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AD 806831

# HIGH POWER RF WINDOW STUDY

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## FOREWORD

This final report was prepared by Varian Associates, Eimac Division, San Carlos, California under Contract AF30(602)-3790, Project 5573, Task 557305. The RADC project engineer is Mr. Dirk T. Bussey, EMATE. The work was performed during the period of April 1, 1966 through September 30, 1966.

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This technical report has been reviewed and is approved.

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ABSTRACT

The purpose of this program is to develop a 1.0 megawatt rf window having 10% bandwidth at 8.0 GHz.

Seven window samples were tested during the present report period and with one exception all failed at various power levels between 262 kw CW and one megawatt CW. Individual tests are discussed.

A zero degree sapphire window was tested at one megawatt CW and successfully transmitted this power for 31 minutes. The window did not fail.

A complete summary of all window test results obtained during this program is presented.

## TABLE OF CONTENTS

I. INTRODUCTION . . . . . . . . . . . . . . . . . . . . . . . . . 1

Contractual Information . . . . . . . . . . . . . . . . . . . 1

II. DISCUSSION . . . . . . . . . . . . . . . . . . . . . . . . . . 2

WINDOW PROGRAM . . . . . . . . . . . . . . . . . . . . . . . 2

1. General . . . . . . . . . . . . . . . . . . . . . . . . . . . 2

2. Hot Test Window Performance (Final Report Period) . . . 4

a. Definition . . . . . . . . . . . . . . . . . . . . . . . 4

b. Thin Disc BeO (oversize 1.680 in. dia. x 0.090 thick) Sample #1 . . . . . . . . . . . . . . . . . . . . . . 5

c. Thin Disc BeO (oversize 1.680 in. dia. x 0.090 thick) Sample #2 . . . . . . . . . . . . . . . . . . . . . . 9

d. Thick Disc BeO (undersize 1.316 in. dia., 0.4 $\lambda_g$ thick) Sample #2 . . . . . . . . . . . . . . . . . . . . . . 9

e. Thin Disc BeO (undersize 1.316 in. dia. x 0.065 thick) . . . . . 11

f. Thin Disc Sapphire (normal size 1.608 in. dia. x 0.050 thick) 60 degree cut . . . . . . . . . . . . . . . . . . . . 13

g. Thin Disc Sapphire (undersize 1.316 in dia. x 0.045 thick) 60 degree cut . . . . . . . . . . . . . . . . . . . . 16

h. Thin Disc Sapphire (undersize 1.316 in dia. x 0.050 thick) Zero degree cut. . . . . . . . . . . . . . . . . . . . 16

3. Hot Test Window Performance (Program Summary) . . . . . 18

4. Conclusions . . . . . . . . . . . . . . . . . . . . . . . . 18

## LIST OF FIGURES


Fig. 1 - Damaged Window Assembly . . . . . . . . . . . . . . . . . . 6

Fig. 2 - Diagonal Crack Thin Disc BeO Window - Sample #1 . . . . 8

Fig. 3 - Diagonal Crack Thin Disc BeO Window - Sample #2 . . . . 10

Fig. 4 - Diagonal Crack Thick Disc BeO Window - Sample #2 . . . 12

Fig. 5 - Cracked Thin Disc BeO Window . . . . . . . . . . . . . . 14

Fig. 6 - Thin Disc Sapphire "Y" Shaped Crack . . . . . . . . . . . 15

Fig. 7 - Cracking Pattern of 60 Degree Cut Thin Disc Sapphire . 17

Fig. 8 - Test Results Summarized (Tabular) . . . . . . . . . . . . 19

Fig. 9 - Characteristics Thick Disc BeO (undersized) - Sample #1 . . . . . . . . . . . . . . . . . . . . . . . 20

Fig. 10 - Characteristics Thick Disc BeO (undersized) - Sample #2 . . . . . . . . . . . . . . . . . . . . . . . . 21

Fig. 11 - Characteristics Thin Disc BeO (oversized) - Sample #1 . . . . . . . . . . . . . . . . . . . . . . . . 22

Fig. 12 - Characteristics Thin Disc BeO (oversized) - Sample #2 . . . . . . . . . . . . . . . . . . . . . . . . 23

Fig. 13 - Characteristics Thin Disc BeO (undersized) . . . . . . 24

Fig. 14 - Characteristics Thin Disc Sapphire (normal size) 60 degree cut . . . . . . . . . . . . . . . . . . . . . . 25

Fig. 15 - Characteristics Thin Disc Sapphire (undersized) 60 degree cut . . . . . . . . . . . . . . . . . . . . . . 26

Fig. 16 - Characteristics Thin Disc Sapphire (undersized) Zero degree cut . . . . . . . . . . . . . . . . . . . . . 27

Fig. 17 - Comparative Data - All Samples - Window Loss Versus Transmitted Power . . . . . . . . . . . . . . . . . . . . . 28

Memorandum on Final Report
Contract AF30(602)-3790

This effort was the third in a series directed toward the improvement in average power capabilities of microwave waveguide windows. The work was performed at X-band so that the results would be directly applicable to the super power X-band generator under development for RADC and to facilitate scaling to C, S and L Bands.

At the start of the program a variety of window designs existed that were known to be capable of power levels in excess of 250 kilowatts. These included several designs employing both sapphire and beryllium oxide ceramic (sintered alluminum oxide and quartz had been shown to be inferior during a previous program). The ultimate capabilities of these windows were unknown since power levels in excess of 250 kilowatts were unobtainable. A major portion of this effort was therefore directed toward devising means of achieving higher levels. The approach taken by Eimac was to develop an advanced design resonant ring. The development was successful due primarily to the invention of a new type of in-line tuner capable of over one megawatt CW, and to all around engineering excellence. A number of windows were tested to destruction in the ring. These included thick and thin disc beryllium oxide windows and thin disc sapphire windows using both zero cut and sixty degree cut material. All but one failed at power levels ranging from four hundred kilowatts to one megawatt. The window that did not fail was made of zero cut sapphire and operated thirty minutes at one megawatt CW. The number of tests performed on each window type were severely limited (often to one) due to unexpected difficulties in the resonator development. The results, however, indicate that sapphire is preferable to BeO at least at the higher frequencies and that the zero cut material may be preferable to the sixty degree material in spite of its much higher cost. At the conclusion of this effort a point has been reached where conventional windows can be evaluated to destruction. This will for the first time allow engineers to vary design parameters and evaluate results without placing an actual tube in jeopardy. With these simplified evaluation procedures available improved designs should be achieved in the near future.

Dirk T. Bussey
DIRK T. BUSSEY
Project Engineer
Electron Devices Section

# I. INTRODUCTION

## Contractual Information

This publication is a report of work performed under U.S. Air Force Contract AF 30(602)-3790 during the six-month period of April 1, 1966 through September 30, 1966, and a summary of results obtained during the complete work period dating June 1, 1965 - September 30, 1966. The initiating and supervising agency is Rome Air Development Center, Griffiss Air Force Base, New York, which awarded the contract on May 28, 1965 in accordance with R.A.D.C. Exhibit "A" dated 3 December 1964. The assigned Air Force Project Engineer is Dirk Bussey.

## II. DISCUSSION

### WINDOW PROGRAM

1. General

During this report period, seven window assemblies were tested and with the exception of one, all were tested to their ultimate power limit. The one exception, a zero degree cut sapphire window of 1.316 in. diameter was tested up to, and successfully transmitted one megawatt of CW power at 8245 MHz for a continous 31 minutes. This sample is still in perfect condition (vacuum tight and unmarked) and the ultimate power handling capability of this material is still undetermined.

The testing of the seven window configurations mentioned above completes the planned study program.

Before discussing in detail the test results of individual window designs, it is interesting at this point to make several observations of a more general nature on window performance during the entire program.

In all, eight window designs were tested, five were BeO 99.5 percent purity and the other three were single crystal alumina (sapphire). Of the eight tested samples the lowest power achieved was 262 kw CW -- very respectable performance in view of the latest published window data. There seems no question that beryllium oxide and sapphire are superior in CW handling capability to anything available in practical form to date.

Another observation of particular interest in considering a window design for use in high power CW devices was the thermal tuning of ghost modes. As the temperature of the window increases with increasing power, the dielectric constant of the window material increases also and ghost modes are "tuned" to lower frequencies. Apparent increases in dielectric losses were detected while testing windows 1.5 percent below measured ghost mode frequencies. Resonant ring stability was affected to such a degree that testing at that particular frequency was impossible. Testing at a frequency four percent below the ghost mode frequency eliminated the problem of "runaway" heating.

In the case of a resonant ring, the dielectric constant change which tunes the ghost mode to a lower frequency also detunes the ring and in this way is self-protecting. If such a phenomena were to occur in the output window of a high power transmitting tube (klystron, etc.) which would not be unduly affected by the small VSWR change in the output line, a runaway condition would exist and could easily cause destruction of the window. It is clear then that selection of a window design for a particular application must consider this factor and when power densities and frequencies are of the nature of those described in this study, a ghost mode "clear" region of at least three percent or four percent must be provided above the band of interest.

It has also become clear during the testing program that we have exceeded the practical upper limit of power generation in our present ring resonator design. Thermal instabilities due to dielectric constant change in the dielectric under test made testing impractical although not impossible at very high powers (above 600 kw). Most troublesome is the VSWR change in the ring due to the changing dielectric constant of the sample. The present variable VSWR phase shifter used to cancel ring reflections cannot be moved quickly or sensibly enough to follow changes in ring VSWR. In addition an extremely stable driving power source must be provided. This source must not only be frequency stable but power stable at approximately 20 kw. The latter problem can be practically solved but it is costly. However, if the driving source was absolutely stable the problem of chasing a changing ring VSWR might possibly disappear.

In the following paragraphs a short description of each window sample test conducted in the final report period is given.

## 2. Hot Test Window Performance (Final Report Period)

### a. Definition

As noted in progress report Nos. 1, 2 and 3, a normal round window is defined as 1.608 inches in diameter. Smaller windows will be called "undersized", whereas larger diameters will be considered "oversized".

b. Thin Disc BeO (oversized 1.680 in. dia. x .090 thick) Sample #1

As noted in the third progress report, initial tests had been started on a thin disc BeO window design. The high losses and thermal instabilities experienced were unexpected and at the time, unexplained. The problem has since been resolved, and the fault found to be a poor rf joint within the window assembly. The joint had apparently been arcing and burning continuously through the initial testing period as considerable damage was in evidence. This is shown in Fig. 1. This would obviously explain the unstable operation and, in addition, the heat generated at the poor contact has a direct conduction path to the window water jacket and appeared as additional loss. This additional loss would also be a variable, depending on the pressure applied to the contact area. This explains why the window loss apparently decreased at higher power levels. As the power level increased, the expansion caused by the heated copper waveguide apparently applied more pressure to the joint and reduced the losses at the poor contact.

