The Effects of Ultrasonic Cleaning on Device Degradation — Quartz Crystal Devices

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ABSTRACT — Although the use of ultrasonic agitation on quartz crystal devices during PCB cleaning has long been suspected to be detrimental, little or no data exist to substantiate or quantify the resultant effects. This paper summarises the results of a limited study into these effects for a range of quartz crystal devices, using both CFC and aqueous solvents. The variations with exposure time, and the types and mechanisms of failure are discussed. The results are encouraging and suggest that, although these devices are more susceptible to damage than ICs, once manufacturing defects have been screened out they will withstand ultrasonic exposure without deleterious effects for periods several times longer than those used for cleaning PCBs.

INTRODUCTION

It has long been recognised that cleaning of PCBs can be enhanced considerably by using ultrasonic agitation. Indeed, results from the major UK collaborative exercise to evaluate non-CFC cleaning technologies[1] clearly indicate that 'assisted' cleaning offers remarkable benefits either in terms of cleanliness of PCBs or in terms of time taken to achieve a given cleanliness level. With the increasing use of surface mount technology (SMT), components with smaller stand-off heights, larger and more complex packages, and the loss of CFCs as the mainstream solvents, the attractions of using ultrasonic agitation to aid in the cleaning of PCBs are becoming irresistible.

Until recently, this process had been suspected of causing irreversible damage to components and soldered joints, and/or long-term reliability problems. However, the results of an in-depth investigation of such damage accumulation[2-5] have shown that, under standard conditions required to produce clean assemblies, there is a large margin of safety before any damage to good quality components is incurred. *It was emphasised that this safety margin applied only to the range of components studied in that investigation, and to components of proven quality. If poor quality components are used, then ultrasonic agitation will simply highlight their unacceptability.* Damage to good quality components can only be induced by the use of anomalously longer times or high power densities. For potential users of ultrasonic cleaning of PCBs, therefore, the results were encouraging and suggest that there is a large margin of safety when employing currently accepted regimes of operation.

In spite of these results, concern has persisted regarding the use of ultrasonics in conjunction with quartz crystal devices (which were not included in the earlier work). The potential sensitivity of quartz crystal devices (QCDs) to ultrasonic agitation had long been suspected by engineers wishing to clean boards containing such devices, since QCDs were thought (by virtue of their construction) to be mechanically unstable under ultrasonic exposure. Consequently, an assessment of the effects of ultrasonic exposure on quartz crystal devices was carried out as an extension to the earlier programme. The study addressed a specific question: does ultrasonic exposure damage modern QCDs and, if so, what are the modes and mechanisms of failure? The purpose of this paper is to present the results of these further investigations and to suggest a suitable device screening protocol.

OBJECTIVES

The main aims mirror those of the earlier stages[2, 3] of the programme, and are as follows:

- (i) to identify the nature of any changes in the performance of the QCDs (via certain electrical parameters) after ultrasonic exposure;
- (ii) to assess the accumulation of these changes as a function of exposure time and power density;
- (iii) to identify the nature of any physical damage induced by the ultrasonic exposure;
- (iv) to assess the regimes of safe operation.

INVESTIGATION

The programme took the form of a short exercise to ascertain the extent of any deleterious effects on QCDs, using a relatively small number of each device within a selected range of devices. A specially designed board (see Figure 1) which accommodated seven devices (six resonators and an oscillator) was used, and the components were chosen to provide a range of package styles, crystal sizes, methods of mounting, frequency of operation etc., typical of the products used in the industry (see Table 1).

