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Long-Term Aging of Oscillators

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***Abstract*— A search performed in connection with a recent review of the literature on oscillator aging has revealed very few reports on the long term (e.g., for periods greater than 1 year) aging of oscillators. The purpose of this paper is to report aging results for more than 40 oscillators, from a variety of sources, for periods ranging from 1 year to more than 10 years. The aging data were accumulated with an automated aging facility. The oscillators that have been on test include temperature compensated crystal oscillators (TCXO's) and oven-controlled crystal oscillators (OCXO's). The TCXO's were maintained in a controlled temperature environment. Several of the TCXO'zs were built for a gun-launched sensor application and have been shown to be capable of surviving more than 30 000-g shock levels of 12 ms duration. The aging of these ruggedized TCXO's are surprisingly good ($<2 \times 10^{-10}$/d). The better OCXO's exhibit long term aging of a few parts in 10^{12}/d.**

I. Introduction

AGING is the systematic variation of frequency with time when all environmental parameters are held constant [1]. A search performed in connection with a recent review of the literature on oscillator aging [2] revealed very few reports on long term aging (e.g., for periods greater than 1 year.) The purpose of this paper is to report representative aging results from tests on more than 40 oscillators, from a variety of sources, for periods ranging from 1 year to more than 10 years. (Since many of the commercial oscillators were purchased 10 or more years ago, the aging results reported on in the following may not have much relevance to current capabilities.) Some of the oscillators were not well behaved, i.e., some exhibited short term instabilities much greater than the aging per day. Oscillators that were not well behaved initially did not improve upon extended aging. Only the aging of well behaved oscillators are shown in Figs. 1–32.

The oscillators that have been on test include commercially available and prototype temperature compensated crystal oscillators (TCXO's), commercially available ovenized crystal oscillators (OCXO's), prototype ovenized tactical miniature crystal oscillators (TMXO), [3] and prototype bulk-wave crystal resonators in specially built ovenized test oscillators [3]. All of the oscillators and prototype resonators were less than 1 year old when started on aging.

TCXO aging data were collected while the devices were maintained in a controlled temperature environment at $+60° \pm 1°$C or at $-40° \pm 2°$C. The ovenized oscillators were in laboratory ambient whenever data were being collected (the internal thermal control circuit maintained the resonators at a turnover temperature.) In several instances, oscillators were subjected to temperature changes; in some cases a return to room temperature, in other cases the oscillators were cooled to temperatures below $-40°$C.

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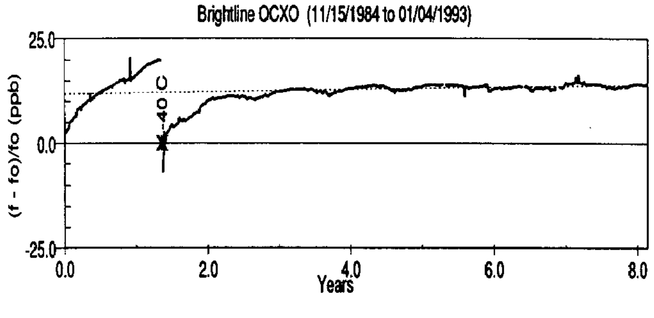


Fig. 1. OCXO–5.0 MHz, 5th O/T, AT-cut, glass enclosed resonator. The slope of the reference line is $+7.5 \times 10^{-13}$/d. (Resonator: Bliley Electric Co.; Oscillator: Brightline, Inc.)

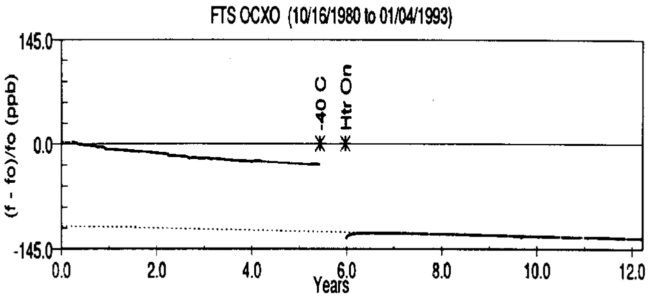


Fig. 2. OCXO–5.115 MHz, 5th O/T, AT-cut resonator. The slope of the reference line is -3.7×10^{-12}/d. The thermal fuse failed during exposure to $-40°$C. The oscillator was running but the heater was not on between the time marked "$-40°$C" and the time marked "Htr On." (Resonator: Bliley Electric Co.; Oscillator: Model 1001, Frequency & Time Systems.)

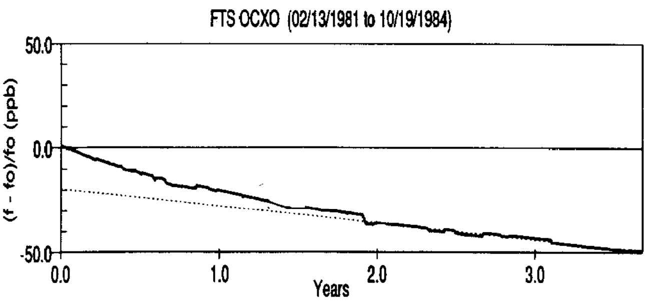


Fig. 3. OCXO–5.0 MHz, 5th O/T, AT-cut resonator. The slope of the reference line is -2.2×10^{-11}/d. (Resonator: Bliley Electric Co.; Oscillator: Model 1100, Frequency & Time Systems.)

