagon, Fort Monmouth, N. J. on 20 May 1965 at the High Power Microwave Tubes Symposium co-sponsored by The U.S.Army Electronics Command and The Advisory Group on Electron Devices.

3.4.1 Authors: Louis W. Roberts, Dr. Edwin Langberg William R. Ghen.

3 3.4.2 Title: High Power Plasma Duplexer Study.

4. Control Of The Duplexer Recovery

It has been apparent that the recovery time of pure noble gases or noble gas Penning mixtures in the cylindrical TE_{11} cavity is too long for most practical duplexer applications when an effective confining magnetic field is used. Three methods of controlling this recovery time have been investigated during the quarter: a) the oversize cavity method, b) the use of d.c. "sweeping" field, and c) the reduction of average umbipolar diffusion distance by filling the gas container with thin dielectric fibers.

4.1 The Oversize Cavity Method

The recovery of the TE_{11} cylindrical cavity has indicated that it is possible to transmit a low level signal through it while the gas is still partially ionized.

The most significant variable which determines the transmissions through the plasma is the plasma frequency. The effective dielectric constant of the plasma is

$$\epsilon = \epsilon_o \left[1 - (\omega_p/\omega)^2 \right] \qquad \ldots(4.1)$$

Immediately after the transmitter pulse

$$\omega_p \gg \omega \qquad \ldots(4.2)$$

and the plasma behaves as a microwave reflector and little penetration of the plasma takes place.

When

$$\omega_p \lesssim \omega \qquad ..(4.3)$$

the dielectric constant of the plasma is less than that for free space, detuning the cavity and resulting in some reflection and some transmission.

Finally when

$$\omega_p << \omega \qquad ..(4.4)$$

the plasma is basically transparent, and has no effect on the transmission of microwaves.

The condition where $\omega_p \lesssim \omega$ is the one of interest in attempting to use the partially deionized plasma to tune the cavity. At this time, the dielectric constant is less than that for free space, and the cavity resonant frequency should be considerably higher than without any plasma. Therefore, by appropriately increasing the cavity size, it should be resonant at the desired frequency during the time that the plasmas has a relative dielectric constant less than unity.

4.2 The Use of d.c. "Sweeping" Fields

Certain types of TR tubes have used d.c. electric "sweeping" fields as a means of recovery time control. Such fields are established between an auxiliary electrode or grid and the metal microwave electrode structure of the tube in such a way that the sweeping electrode is shielded from the microwave fields (or suitably choked), but the d.c. electric fields tend to rapidly remove electrons from the microwave interaction region. Such sweeping devices typically reduce recovery time by a factor of 10 to 30 without significantly changing the high power performance of the tubes. The quartz bottles used in the cylindrical TE_{111} cavity do not lend themselves to the convenient installation of sweeping electrodes. However, a preliminary investigation to determine the feasibility of this approach was carried out, and the results are discussed in Section 5 of this report.

4.3 The Reduction of Average Ambipolar Diffusion Distance By Filling The Gas Container With Thin Dielectric Fibers

Filling the bottle with thin fibers of quartz has the effect of increasing the surface area for ion-electron recombination and reducing the average ambipolar diffusion distance. The primary result is the reduction of the recovery time. One of the reasons for using magnetic confinement is to decrease ambipolar diffusion. In this respect the effect of quartz wool counteracts the effect of the magnetic field and no significant effect of the magnetic field on the recovery time can be expected.

However, the magnetic field has two other effects: It changes the complex dielectric constant of the plasma as well as the plasma shape within the bottle. One can, therefore, expect that a magnetic field can change the arc loss to some extent even in the presence of quartz wool. This arc loss change does not necessarily influence the quartz bottle wall temperature. The heat is dissipated primarily in the quartz fibers inside. Due to transparency of the quartz bottle, the heat transfer from the interior may be largely by radiation directly to the cavity walls.

5. Experimental Program

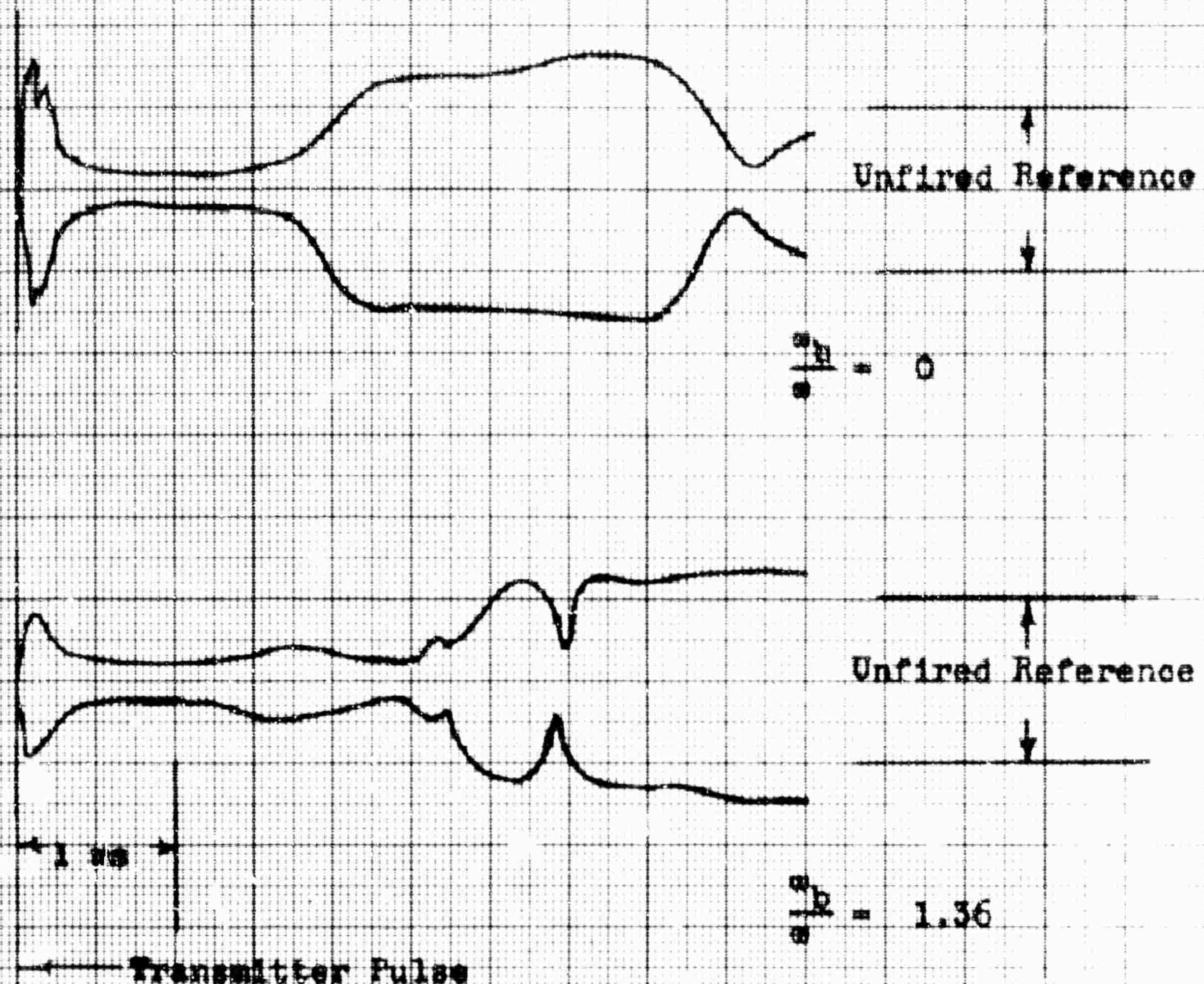
The experimental program for the eighth quarter consisted of the investigation of the three methods of recovery time control discussed in Section 4 of the report.

