ULTRA^3 HIGH RELIABILITY SPACE OCXO & 4-POINT MOUNT 5x7mm SMT HYBRID OSCILLATOR SPACE QUALIFIED

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Richard L. Duong [1], Sergei Gulin [2]

[1] Q-Tech Corporation
10150 W. Jefferson Blvd.,
Culver City, CA 90232, USA
richard.duong@q-tech.com

[2] Q-Tech Corporation
10150 W. Jefferson Blvd.,
Culver City, CA 90232, USA
sergei.gulin@q-tech.com

ABSTRACT
Small size high performance Oven Controlled Crystal Oscillators (OCXOs) are in increasing demand as a reference source for satellite communication payloads and other space flight applications. The QT4200 maintains a space heritage from its predecessor QT4100 and obtains the following key features: Ultra miniature, ultra-rugged, and ultra-stable. It is designed to withstand radiation level up to 100 kRad(Si) total dose gamma exposures (with option 300kRad) as well as Heavy ion with no latch up behavior, high shock and vibration using low g-sensitivity SC cut crystal This paper addresses the development of the product starting with the selection of EEE parts, full Class S/K qualified to TOR-2006(8253)-5236 [1], radiation hardened at the highest quality level 1 suitable for missions requiring the highest reliability and lowest level of risk. It also presents the design using technology with a combination of both discrete component and hybrid module technology with exceptional electrical performance and reliability aspects through screening per MIL-PRF-55310, Level S and qualification tests including Random Vibration per MIL-STD-202, Test method 214, Condition IK (47.3grms) and mechanical shock per MIL-STD-883, test method 2002. Electrical Stress Analysis (ESA) and Worst Case Analysis (WCA) are also discussed to see the effect of degradation due to components variation due to temperature, radiation, and environment over the life of 15 years' operating in space.

The QT184 is the smallest offering surface Mount (SMT) 5x7mm space qualified hybrid crystal oscillator using a 4-point mount tested and qualified to MIL standards with highest reliability under extreme conditions. The paper presents the development through

components selection, screening and qualification steps which include random vibration at 46.32grms and mechanical shock at 20,000g peak, half-sine.

I. QT4200 Ovenized Crystal Controlled Oscillator (OCXO) INTRODUCTION

This first section of this paper presents an introduction of Q-Tech Ultra miniature, Ultra rugged, and Ultra stable Space grade OCXO QT4200 with outline dimensions of 2” x 1” x 0.75” (50.8mm x 25.4mm x 19.05mm).

Export Control Classification Number (ECCN): 9A515.e.1

Design and construction

The product level is S and designed as a Class 3 (Oscillators using mixed technology between hybrid and discrete technology) hermetically sealed to maximize the components layout in a package.

Figure 1. QT4200 OCXO

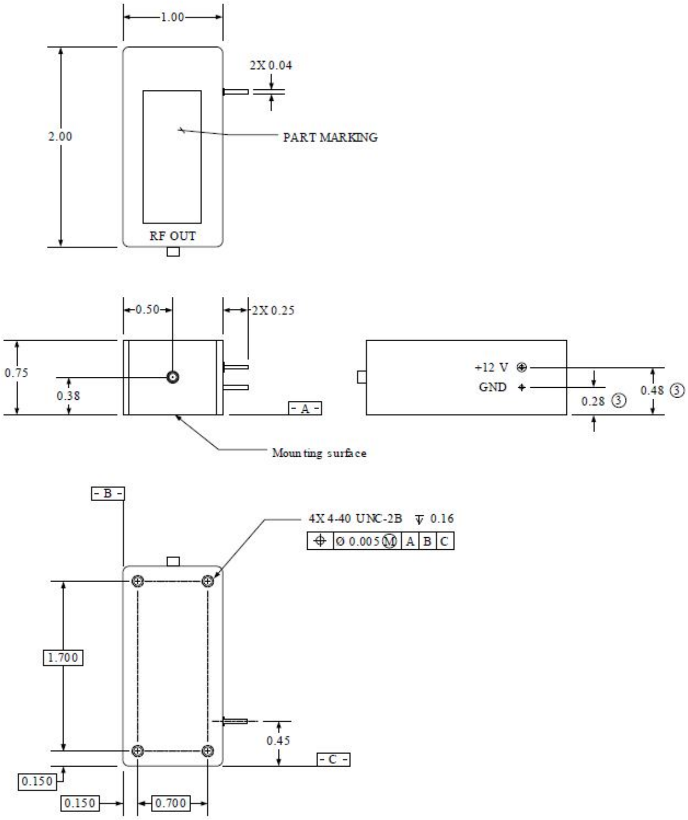


Figure 2. OCXO package outline
(Dimensions are in inches)

The construction and layout involved separate sections optimized for power supply management with power supply decoupling and bypassing capacitors as well as ground plane, along with thermal management controlling the air flow and heat transfer to reach and sustain thermal equilibrium.