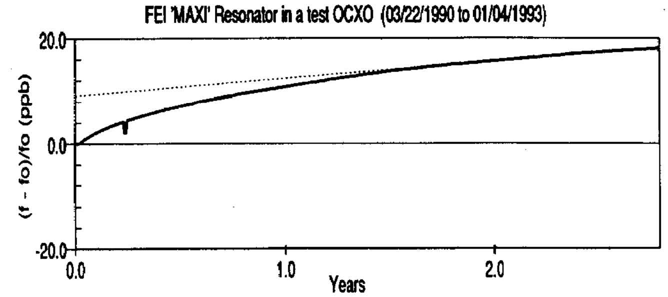


Fig. 4. OCXO–2.5 MHz, 25 mm diameter, SC-cut resonator. The slope of the reference line is $+9.1 \times 10^{-12}$/d. (Resonator: Frequency Electronics, Inc.; Test oscillator: Bendix Corp.)

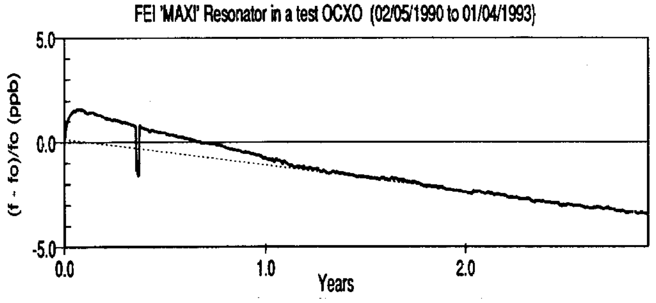


Fig. 5. OCXO–2.5 MHz, 25 mm diameter, SC-cut resonator. The slope of the reference line is -3.4×10^{-12}/d. (Resonator: Frequency Electronics, Inc.; Test oscillator: Bendix Corp.)

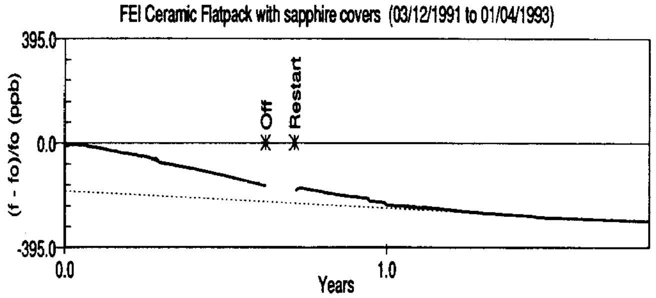


Fig. 6. OCXO–5.0 MHz, 3rd O/T, SC-cut resonator enclosed in a ceramic flatpack with sapphire covers. The slope of the reference line is -1.7×10^{-10}/d. The oscillator and oven was off between the time marked "Off" and the time marked "Restart." (Resonator: Frequency Electronics, Inc.; Test oscillator: Bendix Corp.

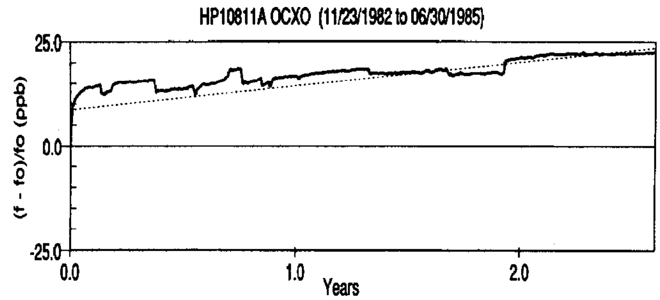


Fig. 7. OCXO–10 MHz, 3rd O/T, SC-cut resonator. The slope of the reference line is $+1.6 \times 10^{-11}$/d. (Resonator and Model 10811A oscillator: Hewlett-Packard Co.)

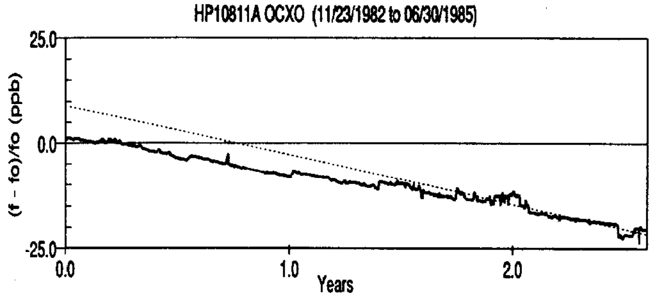


Fig. 8. OCXO–10 MHz, 3rd O/T, SC-cut resonator. The slope of the reference line is -3.2×10^{-11}/d. (Resonator and Model 10811A oscillator: Hewlett-Packard Co.)

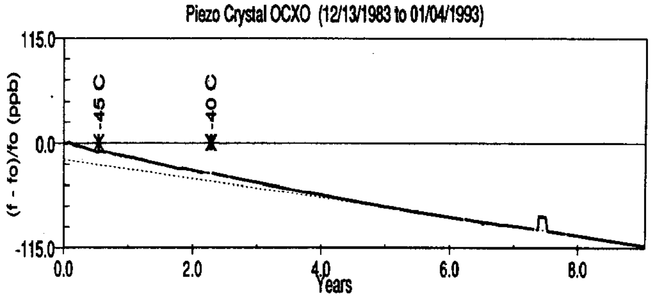


Fig. 9. OCXO–10 MHz, 3rd O/T, SC-cut resonator. The slope of the reference line is -2.9×10^{-11}/d. The oven and oscillator was turned off for 3 d on 2 occasions. Once for exposure to −45°C and once for exposure to −45°C. (Resonator and model 2810007-1 oscillator: Piezo Crystal Co.)