The damaged joint was machined and the window assembly rebuilt with a redesigned rf joint. The window assembly was re-installed in the ring resonator and testing resumed. The initial power level was 42 kw. The thermal instabilities noted before, even at 27 kw, were not present. The window

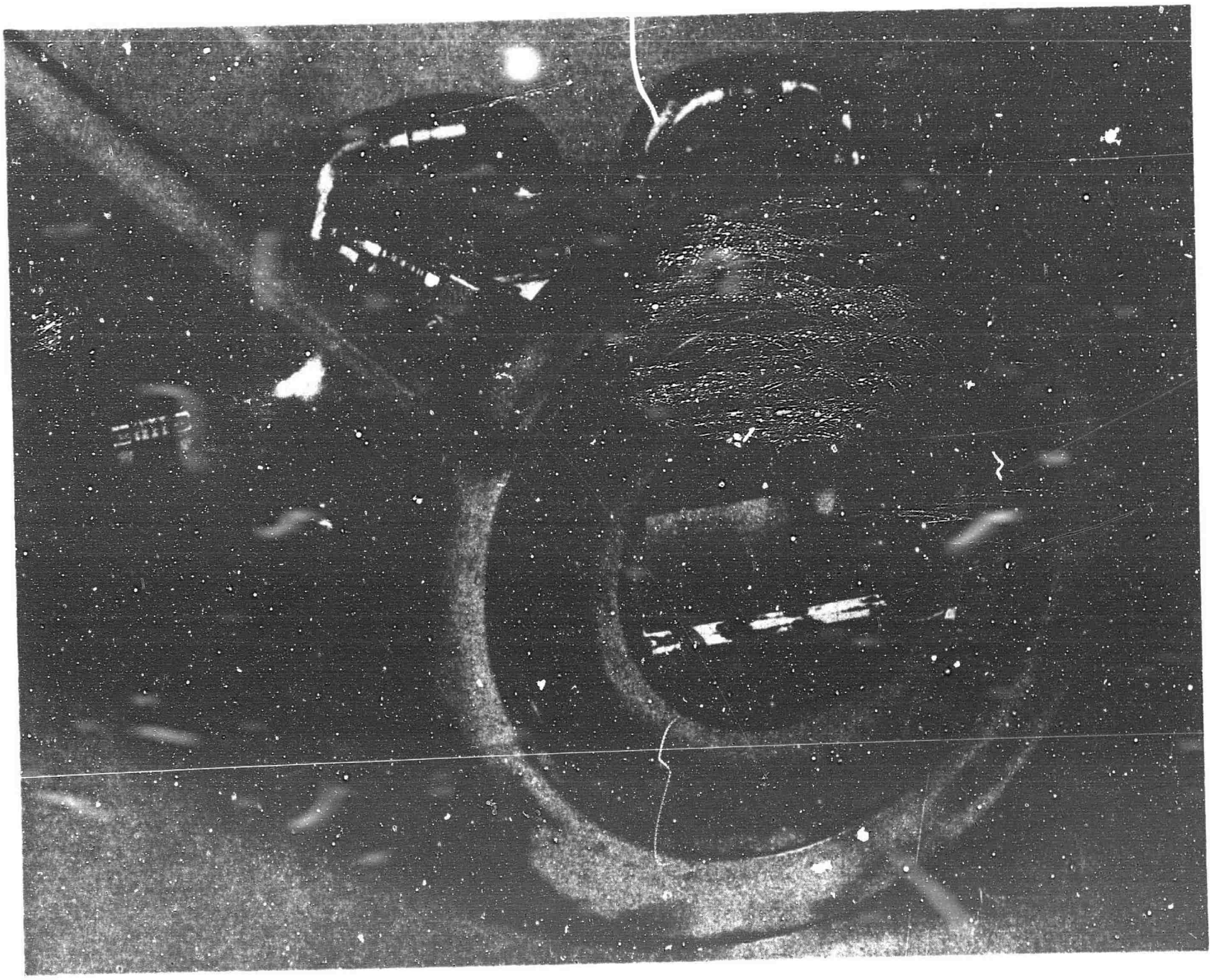


Figure 1 DAMAGED WINDOW ASSEMBLY

loss measured 0.285 percent at this level as compared to 0.625 percent measured before the assembly was rebuilt.

The power level was increased incrementally to 326 kw CW. At this level, thermal drift became noticeable, but caused no problem. The power level was raised to 400 kw. No problems were encountered. The power level was increased to 463 kw. After running at 463 kw for approximately 30 seconds, a loud popping sound was heard as amplified by the "audio detector". A window crack was assumed. The window assembly was removed from the resonator to verify this fact. The BeO disc was dye-checked and found to have a diagonal crack approximately 90 percent across its diameter. The angle of the crack was mid-way between the angle of the rectangular waveguide diagonal and the vertical axis representing maximum "E" field. This is shown in Fig. 2. There may or may not be any significance to the fact that the crack was diagonal rather than vertical. The crack may simply represent the weakest plane of the particular sample under test.

The average loss measured over the 42-463 kw range was 0.296 percent, comparable to the thick disc window previously tested. Since the thick disc window is 2.6 times as thick as the thin disc under discussion, it appears that the thin disc configuration subjects a window to electric fields sufficient to cause significantly higher volumetric

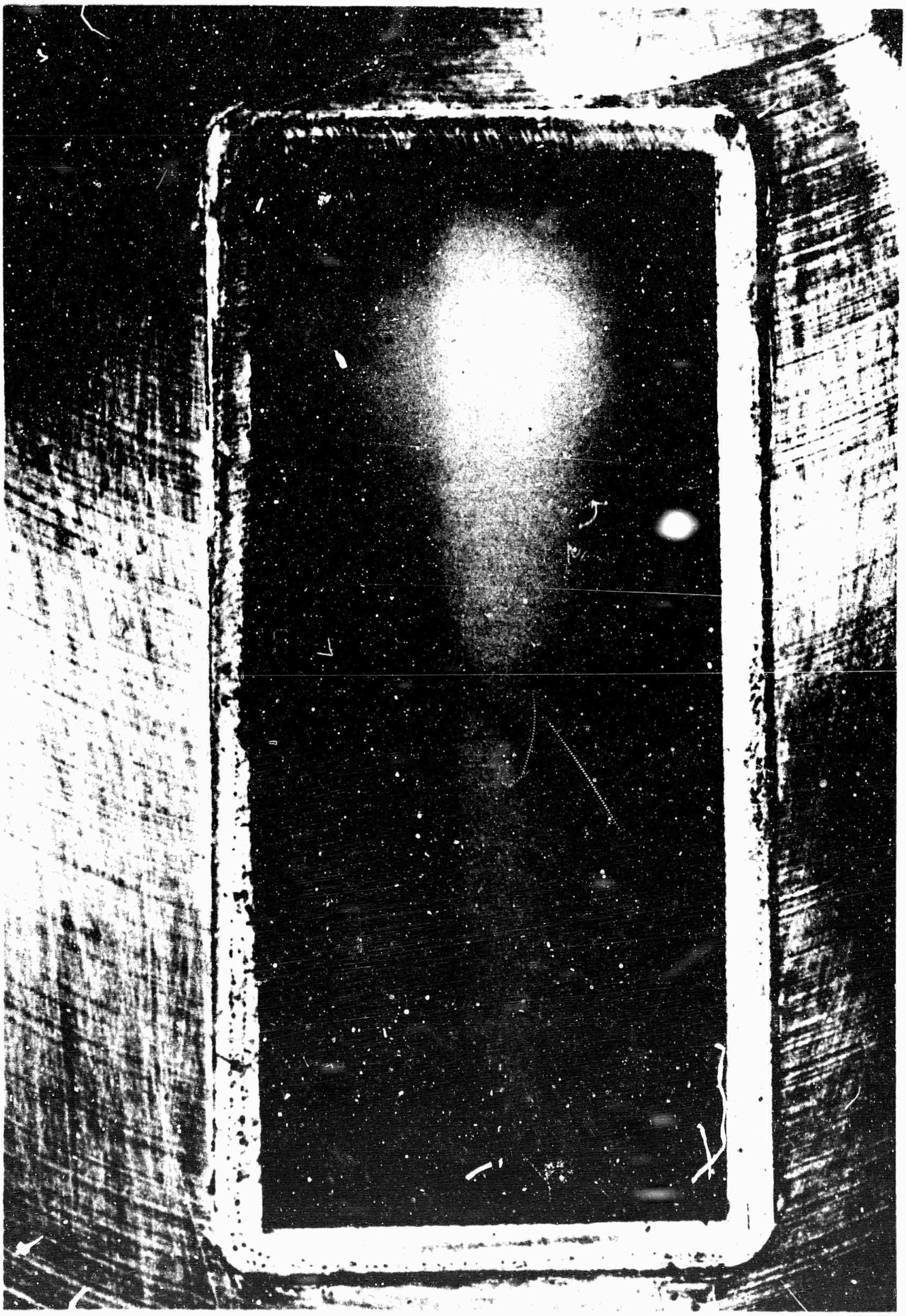


Fig. 2 - DIAGONAL CRACK, THIN DISC BeO WINDOW

SAMPLE #1

losses than the "long pill-box" thick disc configuration. Despite this excessive loss, the thin disc did reach a higher power level than anticipated on the basis of its total loss, suggesting that the thin section is more able to withstand higher temperature gradients.

c. Thin Disc BeO (oversized 1.680 in. dia. x 0.090 thick) Sample #2

The second thin disc BeO window was hot tested in the ring resonator and the failure level found to be 400 kw CW. This result agrees quite closely with that of the first sample of this design, which failed when the power level was raised from 400 kw to 463 kw. The average loss measured was 0.27 percent which is also comparable to the 0.296 percent for the first sample. The diagonal crack experienced in the first test window was also duplicated and is shown in Fig. 3. No explanation has yet been found for this phenomenon.

d. Thick Disc BeO (undersized 1.316 in. dia., 0.4 $\lambda_g$ thick) Sample #2

The second sample of the thick disc BeO 0.4 $\lambda_g$ thick (0.238 in.) x 1.316 in. diameter was tested to destruction in the ring and showed a failure level of 800 kw CW. This is noticeably higher than the first sample which failed when the power level was raised from 600 to 720 kw. The discrepancy is not so large however as to be completely unexpected. The loss percentage was somewhat lower than the first sample:

