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Characteristics and Development Report for the SA3760 AT Strip Resonator for Use With the MC4033 Common Radar

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Abstract

The MC4033 Common Radar, developed for the B61/83 Stockpile Improvement Program, required a small, rugged crystal resonator in an all-ceramic package capable of providing a frequency of 20 MHz. A commercially available crystal resonator, manufactured by Statek Corporation, met this requirement. This report describes the design intent, component characteristics, and evaluation test results for this device.

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Acknowledgments

The evaluation, procurement, and qualification activities of the SA3760 was a team effort comprised of members from Sandia National Laboratories (SNL), Pinellas Plant (PP), and Statek Corporation. These members and their roles in this endeavor are summarized below.

Name	Location	Role
David B. Beightol	SNL	Technical support
Richard E. Heintzleman	SNL	MC4033 design engineer
Richard T. Jankowski	SNL	Product engineer
Paul T. Vianco	SNL	Soldering and surface mount evaluation
Dale Beetley	PP	Senior development engineer
Robert D. Waterbury	PP	Product engineer
S. Chuang	Statek	Vice President, Research & Development

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Characteristics and Development Report for the SA3760 AT Strip Resonator for Use With the MC4033 Common Radar

Introduction

The SA3760 is a 20-MHz quartz crystal resonator used in the MC4033 common radar that was designed for use in the B61/83 Stockpile Improvement Program. The baseline design considerations for the MC4033 common radar required that the crystal resonator be as small as possible, surface-mountable, and inexpensive. Furthermore, the resonator had to be robust enough to satisfy the electrical, mechanical, and thermal requirements imposed upon it. Finally, it was necessary that the resonators be procured in a timely fashion in order to meet the build schedule for the radar.

To satisfy the requirements of performance, cost, and schedule, a miniature quartz crystal resonator, manufactured by Statek Corporation, was chosen for this application. A qualified quartz tuning fork, manufactured by Statek, was already being procured by the Kansas City Division of Allied Signal Corporation for a different application. Moreover, Statek was the

only U.S. manufacturer of such devices willing to work with the Department of Energy (DOE) complex in providing the devices. Other U.S. manufacturers either did not have the capability or were unwilling to work with a government agency. The only other sources for such devices are Japan and Switzerland. The capability to manufacture such small devices within the DOE production complex does not exist, and it would have been necessary to develop the wherewithal from scratch.

Design Intent

The electrical, mechanical, and thermal requirements for the SA3760 are listed in Table 1, and the corresponding axis notation is illustrated in Figure 1. In addition to these requirements, the SA3760 had to be surface-mountable and thus be able to withstand the high temperatures involved in surface mount processes.

Table 1. Electrical, mechanical, and thermal requirements for the SA3760.

Electrical and thermal requirements:

Drive level: 0.1 mW nominal, 0.5 mW maximum
Operating temperature: -55°C to $+125^{\circ}\text{C}$
Storage temperature: -55°C to $+70^{\circ}\text{C}$
Frequency over operating temperature: $20.000000\text{ MHz} \pm 500\text{ ppm}$
Effective series resistance over temperature: $100\ \Omega$ maximum
Operating mode: parallel, fundamental, $C_L = 22\text{ pF} \pm 1\text{ pF}$
Nominal shunt capacitance: 4.0 pF maximum
Shelf life: 28 years

Mechanical requirements (Appendix B):

Shock: Mil-Std 883C, Method 2002.3, Test Condition B
Vibration: Mil-Std 883C, Method 2007.1, Test Condition B

Figure 2 illustrates how the SA3760 is used in the circuitry of the MC4033. The MC4033 common radar has a 20-MHz Pierce oscillator, which is part of the timing clock circuit on the radar logic board. The SA3760 AT strip resonator provides a stable 20-MHz

frequency source for the timing clock. The sinusoidal output of the oscillator drives a comparator to achieve a square wave output that provides the timing signals for the radar.

Figure 1. SA3760 axis convention.

Figure 2. MC4033 logic clock oscillator. The SA3760 is denoted by Y1 in the schematic

Component Characteristics

Physical

The SA3760 is an example of what is commonly referred to as an "AT strip" resonator. This term means that the crystal is a small rectangular plate of AT-cut quartz that is typically fully electroded in the width direction [Dworsky 1987]. The term AT refers to a specific crystallographic orientation with respect to the synthetically grown quartz bar, as illustrated in Figure 3 [Heising 1985, 24]. The various cuts shown in this figure are ways of obtaining desired vibration modes without (or at least minimizing) coupling to unwanted modes. Additionally, the various cuts illustrated in Figure 3 have unique frequency vs. temperature characteristics, as shown in Figures 4 and 5 [Heising 1985, 24; Bottom 1982, 146-7]. As illustrated by these figures, the small frequency variation of the AT cut with respect to temperature, compared to most other cuts, makes this orientation particularly desirable.

The basis for using the AT-cut quartz crystal came from the fact that crystal oscillators often used thickness vibrating crystals whose frequencies were determined by the thicknesses of the crystals—i.e., their smallest dimension. Since the thickness dimension can be made very small, high frequencies were therefore attainable [Heising 1985, 23-24]. Initially, X-cut plates were used, but the presence of many harmonic and overtone modes near the desired frequency eventually led to the use of Y-cut plates, which did not have as many secondary modes of motion. While the use of Y-cut plates considerably improved oscillator performance, the main drawback was that the frequency of such a crystal increased by about 86 parts per million (ppm) for every degree Celsius increase in temperature [Heising 1985, 23-24]. To improve upon the performance of the Y-cut crystal, studies were conducted in which the orientation angle was varied, and it was discovered that the AT and BT cuts showed a frequency dependence nearly independent of temperature [Heising 1985, 23-24; Bottom 1982, 73]. The BT cut eventually fell into disfavor because its frequency tolerance deviates by ± 100 ppm over the temperature range of -60°C to $+100^{\circ}\text{C}$, whereas the AT cut may be fabricated to have a frequency tolerance of only ± 15 ppm over the same temperature range [Bottom 1982, 145].