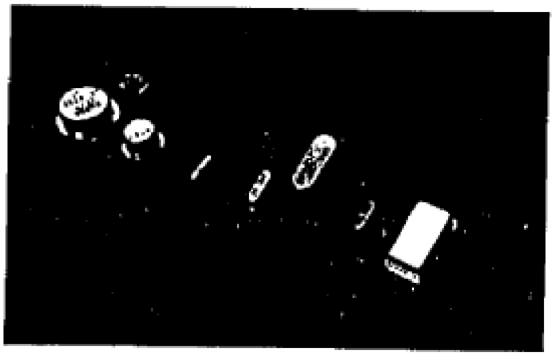

Fig. 1 *Photograph of test board and quartz crystal units.*

Table 1

Description of Devices used on Test Boards

Type	*Operating Frequency*	*Package*	*Description*
Oscillator	32 MHz	DIL	Circular crystal held horizontally using a 3-pt fixing and silver-loaded epoxy to provide a high shock resistance mounting.
A Resonator	8.192 MHz	HC49/J	Circular crystal held vertically in slotted Ni tapes using silver-loaded epoxy; silver electrodes.
B Resonator	1.256 MHz	HC33	As A; gold electrodes.
C Resonator	20 MHz	HC49/5H	Typical of low-cost product used in microprocessors; manufactured automatically in large volume. Rectangular crystal held horizontally using a 2-pt fixing and silver-loaded epoxy; silver electrodes.
D Resonator	32.767 kHz	3 x 8 mm cylindrical	Typical of low-cost product used in watches; manufactured automatically in large volume. The 'tuning fork' is mounted vertically using a Sn-Pb alloy; silver electrodes.
E Resonator	20 MHz third overtone	HC35/U (TO5)	High-quality precision resonator using highly polished miniature plano-convex crystal; gold electrodes.
F Resonator	12 MHz	HC37/U (TO8)	High-quality precision resonator using highly polished crystal; gold electrodes.

It was appreciated that, by their very nature, products containing high-cost devices would not normally be subjected to processing involving ultrasonic agitation, but this type of QCD was nevertheless used in order to provide a more complete picture of any damage accumulation.

The test boards were stressed by mounting them rigidly in a small rack (capable of taking 21 boards) which was suspended into the ultrasonic tank. A summary of the boards examined, the exposures given and the examination intervals is presented in Table 2.

Table 2

Details of the Boards, Exposures and Examination Intervals

Solvent	*Power Density (W/litre)*	*Exposure Time (Minutes)*	*No. of Boards*	*Board Nos.*	*Examination Intervals (Minutes)*
CFC	11	10	5	3-7	0, 1, 2, 3, 5, 10
	11	60	1	2	5, 10, 20, 30, 40, 50, 60
	30	10	4	17-20	0, 1, 2, 3, 5, 10
	30	480	1	1	0, 60, 120, 180, 240, 300, 480
Aqueous	24	3	4	13-16	0, 1, 2, 3

Two cleaning units were used, both operating at 38 kHz: an ICI Cleanline 2 type R2812UV28 operating at a mean output electrical power density of about 11 W/litre, and a Kerry KS451 tank with a Class D driver unit with variable output power to a maximum of 32 W/litre. Both CFC and aqueous solvents were used in the studies. In the first case, Freon TMS was used; it was expected that the acoustic properties of CFC solvents would show little variation from each other, and the temperature was set to 30°C. In the second, a 1% solution of ICI Synperonic NP-12 surfactant was added to ensure that the acoustic coupling was equivalent to that expected in a production situation. The temperature was set to 70°C. Although the QCDs were exposed to both high and lower power density agitation with the CFC solvents, only high power density exposure was used with the aqueous solvent.

POSSIBLE FAILURE MODES

It was expected that two types of QCD 'failure' might occur: alteration in the electrical parameters, and/or catastrophic breakage of either the quartz slice itself or its mount. The test board was therefore designed to be compatible with automatic monitoring equipment available for the precision measurement and evaluation of crystal resonators. Using this equipment, any changes in electrical parameters could be readily recorded. In all cases four main features were monitored:

1 Complete catastrophic failure. In these cases the packages were opened and examined in order to identify the failure mode using standard failure analysis methodology/techniques.

2 Any changes in R_m, the inherent resistance in the electrical path to the electrodes. Experience concerning reliability and service performance has shown that, for the low-cost high-volume product, changes in R_m of > ±10% are indicative of potential problems during life. However, for other devices in which the absolute value of R_m is very low, a change of 10% is of the order of the contact resistance and measurement accuracy/repeatability. Hence, in these cases, changes in R_m of > ±25% may represent a better indication of potential problems during life.

3 The resonant frequency. It should be remembered that, as far as the vast majority of users is concerned, this is the parameter of prime importance, and small changes in R_m are of little significance. However, in the majority of the results obtained the frequency exhibited little, if any, change from its initial time zero value. Such subtle changes as were observed followed closely those more marked changes occurring in R_m.

