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DESIGN, DEVELOPMENT AND EVALUATION OF A DOUBLY ROTATED AK-CUT QUARTZ CRYSTAL

Frequency Electronics, Inc.

B. Goldfrank

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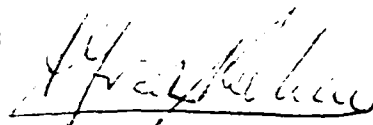
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| <p>This report describes the work accomplished in designing, developing and evaluating a doubly rotated AK-cut quartz crystal. Standard production processes were used to fabricate AK-cut crystals with $\theta = 36.48^\circ$, $\theta = 26.00^\circ$ or $\theta = 35.00^\circ$ and $\theta = 25.00^\circ$. Frequency versus temperature characteristics, room temperature mode spectra and "G" sensitivity data were the main sources of data for evaluation. Crystals were fabricated at low frequencies and through subsequent lapping and polishing operations the frequencies were increased to determine a range of useful frequencies. Variations in shape, contour, blank size, electrode diameter and designed plateback were evaluated. Comparisons were made of "B" mode to "C" mode coupling and separation, unwanted mode suppression, angular rotation tolerances and "G" sensitivity. AK-cut lateral field resonators (AK-LFR) were also evaluated.</p> | | | | | | |
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CONTENTS

| | <u>Page</u> |
|----------------------------------|-------------|
| Introduction | 1 |
| Blank Fabrication and Processing | 4 |
| Results | 6 |
| Conclusions | 9 |
| Proposed Future Studies | 11 |
| Appendix | 35 |



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| | Special | |
| A-1 | | |

LIST OF FIGURES

| <u>FIGURE NO.</u> | | <u>PAGE</u> |
|-------------------|---|-------------|
| 1 | AK RESONATOR ASSEMBLY | 15 |
| 2 | THICKNESS CONSTANT (K) VS. INVERSE RADIUS OF CURVATURE ($1/R_C$) | 20 |
| 3a | FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL OVERTONE, 'C' AND 'B' MODE ON AN AK-CUT CRYSTAL S/N 23124 CENTER FREQUENCY = 3.250 MHz | 28 |
| 3b | FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE, 'C' MODE ON AN AK-CUT CRYSTAL S/N 23124 CENTER FREQUENCY = 9.0 MHz | 28 |
| 3c | FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE, 'B' MODE ON AN AK-CUT CRYSTAL S/N 23124 CENTER FREQUENCY = 9.7 MHz | 29 |
| 3d | FREQUENCY RESPONSE PLOT FOR UNIDENTIFIED MODE ON AN AK-CUT CRYSTAL S/N 23124 CENTER FREQUENCY = 14.1455 MHz | 29 |
| 3e | FREQUENCY RESPONSE PLOT FOR 5TH OVERTONE 'C' MODE ON AN AK-CUT CRYSTAL S/N 23124 CENTER FREQUENCY = 14.60 MHz | 30 |
| 3f | FREQUENCY RESPONSE PLOT FOR 5TH OVERTONE 'B' MODE ON AN AK-CUT CRYSTAL S/N 23124 CENTER FREQUENCY = 16.279 MHz | 30 |
| 4a | FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL 'C' MODE AND 'B' MODE ON AN AK-CUT CRYSTAL S/N AKLFR-6 CENTER FREQUENCY = 3.25 MHz | 31 |
| 4b | FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL 'C' MODE ON AN AK-CUT CRYSTAL S/N AKLFR-6 CENTER FREQUENCY = 3.0013 MHz | 31 |
| 4c | FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE 'C' MODE ON AN AK-CUT CRYSTAL S/N AKLFR-6 CENTER FREQUENCY = 9.0 MHz | 32 |

LIST OF FIGURES

| <u>FIGURE NO.</u> | | <u>PAGE</u> |
|-------------------|--|-------------|
| 4d | FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE 'B' MODE ON AN AK-CUT CRYSTAL S/N AKLFR-6 CENTER FREQUENCY = 9.7 MHz | 32 |
| 4e | FREQUENCY RESPONSE PLOT UNIDENTIFIED MODE ON AN AK-CUT CRYSTAL S/N AKLFR-6 CENTER FREQUENCY = 14.145 MHz | 33 |
| 4f | FREQUENCY RESPONSE PLOT FOR FIFTH OVERTONE 'B' MODE ON AN AK-CUT CRYSTAL S/N AKLFR-6 CENTER FREQUENCY = 14.60 MHz | 33 |
| 4g | FREQUENCY RESPONSE PLOT FOR FIFTH OVERTONE 'B' MODE ON AN AK-CUT CRYSTAL S/N AKLFR-6 CENTER FREQUENCY = 16.279 MHz | 34 |

LIST OF TABLES

| <u>TABLE NO.</u> | | <u>PAGE</u> |
|------------------|---|-------------|
| 1 | FREQUENCY, RESISTANCES AND TURNOVER TEMPERATURES OF FUNDAMENTAL "C" AND "B" MODE RESPONSES FOR AK CRYSTALS | 12 |
| 2 | FREQUENCY, RESISTANCES AND TURNOVER TEMPERATURES OF FUNDAMENTAL "C" AND "B" MODE RESPONSES FOR AK CRYSTALS | 13 |
| 3 | SUMMARY OF TYPES OF AK CUT RESONATORS FABRICATED | 14 |
| 4 | MODE AND OVERTONE RATIOS FOR SELECTED AK-CUT CRYSTALS | 16 |
| 5 | TYPICAL VALUES OF $3F_F/F_3$ FOR VARIOUS AK-CUT CRYSTALS (DATA SELECTED FROM TABLE 4) | 17 |
| 6 | AVERAGE TURNOVER TEMPERATURE VS. CURVATURE AND ANGLES OF CUT | 18 |
| 7 | AVERAGE FREQUENCIES, THICKNESSES AND THICKNESS CONSTANTS FOR AK-CUT CRYSTALS | 19 |
| 8 | TYPICAL AK-CUT DATA AT 3.0 MHz (FUNDAMENTAL "C" MODE) | 21 |
| 9 | ROOM TEMPERATURE DATA FOR $1.0F^2$ AND $0.5F^2$ PLATE BACK | 22 |
| 10 | COMPARISON OF R, C_1 AND Q AT TWO ELECTRODE DIAMETERS (.265" AND .221") FOR .550 AND .590 INCH DIAMETER AK-CUT CRYSTALS | 23 |
| 11 | "G" SENSITIVITY DATA TAKEN ON THE FUNDAMENTAL AND THIRD OVERTONES OF VARIOUS AK-CUT CRYSTALS | 24 |
| 12 | "G" SENSITIVITY DATA TAKEN ON THE THIRD OVERTONE OF VARIOUS AK-CUT CRYSTALS | 25 |
| 13 | "G" SENSITIVITY OF THE 10.0 MHz/3/AK AND 8.0 MHz/3/AK CRYSTALS WITH DIFFERENT ELECTRODE DIAMETERS | 26 |
| 14 | AK LATERAL FIELD ROOM TEMPERATURE DATA FOR DIFFERENT FIELD ROTATION ANGLES (ω) | 27 |

Introduction.

The principal objective of this contract was the development of a doubly rotated (AK-cut) quartz crystal resonator. The resonator was to be characterized and optimized for turnover temperature, blank geometry, overtone operation, "B" to "C" mode coupling and separation, unwanted mode suppression, angular rotation tolerances and "G" sensitivity. Additionally, sufficient design information was to be obtained and presented to allow for ease of fabrication.

The primary advantage of the AK-cut is that there are large angle cutting tolerances. An error in cutting an AK crystal of ± 15 minutes in ϕ or θ does not affect the measured turnover temperature by more than $\pm 1^\circ\text{C}$ near 80°C . In contrast, for an SC-cut crystal the equivalent tolerance is approximately ± 6 seconds, and for an AT-cut crystal the equivalent tolerance is approximately ± 15 seconds. This was the third contract under which the AK-cut was studied. Tables 1 and 2 show a summary of prior data taken on the fundamental mode for both the "C" and "B" modes (P.O.'s F19650-82-B-0578 and F19650-83-M-0713, respectively). For the present contract, we decided to confine our investigation to AK cut crystals with $\phi = 36.58^\circ$ and $\theta = 26.00^\circ$. This angle was chosen for ease of x-raying, as a cross check to the cutting operations, and because of the theoretical turnover which is approximately 80°C . During the course of this study it was decided to also process crystals with a $\phi = 35.00^\circ$ and $\theta = 25.00^\circ$. This decision was based on the desire to investigate

crystals that had similar performance to those crystals cut at $\theta = 36.00^\circ$ and $\phi = 24.45^\circ$, where the fundamental and third overtone turnover temperature (T_{to}) are equal on the main mode. The theoretical T_{to} is also near 80° and would help confirm the shape of the theoretical isotherm previously referenced.

Various lots of crystals were processed. Typically starting at low fundamental frequencies and shallow curvatures, the blanks were processed and tested and then stripped, relapped and repolished to higher frequencies with, in some cases, an increase in curvature. Some crystals proved to be unmeasurable for any meaningful electrical responses, specifically the -1.75 diopter (plano-concave) and 0.00 diopter (plano-plano) crystals. These designs were quickly discarded. All other crystals were plano-convex. A complete summary of all frequencies, angles and contours studied is shown in Table 3.

Throughout the program difficulties were encountered in measuring the overtones. The third overtone has a multiplicity of anharmonic modes of varying strength^{1,2} and the fifth overtone consistently had high resistance, which made measurements difficult.

1. A. Kahan and F.K. Euler, AK-Cut Quartz Resonators, J. Appl. Phys. 57(9), 4461 (1985).
2. A. Kahan, F.K. Euler, Proc. of 14th Precise Time and Time Interval (PTTI) Application and Planning Meeting NASA Conf. Publ. 2265, 1982, p. 577.

Prior work on SC-Cut crystals, which also have strongly coupled "B" modes showed that SC-cut blanks fabricated as lateral field resonator (LFR's)^{3,4} were found to have superior performance and the "B" mode was completely eliminated. In a transverse mode resonator, the electric field is applied normal to the crystal thickness, whereas in the lateral field configuration the electric field is parallel to the major surfaces. As a final comparison of designs, we decided to fabricate some AK crystals as lateral field crystals. These crystals were designated AK-LFR'S. This effort was directed toward reducing the unwanted modes and thus improving the AK resonator performance and enhancing the feasibility of its use.

3. A.W. Warner and B. Goldfrank, "Lateral Field Resonators" 39th FCS p. 473, 1985.

4. U.S. Patent 4701661 "Piezo Electric Resonators Having a Lateral Field Excited SC Cut Quartz Crystal Elements."

Blank Fabrication and Processing.

All work on the first two contracts used a 0.55 inch (14mm) diameter crystal blank while the current study used a 0.59 inch (15mm) diameter crystal blank. The testing indicates that a larger crystal blank has improved performance, by reducing the "C" mode resistance. We were unable to study larger crystals under the scope of this contract. It is possible that additional improvements could be made by fabricating larger crystal blanks.

Table 3 is a summary of the various crystal frequencies investigated during the contract. Four separate lots were made. The first crystals evaluated were cut at $\theta = 36.58^\circ$ and $\phi = 26.00^\circ$. These were fabricated as 10.0/3/AK and were also tested on the fundamental and fifth overtones. A second group of crystals with the same angles of cut were fabricated as 2.124/F/AK, and tested on all overtones where meaningful responses were obtained. We defined meaningful response as a frequency response with a resistance less than 800 Ω . This group of crystals was subsequently reprocessed and retested at 2.500/F/AK and 5.00/F/AK. A third group of crystals was then fabricated at 3.0/F/AK. These crystals were then reprocessed into 4.0/F/AK crystals. A final group of AK ($\theta = 36.58^\circ$, $\phi = 26.00^\circ$) crystals was fabricated at 3.0/F/AK for the lateral field experiments (AK-LFR). These crystals are also shown in Table 3.

After the AK-LFR blanks were fabricated they were tested for electric field rotation, omega ω . ω is defined as field rotation from the -x axis of the quartz blank.^{5,6} Testing consisted of rotating the field, ω , in 30° increments and evaluating the blank resistance response. Two field rotations, $\omega = 105^\circ$ and $\omega = 225^\circ$ were found to have reasonably low resistances. The AK-LFR crystals were processed using a variety of field rotations about these two angles.

An additional group of crystals was cut at $\theta = 35.00^\circ$ and $\phi = 25.00^\circ$. These were processed initially as 2.00/F/AK crystals, and then reprocessed as 10.0/3/AK crystals, which is equivalent to a 3.4/F/AK. The crystals with a 10.0 diopter curvature were tested at 2.8 MHz. The edge thickness would have been too thin, resulting in large edge chips, if we had attempted to increase the frequency to 3.4 MHz.

All the AK-cut crystals fabricated were cut from pure Z, Premium Q, unswept, cultured quartz bars. The AK crystals were pasted in "C" headers and were supported at three points, 90° apart (see Figure 1), except for the AK-LFR crystals which were supported at four points, 90° apart.

5. Final Report "Development of SC-Cut Lateral Field Resonators" LABCOM, Fort Monmouth, NJ, Contract DAAK20-83-C-0418-3.

6. U.S. Patent 4,701,661, Oct. 20, 1987

Results.

As the various lots were processed and tested, the following observations were made.

Table 4 shows that the "C" to "B" mode ratio was reasonably constant for all overtones with varying curvatures. The curvature is always listed in diopters. The actual radius of curvature in inches is defined as:

$$R_c = \frac{20.866}{\text{diopter number}}$$

The ratios $3F_F/F_3$ and $5F_F/F_5$ increased with increasing curvature. This is also shown in Table 5. These ratios also seem to vary slightly with frequency and angles of cut as shown in Table 5.

The turnover temperatures decrease with increasing curvature on the fundamental and fifth overtones. The third overtone turnover appears to remain constant, while the first anharmonic of the third overtone showed an increase in turnover with increasing curvature as shown in Table 6.

The thickness constant increases with increasing curvature. Table 7 shows the average thickness constants for the AK cuts fabricated, varying both the frequency and radius of curvature. Figure 2 shows the same data, in graph form. Note that the 2.0/2.1 MHz data lines are essentially parallel, as are the 3.0/3.4 MHz data lines.

The resistance increases with increasing curvature, as shown in Table 8, with a subsequent decrease in Q, on the fundamental "C" mode.

Lighter plate-backs, or the amount of metal deposited on the surface of the resonator, appear to degrade performance. Only $1.0F^2$ and $0.5F^2$ were used in the comparison. $1.0F^2$ (in kHz) is defined as the fundamental frequency (in MHz), squared, times the overtone, ($1.0F^2 = \left(\frac{f}{n}\right)^2 \times n$, where f is the crystal frequency and n is the overtone.) This term is also used as a design tool to insure that the proper blank frequency is obtained, by adding the designed plate-back to the desired final frequency. For example, a 3.0 MHz, fundamental mode AK cut thickness field resonator with a designed plate-back of $0.85F^2$ should have a polished blank frequency of 3.007650 MHz. There was a 40% increase in resistance, with a resultant reduction in Q, using the lower plate-back, as shown in Table 9. Plate-back variations may warrant further investigation.

A larger blank diameter and a larger electrode diameter reduces the resistance and improves the Q as shown in Table 10. Both sets of angles tested showed improvement in both R and Q over the previously fabricated crystals which were all 0.550 inch diameter, with a 0.265 inch diameter electrode. This suggests that the larger crystal size should be used.

Tables 11 and 12 show the typical "G" data obtained. The "G" sensitivity on the third overtone of the AK crystal is approximately three times better than on the fundamental. The "G" data is comparable on the fundamental and third overtone to similar SC cut crystals. Note also that increasing the electrode diameter improves the "G" sensitivity on the AK-cut crystal as shown in Table 13. This is similar to the previously reported improvement in resistance. No effort was made on this program to try to optimize the "G" performance.

The AK-LFR crystals were quite successful. Typical fundamental mode lateral field data is contained in Table 14. Included with this data is the angle of rotation $\vec{\omega}$ of the field. Most of the spurious modes, including the "B" mode and some higher overtones, were suppressed. Figures 3A through 3F are typical mode spectra for a 3.0 MHz perpendicular field fundamental mode AK cut crystal with a 4.13 diopter curvature. Figures 4A through 4G show a similar crystal, fabricated as an AK-LFR with a 0.075 inch gap at $\vec{\omega} = 105^\circ$.

Note that on all spur plots, the depicted level does not represent the actual strength. The actual levels were determined by peaking in each response on an HP3577A network analyzer using the smallest span possible. The actual levels are recorded on each spur plot.

An Appendix is attached to this report. It contains additional data similar to that presented in the preceding text. Its purpose is to provide additional information as well as to show the uniformity with which AK cut resonators may be fabricated.

Conclusions.

The AK-cut crystal makes an excellent fundamental mode resonator, both in a perpendicular and lateral field excitation. The current useful range is approximately 2.8 MHz to 4.7 MHz for the two sets of angles studied, based on typical performance data, and the desire to maximize Q. For SC cut crystals, oscillators are designed to suppress the "B" mode. The same oscillators can be utilized to suppress the "B" mode for AK-cut crystals.

The blank geometry must be plano-convex with a minimum diameter of 0.55 inches. Epoxy mount techniques are required because of small edge thicknesses.

The lateral field design suppresses most of the spurious responses, particularly the "B" mode. Additional investigations of the AK fundamental mode are required to further understand the suppression of the anharmonics and spurious modes so that the circuit design can be simplified by removing the "B" mode trap, and thus reducing the cost.

The "G" sensitivity of the AK crystal on the third overtone is better than that of the AT cut, and comparable to similar SC cut units. Improvement would require a separate study program to determine optimum mounting.

Recommended AK Crystal Specifications.

1. Optimum fundamental frequency range between 2.8 MHz and 4.7 MHz.
2. Optimum curvature is between 2.5 and 6.0 diopters (8.346 inch radius of curvature to 3.478 inch radius of curvature, respectively).
3. Minimum electrode diameter is 0.265 inches.
4. Minimum crystal blank diameter is 0.550 inches.
5. Minimum designed plate-back is estimated at $.85F^2$. This is based on the presented data and our experience with SC cut crystals.

Proposed Future Studies.

1. AK cut crystals with higher θ angles that have higher "C" to "B" mode ratios. This recommendation is made because lower turnover temperatures can be achieved through contouring.
2. AK lateral field crystal study to evaluate curvature, electrode spacing, and field direction angle ($\vec{\omega}$).
3. Large diameter AK cut crystal evaluation. The purpose of this study would be to increase the useful frequency range by using a 0.986 inch diameter crystal, because lower frequencies could be evaluated and improvements in the mounting techniques, such as thermo-compression bonding, may become feasible, because the edge of the crystal blank will be thicker.
4. "G" sensitivity study on current designs. Determination of optimum mounting angle and techniques. This could be combined with proposal three above.
5. Evaluate an optimized design in a standard ceramic flat pack. Trade-offs would have to be made due to lower Q with a smaller blank diameter. The advantage of the ceramic flat pack include better mounting techniques, limited air exposure during processing and lower vacuum levels during sealing.