The construction of an AT strip resonator is illustrated in Figure 6. The electroded AT-cut quartz

crystal is attached to two conductive mounting pads located inside a small ceramic package. Silver epoxy is used as a conductive adhesive to bond the crystal to the contact pads connected to the package's external terminations through tungsten via holes. A glass, ceramic, or metal cover is then sealed to the package using a gold/tin (Au/Sn) eutectic solder in vacuum [Chuang and Burnett 1990]. For the SA3760, a high-temperature Au/Sn eutectic solder preform (80 wt% Au, 20 wt% Sn, melting point 280°C) is used to seal a ceramic lid to the package, the ceramic lid having been suggested by Statek in order to easily meet the stated mechanical and thermal requirements. One preform is then brazed onto the lid and another onto the package frame in a reducing atmosphere in order to remove oxides and organic contaminants, as well as to establish a good bond between the sealing material and the package [Chuang and Burnett 1990; Dvorack 1992]. After mounting the quartz crystal into the package, a high-temperature bake at 300°C is performed for further outgassing. After this high-temperature bake, the lid and package are pressed together in a high-vacuum system for sealing at high temperature [Chuang and Burnett 1990].

The external terminations for the AT strip resonator package are illustrated in Figure 7. Three types of terminations are used, designated as SM1, SM2, and SM3. The simplest is the SM1, which consists of a tungsten layer that is screened onto the package's ceramic surface (94% alumina), followed by an electroless plating of a very thin layer of gold, specified to be around $75\text{ }\mu\text{inches}$ thick. The tungsten layer defines the electrode pattern seen on the package. Bonding between the gold and the tungsten is enhanced by a high-temperature sintering process. The T-shaped electrode identifies the end of the package within which the AT-cut quartz plate is epoxied. The SM2 termination, in turn, merely adds a thick nickel barrier over the gold. The nickel is then covered with either (1) a tin plate ($\sim 95\%$ Sn) which results in a bright termination finish, or (2) a solder plate ($\sim 63\%$ Sn/ 37% Pb), resulting in a dull finish. Both the nickel and subsequent tin (or solder) platings are carried out in what is referred to as "barrel" or "tumble" plating. The SM1 packages are initially placed in a bath contained within a barrel, which has a center wire serving as one electrode. The wall of the barrel acts as the other electrode. Plating of nickel, for example, occurs when the devices tumbling around in the bath touch the center wire. Hence, this process is electrolytic in nature.

Figure 3. Orientation of various quartz crystal cuts with respect to synthetically grown quartz bar.

Figure 4. Frequency vs. temperature characteristics (from 0°C to $+110^\circ\text{C}$) for several of the quartz crystal cuts illustrated in Figure 3.

Figure 5. Representative frequency vs. temperature characteristics for the AT and BT cuts (from -6°C to $+100^{\circ}\text{C}$). Note the “sinusoidal” nature of the AT characteristics.

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SINGLE-ENDED AT STRIP RESONATOR

GLASS COVER

ELECTRODED
AT STRIP
RESONATOR

CERAMIC PACKAGE

M.A.D. 8/1/89
89M2000.67

Figure 6. Basic construction of a miniature AT-strip resonator. The SA5730 uses a ceramic, rather than a glass, cover. The term "single-ended" refers to the canfilever mounting scheme of the quartz crystal plate within the ceramic package.

(a) Electrode pattern on the bottom of the package. The T-shaped electrode indicates where the mounting pads are within the package interior.

(b) Schematic cross-section representation of the SM2 electrode configuration. The thickness of the metallized layers are not to scale.

Figure 7. Electrode configuration of a miniature AT strip resonator.

The ensuing nickel plate is usually thin in the middle and thick along the edges. The minimum specified thickness of the nickel plate is 150 μ inches, with a maximum of 600 μ inches. Upon completion of the nickel plating process, the parts are then subjected to either tin or solder plating, again using the barrel process. The resulting plate is typically thick in the middle and thin along the edges. This final plate has a minimum specified thickness of 250 μ inches with a maximum of 650 μ inches (Figure 7) [Chuang and Burnett 1990; Dvorack 1992]. Finally, the SM3 termination is formed by taking the SM2 termination and performing a hot solder dip. The specified thickness for this solder dip is approximately 2000 μ inches [Dvorack 1992]. The SA3760 was made of SM2 terminations.

Fabrication of the quartz crystals is accomplished by photolithographic and chemical etching methods which have been in use at Statek Corporation since 1970 [Chuang and Burnett 1990]. Since this process can control crystal dimensions much more accurately

than by conventional mechanical means, miniaturization of quartz resonators can be easily achieved. Furthermore, since this process makes efficient use of the starting quartz wafer, many crystals can be batch-produced at one time, resulting in low production costs.

Quartz processing begins with a wafer that is optically polished on both sides. Both surfaces are then metallized with chromium and gold films. A photomask with an array of the image of the quartz resonator structure produces the same image on both sides of the quartz wafer with the use of photoresist material. After developing the photoresist material and chemically etching the gold and chromium films, the wafer is ready for quartz etching. In this etching process, gold film in the form of electrode patterns is used as a mask to protect the quartz surface while the resonator structure is being generated [Chuang and Burnett 1990]. Approximately 30 resonators can be made from a single quartz wafer [Chuang 1990a], in which the size of a single SA3760 resonator is approx-

imately 0.222 × 0.061 inch with a thickness of 0.0032 inch.* Because of the low radiation requirements for this device, electronic-grade quartz was used.

A schematic showing the physical dimensions of the SA3760 is shown in Figure 8; photos of this component are shown in Figures 9 and 10.

* Measurements performed by P. T. Vianco, Org. 1831, November 28, 1990.

INCHES (MILLIMETERS)			
REF	MIN	NOM	MAX
A	.053 (1.35)	.065 (1.65)	.080 (2.03)
B	.130 (3.30)	.140 (3.55)	.160 (4.06)
B1	.055 (1.40)	.060 (1.52)	.065 (1.65)
D	.305 (7.75)	.315 (8.00)	.335 (8.51)
L	.040 (1.02)	.050 (1.27)	.060 (1.52)
L1	.065 (2.41)	.105 (2.67)	.125 (3.18)

Figure 8. Physical dimensions of the SA3760.

Figure 9. Top and bottom views of the SA3760. The bottom view shows the SM2 termination (i.e., solder plate). Magnification is about 9.3X.

Figure 10. Three-dimensional view of the SA3760. Magnification is about 9.3X.

Electrical*

Figure 11 shows the equivalent circuit of a piezoelectric resonator. The elements R_1 , L_1 , and C_1 are the motional resistance, inductance, and capacitance, respectively, and are associated with the motion of the piezoelectric plate [Bottom 1982, 98]. The capacitance term C_0 is known as the static capacitance, and represents the static capacitance between the electrodes of the piezoelectric crystal, as well as any capacitance due to the crystal holder and lead wires [Heising 1985, 458]. Table 2 contains representative equivalent circuit values for the SA3760.

