Hysteresis effects after reflow soldering of surface mounted crystal oscillators

Bernd W. Neubig
TELE QUARZ Group, D-74924 Neckarbischofsheim, Germany

1. Summary

After reflow soldering on the user's p-c-board, surface mount crystal oscillators show a positive frequency shift up to several ppm, which decays with a time constant of several days. This effect is usually not described or specified in data sheets. It is however very significant and important for the users, particularly for oscillators with tight temperature tolerances, such as TCXOs and the upcoming SMT OCXOs.
In modern equipment manufacturing lines, p-c-board are often finally adjusted and tuned within a short time after the soldering process. If the board contains a SMT crystal oscillator, a strong negative frequency shift can be observed after approximately one week, the oscillator seems to have aged strongly, but this is due to a hysteresis effect connected with the thermal stress of the reflow soldering process.
MIL-PRF-55310 distinguishes between "thermal hysteresis" and "retrace". Retrace is the non-repeatability of the f vs. T characteristic (of an OCXO), at a fixed temperature, upon on-off cycling an oscillator under specified conditions, while hysteresis (of a TCXO) is the maximum value of the non-repeatability in the f vs. T characteristics during a temperature cycle. However the time - dependency of this effect is not considered. The phenomenology and theory of thermal hysteresis was reviewed extensively by J. Kusters and J. Vig in [1].
The reflow hysteresis, as defined within this paper, is caused by a single (or multiple) temperature peak(s), and the effect is described as frequency excursion over a period of time of several days. The typical temperature profile of infrared and convection reflow soldering processes is depicted in Fig. 1.
The highest temperature stress is during the liquidus time, which is between 10 sec and 40 sec at or above 215 °C.
The mechanisms that can produce it are mentioned to be "stress relief in the electrodes, and contamination transfer within the resonator enclosure"

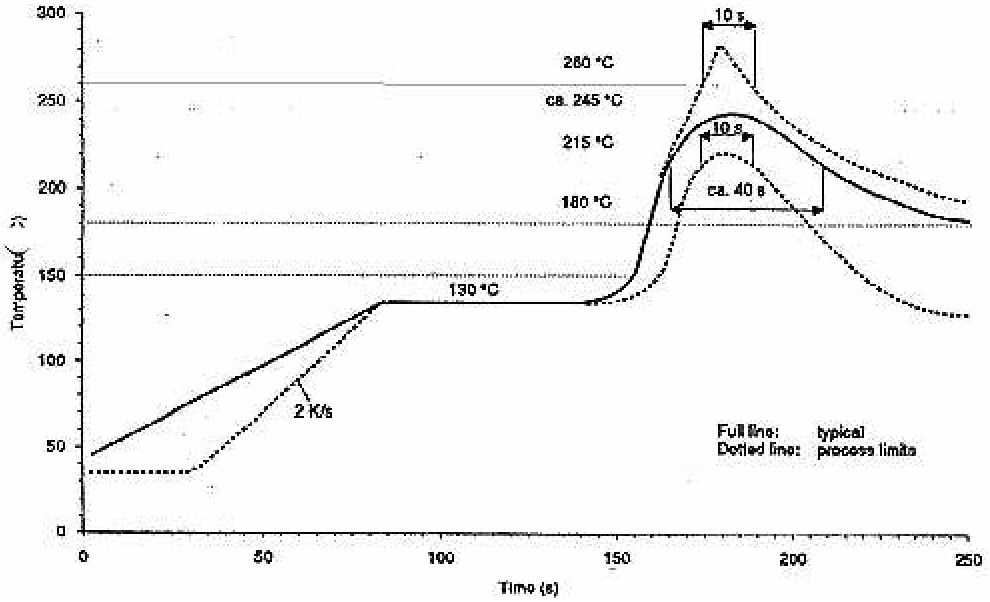

Fig.1: Typical temperature profile of reflow soldering processes

2. Experimental results

2.1 Quartz Crystal Units

A set of approx. 300 fundamental mode AT-cut crystals at 32.768 MHz in HC-49/U with blank diameter 8.0 mm were produced with 13 different batches, where different process parameters were varied. They have been subjected to a reflow soldering temperature profile as in Fig.1. The resonance frequency was measured 4 hours, 24 hours, and 40 days after the soldering. The mean values per batch of the frequency deviation of each of the 13 batches is shown in Table 1 and is graphically displayed in Fig. 2. The values are referred to the frequency observed after 40 days.

