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COMPARISON OF PASSIVE AND ACTIVE AGING OF SC-CUT AND AT-CUT CRYSTALS

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1. ABSTRACT

This paper reports on the results of pre-aging of four different types of OCXO crystal units. It compares the aging behaviour for a passive aging at +80°C over 28 days and 12 days at different drive levels and the active aging in the following 34 days with the crystals continuously operating in oscillators. For the aging rates good correlation was found. One crystal of each group was additionally aged for 240 days. The measured long-term aging results are compared to the aging prediction derived from the first 30 days.

2. INTRODUCTION

Pre-aging of OCXO crystal units is commonly done in order to remove the initial aging and to verify the long-term stability of the device. This is either done in test oscillators or in the final oscillator unit as a so-called active pre-aging, where the crystal is vibrating continuously and the output frequency is observed over time.

In the passive aging method the crystal unit is measured periodically in a suitable measurement system, and thus the crystal is not "active" most of the time and is only vibrating for a short instance during the measurement. The advantages of the passive pre-aging method are:

- only the crystal itself (without the influence of a test oscillator) is measured.
- the crystal behavior over time can not only be characterized by the resonance frequency but also by the resistance and - if necessary - the other crystal parameters.
- the crystal can be operated at arbitrary drive levels.
- other effects of the crystal, e.g. drive level dependency (DLD), which can cause irregular aging, can be easily detected.
- no soldering and de-soldering of the crystal (source of reliability risks) is necessary.

Common measurement systems do not have sufficient accuracy required for passive aging tests of high precision units. The micro-bridge technique developed by Erich Hafner [8] in connection with a precision temperature chamber with mK-stability was meanwhile improved to such an extend, that this system (XOTEX QXMS-A) allows an accuracy and reproducibility of parts in 10^{-10} for the frequency measurement an of 10^{-3} for the motional crystal parameters.

The focus of our experiments was to find out, if and how the results of passive pre-aging correlate with those of active aging and if irregularities in the active aging can be identified also in the passive pre-aging. From previous publications such as [10] and [13] only very few data are available about such a correlation.

3. EVALUATION METHODS FOR AGING DATA

The aging of quartz crystal units as seen by the manufacturer can be subdivided into three intervals:

- stabilization period or initial aging,
- aging test period and
- extrapolated period.

The stabilization period starts after power-on, when the OCXO / resonator has reached its operation temperature equilibrium and lasts about one or a few days. This is the period of initial aging, which is determined by physical processes with shorter „time constants". The initial aging rate is usually stronger than the aging rate observed later, and the slope of the initial aging rate may be positive or negative, and does not necessarily correlate with the longer-term aging rate observed thereafter.

In a production environment the aging test period usually lasts several weeks. A logarithmic shape of the frequency vs. time aging curve is expected in well-behaved crystal units, and it is also observed quite frequently, when one aging process clearly dominates over the others.

Several different aging functions are reported in literature, which stand for different aging mechanisms. Some of them are purely mathematical approaches without any assignment to physical processes. Very often linear combinations of functions are used in order to consider more than one aging mechanism. The most commonly used functions for the frequency change over time are:

- pure log function [5],[6],[11],[19]
  (1) $\Delta f/f_0 = A_0 + A_1 \log t$ **or**
  (2) $\Delta f/f_0 = A_0 + A_1 \ln t$ **where** $t>=1$
- modified log function [3],[4],[5],[9],[11],[20],[22]
  (3) $\Delta f/f_0 = A_0 + A_1 \log (1+ A_2 t)$
  This function - which is also used in MIL-C-49468 [25] and MIL-O-55310 [26] - is the most frequently used approach.
- exponential function [5],[11]
  (4) $\Delta f/f_0 = A_0 + A_1 (1 - \exp(-A_2 t))$
- polynomial functions [5],[11],[22]
  (5) $\Delta f/f_0 = A_0 + A_1 t^{A2}$
  (6) $\Delta f/f_0 = A_0 + A_1(t - A_2)^N$ **(N=0,5 in [5],[11])**
  (7) $\Delta f/f_0 = A_0 + A_1 t + A_2 t^{0,5}$
- Kalman filtering technique [12],[14],[16], a recursive computation based on a weighted sum of the modified log function
  (8) $\Delta f/f_0 |_{k+1} = \Delta f/f_0 |_k + \sum_j A_1^{j,k} \log \frac{1+ A_2 t_{k+1}}{1+ A_2 t_k}$

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The coefficients A_1, A_2 may include other variables, which have an impact on aging, such as temperature or temperature gradients etc. [23]. A_2 in equations (3), (4) has the dimension s^{-1}, therefore $A_2^{-1} = \tau_2$ stands for a time constant.