5.1 The Oversize Cavity Method of Recovery Time Control

The TE_{111} cylindrical cavity was modified to lower its resonant frequency substantially by adding a section of pipe to increase the cavity length by approximately 150 electrical degrees at the operating frequency. A style 2 quartz bottle centrally located in the cavity was used as the plasma container, The electromagnets were used to develop the cusp magnetic field. The cavity, modified as described above, had a low level insertion loss of about 8 db., and was resonant below the cut-off frequency of the rectangular S-band waveguide. The recovery response of the cavity is shown in Figure 5.1. Without magnetic field, the cavity had a very pronounced transmission of the probing signal during the time when $\omega_p \approx \omega$. However, the start of this transmission period was nearly 2 ms after the transmitter pulse, and lasted about 2 ms. With magnetic field, this transmission period was considerably less pronounced.

FIGURE 5.1

TE_{111} Cylindrical Oversize Cavity Recovery Response



Cavity 150° oversize
Cusp Magnetic Field
Fill: 100 μ Argon
Peak Power = 2.0 Megawatts
Average Power = 2.0 Kilowatts

The cavity extension was shortened in several steps, until at 75 degrees oversize, the cavity recovery began to approach the standard cavity recovery. None of the intermediate length showed any more useful recovery characteristics than the 150° extension.

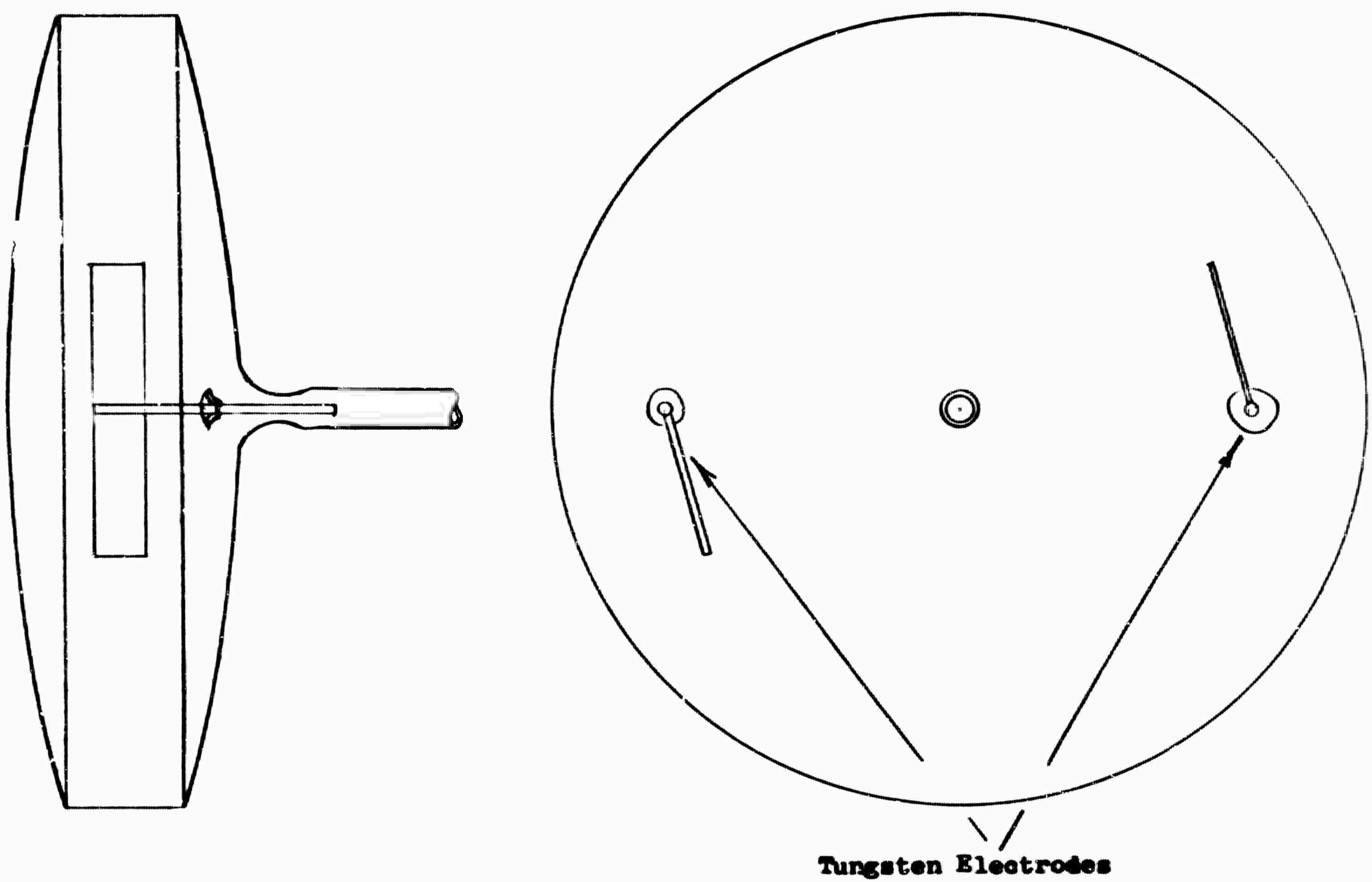
It should be pointed out that to properly evaluate the oversize cavity approach to recovery control, the cavity diameter, as well as length should be increased, or with the standard cavity, the operating frequency should be increased considerably. An increase in cavity diameter, beside requiring a new cavity and quartz bottle, would require a new pair of electromagnets, and probably a new magnet d.c. power source. An increase in the operating frequency of the high power experimental equipment would require a new magnetron, and all new waveguide. Both of these alternatives are beyond the scope of the present contract.