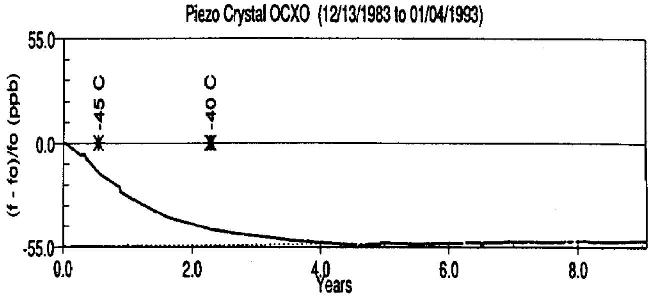


Fig. 10. OCXO–10 MHz, 3rd O/T, SC-cut resonator. The slope of the reference line is $+9.4 \times 10^{-13}$/d. (Resonator and model 2810007-1 oscillator: Piezo Crystal Co.) The oven and oscillator was turned off for 3 d on 2 occasions. Once for exposure to −45°C and once for exposure to −40°C.

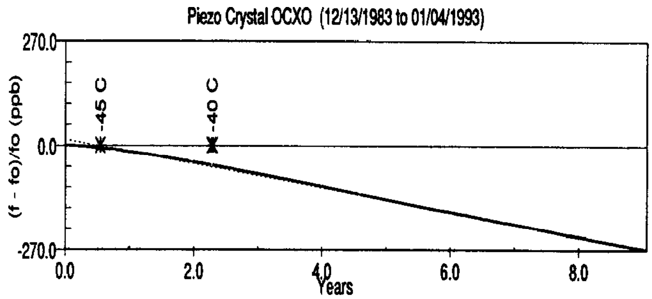


Fig. 11. OCXO–10 MHz, 3rd O/T, SC-cut resonator. The slope of the reference line is -8.6×10^{-11}/d. The oven and oscillator was turned off for 3 d on 2 occasions. Once for exposure to −45°C and once for exposure to −40°C. (Resonator and model 2810007-1 oscillator: Piezo Crystal Co.)

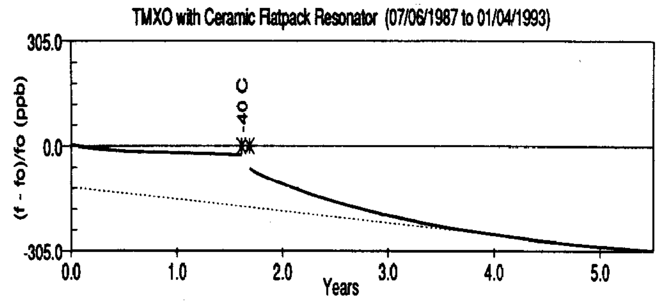


Fig. 12. TMXO–10 MHz, 3rd O/T, SC-cut, ceramic flatpack enclosed resonator. The slope of the reference line is -9.5×10^{-11}/d. The oven and oscillator were turned off for 3 d for exposure to $-40°$C. (Resonator: Army/GEND; Oscillator: Bendix Corp.)

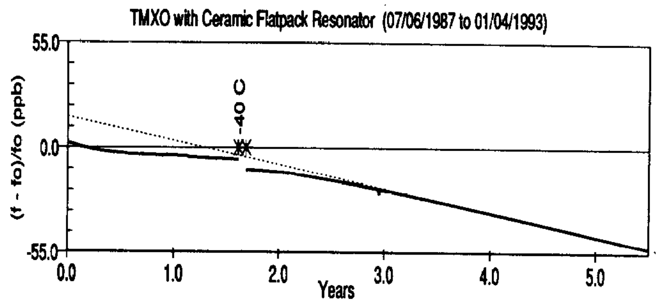


Fig. 13. TMXO–10 MHz, 3rd O/T, SC-cut, ceramic flatpack enclosed resonator. The slope of the reference line is -3.4×10^{-11}/d. The oven and oscillator were turned off for 3 d for exposure to $-40°$C. (Resonator: Army/GEND; Oscillator: Bendix Corp.)

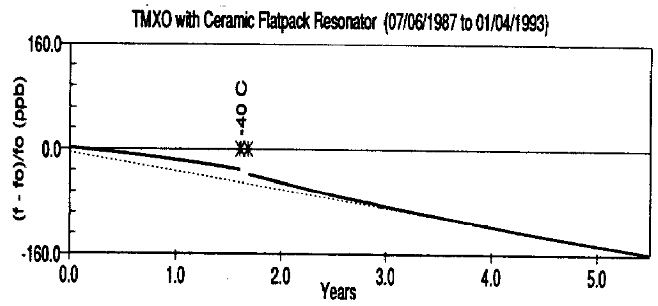


Fig. 14. TMXO–10 MHz, 3rd O/T, SC-cut, ceramic flatpack enclosed resonator. The slope of the reference line is -7.7×10^{-11}/d. The oven and oscillator were turned off for 3 d for exposure to $-40°$C. (Resonator: Army/GEND; Oscillator: Bendix Corp.)