4 The value of Q. This parameter has a strong dependence on R_m.

In view of these points, it was decided that in the assessment of results particular emphasis would be placed on points 1 and 2. In addition, particular note was taken of those devices (types A, B and C) which exhibited R_m changes of > ± 10%, and of those devices (types E and F) which exhibited R_m changes of > ± 25%. The manner in which any changes occurred in R_m (e.g., steady drift, sudden increases, erratic behaviour etc.) were also noted as an indication of the likely failure mode. The latter is probably associated with cracking of the mounting medium or the support tapes. For example, if there is a steady increase in R_m then it is probable that micro-cracks will appear in the mounting medium, and as they coalesce and/or propagate, there is a corresponding progressive increase in R_m. Sudden increases in R_m can be attributed to larger cracks suddenly appearing, and constant (but non-increasing) high values might be associated with the presence of non-propagating cracks. Finally, the erratic behaviour noted on some devices is probably associated with a relatively 'loose fit' of the crystal in its mounting (possibly following

Table 3

Summary of Results for Resonator A

Solvent	*Power Density (W/litre)*	*Maximum Time (minutes)*	*Bd. No.*	*Full Failure*	*R_m Drift*	*Comments*
CFC	11	10	3 4 5 6 7	√	√	No. 5 exhibited a severe R_m drift between 0-1 minute, and failed completely between 2-3 minutes. On examination no obvious damage was apparent either to the crystal or its supports.
	11	60	2		√	Severe R_m drift after 10 minutes. No obvious damage was apparent to either the crystal or its support medium.
	30	10	17 18 19 20			No failures. No R_m drifts.
	30	480	1		√	Large R_m drift after 60 minutes. Crystal very loose in support — fell away when lid removed. The can had a large crack at one end.
Aqueous	24	3	13 14 15 16		√	No. 15 >10% R_m between 2-3 minutes.

cracking of the mounting medium), and as ultrasonic agitation occurs the crystal 'rattles' in the mounting, giving rise to erratic variations in R_m.

The measurement technique employed was not appropriate for the assessment of device D, and hence in this case only limited studies were undertaken, with only the frequency being monitored. In the case of the oscillators, a simple measurement was made of the frequency and the associated waveform, with any changes (> 0.5%) from the time zero values being noted.

RESULTS

Quartz Crystal Resonator A

The results are summarised in Table 3 and the variation of R_m as functions of exposure time in CFC are presented in Figures 2 and 3. The salient features are as follows:

- Using low power density exposure, only one failure was encountered. The device failed completely fairly quickly and is regarded as an 'infant mortality' (i.e., failure due to manufacturing defects). A second device exhibited an R_m change > 10% after 10 minutes.
- The majority of devices which survive the first 2 minutes' exposure seem subsequently to operate successfully for at least 10 minutes. This suggests the possibility of using the technique as a quality screen.
- With one exception, all the devices subjected to high power density exposure (CFC or aqueous solvents) survived for periods between 10 and 60 minutes. The exception exhibited an R_m drift > 10% between 2 and 3 minutes.
- The mode of failure of one device which failed completely is not known, but the initial severe R_m drift suggests a problem associated with the crystal support(s).

Quartz Crystal Resonator B

The results are summarised in Table 4 and the variations of R_m as functions of exposure time are presented in Figures 4 and 5. The salient features are as follows:

- These devices performed well under all test conditions.
- There was only one complete failure (under high power density, aqueous solvent, between 1 and 2 minutes) which was associated with

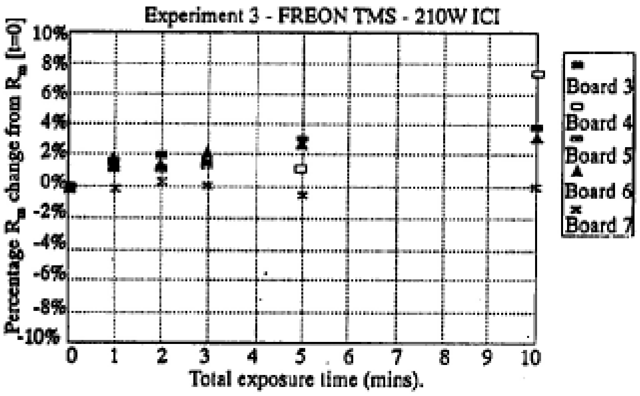

Fig. 2 *Variation of R_m as a function of exposure time for low power density exposure for resonator A.*