5.2 The Use Of d.c. "Sweeping" Field

Two metal electrodes were sealed into a style 1 quartz bottle as shown in Figure 5.2. The entire electrode structures were made of tungsten to withstand the heat of sealing to quartz, and for its inherent resistance to sputtering. Small insulated wires were attached to the outside terminals of the electrodes, and brought out of the cavity through the

FIGURE 5.2

STYLE I Quartz Bottle With
Sweeping Electrodes



output coupling aperture in such a way as to minimize coupling to the r.f. fields. No significant detuning of the cavity was produced by the electrodes and leads. The bottle was mounted conventially in the cylindrical TE_{111} cavity, and the standard cusp magnetic field was used. The cavity was operated at powers up to 2 megawatts peak, 2 kilowatts average with argon fills from 10 microns to 2000 microns. The bottle was rotated in the cavity to change the position of the sweep electrodes relative to the microwave electric field within the cavity. No reduction in recovery time was observed under any conditions without magnetic field. Under certain conditions, the application of a d.c. sweeping voltage produced a very slight recovery time reduction (1-2%), with magnetic field. The only electrode d.c. polarity which produced any observable sweeping action was with one electrode positive and the other negative. Under these conditions, the maximum d.c. voltage was limited to about 300V. Above 300V. a d.c. glow discharge was initiated by the r.f. and sustained by the d.c. voltage resulting in several db. insertion loss, and considerable noise generation. When the quartz bottle was removed from the cavity after a total operating time of about six hours, at power levels up to 2 MW peak, the inside surfaces of the quartz near the tungsten electrodes were heavily coated with sputtered metal.

5.3 The Reduction Of Average Ambipolar Diffusion Distance By Filling The Gas Container With Thin Dielectric Fibers

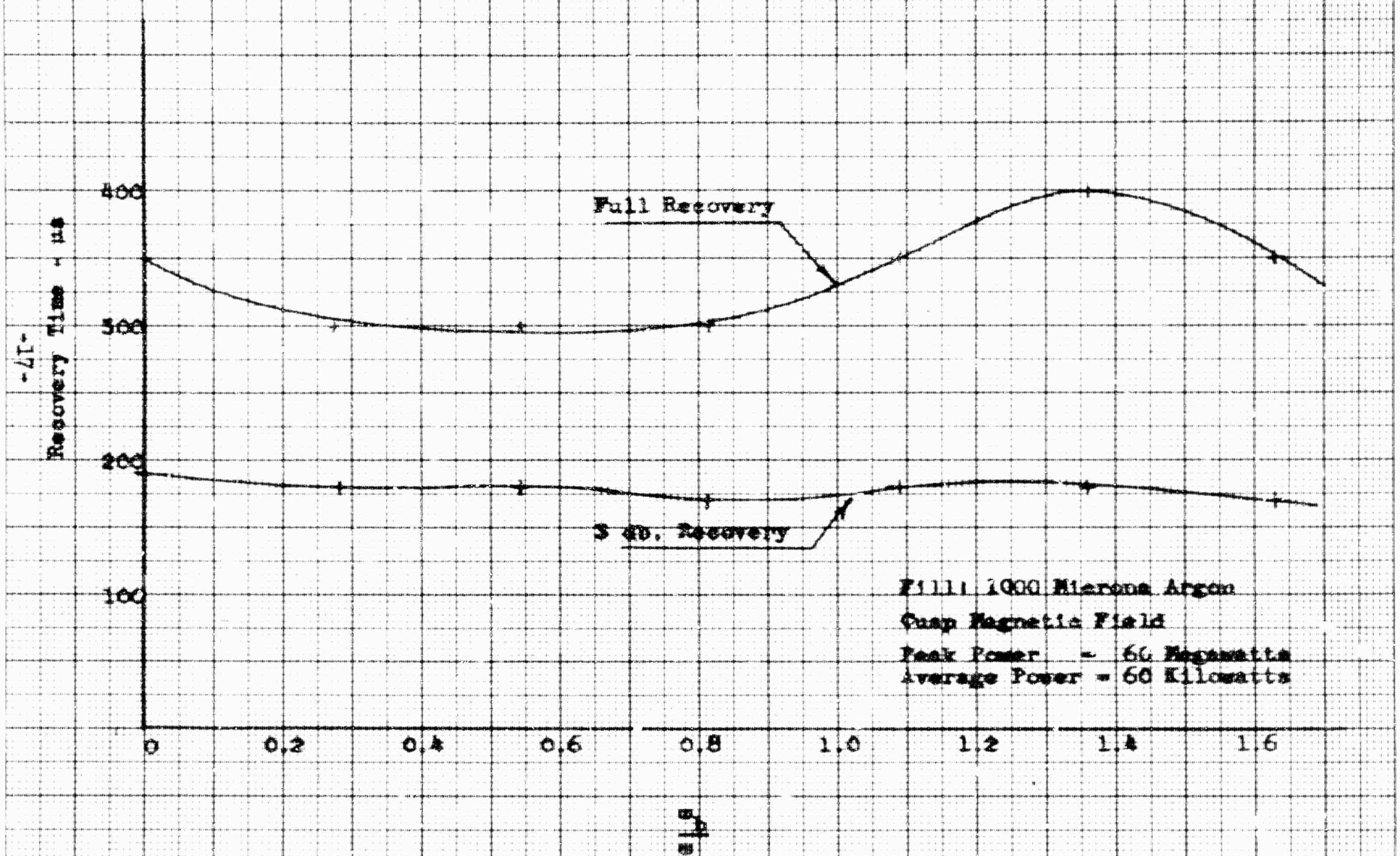
A style 2 quartz bottle was completely filled with loosly packed high purity quartz fibers. An attempt was made to keep the fiber density as uniform as possible, but because of the necessity of filling the bottle through a small hole, some non-uniformity was unavoidable.

The fiber filled bottle was then mounted in the TE_{111} cavity and connected to the tube exhause system. The bottle was outgassed by r.f. ionization as described in Section 5.1 of the Sixth Quarterly Report. The quartz fibers retain a large amount of water, and require many hours of outgassing before a stable gas fill can be achieved. Initially, the complete recovery time was about 10 μs due to the large amount of water vapor driven out of the quartz fibers. The recovery time gradually increased to about 400 μs after several days of outgassing. The arc loss decreased until the full recovery time increased to about 100μs, then remained essentially constant, although the recovery time eventually increased to about 400μs.