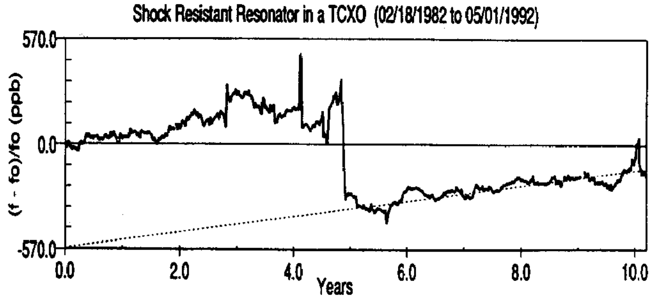


Fig. 15. TCXO–Shock resistant, 21.9375 MHz, fundamental mode, AT-cut, ceramic flatpack enclosed resonator. The slope of the reference line is

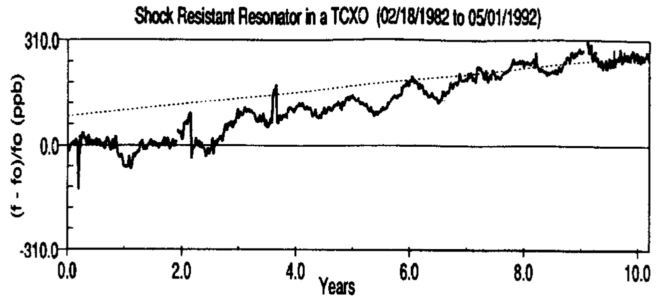


Fig. 16. TCXO–Shock resistant, 21.9375 MHz, fundamental mode, AT-cut, ceramic flatpack enclosed resonator. The slope of the reference line is $+4.9 \times 10^{-11}$/d. (Resonator: Army/GEND; Oscillator: RCA.)

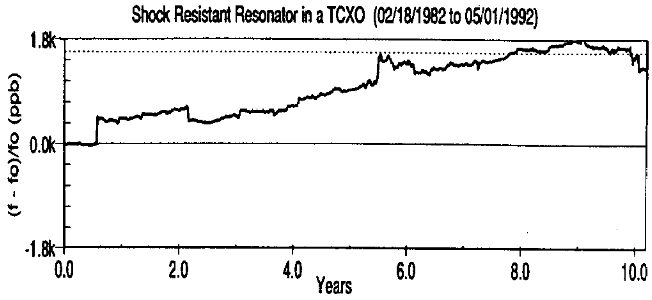


Fig. 17. TCXO–Shock resistant, 21.9375 MHz, fundamental mode, AT-cut, ceramic flatpack enclosed resonator. The slope of the reference line is -3.4×10^{-12}/d. (Resonator: Army/GEND; Oscillator: RCA.)

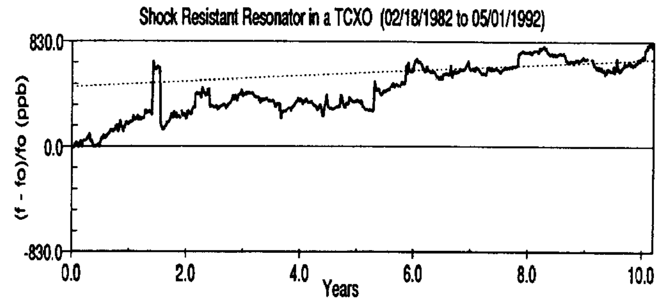


Fig. 18. TCXO–Shock resistant, 21.9375 MHz, fundamental mode, AT-cut, ceramic flatpack enclosed resonator. The slope of the reference line is $+5.8 \times 10^{-11}$/d. (Resonator: Army/GEND; Oscillator: RCA.)

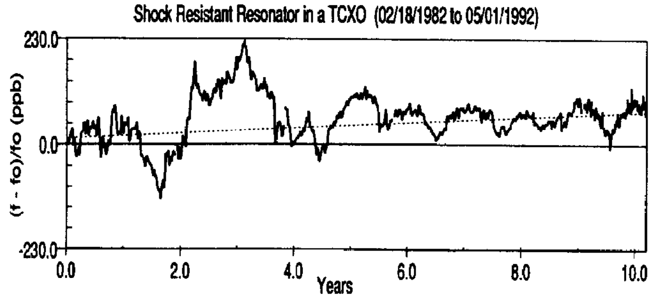


Fig. 19. TCXO–Shock resistant, 21.9375 MHz, fundamental mode, AT-cut, ceramic flatpack enclosed resonator. The slope of the reference line is

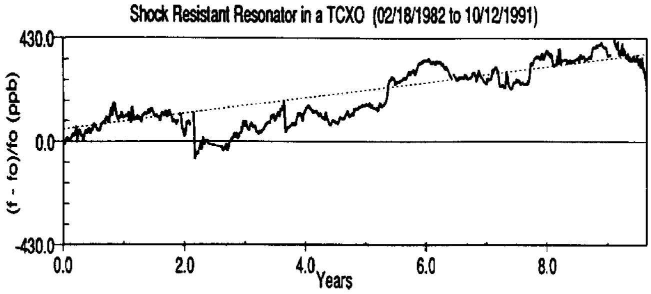


Fig. 20. TCXO–Shock resistant, 21.9375 MHz, fundamental mode, AT-cut, ceramic flatpack enclosed resonator. The slope of the reference line is $+9.0 \times 10^{-11}$/d. (Resonator: Army/GEND; Oscillator: RCA.)

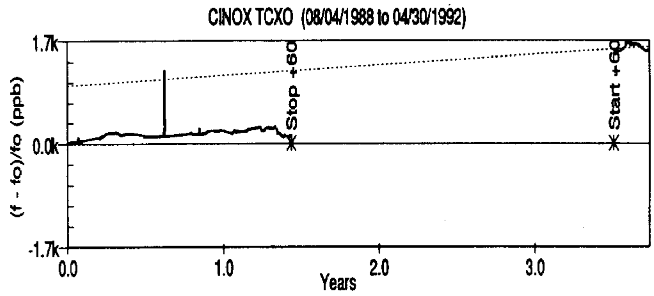


Fig. 24. TCXO–3.2 MHz. The slope of the reference line is $+4.6 \times 10^{-10}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: Cinox.)