Batch	4 hours	24 hours	40 days
A1	2.5 ppm	1.5 ppm	0.0
A2	1.5 ppm	1.0 ppm	0.0
B	2.8 ppm	1.3 ppm	0.0
C	2.0 ppm	1.5 ppm	0.0
D	2.0 ppm	1.6 ppm	0.0
E	2.0 ppm	1.9 ppm	0.0
F1	1.6 ppm	1.2 ppm	0.0
F2	1.7 ppm	1.3 ppm	0.0
G	2.2 ppm	1.8 ppm	0.0
H	1.9 ppm	1.5 ppm	0.0
I	2.0 ppm	1.2 ppm	0.0
K	2.1 ppm	1.2 ppm	0.0
L	2.2 ppm	1.2 ppm	0.0
mean value	**2.0 ppm**	**1.4 ppm**	**0**
std deviation	**0.35 ppm**	**0.25 ppm**	

Table 1: Frequency deviation of 32.768 MHz crystals after reflow soldering

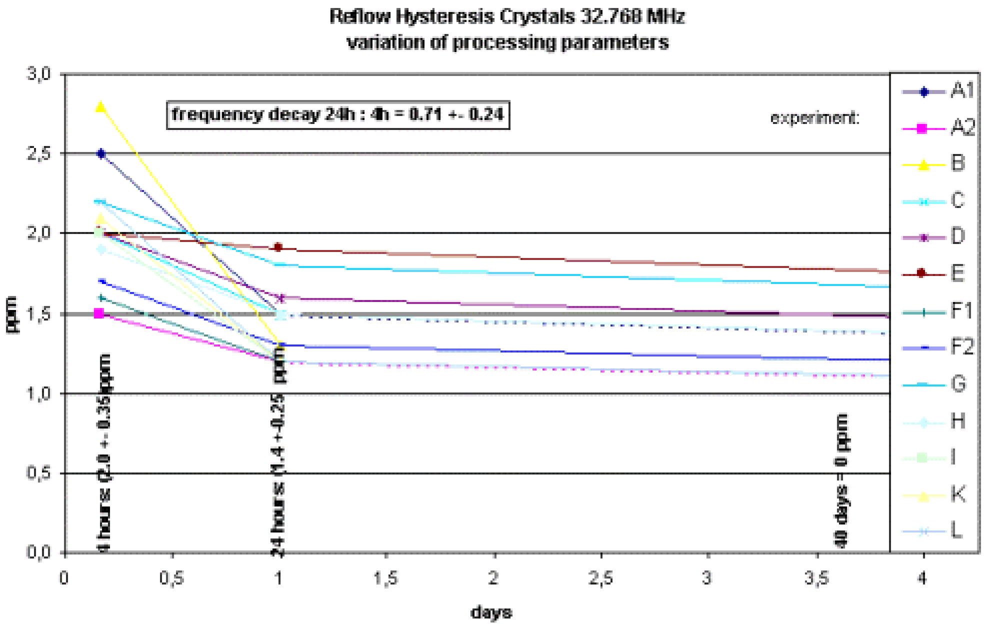

Fig. 2: Frequency deviation of 32.768 MHz AT fund crystals after reflow soldering

The average reflow hysteresis after one day is 71% of the frequency shift observed after 4 hours. One notable result is, that the lowest reflow hysteresis effects was observed in batches A2 , F1 and F2, in which the crystals were subject to extended bake-out procedures prior to sealing.