TABLE 1

FREQUENCY, RESISTANCES AND TURNOVER TEMPERATURES OF
FUNDAMENTAL "C" AND "B" MODE RESPONSES FOR AK CRYSTALS

| ϕ/θ | SER. NO. | "C" MODE | | | "B" MODE | | |
|---------------|----------|------------|--------------|--------------|------------|--------------|--------------|
| | | F_s (Hz) | R | T.O. (°C) | F_s (Hz) | R | T.O. (°C) |
| 46.06°/23.55° | 9338 | 3361422 | <10 Ω | 136° | 3622437 | >500 | NA |
| | 9339 | 3361117 | <10 Ω | 136° | 3622716 | >500 | NA |
| | 9340 | 3361381 | <10 Ω | 136° | 3621094 | >500 | NA |
| | 9342 | 3360750 | <10 Ω | 136° | 3617986 | >500 | NA |
| 40.90°/23.55° | 9980 | 3356768 | <10 Ω | 95° | 3726759 | 140 Ω | NA |
| | 9981 | 3357249 | <10 Ω | 95° | 3726951 | 50 Ω | NA |
| | 9982 | 3357024 | <10 Ω | 95° | 3726945 | 60 Ω | NA |
| 36.00°/24.44° | 10132 | 3368171 | 10 Ω | 78° | 3793594 | 20 Ω | NA |
| | 10134 | 3367539 | 28 Ω | 78° | 3798211 | 80 Ω | NA |
| 40.90°/21.00° | 10123 | 3356390 | 60 Ω | 115° | 3912582 | 20 Ω | NA |
| | 10124 | 3357853 | 36 Ω | 115° | 3914411 | 40 Ω | NA |
| | 10125 | 3357370 | 28 Ω | 115° | 3913607 | 20 Ω | NA |
| 40.9°/27.00° | 9991 | 3557338 | <10 Ω | 104° | 3540515 | 60 Ω | NA |
| | 9992 | 3365651 | <10 Ω | 104° | 3554006 | 40 Ω | NA |

Data presented was taken during initial AK study under P.O. Number
F19650-82-B-0578

NA = Not applicable

TABLE 2

FREQUENCY, RESISTANCES AND TURNOVER TEMPERATURES OF
FUNDAMENTAL "C" AND "B" MODE RESPONSES FOR AK CRYSTALS

| ϕ/θ | SER. NO. | "C" MODE | | | "B" MODE | | |
|---------------|----------|---------------------|-------|--------------|---------------------|------|--------------|
| | | F _S (Hz) | R | T.O. (°C) | F _S (Hz) | R | T.O. (°C) |
| 33.00°/24.44° | 14322 | 3380101 | 80Ω | 95° | 3865564 | 145Ω | NA |
| | 14325 | 3381189 | 110Ω | 95° | 3864619 | 90Ω | NA |
| | 14327 | 3380725 | 60Ω | 95° | 3857568 | 60Ω | NA |
| | 14328 | 3380014 | 50Ω | 95° | 3858736 | 60Ω | NA |
| 34.00°/22.00° | 14332 | 3380450 | 55Ω | 115° | 4007522 | 50Ω | NA |
| | 14338 | 3379060 | 105Ω | 115° | 4006092 | 80Ω | NA |
| | 14339 | 3380311 | 145Ω | 115° | 4006070 | 55Ω | NA |
| | 14340 | 3379987 | 170Ω | 115° | 4996473 | 80Ω | NA |
| | 14341 | 3379919 | 200Ω | 115° | 4006437 | 40Ω | NA |
| 34.00°/26.00° | 14349 | 3381447 | 60Ω | 81° | 3748189 | 110Ω | NA |
| | 14350 | 3382619 | 205Ω | 81° | 3750043 | 275Ω | NA |
| | 14351 | 3382448 | 145Ω | 81° | 3749148 | 300Ω | NA |
| 34.00°/28.44° | 14358 | 3380665 | 500Ω | 106° | 3622914 | 90Ω | NA |
| | 14360 | 3380312 | 500Ω | 106° | 3623723 | 80Ω | NA |
| | 14365 | 3381266 | >500Ω | 106° | 3629341 | 145Ω | NA |
| 36.58°/22.00° | 14373 | 3384436 | 30Ω | 90° | 3948761 | 15Ω | NA |
| | 14375 | 3384011 | 15Ω | 90° | 3948741 | 15Ω | NA |
| | 14376 | 3383489 | 20Ω | 90° | 3948896 | 20Ω | NA |
| 36.58°/26.00° | 14386 | 3394076 | 40Ω | 76° | 3713306 | 450Ω | NA |
| 38.50°/26.00° | 14398 | 3404212 | 30Ω | 81° | 3690441 | 110Ω | NA |
| | 14399 | 3404481 | 10Ω | 81° | 3688878 | 80Ω | NA |

Data presented was taken during second AK study under P.O. Number
F19650-83-M-0713

NA = Not applicable

TABLE 3
SUMMARY OF TYPES OF AK CUT RESONATORS FABRICATED
 (All are perpendicular field resonators, except where noted.)

| ANGLES OF CUT: $\phi = 36.58^\circ$ $\theta = 26.00^\circ$ | | | | ANGLES OF CUT: $\phi = 35.00^\circ$ $\theta = 25.00^\circ$ | | | |
|---|------|-------|------------------------------|---|------|-------|----------------------------|
| NOMINAL FREQUENCY (IN MHZ) BY OVERTONE | | | CURVATURE (IN DIOPTERS) | NOMINAL FREQUENCY (IN MHZ) BY OVERTONE | | | CURVATURE (IN DIOPTERS) |
| F | 3 | 5 | | F | 3 | 5 | |
| 2.124 | 6.27 | 10.51 | 1.75, 2.63, 4.13, 10.0, 13.0 | 2.000 | 5.80 | 9.90 | 1.75, 2.63, 4.13, 10.0 |
| 2.500 | 7.38 | 12.38 | 4.13, 6.0, 8.0, 10.0 | | | | |
| 3.000 | 8.8 | 14.85 | 4.13, 6.0, 8.0, 10.0 | 2.8 | | | 10.0 |
| 3.331 | 10.0 | 16.78 | 1.75, 2.63, 4.13 | | | | |
| 4.000 | 11.9 | 19.80 | 4.13 | 3.45 | 10.0 | 16.78 | 4.13, 6.0, 8.0, |
| 5.000 | 14.8 | N.D. | 1.75, 2.63, 4.13 | | | | |
| 3.000 | 8.8 | 13.80 | 4.13* | | | | |

*Lateral Field AK cut resonators.

| NOTES: | | REVISIONS | | | | | | | | | | | | | |
|--|-------------|---|--------|-----|--|-----|-------------|----|------|-----|---|----------|--|--------|--|
| 1. CRYSTAL FREQUENCY 3.391000 MHz 2. ITEM 2 WELDED TO ITEM 4 3. ITEM 1 ATTACHED TO ITEM 2 WITH ITEM 5 4. ITEM 3 COLQ WELDED TO ITEM 4 5. ITEM 3 MARKED WITH ITEM 6 | | <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th>REV</th> <th>DESCRIPTION</th> <th>BY</th> <th>DATE</th> <th>APP</th> </tr> <tr> <td>1</td> <td>INITIALS</td> <td></td> <td>7/1/68</td> <td></td> </tr> </table> | | | | REV | DESCRIPTION | BY | DATE | APP | 1 | INITIALS | | 7/1/68 | |
| REV | DESCRIPTION | BY | DATE | APP | | | | | | | | | | | |
| 1 | INITIALS | | 7/1/68 | | | | | | | | | | | | |

| QTY | REMARKS | REL | CODE | PART NO | REL PART NO | DESCRIPTION | REMARKS |
|-----|---------|-----|------|-----------|-------------|----------------|---------|
| 1 | | | | 7220 | | INK, BLACK | 6 |
| 1 | | | | 5554 | | EPKXY | 5 |
| 1 | | | | 10203-883 | | HEADER, C | 4 |
| 1 | | | | 27572-883 | | COVER C | 3 |
| 1 | | | | 27572-883 | | MOUNT | 2 |
| 1 | | | | | | QUARTZ CRYSTAL | 1 |

| MATERIALS AND TABULATED ITEMS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---------|---------|------|---------|-------------|-------------|-------------|---------|---|--|--|--|--|--|--|--|---|-----|---------|-----|------|---------|-------------|-------------|---------|---|--|--|--|--|--|--|--|
| <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th>QTY</th> <th>REMARKS</th> <th>REL</th> <th>CODE</th> <th>PART NO</th> <th>REL PART NO</th> <th>DESCRIPTION</th> <th>REMARKS</th> </tr> <tr> <td>1</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> </table> | QTY | REMARKS | REL | CODE | PART NO | REL PART NO | DESCRIPTION | REMARKS | 1 | | | | | | | | <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th>QTY</th> <th>REMARKS</th> <th>REL</th> <th>CODE</th> <th>PART NO</th> <th>REL PART NO</th> <th>DESCRIPTION</th> <th>REMARKS</th> </tr> <tr> <td>1</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> </table> | QTY | REMARKS | REL | CODE | PART NO | REL PART NO | DESCRIPTION | REMARKS | 1 | | | | | | | |
| QTY | REMARKS | REL | CODE | PART NO | REL PART NO | DESCRIPTION | REMARKS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| QTY | REMARKS | REL | CODE | PART NO | REL PART NO | DESCRIPTION | REMARKS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

| ASSOCIATED DRAWINGS | | UNLESS OTHERWISE SPECIFIED | | FREQUENCY ELECTRONICS, INC. | |
|---|---------------|---|-----------|-----------------------------|---------------------------|
| QTY REC'D FINAL ASY | FIRST USED ON | NEXT ASY | QTY REC'D | QTY REC'D | NEW YORK, NEW YORK, 11040 |
| B 20773-883 | | B 20773-883 | | AK RESONATOR ASSEMBLY | |
| 1. QUANTITY OF PARTS TO BE MANUFACTURED 2. QUANTITY OF PARTS TO BE MANUFACTURED 3. QUANTITY OF PARTS TO BE MANUFACTURED 4. QUANTITY OF PARTS TO BE MANUFACTURED 5. QUANTITY OF PARTS TO BE MANUFACTURED 6. QUANTITY OF PARTS TO BE MANUFACTURED 7. QUANTITY OF PARTS TO BE MANUFACTURED | | 1. QUANTITY OF PARTS TO BE MANUFACTURED 2. QUANTITY OF PARTS TO BE MANUFACTURED 3. QUANTITY OF PARTS TO BE MANUFACTURED 4. QUANTITY OF PARTS TO BE MANUFACTURED 5. QUANTITY OF PARTS TO BE MANUFACTURED 6. QUANTITY OF PARTS TO BE MANUFACTURED 7. QUANTITY OF PARTS TO BE MANUFACTURED | | CODE IDENT NO 14844 | |
| SIZE B | | DRAWING NO 39250-9586 | | REV A | |
| SCALE 1:1 | | DO NOT SCALE DRAWING | | SHEET 1 OF 2 | |

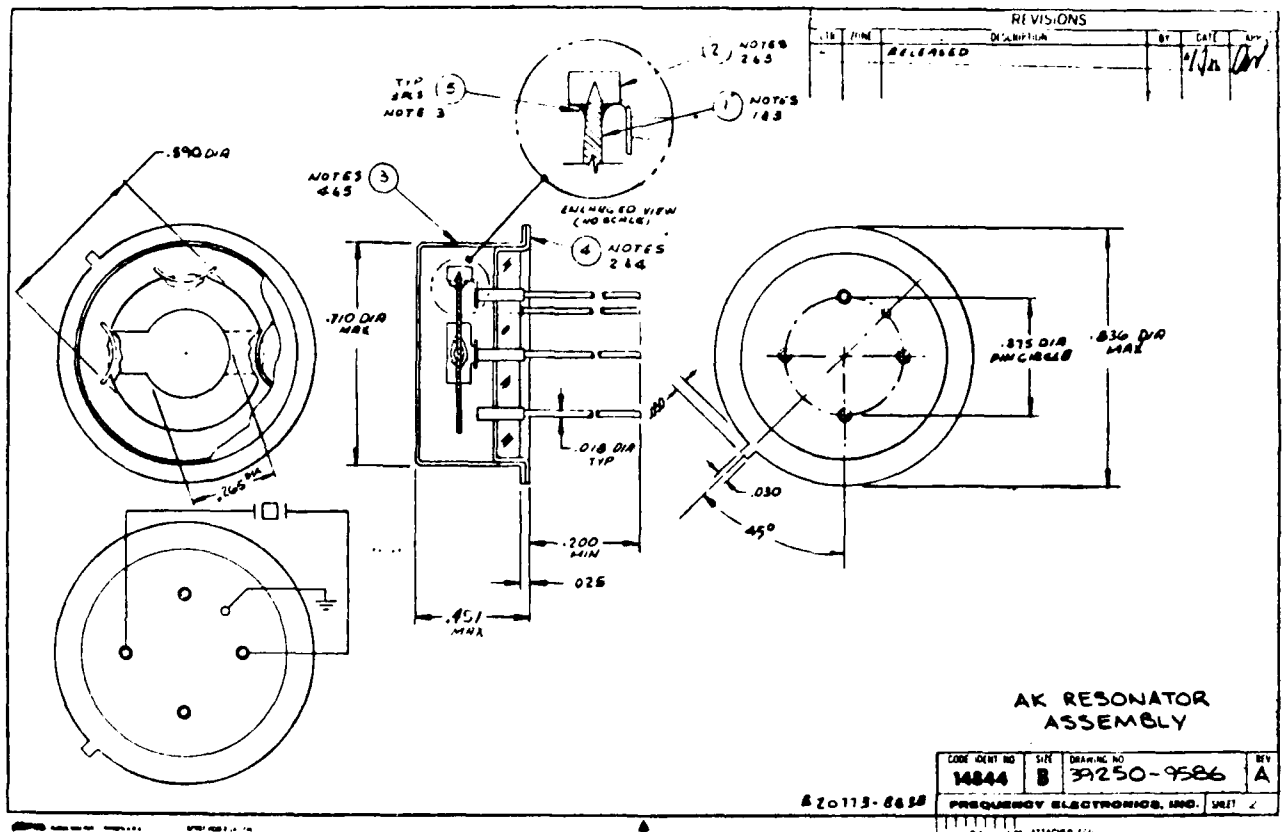


FIGURE 1

TABLE 4

MODE AND OVERTONE RATIOS FOR SELECTED AK-CUT CRYSTALS

| NOMINAL FUNDAMENTAL FREQUENCY | ANGLES OF CUT | CURVA- TURE ⁴ | C/B RATIOS | | | C MODE RATIOS | |
|-------------------------------------|------------------------|-----------------------------|--------------------|--------------------|-------------------|---------------------------------|---------------------------------|
| | | | F | 3d | 5th | 3F _F /F ₃ | 5F _F /F ₅ |
| 2.00 MHz | $\phi = 35.00^\circ$ | 1.75 | .8908 | .8908 | .8649 | 1.019 | 1.048 |
| | $\theta = 25.00^\circ$ | 2.63 | .8907 | N.D. ¹ | N.D. ¹ | 1.022 | N.D. ¹ |
| | | 4.13 | .8899 | .9301 | .8640 | 1.027 | 1.058 |
| | | 10.0 | .9102 | .8795 | .8638 | 1.040 | 1.074 |
| 2.124 MHz | $\phi = 36.58^\circ$ | 1.75 | .9104 | .9027 | .9107 | 1.019 | 1.018 |
| | $\theta = 26.00^\circ$ | 2.63 | .9105 | .9024 | .9102 | 1.022 | 1.020 |
| | | 4.13 | .9112 | .9020 | .9102 | 1.029 | 1.028 |
| | | 10.0 | .9131 ² | .9006 ³ | .9102 | 1.041 | 1.041 |
| | | 13.5 | .9156 | .8973 | .9116 | 1.049 | 1.048 |
| 3.000 MHz | $\phi = 36.58^\circ$ | 6.0 | .9244 | .9050 | .9165 | 1.0289 | 1.0264 |
| | $\theta = 26.00^\circ$ | 8.0 | .9182 | .9022 | .9166 | 1.0327 | 1.0302 |
| | | 10.0 | .9112 | .9015 | .9086 | 1.0356 | 1.0371 |
| 3.391 MHz | $\phi = 36.58^\circ$ | 1.75 | .9116 | .9047 | .9113 | 1.0161 | 1.0139 |
| | $\theta = 26.00^\circ$ | 2.63 | .9112 | .9037 | .9113 | 1.0190 | 1.0168 |
| | | 4.13 | .9116 | .9018 | .9111 | 1.0229 | 1.0210 |
| 4.000 MHz | $\phi = 36.58^\circ$ | 4.13 | .9142 | .9053 | .9148 | 1.0217 | 1.0192 |
| | $\theta = 26.00^\circ$ | | | | | | |

1. No data, responses unstable.
2. Averaged data due to split mode.
3. Estimated.
4. Curvature in diopters.

TABLE 5

TYPICAL VALUES OF $3F_F/F_3$ FOR VARIOUS AK-CUT CRYSTALS
(DATA SELECTED FROM TABLE 4)

| CURVATURE ¹ | $\phi = 36.58^\circ$ $\theta = 26.00^\circ$ | | $\phi = 35.00^\circ$ $\theta = 25.00^\circ$ |
|------------------------|--|-----------------------------|--|
| | $3F_F/F_3$ (10.0 MHz/3) | $3F_F/F_3$ (2.124 MHz/F) | $3F_F/F_3$ (2.0 MHz/F) |
| 1-3/4 D | 1.016 | 1.020 | 1.019 |
| 2-5/8 D | 1.019 | 1.022 | 1.022 |
| 4-1/8 D | 1.023 | 1.029 | 1.027 |
| 10 D | N/D ² | 1.041 | 1.040 |
| 13-1/2 D | N/D ² | 1.047 | N/D ² |

1. Curvature in diopters.
2. No data.

TABLE 6

AVERAGE TURNOVER TEMPERATURE VS. CURVATURE AND
ANGLES OF CUT

| ANGLES OF CUT | NOMINAL FREQUENCY FUNDAMENTAL | RADIUS OF CURVATURE IN DIOPTERS | TURNOVER TEMPERATURE BY OVERTONE | | | |
|---|-------------------------------------|---------------------------------------|-------------------------------------|-------------------|-------------------|-------------------|
| | | | 1st | 3d | 5th | 3d ¹ |
| $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$ | 2.1 MHz | 4.13 | 67 | N.D. ² | N.D. ² | N.D. ² |
| | | 10.00 | 55 | N.D. ² | N.D. ² | N.D. ² |
| $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$ | 3.4 MHz | 1.75 | 81 | 69 | 74 | 93 |
| | | 2.63 | 75 | 68 | 75 | 96 |
| | | 4.13 | 74 | 70 | 72 | N.D. ² |
| $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$ | 5.0 MHz | 1.75 | 80 | N.D. ² | N.D. ² | N.D. ² |
| | | 2.63 | 77 | | | |
| | | 4.13 | 76 | | | |
| $\emptyset = 35.00^\circ$ $\theta = 25.00^\circ$ | 2.1 MHz | 4.13 | 70 | 93 | N.D. ² | N.D. ² |
| | | 10.00 | 60 | 99 | N.D. ² | N.D. ² |
| $\emptyset = 35.00^\circ$ $\theta = 25.00^\circ$ | 2.8 MHz | 10.00 | 63 | N.D. ² | N.D. ² | N.D. ² |
| $\emptyset = 35.00^\circ$ $\theta = 25.00^\circ$ | 3.4 MHz | 4.13 | 75 | N.D. ² | N.D. ² | N.D. ² |
| | | 5.00 | 72 | | | |
| | | 8.00 | 68 | | | |

1. Second third overtone. First third overtone 10.010 MHz with a 450 ohm resistance; second third overtone 10.060 MHz with a resistance of 250 ohms.
2. N.D. = no data. Resistance of overtone greater than 800 Ω or so unstable as to prohibit equipment from tracking frequency versus temperature.