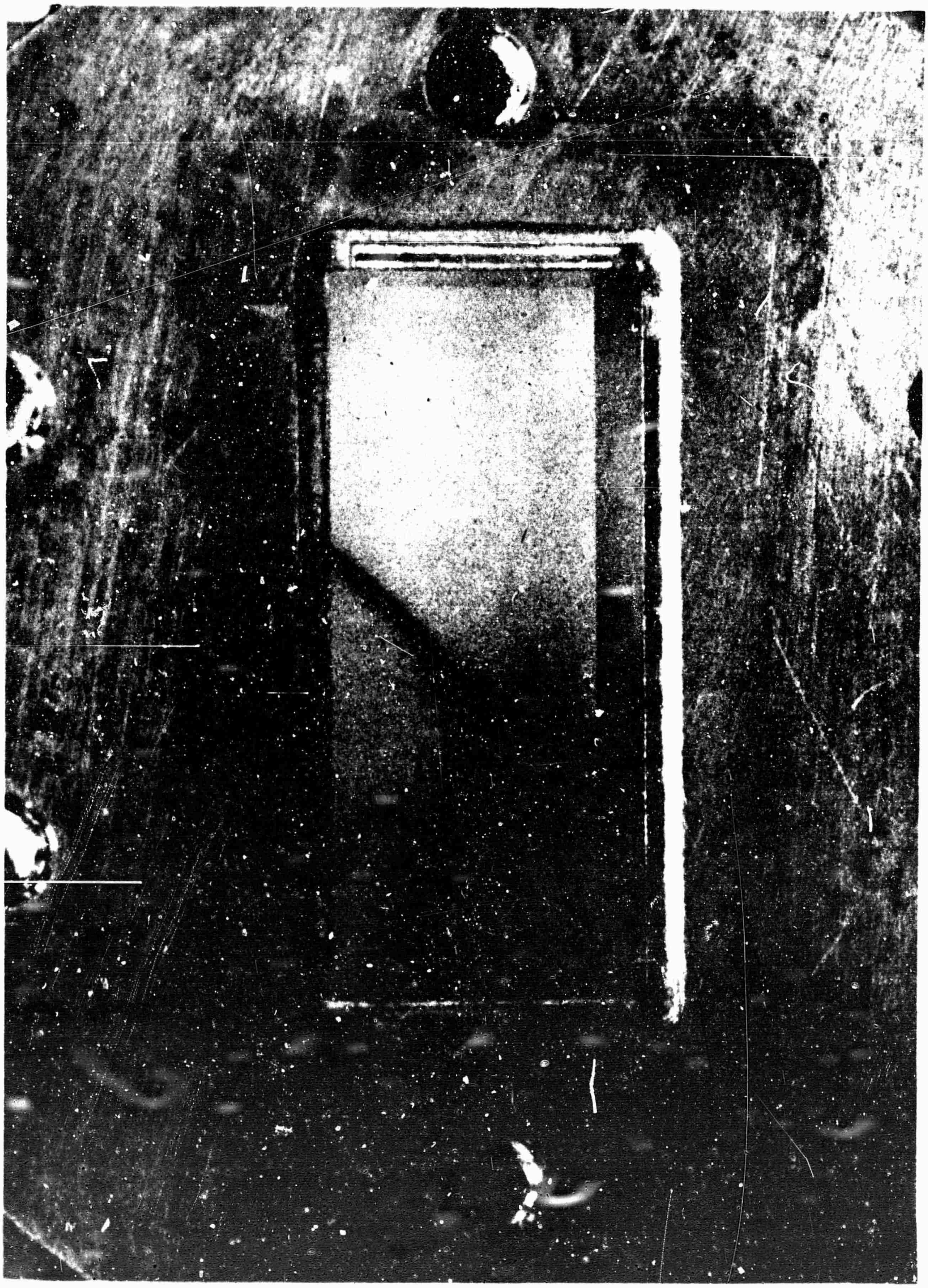


Fig. 3 - DIAGONAL CRACK - THIN DISC BeO WINDOW

SAMPLE #2

0.22 percent compared to 0.254 percent and this factor alone could explain the difference. One notable difference was the production of a diagonal crack (shown in Fig. 4) similar to the crack in the thin disc windows. This is in contrast to the first thick disc sample which failed due to a vertical crack along the path of maximum "E" field as expected. As mentioned previously, there is still no explanation for the diagonal cracking.

e. Thin Disc BeO (undersized 1.316 in dia. x 0.065)

This is the first sample employing "J" to "H"-band waveguide tapers to obtain greater bandwidth centered at 8.0 GHz. Initial tests were conducted at 8.055 GHz, but it was found that a ghost mode at 8255 was apparently tuning down in frequency and causing a non-linear dielectric loss effect. The ring resonator was tuned lower in frequency by shimming its length to resonate at 7985 GHz. This eliminated the dielectric loss problem.

The power level was raised until at 262 kw a loud click was heard from the audio "detector". However no arc was detected and the power in the ring remained stable. This has not been the case for all previous samples. It was thought that the noise was extraneous and the power level was raised further to 320 kw. At the 320 kw level another loud cracking sound was heard and again no arc was detected or detuning of the ring noted. The ring was disassembled however and the

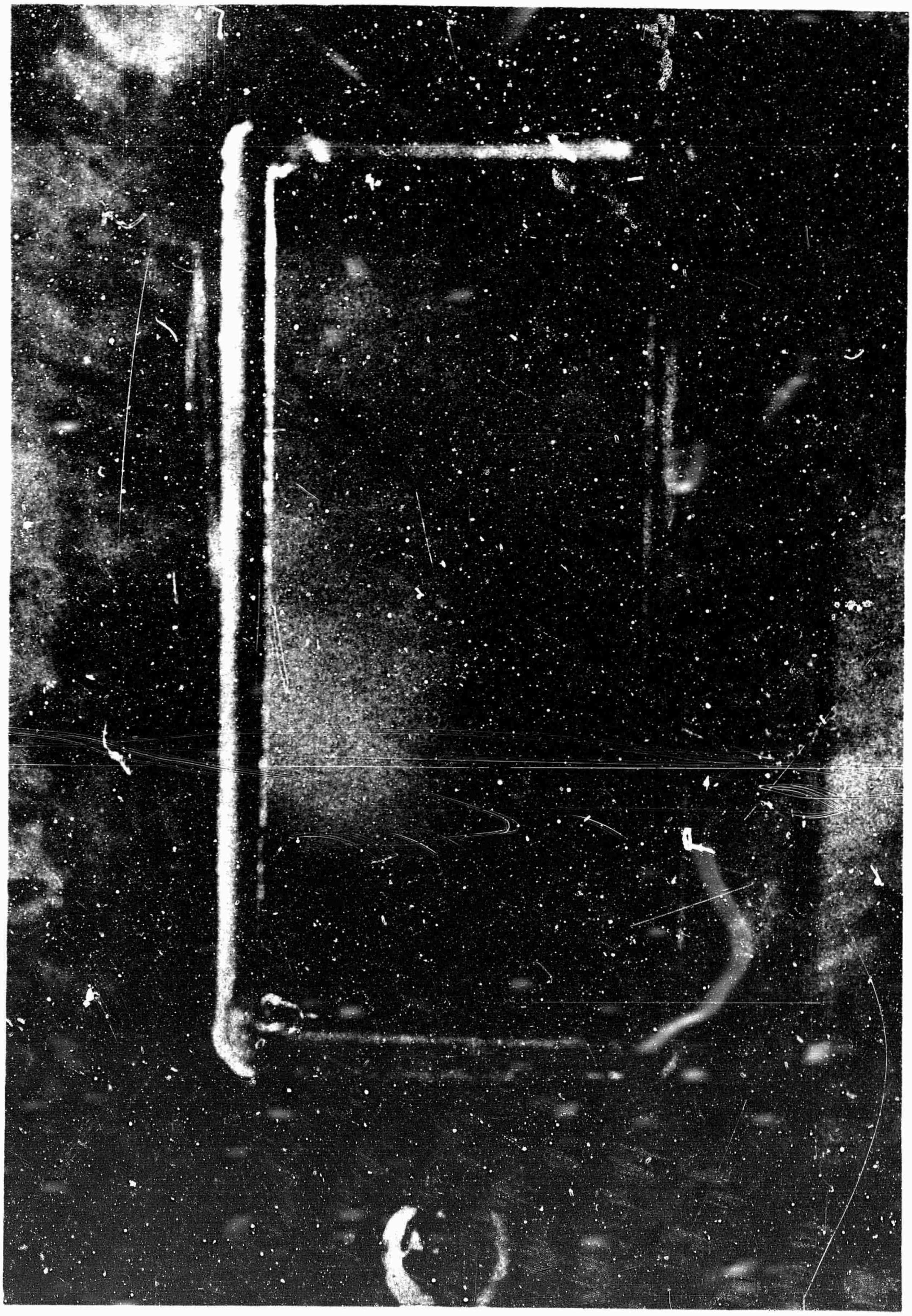


Fig. 4 - DIAGONAL CRACK, THICK DISC BeO WINDOW

SAMPLE #2

window examined. The window was thoroughly cracked as shown in Fig. 5. Presumably a crack had occurred at 262 kw and another at 320 kw. On the basis of this one sample no conclusions can be drawn as to the merits or disadvantages of this particular window configuration.

f. Thin Disc Sapphire (normal size 1.608 in. dia. x 0.050 thick) 60 degree cut

The first thin disc sapphire window was tested to a power level of 1.05 megawatts. Total running time at this level was seven minutes. The window survived approximately 30 minutes of running time at various power levels in excess of 800 kw CW. Dielectric losses were the lowest of all windows tested thus far at 0.123 percent.

After seven minutes at 1.05 megawatts the sapphire cracked with the now typical diagonal patte... In addition, a vertical crack was produced which ran from the center of the diagonal crack to the top of the circular guide giving the general appearance of the letter "Y". See Fig. 6.

The only problem experienced during the test was that of thermal drift during initial phases of the test. The starting test frequency was 7978 MHz. A nearby ghost mode, at 8060 MHz, drifted down to the ring frequency as the dielectric began to heat and caused a runaway condition. Two copper spacers were inserted in the ring to increase its length by 0.7 inches and lower its resonance to 7906 MHz. After this was done, thermal drift was no longer a problem.