2.2 TCXO 38.88 MHz

125 TCXOs with analogue indirect compensation technique, which incorporate fundamental mode 38.88 MHz AT - cut crystals in HC-52 enclosure were subjected to a simulated reflow soldering process. The output frequency was observed over totally 50 days. Fig.3 shows the mean value and the ± 1 sigma limits of the reflow hysteresis response. After 48 hours the mean frequency deviation is (1.1 ± 0,22) ppm, and the frequency stabilizes after about 30 days.

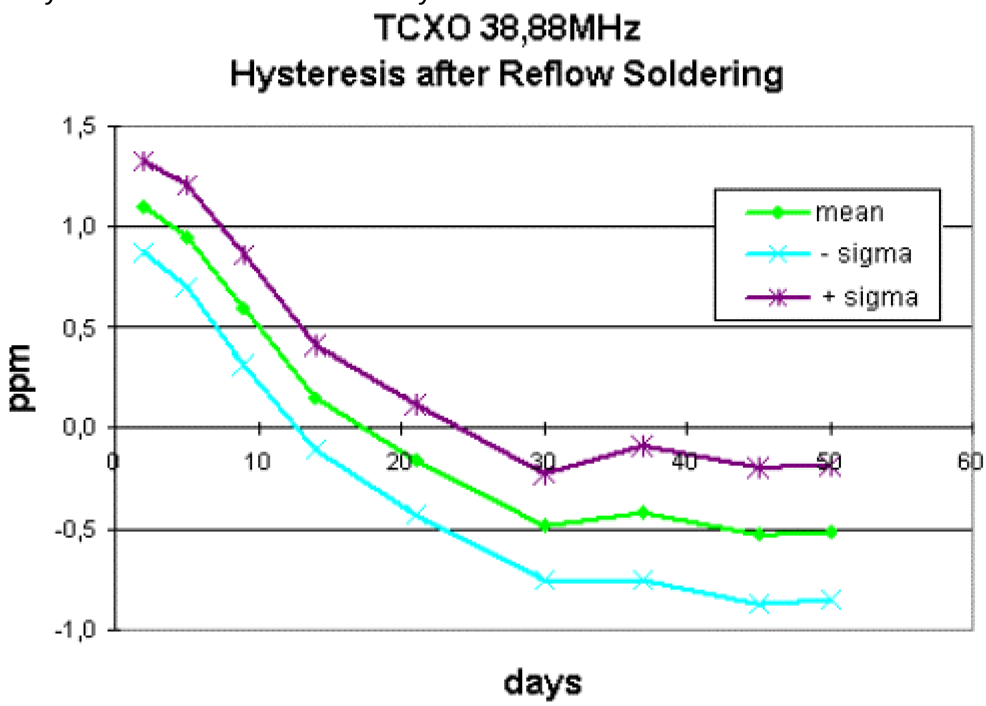

Fig. 3: Frequency deviation of 38.88 MHz TCXOs after reflow soldering

2.3 TCXO 19.44 MHz

This experiment shows the reflow hysteresis after a repeated reflow soldering process. The crystals used in the 25 pieces TCXO are 19,44 MHz AT fundamental

mode in HC-52/U Slim Line. The second reflow soldering was done 38 days after the first reflow soldering and measured over 7 days.
Fig. 4 shows the mean value and the ± 1 sigma limits of the reflow hysteresis response. The hysteresis effect is very strong:
(7,9 ± 2.6) ppm after 1 hour
(5,4 ± 1.7) ppm after 24 hours
and decays after one day to 69% of the initial value after 1 hour.
The mean response was fitted to an exponential function, which is shown as a dashed line in fig. 4.

$$\frac{\Delta f}{f} = a \exp\left(\frac{-t}{\tau}\right)$$

The matching is only poor as its curvature cannot follow the steep response. However a logarithmic curve fitting (see dotted line in fig. 4)

$$\frac{\Delta f}{f} = f_0 - a \log(bt + 1)$$

shows an excellent fitting. The parameter b in equation (2) with the dimension of $(\text{time})^{-1}$ can be regarded as "inverse time constant". In this case the value of 1/b is equal to 0.28 days.