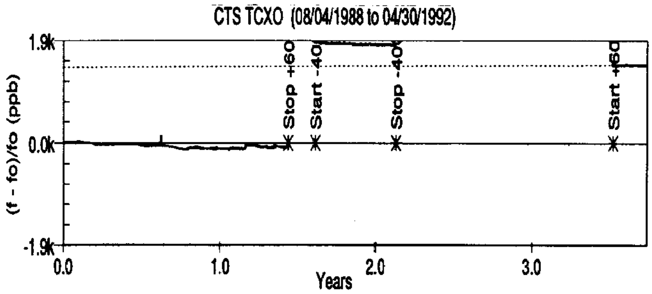


Fig. 21. TCXO–3.2 MHz. The slope of the reference line is $+3.2 \times 10^{-11}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: CTS.)

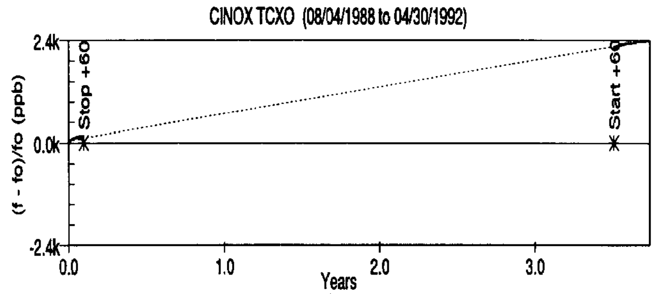


Fig. 25. TCXO–3.2 MHz. The slope of the reference line is $+1.7 \times 10^{-9}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: Cinox.)

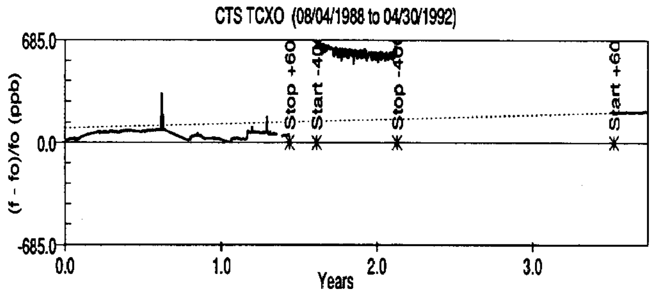


Fig. 22. TCXO–3.2 MHz. The slope of the reference line is $+7.8 \times 10^{-11}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: CTS.)

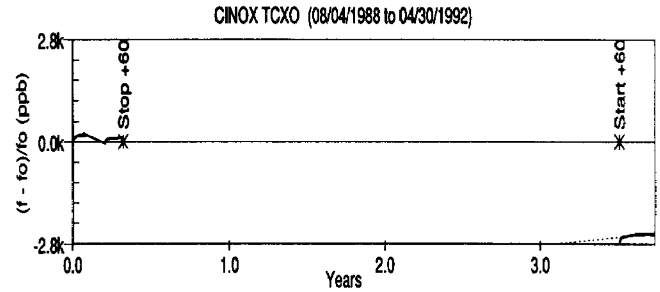


Fig. 26. TCXO–3.2 MHz. The slope of the reference line is $+1.3 \times 10^{-9}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: Cinox.)

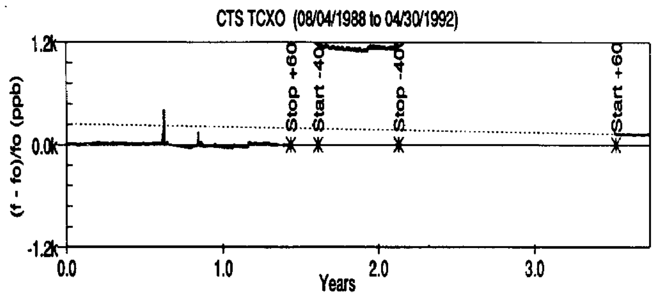


Fig. 23. TCXO–3.2 MHz. The slope of the reference line is -9.5×10^{-11}/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: CTS.)

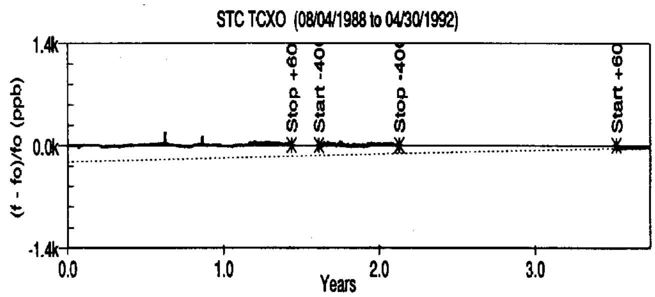


Fig. 27. TCXO–3.2 MHz. The slope of the reference line is $+1.4 \times 10^{-10}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: STC.)

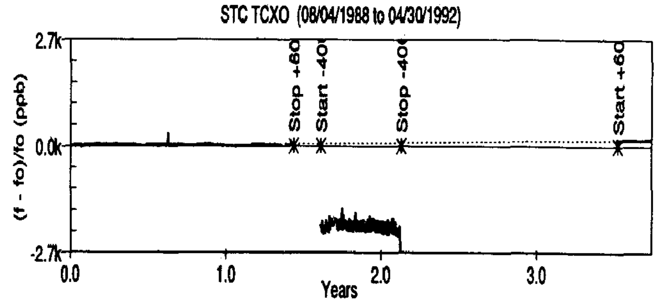


Fig. 28. TCXO–3.2 MHz. The slope of the reference line is $+1.4\times10^{-10}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: STC.)