The 3 db. and full recovery time as a function of magnetic field are shown in Figure 5.3. The magnetic field does not increase the recovery time very much - in fact, the 3 db.

FIGURE 5.3

TE_{111} Cylindrical Cavity Recovery Time
As A Function of Magnetic Field
Quartz Wool Filled Bottle



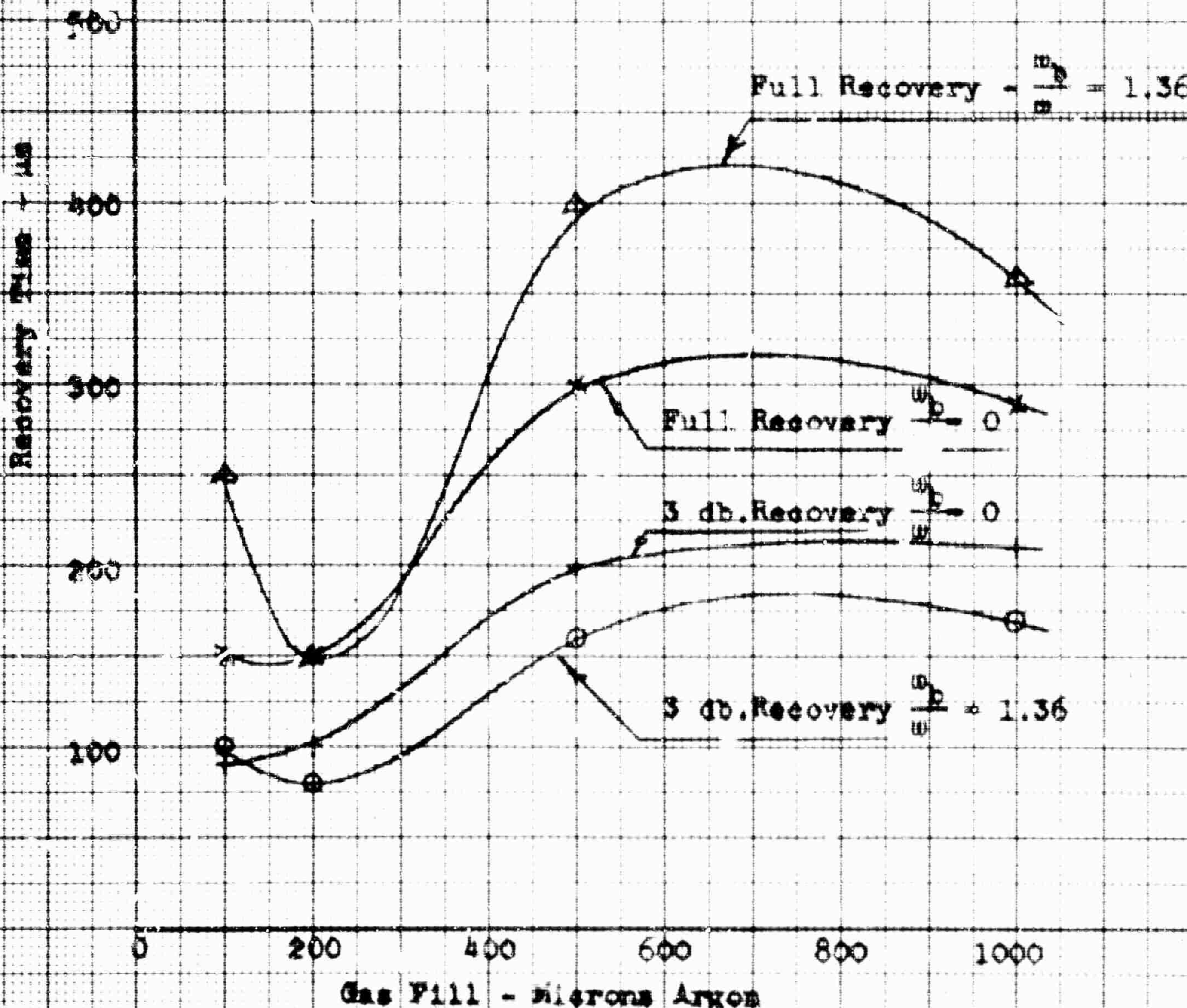
recovery tends to be decreased slightly by the cusp magnetic field. This is probably due to the redistribution of plasma in the bottle. The magnetic field tends to move the plasma away from the inside surface of the quartz bottle, where the quartz fibers are less dense, toward the center of the bottle, where the fiber density is more uniform. The recovery time variation with gas fill pressure is shown in Figure 5.4.

The magnetic field reduced the 3 db. recovery time throughout the gas fill pressure range of 120 microns to above 1000 microns. The overall effect of the quartz fibers on recovery time was about a ten-fold reduction in both the 3 db. and full recovery compared to the same gas fills without the quartz fibers.

It is reasonable that such a reduction in recovery time might be accompanied by some increase in arc loss. However, the increase in arc loss is not as severe as might be expected. Figure 5.5 shows the arc loss as a function of gas pressure with and without magnetic field. This represents about double the loss under the same conditions without quartz fibers. It is significant that the arc loss is consistantly about 50% higher without magnetic field than with a field of $\omega_b/\omega = 1.36$. The variation of arc loss with magnetic field is shown in Figure 5.6.

FIGURE 5.4

TE_{111} Cylindrical Cavity Recovery Time
As A Function of Gas Pressure
Quartz Wool Filled Bottle