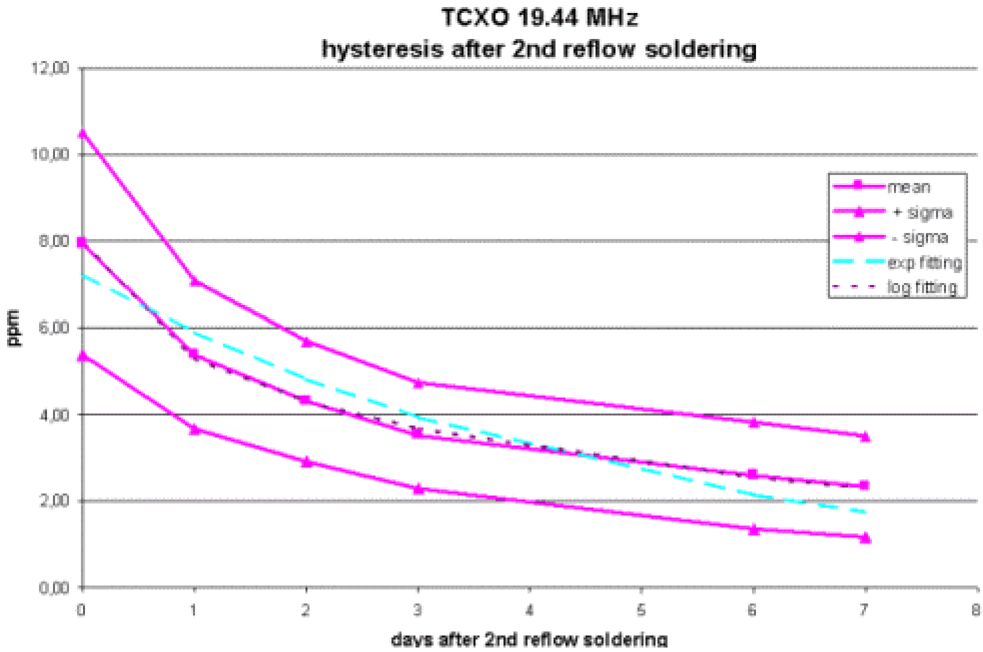

Fig. 4: Frequency deviation of 19.44 MHz TCXOs after a second reflow soldering

2.4 TCXO 40,96 MHz

Six oscillators using 40,96 MHz AT fundamental crystals in HC-52/U Slim Line were reflow soldered, and after an observation time of 42 days the reflow solder process was repeated. The reflow hysteresis of the first and the second processing was compared.
The hysteresis effect following the first soldering is shown in Fig. 5.
The irregularity between the 22nd and the 24th days obviously is related to measurement inaccuracy due to changed ambient temperature. The mean curve of all 6 oscillator responses was fitted by an exponential and a logarithmic function as described in clause 2.3 (see dotted lines in Fig. 5). While the exponential decay function shows a too small curvature, which is not able to follow the steepness of the initial phase of hysteresis, the logarithmic curve matches rather smoothly to the experimental values.