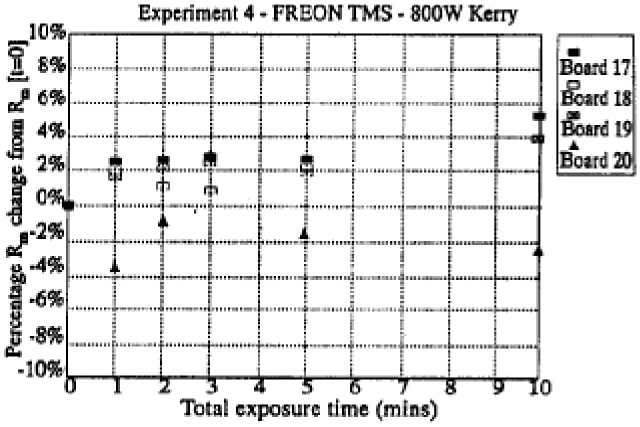

Fig. 3 *Variation of R_m as a function of exposure time for low power density exposure for resonator A.*

Table 4

Summary of Results for Resonator B

Solvent	*Power Density (W/litre)*	*Maximum Time (minutes)*	*Bd. No.*	*Full Failure*	*R_m Drift*	*Comments*
CFC	11	10	3		√	No. 3 >10% R_m drift between 1-2 minutes, then constant to 10 minutes. No. 4 was non-operational from time zero: there was no apparent damage when the package was opened.
			4	—	—	
			5			
			6			
			7			
	11	60	2			Steady positive R_m drift but still <10% after 60 minutes.
	30	10	17			No failures. No R_m drifts.
			18			
			19			
			20			
	30	480	1			Small erratic R_m drift. No failure.
Aqueous	24	3	13			No. 14 >10% R_m drift between 0-1 minute. No. 15 was non-operational from time zero: no obvious damage to the crystal or its supports. No. 16 failed between 1-2 minutes. Microcracks apparent in support medium.
			14		√	
			15	—	—	
			16	√		

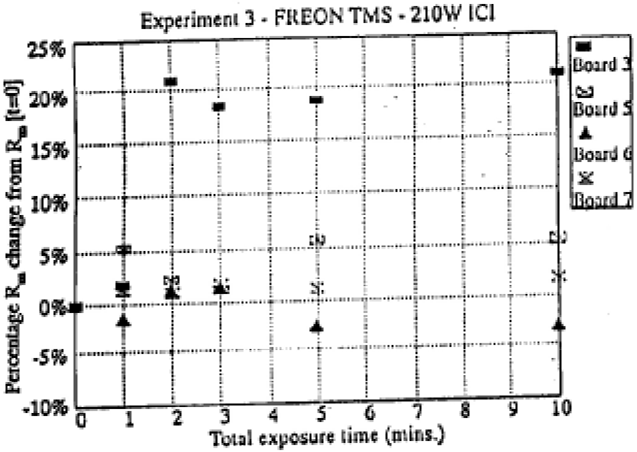

Fig. 4 *Variation of R_m as a function of exposure time for low power density exposure for resonator B.*

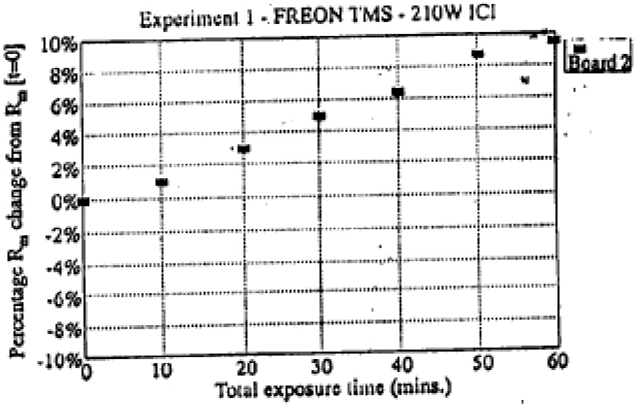

Fig. 5 *Variation of R_m as a function of exposure time for low power density exposure for resonator B.*