The two most important frequencies that can be obtained from the equivalent circuit are the series resonant frequency, f_s , and the parallel resonant (or antiresonant) frequency, f_a . It can be shown that these frequencies are given by the following expressions [Bottom 1982, 103-4]:

$$f_s = \frac{1}{2\pi} \sqrt{\frac{1}{L_1 C_1}}$$

$$f_a = \frac{1}{2\pi} \sqrt{\frac{1}{L_1 C_1} + \frac{1}{L_1 C_0}}$$

If a load capacitance, C_L , is connected in parallel with C_0 , then C_t is used instead of C_0 in the above expression for f_a , where $C_t = C_0 + C_L$. It can be seen from these two equations that, for a load capacitance of, say, 30 pF, the parallel resonant frequency will be slightly greater than the series resonant frequency.

Another important term is the quality factor, or Q , of the resonator. Q is defined by the expression [Frerking 1978, 29]:

$$Q = \frac{2\pi f L_1}{R_1}$$

where f is the operating frequency (e.g., f_s or f_a). This term is a measure of how long the energy within a piezoelectric crystal oscillates before dying out. The higher the Q , the better the short-term frequency stability of the crystal [Matthys 1983]. Table 2 contains representative values of Q for the SA3760.

* Quartz belongs to a class of materials called piezoelectric materials. In these materials, an applied stress causes an electric polarization. This effect is called the direct piezoelectric effect. Conversely, strain is induced in a piezoelectric crystal when placed in an electric field. This latter phenomenon is called the converse piezoelectric effect [Halliburton et al. 1985].

Figure 11. Equivalent circuit of a piezoelectric crystal resonator with a load capacitance, C_L . The elements R_1 , L_1 , and C_1 are the motional resistance, inductance, and capacitance, respectively, whereas C_0 represents the static capacitance.

Table 2. Representative room ambient equivalent circuit and Q values for the SA3760.

S/N	f_s (MHz)	R_1 (Ω)	L_1 (mH)	C_1 (fF)	C_0 (pF)	$Q \times 10^3$
1	19.99600	21.3319	8.05945	7.86043	3.59306	47.47
2	19.99620	21.3463	6.71064	9.44022	3.70806	39.50
3	19.99615	23.2318	6.42631	9.85783	3.46264	34.75
4	19.99625	19.2876	7.73276	8.19290	3.57815	50.37
5	19.99580	17.9895	7.53842	8.40394	3.56895	52.65

In specifying the operating characteristics of a crystal resonator, the term "effective resistance" is often used. Not to be confused with the motional resistance, the effective resistance is calculated when the crystal is being operated with a load capacitance

C_L . It can be shown that the effective resistance is related to the crystal's motional resistance by the relation [Frerking 1978, 229-30]:

$$R_E = R_1 \left(\frac{C_L + C_0}{C_L} \right)^2.$$

The crystal resonator's series resonant frequency and equivalent circuit parameters are determined by measuring the device on a network analyzer. For the SA3760 work, a Hewlett-Packard HP-4194A or HP-4195 network analyzer was used; a representative output is discussed in Appendix A. Slew measurements, which are measurements of series resonant frequency, equivalent circuit parameters, and Q vs. temperature ranging from -55°C to $+125^\circ\text{C}$, in 1°C increments at a drive level of 0 dBm, are performed in a Saunders temperature chamber interfaced to a computer and an HP-4195A network analyzer. Resulting plots of frequency and motional resistance vs. temperature can indicate the presence of unwanted vibration modes, as indicated by "bumps" in a frequency vs. temperature plot. Furthermore, the slew plots provide information on the deviation of both frequency and motional resistance from the nominal values with respect to temperature. Finally, as discussed earlier, the shape of the frequency vs. temperature plot is indicative of the type of quartz cut used to make the resonator.

Evaluation Testing

To ensure that the SA3760 would easily satisfy the electrical, mechanical, and thermal requirements, evaluation testing was performed in several areas, as illustrated in Figure 12. The devices that underwent such testing were characterized by slew measurements in which pre- and post-testing plots were superimposed on each other. Some of the mechanical and vibration tests were performed per Military Standard Test Methods and Procedures for Microelectronics [Mil-Std 883C]. The specific Mil-Std 883C test methods and procedures used in the mechanical shock, vibration, acceleration, and thermal shock testing of the SA3760 are listed in Appendix B. The non-Mil-Std conditions, which were also used in the evaluation testing, are listed in Table 3.

Figure 12. SA3760 evaluation summary.

Table 3. Non-Mil-Std test conditions used in evaluating the SA3760.

Test	Condition
Vibration	0.133 g ² /Hz, 10 to 3000 Hz, 20 g rms
Mechanical shock	10,000 g, 0.5 ms haversine, 6 axes, 3 shocks/axis
Thermal cycling	+25°C to -60°C to +130°C to +25°C, 30 min dwell time, ±6°C/min ramp rate
Constant acceleration	<ul style="list-style-type: none"> • Hold at 80 g for 4 sec and for 30 sec • Hold at 100 g for 10 sec • Hold at 200 g for 10 sec

Environmental Tests

Environmental testing of SA3760 units consisted primarily of having devices undergo a series of tests in succession, as illustrated in Figure 13. Failures were defined to be either breakage of the units or post-test slew plots that showed significant deviation with respect to the original slews taken initially. Results obtained for two devices, using the testing schemes shown in Figure 13(a) and (b), respectively, are presented in Figures 14 through 16. As illustrated by these figures, no significant degradation occurred in the frequency and motional resistance vs. temperature plots for these particular devices, which was representative of the others that had undergone such testing. These figures also show that mechanical shock can induce some frequency shift and motional resistance changes [Frerking 1978, 34]. As already noted in Figure 12, failures occurred only during mechanical shock testing at Mil-Std levels that were Condition C or greater. Such results were not surprising, because the Statek specifications for such devices call for a survival shock of 3000 g for a 0.5-ms sine pulse, the number of shocks per axis not being stated [Statek Corp.].

A final word about Figures 15 and 16. Note that there is a "bump" in the frequency vs. temperature characteristics at approximately 45°C (Figure 15) that coincides with a correspondingly large increase in the motional resistance at the same temperature (Figure 16). This effect is indicative of a "coupled mode," which is caused by coupling between the desired vibration mode of operation and some other vibrational mode that happens to have the same frequency at that temperature [Bottom 1982, 148-50]. The desired vibrational mode for an AT strip resonator is the fundamental "thickness shear" mode, whereby the main faces of the plate vibrate in a shearing motion in the x-direction, perpendicular to

that of the thickness. This thickness shear vibration mode, resulting in the frequency vs. temperature characteristic shape of Figure 14(a), is also known as the C thickness mode. (The B thickness shear mode is along the z-direction, whereas the A thickness mode is a dilatational vibrational mode along the y-direction.) These vibrational modes are illustrated in Figure 17 [Koehler 1992]. The unwanted mode that is coupled to the fundamental thickness shear vibrational mode cannot be deduced from Figures 15 and 16. This unwanted mode could be an inharmonic thickness shear mode, a face shear mode or one of its harmonics, a flexural mode, or a longitudinal mode [Bottom 1982, 148-50].