TABLE 7

AVERAGE FREQUENCIES, THICKNESSES AND THICKNESS CONSTANTS
FOR AK-CUT CRYSTALS

| ANGLES OF CUT | CURVE DIOPTERS | NOMINAL FREQUENCY (FUNDAMENTAL) IN MHZ | THICKNESS INCHES (mm) | THICKNESS CONSTANT X 10 ⁴ (kHz-in) |
|--|-------------------|---|--------------------------|---|
| $\phi = 36.58^\circ$ $\theta = 26.00^\circ$ | 1.75 | 2.127482 | .037157 (.9438) | 79.05 |
| | 2.625 | 2.127942 | .037244 (.9460) | 79.25 |
| | 4.125 | 2.127818 | .037555 (.9539) | 79.91 |
| | 10.0 | 2.127935 | .038212 (.9706) | 81.31 |
| | 4.125 | 3.008863 | .026472 (.6724) | 79.65 |
| | 6.0 | 3.009053 | .026638 (.6788) | 80.16 |
| | 8.0 | 3.009309 | .026772 (.6800) | 80.56 |
| | 10.0 | 3.009783 | .026787 (.6804) | 80.66 |
| $\phi = 35.00^\circ$ $\theta = 25.00^\circ$ | 1.75 | 2.003645 | .038720 (.9835) | 77.58 |
| | 2.625 | 2.004097 | .038890 (.9878) | 77.94 |
| | 4.125 | 2.003921 | .039173 (.9950) | 78.50 |
| | 10.0 | 2.003869 | .039882 (1.0130) | 79.92 |
| | 4.125 | 3.423285 | .022646 (.5752) | 77.80 |
| | 6.0 | 3.450943 | .022677 (.5760) | 78.26 |
| | 8.0 | 3.463886 | .022716 (.5770) | 78.68 |
| | 10.0 | 2.780897 | .028543 (.7250) | 79.38 |

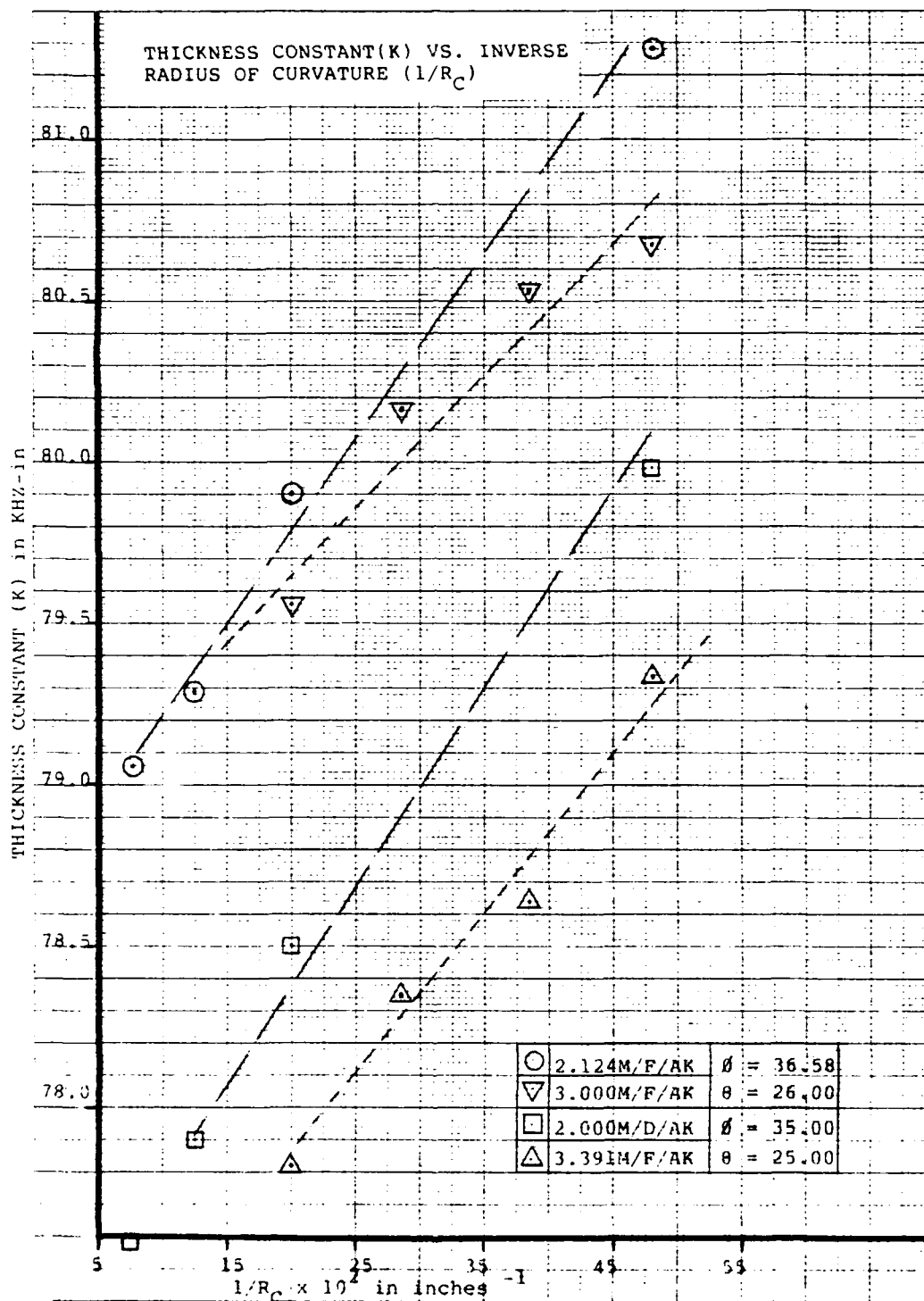


FIGURE 2

TABLE 8

TYPICAL AK-CUT DATA AT 3.0 MHz (FUNDAMENTAL "C" MODE)
($\theta = 36.58^\circ$, $\theta = 26.00^\circ$)

Designed Plate Back = 1.0F2

| CURVA-TURE | f_s @ 25°C | R (Ω) | f_p @ 25°C w/ C_L | Δf | C_0 | C_1 $\times 10^{+16}$ | Q $\times 10^{-6}$ |
|------------|--------------|----------------|-----------------------|------------|-------|----------------------------|-----------------------|
| 4.13 | 3003197 | 25 | 3003317 | 120 | 3.2 | 10.5 | 2.0 |
| | 3002833 | 22 | 3002957 | 124 | 3.2 | 10.9 | 2.2 |
| 6.0 | 3003258 | 27 | 3003364 | 106 | 3.2 | 9.3 | 2.1 |
| | 3003176 | 33 | 3003278 | 102 | 3.2 | 9.0 | 1.8 |
| 8.0 | 3003268 | 44 | 3003267 | 99 | 3.2 | 8.8 | 1.4 |
| | 3002975 | 38 | 3003072 | 97 | 3.2 | 8.6 | 1.6 |
| 10.0 | 3003463 | 175 | 3003548 | 85 | 3.2 | 7.5 | 0.4 |
| | 3003288 | 225 | 3003374 | 86 | 3.2 | 7.6 | 0.3 |

$$\Delta f = f_p - f_s$$

$$C_1 = \frac{2 (\Delta f) \times (C_0 + C_L)}{f_s} \quad \text{where } C_L = 10 \text{ pf}$$

$$Q = \frac{1}{2\pi f_s R C_1}$$

TABLE 9

ROOM TEMPERATURE DATA FOR 1.0F2 and 0.5F2 PLATE BACK

| PLATE BACK | SER. NO. | f_s @ 25°C | R | f_p @ 10 pf @ 25°C | Δf ($f_p - f_s$) | C_o | C_1 $\times 10^{+16}$ | Q $\times 10^{-6}$ |
|---------------|----------|--------------|----|----------------------|-------------------------------|-------|----------------------------|-------------------------|
| 1.0F2 | 23124 | 4004005 | 19 | 4004161 | 156 | 3.8 | 1.1 | 1.9 |
| | 23125 | 4003480 | 18 | 4003639 | 159 | 3.8 | 1.1 | 2.0 |
| | 23126 | 4003706 | 18 | 4003865 | 159 | 3.8 | 1.1 | 2.0 |
| | 23127 | 4007475 | 22 | 4007613 | 138 | 3.8 | 1.0 | 1.9 |
| 0.5F2 | 23124R | 4010032 | 24 | 4010182 | 150 | 3.8 | 1.1 | 1.6 |
| | 23126R | 4009236 | 22 | 4009390 | 154 | 3.8 | 1.1 | 1.7 |
| | 23127R | 4012911 | 27 | 4013056 | 145 | 3.8 | 1.0 | 1.4 |

$$\Delta f = f_p - f_s$$

$$C_1 = \frac{2 (\Delta f) \times (C_o + C_L)}{f_s} \quad \text{where } C_L = 10 \text{ pf}$$

$$Q = \frac{1}{2\pi f_s R C_1}$$

TABLE 10
COMPARISON OF R, C₁ AND Q AT TWO ELECTRODE DIAMETERS (.265" AND .221")
FOR .550 AND .590 INCH DIAMETER AK-CUT CRYSTALS

| BLANK DIAM | CURVE | RESISTANCE R (OHMS) | | C ₁ x 10 ⁺¹⁶ | | Q x 10 ⁻⁶ | |
|------------|---------|---------------------|---------|------------------------------------|---------|----------------------|---------|
| | | (.265") | (.221") | (.265") | (.221") | (.265") | (.221") |
| .590 | 4.13 D | 16.01 | 22.32 | .997 | .842 | 2.93 | 2.51 |
| .590 | 6.00 D | 17.58 | 22.85 | .878 | .732 | 3.02 | 2.77 |
| .590 | 8.00 D | 27.4 | 41.34 | .799 | .692 | 2.12 | 1.62 |
| .590 | 10.00 D | 210.11 | 265.09 | .736 | .656 | 0.37 | 0.33 |
| .550 | 4.13 | 40 | ND | 1.4 | ND | 0.88 | ND |

NOTE: Values shown are averages.

ND = No data.

TABLE 11

"G" SENSITIVITY DATA TAKEN ON THE FUNDAMENTAL AND THIRD OVERTONES OF VARIOUS AK-CUT CRYSTALS

| ANGLES OF CUT: $\theta = 36.58^\circ$, $\theta = 26.00^\circ$ | | | | | | | | | |
|--|-------|-------------------------------|----------------------------------|--------------|-------|-------------------------------|--------------|-------|-------------------------------|
| 3.4 MHz/F/AK | | | | 5.0 MHz/F/AK | | | 3.0 MHz/F/AK | | |
| SER. NO. | CURV. | FUND ($\times 10^{-10}$) | $\sqrt{3D}$ $\times 10^{-10}$ | SER. NO. | CURV. | FUND ($\times 10^{-10}$) | SER. NO. | CURV. | FUND ($\times 10^{-10}$) |
| 001 | 1.75 | 24.5 | 7.72 | 21378 | 1.75 | 10.40 | | | |
| 002 | 1.75 | 18.7 | 3.91 | | | | | | |
| 001 | 2.625 | 31.6 | 6.62 | 21373 | 2.625 | 9.09 | | | |
| 002 | 2.625 | 21.4 | 4.55 | | | | | | |
| 004 | 4.125 | 22.3 | 5.55 | | | | 23124 | 4.125 | 11.38 |
| 005 | 4.125 | 17.6 | 5.99 | | | | 23128 | 6.0 | 17.91 |
| | | | | | | | 23132 | 8.0 | 7.62 |
| | | | | | | | 20440RR | 10.0 | 6.79 |

NOTE: FVIB = 100 Hz, Electrode DIA = .265"

TABLE 12

"G" SENSITIVITY DATA TAKEN ON THE
THIRD OVERTONE OF VARIOUS AK-CUT CRYSTALS

| ANGLES OF CUT: $\phi = 35.00^\circ$, $\theta = 25.00^\circ$ | | | | | |
|--|-------|-----------------------------------|---------------------------|-------|-----------------------------------|
| 10.0 MHz/3/AK | | | 8.0 MHz/3/AK ¹ | | |
| SER. NO. | CURV. | $\sqrt{3}D$ ($\times 10^{-10}$) | SER. NO. | CURV. | $\sqrt{3}D$ ($\times 10^{-10}$) |
| 20456R | 4.125 | 5.92 | | | |
| 20448R | 6.0 | 5.68 | | | |
| 20452R | 8.0 | 5.68 | | | |
| | | | 20460R | 10.0 | 7.05 |

NOTE: $F_{VIB} = 100$ Hz, Electrode DIA = .265"

¹Approximately 2.8 MHz, fundamental.

TABLE 13

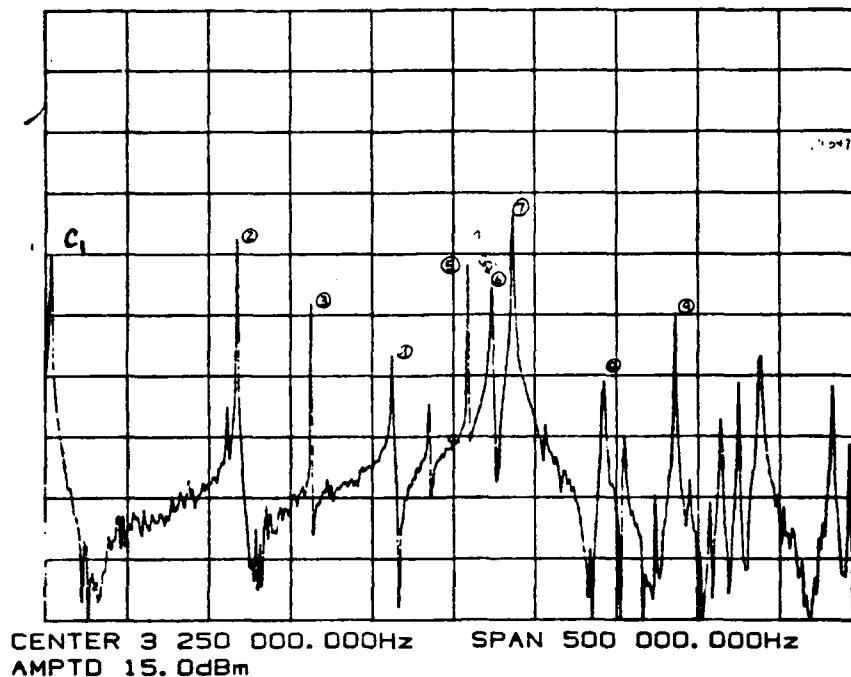
"G" SENSITIVITY OF THE 10.0 MHz/3/AK AND 8.0 MHz/3/AK CRYSTALS
WITH DIFFERENT ELECTRODE DIAMETERS
IN PARTS 10^{10}

| ANGLES OF CUT: $\phi = 35.00^\circ$, $\theta = 25.00^\circ$ | | |
|--|--------------------|--------------------|
| CURVE | .265" ELECTRODE | .221" ELECTRODE |
| 4.125 | 5.92 | 12.62 |
| 6.0 | 5.68 | 8.22 |
| 8.0 | 5.68 | 8.22 |
| 10.0 | 7.05 | 10.97 |

TABLE 14
AK LATERAL FIELD ROOM TEMPERATURE DATA FOR DIFFERENT FIELD ROTATION ANGLES ($\vec{\omega}$)

| NO. | f_s @ 25°C | R (Ω) | f_p @ 25°C w/10 pf | Δf ($f_p - f_s$) | C_0 | C_1 $\times 10^{+17}$ | Q $\times 10^{-6}$ | $\vec{\omega}$ |
|-----|--------------|----------------|----------------------|-------------------------------|-------|----------------------------|-------------------------|----------------|
| 2 | 3000914.5 | 570 | 3000920.3 | 5.8 | 0.61 | 4.09 | 2.27 | 60° |
| 4 | 3001136.3 | 380 | 3001148.0 | 11.7 | 0.62 | 8.27 | 1.67 | 90° |
| 6 | 3001310.6 | 480 | 3001318.6 | 8.0 | 0.61 | 5.65 | 1.96 | 105° |
| 8 | 3001130.8 | 355 | 3001139.3 | 8.5 | 0.61 | 6.01 | 2.49 | 120° |
| 12 | 3001381.9 | 645 | 3001387.1 | 5.2 | 0.60 | 3.67 | 2.24 | 255° |

REF LEVEL /DIV MARKER 3 250 000.000Hz
0.000dB 10.000dB MAG(S21) -70.468dB



10 SEC SWEEP
113003184.400 -3.544 dB
213117440.000 -24.714 dB
313162456.750 -3.934 dB
413212947.000 -16.474 dB
513258585.750 -25.404 dB
613273404.500 -18.559 dB
713286475.250 -21.294 dB
813341908.750 -25.781 dB
913386085.500 -37.738 dB

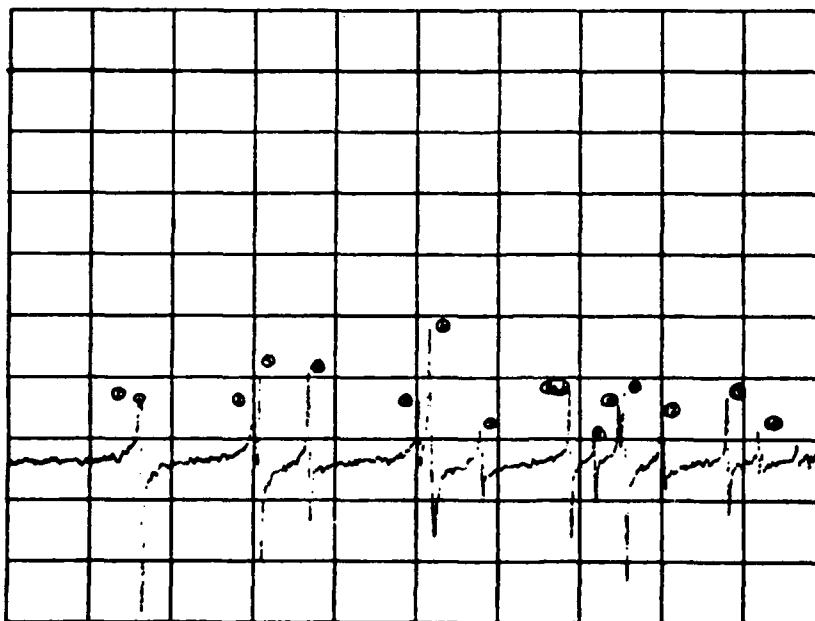
C1/B1
if B1 #6 C1/B1 = .9174
if B1 #7 C1/B1 = .9138
if B1 #8 C1/B1 = .8986

S/N 23124 3.0M/F/AK
FSO 5249AA 4.125D

FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL OVERTONE,
'C' AND 'B' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 3.250 MHz

REF LEVEL /DIV MARKER 8 900 000.000Hz
0.000dB 10.000dB MAG(S21) 63.331dB

if C1 is 1 $\frac{C1}{C3} = 1.024$
if C1 is 2 $\frac{C1}{C3} = 1.014$



118796514.975 -17.910 dB
218880439.500 -19.161 dB
318883979.250 -23.659 dB
418919904.575 -24.963 dB
519001068.375 -31.297 dB
619008696.025 -19.641 dB
719047071.475 -26.764 dB
8a19112153.500 -33.197 dB
8b19113031.750 -33.604 dB
919130810.000 -33.227 dB
1019148394.500 -36.365 dB
1119152167.250 -21.714 dB
1219179272.000 -29.704 dB
1319227824.250 -30.704 dB
1419250234.500 -43.744 dB

-Steep temp slope at room temp.