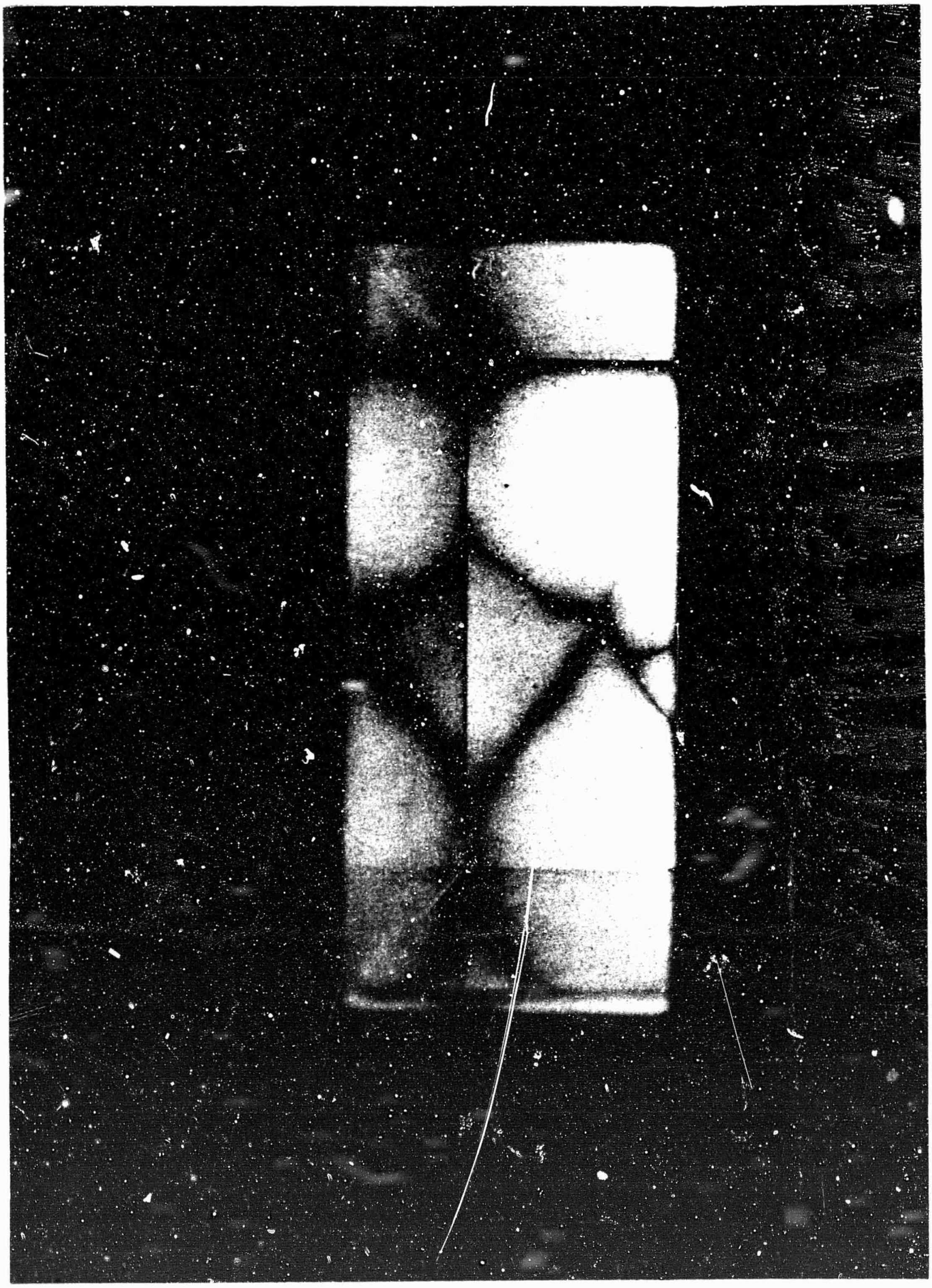


Fig. 5 - CRACKED THIN DISC BeO WINDOW

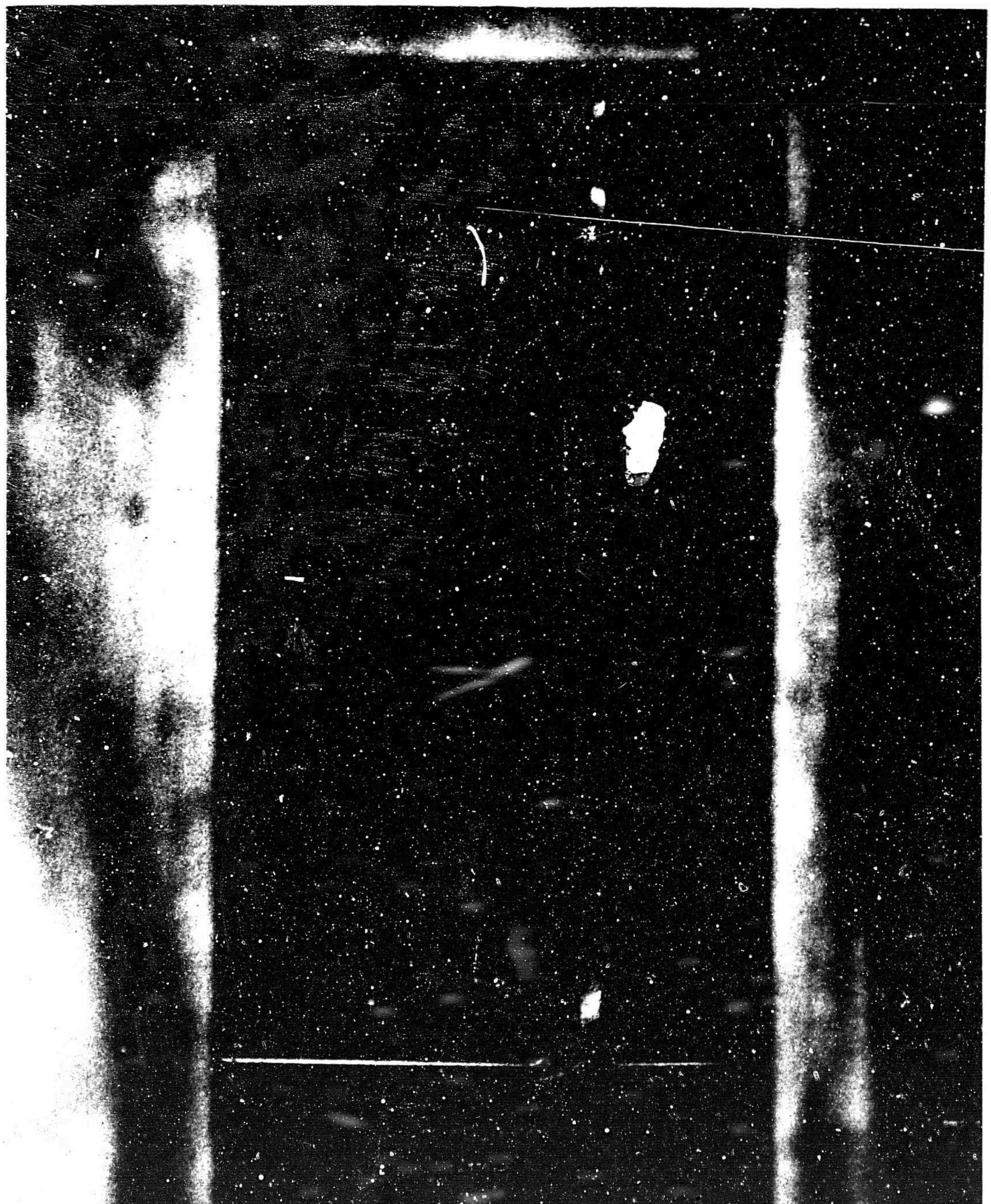


Fig. 6 - THIN DISC SAPPHIRE, "Y"-SHAPED CRACK

g. <u>Thin Disc Sapphire (undersize 1.316 in. dia. x 0.045 thick) 60 degree cut</u>

This design is the second employing "J" to "H"-band waveguide tapers and its configuration is essentially identical to that of the thin disc BeO sample of paragraph (e), the intention being to draw a direct comparison between BeO and 60 degree cut sapphire.

The sample failed at 400 kw, approximately. Failure at such a low level was unexpected since a previous 60 degree sapphire window, only slightly larger in diameter (1.608 in.), had been pushed to 1.05 megawatts before cracking. However, since only one sample is involved, no sound conclusions can be drawn. The cracking pattern was somewhat unusual, i.e., essentially horizontal as opposed to the vertical or slanted patterns noted in previous window tests. This is shown in Fig. 7.

It is suspected that this sample failed prematurely due to a strain established during fabrication. More tests are required to establish a proper pattern.

h. <u>Thin Disc Sapphire (undersize 1.316 in. dia. x 0.050 thick Zero degree cut</u>

This is the third sample employing "J" to "H"-band waveguide tapers as in samples of paragraphs (e) and (g). Its configuration is essentially identical to those in (e) and (g), the intention being to draw a direct comparison between BeO, 60 degree sapphire, and zero degree sapphire.

Fig. 7 - CRACKING PATTERN OF $60^{\circ}$ CUT THIN DISC SAPPHIRE

This sample was tested successfully to 1.0 megawatt CW power and gave no evidence of failure. The transmitted power was held at 1.0 megawatt for 31 minutes of continuous operation. At this point, the resonant ring was disassembled and the window examined to determine if by chance it had failed at a lower level without giving any indication of failure. This was not the case. The window appeared to be in perfect condition and was found to be vacuum tight. Again, it is impossible to draw any conclusions from a one-sample test, but at least the indications are in an optimistic direction.

The zero degree cut window very nearly meets the objective bandwidth requirements in that it has a flat VSWR over a 15 percent band (excepting ghost modes) and a 10.4 percent ghost mode-free bandwidth centered about 7670 MHz instead of the objective 8000 MHz.

3. Hot Test Window Performance (Program Summary)

On the following pages, Figs. 8-17 inclusively, a summary of all pertinent data and operating characteristics of those samples tested during the study program is presented.