At TELE QUARZ we are currently using the modified log-function (3) and the polynomial function (7) and choose the significantly better fitting one (if comparable, we choose the modified log-fit).

It is common practice to derive the expected long-term aging behavior from the curve-fitted aging data in the test period by extrapolation. The aging rates per day, per month, per year are computed from the fitted curve for 30 days of operation.

4. AGING TEST CONDITIONS

The aging tests were performed with 12 crystals of 4 different types of industrially manufactured AT-cut and SC-cut OCXO crystals (see table 1).

TABLE 1: Survey of crystals under test

freq. [MHz]	cut	over tone	enclo-sure	nom. C_1 [fF]	P_Q [µW]	TOP [°C]
16,384	AT	3rd	HC-27/U	2,0	50	85
16,384	SC	3rd	HC-27/U	0,35	200	78
10,0	AT	fund	HC-26/U	7,0	100	78
13,0	AT	fund	HC-26/U	7,0	10	75

The passive aging was done in an automatic test systems using the micro-bridge technique developed by Erich Hafner [8] in connection with a precision temperature chamber with mK-stability. This system (XOTEX model QXMS-A) allows an accuracy and reproducibility of parts in 10^{-10} for the frequency measurement an of 10^{-3} for the motional crystal parameters. The passive aging test was performed at +80°C in two subsequent periods of 28 days and 12 days. While in the first period all crystals were measured with the same RF generator output level, in the second period the generator was set such that each crystal operated at its nominal drive level as indicated in table 1. The crystals were measured approximately every four hours and therefore vibrated only during the measurement time for a few minutes. In each measurement a complete set of crystal data, i.e. series resonance frequency f_s, series resonance resistance R_1, motional capacitance C_1 etc. was determined and was stored together with the values of drive level, chamber temperature and date/time of measurement. Only frequency and resistance data were used in our evaluation.

The crystals were then removed from the XOTEX system and were built into OCXOs. The active aging test over 34 days was done afterwards in an automatic aging system (PRA model 2350), which operates at room temperature. The oscillators were continuously operating at the individually set crystal turn-over temperature with the crystals driven at their nominal drive level. The system measured every two hours the output frequency and the current consumption of the OCXO and stores the data.

5. TEST RESULTS

5.1 AT-CUT 16,384 MHZ / 3RD OVERTONE

Figures 1a to 3a show the frequency aging for the two passive periods and the active period. While the passive measurements are referred to nominal frequency and thus can be compared between each other, the active measurement is referred to the first measurement after 1 day stabilization time. The step between the two pasive periods is due to the DLD sensitivity of the crystal. Figures 1b to 3b show the resistance changes in the passive aging periods referred to the initial measurement. The R_1 of all 3 crystals is approx. 10,5Ω, the Q is approx. 460 000.

Crystal #25942 (Fig.1) shows a constant aging rate of -0,34ppb/day in the 1st period, which repeats exactly (0,36ppb/day) in the active aging. In the 2nd passive period a flat aging rate is reached after 3 days stabilization after a DLD step of +26ppb. R_1 is constant through both periods. The other two crystals also show a fairly constant aging rate in the 1st passive aging (1,12ppb/d and 0.53ppb/d), which is flatter in the 2nd period. The active aging displays a logarithmic shape, which ends in the same aging rate as in the first aging period. It is remarkable, that the resistances are much noisier, particularly in the 2nd period, and are increasing with time, which may be related to the stronger aging. The DLD effect of frequency is -24...+42ppb in both directions, while the DLD effect of resistance is +10%.

5.2 SC-CUT 16,384 MHZ / 3RD OVERTONE

Figs. 4 to 6 show the aging curves of this crystal type, which has the same Q (≈460 000) as the AT-cut above. Initial passive aging is negative and weaker than above. The aging rates of passive and active aging are well comparable in all three cases and are in the order of 0.1ppb/day, i.e. by a factor of 5...10 better than the AT-cut. The initial log aging approaches a slope, which continues in the subsequent periods. The R_1 curves ($R_1 \approx 60\Omega$) are smooth with a DLD-effect of -5,8% (#488) or <1%, the DLD of f_s is +53...-74ppb with both signs occuring.