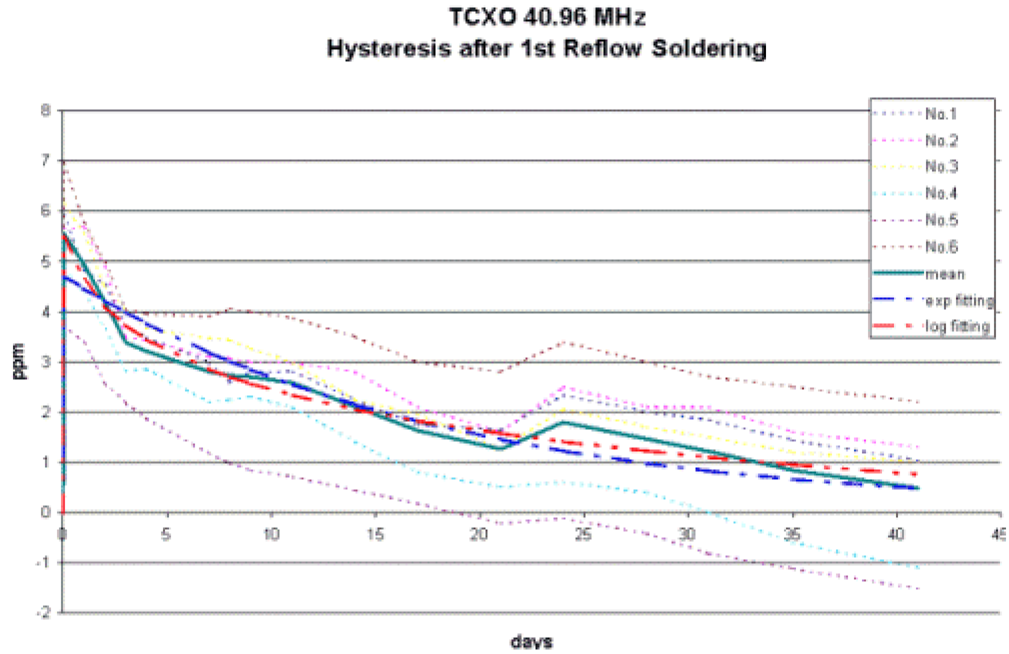

Fig. 5: Frequency deviation of 40,96 MHz TCXOs after first reflow soldering

In Fig. 6 the reflow hysteresis due to the second reflow soldering 42 days after the first soldering is depicted over a period of 30 days.

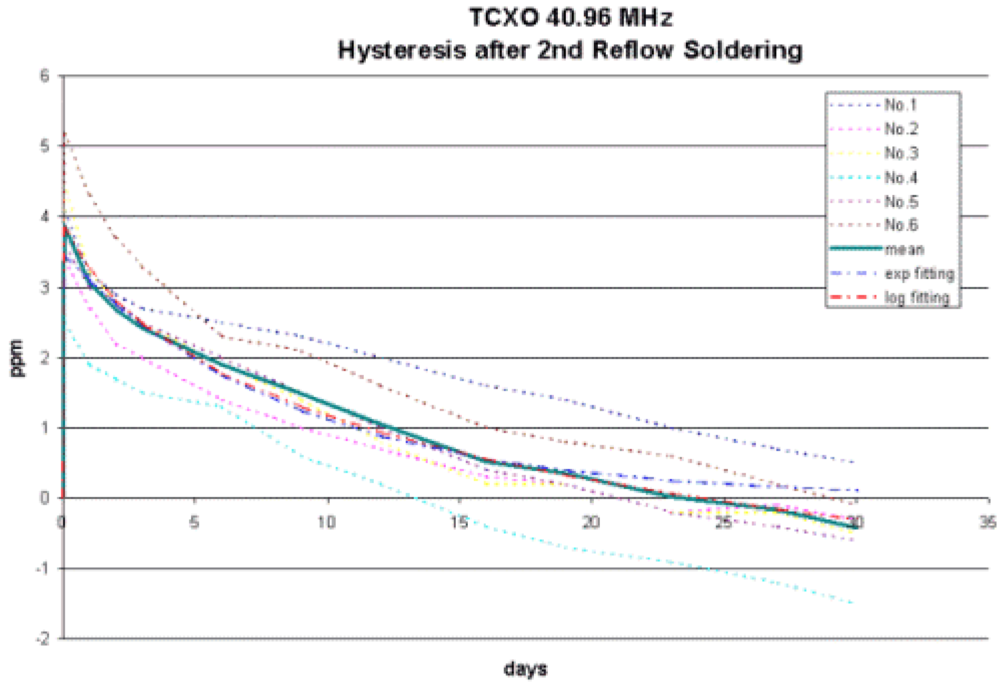

Fig. 6: Frequency deviation of 40,96 MHz TCXOs after second reflow soldering

Also here the mean value response was curve-fitted following the exponential and the logarithmic functions described above. Again the exponential function showed a insufficient fitting because its curvature was too "flat" , while the logarithmic function describes the hysteresis response very well.