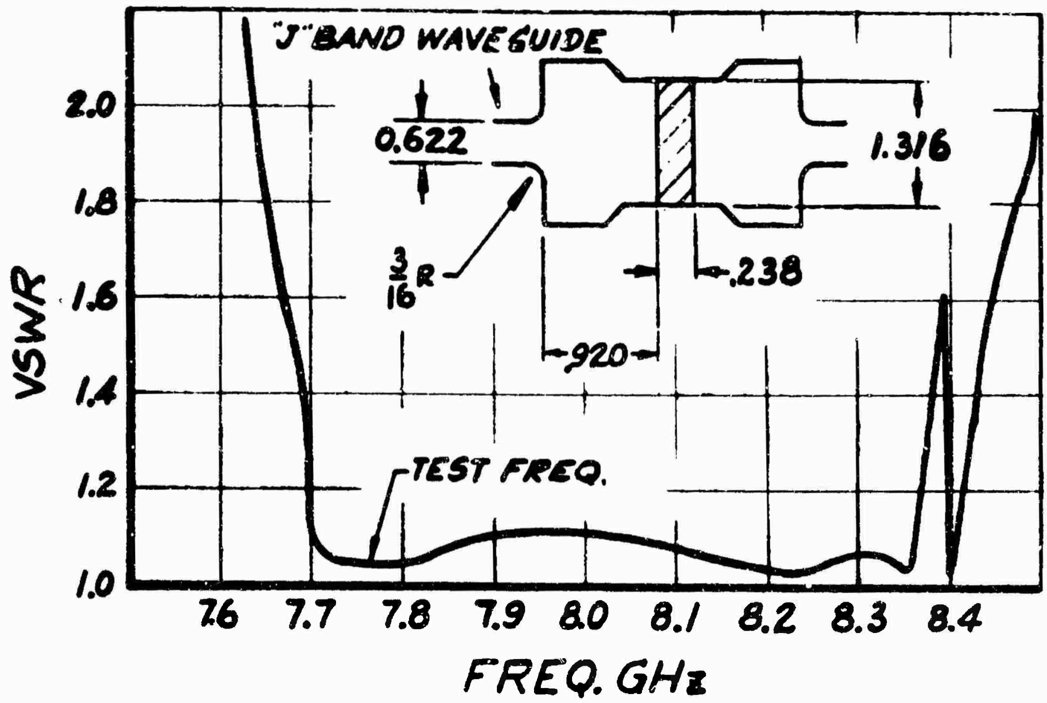
4. Conclusions

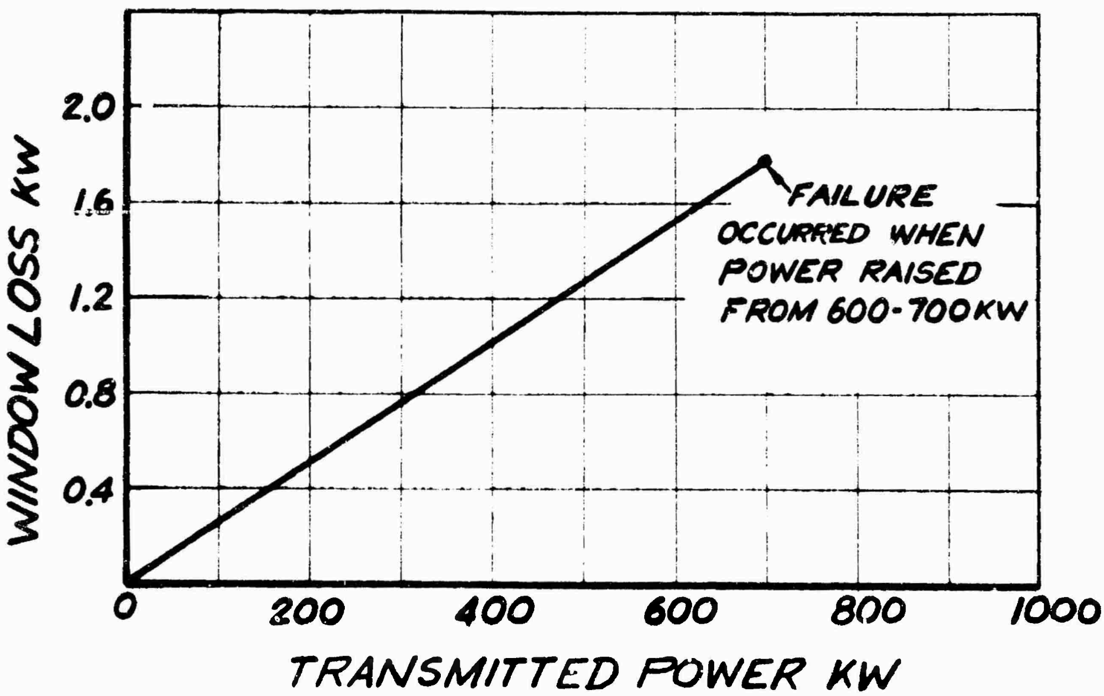
Perhaps the most obvious and sound conclusion that can be drawn from the now completed window study program is that data of adequate statistical value have not been obtained. The testing

## Fig. 8 - WINDOW TEST RESULTS SUMMARIZED

| MATERIAL | TYPE | THICK. | DIAM. | TRANSITION RADIUS | % LOSS* | VOLUMETRIC DISSIPATION RATE watts/kw/cm$^3$ | TRANSMITTED POWER | COMMENTS |
|---|---|---|---|---|---|---|---|---|
| 99.5% BeO #1 | Thick Disc Long Pill-Box Undersize | 0.238 | 1.316 | 0.187 | 0.254 | 1.22 | 600-700 kw | Window failed when power was raised from 600-700 kw - vertical crack. |
| 99.5% BeO #2 | Thick Disc Long Pill-Box Undersize | 0.238 | 1.316 | 0.187 | 0.22 | 1.06 | 810 kw | Window failed while running at 810 kw - diagonal crack. |
| 99.5% BeO #1 | Thin Disc Short Pill-Box Oversize | C.090 | 1.680 | 0.063 | 0.296 | 2.31 | 400-463 kw | Window failed when power was raised from 400-463 kw - diagonal crack. |
| 99.5% BeO #2 | Thin Disc Short Pill-Box Oversize | 0.090 | 1.680 | 0.063 | 0.27 | 2.1 | 400 kw | Window failed after 2 minutes at 400 kw - diagonal crack. |
| 99.5% BeO | Thin Disc Short Pill-Box Undersize | 0.065 | 1.316 | 0.187 | 0.145 | 2.5 | 262 kw | Appears to have cracked twice -- once at 262 kw and again at 320 kw |
| Sapphire 60° cut | Thin Disc Short Pill-Box Normal size | 0.050 | 1.608 | 0.187 | 0.116 | 1.78 | 1050 kw | Failed after running at 1.05 megawatts for 7 min. - "Y"-shaped crack. |
| Sapphire 60° cut | Thin Disc Short Pill-Box Undersize | 0.045 | 1.316 | 0.187 | 0.07 | 1.78 | 400 kw | Failed at 400 kw after running approx. 30 sec. - jagged crack nearly horizontal. |
| Sapphire 0° cut | Thin Disc Short Pill-Box Undersize | 0.050 | 1.316 | 0.187 | 0.095 | 2.16 | 1000 kw | DID NOT FAIL. Continuous running time at 1.0 megawatt = 31 min. Total time at 1.0 megawatt = 39 min. |

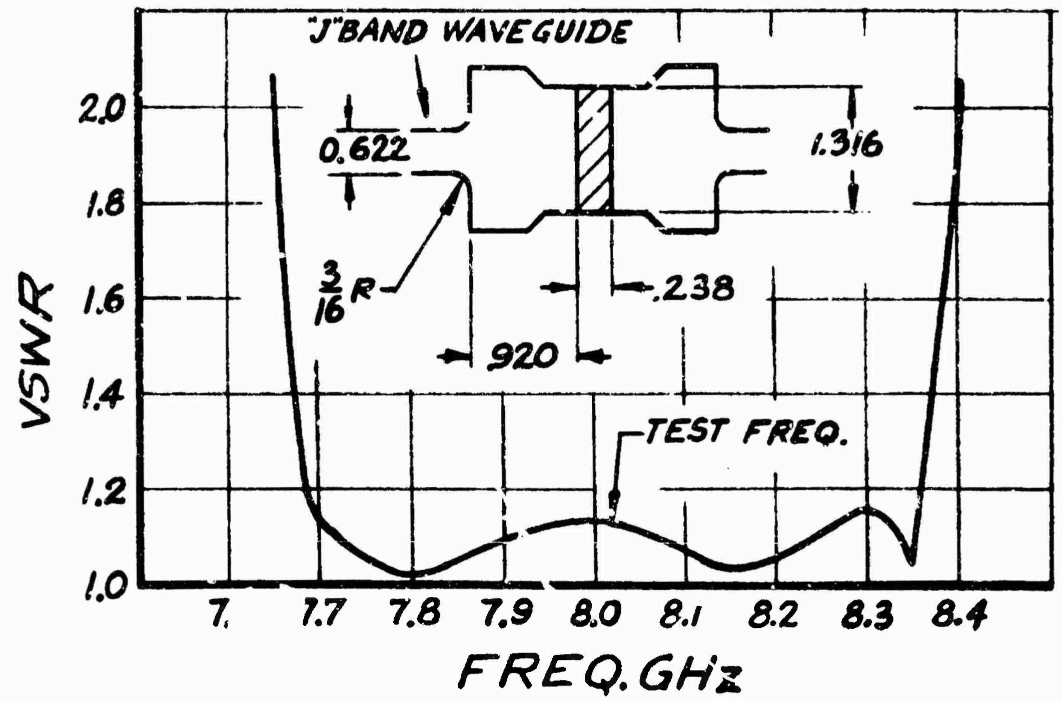
*(Corrected) calculated copper losses subtracted.

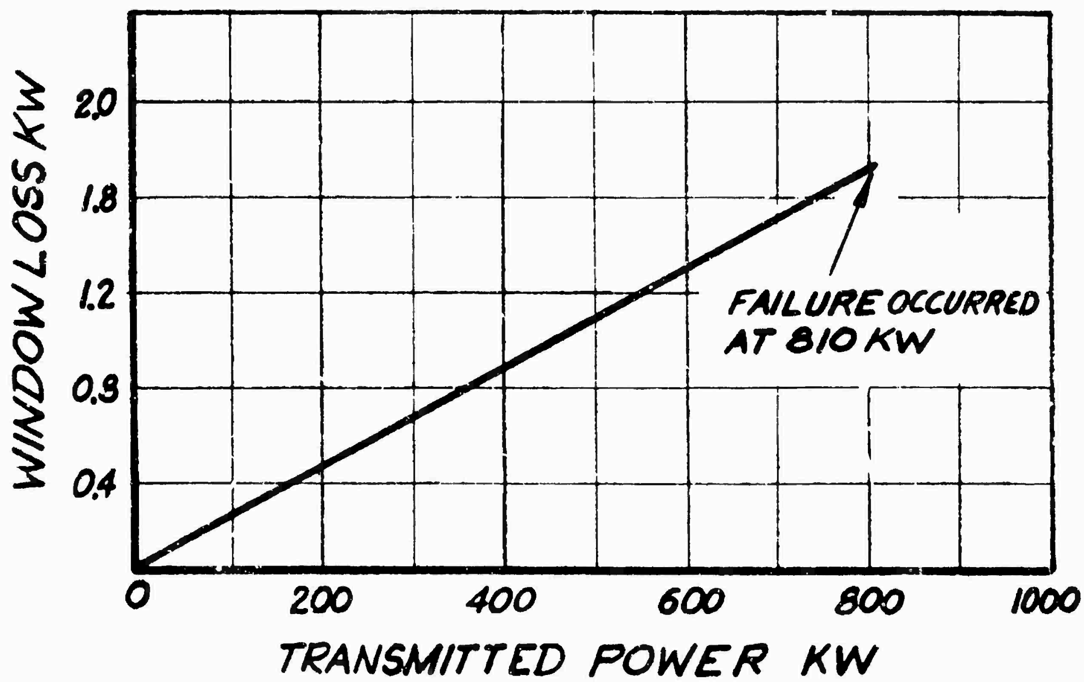



CHARACTERISTICS THICK DISC $B_eO$

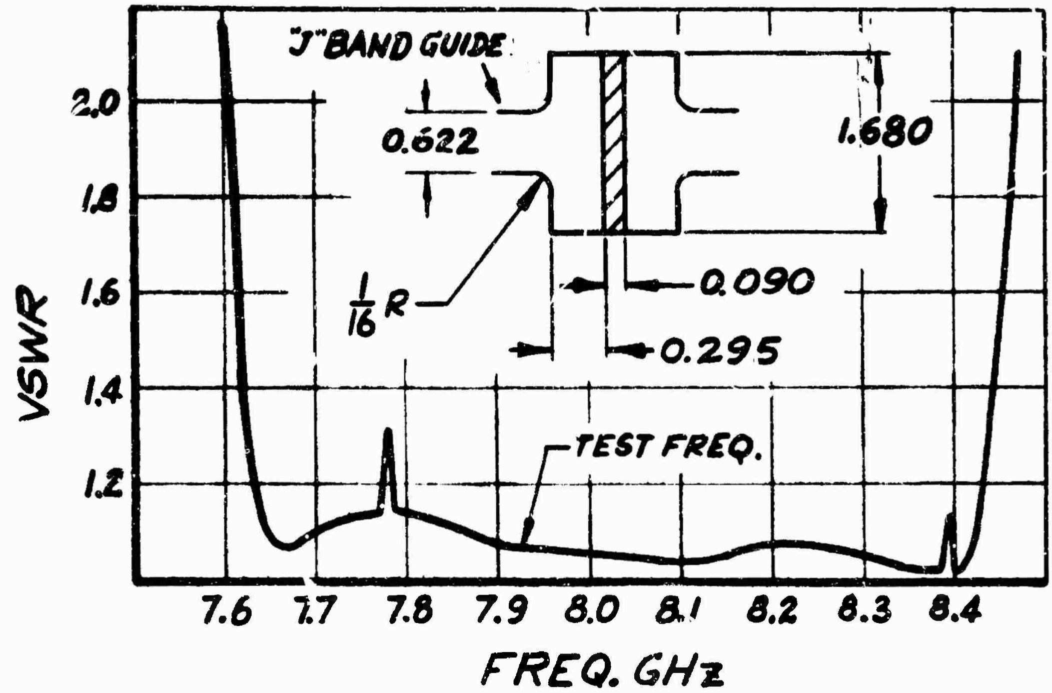
FIG. 9 SAMPLE #1 (UNDER SIZED)