Effect of Physical Contact With a Soldering Iron

To address concerns regarding the ruggedness of the SA3760 during next-assembly rework, a simple experiment was performed in which a soldering iron was placed in direct contact with several units. The soldering iron was heated to 709°F ± 3°F (376.1°C ± 1.7°C) and allowed to stabilize at this temperature before making contact with the devices. This temperature is well above the maximum seal rim temperature of 280°C. The points of contact and the corresponding identification numbers of the devices are shown in Figure 18. Except for contact made at the center of the package lid, all points of contact with the devices were made at the seal rim. Contact duration was kept at 10 seconds in all cases, which is in excess of the 8-second maximum requirement [Material & Process Spec]. Furthermore, since this experiment was intended to "simulate" potential next-assembly soldering iron activities after the devices had already been surface-mounted, no contact was ever made to the bottom of any device.

Figure 13. Testing sequences used in performing most of the evaluation studies of the SA3760. Testing sequence (a) was carried out using devices with glass lids, whereas the other two sequences employed devices using ceramic lids.

(a) Frequency vs. Temperature

(b) Motional Resistance vs. Temperature

Figure 14. Series resonant frequency and motional resistance vs. temperature plots obtained for an SA3760 device, with a glass lid, while undergoing the testing sequence of Figure 13(a).

Figure 15. The effect of mechanical shock on the series resonant frequency of an SA3760 device, having a ceramic lid, while undergoing the testing sequence of Figure 13(b).

Figure 16. The effect of mechanical shock on the motional resistance of the SA3760 device described in Figure 15.

(a) Illustration of the three types of thickness vibration modes. Mode A is a dilatational mode along the thickness (y-) direction, B is the thickness shear vibrational mode along the z-direction, and C is the thickness shear vibrational mode along the x-direction. The SA3760 operates in the fundamental C mode, which produces the "sinusoidal" frequency vs. temperature characteristics of Figure 5(a).

(b) Illustration of the C thickness shear vibrational mode at two instants of time, as seen from the end of the plate.

Figure 17. Thickness vibrational modes of an AT-cut quartz plate.

Figure 18. AT strip resonator with a ceramic lid, showing the locations of direct contact with a soldering iron heated to 709°F. Identification numbers of individual devices that made direct contact with the soldering iron at specific locations are also indicated. Contact duration was 10 seconds in all cases.

Room ambient series resonant frequency and equivalent circuit parameter measurements were taken on all the resonators before making any contact with the soldering iron. Upon making direct contact, per Figure 18, the room ambient measurements were repeated. These readings are summarized in Table 4. A reference crystal that had not made contact with the soldering iron was measured at the same time as the others in order to obtain some idea of measurement variability.

The measurements listed in Table 4 indicate that no adverse effects were observed at room ambient temperature due to contact with the soldering iron for the duration chosen (10 seconds). These results infer that the integrity of the package-lid solder seal (80 wt% Au/20 wt% Sn, melting point 280°C) had been maintained. Since the devices were first measured individually in the same fixture, followed by heating with the soldering iron, and then reinserted into the same fixture for repeat measurements, minor differences that exist in the table can be attributed to the fixture itself (e.g., the slight variability due to placing a device within the fixture for several measurements).

A final test with the soldering iron was performed by taking device #10 and subjecting it to long contact times (~10 seconds along each width and ~20 sec-

onds along each length) with the soldering iron tip at the seal rim. This long contact time enabled the exposed surface of the seal solder to reflow when the tip, along a given side, was moved from one end to the other. The temperature of the soldering iron tip in this case was $714^{\circ}\text{F} \pm 1^{\circ}\text{F}$ ($378.9^{\circ}\text{C} \pm 1.1^{\circ}\text{C}$). As illustrated in Table 5, even a severe test such as this failed to result in any significant change in the resonator's room ambient equivalent circuit parameters. Furthermore, during this particular test it was impossible to move the lid at all while the soldering iron was in contact with the device.

Effect of Hermeticity Loss

To determine the effect of package hermeticity loss on the characteristics of the SA3760, several units having the same vacuum sealing pressure (1×10^{-11} torr) as those with ceramic lids were selected. After initially measuring the room ambient series resonant frequency and equivalent circuit parameters for each device, the lid of each device was either deliberately cracked or had a hole punched through it in order to break the vacuum. Figures 19 and 20 illustrate a crack and a hole in the glass lid for two given devices. The devices were then remeasured at room ambient; the results are summarized in Table 6.

Table 4. Comparison of room ambient frequencies and equivalent circuit values.

These were made before and after contact with a soldering iron tip having a temperature of $376.1^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$, for devices 1 through 8. The locations are those illustrated in Figure 17. The reference crystal (#9) had no contact with the soldering iron tip, and its frequency and equivalent circuit values were recorded after each set of measurements in order to have some idea of measurement variability between the respective readings.

Location	F (MHz)		R ₁ (Ω)		L ₁ (mH)		C ₁ (fF)		C ₀ (pF)		
	Before	After	Before	After	Before	After	Before	After	Before	After	
Top	#1	19.99625	19.9964	20.9173	20.4042	7.32739	7.24847	8.64555	8.73963	4.57987	4.6329
	#2	19.99725	19.99715	36.2572	36.2886	5.94637	5.95705	10.6525	10.6334	4.26075	4.30125
Corner	#3	19.99625	19.99625	19.4625	19.3926	5.34050	5.33178	11.8261	11.8815	4.27300	4.18550
	#4	19.99625	19.99625	46.6914	46.2784	7.33923	7.38271	8.63162	8.58075	4.30614	4.46403
Width	#5	19.99625	19.99625	20.5209	20.4552	8.07511	8.00533	7.84504	7.91340	4.56467	4.43947
	#6	19.99610	19.99625	26.5986	26.5583	7.24661	7.21882	8.74204	8.77565	4.61231	4.68274
Length	#7	19.99640	19.99640	30.1701	30.1968	6.56610	6.57060	9.64778	9.64116	4.54689	4.61139
	#8	19.99655	19.99655	41.2261	41.3327	6.05511	6.08658	10.4619	10.4077	4.07108	3.88189
Reference Unit	#9	19.99610	19.99610	30.3990	30.3902	7.11444	7.11077	8.90453	8.90912	4.29436	4.3904

Table 5. Comparison of room ambient frequencies and equivalent circuit values of device #10.