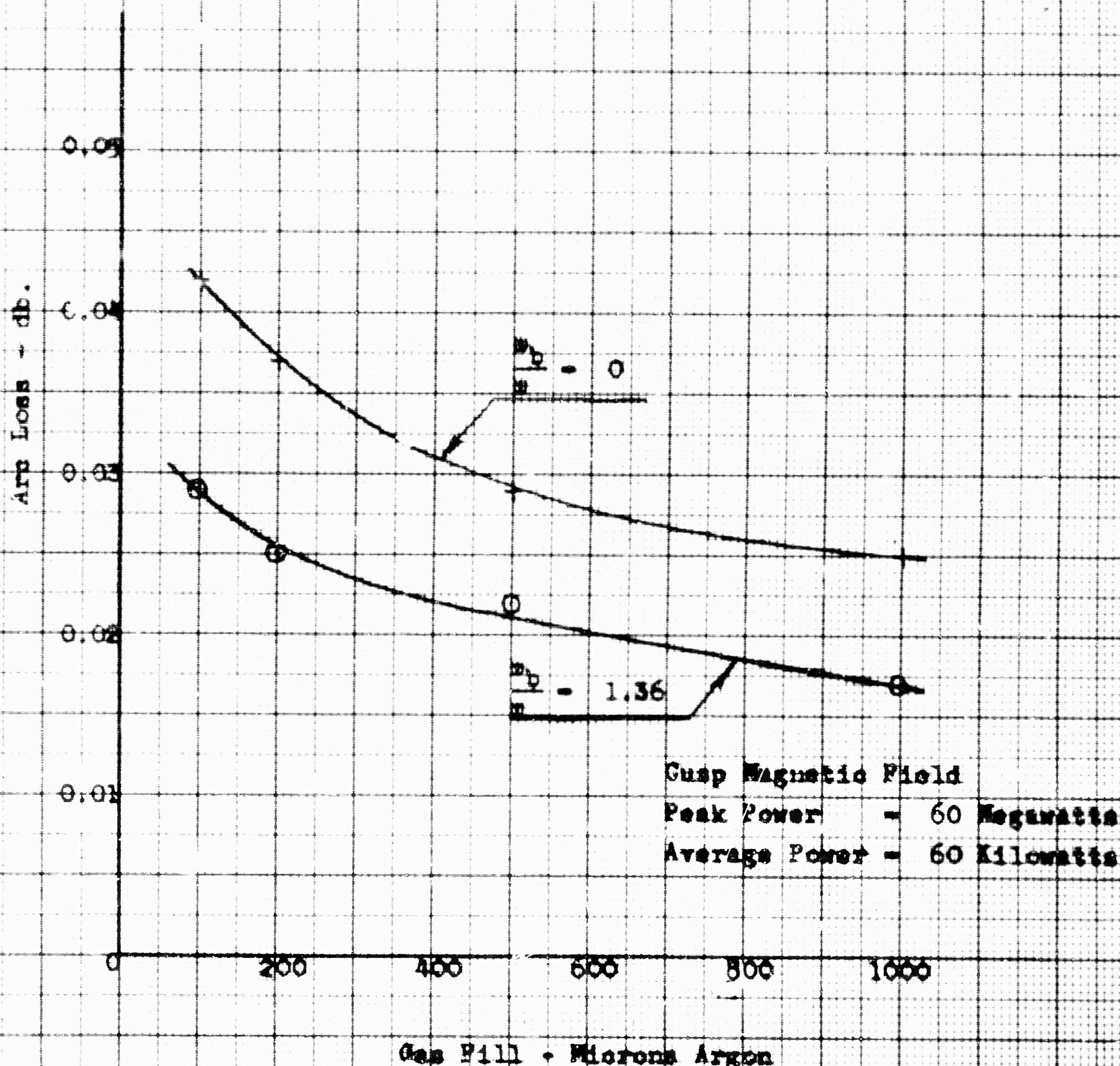
Cusp Magnetic Field
Peak Power = 60 Megawatts
Average Power = 60 Kilowatts

FIGURE 5.5

TE_{111} Cylindrical Cavity Arc Loss

As A Function Of Gas Pressure

Quartz Wool Filled Bottle



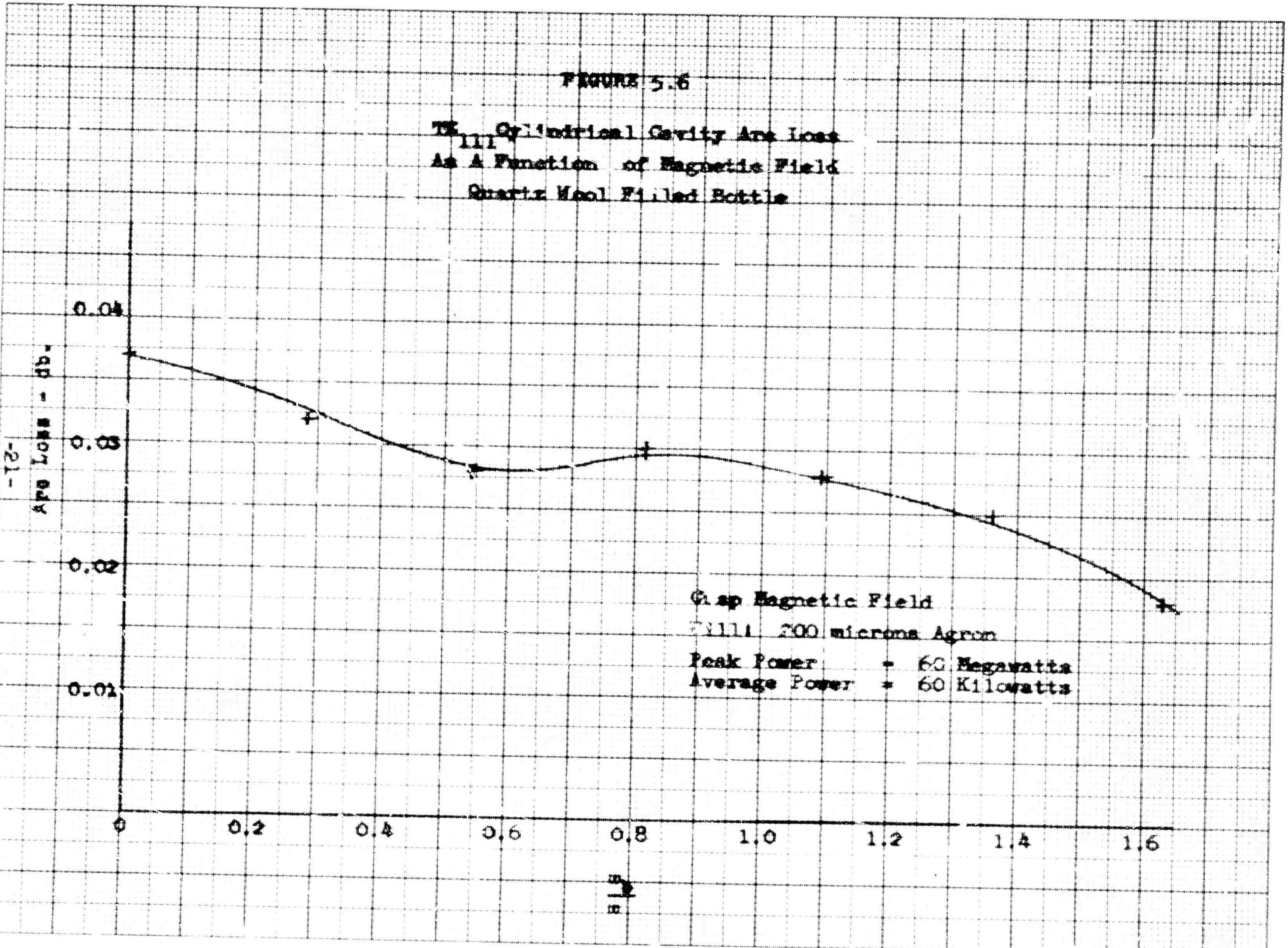


FIGURE 5.6

TM_{111} Cylindrical Cavity Arc Loss
As A Function of Magnetic Field
Quartz Wool Filled Bottle

The quartz fiber had little effect upon the high power attenuation of the cavity. The 30 db. to 33 db. attenuations shown in Figures 5.7 and 5.8 are typical of argon fills without quartz fibers.

