PART II

DESIGN DATA

Foreword

This foreword will begin (1) with a very important statement about the limitations of existing design data, as they limit and define the scope of the material in Part II. The basic principle and purpose of the design data section will then be defined (2), followed by an evaluation (3) of the various categories of data, and by suggestions (4) for the practical use of the data.

1. Limitations of Available Design Data

An early decision by the technical representatives of the U.S. Army Signal Supply Agency determined that this *Handbook* was not to be tied to specific, existing, military quartz resonator types, but was to be as general as possible. This decision was based upon the obvious fact that military specifications were changing rapidly, and that, therefore, any limitation to current military types would insure a very early obsolescence of the material.

Current military types of quartz resonators do, however, impose a kind of limitation which cannot altogether be escaped. Since the Armed Services have been and are a major customer for quartz resonators, since they have supported research and development concentrated upon their needs, since civilian customers have found it convenient and economical to use military types whenever they were suitable, and since the results of research and development work to meet non-military requirements are not as available as the results associated with government sponsored projects, *most of the available data is in the area occupied by the current and anticipated military types. Throughout this book, therefore, it is to be understood that unless the contrary is evident, the statements apply to resonators in the general neighborhood of the current and the experimental military types, and that the validity of the data for significant departures from this area is more or less uncertain. The efforts to overcome this limitation will be evident in the text.*

By "limited to the neighborhood" of the current military types is meant: (1) In the frequency range from 800 kc to 8000 kc knowledge is largely restricted to miniaturized units, since, if the military specifications did not limit the holder to the relatively small HC-6/U, there would have been more experimentation with larger plates throughout this area. (2) The military specifications, with very few exceptions, specify the choice of harmonic order, so that very little is known about 3rd or 5th harmonics over any considerable range of frequencies below about 17 mc, or about the fifth harmonic below about 50 mc. (3) Most military units are specified for a maximum shunt capacitance of 7 μμf. Consequently, except at the low frequencies where this value cannot be achieved in the relatively small units specified, most data is on units with shunt capacitances between 6 and 7 μμf. This is a very important limitation, which is currently being removed by government and privately sponsored work on filter and ultra-miniature units, but which is still felt in this book because the current work is still quite incomplete. (4) Military specifications either call for operation at a controlled temperature (75°C, 85°C, 125°C) or for operation over a wide temperature range (-55°C to +90°C or to +105°C). Consequently very little is known directly about closer tolerance operation at control temperatures lower than 75°C or over much narrower ambient temperature ranges. In this case, however, the limitation is not very severe, since the facts gathered within the military area are capable of significant extrapolation into other areas. (5) Most military units are specified in terms of equivalent resistance, and not in terms of electrical reactance or Q. This limitation, like that imposed by the specification of shunt capacitance (3 above) is currently being removed, but very little of the data which will soon be available was available for this book. (6) Most military types call for plated electrodes. Old uses of pressure mounts (space between electrodes and quartz plate except at clamping points on the edge, usually at the corners of rectangular plates) may be regarded as obsolete except for a few special applications, such as resonators required to withstand a very high drive level. (7) Many manufacturers find it much easier to process round plates, although there is still use of precisely dimensioned rectangular plates for relatively low frequencies in the AT range. For practical process reasons, it is likely that future departures from the round plate will take the direction of removing, in a late processing stage, unessential portions of the round plate in order to fit it into a specified holder. Consequently, data on round plates is basic. (8) Most military units are supported by wires, pins, or strips, which also serve as electrical leads, and which make electrical contact to plated strips on opposite ends of a diameter of the quartz plate (180°). Current miniaturization is resulting in a modification of this system in which the plated strips are brought out at an angle of less than 180°, such as 90°, in order to conserve space. It is also possible that further miniaturization will result in radical modifications of this system, perhaps even new mounts of the pressure type without plated electrodes.

As a result of the prevalent use of the music wire, pin, or strip mounting system, there are among current mounts relatively narrow ranges of holder and mount capacitance, lead resistance, and lead inductance. Holder and mount capacitance is important at high frequencies, and at low frequencies if small electrodes are employed, as in some units designed for filter use. Lead resistance, and metallic resistance as a whole, is important at high frequencies because of skin effect, and at lower frequencies as a significant percentage of very low equivalent resistance. Lead inductance is important at very high frequencies.*

2. Basic Purpose of Design Data.

The hypothesis upon which Part II is based is that if all of the electrical characteristics of a quartz resonator could be related analytically and quantitatively to measurable physical parameters, a complete design could be created without the necessity for experimentation in particular cases and without the necessity of defining units by process variables. For example, if the effective surface finish could be defined and measured, and related quantitatively to the electrical characteristics, especially to the equivalent resistance, it would be unnecessary to describe a quartz plate in terms of the finishing machine, the grade of the abrasive, the duration of the lapping or polishing process, and the amount of etch. This would be, practically, very desirable since it is, and will remain, extremely difficult to create adequate definitions of such process variables.