These were made both before and after long-term contact, at the package-lid seal rim, with a soldering iron having a temperature of 378.9°C (714°F). The contact duration was ~10 seconds along each width and ~20 seconds along each length.

F (MHz)	R ₁ (Ω)		L ₁ (mH)		C ₁ (fF)		C ₀ (pF)		
	Before	After	Before	After	Before	After	Before	After	
19.99625	19.99625	19.3025	19.5090	6.99229	6.96085	9.05991	9.10079	4.44310	4.35060

Table 6. Room ambient frequency and equivalent circuit parameters of 20-MHz single-ended AT strip resonators with glass lids.

Measurements were taken before and after exposure of the quartz plates to air. Devices #3, 4, and 5 had the lids cracked with a hammer, whereas devices #7, 8, 9, and 10 had holes punched through the lids (Figure 18). After creating a crack or a hole, an attempt was made to remove as much debris as possible from the quartz plate before measuring the resulting frequency and equivalent circuit parameters. Device #1, a reference crystal, was measured before and after the experiment in order to obtain some idea of the variability between readings. It is not clear why device #4 showed a dramatic increase in both frequency and motional resistance upon exposing the quartz plate to air.

Device #	F (MHz)		R ₁ (Ω)		L ₁ (mH)		C ₁ (fF)		C ₀ (pF)	
	Before	After	Before	After	Before	After	Before	After	Before	After
1*	19.99520	19.99515	33.6085	33.6592	6.69587	6.64727	9.46206	9.53120	4.01882	4.04881
3	19.99530	19.99530	39.0835	43.4221	6.56201	6.51951	9.65496	9.71794	4.10017	4.13797
4	19.99550	20.01915	35.7691	1.1143K	6.61776	421.539	9.57348	149.9E-3	3.85010	844.2E-3
5	19.99515	19.99500	45.8571	50.5285	6.00609	5.95860	10.5488	10.6329	4.28568	4.30717
7	19.99530	19.99530	32.7733	41.6722	5.99180	5.98145	10.5738	10.5781	3.99827	4.14889
8	19.99515	19.99515	44.7041	49.2815	6.45183	6.44846	9.81996	9.82515	4.03002	4.05207
9	19.99530	19.99515	34.9590	45.3537	6.16867	6.10225	10.2706	10.3826	4.09827	4.02337
10	19.99350	19.99335	35.5777	39.6122	5.64032	5.54432	11.2347	11.4293	4.05116	4.11936

*Reference Crystal

Device #3

Figure 19. SA3760 device (#3) with a glass lid showing a crack created by impact with a hammer. The magnification is about 19X.

Device #9

Figure 20. SA3760 device (#9) with a hole (upper right corner) punched through a glass lid. The magnification is about 19X.

In studying Table 6, it is worthwhile to note what should occur upon exposing these resonators, initially sealed in vacuum, to air. For example, Pinellas Plant has reported to Sandia that, for a 20-MHz circular resonator (AT-cut, thickness shear vibration mode) having a diameter of 0.25 inch, there will be a frequency shift of about 160 Hz, or 8 ppm [Koehler 1991]. On the other hand, exposure to air (from vacuum) of this resonator may not result in an observed frequency shift, since the thickness shear mode is not that sensitive to gaseous damping [Vianco 1991]. Additionally, Statek reported that a leak in the package of an AT strip resonator will result in an increase in the motional resistance [Chuang 1990b]. As can be seen in Table 6, every damaged resonator except one showed an increase only in the motional resistance, as predicted by Statek. Furthermore, Table 7 shows that no significant change in frequency was observed even after 4 days.

Thirty-Day Aging

To obtain some estimate of the frequency drift characteristics of the SA3760 over the proposed shelf life, thirty-day aging studies were performed on some units under the direction of R. S. Berg and D. B. Beightol (SNL Org. 2234). Results for two devices at 80°C are presented in Figure 21. It can be seen from these plots that the frequency drift is much less than 1 ppm for both units after 30 days. Projections based on plots like these indicate that the SA3760 can meet the ± 500 ppm drift requirement over 28 years.

Double-Ended Devices

The limiting factor in using commercially available miniature AT strip resonators is the mechanical shock requirement. This limitation is because the devices use a single-ended, or cantilever, design for the quartz crystal mounted within the package. As stated earlier, the specification for single-ended devices calls out mechanical shock levels of up to 3000 g peak for a 1-ms, half-sine pulse duration. Hence, for applications in a high-g shock mechanical environment (≥ 3000 g), modification in the resonator package design is necessary.

Statek Corporation was asked to carry out the design and fabrication of high-g shock miniature AT

strip resonators, based on the SA3760. As part of this requirement, it was specified that the external package configuration be identical to that of the current SA3760 design—that is, the same external physical dimensions and electrode footprints. This requirement would enable a user to replace the current SA3760 in a future design if the mechanical shock requirements became more severe.

The internal design of the package was to be such that the quartz crystal could easily withstand high-g shock levels as high as 20,000 g peak for both short (≤ 0.5 ms) and long (≥ 10 ms) pulse durations. To satisfy this requirement, Statek designed what is referred to as a “three-point mount,” or “double-ended,” configuration in which both ends of the quartz plate are secured within the resonator package.

Evaluation of the three-point mount design is currently underway at SNL/NM, and preliminary results are highly promising. The specifics of the design, fabrication, and subsequent evaluation studies of the high-g shock SA3760 are presented in a SAND report [Dvorack 1993].

Conclusion

The evaluation studies described in this report indicate that the SA3760 can meet the stated requirements for use in the MC4033 Common Radar. Furthermore, its low cost and ruggedness make the miniature AT strip resonator attractive for use in other applications as well. For example, a 12.288 MHz AT strip resonator, designated as the SA3812, has been successfully fabricated and qualified for use in the MC4226 clock. Except for the frequency, the SA3812 is identical to the SA3760. Development work is also underway at Statek Corporation for a double-ended (also called a three-point mount) resonator, as opposed to the current cantilever design, for use in high-g shock applications. Preliminary evaluation studies currently being performed at SNL appear to be promising. We anticipate that, as the AT strip resonator gains favorable attention from its use in these two applications, a family of qualified resonators of various frequencies will eventually be available to the DOE complex.

Table 7. Comparison of room ambient frequency and equivalent circuit parameters of devices listed in Table 6 upon initial exposure to air and after 4 days exposure.