+Reduced input amplitude from 0 to -10.0 dBm due to bouncing at peak

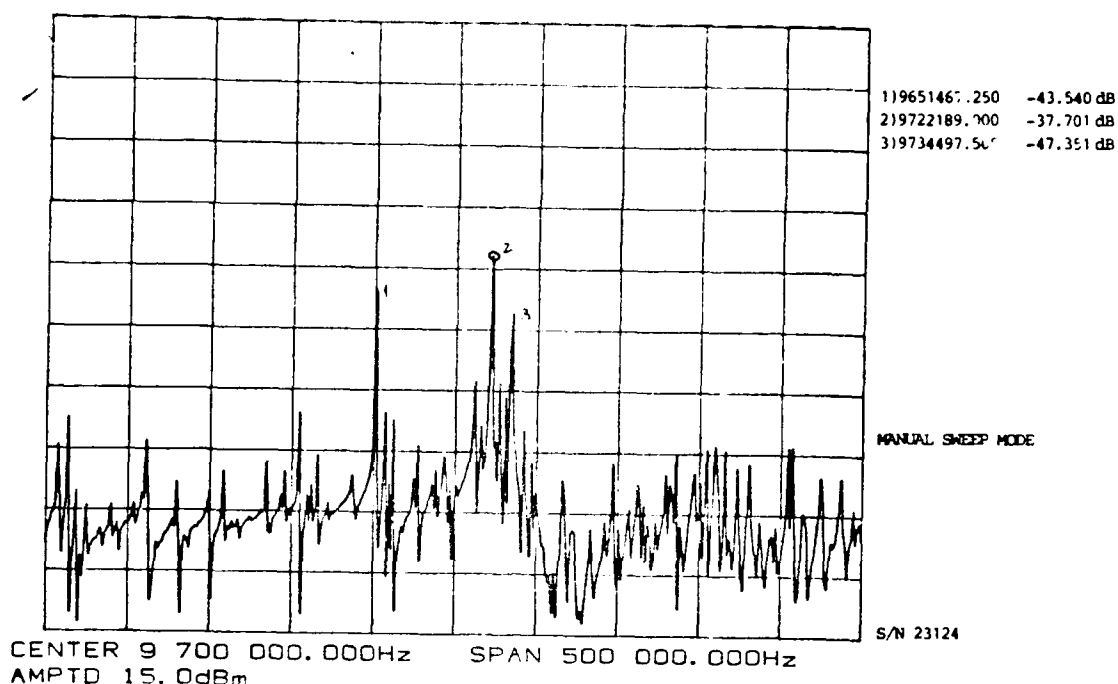
CENTER 9 000 000.000Hz SPAN 600 000.000Hz
AMPTD 0.0dBm

S/N 23124 3.0M/F/AK

FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE,
'C' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 9.0 MHz

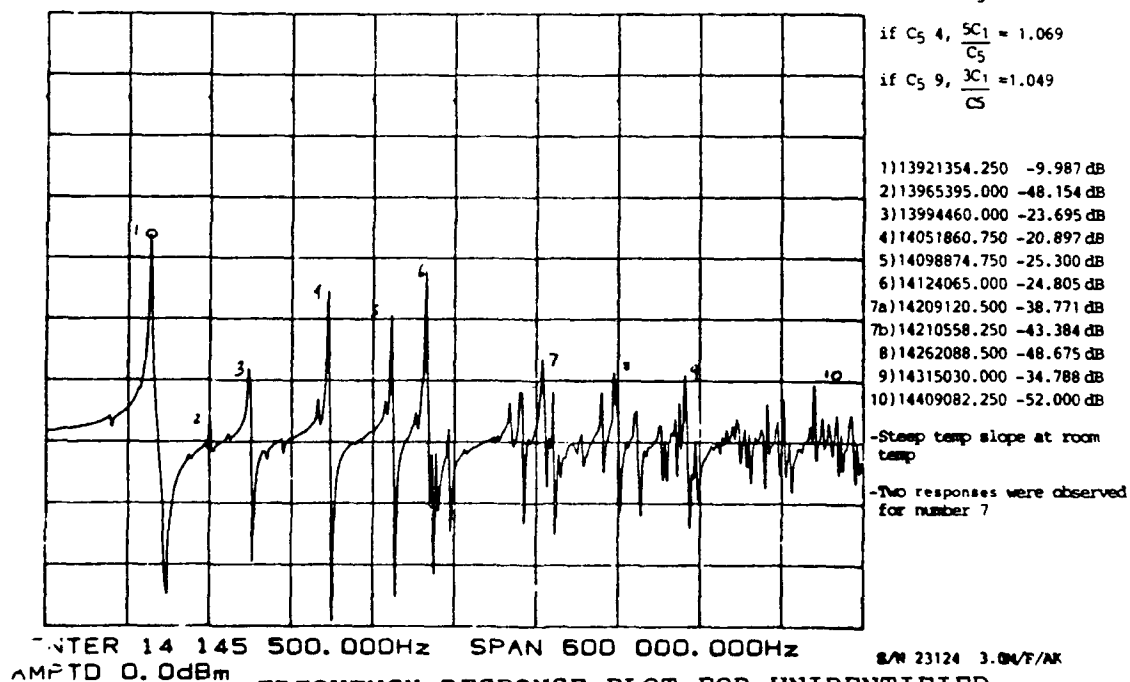
Figures 3a and 3b

REF LEVEL /DIV MANUAL 9 722 218.750Hz
 0.000dB 10.000dB MAG (S21) -37.848dB



FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE,
 'B' MODE ON AN AK-CUT CRYSTAL
 S/N 23124 CENTER FREQUENCY = 9.7 MHz

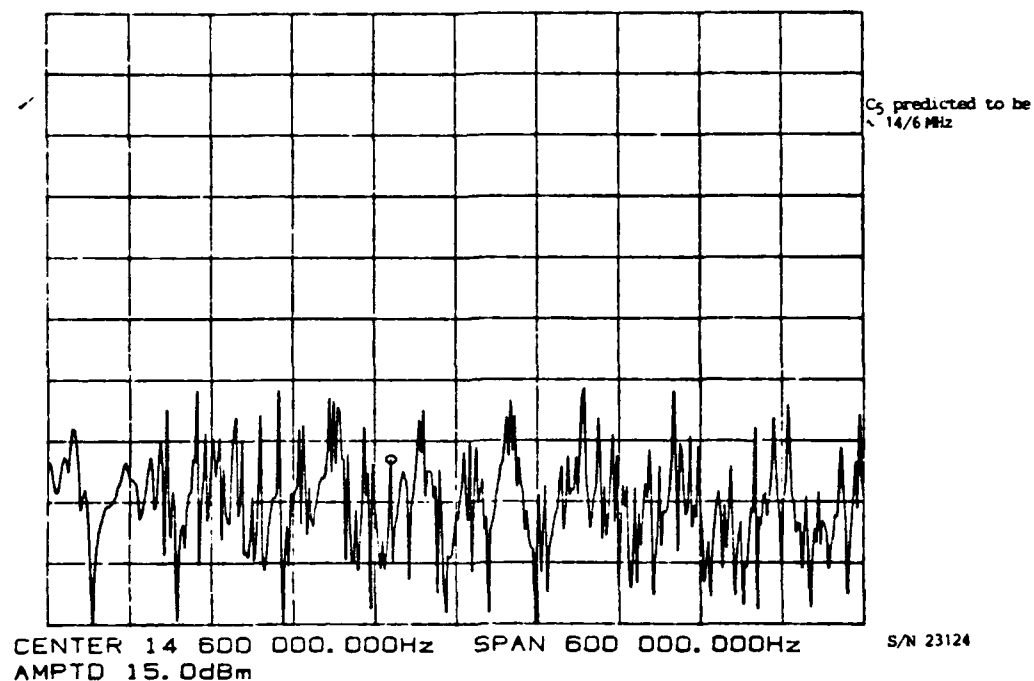
REF LEVEL /DIV MARKER 13 922 000.000Hz if C_5 1, $\frac{SC_1}{C_5} = 1.079$
 0.000dB 10.000dB MAG (S21) -36.023dB if C_5 3, $\frac{SC_1}{C_5} = 1.072$
 if C_5 4, $\frac{SC_1}{C_5} = 1.069$
 if C_5 9, $\frac{3C_1}{C_5} = 1.049$



FREQUENCY RESPONSE PLOT FOR UNIDENTIFIED
 MODE ON AN AK-CUT CRYSTAL
 S/N 23124 CENTER FREQUENCY = 14.1455 MHz

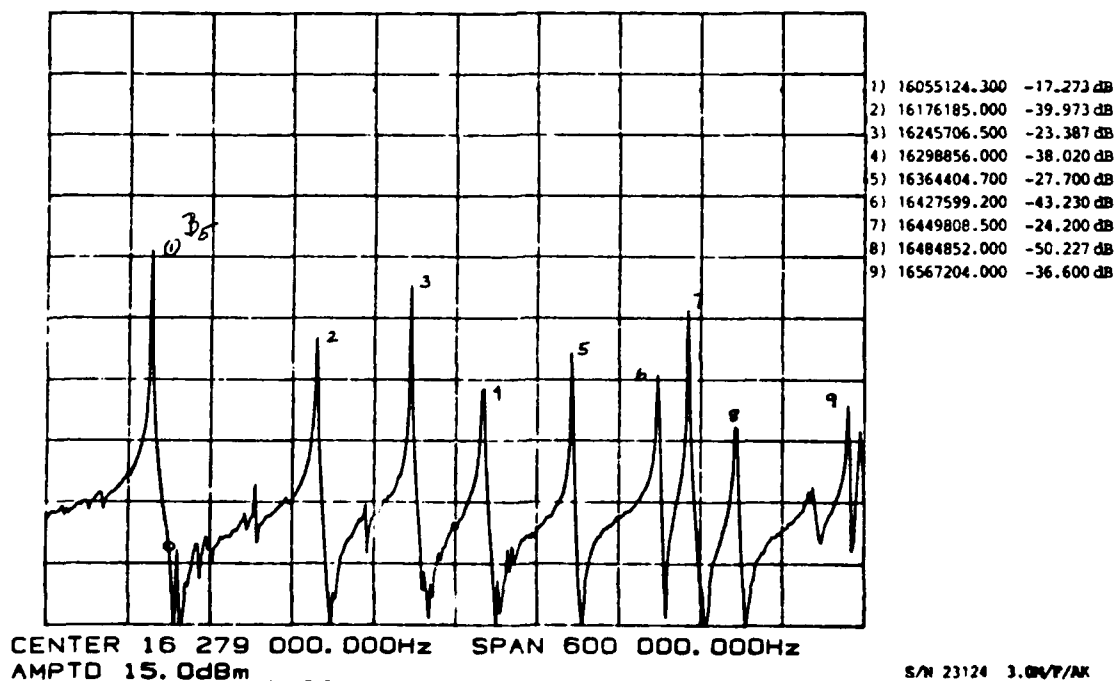
Figures 3c and 3d

REF LEVEL /DIV MARKER 14 552 000.000Hz
0.000dB 10.000dB MAG(S21) -72.991dB



FREQUENCY RESPONSE PLOT FOR 5TH OVERTONE
'C' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 14.60 MHz

REF LEVEL /DIV MARKER 16 069 000.000Hz
0.000dB 10.000dB MAG(S21) -87.294dB

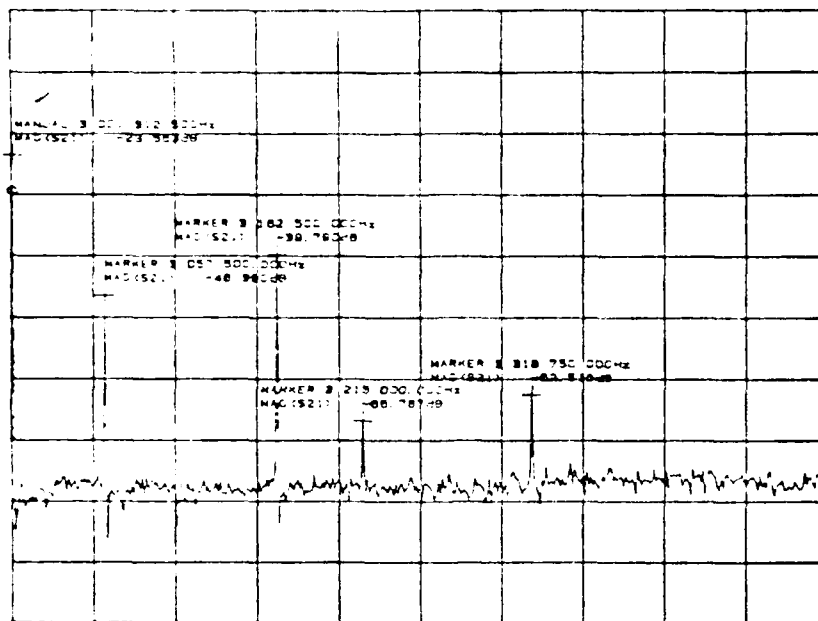


FREQUENCY RESPONSE PLOT FOR 5TH OVERTONE
'B' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 16.279 MHz

Figures 3e and 3f

REF LEVEL /DIV MANUAL 3 001 312.500Hz
0.000dB 10.000dB MAG(S21) -29.458dB

8-20-86
AK LFR #6



- 1) F=305797.3 Hz
@-40.9 dB
- 2) F=316235.3 Hz
@-36.4 dB
- 3) F=321520.4
@-65 dB
- 4) F=327418.7 Hz
@-69 dB
- 5) F=331858.2 Hz
@-61 dB
- 6) F=336837.5 Hz
@-66.7 dB

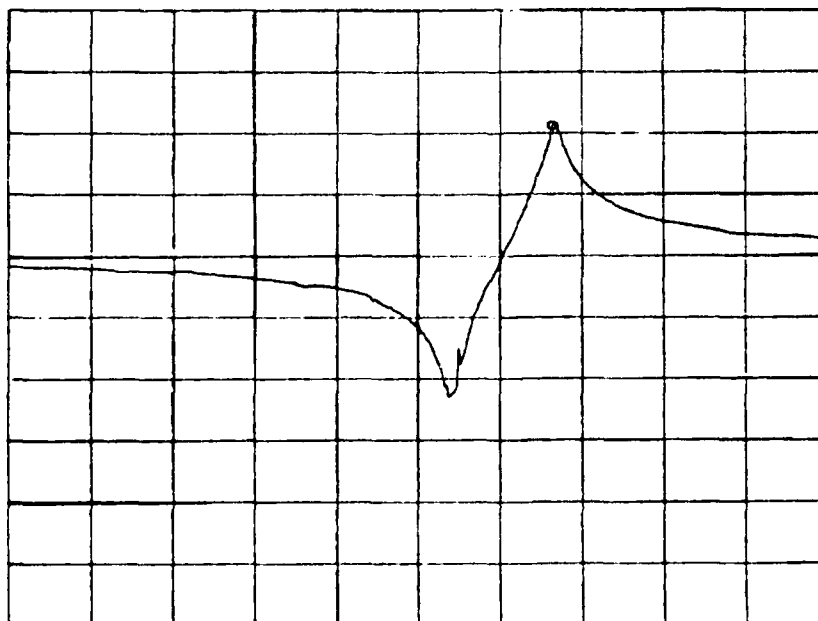
AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
 $\omega = 105^\circ$

CENTER 3 250 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL
'C' MODE AND 'B' MODES ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 3.25 MHz

REF LEVEL /DIV MANUAL 3 001 316.618Hz
0.000dB 10.000dB MAG(S21) -18.787dB

AK LFR #6
9-18



AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
 $\omega = 105^\circ$

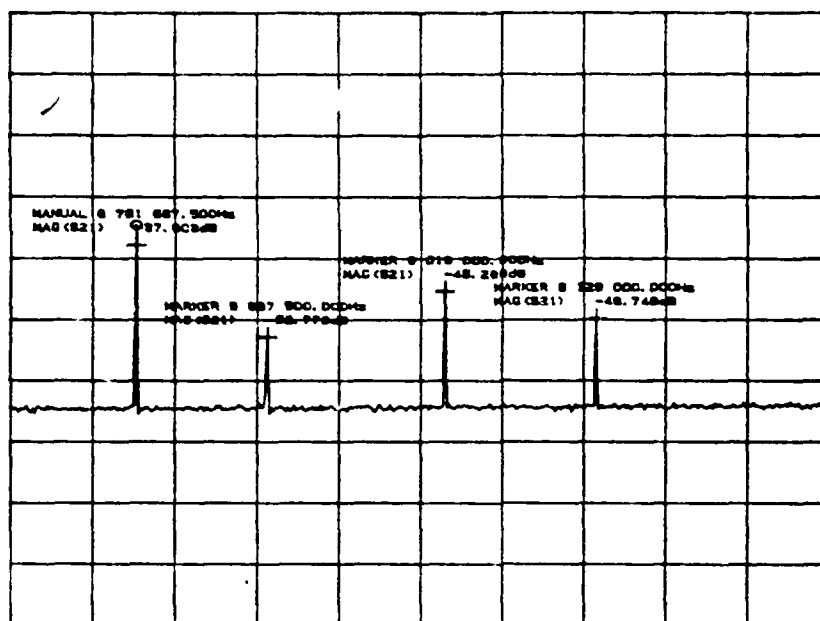
CENTER 3 001 300.000Hz SPAN 100.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL
'C' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 3.0013 MHz