- The main section consists of the oscillator sustaining stage providing gain and phase characteristics to sustain oscillations, the output stage which the signal is buffered with a microcircuit and then fed to a band pass filtering network to generate a sine output. The main board also included the heater MOSFET directly mounted close to the crystal. The crystal used in the design is a cold welded in a TO-5 package stress compensated (SC) that has a lower temperature turn point (LTTP) at the highest practical temperature of 80°C. The crystal was designed and used in the OCXO with several advantages as:

- o High Q factor
- o Low phase noise and best short-term stability
- o Improved warm-up characteristics
- o Improved thermal stability

The disadvantage of the SC cut crystal is it has two modes fairly close together the C and B modes. It is therefore essential that the design must have the capability to trap out the B mode.

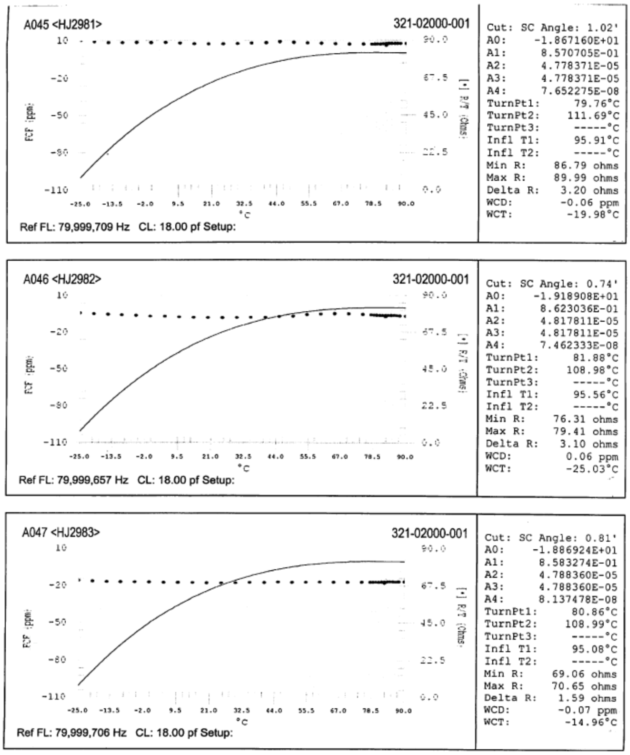


Figure 3. FVT curves showing LTTP of the SC cut 80MHz 5th Overtone

- The regulator section consists of an adjustable regulator set to generate the voltages Vregs for the main board and heater that control the electronics.

- The oven control and heater circuit section consists of the op amps. The oven control circuit is a proportional controller with an electronic system that continuously supplies power to the oven. The thermistor is heat sunk to the oven's case to sense temperature. The oven control varies the oven power constantly to continuously compensate the ambient temperature changes with worst at cold start temperature at -40°C.

Components selection

All components are selected meeting design criteria for quality level, Radiation tolerant, manufacturing processes and assemblies, derating, and meet the worst-case conditions over the life of the mission.

Table 1. Applicable military specification

Coils, chip	MIL-STD-981
Ceramic capacitors	MIL-PRF-123
Capacitors, tantalum, chip	MIL-PRF-55365
Resistors, film, chip	MIL-PRF-55342, level S
Thermistors	MIL-PRF-23648
Microcircuit	Table 960-1, Class K QML
Semiconductor	Table 960-2, Level HC
PCB	IPC-6012, Class S

Qualification tests

Vibration, Random (Operating) Test Standard: MIL-PRF-55310, PSD curve as per MIL-STD-202, Method 214, Condition I-G.