Device #	F (MHz)		R ₁ (Ω)		L ₁ (mH)		C ₁ (fF)		C ₀ (pF)	
	Initial	4 Days	Initial	4 Days	Initial	4 Days	Initial	4 Days	Initial	4 Days
1*	19.99515	19.99520	33.6592	33.7138	6.64727	6.75612	9.53120	9.37772	4.04881	3.98416
3	19.99530	19.99520	43.4221	44.0895	6.51951	6.55954	9.71794	9.65873	4.13797	3.93347
4	20.01915	20.01875	1.1143K	0.9407K	421.539	399.114	149.9E-3	158.4E-3	844.2E-3	815.6E-3
5	19.99500	19.99490	50.5285	49.6823	5.95860	5.99515	10.6329	10.5682	4.30717	4.24517
7	19.99530	19.99505	41.6722	42.9044	5.98145	5.92747	10.5781	10.6888	4.14889	4.20653
8	19.99515	19.99505	49.2815	48.0600	6.44846	6.44930	9.82515	9.82398	4.05207	3.99094
9	19.99515	19.99490	45.3537	44.5998	6.10225	6.06933	10.3826	10.4391	4.02337	4.06202
10	19.99335	19.99325	39.6122	40.9734	5.54432	5.57176	11.4293	11.3732	4.11936	4.07444

*Reference Crystal

DATA FROM 9104sm1_22

DATA FROM 9104sm1_35

Figure 21. Thirty-day aging characteristics of two SA3760 units (#22 and #35) at 80°C.

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APPENDIX A

Impedance Measurements for a Piezoelectric Crystal Resonator

This appendix describes how the impedance (magnitude and phase angle) of a piezoelectric crystal resonator is determined and plotted. The equivalent circuit parameters obtained from a network analyzer are also illustrated.

To determine the impedance of a piezoelectric crystal resonator, use is made of the equivalent circuit shown in Figure A-1. For the sake of simplicity, the following terms are defined, where $\omega = 2 \pi f$:

For the motional arm:

$$X_m = \omega L_1 - 1/(\omega C_1)$$

$$Z_m = R_1 + jX_m .$$

The total reactance of the equivalent circuit is given by:

$$X_T = \omega L_1 - [1/(\omega C_1)] - [1/(\omega C_0)]$$

where

$$Z_0 = -j/(\omega C_0) .$$

The equivalent impedance of the circuit of Figure A-1, Z_e , is thus given by:

$$Z_e = (Z_0)(Z_m)/(Z_0 + Z_m) = [-j/(\omega C_0)] \times [R_1 + jX_m]/(R_1 + jX_T) .$$

After some algebraic manipulations, this last expression for Z_e reduces to:

$$Z_e = R_e + jX_e ,$$

where

$$R_e = (R_1) \times [1/(\omega C_0)]^2 / (R_1^2 + X_T^2)$$

and

$$X_e = [-1/(\omega C_0)] \times (R_1^2 + X_m X_T) / (R_1^2 + X_T^2) .$$

The magnitude of Z_e , $|Z_e|$, is given by $(R_e^2 + X_e^2)^{1/2}$ whereas the corresponding phase angle is given by $\tan^{-1}(X_e/R_e)$. Figure A-2 shows the results of calculating $|Z_e|$ and the corresponding phase angle as a function of frequency for a resonator assumed to have an equivalent circuit in which $R_1 = 50 \Omega$, $L_1 = 10 \text{ mH}$, $C_1 = 9 \text{ fF}$, and $C_0 = 3 \text{ pF}$. (fF stands

Figure A-1. Equivalent circuit for a piezoelectric crystal resonator.

for femtofarad, which is 10^{-15} farads.) Note that the impedance plot has a logarithmic vertical scale, which provides better resolution than a linear scale in identifying the series resonant frequency (where the impedance is a minimum) and the parallel resonant frequency (where the impedance is a maximum).

Figure A-3 shows a representative spectrum and equivalent circuit obtained for the SA3812 from an HP-4194A network analyzer. Note that the spectrum has both the impedance magnitude and phase angle plots (denoted as A and B, respectively) superimposed on each other, with the vertical axis scale for the impedance plot being logarithmic (the vertical axis for the phase angle plot is not displayed). The center of the display is at 12.288 MHz, with an entire span of 50 kHz. The markers (little circles) denote the location of the series resonant frequency and corresponding phase angle which, for this case, are 12.287 MHz and 4.25 degrees, respectively (ideally, the phase angle should be zero). The network analyzer also calculates the equivalent circuit parameters whose values would produce a spectrum closest to that displayed. Five equivalent circuit options are available; circuit E is the one that must be chosen.

Figure A-2. Calculated impedance magnitude and phase angle plots, as a function of frequency, for a piezoelectric crystal resonator having theoretical equivalent circuit values of $R_1 = 50 \, \Omega$, $L_1 = 10 \, \text{mH}$, $C_1 = 9 \, \text{fF}$, and $C_0 = 3 \, \text{pF}$.

A: |Z| B: θ $\circ$ MKR 12 287 000.000 Hz
A MAX 5.000 M Ω MAG 19.3939 Ω
B MAX 100.0 deg PHASE 4.25079 deg

A MIN 5.000 Ω CENTER 12 288 000.000 Hz
B/DIV 20.00 deg SPAN 50 000.000 Hz
SPAN=50000.000 HZ

EQUIVALENT CIRCUIT MODE

SELECTED : E

EQV R 15.4126 Ω EQV Ca 6.55103 fF
EQV L 25.6119 mH EQV Cb 2.49828 pF

SPAN=50000.000 HZ

Figure A-3. Representative room ambient spectrum and equivalent circuit values obtained for an SA3812 from an HP-4194A network analyzer.

APPENDIX B

Mil-Std 883C Test Methods and Procedures for Mechanical Shock, Constant Acceleration, Variable Frequency Vibration, and Thermal Shock

This appendix contains the Mil-Std 883C test methods and procedures used to perform some of the mechanical shock, vibration, and constant acceleration tests, as well as the thermal shock test, on the SA3760. It is important to note that the variable frequency vibration test (Method 2007.1) is not the same as the random vibration test (Method 2026). Although both methods test the component within a specified frequency range, the random vibration test is considered to be more characteristic of modern service-field requirements, such as missiles and rocket engines. However, while the random vibration test is not considered to be destructive, the variable frequency vibration test is considered to be such. The variable frequency vibration test was chosen to evaluate the design of the SA3760.