Figures 4a and 4b

REF LEVEL /DIV MANUAL 8 791 687.500Hz
0.000dB 10.000dB MAG(S21) -34.515dB

9-18
AK LFR #6



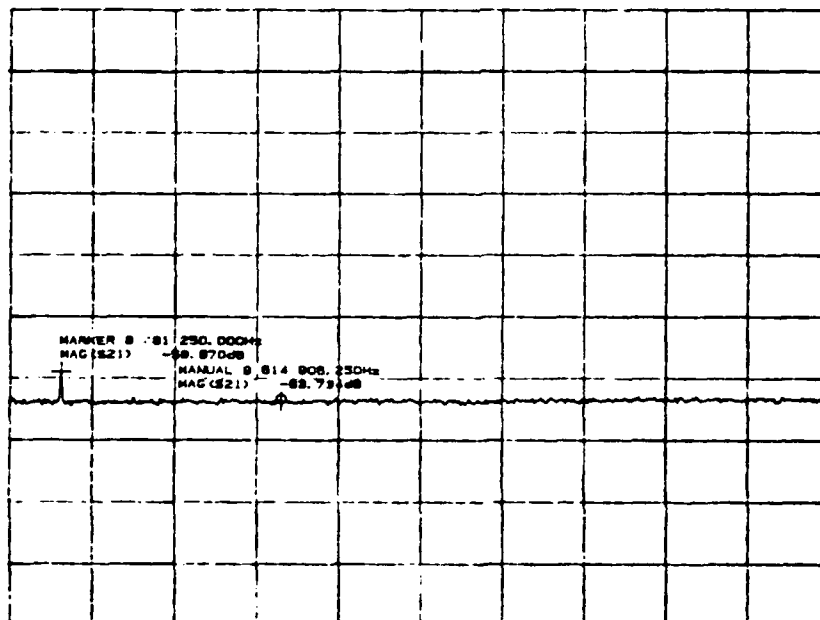
AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
 $\omega = 105^\circ$

CENTER 9 000 000.000Hz SPAN 600 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE
'C' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 9.0 MHz

REF LEVEL /DIV MANUAL 9 614 906.250Hz
0.000dB 10.000dB MAG(S21) -63.373dB

9-18
AK LFR #6



AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
 $\omega = 105^\circ$

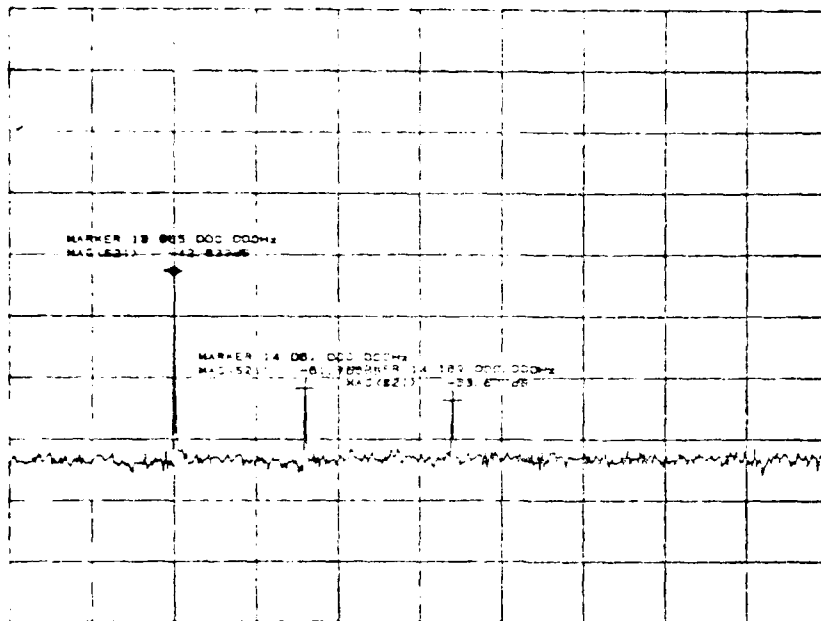
CENTER 9 700 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE
'B' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 9.7 MHz

Figures 4c and 4d

REF LEVEL /DIV MARKER 13 965 000.000Hz
 0.000dB 10.000dB MAG(S21) -42.633dB

9-18
 AF LFR #6



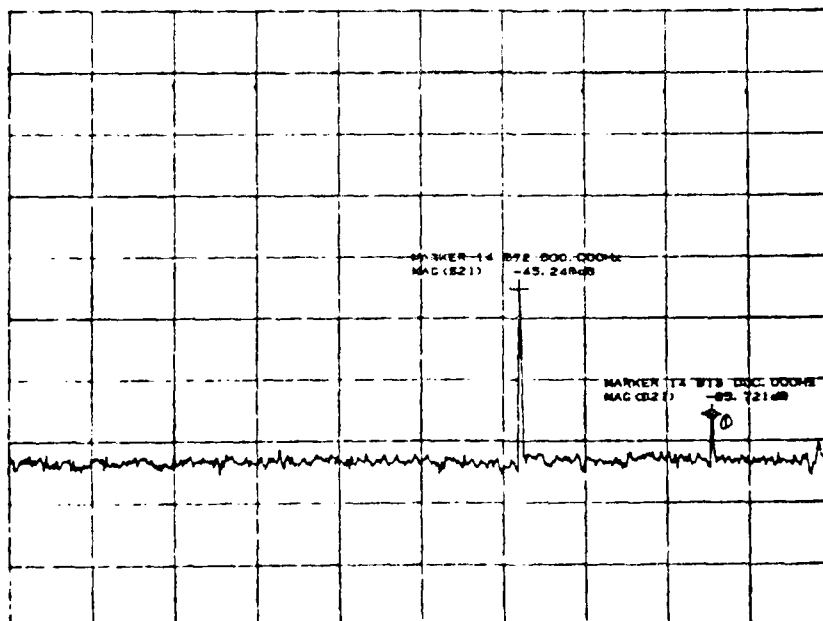
AK-LFR #6
 3.001 MHz/F
 4.125D
 0.075 GAP
 $\omega = 105^\circ$

CENTER 14 145 000.000Hz SPAN 600 000.000Hz
 AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT UNIDENTIFIED MODE
 ON AN AK-CUT CRYSTAL
 S/N AKLFR-6 CENTER FREQUENCY = 14.145 MHz

REF LEVEL /DIV MARKER 14 813 000.000Hz
 0.000dB 10.000dB MAG(S21) -65.721dB

9-18
 AK LFR #6



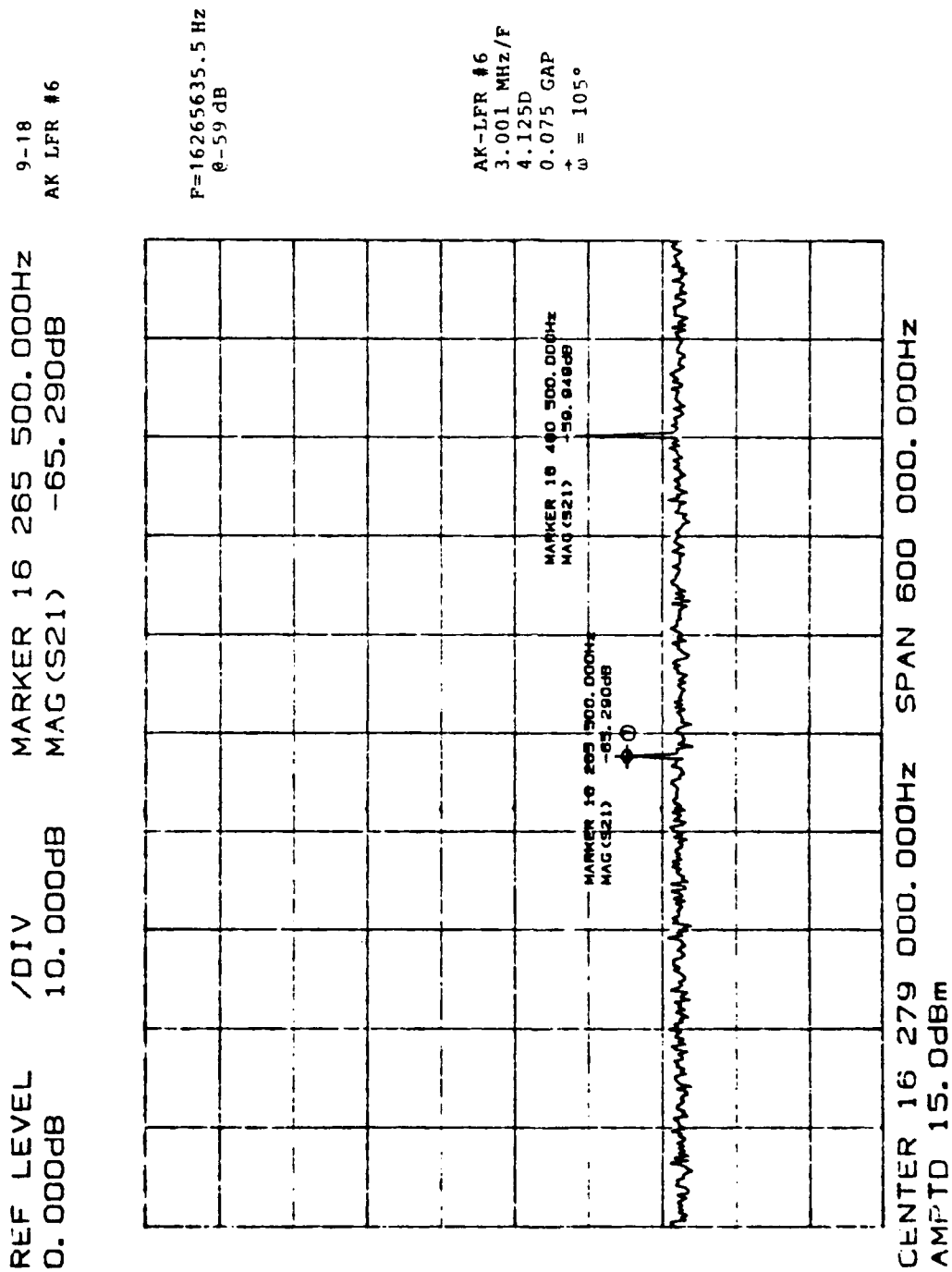
1) F=14813070 Hz
 @-62 dB

AK-LFR #6
 3.001 MHz/F
 4.125D
 0.075 GAP
 $\omega = 105^\circ$

CENTER 14 600 000.000Hz SPAN 600 000.000Hz
 AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR FIFTH OVERTONE
 'B' MODE ON AN AK-CUT CRYSTAL
 S/N AKLFR-6 CENTER FREQUENCY = 14.60 MHz

Figures 4c and 4f



FREQUENCY RESPONSE PLOT FOR FIFTH OVERTONE
 'B' MODE ON AN AK-CUT CRYSTAL
 S/N AKLFR-6 CENTER FREQUENCY = 16.279 MHz

Figure 4g

APPENDIX

The accompanying appendix contains additional data on selected AK-cut crystals.

| FIGURE(S) | DESCRIPTION |
|--------------|---|
| A-1 | Quality Factor (Q) versus Fundamental Frequency for Various Curvatures and Platebacks |
| A-2 to A-5 | Fundamental "C" Mode Temperature Slews |
| A-6 to A-10 | Frequency Sweep Tables of Selected AK-Cut Crystals Listing Fundamental Third and Fifth Overtone Responses |
| A-11 to A-20 | Frequency Response Plots for AK Resonators |
| A-21 to A-25 | Frequency Response Plots for AK-LFR S/N 12 |

QUALITY FACTOR(Q) VS. FUNDAMENTAL
FREQUENCY FOR VARIOUS CURVATURES AND
PLATE BACKS

($\phi = 36.58^\circ$; $\theta = 26.00^\circ$)