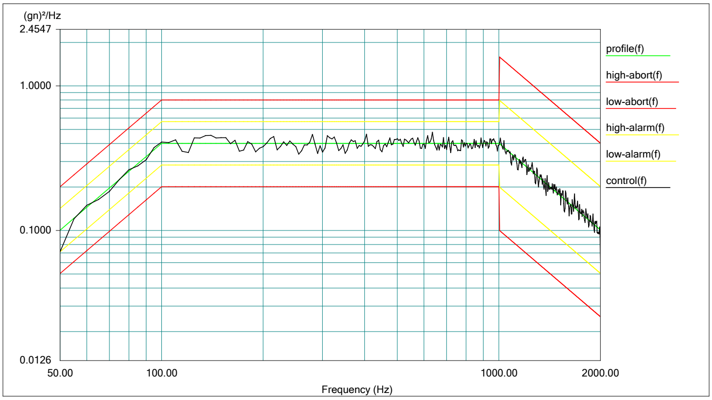


Figure 4. Random Vibration Qualification profile

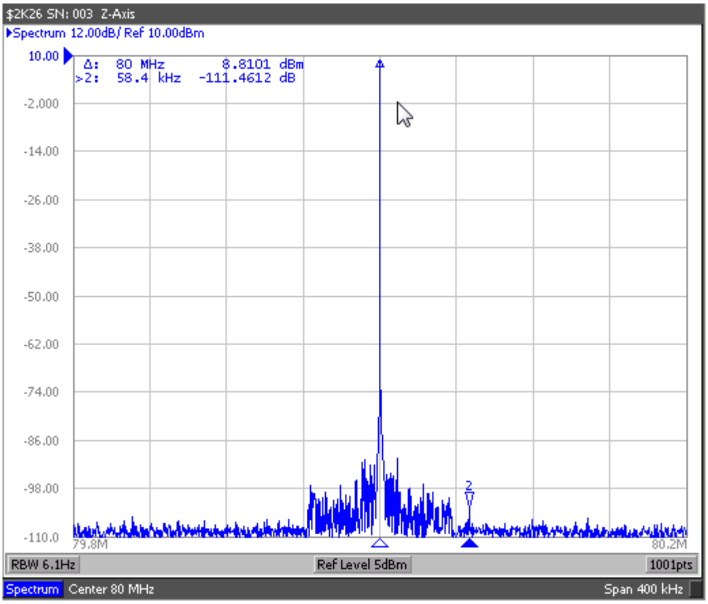


Figure 5. Output spectrum during Operating Vibration

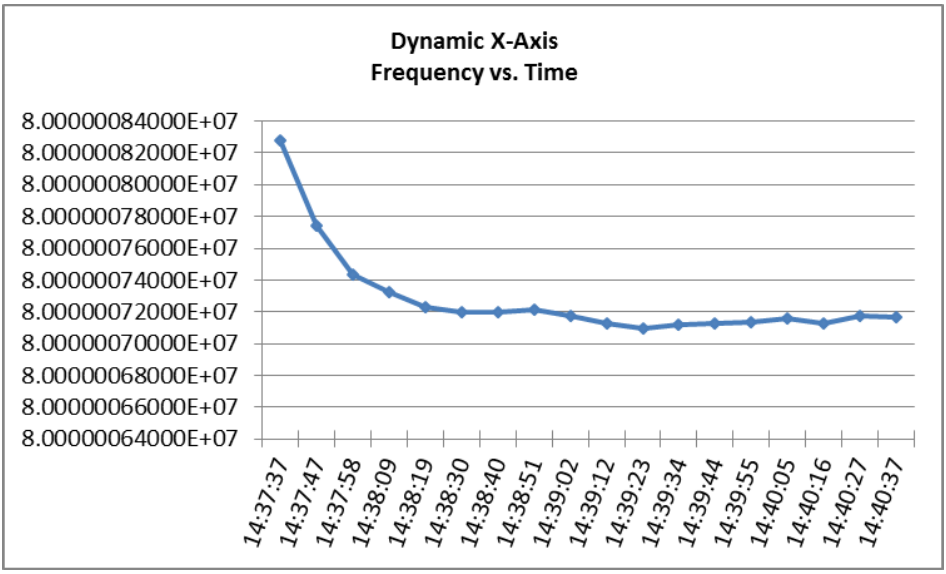


Figure 6. Frequency test during Operating Vibration

Mechanical shock Qualification tests

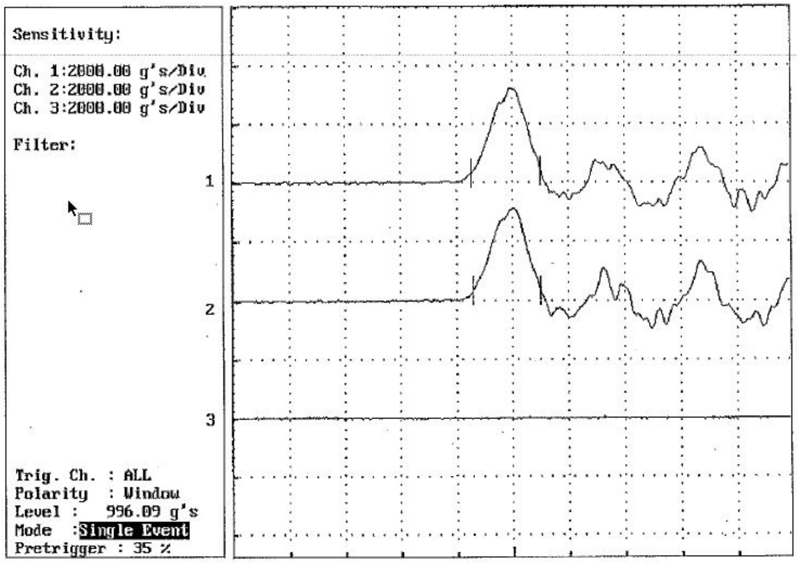
Shock (Operating) Test Standard: MIL-STD-883, Method 2002, Condition C