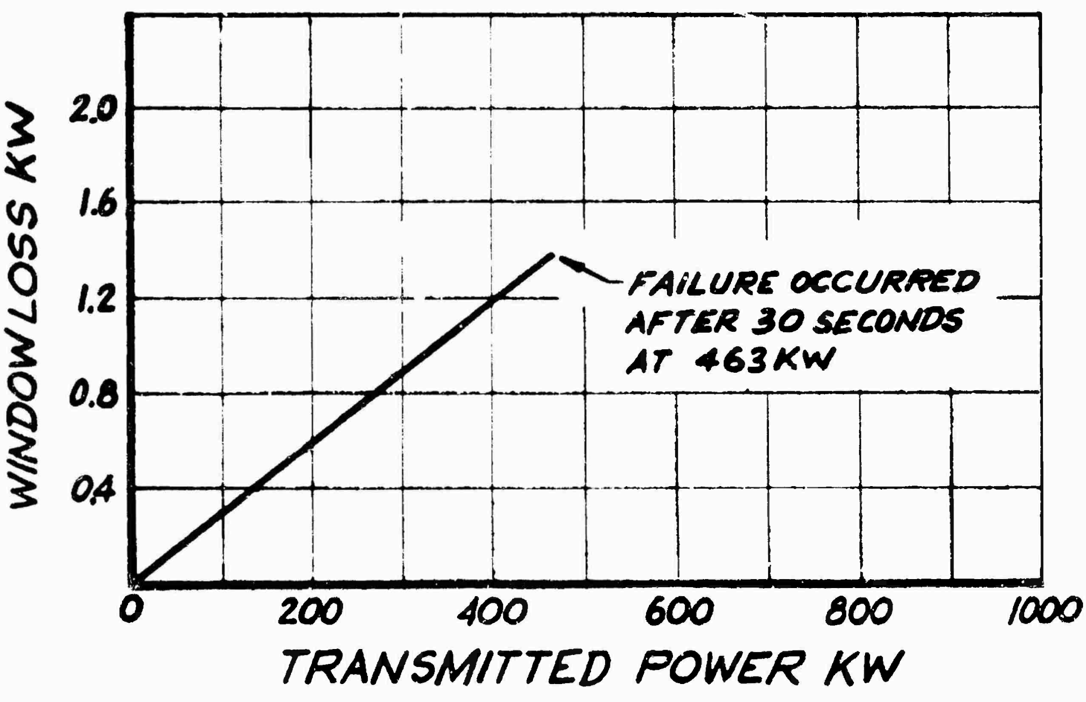



CHARACTERISTICS THICK DISC BeO

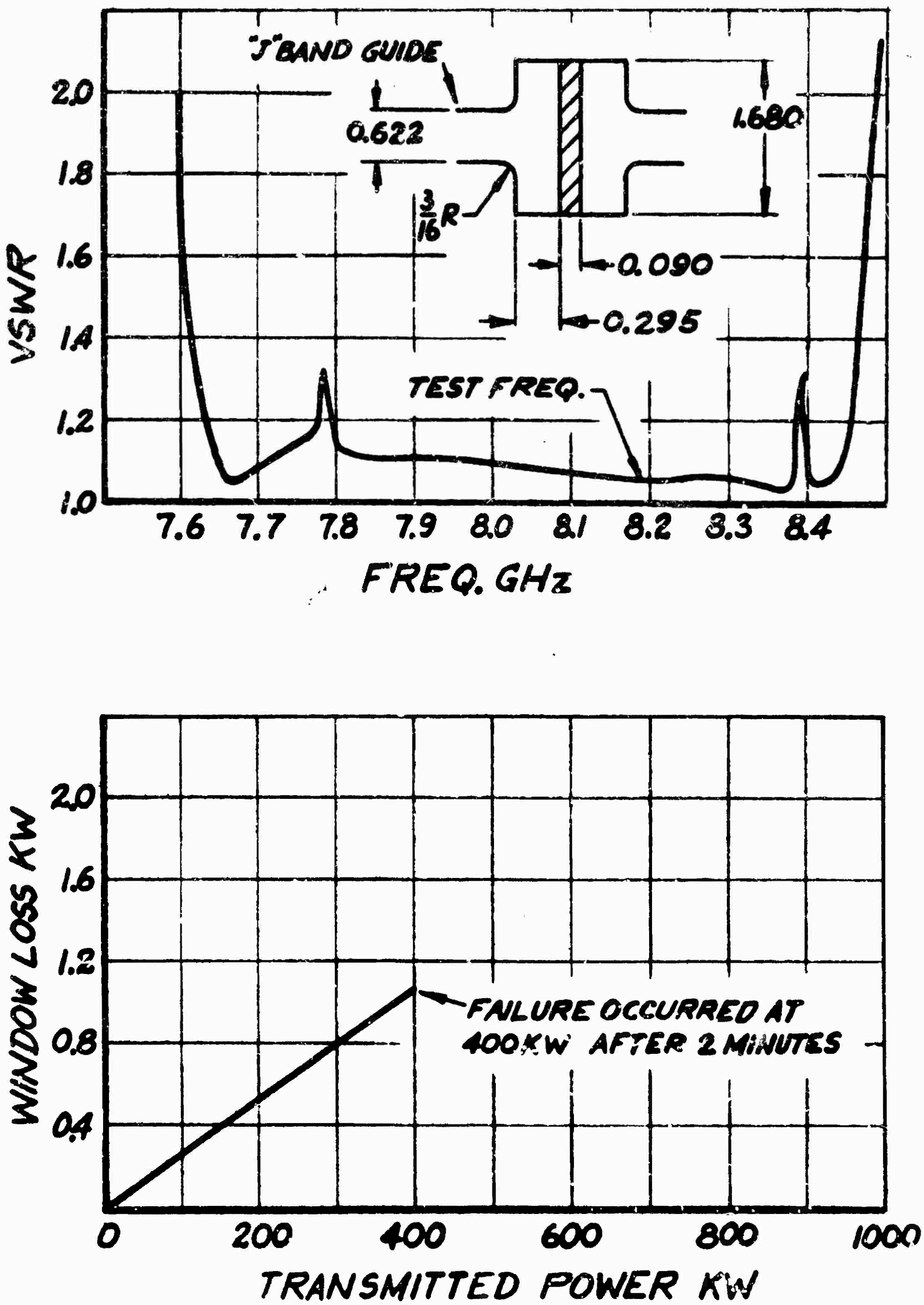
FIG. 10 SAMPLE #2 (UNDER SIZED)



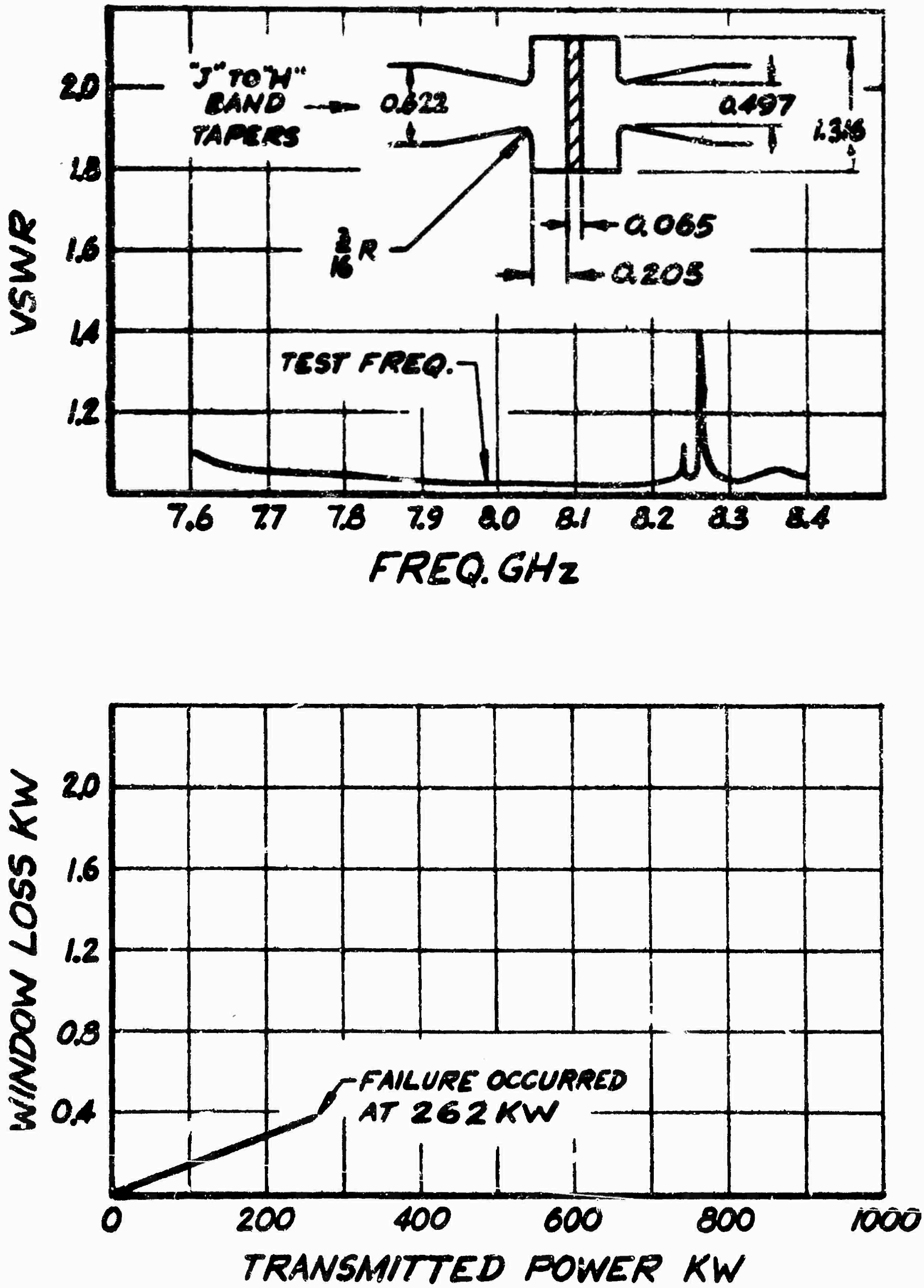

CHARACTERISTICS THIN DISC $B_eO$

FIG. 11 SAMPLE #1 (OVER SIZED)