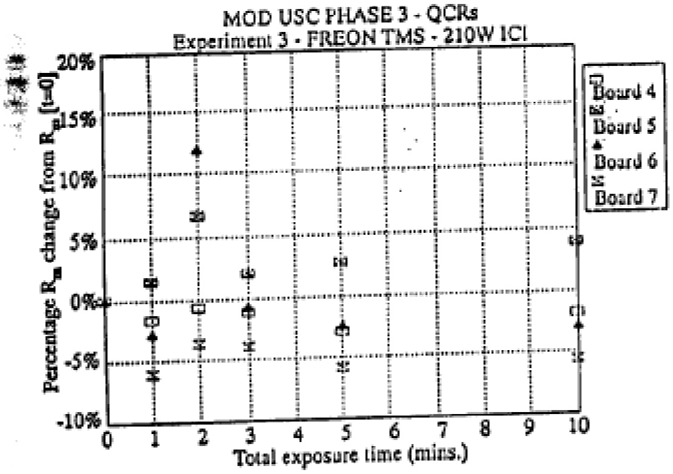

Fig. 6 *Variation of R_m as a function of exposure time for low power density exposure for resonator C.*

extensive micro-cracking in the support medium (see Figure 6).

- Only two devices exhibited a drift in R_m > 10%.

Quartz Crystal Resonator C

These results are summarised in Table 5 and Figures 7 and 8. The main points were as follows:

- These devices performed reasonably well under all test conditions, and the results again suggest that, once infant mortalities have been screened out, the devices will survive for acceptable lengths of time.
- Using low power density exposure, only one complete failure occurred. The failure was a breaking of the crystal itself (see Figure 9) and the location of the break (at one corner) suggested that it was associated with a manufacturing defect (i.e., an infant mortality): the support appeared to be undamaged.
- No device exhibited an R_m drift in excess of 10% under low power density exposure.
- Using high power density exposure, two complete failures were experienced. In one, the crystal had become loose due to cracking of the support material. The mode of failure of the second device was again a breaking of the crystal at one corner.
- There were no failures following exposure using the aqueous solvent and high power density agitation.

Table 5

Summary of Results for Resonator C

Solvent	*Power Density (W/litre)*	*Maximum Time (minutes)*	*Bd. No.*	*Full Failure*	*R_m Drift*	*Comments*
CFC	11	10	3 4 5 6 7	√		No. 3 failed between 0-1 minute. The crystal had broken, and the position of the break suggested it was associated with a manufacturing defect. The support and the mounting medium were undamaged.
	11	60	2			No R_m drift >10%.
	30	10	17 18 19 20	√		No. 18 >10% drift between 2-3 minutes: failed between 5-10 minutes. The crystal was loose in its support, and broke as the lid was removed.
	30	480	1	√		Failed between 0-60 minutes.
Aqueous	24	3	13 14 15 16			No failures. No R_m drifts >10%.

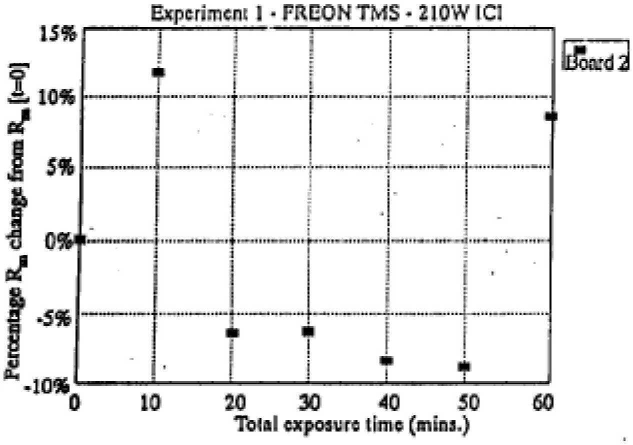

Fig. 7 *Variation of R_m as a function of exposure time for low power density exposure for resonator C.*