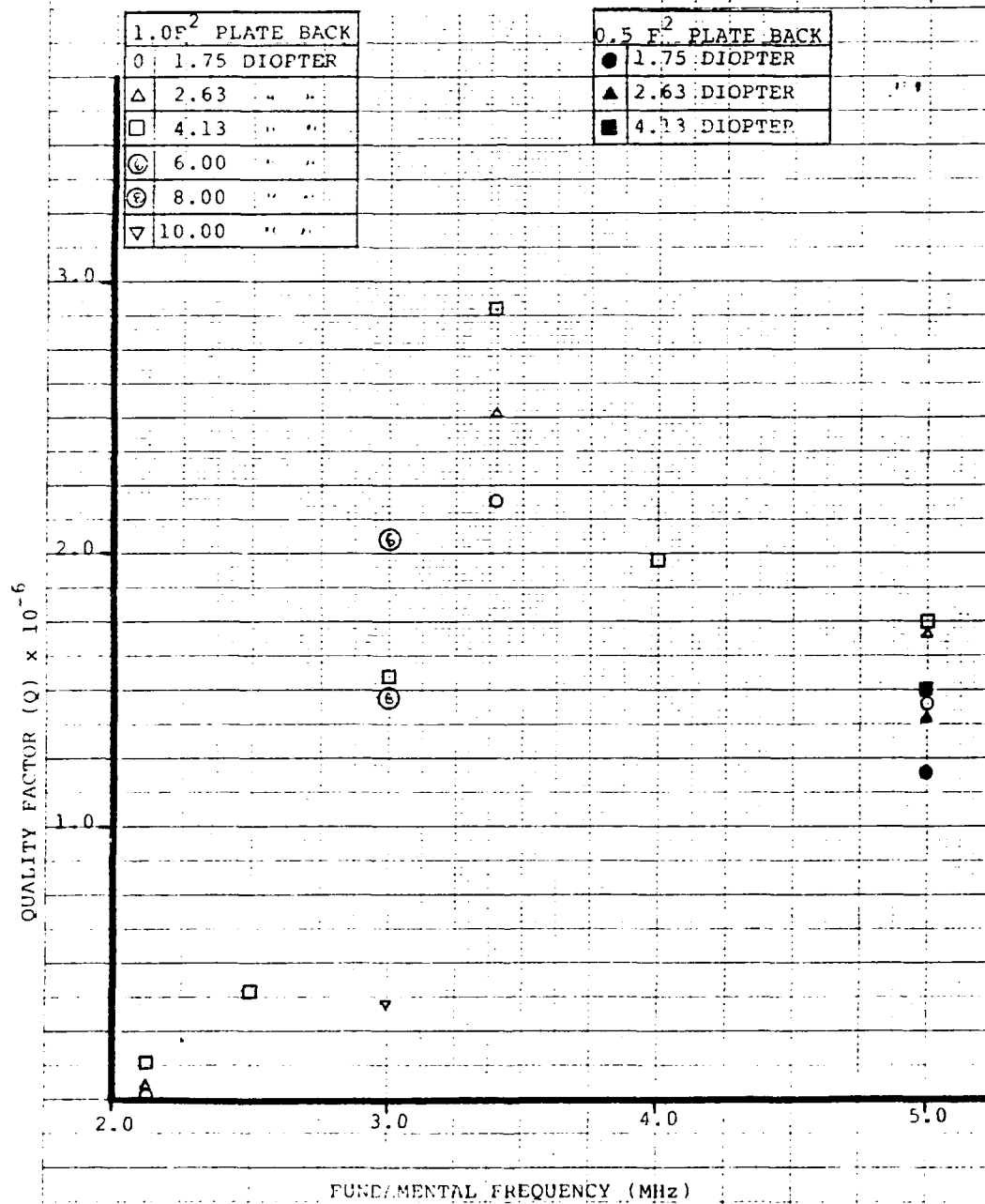


FIGURE A-1

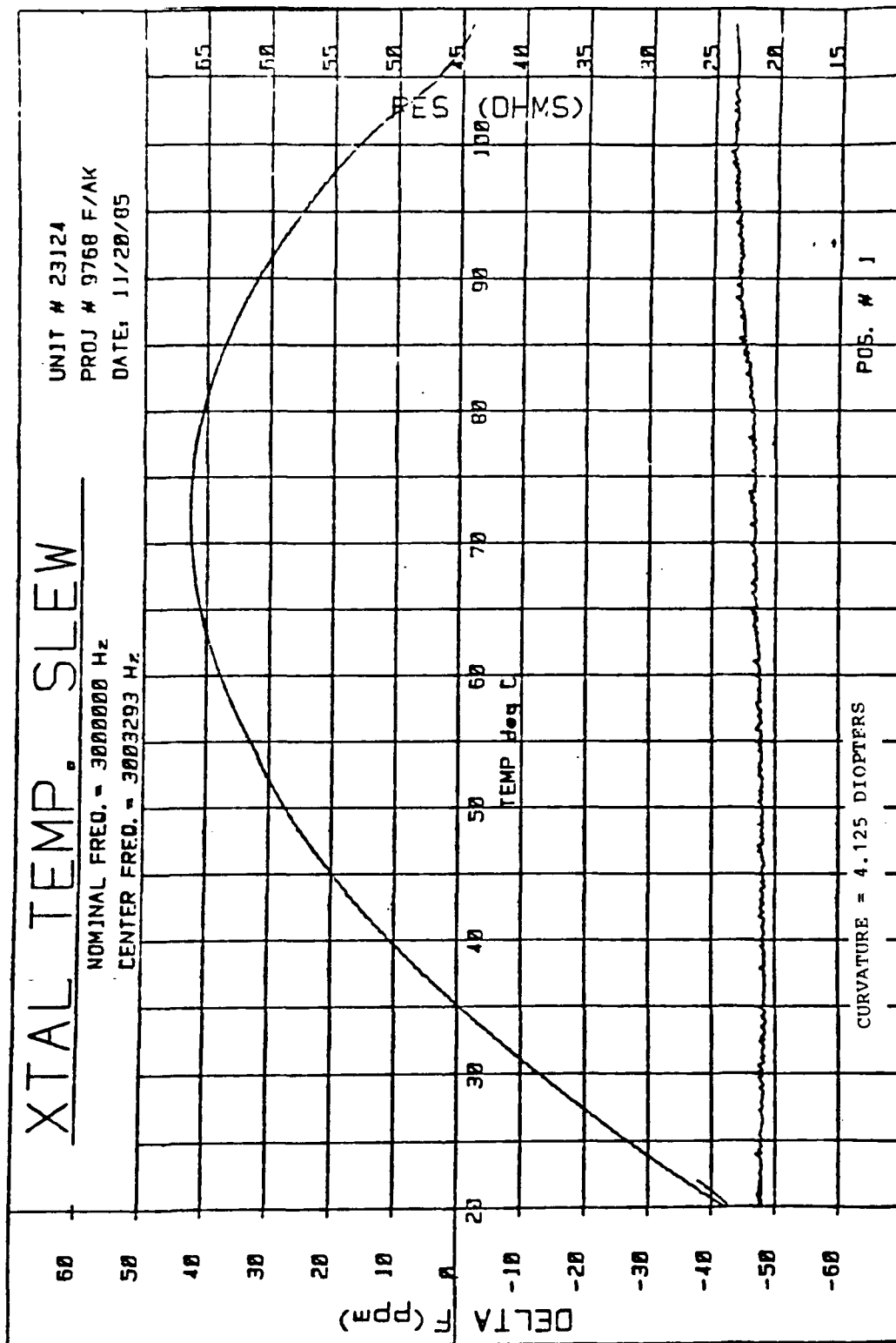


FIGURE A-2

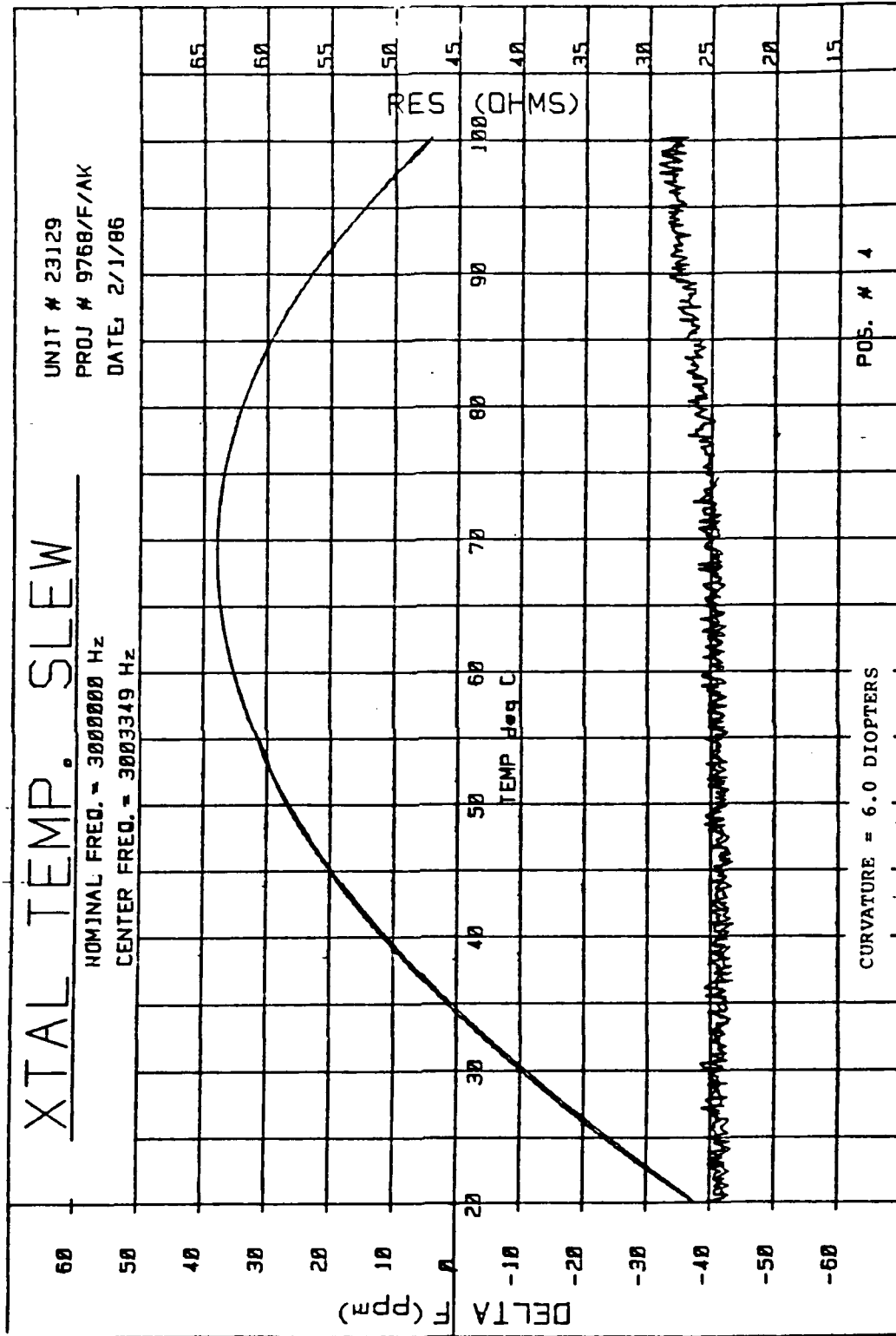


FIGURE A-3

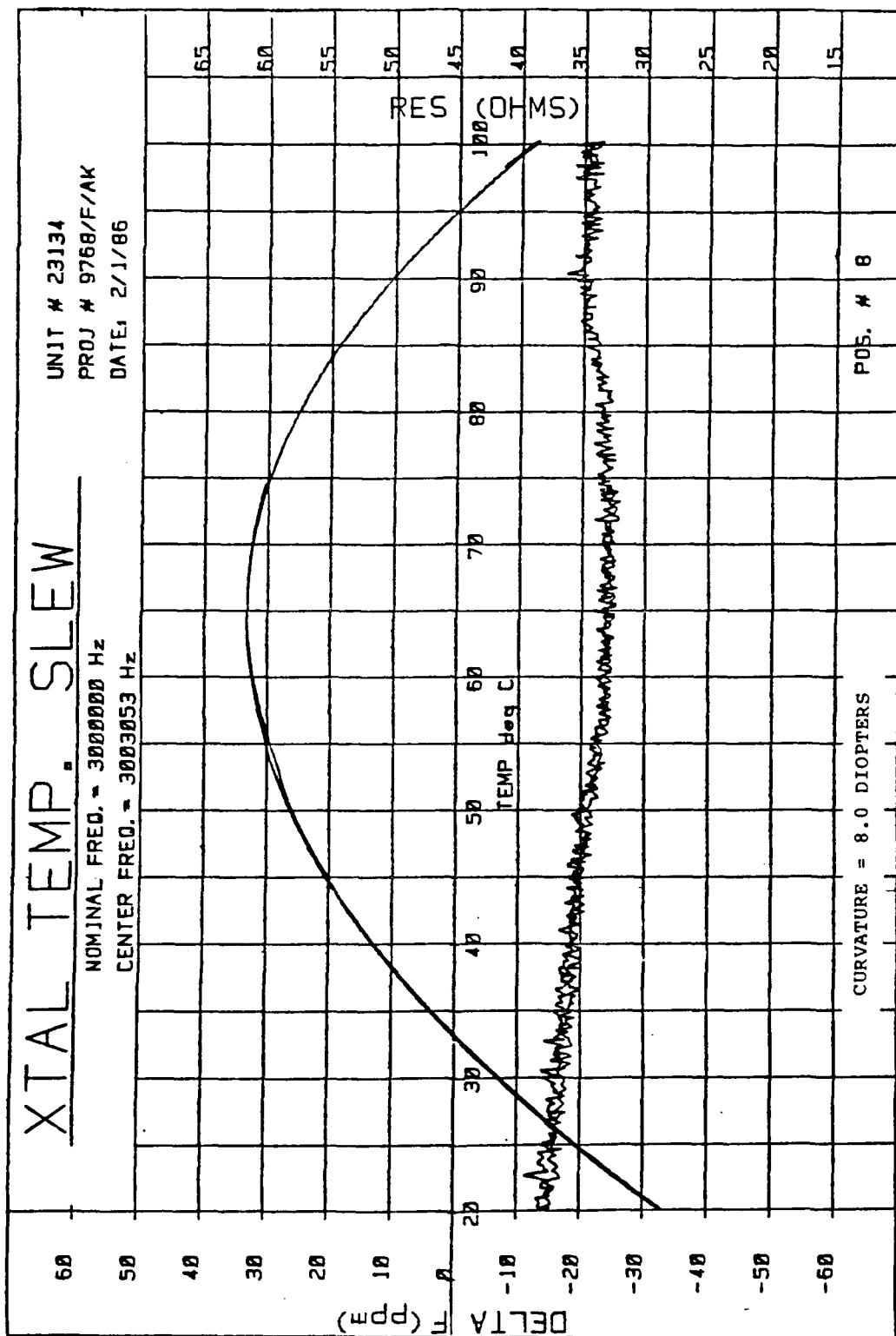


FIGURE A-4

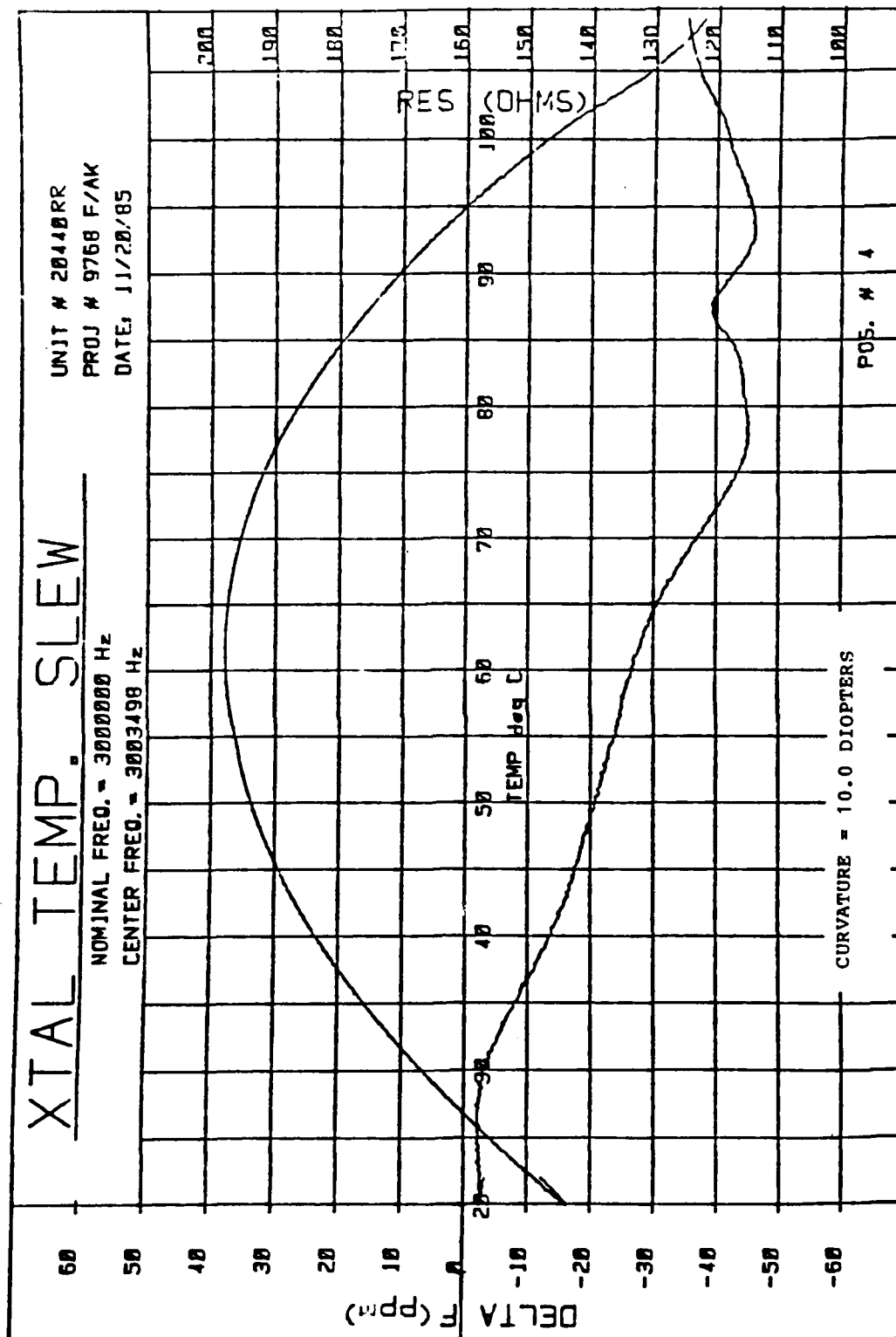


FIGURE A-5

FREQUENCY SWEEP

3.00/F/AK S/N 23129 $1F^2$ PB $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$

Curvature = 6.0 Diopter

| FREQUENCY(HZ) | LEVEL(dB) | NOTE | RATIO |
|---------------|-----------|-------------------------|--------------------|
| 3003248 | -3.97 | 'C' Mode Fundamental | |
| 3141000 | -27.1 | | |
| 3248615 | -7.02 | 'B' Mode Fundamental | $C_F/B_F = .924$ |
| 3283000 | -25.1 | | |
| 8756535 | -21.2 | 'C' Mode Third O.T. | $C_3/B_3 = .916$ |
| 8867119 | -18.68 | | $3F_F/F_3 = 1.020$ |
| 8905850 | -31.56 | | |
| 9026700 | -19.6 | | |
| 96737700 | -41.6 | | |
| 9676205 | -37.0 | 'B' Mode, Third O.T. | |
| 9689150 | -48.5 | | |
| 9805700 | -53.0 | | |
| 9864300 | -50.0 | | $5F_F/F_5 = 1.026$ |
| 13836500 | -13.5 | 'A' Mode | |
| 14629740 | -37.5 | 'C' Mode Fifth O.T. | $C_5/B_5 = .916$ |
| 15962311 | -19.8 | 'B' Mode Fifth O.T. | $5F_F/F_5 = 1.026$ |
| 16109375 | -46.7 | | |
| 16196000 | -24.2 | | |

TABLE A-6

FREQUENCY SWEEP

3.00/F/AK S/N 23133 1F² P.B. $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$
Curvature = 8.0 Diopter

| FREQUENCY (HZ) | LEVEL (dB) | NOTES | RATIOS |
|----------------|------------|-------------------------|---|
| 3003259 | -5.44 | 'C' Mode Fundamental | |
| 3160617 | -41.2 | | |
| 3270971 | -7.42 | 'B' Mode Fundamental | $C_F/B_F = .9182$ |
| 3295250 | -31.9 | | |
| 3298000 | -42.7 | | |
| 8724576 | -20.99 | C Mode, Third O.T. | $C_3/B_3 = .9022$ $3F_F/F_3 = 1.032$ |
| 8858560 | -19.86 | | |
| 9047285 | -24.5 | | |
| 9168500 | -33.1 | | |
| 9639800 | -44.3 | | |
| 9659600 | -47.3 | | |
| 9668255 | -46.0 | | |
| 9669412 | -40.1 | 'B' Mode, Third O.T. | |
| 9678700 | -52.0 | | |
| 14411000 | -50.8 | | |
| 14519000 | -52.1 | | |
| 14575735 | -48.7 | 'C' Mode, Fifth O.T. | $C_5/B_5 = .9166$ |
| 14687000 | -55.0 | | $5F_F/F_5 = 1.030$ |
| 15672000 | -57.2 | | |
| 15901161 | -24.8 | 'B' Mode, Fifth O.T. | |
| 1670900 | -40.6 | | |

TABLE A-7

FREQUENCY SWEEP

3.00/FWAK S/N 20440RR 1.0F² P.B. $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$
Curvature = 10.0 Diopter

| FREQUENCY(HZ) | LEVEL(dB) | NOTES | RATIO |
|---------------|-----------|-------------------------|---|
| 3003447 | -16.31 | 'C' Mode Fundamental | |
| 3180000 | -48.0 | | |
| 3239972 | -39.0 | | $C_F/B_F = .9112$ |
| 3295897 | -17.6 | 'B' Mode Fundamental | |
| 3325938 | -37.1 | | |
| 3469040 | -46.0 | | |
| 8700212 | -35.6 | 'C' Mode, Third O.T. | $C_3/B_3 = .9015$ $3F_F/F_3 = 1.036$ |
| 8862700 | -37.4 | | |
| 8896145 | -38.1 | | |
| 9082412 | -47.2 | | |
| 9317200 | -50.2 | | |
| 9650475 | -50.3 | 'B' Mode, Third O.T. | |
| 13778782 | -37.1 | | |
| 14480000 | -54.0 | 'C' Mode, Fifth O.T. | $C_5/B_5 = .9086$ |
| 15935000 | -51.8 | 'B' Mode, Fifth O.T. | $5F_F/F_5 = 1.037$ |
| 16240000 | -53.0 | | |

TABLE A-8

FREQUENCY SWEEP

4.00MHZ/F/AK S N 23125 1F P.B. $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$
Curvature = 4.13 Diopter

| FREQUENCY(HZ) | LEVEL(dB) | NOTES | RATIOS |
|---------------|-----------|-------------------------|---------------------|
| 4003466 | -2.78 | 'C' Mode Fundamental | $C_F/B_F = .9148$ |
| 4135720 | -5.81 | | |
| 4249518 | -8.67 | | |
| 4270759 | -17.03 | | |
| 4361805 | -9.26 | | |
| 4367663 | -6.26 | | |
| 4376120 | -4.67 | 'B' Mode Fundamental | |
| 11753493 | -20.23 | 'C' Mode, Third O.T. | $C_3/B_3 = .907$ |
| 11987898 | -18.69 | | $3F_F/F_3 = 1.0219$ |
| 12148668 | -20.50 | | |
| 12150602 | -27.27 | | |
| 12378034 | -25.75 | | |
| 12786029 | -41.05 | | |
| 12947587 | -35.32 | 'B' Mode, Third O.T. | |
| 12959950 | -40.24 | | |
| 19639789 | -23.20 | 'C' Mode, Fifth O.T. | $C_5/B_5 = .9158$ |
| 21444624 | -15.77 | 'B' Mode, Fifth O.T. | $5F_F/F_5 = 1.0192$ |
| 21586575 | -33.23 | | |
| 21664660 | -21.73 | | |
| 21730012 | -26.08 | | |

TABLE A-9

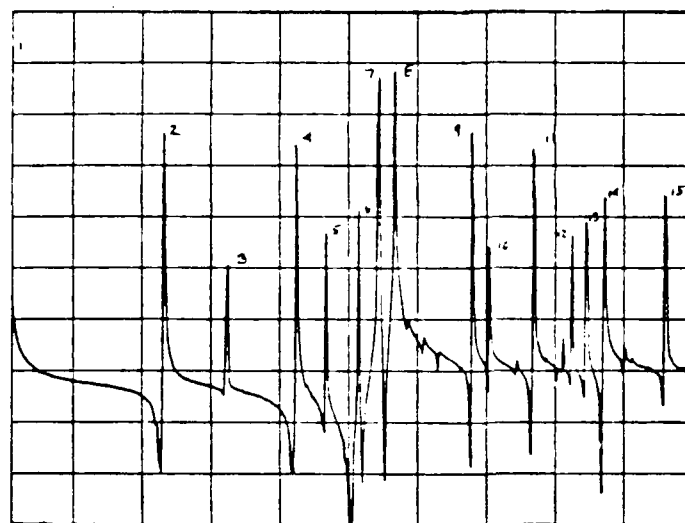
FREQUENCY SWEEP

4.00MHZ/F/AK S/N 23126 0.51 P.B. $\theta = 36.58^\circ$ $\theta = 26.10$

Curvature = 4.13 Diopter

| FREQUENCY(HZ) | LEVEL(dB) | NOTES | RATIOS |
|---------------|-----------|-------------------------|--|
| 4009233 | -3.32 | C Mode Fundamental | $C_F/B_F = .9142$ |
| 4141413 | -6.27 | | |
| 4373516 | -8.57 | | |
| 4385329 | -3.23 | 'B' Mode Fundamental | |
| 11771949 | -20.17 | 'C' Mode, Third O.T. | $C_3/B_3 = .9053$ $3F_F/F_3 = 1.0217$ |
| 11863279 | -19.50 | | |
| 11914457 | -25.50 | | |
| 12006172 | -18.91 | | |
| 12131465 | -27.6 | | |
| 12166705 | -21.8 | | |
| 12168700 | -27.54 | | |
| 12966461 | -32.9 | | |
| 12978300 | -35.4 | | |
| 12987005 | -33.9 | | |
| 12995569 | -30.85 | | |
| 13003026 | -23.96 | 'B' Mode, Third O.T. | |
| 13032632 | -33.4 | | |
| 19669108 | -23.33 | 'C' Mode, Fifth O.T. | $C_5/B_5 = .9149$ |
| 21499297 | -15.75 | 'B' Mode, Fifth O.T. | $5F_F/F_5 = 1.0192$ |
| 21640945 | -25.62 | | |
| 21718613 | -20.17 | | |
| 21783812 | -28.73 | | |