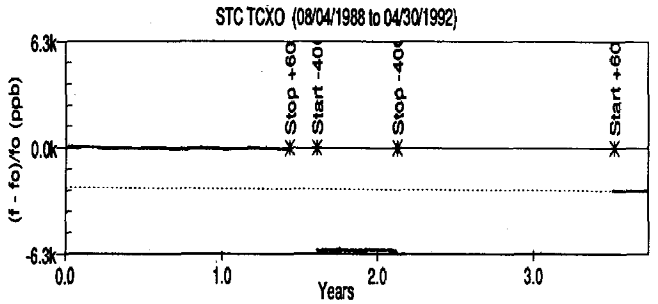


Fig. 29. TCXO–3.2 MHz. The slope of the reference line is -1.3×10^{-10}/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: STC.)

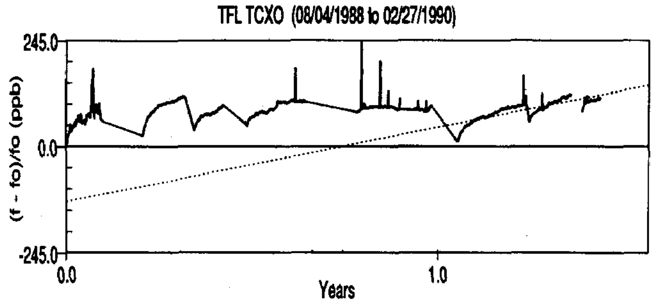


Fig. 30. TCXO–3.2 MHz. The slope of the reference line is $+4.7\times10^{-10}$/d. (Oscillator: TFL.)

The aging data were accumulated with an automated aging facility established in 1980 [4]. The frequency reference was an HP5601 cesium standard. Frequency was measured with an HP5345 counter from a single reading with a gate time of 100 s, or an HP5335 or HP5370 counter from an average of 10 readings each with a gate time of 10 s for a typical resolution of parts in 10^{11}.

II. Aging Graphs

The aging graphs show aging behaviors, and the effects of interruption and temperature change. On all of the aging graphs, the ordinate is the reduced frequency, y, in units of parts per billion (ppb), where

$$y_k = \frac{\Delta f_k}{f_o} = \frac{f_k - f_o}{f_o}$$

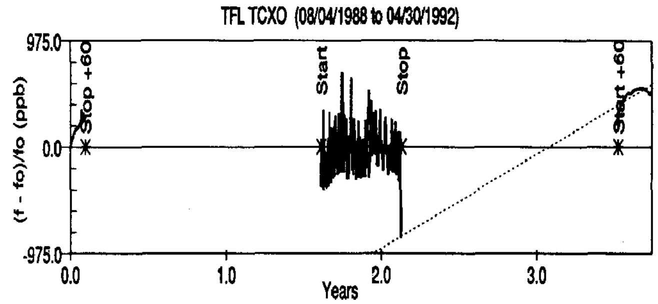


Fig. 31. TCXO–3.2 MHz. The slope of the reference line is $+2.4\times10^{-9}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: TFL.)

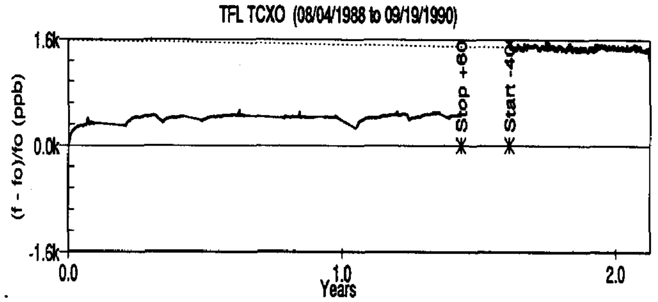


Fig. 32. TCXO–3.2 MHz. The slope of the reference line is $+1.8\times10^{-10}$/d. The oscillator was at room temperature and not powered during the periods without data. (Oscillator: TFL.)

On each graph there is a straight line included for reference. The slope and intercept of this straight line are determined from a least squares fit to the data between the days indicated. This straight line is not intended to indicate that the aging rate is constant, but is included to facilitate comparison of aging behaviors.

Table I is a summary of the OCXO's and Table II is a summary of the TCXO's. That the TCXO's generally exhibited a higher aging rate than the OCXO's is probably due to the fact that TCXO's use fundamental mode resonators, whereas the OCXO's use third and fifth overtone resonators. Fundamental mode resonators (of the same frequency) have a higher surface to volume ratio, which results in larger frequency shifts due to the effects of surface related phenomena such as adsorption and desorption of contamination and changes at the electrodes. Also, since fundamental mode resonators have a larger motional capacitance than overtone resonators, oscillators using fundamental mode resonators are more susceptible to changes in the oscillator circuitry (i.e., to changes in load reactance).