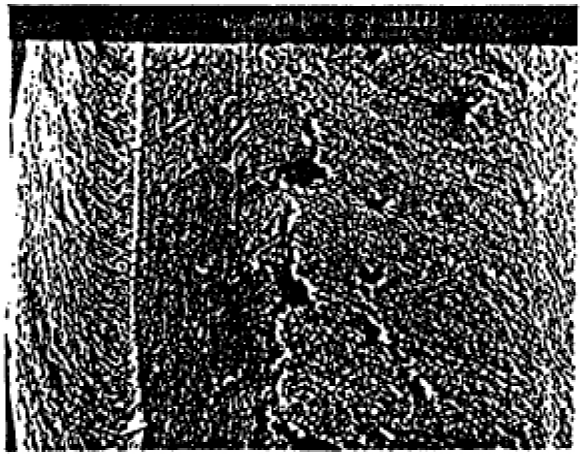

Fig. 8 *Micro-cracking of support medium of QC resonator D.*

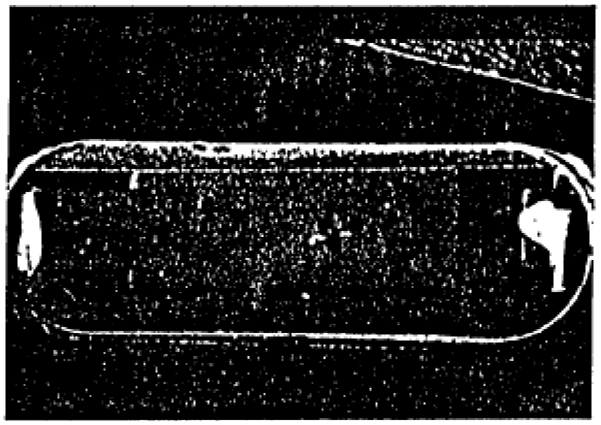

Fig. 9 *Broken crystal in QC resonator C.*

Quartz Crystal Resonator D

Although only the frequency was measured at each time interval, the data (see Table 6) were sufficient to indicate that no catastrophic failures occurred. The fact that two (of 15) of the devices were time zero failures probably reflects the manufacturing quality of this type of high volume, very low cost device. Once these are eliminated (screened electrically when used in actual systems production environments) the devices appear to be quite robust — a fact clearly reflected in their widespread use worldwide.

Table 6

Summary of Results for Resonator D

Solvent	*Power Density (W/litre)*	*Maximum Time (minutes)*	*Bd. No.*	*Full Failure*	*Comments*
CFC	11	10	3 4 5 6 7		
	11	60	2		
	30	10	17 18 19 20	✓	No. 19 was non-operational from time zero. No obvious damage when opened.
	30	480	1		
Aqueous	24	3	13 14 15 16	✓	No. 14 was non-operational from time zero. No obvious damage when opened.

Quartz Crystal Resonator E

The results are summarised in Table 7 and the main points were as follows:-

- The devices performed well under all test conditions. There were no infant mortalities, and failures were observed only after quite severe exposures.
- Using low power density (with CFC solvent) the devices performed very well, with only one complete failure between 20 and 30 minutes. No devices exhibited excessive R_m changes.
- Devices exposed to high power density agitation (with CFC solvent) still performed well, with R_m drifts in excess of 10% occurring only after several minutes. One complete failure occurred after 300 minutes' exposure.
- In both instances of complete failure, the mode of failure was one of cracking of the support material (see Figure 10) between the clip and the quartz crystal.

Fig. 10 *Cracked support medium of QC resonator E.*

Table 7

Summary of Results for Resonator E

Solvent	Power Density (W/litre)	Maximum Time (minutes)	Bd. No.	Full Failure	R_m Drift	Comments
CFC	11	10	3 4 5 6 7			No R_m changes >25%. No failures.
	11	60	2	√		Failed between 20-30 minutes. Cracks apparent in support medium.
	30	10	17 18 19 20			No R_m drifts >25%. No failures.
	30	480	1	√	√	>30% R_m change after 120 minutes. >150% R_m change after 240 minutes. Failed after 300 minutes; support medium cracked.
Aqueous	24	3	13 14 15 16		√	No. 14 >25% R_m drift between 0-1 minute.