The thermal shock test was carried out as closely as possible to the Mil-Std test method, with the following exceptions: (1) air-to-air as opposed to liquid-to-liquid; (2) ~30 second transition time between temperature extremes rather than a 10-second transition time, and (3) a 10-minute dwell time was used at each temperature extreme rather than the 5-minute dwell time called out in the test method. These deviations from the Mil-Std test method were due to the fact that the climatic test facility was not set up for performing liquid-to-liquid thermal shocks.

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METHOD 1011.8

THERMAL SHOCK

1. PURPOSE. The purpose of this test is to determine the resistance of the device to sudden exposure to extreme changes in temperature. These conditions may be encountered in equipment operated intermittently in low temperature areas. Permanent changes in operating characteristics and physical damage produced during temperature shock result principally from variations in dimensions and other physical properties. Effects of thermal shock include cracking and delamination of substrates or wafers, opening of terminal seals and case seams, and changes in electrical characteristics due to moisture effects or to mechanical displacement of conductors or insulating materials.

* 2. APPARATUS. Suitable temperature-controlled baths containing liquids shall be chosen to obtain the temperature excursion specified in table I. See table II for physical property requirements of the perfluorocarbon fluids suggested for test conditions B, C, D, E, and F. The mass and arrangement of the load shall be such that the devices are uniformly exposed to the thermal shock extremes and the bath temperature shall not drift outside the specified tolerance.

3. PROCEDURE. The device shall be preconditioned by being immersed and in intimate contact with a suitable liquid at the temperature specified in step 1 of the specified test condition for a minimum of 5 minutes. Immediately upon conclusion of the preconditioning time, the device shall be transferred to a liquid at the temperature specified in step 2 of the specified test condition. The device shall remain at the low temperature for a minimum of 5 minutes and then be transferred to a liquid at the step 1 temperature. The device shall remain at the high temperature for a minimum of 5 minutes. Transfer time from high temperature to low temperature and from low temperature to high temperature shall be less than 10 seconds. Unless otherwise specified, using test condition A, the duration of the test shall be 15 complete cycles, where one cycle consists of proceeding from step 1 to step 2 and back to the beginning of step 1. One cycle consists of steps 1 and 2 or the applicable test condition and must be completed without interruption to be counted as a cycle. Completion of the total number of cycles specified for the test may be interrupted for the purpose of test chamber loading or unloading of device lots or as the result of power or equipment failure. However, if the number of interruptions for any given test exceeds 10 percent of the total number of cycles specified, the test must be restarted from the beginning.

3.1 Examination. After completion of the final cycle, an external visual examination of the marking shall be performed without magnification or with a viewer having a magnification no greater than 3X and a visual examination of the case, leads, or seals shall be performed at a magnification between 10X and 20X except the magnification for examination shall be 1.5X minimum when this method is used for 100 percent screening. This examination and any additional specified measurements and examination shall be made after completion of the final cycle or upon completion of group, sequence, or subgroup of tests which include this test.

3.2 Failure criteria. After subjection to the test, failure of any specified end-point measurements or examinations (see 4.d), evidence of defects or damage to the case, leads, or seals, or illegible markings shall be considered a failure. Damage to marking caused by fixturing or handling during tests shall not be cause for device rejection.

METHOD 1011.8
22 March 1989

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* TABLE I. Thermal shock temperature tolerances and suggested fluids. 1/

Test conditions		A	B	C	D	E	F
		Temperature	Temperature	Temperature	Temperature	Temperature	Temperature
Step 1	Temperature tolerance, °C	100 +10 -2	125 +10 -0	150 +10 -0	200 +10 -0	150 +10 -0	200 +10 -0
	Recommended fluid	Water 2/	Perfluoro-carbon 3/	Perfluoro-carbon 3/	Perfluoro-carbon 3/	Perfluoro-carbon 3/	Perfluoro-carbon 3/
Step 2	Temperature tolerance, °C	-0 +2 -10	-55 +0 -10	-65 +0 -10	-65 +0 -10	-195 +5 -10	-195 +5 -10
	Recommended fluid	Water 2/	Perfluoro-carbon 3/	Perfluoro-carbon 3/	Perfluoro-carbon 3/	Liquid nitrogen	Liquid nitrogen

1/ Ethylene glycol shall not be used as a thermal shock test fluid.

2/ Water is indicated as an acceptable fluid for this temperature range. Its suitability chemically shall be established prior to use. When water is used as the fluid for condition A and the specified temperature tolerances are insufficient due to altitude considerations, the following alternate test conditions may be used:

a. Temperature: 100°C -6°C, 0°C +6°C.

b. Cycles shall be increased to 20.

3/ Perfluorocarbons contain no chlorine or hydrogen.

* TABLE II. Physical property requirements of perfluorocarbon fluids. 1/

Test condition		B	C	D	E	F	ASTM test method
Step 1	Boiling point, °C	>125	>150	>200	>150	>200	D1120
	Density at 25°C gm/ml	>1.6					D941
	Dielectric strength volts/ml	>300					D877
	Residue, microgram/gram	<50					D2109
Step 2	Appearance	Clear, colorless liquid					Not applicable
	Density at 25°C gm/ml	>1.6					D941
	Dielectric strength volts/ml	>300					D877
	Residue, micrograms/gram	<50					D2109
	Appearance	Clear, colorless liquid					Not applicable

1/ The perfluorocarbon used shall have a viscosity less than or equal to the thermal shock equipment manufacturer's recommended viscosity at the minimum temperature.

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4. SUMMARY. The following details shall be specified in the applicable acquisition document:

- a. Special mounting, if applicable.
- b. Test condition, if other than test condition A (see 3).
- c. Number of test cycles, if other than 15 cycles (see 3).
- d. End-point measurements and examinations (see 3.1) (e.g., end-point electrical measurements, seal test (method 1014), or other acceptance criteria).

METHOD 2001.2
CONSTANT ACCELERATION

1. PURPOSE. This test is used to determine the effects of constant acceleration on microelectronic devices. It is an accelerated test designed to indicate types of structural and mechanical weaknesses not necessarily detected in shock and vibration tests. It may be used as a high stress test to determine the mechanical limits of the package, internal metallization and lead system, die or substrate attachment, and other elements of the microelectronic device. By establishing proper stress levels, it may also be employed as an in-line 100 percent screen to detect and eliminate devices with lower than nominal mechanical strengths in any of the structural elements.

2. APPARATUS. Constant acceleration tests shall be made on an apparatus capable of applying the specified acceleration for the required time.