The electrical characteristics of a quartz resonator plate are determined by:

1. The material of the resonator plate.
2. The geometry of the plate (shape and dimensions).
3. The orientation of the plate with reference to the natural crystallographic axes.
4. The surface finish of the plate.
5. The material of the electrodes.

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* It will be noted that the word Most has been used freely. There are exceptions, such as a few isolated harmonic units at relatively low frequencies, but what is said above under (1 through 8) applies to the great bulk of data which is old enough to be fully developed and checked.

6. The physical state of the electrodes, since thin films appear to be differently constituted, according to thickness, method of deposition, etc.

7. The thickness, size, and shape of the electrodes.

8. The orientation of the electrode geometry with reference to the orientation of the quartz plate, and its geometry.

9. The material, size, shape and position of the connecting leads and mounting supports.

10. The material, size, shape, and position of any bonding cement or solder used to attach the mounting supports (usually serving also as connecting leads) to the electrodes.

11. The material, size, shape, and position of the enclosure.

12. The atmosphere within the enclosure.

13. Any other material such as dirt, oxides, or other salts of metals, moisture, etc. which may be inside the enclosure.

3. Evaluation of Design Data Categories

Of the above, numbers 1, 6, and 13 must be dismissed briefly.

1. It is probable that natural quartz, free from obvious defects such as twinning, fractures, inclusions, etc. may still have different characteristics, but very little is known of these differences. Certain types of cultured quartz have different characteristics, a different temperature coefficient of frequency, for example. The Y-bar quartz normally used for AT resonator plates has approximately the same temperature-coefficient of frequency as natural quartz. It has a lower Q, which is detectable at extremely low temperatures, and at normal temperatures when used for certain very special units with Q's near the maximum possible, that is, with very small losses from mounting, atmospheric loading, and from imperfections such as geometrical aberrations and poor surface finish.

6. Very little is known about the effective differences among evaporated, sputtered, and electroplated thin films. Such differences appear to exist, however. Sputtered gold films often have

higher resistances than evaporated gold films, for example, and different solutions for the electroplating of nickel appear to result in differences in behavior.

13. The presence of minute quantities of foreign materials and corrosion products within the enclosure or holder is a subject of very great importance, which, however, does not yield itself readily to analysis. It is dealt with briefly in the Process Notes section of the Appendix.

In all of the other areas a beginning has been made toward the establishment of quantitative relationships. Perhaps the most precise area is that of No.12, atmosphere, and the least precise are Nrs. 4, 9, 10, and 11, covering surface finish and various parameters of the holder and mount, although in many cases the lack of complete information is balanced by the limitation of practical alternatives so that existing knowledge is more or less adequate for existing problems.

It must be noted again, however, that because most existing data is limited to a very narrow range of shunt capacitance, present knowledge of the interrelation of electrode and plate geometry is very unsatisfactory for use outside the area of current military specifications.

4. Suggestions for Practical Use of Design Data

The first sections of design data deals with holders, mounts, and bonding cements. The holder and mount, usually specified, determine the maximum possible diameter of a round plate. (Bonding cements must be selected in connection with the mount.) Thickness, as a function of frequency is treated next. At this point a designer who has started with a specified holder and frequency, harmonic order, and maximum resistance, can calculate, at least to a usable approximation, the maximum possible diameter to thickness ratio.

Knowing the maximum possible diameter to thickness ratio and whether or not he needs to use the maximum, the designer is ready to select a shape. The first part of the section on Shape and Contour will indicate whether or not contour is required, and whether or not he is in an area where the parallelism of the plate is desirable and critical. He now has the size and shape of his plate determined, and is ready to determine the orientation of the plate. Knowing, size, shape, and orientation angle, he has all the information required for all processes, through the first one or two lapping stages. Before the remaining processes and the lapping, polishing, and etching processes can be specified, he must determine the surface finish. He has, already presumably evaluated the data on diameter and contour, if necessary, in terms of the specified maximum resistance, being careful to select the best possible size and shape if the specified maximum resistance is low. He now takes resistance into account as a major factor in the selection of the material, thickness, and size of his electrodes. If the atmosphere in which the unit is to be sealed has not been specified he also selects an atmosphere at this time in terms of specified maximum resistance and other factors such as heat dissipation and stability with age.

The approach can be made clear by taking a specific example. Let us assume that the specification is for units of the military type, CR-18, at 4 megacycles. An engineer familiar with CR-18's will, of course, leaf through Part II quickly to find the data on diameter and contour. Let us suppose, however, that an engineer has not encountered the CR-18 before.