A comparison of the two hysteresis characteristics is summarized in Table 2.

Hysteresis after ...	First reflow soldering	Second reflow soldering	2^{nd} to 1^{st} reflow
1hour	(5.5 ± 1.1) ppm	(3.9 ± 0.9) ppm	0.7
24 hours	(4.9 ± 0.9) ppm	(3.0 ± 0.8) ppm	0.6
d f/f (24h) / df/f (1h)	0.89 ± 0.07	0.78 ± 0.05	0.87
"time constant" 1/b	0.93 days	1.93 days	2.07

Table 2: Comparison of first and second reflow hysteresis of 40,96 MHz TCXO

The influence of the second temperature stress on frequency shifts is about 30 % to 40% reduced, while the hysteresis decay is slower by a factor of approximately two compared to the first stress.

2.5 OCXO 26 MHz with AT 3rd overtone crystal

OCXOs usually possess a higher thermal mass than TCXOs and therefore the resonator is not heated up to such an extend during reflow soldering. The model tested here does not have a metal heater block as in conventional OCXOs, but uses a directly heated ceramic substrate, on which the oscillator circuit and the HC-26/U crystal are mounted.

Prior to the reflow soldering the oscillator was powered-up for 24 hours for stabilization. After reflow soldering one hour was waited for cooling-down before the measurements started. The frequency change over time was recorded every two minutes. The frequency shift over both periods is given in Fig. 7

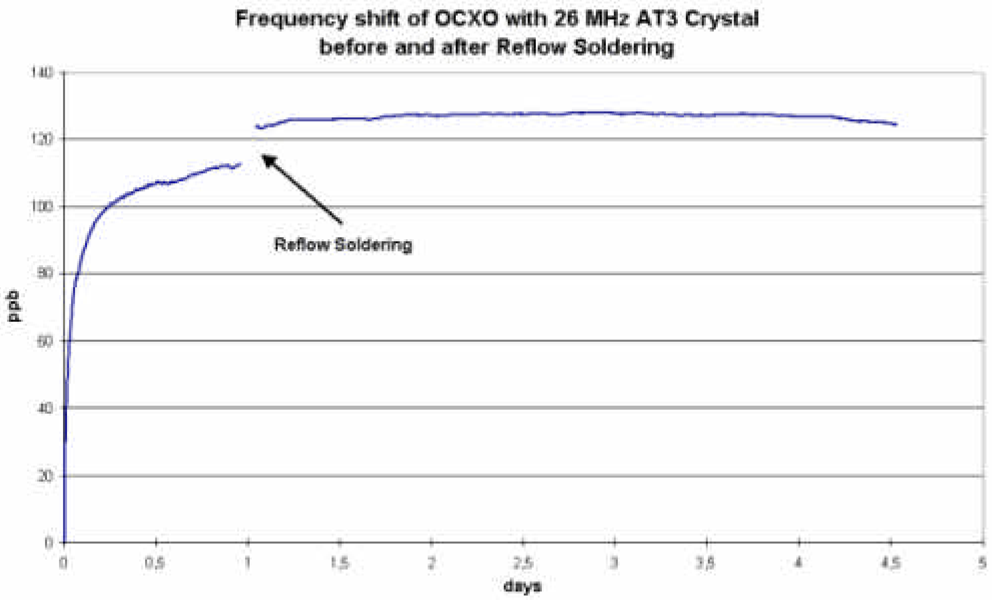

Fig. 7: Frequency shift of OCXO with 26 MHz AT3 Crystal before and after reflow soldering

At first glance there seems to be no sign of hysteresis. However it has to be noted, that the frequency shift observed after reflow soldering is a superposition of the regular OCXO warm-up characteristic and the hysteresis. If we assume, that the warm-up characteristic after reflow soldering is about the same as it was prior to it, we can subtract the response of the first warm-up from the measured frequency response after reflow soldering. We then get approximately the net effect of the reflow hysteresis, which is shown in Fig. 8. It can be seen that the hysteresis is significantly smaller than that observed with TCXOs, which is because the OCXO crystals are manufactured with more extended bake-out and pre-aging processes, and secondly because of the higher thermal mass of the oscillator units.