TABLE A-10



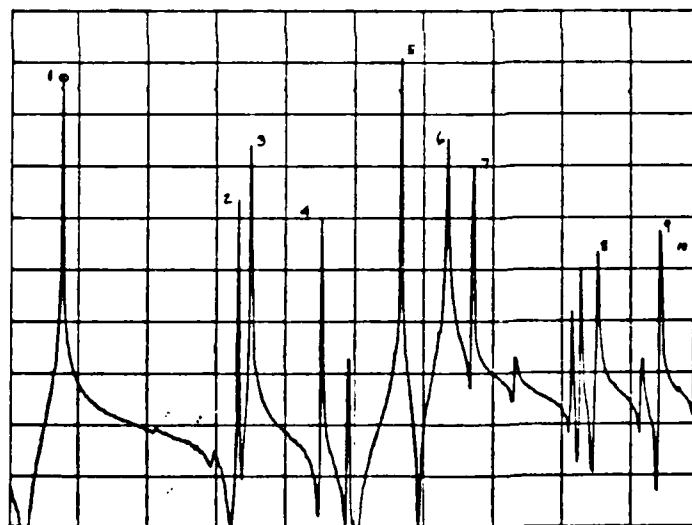
3.000MHz - START FREQUENCY
3.500MHz - STOP FREQUENCY

| NO | FREQ (Hz) | dB LEVEL |
|----|-------------|----------|
| 1 | 3002916.500 | -3.251 |
| 2 | 3116574.500 | -16.241 |
| 3 | 3161690.725 | -26.076 |
| 4 | 3212600.500 | -16.315 |
| 5 | 3233715.750 | -42.524 |
| 6 | 3257733.000 | -21.508 |
| 7 | 3271902.500 | -8.643 |
| 8 | 3284060.500 | -7.951 |
| 9 | 3340323.000 | -17.136 |
| 10 | 3352505.500 | -45.620 |
| 11 | 3384612.750 | -26.756 |
| 12 | 3412693.000 | -43.304 |
| 13 | 3423094.000 | -41.074 |
| 14 | 3430265.000 | -36.213 |
| 15 | 3460577.250 | -33.725 |

NOTES

1. NUMBERS 1 THRU 15 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF LEVEL -0.000dB
3. 3.0MHz/F/AK AT 4.125 DIOPTER.
4. CRYSTAL S/N 23125

Figure A-11. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 4.13 Diopter



3.965MHz - START FREQUENCY
3.465MHz - STOP FREQUENCY

| NO | FREQ (Hz) | dB LEVEL |
|----|-------------|----------|
| 1 | 3003262.875 | -3.876 |
| 2 | 3131475.500 | -30.656 |
| 3 | 3140406.000 | -26.137 |
| 4 | 3191723.000 | -40.141 |
| 5 | 3246632.250 | -6.956 |
| 6 | 3262435.750 | -24.851 |
| 7 | 3300644.250 | -22.466 |
| 8 | 3391136.000 | -46.735 |
| 9 | 3436751.750 | -42.760 |
| 10 | 3461624.000 | -45.261 |

NOTES

1. NUMBERS 1 THRU 10 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF LEVEL -0.000dB
3. 3.0MHz/F/AK AT 6.0 DIOPTER
4. CRYSTAL S/N 23129

Figure A-12. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 6.0 Diopter

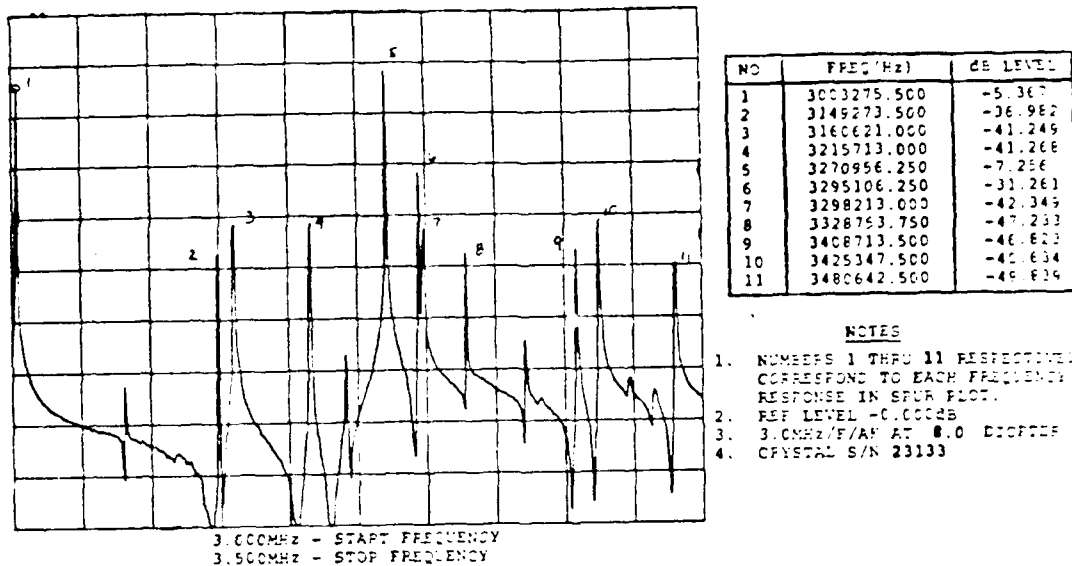


Figure A-13. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 8.0 Diopter

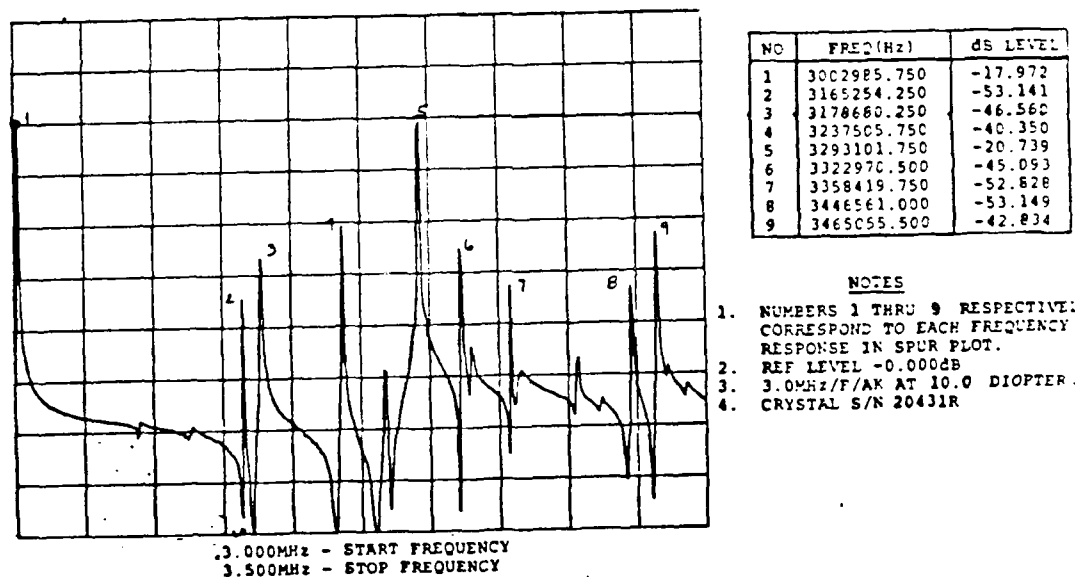
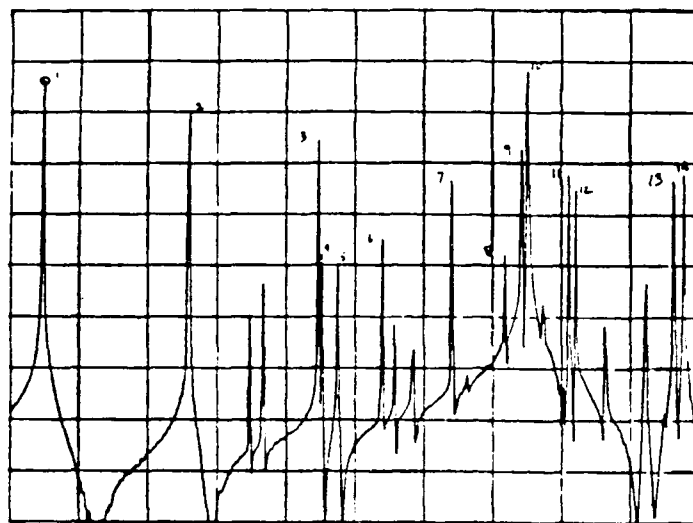


Figure A-14. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 10.0 Diopter



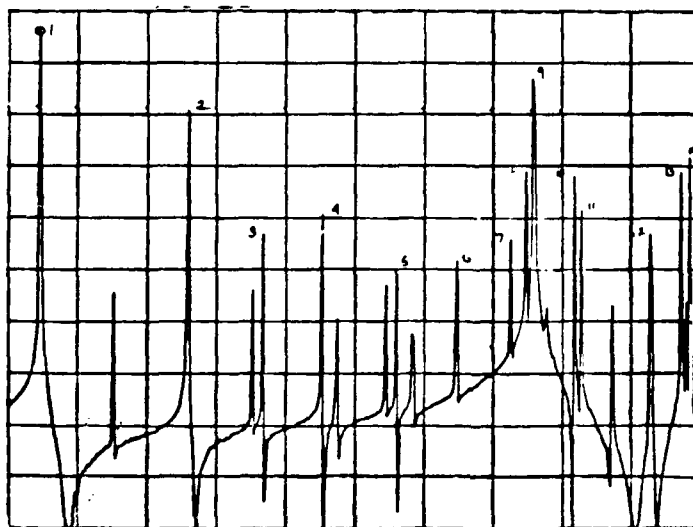
3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

| NO | FREQ (Hz) | dB LEVEL |
|----|-------------|----------|
| 1 | 3428006.250 | -3.478 |
| 2 | 3555326.000 | -9.161 |
| 3 | 3668531.750 | -15.797 |
| 4 | 3671496.000 | -29.187 |
| 5 | 3689589.750 | -49.689 |
| 6 | 3723444.750 | -36.594 |
| 7 | 3784520.000 | -25.456 |
| 8 | 3830947.650 | -32.399 |
| 9 | 3845024.000 | -27.149 |
| 10 | 3850393.500 | -11.206 |
| 11 | 3885665.250 | -31.885 |
| 12 | 3891791.500 | -29.182 |
| 13 | 3978086.000 | -31.791 |
| 14 | 3985829.500 | -31.950 |

NOTES:

1. NUMBERS 1 THRU 14 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 4.125 DIOPTER.
4. CRYSTAL S/N 20457R
5. .265" DIAMETER ELECTRODE

Figure A-15. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 4.125 Diopter Plated With A .265" Diameter Electrode



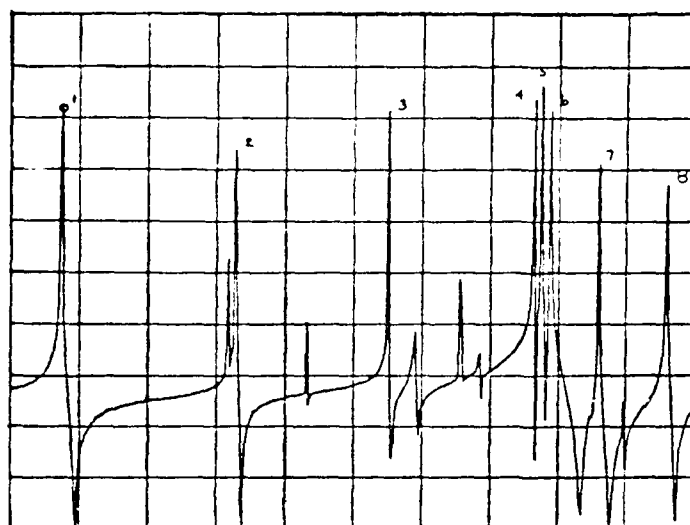
3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

| NO | FREQ (Hz) | dB LEVEL |
|----|-------------|----------|
| 1 | 3427715.000 | -3.973 |
| 2 | 3555594.250 | -15.995 |
| 3 | 3620195.250 | -42.431 |
| 4 | 3671601.000 | -21.110 |
| 5 | 3736369.250 | -49.950 |
| 6 | 3787882.750 | -33.723 |
| 7 | 3835389.250 | -31.178 |
| 8 | 3848436.500 | -30.254 |
| 9 | 3855200.750 | -12.432 |
| 10 | 3890792.500 | -27.713 |
| 11 | 3896094.750 | -36.623 |
| 12 | 3957204.250 | -42.448 |
| 13 | 3983860.000 | -22.753 |
| 14 | 3999461.500 | -23.852 |

NOTES:

1. NUMBERS 1 THRU 14 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 4.125 DIOPTER.
4. CRYSTAL S/N 20459R
5. .221" DIAMETER ELECTRODE

Figure A-16. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 4.125 Diopter Plated With A .221" Diameter Electrode



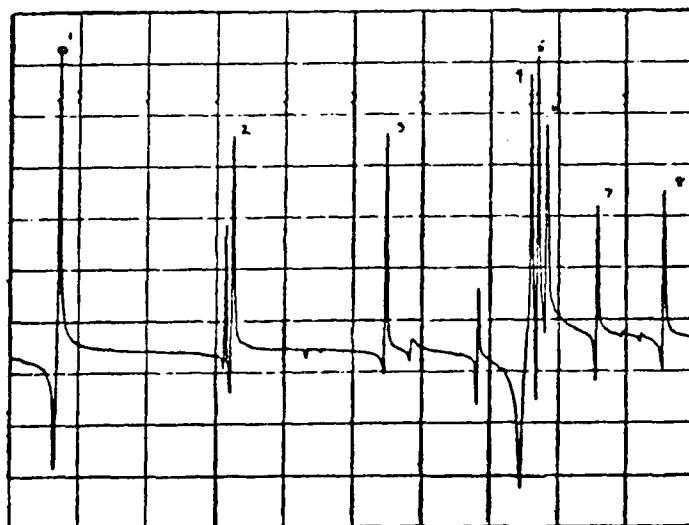
3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

| NO. | FREQ(MHz) | dB LEVEL |
|-----|-------------|----------|
| 1 | 3444275.250 | -3.269 |
| 2 | 3597090.250 | -25.072 |
| 3 | 3729845.500 | -14.014 |
| 4 | 3858367.250 | -15.965 |
| 5 | 3864836.250 | -9.400 |
| 6 | 3872884.250 | -18.401 |
| 7 | 3916194.750 | -28.560 |
| 8 | 3976117.525 | -31.903 |

NOTES:

1. NUMBERS 1 THRU 8 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 6.0 DIPTER.
4. CRYSTAL S/N 20448R
5. .265" DIAMETER ELECTRODE

Figure A-17. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 6.0 Diopter Plated With A .265" Diameter Electrode



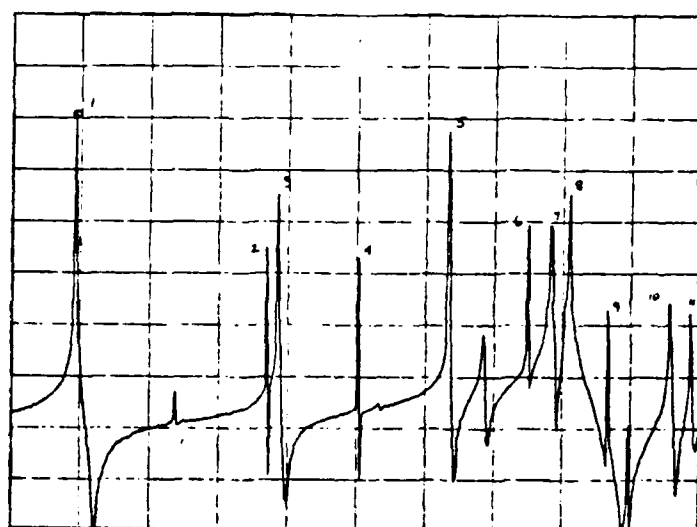
3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

| NO | FREQ(MHz) | dB LEVEL |
|----|-------------|----------|
| 1 | 3443770.250 | -3.889 |
| 2 | 3595500.500 | -21.457 |
| 3 | 3729142.000 | -18.071 |
| 4 | 3856386.250 | -9.740 |
| 5 | 3862234.500 | -5.872 |
| 6 | 3870104.500 | -20.352 |
| 7 | 3914062.500 | -37.875 |
| 8 | 3973399.000 | -34.807 |

NOTES:

1. NUMBERS 1 THRU 8 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 6.0 DIPTER.
4. CRYSTAL S/N 20450R
5. .221" DIAMETER ELECTRODE

Figure A-18. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 6.0 Diopter Plated With A .221" Diameter Electrode



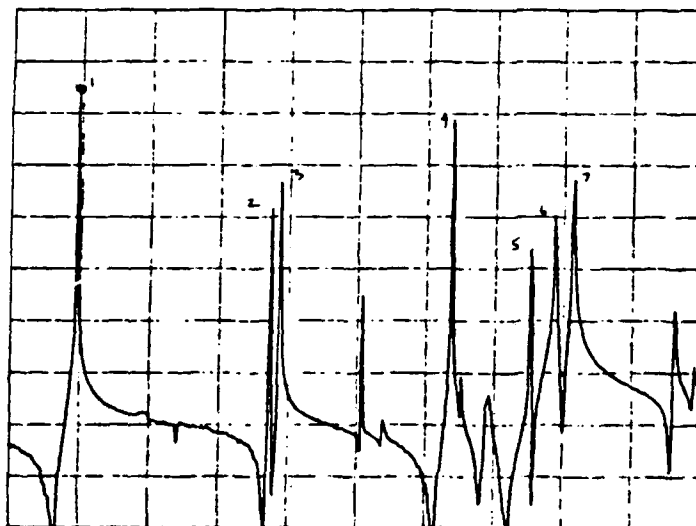
3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

| NO | FREQ(MHz) | dB LEVEL |
|----|-------------|----------|
| 1 | 3456012.000 | -4.088 |
| 2 | 3622682.750 | -37.202 |
| 3 | 3631330.250 | -34.678 |
| 4 | 3701028.250 | -46.744 |
| 5 | 3780198.500 | -16.684 |
| 6 | 3849718.000 | -38.586 |
| 7 | 3870074.750 | -40.278 |
| 8 | 3885644.000 | -34.586 |
| 9 | 3920177.250 | -56.172 |
| 10 | 3974590.000 | -55.857 |
| 11 | 3992766.750 | -57.685 |

NOTES:

1. NUMBERS 1 THRU 11 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 8.0 DIOPTER.
4. CRYSTAL S/N 20452R
5. .265" DIAMETER ELECTRODE

Figure A-19. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 8.0 Diopter Plated With A .265" Diameter Electrode



3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

| NO | FREQ(MHz) | dB LEVEL |
|----|-------------|----------|
| 1 | 3457390.000 | -5.319 |
| 2 | 3624423.750 | -24.533 |
| 3 | 3632988.250 | -33.395 |
| 4 | 3782579.000 | -19.757 |
| 5 | 3852129.500 | -46.140 |
| 6 | 3872562.250 | -39.605 |
| 7 | 3888541.500 | -32.717 |