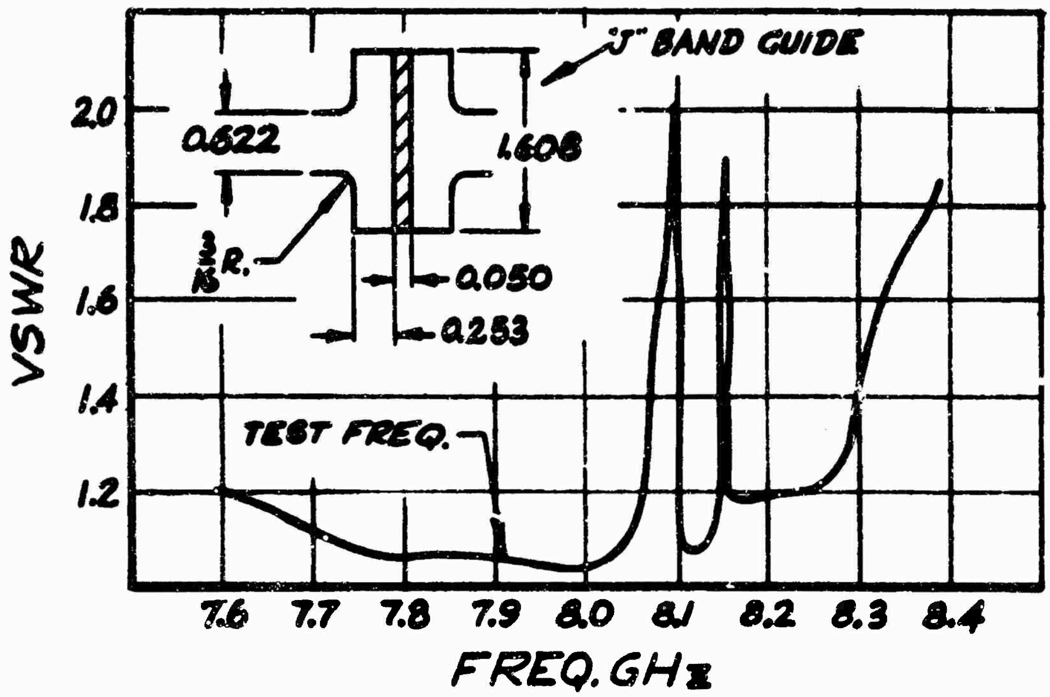

CHARACTERISTICS THIN DISC BeO

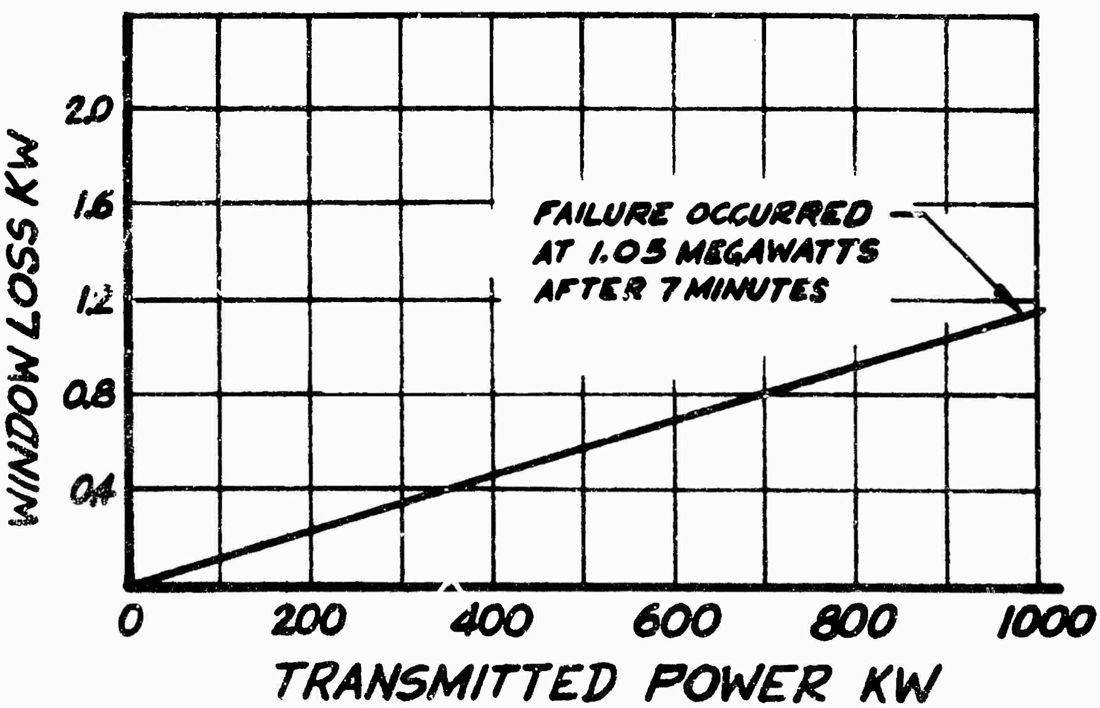
FIG. 12 SAMPLE #2 (OVER SIZED)




CHARACTERISTICS THIN DISC $B_eO$

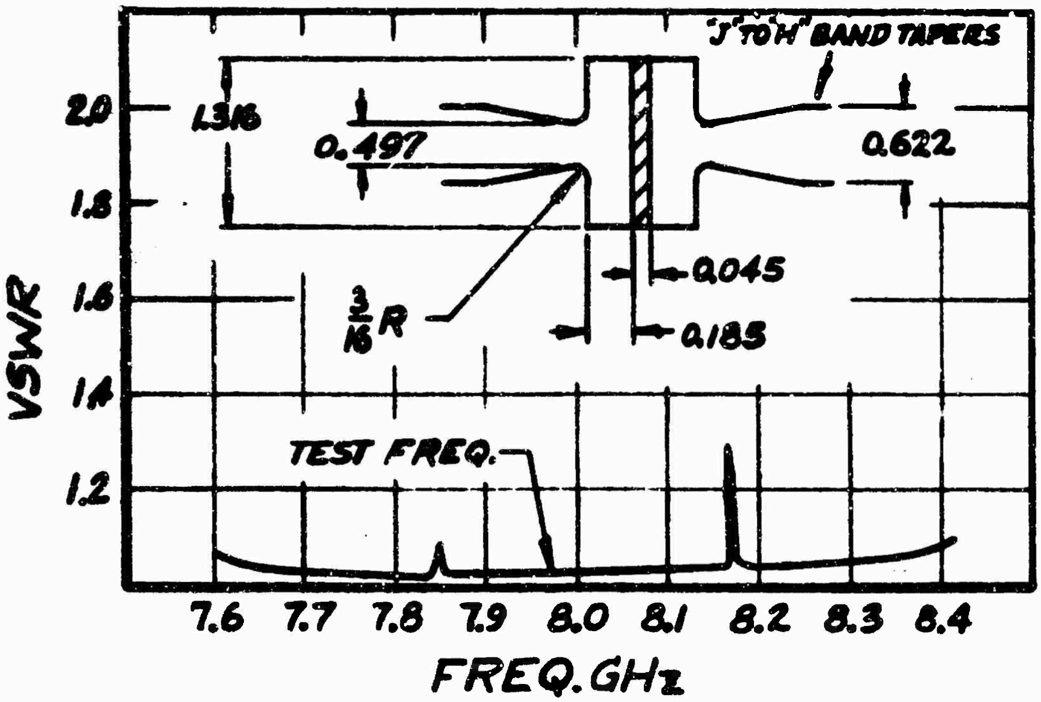
FIG. 13 (UNDER SIZED)