First he notes in the specifications that CR-18 must be enclosed in the HC-6/U. On page 37 he finds that the maximum diameter of blanks which can be put in this holder without special mounting is 0.600", and that 0.640" is about the maximum under any circumstances. From Figure 23 he obtains a very rough estimate of the thickness of the 4 mc blank, 0.016". This gives a diameter to thickness ratio of

$\frac{0.600}{0.016} = 38$ or $\frac{0.640}{0.016} = 40$. Figure 23 does not purport to be accurate for values this low, but turning to page 57, he finds that the minimum diameter to thickness ratio for an uncontoured (that is plane-parallel plate without either contour or bevel) is in the neighborhood of 67. If his frequency were higher, say 7 mc, or 8 mc, and his specifications for maximum resistance were made lower than for the military type, he would recognize from a reading of the text, that he was in a border-line area and that some experimentation might be needed, but with a diameter to thickness of 40 or less, he clearly must contour his plate. Turning to Figures 31 and 32, he finds that there is a relatively easy design system for this frequency and size. If he uses a diameter greater than 0.450" and less than some value which is much too large for his holder, he can use any curvature for a plano-convex contour between 1.75 diopters and 2.5 diopters. So he selects a convenient diameter, nearer 0.600" than 0.450" if he is cautious, and a contour corresponding to an available spherical lap, probably 2 diopters in this case.

This has turned out to be a simple case, with wide tolerances. Had his frequency been 2.9 MC instead of 4 MC, his minimum diameter would have been about 0.620", an inconveniently large plate for his holder. His optimum contour would be 1.5 diopters, with a wide tolerance. He should, however, in view of the inconvenience of even a minimum diameter according to this design system, turn to the second system, given in Figure 33. Here he finds that by increasing his curvature, still not critical, to the general area between 3 and 5 diopters, he can use plates much smaller than 0.620". He will probably select some convenient diameter greater than 0.500" and no greater than 0.600", and a curvature of 4.5 or 5 diopters. At still lower frequencies he would find the situation more complex, and the tolerances tighter.

Returning now to the simple case of the 4 MC frequency, our designer has decided upon a diameter, of,let us say 0.550" and a plano-convex contour of, let us say, 2 diopters. He has also decided upon a suitable mount. Having determined the size and shape of his 4 MC plate, he is ready to determine the orientation angle. The CR-18/U specification calls for a maximum frequency deviation from nominal of ±0.005% over the temperature range -55° to +105°C. On page 89 he finds a <u>Table of Reference Values for Use of Generalized Curves</u>, and in it that for this simple case he has a zero angle of 35°8.5'. Therefore he assigns the value, 35°8.5' to the curve marked zero in Figure 39, determines the maximum and minimum angle which will meet the specification, and from them the design center angle, which will be close to 35°16' ±6' to 7' according to how conservatively he reads the curves. He should allow at least $\pm\frac{1}{2}$' for possible inaccuracies of the table on page 89 and of Figure 39, and between $\pm1\frac{1}{2}$' and $\pm3\frac{1}{2}$' for inaccuracies of process measurements and adjustments to nominal frequency, thus establishing a production tolerance of ±3' to ±5'.

This again was a simple and easy case. If, on the other h hand the specification were for a different temperature range or a tighter tolerance, it would be necessary for the designer to study the material on pages 77-103 much more carefully. In the case of some of the very tight tolerances, this material, because of its own possible inaccuracy, because of secondary variables, and because of the relatively large importance of small, systematic processing variables, could only furnish him with a starting point for his experiments, experiments employing his own equipment, and organized around the particular, tight specification.

Our designer now has a complete geometrical specification for his quartz plate: size, shape, and angle of cut. He must next consider the surface finish. On page 104 he finds that he is in an uncritical area. So he specifies a standard contouring process and the specified amount of etch. He now has the quartz completely specified and is ready to turn to the electrodes. On page 114 he learns that at this frequency he can use gold without any significant loss in resistance, and since gold is more inert than silver or aluminum, it will probably be his choice. When he selected his diameter and contour he noted on Figure 32 that his maximum electrode diameter was 0.325". Consulting pp. 107-109 he will find by a rough calculation that he is in little danger of exceeding his specified maximum shunt capacitance of 0.7 μμf. So he uses the 0.325" electrode diameter, or one slightly smaller. He has already selected a mount, and in connection with the selection of contour, learned that for this particular plate it is not necessary to orient the mount with reference to the crystallographic axes of the quartz plate. He is not, by specification, allowed to use either helium or a vacuum to reduce the equivalent resistance, although he may find the material on atmosphere informative if he wishes to know why his finished units behave as they do.

His design is now complete. Process details remain to be worked out. It is hoped that the text will make it clear, however, that for a relatively easy-to-make crystal of a common type, the data furnished will eliminate nearly all experimentation with different physical parameters, whereas for difficult and uncommon units, the data will at least be a guide by which experimentation can be limited.