On the other hand, this experiment proves, that the warm-up characteristic and the reflow hysteresis exactly compensate each other, which leads to the assumption, that both processes have the same physical origin.

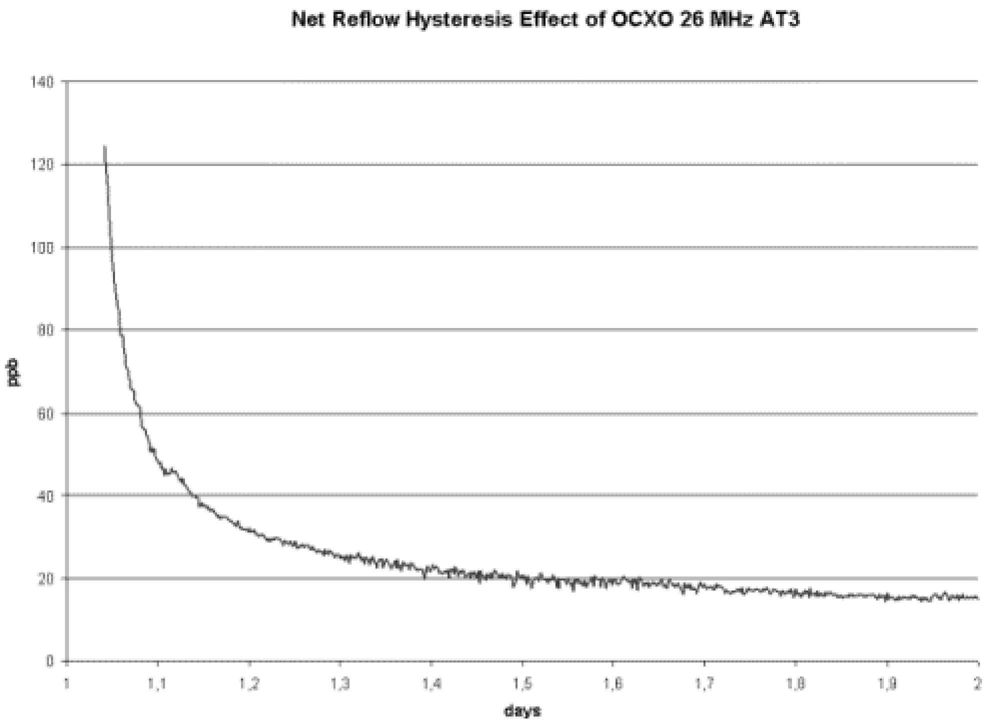

Fig. 8: Net reflow hysteresis of OCXO with 26 MHz AT3 crystal after subtraction of warm-up

2.6 OCXO 26 MHz with SC 3rd overtone crystal

This oscillator also uses direct heating of crystal and oscillator circuit through a ceramic substrate, however, due to the HC-37/U size crystal unit it is bulkier than the OCXO described in clause 2.5. The experiment was conducted with the same sequence as above, the overall frequency shift is shown in Fig. 9.