The increase in arc loss associated with the addition of quartz fibers naturally results in some increase in the temperature rise of the quartz bottle. The quartz fiber-filled bottle was baked at 1000°C and tipped off so that all temperature rise experimentation could be done with the same fill. The bottle, after the 1000°C had a slightly longer recovery time than previously, when it had been outgassed with r.f., probably because some regions of the fibers are not subjected to sufficiently high energy ion bombardment to completely outgas them. The recovery transmission curves of the baked, quartz fiber-filled bottle are shown in Figure 5.9. All other high power performance characteristics were the same with the baked bottle as they had been with the bottle connected to the tube exhaust system.

The temperature rise of the quartz bottle was measured by painting a series of dots on both the input and output ends of the bottle with temperature sensitive paint. The effect of magnetic field upon temperature rise was somewhat inconclusive, probably due to the non-uniformity of temperature rise caused by variations in quartz fiber density. The

FIGURE 5.7

TE_{111} Cylindrical Cavity High Power Attenuation
As A Function of Gas Pressure
Quartz Wool Filled Bottle

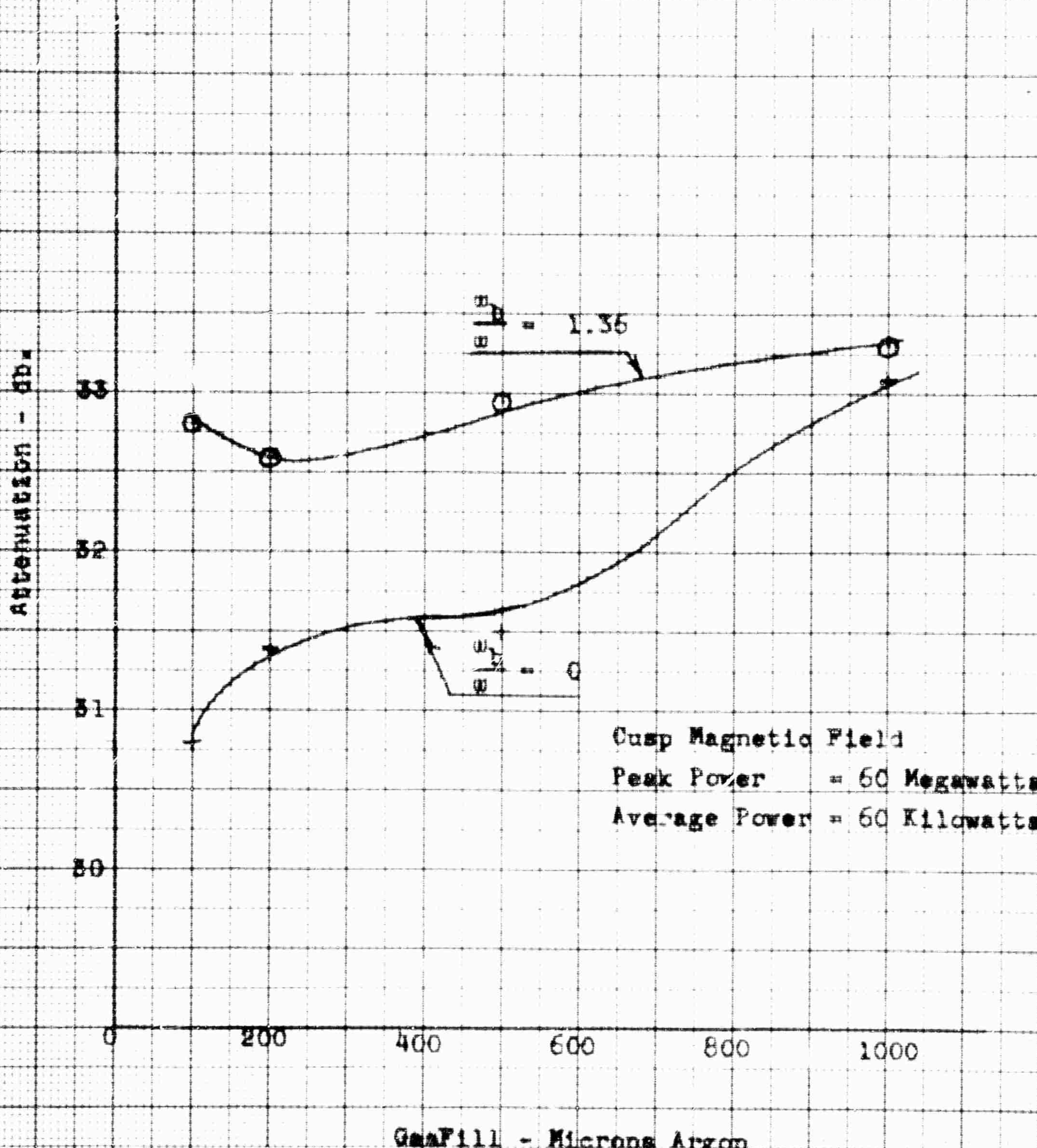


FIGURE 5.8

TE_{111} Cylindrical Cavity High Power Attenuation
As A Function of Magnetic Field