III. Logarithmic Fit

The function $y = A\ln(Bt+1)$ has been proposed as a candidate for extrapolation of the initial 30 d of aging data to periods in excess of 1 year [2], [5]. For many oscillators, extrapolation of the logarithmic function obtained from fitting the first 30 d of data is a poor predictor of the subsequent aging. In general, for well-behaved oscillators that are maintained at a constant temperature, using a longer period to curve fit the data results in a logarithmic function that usually provides a better

TABLE I
SUMMARY OF O VERSIZED OSCILLATORS

Fig	Osc. Manufact.	Freq	Cut	O/T	Package	Res. Manufact.	Start	Stop	Notes
1	Brightline	5	AT	5th	Glass	Bliley	11/84	1/93	Subjected to −40°C
2	FTS	5	AT	5th	Glass	Bliley	10/80	1/93	Subjected to −40°C; Heater failed (Oven off)
3	FTS	5.115	AT	5th	Glass	Bliley	2/81	1/84	Oven on continuously
4	Bendix Test Osc.	2.5 25 mm	SC	3rd	Metal/glass	FEI	3/90	1/93	Oven on continuously
5	Bendix Test Osc.	2.5 25 mm	SC	3rd	Metal/glass	FEI	3/90	1/93	Oven on continuously
6	Bendix Test Osc.	5.0	SC	3rd	Ceramic/sapphire	FEI	3/91	1/93	Oven off for a period
7	HP	10	SC	3rd	Metal/ceramic	HP	11/82	6/85	Oven on continuously
8	HP	10	SC	3rd	Metal/ceramic	HP	11/82	6/85	Oven on continuously
9	Piezo	10	SC	3rd	Metal/glass	Piezo	12/83	1/93	Subjected to −45°C and −40°C
10	Piezo	10	SC	3rd	Metal/glass	Piezo	12/83	1/93	Subjected to −45°C and −40°C
11	Piezo	10	SC	3rd	Metal/glass	Piezo	12/83	1/93	Subjected to −45°C and −40°C
12	Bendix TMXO	10	SC	3rd	Ceramic	GEND	7/87	1/93	Subjected to −40°C
13	Bendix TMXO	10	SC	3rd	Ceramic	GEND	7/87	1/93	Subjected to −40°C
14	Bendix TMXO	10	SC	3rd	Ceramic	GEND	7/87	1/93	Subjected to −40°C

TABLE II
SUMMARY OF TEMPERATURE COMPENSATED CRYSTAL OSCILLATORS

Fig	Osc.	Start	Stop	Freq	
15	RCA	2/82	5/92	22	(Note A)
16	RCA	2/82	5/92	22	(Note A)
17	RCA	2/82	5/92	22	(Note A)
18	RCA	2/82	5/92	22	(Note A)
19	RCA	2/82	5/92	22	(Note A)
20	RCA	2/82	5/92	22	(Note A)
21	CTS	8/88	4/92	3.2	(Note B)
22	CTS	8/88	4/92	3.2	(Note B)
23	CTS	8/88	4/92	3.2	(Note B)
24	CINOX	8/88	4/92	3.2	(Note C)
25	CINOX	8/88	4/92	3.2	(Note C)
26	CINOX	8/88	4/92	3.2	(Note C)
27	STC	8/88	4/92	3.2	(Note B)
28	STC	8/88	4/92	3.2	(Note B)
29	STC	8/88	4/92	3.2	(Note A)
30	TFL	8/88	2/90	3.2	(Note A)
31	TFL	8/88	4/92	3.2	(Note B)
32	TFL	8/88	4/92	3.2	(Note D)

Note A: Aged continuously at +60°C.

Note B: Aged at +60°C; stored at room temperature; aged at −40°C; stored at room temperature; then aged again at +60°C.

Note C: Aged at +60°C; stored at room temperature; then aged again at +60°C.

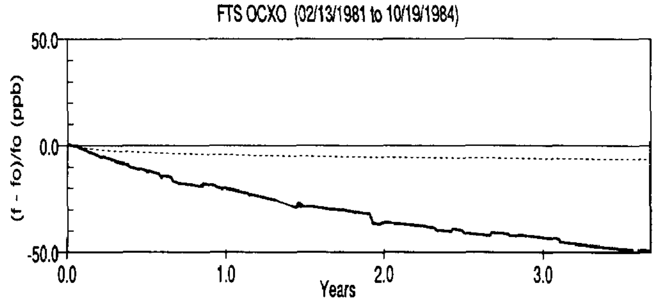
Note D: Aged at +60°C; stored at room temperature; then aged again at −40°C.

from the first 30 d of aging data is a poor predictor of the initial 60 and 300 d (Fig. 33(b) and (c)) provide better and better ability to predict the actual aging. Fig. 34(a)–(c) shows a counterexample; extrapolation from the 60-d fit (Fig. 34(b)) deviates more from the actual long term aging data than does extrapolation from a 30-d fit (Fig. 34(a)), although the 300-d fit (Fig. 34(c)) matches the actual data well.

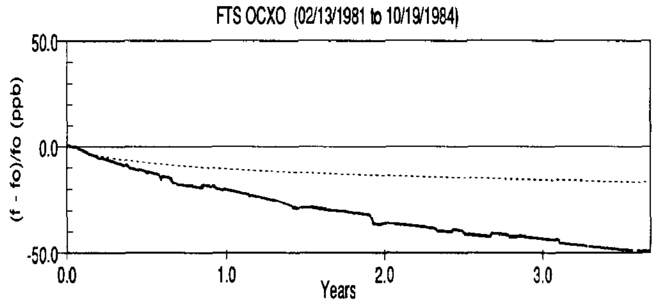
A review of the aging graphs will show that "nonlogarithmic" behavior seems to be the norm and not the exception. If the temperature changes or the power is interrupted, the situation is even worse. The parameters of the logarithmic aging model obtained from the first 30 d of data may be a good indicator of process control but are not very useful as a performance indicator during long term field use.