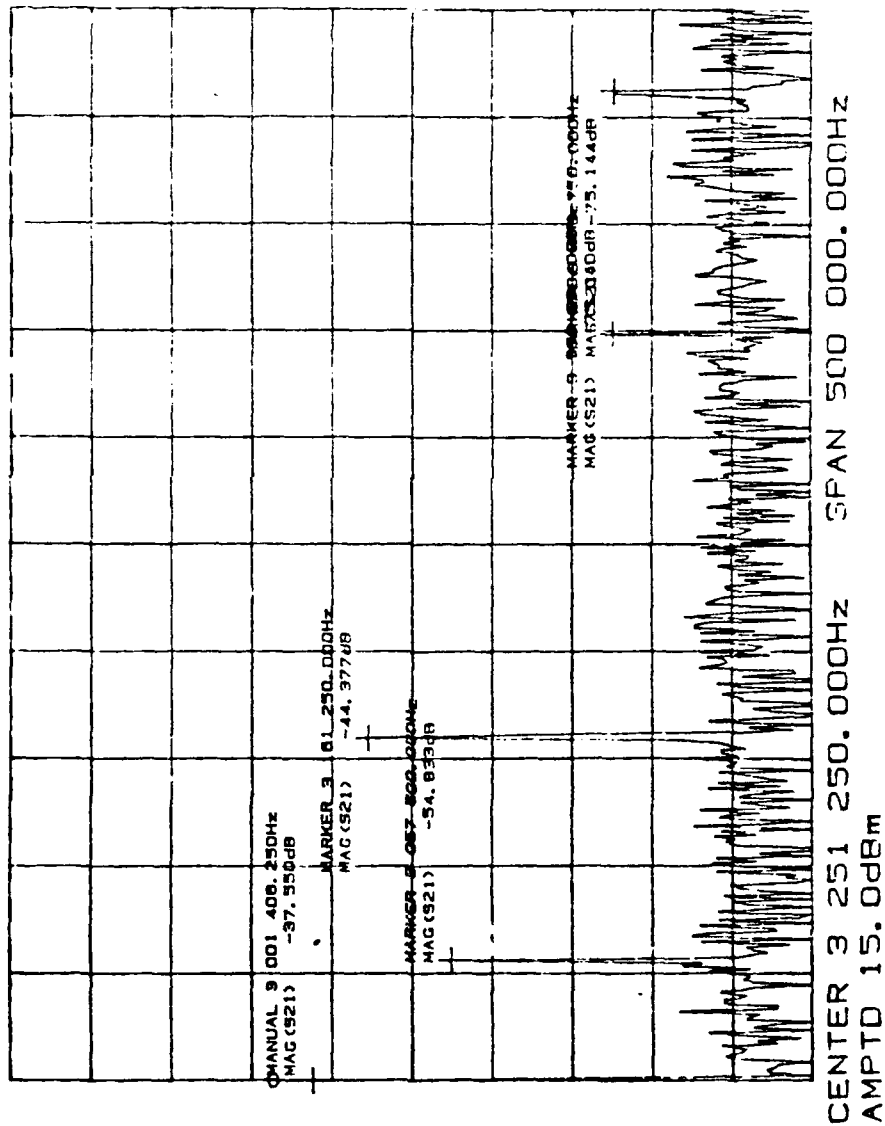
NOTES:

1. NUMBERS 1 THRU 7 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 8.0 DIOPTER.
4. CRYSTAL S/N 20457R
5. .221" DIAMETER ELECTRODE

Figure A-20. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 8.0 Diopter Plated With A .221" Diameter Electrode

REF LEVEL /DIV MANUAL 3 001 406.250Hz
 0.000dB 10.000dB MAG(S21) -32.683dB

AK LFR #12



3.001401 -23.8
 3.057592 -47.3
 3.161812 -40.8
 3.350000 -71.7
 3.463750 -73.0

Fundamental Mode
 Frequency Response
 on an AK-LFR
 Gap = 0.075
 $\omega = 255^\circ$

FIGURE A-21

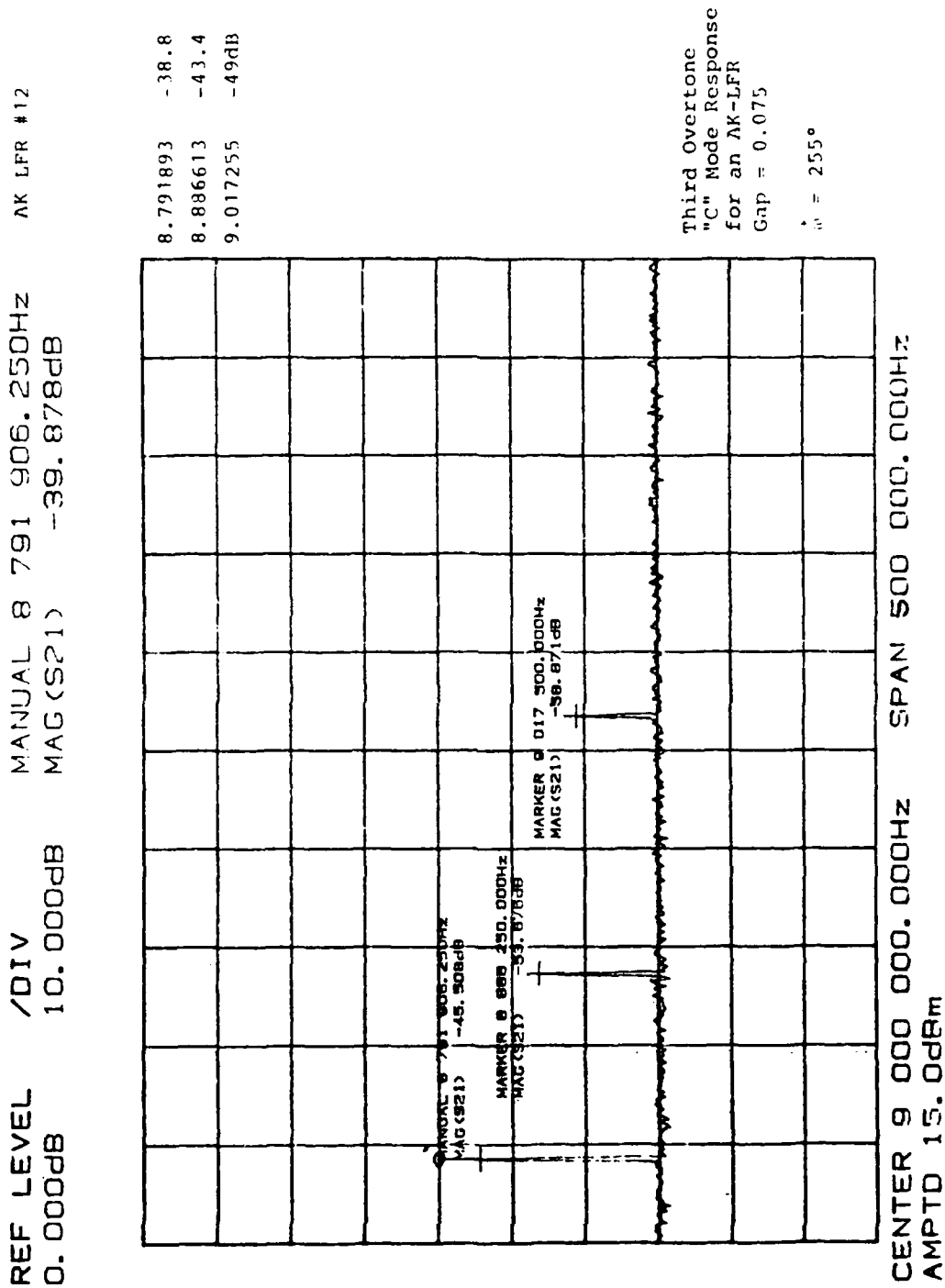


FIGURE A-22

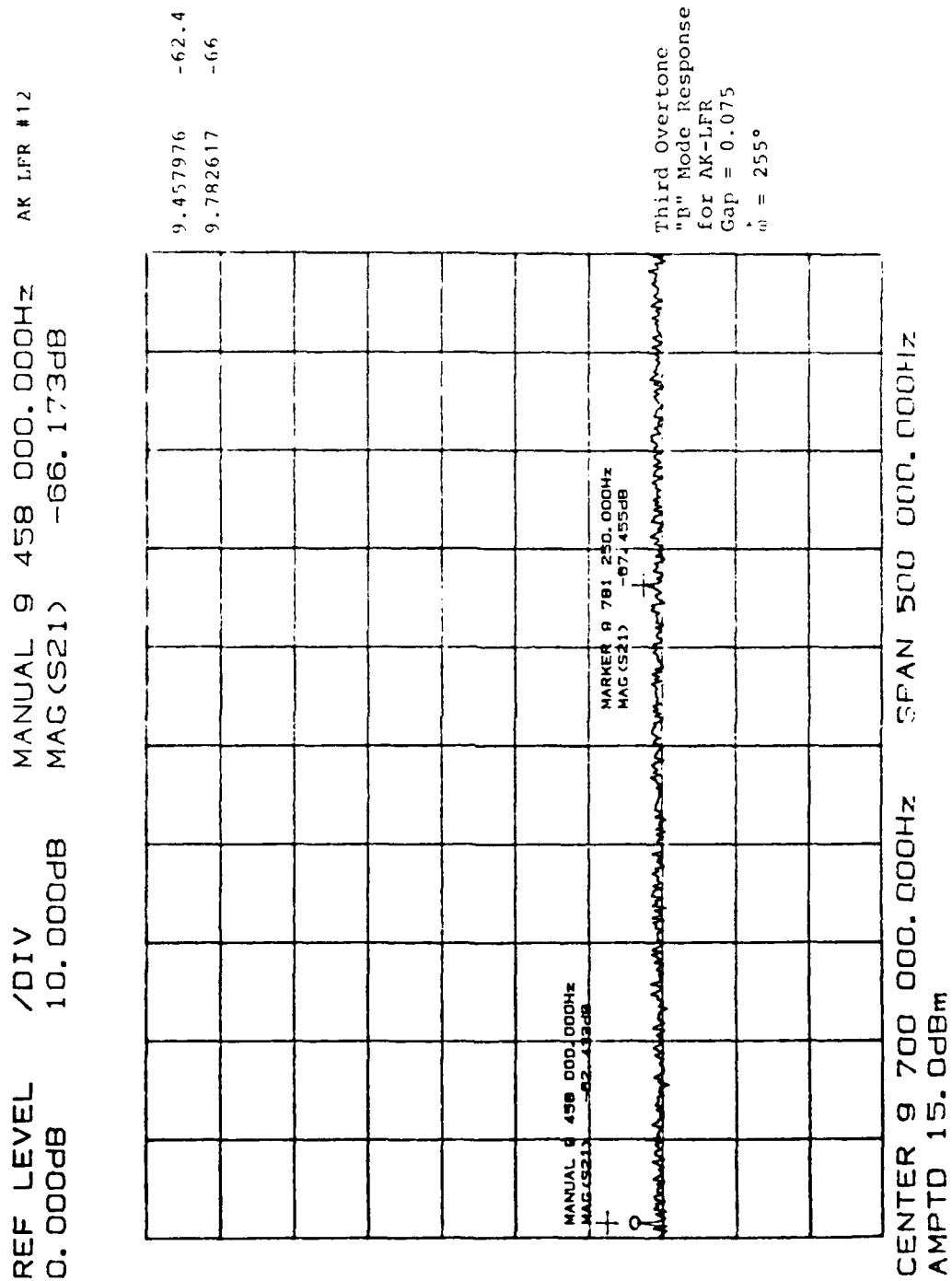


FIGURE A-23

REF LEVEL 0.000dB /DIV 10.000dB MANUAL 14 673 593.750Hz AK LFR #12
MAG(S21) -49.676dB

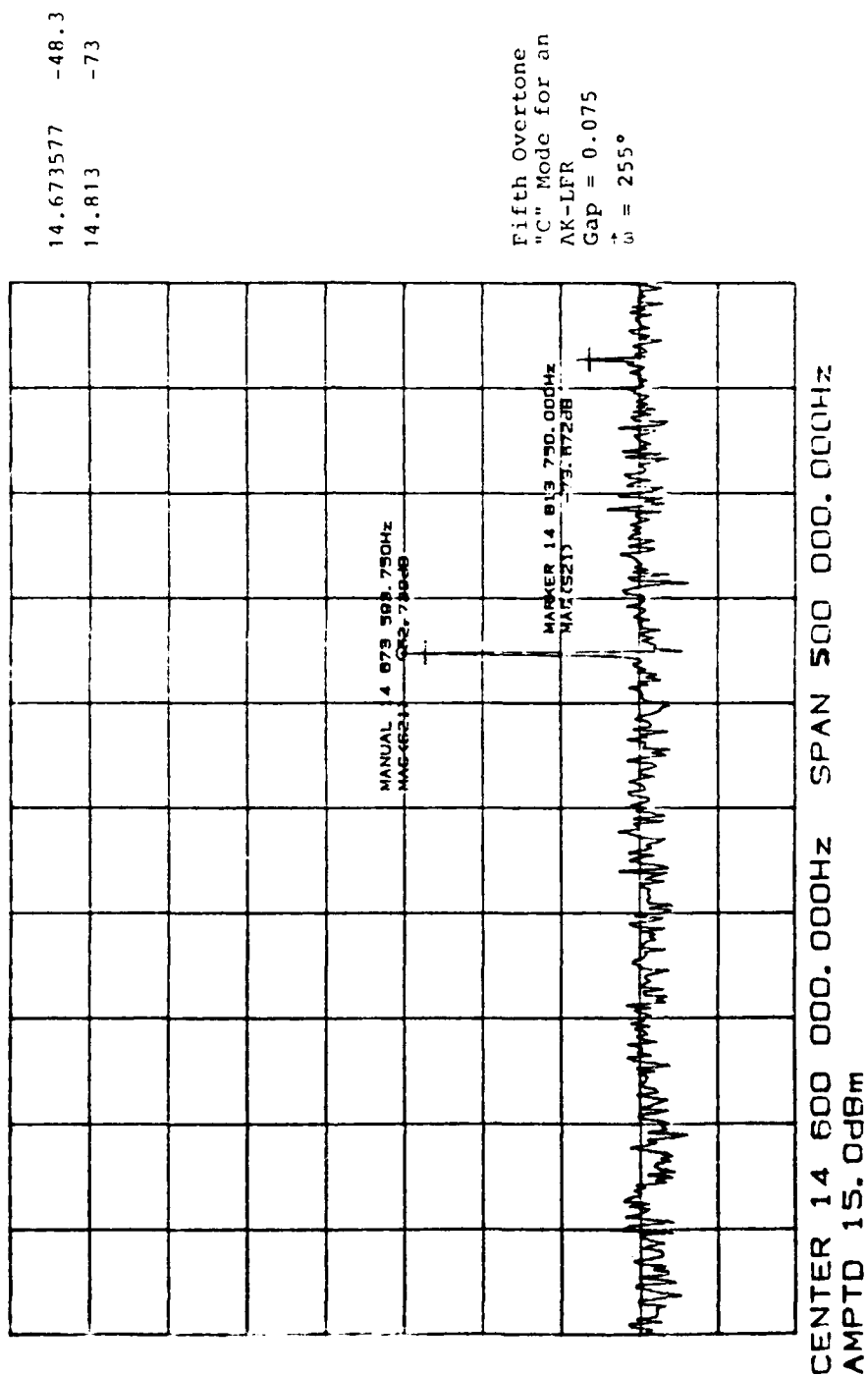


FIGURE A-24

REF LEVEL /DIV MANUAL 16 358 312.500Hz AK LFR# 12
 0.000dB 10.000dB MAG(S21) -79.801dB

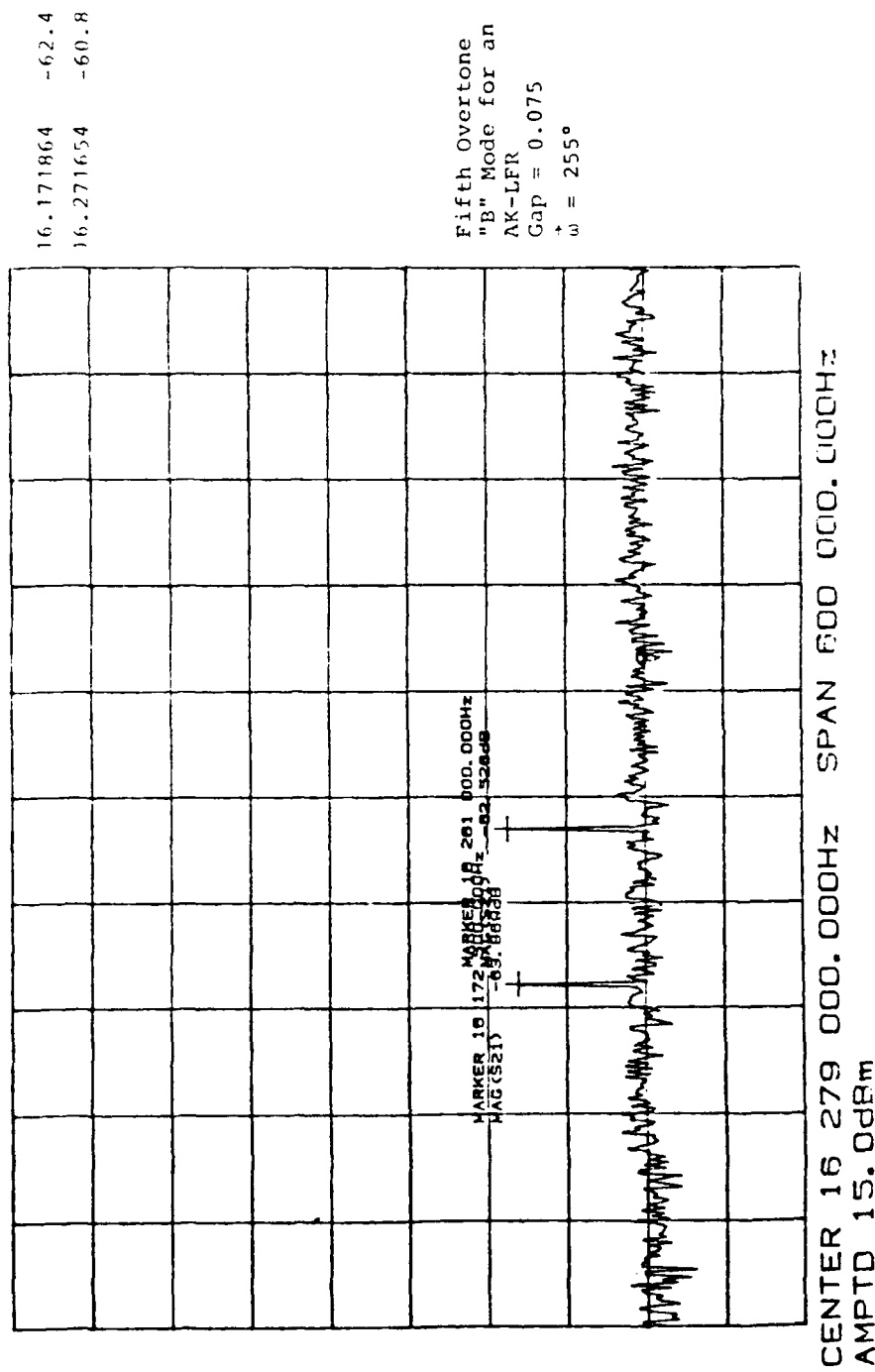


FIGURE A-25



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