Quartz Wool Filled Bottle

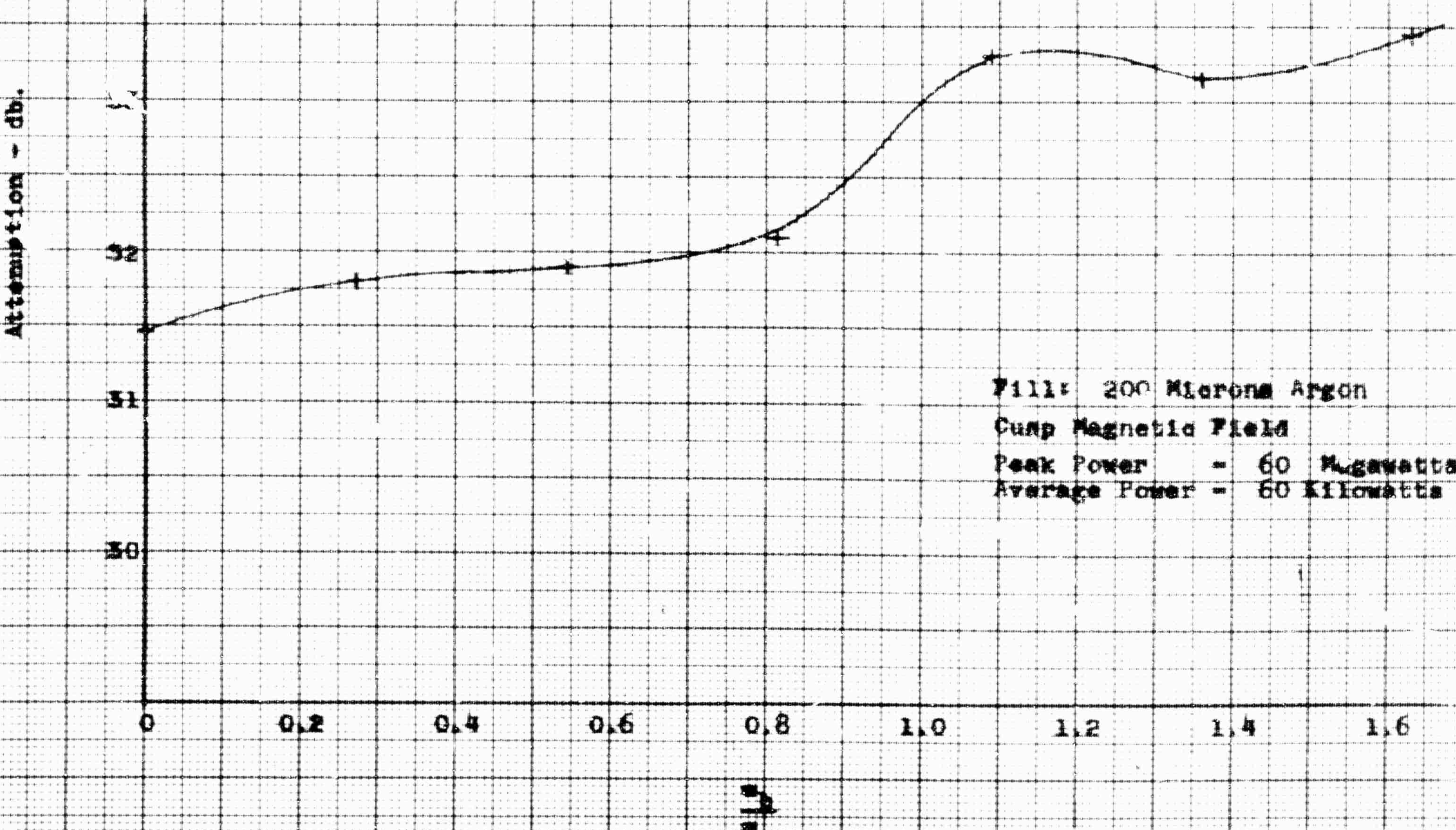
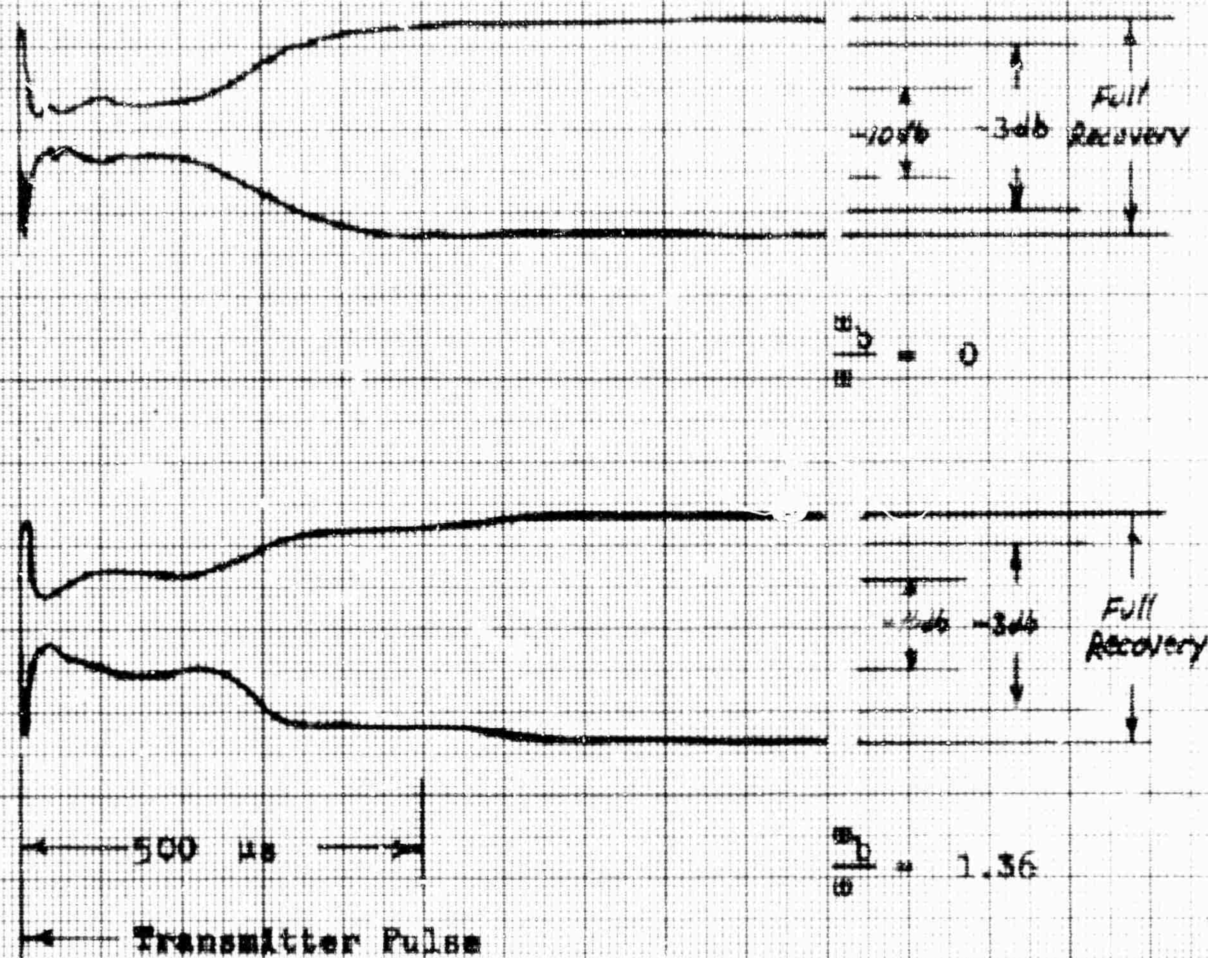


FIGURE 5.9

TE_{111} Cylindrical Cavity Recovery Response

Quartz Wool Filled Bottle



Cusp Magnetic Field

Fill: 1000 microns Argon

Peak Power = 50 Megawatts
Average Power = 50 Kilowatts

magnetic field lowered the temperature of the input end of the bottle slightly, and increased the temperature of the output end. The maximum temperature rises of the input and output ends were 300°C and 160°C respectively at a power of 50 megawatts peak, 50 kilowatts average. No cavity cooling was used.