Waveform Test Report

GHI SYSTEMS, INC. CAT SYSTEM

DATE / TIME : Wed Apr 16 14 14:08
CUSTOMER : Q-Tech
PROJECT NO. : PR028200

TEST PROCEDURE: MIL-STD-883J Condition C
TEST TITLE : Mechanical Shock



CH	TIME	CUR AMP	PEAK AMP	1ST INT	2ND INT	TIME/DIV
* 1	240.00 µS	423.28 g's	3235.78 g's	193.29 In/s		0.2 mS
2	240.00 µS	358.28 g's	3141.48 g's	181.25 In/s		0.2 mS
3	46.08 mS	2.14 g's	-51.57 g's	-21.16 In/s		12.8 mS

Figure 7. Shock Response Spectrum SRS

g-sensitivity tests

Table 2. Vibration frequencies and side band amplitude on each axis

	Side Band Amplitude[dBc] X-Axis														
Vibration Frequency (Hz)	10	30	50	70	90	100	300	500	600	700	900	1000	1400	1700	2000
S/N 0003	-76.57	-88.01	-93.91	-97.20	-99.94	-101.83	-110.39	-95.98	-91.30	-107.80	-120.08	-118.69	-127.31	-129.16	-130.81

	G-Sensitivity[PPB/G] X-Axis														
Vibration Frequency (Hz)	10	30	50	70	90	100	300	500	600	700	900	1000	1400	1700	2000
S/N 0003	0.07	0.06	0.05	0.05	0.05	0.04	0.05	0.40	0.82	0.14	0.04	0.06	0.03	0.03	0.03

	Side Band Amplitude[dBc] Y-Axis														
Vibration Frequency (Hz)	10	30	50	70	90	100	300	500	600	700	900	1000	1400	1700	2000
S/N 0003	-67.14	-77.25	-80.96	-84.00	-86.07	-87.73	-94.66	-88.88	-82.47	-96.72	-107.42	-111.19	-119.30	-121.03	-114.72

	G-Sensitivity[PPB/G] Y-Axis														
Vibration Frequency (Hz)	10	30	50	70	90	100	300	500	600	700	900	1000	1400	1700	2000
S/N 0003	0.22	0.21	0.22	0.22	0.22	0.21	0.28	0.90	0.90	0.51	0.19	0.14	0.08	0.08	0.18

	Side Band Amplitude[dBc] Z-Axis														
Vibration Frequency (Hz)	10	30	50	70	90	100	300	500	600	700	900	1000	1400	1700	2000
S/N 0003	-86.14	-99.06	-105.42	-109.08	-112.99	-109.48	-122.25	-104.83	-93.65	-106.49	-124.51	-122.70	-125.95	-127.43	-128.48

	G-Sensitivity[PPB/G] Z-Axis														
Vibration Frequency (Hz)	10	30	50	70	90	100	300	500	600	700	900	1000	1400	1700	2000
S/N 0003	0.02	0.02	0.01	0.01	0.01	0.02	0.01	0.14	0.62	0.17	0.03	0.04	0.04	0.04	0.04

g-sensitivity = 1.3ppb/g

Performance results OCXO 80MHz, 11V, Sine wave, +8dBm output

Table 3. Test data 80MHz OCXO

S/N	Warm-up current (mA)	Steady state input current (mA)	Cold start (ms)	Output power (dBm)	Output frequency from nominal (ppm)	Harmonics (-dBc)
0597	334	143	8	8.51	-5.61	-52
0598	333	148	5	8.22	-4.28	-52
0599	334	166	5	8.48	-2.41	-52
0600	331	153	5	8.40	-3.69	-47

Table 4. Test data 80MHz OCXO (con'd)