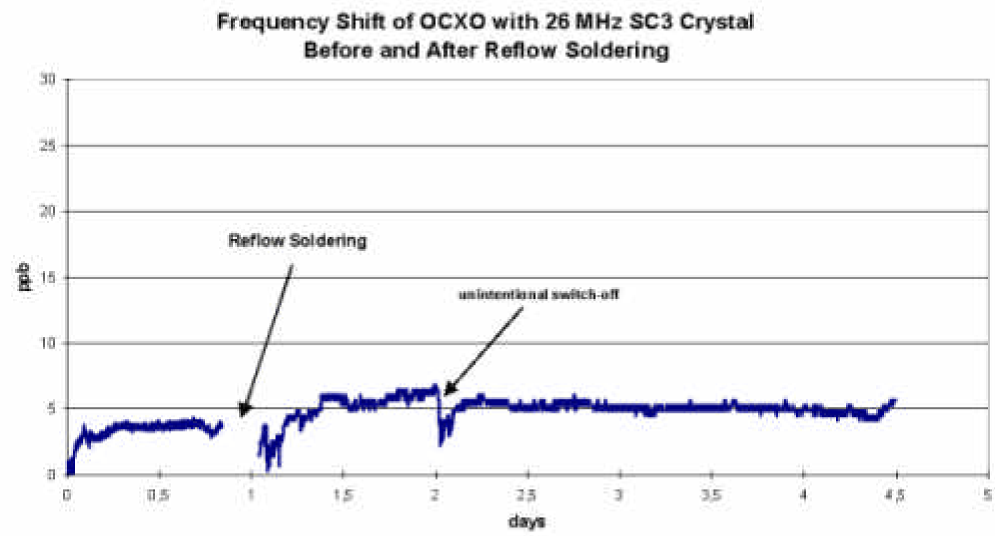

Fig. 9: Frequency shift of OCXO with 26 MHz SC3 Crystal before and after reflow soldering

There was no noticeable difference in the warm-up behavior which was larger than the irregularities caused by RF noise in the laboratory environment and an unintentional switch-off. Therefore the reflow hysteresis for these SC-cut crystals is neglectable. The crystals used in this OCXO were produced with a different process than the AT cut 26 MHz, where a higher bake-out temperature was used.

3. Causes for Reflow Hysteresis Conclusions

The observed reflow hysteresis effects show a positive frequency shift of + 2 ppm to + 8 ppm for TCXOs and up to 100 ppb for (AT -) OCXOs.

$$\frac{\Delta f}{f} = f_0 - a\log(bt+1)$$

This frequency offset decreases slowly within one to four weeks and can be described by a logarithmic function

The potential causes for hysteresis effects related to reflow soldering temperature stresses can be connected to several mechanisms, as they are summarized in John Vig's Tutorial [2]:

(1) stresses on the quartz plate caused by thermal expansion coefficient differences, residual stresses due to clip forming, welding, sealing, intrinsic stresses in electrodes, bonding stress, surface damage due to cutting, lapping, polishing, stresses in the quartz material etc. (2) mass transfer due to contamination, residual moisture, outgassing, diffusion, chemical reactions etc., as they are typical for aging mechanisms.

Regarding the facts, that

- Long time constants in the order of several days to weeks were observed, which are more likely related to mass transfer and diffusion processes etc. than with stress relief,
- Extended bake-out processes prior to sealing of the quartz crystal units reduces reflow hysteresis,
- Hysteresis after a second reflow soldering process is smaller than after the first one,
- A logarithmic function describes this hysteresis effect much better than an exponential decay function,
- The hysteresis has identical shape but opposite sign as the warm-up characteristic of OCXOs

we have good reasons to assume, that the observed reflow hysteresis effects are mainly related to the same mechanisms which are causing frequency aging, namely mass transfer of moisture, diffusion etc..

While the main challenge to reduce the reflow hysteresis lies in the crystal production technologies, much further work is necessary to determine the contribution from various other effects, like those inherent in quartz material, the influence of oscillator circuit elements such as chip capacitors, inductors, and thermistors and others.

4. Acknowledgement

I want to thank the engineers of the TELE QUARZ R&D departments, the technicians from the oscillator production, and from quality assurance for preparing and supplying the large amount of data, on which this work is based, namely Udo Fieger, Matthias Grimm, Bernhard Hug, Oliver Leibfried, Walter Reibold, Ralf Scheib.

5. References

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[2] Vig, J.R.: Quartz Crystal Resonators and Oscillators For Frequency Control and Timing Application - A Tutorial ; U.S. Army Communications-Electronics Command, Report No. SLCET-TR-88-1(Rev.8.0), Sept. 1997

[3] Neubig, B.: Comparison of Passive and Active Aging of SC-Cut and AT-Cut Crystals; Proc. 50t Annual Freq. Contr. Symposium,(1996), p.316ff