6. Conclusions

6.1 Recovery Time Control By The Oversize Cavity Method

The investigation of the oversize cavity method of recovery time control indicates that it may be possible to have sufficiently good low level signal transmission during the time when the plasma is partially deionized to be useful as a duplexer. Such a system would have a definite lower limit to the pulse repetition rate, as the low level transmission would be unsatisfactory when the plasma is fully deionized.

There are many problems in designing a suitable oversize cavity and gas container. The adjustment of the cavity for low power signal transmission, a cut-and-try process usually done on a low level test bench with a sheet metal mock-up cavity, must be done at high power with a fully operational, leak tight cavity and gas container. There is no known material which can simulate the dielectric properties of a plasma when $\omega_p \gtrsim \omega$. The remaining time and funds in the present contract do not permit such a program, and no further experimental work will be done on this approach.

6.2 The Use of d.c. Sweeping Fields To Reduce Recovery Time

The results of the investigation of d.c. sweeping fields as a means of recovery time control do not warrant any further experimental efforts on this approach. A more effective electrode design could probably be found, but the problems of cavity detuning, r.f. coupling to the lead wires, and sputtering of the electrode material would be very difficult to overcome, and no further work will be done with d.c. sweeping fields.

6.3 The Reduction Of Average Ambipolar Diffusion Distance By Filling The Gas Container With Quartz Fibers

The quartz fiber method of recovery time control is a compromise between effective magnetic confinement and an acceptable recovery time. However, the magnetic field is effective in reducing the arc loss, and probably in reducing gas clean-up at the inside surface of the quartz container.

The quartz fiber filled bottle provides satisfactory duplexer performance over a fairly wide pressure range. Most of the experimental work was done at pressures between 100 and 1000 microns. Nothing seems to limit the upper pressure which can be used, although at pressures above 1000 microns, magnetic confinement will be less effective. The lower pressure limit will be determined by the maximum acceptable arc loss. At pressures below 200 microns, arc loss increases rather rapidly (see Figure 5.5), and this probably represents about the lower limit for useful duplexing.

No experimental work has been done to establish the gas clean-up rate using quartz fibers. It is expected that, after a brief period of gas absorption by the fibers, the effects of saturation will reduce the clean-up rate so that it is not very different than a plain quartz bottle. The fibers may even act as a gas reservoir, releasing some of the absorbed gas as the pressure decreases and arc loss (and temperature) rises. The fiber filled bottle was operated for about 40 hours at power levels between 40 and 70 megawatts peak, 40 to 70 kilowatts average. No evidence of gas pressure charge, other than the initial outgasing, or of any deterioration of the quartz fibers was observed. Quartz fiber filled bottles will be used as the means of recovery time control in the exploratory model duplexer.

7. <u>Program For The Next Interval</u>

1. Complete the fabrication of the exploratory model duplexer.

2. Evaluate the duplexer at the highest power available.

8. Identification of Key Technical Personnel

8.1 Louis W. Roberts — 126 Hours

M.S. in Physics, University of Michigan, Pre-doctoral studies, Massachusetts Institute of Technology. 1944-1950: engaged in microwave tube development at Sylvania, finally as Manager, Tube Development, Electronics Division 1950-1955: Founder and Vice President and Director of Research, Microwave Associates. 1955-1959: Staff Physicist, Bomac Laboratories contributing to company research and development programs in microwave power and duplexer tubes. 1959 - present: Vice President, Research and Engineering, Metcom, Inc. directing technical aspects of all company activities in microwave power and duplexer tubes and solid state devices. November, 1963 - present: President of Elcon Laboratory, Inc.

8.2 Dr. Edwin Langberg — 119 Hours

Ph.D. in Electrical Engineering, Princeton University 1956. 1946-1947: Design Engineer in the Development Lab. of Czechoslovak Telefunken Company engaged in the design of electronics laboratory test equipment, Sobell Industrial Ltd., England. 1949-1953: Moore School of Electrical Engineering, University of Pennsylvania, concerned with analog computers and development of a novel plasma switch. 1953-1957: Member of Technical Staff, RCA Laboratories Division, concerned with studies of ion impact erosion of metals and with the generation of millimeter waves. 1957 - 1958: Head, Applied Physics Group, Avco Research and Advanced Development Division, and Project Director of Direct Re-Entry Telemetry System, concerned with studies of propagation of electro-magnetic radiation through ionized gases. 1958 - Present: Founder, President, and lately, Research Director and Chairman of the Board of Elcon Laboratory, engaged in research in the fields of plasmas, physical electronics and optics.

8.3 William Ghen 471 Hours

B.S. in Electrical Engineering, Northeastern University, 1952. 1952-1959: Assistant Chief Engineer, Gas Switch Tube Department, Bomac Laboratories, participating in the direction of technical programs in the field of gaseous TR and ATR devices, as well as complete duplexing systems, and did pioneering work on traveling wave resonators now widely used in high power testing of microwave duplexer devices. 1959 - present; Chief Engineer, Gas Switching Tubes, Metcom, Inc. responsible for research and development supervision in the field of gaseous switching devices at all power levels presently achievable.

9. List of Symbols

ω	Microwave Frequency
ω_b	Cyclotron Frequency
ω_p	Plasma Frequency
ϵ	Absolute Dielectric Constant
ϵ_o	Absolute Dielectric Constant of Free Space

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Langberg Edwin Dr.; Ghen William

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13. ABSTRACT

Three methods of reducing the recovery time of the magnetically confined plasma duplexer are investigated. One method, the use of a plasma tuned cavity, is partially successful, but is too complicated to be practical. A second method using d.c. sweeping electric fields is unsuccessful. A third method, using thin dielectric fibers to reduce the average ambipolar diffusion distance in the plasma is a satisfactory compromise solution to the problem of achieving an acceptable recovery time and having a very effective confining magnetic field.

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14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.