S/N	Phase noise (dBc/Hz)					Spurious (dBc)	Short-term stability	
	10Hz	100Hz	1kHz	10kHz	100kHz		1s	10s
0597	-99.9	-130.7	-151	-161.4	-161.5	-108	1.97×10^{-10}	6.2×10^{-10}
0598	-104	-133.2	-151	-160.8	-162	-121	1.97×10^{-10}	1.97×10^{-10}
0599	-103	-132	-153	-160	-162	-121	1.72×10^{-10}	6.8×10^{-10}
0600	-108	-134.8	-153	-160	-162	-120	1.63×10^{-10}	5.6×10^{-10}

Figure 8. Phase noise 80MHz OCXO

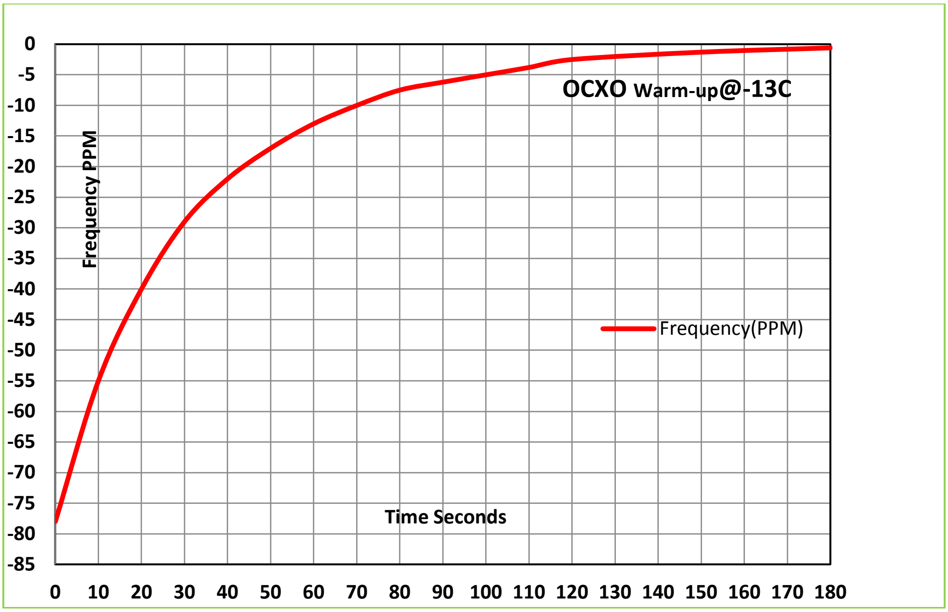


Figure 9. Warm-up time versus frequency

Worst-Case Analysis

This analysis [2] will verify that the part will operate under worst-case conditions of tolerance, power supply, temperature, radiation, end-of-life effects and thermal shock.

The worst-case analysis analyzes the followings:

- Component variations with combined tolerance EOL plus thermal shock and Radiation effect, if any.
- The start-up gain with different hFE between the low and high values. The simulation shows that with hFE equal or greater than the high values might cause the oscillator to start at a higher frequency.
- The start-up and undesired mode rejection between the C and the B mode.
- Aging by measurement and prediction 0.6ppb/day and prediction of 0.22ppm over the life of the mission of 15 years.
- Phase noise at BOL and EOL
- Frequency stability over temperature at BOL and EOL
- Load sensitivity
- Output amplitude at BOL and EOL
- Harmonic distortion
- The analysis is divided into three sections:
    - Voltage regulator (worst-case delta of voltage)
    - Oscillator (Impedance, start-up gain, and gain margin between C and B modes)

- Output (worst-case output power, and harmonics derived from the band-pass filter circuit and response)
- Oven Control and Heater (The control circuit is viewed as a closed loop servo system. Both electrical and thermal feedback are employed in the OCXO, resulting in a complex analysis that approximates the warm up and cool down time constants as well as thermal resistances. This analysis needs to be confirmed by actual measurement of the response of the heater circuitry. For this review, an actual measurement of circuit performance was conducted in lieu of a completed theoretical analysis.

For complete details please download the data sheet in Q-Tech web site www.q-tech.com under Space application, catalog number QPDS-0106.

II. 5x7mm SPACE QUALIFIED CLOCK OSCILLATOR INTRODUCTION

This section of this paper presents an introduction of Q-Tech smallest surface Mount (SMT) 5x7mm space qualified hybrid crystal oscillator using a 4-point mount tested and qualified to MIL standards with highest reliability under extreme conditions [5].
Export Control Classification Number (ECCN): EAR99

Design and construction
The product level is S and designed as a Class 2 (Oscillators using hybrid technology) hermetically sealed with active die 100 kRad (Si) tolerant and an AT-cut swept quartz.