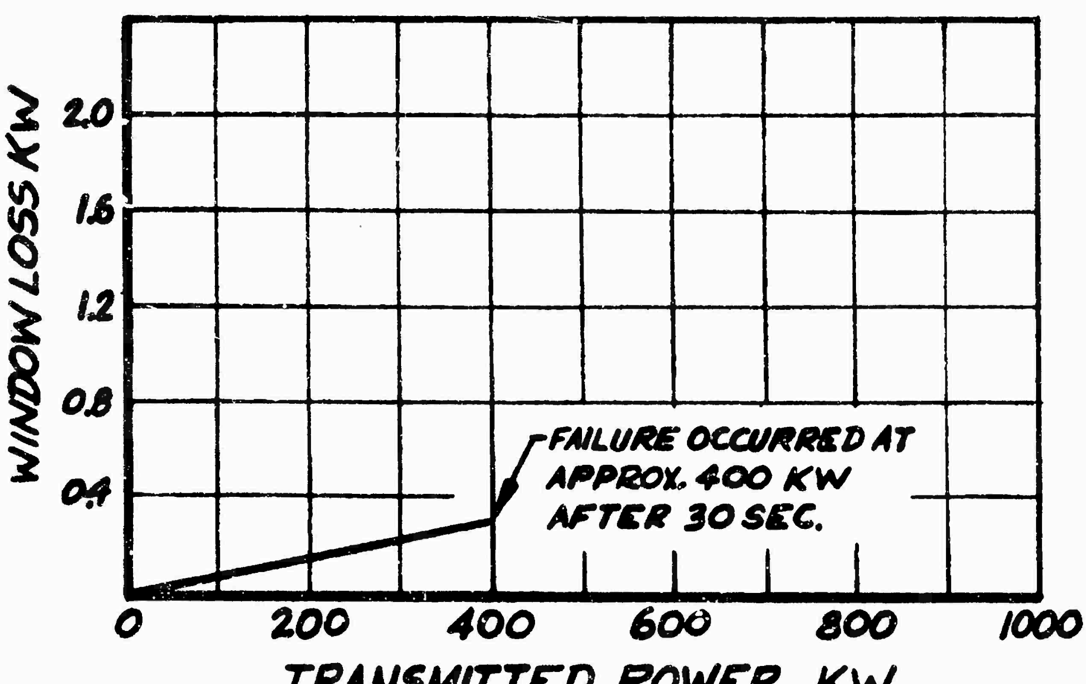



CHARACTERISTICS THIN DISC SAPPHIRE 60° CUT

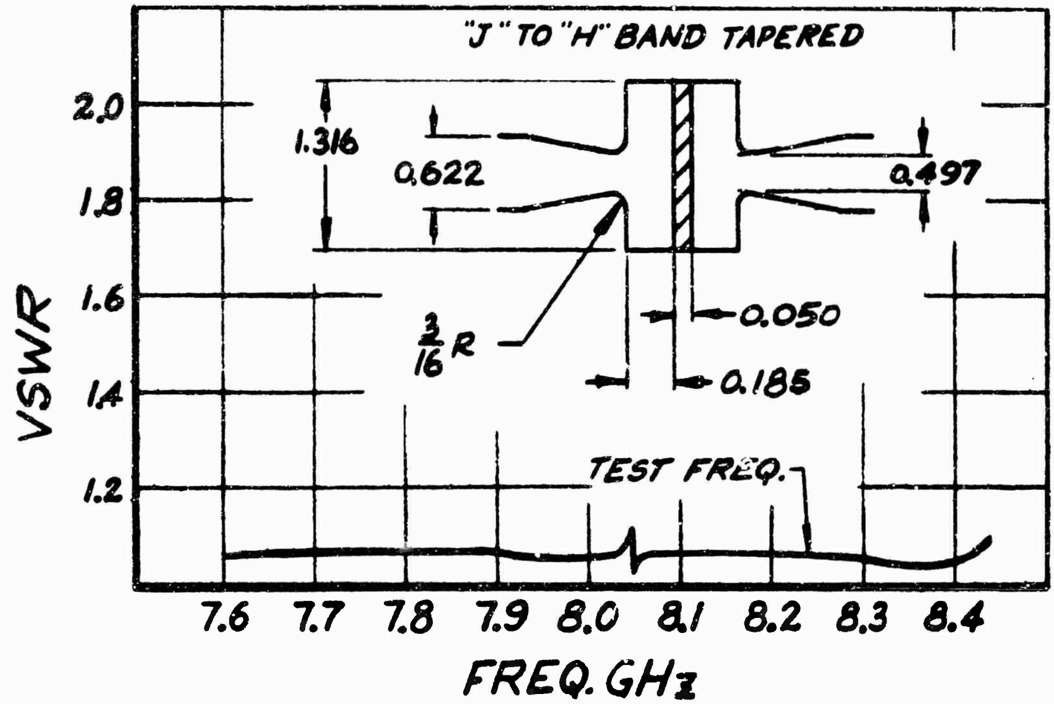
FIG. 14 (NORMAL SIZE)

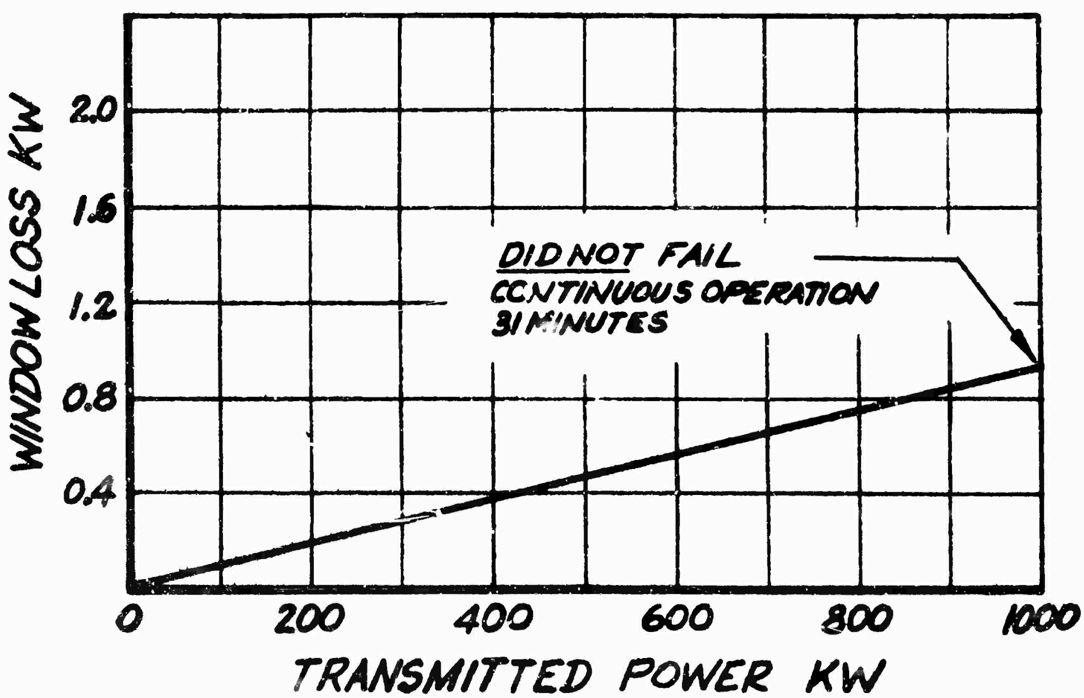



CHARACTERISTICS THIN DISC SAPPHIRE 60° CUT

FIG. 15 (UNDER SIZED)




CHARACTERISTICS THIN DISC SAPPHIRE 0° CUT

FIG. 16 (UNDERSIZE)

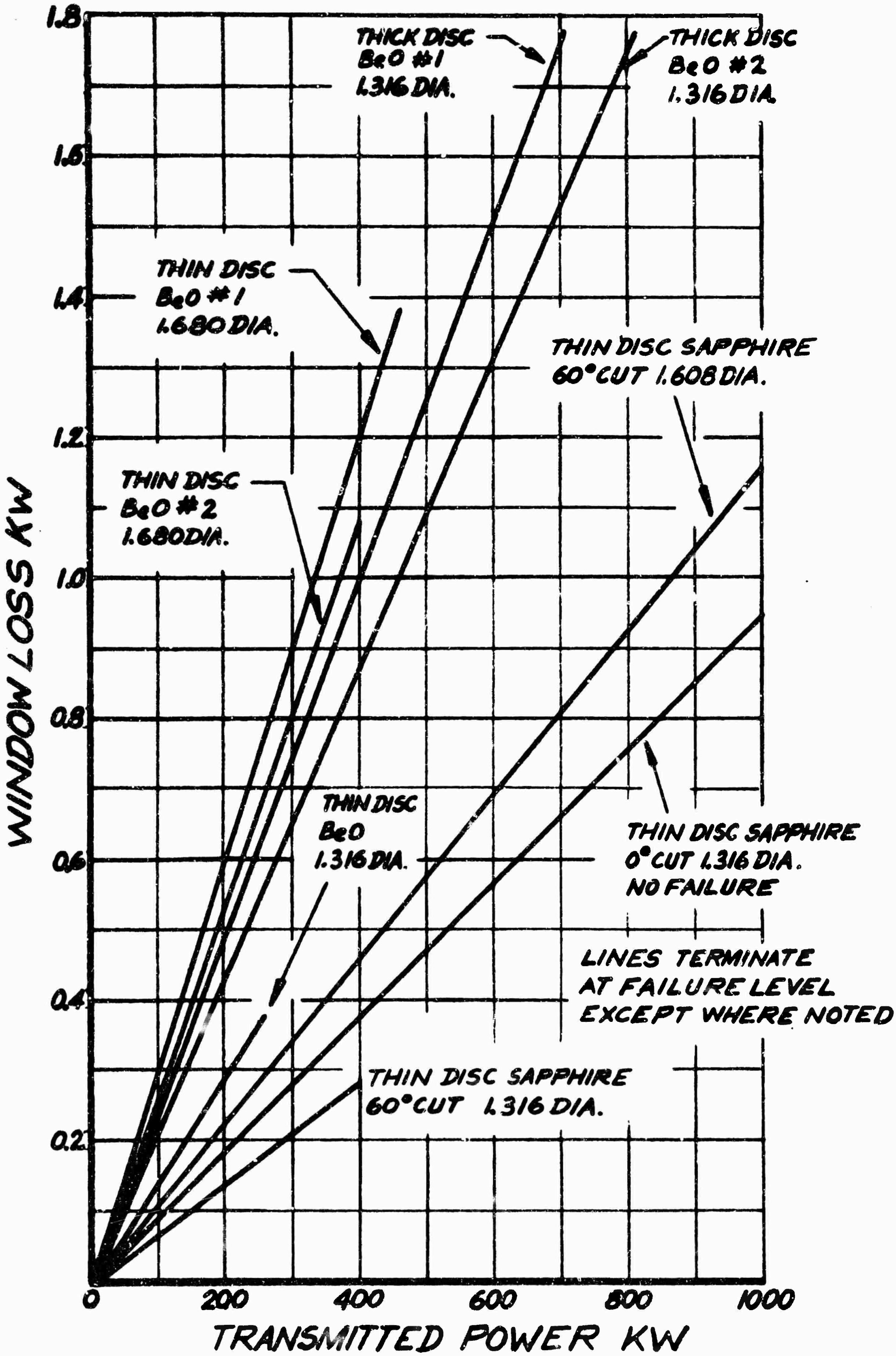



FIG. 17 COMPARATIVE DATA ALL SAMPLES

phase of this program was abbreviated because a major portion of our effort was expended on the development of a ring resonator with which to carry on the window investigation. This effort was necessary because one megawatt rings were beyond the state-of-the-art at the inception of the program.

Another point made obvious through the testing program is that the present ring design, although capable of achieving one megawatt operation, is difficult to handle and just about at its own ultimate limit. If future windows are to be tested for one megawatt reliability, a ring capable of generating at least 1.5 megawatts and more practically 2.0 megawatts would be required. Thus even more effort must be devoted to the "tools" of investigation. With our present knowledge, it is suggested that the proper approach would be to use driver sources capable of much higher power used in conjunction with rings of much lower gain.

Due to the lack of adequate sampling, the facts gathered are presented here in tabular and graphical form without editorial comment. However at this time we do not feel presumptuous in pointing up several observations and suggesting only that further investigation be undertaken.

In reviewing Fig. 8 for example, it can be seen that the volumetric loss rate of the long pill-box BeO design, is considerably lower than all other samples. (This long pill-box window design was employed as an output window on the Eimac X-3030 CW klystron. Window loss measurements made when the tube was operating at 350 kw CW verify the results reported above.) The prime consideration in the design of this window was the lowering of the rf voltages across the window by proper location of the dielectric in the standing-wave pattern of the window assembly. This was accomplished by moving the transition point of rectangular-to-circular guide relatively far from the dielectric center line. A sacrifice in bandwidth was made but it would appear that the effects of the lower gradients have caused this design to out perform all other BeO samples. Obviously more work should be performed along these lines, with emphasis on lowering field gradients even further, and substituting sapphire as a further means for improving power handling capabilities.

Another line of inquiry should be the definite establishment of the comparative merits of BeO versus 60 degree cut sapphire versus zero degree cut sapphire. We do not feel that this has been accomplished here.

Of particular importance is the necessity to establish the merits of 60 degree cut sapphire versus zero degree sapphire, for the cost and scarcity of large zero degree cut sapphire samples is of great concern. Small samples of 60 degree cut are one-third the cost of zero degree cut of the same size and large samples of zero degree cut (over 2 inches) are not available at this time.

Hopefully, further testing programs will be forthcoming that will allow substantiation of trends indicated in this program and provide opportunity for further advancement in the field of rf transmission.

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Security Classification

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13. ABSTRACT

The purpose of this program is to develop a 1.0 megawatt rf window having 10% bandwidth at 8.0 GHz. Seven window samples were tested during the present report period and with one exception all failed at various power levels between 262 kw CW and one megawatt CW. Individual tests are discussed. A zero degree sapphire window was tested at one megawatt CW and successfully transmitted this power for 31 minutes. The window did not fail. A complete summary of all window test results obtained during this program is presented.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Power Amplifiers<br>Microwaves<br>Materials | | | | | | |

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