3. PROCEDURE. The device shall be restrained by its case, or by normal mountings, and the leads or cables secured. Unless otherwise specified, a constant acceleration of the value specified shall then be applied to the device for 1 minute in each of the orientations X_1 , X_2 , Y_2 , Y_1 , Z_1 , and Z_2 . For devices with internal elements mounted with the major seating plane perpendicular to the Y axis, the Y_1 orientation shall be defined as that one in which the element tends to be removed from its mount. Unless otherwise specified, test condition E shall apply.

<u>Test condition</u>	<u>Stress level (g)</u>
A - - - - -	5,000
B - - - - -	10,000
C - - - - -	15,000
D - - - - -	20,000
E - - - - -	30,000
F - - - - -	50,000
G - - - - -	75,000
H - - - - -	100,000
J - - - - -	125,000

4. SUMMARY. The following details shall be specified in the applicable procurement document:

- a. Amount of acceleration to be applied, in gravity units (g) if other than test condition E (see 3).
- b. When required, measurements to be made after test.
- c. Any variations in duration or limitations to orientation (e.g., Y_1 only) (see 3).
- d. Sequence of orientations, if other than as specified (see 3).

METHOD 2001.2
31 August 1977

METHOD 2002.3

MECHANICAL SHOCK

1. **PURPOSE.** The shock test is intended to determine the suitability of the devices for use in electronic equipment which may be subjected to moderately severe shocks as a result of suddenly applied forces or abrupt changes in motion produced by rough handling, transportation, or field operation. Shocks of this type may disturb operating characteristics or cause damage similar to that resulting from excessive vibration, particularly if the shock pulses are repetitive.

2. **APPARATUS.** The shock-testing apparatus shall be capable of providing shock pulses of 500 to 30,000 g (peak) as specified with a pulse duration between 0.1 and 1.0 millisecond, to the body of the device. The acceleration pulse shall be a half-sine waveform with an allowable distortion not greater than ± 20 percent of the specified peak acceleration, and shall be measured by a transducer and optional electronic filter with a cut-off frequency of at least 5 times the fundamental frequency of the shock pulse. The pulse duration shall be measured between the points at 10 percent of the peak acceleration during rise time and at 10 percent of the peak acceleration during decay time. Absolute tolerances of the pulse duration shall be the greater of ± 0.1 millisecond or ± 30 percent of the specified duration.

3. **PROCEDURE.** The shock-testing apparatus shall be mounted on a sturdy laboratory table or equivalent base and leveled before use. The device shall be rigidly mounted or restrained by its case with suitable protection for the leads. Means may be provided to prevent the shock from being repeated due to "bounce" in the apparatus. Unless otherwise specified, the device shall be subject to 5 shock pulses of the peak (g) level specified in the selected test condition and for the pulse duration specified in each of the orientations X_1 , X_2 , Y_2 , Y_1 , Z_1 , and Z_2 . For devices with internal elements mounted with the major plane perpendicular to the Y axis, the Y_1 orientation shall be defined as that one in which the element tends to be removed from its mount. Unless otherwise specified, test condition B shall apply.

Test condition	g Level (peak)	Duration of pulse (ms)
A - - - - -	500	1.0
B - - - - -	1,500	0.5
C - - - - -	3,000	0.3
D - - - - -	5,000	0.3
E - - - - -	10,000	0.2
F - - - - -	20,000	0.2
G - - - - -	30,000	0.12

3.1 **Examination.** After completion of the test, an external visual examination of the marking shall be performed without magnification or with a viewer having a magnification no greater than 3X and a visual examination of the case, leads, or seals shall be performed at a magnification between 10X and 20X. This examination and any additional specified measurements and examination shall be made after completion of the final cycle or upon completion of a group, sequence, or subgroup of tests which include this test.

3.2 **Failure criteria.** After subjection to the test, failure of any specified measurements or examination (see 3 and 4), evidence of defects or damage to the case, leads, or seals, or illegible markings shall be considered a failure. Damage to marking caused by fixturing or handling during tests shall not be cause for device rejection.

4. **SUMMARY.** The following details shall be specified in the applicable procurement document:

- Test condition, if other than test condition B (see 3).
- Number and direction of shock pulses, if other than specified (see 3).
- Electrical-load conditions, if applicable (see 3).
- When required, measurement made after test (see 3 and 3.1).
- When required, measurement during test.

METHOD 2007.1

VIBRATION, VARIABLE FREQUENCY

1. **PURPOSE.** The variable frequency vibration test is performed for the purpose of determining the effect on component parts of vibration in the specified frequency range. This is a destructive test.

2. **APPARATUS.** Apparatus for this test shall include equipment capable of providing the required variable frequency vibration at the specified levels and the necessary optical and electrical equipment for post-test measurements.

3. **PROCEDURE.** The device shall be rigidly fastened on the vibration platform and the leads or cables adequately secured. The device shall be vibrated with simple harmonic motion having an amplitude of either 0.06 inches double amplitude (maximum total excursion) or the peak acceleration for test condition A, B, or C, as specified, whichever is less. The vibration frequency shall be varied approximately logarithmically between 20 and 2,000 Hz. The entire frequency range of 20 to 2,000 Hz and return to 20 Hz shall be traversed in not less than 4 minutes. This cycle shall be performed 4 times in each of the orientations X, Y, and Z (total of 12 times), so that the motion shall be applied for a total period of approximately 48 minutes, minimum. When specified, devices with an internal cavity containing parts or elements subject to possible movement or breakage during vibration shall be further examined by radiographic examination in accordance with Method 2012 or by delidding or opening and internal visual examination at 30X magnification to reveal damage or dislocation. Where this test is performed as part of a group or subgroup of tests, the post-test measurements or inspections need not be performed specifically at the conclusion of this test, but may be performed once at the conclusion of the group or subgroup.

<u>Test condition</u>	<u>Peak acceleration, g</u>
A - - - - -	20
B - - - - -	50
C - - - - -	70

3.1 **Examination.** After completion of the test, an external visual examination of the marking shall be performed without magnification or with a viewer having a magnification no greater than 3X and a visual examination of the case, leads, or seals shall be performed at a magnification between 10X and 20X. This examination and any additional specified measurements and examination shall be made after completion of the final cycle or upon completion of a group, sequence, or subgroup of tests which include this test.

3.2 **Failure criteria.** After subjection to the test, failure of any specified measurement or examination (see 3 and 4), evidence of defects or damage to the case, leads, or seals, or illegible markings shall be considered a failure. Damage to marking caused by fixturing or handling during tests shall not be cause for device rejection.

4. **SUMMARY.** The following details shall be specified in the applicable procurement document:

- a. Test condition (see 3).
- b. Measurements after test (see 3 and 3.1).

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