5x7mm 4-point mount Space grade product offerings

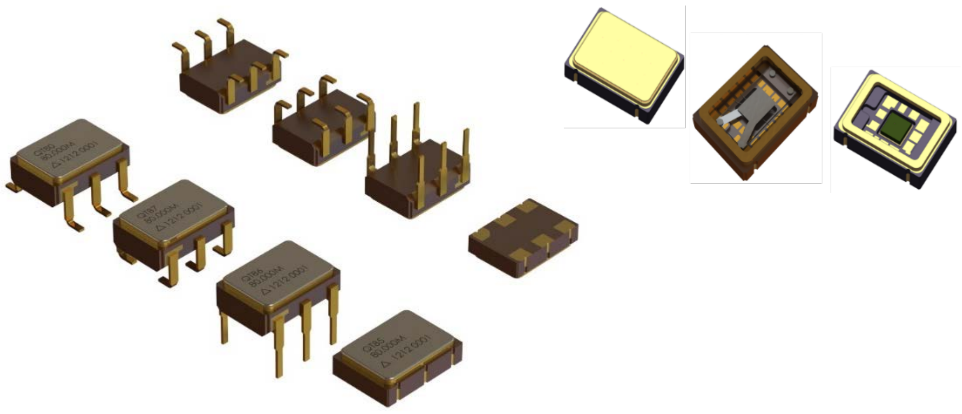


Figure 10. Packages 5x7mm SMT and leaded 4-point mount

Table 5. Products logic, voltage, and frequency range

Logic	Frequency range (MHz)	Supply voltage (V)	5x7mm Packages
ACMOS	0.5 - 85	5	All
ACMOS	0.5 - 70	3.3	All
CMOS	70 – 162.5	3.3 & 2.5	All
LVDS	80 – 200	3.3 & 2.5	6-pads SMT & leaded
LVPECL	80 – 200	3.3 & 2.5	6-pads SMT & leaded

AT cut quartz crystals and resonator electrodes are designed uniquely for each application to overcome issues with couple mode and activity dips. Crystal angles and quartz blank geometry are selected carefully to optimize over the wide range of operating temperature [3].

The oscillator electronics integrated circuit (IC) is mounted on a ceramic high temperature co-fired header with gold metallization suitable for gold and aluminum wire bonding.

A unique mounting process has been developed for the crystal and oscillator electronics as shown in Figure 10. The design is optimized to enable high performance in harsh environmental conditions. Verification and validation tests are performed per MIL-PRF-55310 Level S as well as MIL-PRF-38534, Class K.

The critical aspect of the design is to decouple the quartz crystal from the severe mismatch of the expansion coefficients or quartz crystal in the X and Z directions to the ceramic package in all planes. To do this, a special adhesive was developed for this purpose. Also, the mounting stresses and torque applied the quartz blank during the mounting and curing processes had been optimized. The curing process had to be developed to minimize all stress and also maximize the degassing of the adhesive and package components for best aging [4]. The materials and process are proprietary to Q-Tech Corporation.

Figure 11 shows the aging of a 40MHz over 30 days period per MIL-PRF-55310 at +70°C±2°C. The aging plot, which shows consistency is a key measure of success in decoupling the crystal from its mounting stress.

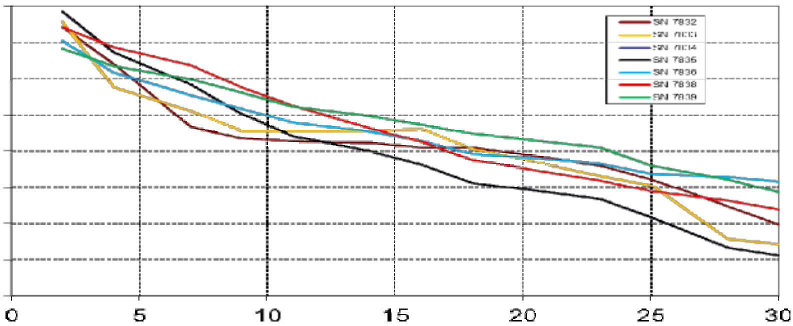


Figure 11. Aging data 30days at +70°C of a 40MHz Fundamental AT-cut 5x7mm

Figure 12 shows the phase noise plot of a 5x7mm 4-point mount 20MHz, 3.3Vdc. G-sensitivity tested is between 2 to 3ppb/g.