IV. CONCLUSIONS

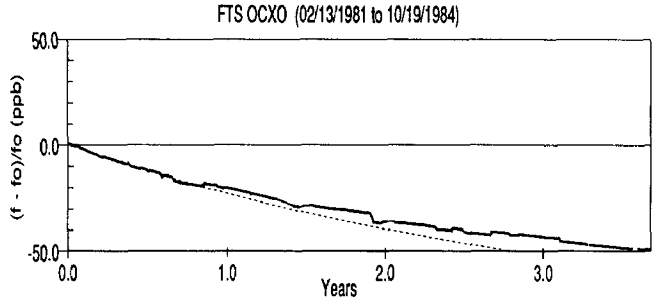
It is difficult to make a general rule about long term aging performance prediction. All one can say is that oscillators which started out good remained good and the poor performers remained poor. It is important to note that aging direction can reverse in time. This usually occurs early, but in one case it happened after 4.5 years (see Fig. 10). A logarithmic fit to the first 30 d is a poor indicator of long term performance especially when the oscillators experience large environmental disturbances (such as a temperature change.) It is true, however, that the aging rate generally decreases with time, although in at least one case, it has been increasing for over eight years (see Fig. 11). A relatively safe upper bound on the frequency change is a linear extrapolation from the slope calculated from a logarithmic curve fit. However, due to the rapidly changing slope of the frequency



(a)

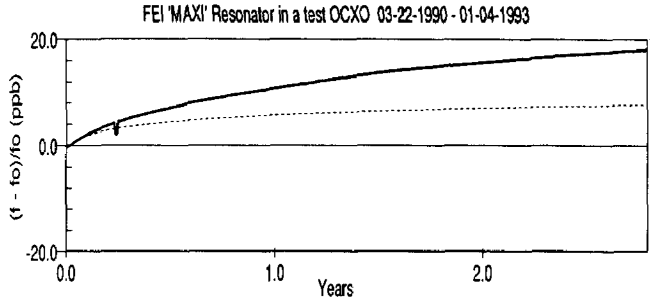


(b)

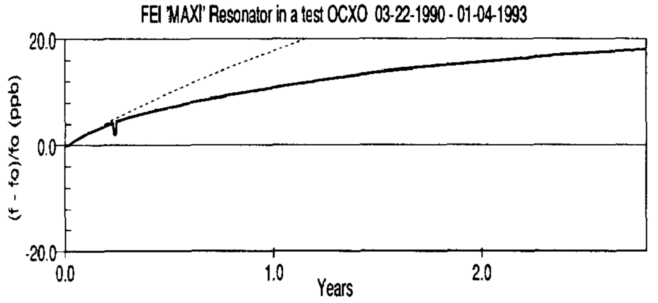


(c)

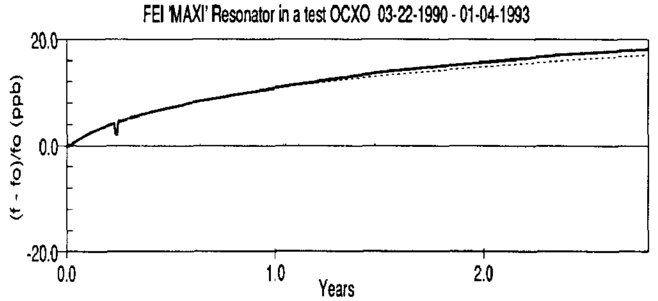
Fig. 33. (a) Logarithmic fit for Oscillator #3 using 30 d of data. The solid line is the actual data, the dashed line is the fitted function $y = A\ln(Bt+1)$. (b) Logarithmic fit for Oscillator #3 using 60 d of data. The solid line is the actual data, the dashed line is the fitted function $y = A\ln(Bt+1)$. (c) Logarithmic fit for Oscillator #3 using 300 d of data. The solid line is the actual data, the dashed line is the fitted function $y = A\ln(Bt+1)$.



(a)



(b)



(c)

Fig. 34. (a) Logarithmic fit for Oscillator #4 using 30 d of data. The solid line is the actual data, the dashed line is the fitted function $y = A\ln(Bt+1)$. (b) Logarithmic fit for Oscillator #4 using 60 d of data. The solid line is the actual data, the dashed line is the fitted function $y = A\ln(Bt+1)$. (c) Logarithmic fit for Oscillator #4 using 300 d of data. The solid line is the actual data, the dashed line is the fitted function $y = A\ln(Bt+1)$.

period is difficult. A compromise between length of test and confidence level is to use the last 30 d of a 100 d (reversal-free) aging test period for the logarithmic fit, calculate the slope at day 100, and use a linear extrapolation with that slope thereafter.

V. Acknowledgment

During the years of this project's existence, many of the author's colleagues contributed at one time or another. They thank P. Thompson for collecting the data on the high shock TCXO's and for his work on the aging test oscillators, V. Rosati and J. Messina for TCXO aging measurements, and J. Kosinski and R. Lindemuth for OCXO and resonator aging measurements and for software maintenance.

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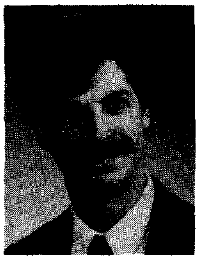

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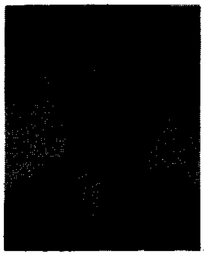

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