Quartz Crystal Resonator F

The results are summarised in Table 8 and the salient points were as follows:

- Under low power density in CFC solvents, two of the six devices exhibited R_m drifts in excess of 10% very quickly (after less than one minute). These may be regarded as infant mortalities.
- Under high power density agitation in CFC solvents, the performance of the devices was apparently poor, with four (of five) devices suffering R_m changes. In three of these devices, the R_m change was large and occurred suddenly. However, in all cases the devices operated acceptably after at least five minutes' exposure.
- The mode of failure of the single catastrophic failure was fatigue through the top of the C-clips used for crystal support (see Figure 11).
- The results under aqueous exposure indicated that two (of four) devices exhibited R_m drifts in excess of 10% in less than one minute.

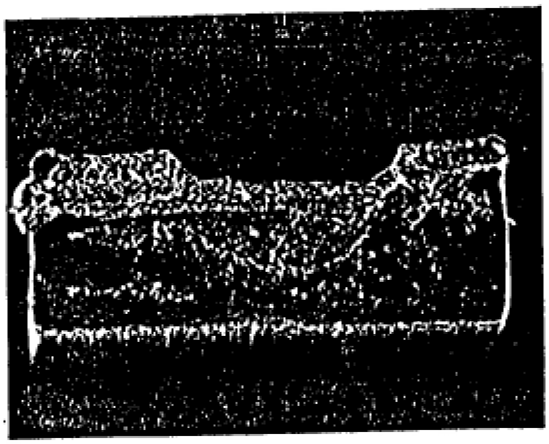

Fig. 11 *Fatigue failure of support mount of QC resonator F.*

Table 8

Summary of Results for Resonator F

Solvent	Power Density (W/litre)	Maximum Time (minutes)	Bd. No.	Full Failure	R_m Drift	Comments
CFC	11	10	3 4 5 6 7		√	No. 6 >25% drift between 5-10 minutes.
	11	60	2			No failure; small erratic R_m changes.
	30	10	17		√	No. 17 >25% change in R_m between 5-10 minutes.
			18		√	No. 18 sudden very large increase in R_m between 5-10 minutes, probably due to micro-cracking.
			19			
			20		√	No. 20 sudden very large increase in R_m between 5-10 minutes.
	30	480	1	√	√	Continuous R_m drift to 120 minutes. Sudden R_m drift after 180 minutes. Failed after 300 minutes. Crystal undamaged, but the metal C-clips had broken (via fatigue).
Aqueous	24	3	13 14 15 16		√ √	No. 14 >25% R_m change between 0-1 minute. No. 15 >25% R_m change between 0-1 minute.

Table 9

Summary of Results for QC Oscillator

Solvent	*Power Density (W/litre)*	*Maximum Time (minutes)*	*Bd. No.*	*Full Failure*	*Comments*
CFC	11	10	3		Nos. 4 and 6 failed after a few minutes only, as a result of manufacturing defects. The remaining three were unaffected after 10 minutes. Failures: quartz broken along crystallographic directions; fragments were shattered. No damage apparent to the crystal supports or the mounting medium.
			4	√	
			5		
			6	√	
			7		
	11	60	2		Unaffected after 60 minutes.
	30	60	17	√	All failures occurred between 10-60 minutes. Quartz cracked and broken as above.
			18	√	
			19	√	
			20	√	
	30	480	1	√	Failure occurred between 5-8 hours. Quartz broken and pieces were fragmented.
Aqueous	24	3	13		No. 16 was non-operational from time zero.
			14		
			15		
			16	√	

Quartz Crystal Oscillator

The results of the simple electrical evaluation of frequency and frequency waveform are summarised in Table 9. The main points were as follows:

- Under high power density the devices survived for periods between a few minutes and a few hours.
- The mode of failure in all cases was cracking and subsequent breaking of the crystal itself along crystallographic directions (see Figure 12). In no instance was there any evidence of degradation of the silver-loaded epoxy used to cement the crystal on the tops of the three support stubs (see Figure 13). It seems that there is no compliance in this type of mounting, and hence any strain is taken by the crystal, which breaks. At high stress levels the crystal breaks and, once broken, the pieces of the shattered crystal cause further associated damage to other components as a result of being shaken around within the package.