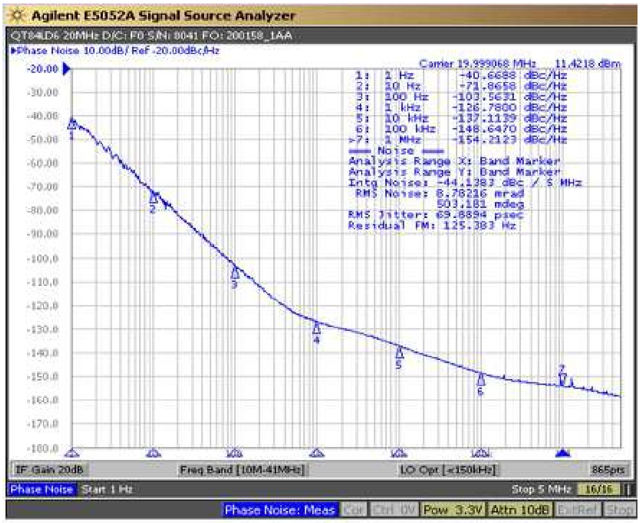


Figure 12. Phase noise plot of a 20MHz Fundamental AT-cut 5x7mm

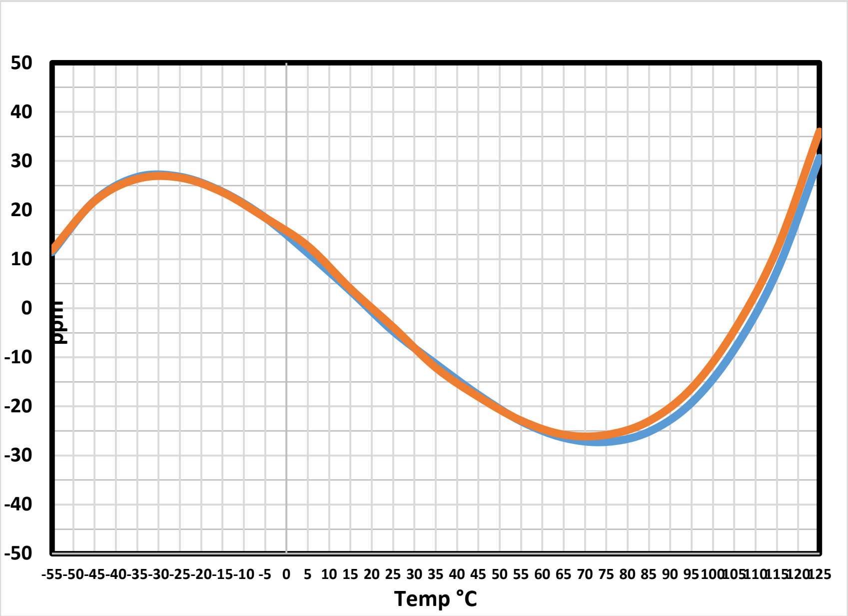


Figure 13. Frequency vs. temperature plot of a 32MHz Fundamental AT-cut 5x7mm

Shock qualification tests

Figure 14 shows the test fixture, shock equipment, shock pulse and response spectra of a 20,000g shock test, half-sine, 0.1ms, 3 shocks in each axis (a total of 18 shocks) on a 5x7mm 4-point mount 32MHz Fundamental AT-cut oscillator. Table 8 shows the delta shift in frequency passes the specification of less than ±3ppm.

Table 6. Delta frequency Pre and Post 20,000g shock, 0.1ms, half-sine

Serial #	Pre-shock ppm	Post-shock ppm	Delta ppm
8437	-52.0	-54.8	-2.8
8438	-45.0	-46.1	-1.1
8439	-51.6	-52.0	-0.4
8440	-25.2	-25.0	0.2
8441	-28.8	-27.6	1.2
8442	-63.4	-63.3	0.1

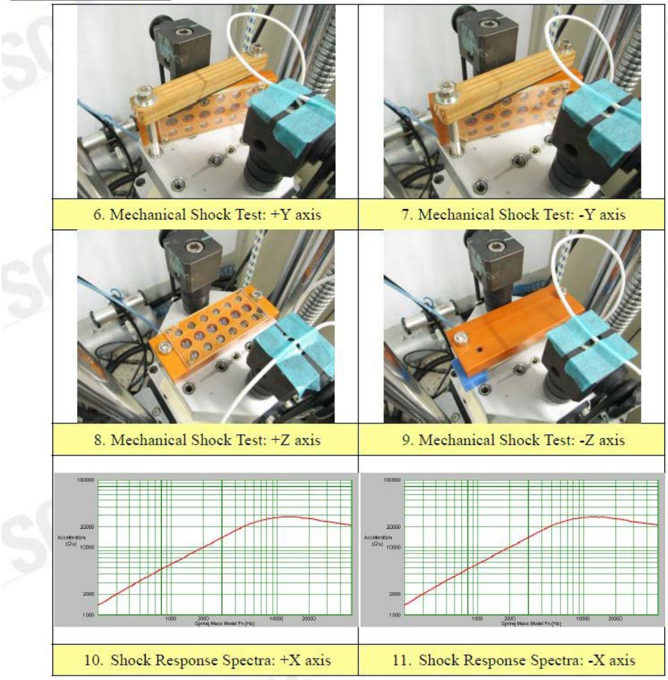


Figure 14. Shock test 20,000g, half-sine, 0.1ms

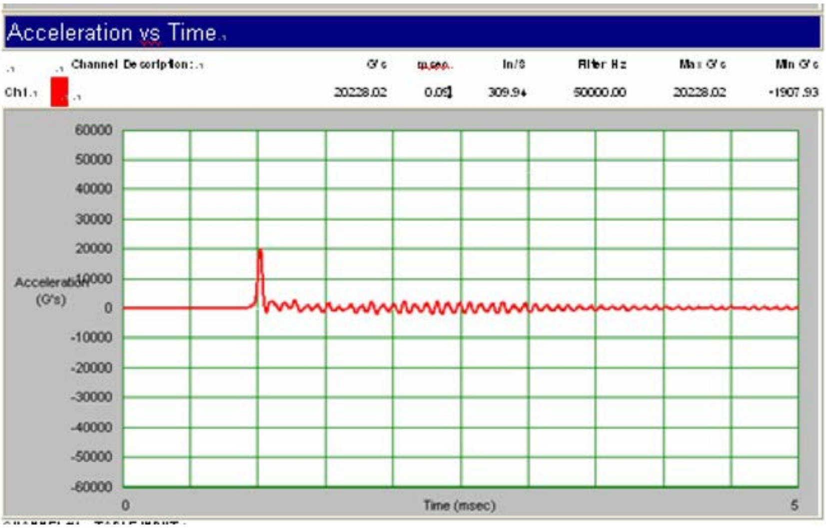


Figure 15. Shock test 20,000g, half-sine, 0.1ms

Table 7 shows initial Qualification tests of the Space qualified 4-point mount hybrid oscillators

Table 7. Qualification tests

Test description	MIL-STD	Method, Cond.	Status
Crystal mount pull test	N/A	20-40gf	Pass
Internal Water vapor (RGA)	883	5011	Pass
Internal Visual	883	5017	Pass
Stabilization Bake	883	1008, C	Pass
Thermal shock	883	101, C	Pass
Temperature Cycling	883	1010, B	Pass
Constant Acceleration	883	2001, A, Y1	Pass
Seal Fine and Gross	883	1014, A1, C	Pass
P.I.N.D test	883	2020, B	Pass
Pre Burn-In	55310	-	Pass
Burn-In	55310	240 hours, +125°C	Pass
Final Electrical	55310	-	Pass
Group A Electrical	55310	100%	Pass
Group B Aging	55310	70°C±3°C, 30 days	Pass
Group C	55310	Subgroups 1 to 4	Pass
Life test	38534	1,000hrs, +125°C	Pass
Mechanical shock	202	213, 10,000g and 20,000g, ½ sine	Pass
Random Vibration	202	214, I-K, 46.30g rms	Pass

For complete details please download the data sheet in Q-Tech web site www.q-tech.com under Space application, catalog number QPDS-0001.

REFERENCES

[1] "Technical Requirements for Electronic Parts, Materials, and Processes used in Space and Launch Vehicles", *2013.*
[2] Benjamin Parzen, "Design of Crystal and Other Harmonic Oscillators", *John Wiley & Sons, Inc. 1983.*
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[5] George Maronich, Annamalai Vishwanathan, and Richard Duong, "A Four Point Mount 5x7mm High Reliability Crystal Oscillator for Extreme Environmental Applications", *2016 IEEE International Frequency Control Symposium (IFCS).*

AUTHOR

Richard Duong [(1)] received the Bachelor of Sciences in electrical engineering degree (BSEE) from California State University Los Angeles in 1990, the Master of Sciences in electrical engineering degree (MSEE) and a candidate of Master of Business Administration (MBA) from California State University Long Beach in 1994.
He joined Q-Tech Corporation, an AS9100 company manufacturing high-reliability of crystal oscillators since 1982. He is now the Director of Engineering at Q-Tech Corporation. His function included the design of hybrid crystal oscillators for both B and S levels of MIL-PRF-55310.
His experience also included eight years in the automotive industry and familiar with QS9000 and AEC-Q200 quality standards.
He is currently a member of IEEE and IMAPS.