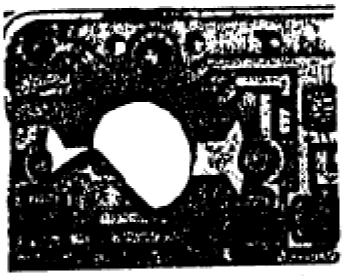

Fig. 12 *Broken crystals of QC oscillator device.*

Fig. 13 *Broken crystal of QC oscillator device.*

DISCUSSION

The results of this limited survey indicated, as might have been anticipated, that quartz crystal devices are much more sensitive to ultrasonic agitation than are ICs or passive components. However, although a range of behaviour was exhibited by the chosen devices, the performance of most was very encouraging. It is convenient to consider the results in two groups: (a) those representing the low-cost, high-volume type of device which would be the most likely to be subjected to ultrasonic agitation during PCB assembly/processing, and (b) those representing high-cost, low-volume types of device which, because of their intended applications, would be unlikely to be subjected to ultrasonic agitation.

Low-cost, High-volume Quartz Crystal Devices

In this category, performance was especially encouraging. In the majority of applications for this type of device, any drifts in R_m are of little consequence and the question of prime importance is whether or not the device fails completely. Bearing this in mind, the results for this type of device suggested that, once infant mortalities have been screened out, the devices will survive ultrasonic agitation (at either normal or high power densities) for lengths of time well in excess of those required for efficient PCB cleaning (i.e., 1-2 minutes).

There are two further points worthy of note. Firstly, the fact that infant mortalities were encountered suggests that manufacturing defects may be present in the devices, but this is not surprising in view of the very low cost of such devices. In addition, it is clear that ultrasonic agitation could be used as a screen for such defects. Secondly, the time zero failures are taken as a reflection of the degree of substandard quality in these low-cost devices.

High-cost, Low-volume Quartz Crystal Devices

In the intended applications for this type of device, any changes in R_m are of considerable importance. In general, the performance of this category (fabricated for very high reliability) is markedly different from that of the low-cost 'dispensable' counterpart. Firstly, there were no infant mortalities due to manufacturing defects, and no time zero failures. This is not surprising for devices of this quality, which are subjected both to stringent manufacturing processes and to extensive testing. Secondly, catastrophic failures occurred only after extended ultrasonic exposure times (a feature associated with the enhanced quality of this type of device). Thirdly, the devices appeared to be more subject to changes in R_m, a clear reflection of the differences in crystal mounting.

It is of interest to consider the mechanisms of failure of the devices, of which there are two:

1. Breaking of the crystal (along crystallographic axes, see Figure 12) in those instances where the style/geometry of the mounting provided little or no compliance. The oscillator was typical of this category.
2. Breaking of the mounting medium in instances where the style/geometry of the mounting did provide a degree of compliance. In this category, failure was via fatigue either of the mounting medium itself (e.g., silver-loaded epoxy) or of the metal support. The former occurred in the low-cost, high-volume type of device, in which the mounting is designed to be compliant to withstand the stresses likely to be experienced.

The initial fatigue quickly leads to micro-cracking (with an associated increase in R_m), eventual separation (see for example Figure 10) and device failure. The latter (only one case, see Figure 11) occurred in a high-cost, high reliability device which would not be expected to be subject to the same levels of stress. If the mechanism of failure is fatigue, then it is possible to extrapolate[2,4] the acceleration factor caused by using the high density agitation. In the earlier work,[2-5] data obtained for ICs and LEDs (in which fatigue was the dominant failure mechanism) indicated that the appropriate acceleration factor was 1000. An acceleration factor appropriate for the breaking of the quartz crystal itself due to the non-compliant nature of the mounting is not known.

CONCLUSIONS

As with results of the earlier work, the present findings are encouraging and indicate that ultrasonically-assisted cleaning of PCBs is not necessarily detrimental to the performance of QCDs. However, the margin of safety is not as large as for ICs and passive components. Salient points were as follows:

- Quartz crystal devices are more susceptible to damage from ultrasonic agitation than are ICs or passive components. Hence, ultrasonic cleaning of boards containing such devices can be undertaken, but with some caution.
- Certain quartz crystal devices are more susceptible than others, this being due largely to the method of mounting the crystals.
- Certain quartz crystal devices contain manufacturing defects which can be screened out as infant mortalities using ultrasonic agitation as the screen.
- Many quartz crystal devices (including screened products) will withstand ultrasonic exposure without any deleterious effects for periods several times that usually used for cleaning PCBs.

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