5.3 AT-CUT 10 MHZ / FUNDAMENTAL

Figs. 7 to 9 show the results for this crystal type (Q≈270 000). Again the aging rate of the active aging reproduces that of the passive aging very well and is in the order of 0,1ppb/day. The DLD effect of f_s for this crystal is strong (≈400ppb), while the DLD of R_1 is very small. Resistance ($R_1 \approx 8{,}5\Omega$) has a weak trend over time, the two R_1 dips coincide with f_s dips and are measurement errors.

5.4 AT-CUT 13 MHZ / FUNDAMENTAL

These crystals (Q≈200 000) show a strong initial passive aging (see Figs. 10 to 12), which continues in the 2nd passive period without any DLD. After the intermission, the active aging starts with an initial aging response, afterwards the aging curves seem to approach those of the prior periods (if the frequency offset between 2nd and 3rd period is removed). The R_1 curves ($R_1 \approx 7{,}5 \ldots 12{,}8\Omega$) are smooth and show no DLD.

5.5 SUMMARY

In Table 2 the results of all four crystal types are summarized.

TABLE 2: Comparison passive vs. Active aging

			aging	aging	DLD	DLD
freq	cut	xtal #	passive	active	of f_s	of R_1
MHz			ppb/d	ppb/d	ppb	%
16,384	AT 3	25942	0,34	0,36	26,3	-0,2%
		25945	1,14	1,12	-24,5	9,6%
		25946	0,58	0,53	42,4	2,1%
16,384	SC 3	488	0,07	0,07	-74,3	-5,8%
		536	-0,17*	-0,17	53,2	0,9%
		513	-0,14	-0,12	69,3	0,5%
10,000	AT 1	25334	-0,06	-0,06	446	0,3%
		25335	-0,13	-0,02	419	0,1%
		25336	0,09	0,18	384	-0,5%
13,000	AT 1	26594	*0,85*	*0,4*	7,6	-0,1%
		26595	*3,67*	*1,16*	33,4	0,2%
		26596	*3,94*	*1,52*	35,3	-6,3%

mean value 1st and 2nd period
italic: log shape

- The aging rates observed with passive aging are in general very close to those observed during active aging.
- In case of strong logarithmic aging - as for the 13 MHz AT 1 - the aging curve of the active aging follows the curve of the preceding passive aging after a stabilization interval. I.e. strong initial aging at passive aging repeats also with active aging.
- The reproducibility is also excellent in cases of strong DLD of frequency and/or resistance. No systematic dependancy of the aging rate on the drive level could be found.
- Coincidence of f_s- and R_1-discontiuities can be used to identify wrong measurements.
- These results demonstrate, that passive aging measurements are capable to deliver reliable results for the selection of well aging crystals prior to their usage in the OCXO.

6. PREDICTIBILITY OF LONG-TERM-AGING

Aging predictions for quartz crystals have a long history. At the 1959 Frequency Control Symposium Mulvihill [1] showed a simple way to compare long-term aging with short-term aging by setting up a „binary correlation chart" of „passed" and „failed" crystals in long-term vs. short-term aging. Ray Filler mentioned already in 1980 [19]:

> „Extrapolating of aging data is usually not a reliable method for determining the long-term aging because the observed aging is usually the sum of the aging produced by various mechanisms."

Nevertheless aging data extrapolation has to be done every day in the industrial OCXO production because the customers (i.e. the applications) require a guaranteed maximum aging (rate) over the specified operation time of the device. Every manufacturer has its own methods to assure this. It has to be noted, that the uncertainity of the correlation between passive and active aging (as the uncertainity of any comparision of aging results under different conditions) cannot be less than the uncertainity of long-term extrapolations as such.

To get an indication of the validity of our results, the aging period for the crystal oscillators of this experiment was extended to 240 days, and the long-term aging was compared with the logarithmic extrapolation derived form the data of the first 30 days of active aging. The results for one crystal of each group are given in Figs. 13 to 16. In all four cases, the aging prediction based on 30 days data and fitted by the modified logarithm (eq.[3]) delivers too optimistic results. The active aging measured after 240 days is in average twice the value predicted from 30 days data as shown in table 3.

TABLE 3: Predicted and measured active aging over 240 days

freq	cut	xtal #	predicted aging	measured aging
MHz			[ppb]	[ppb]
16,384	AT3	25946	70	130
16,384	SC3	513	-6	-35
10,000	AT1	25336	82	120
13,000	AT1	26594	120	220

In table 4 the measured and the predicted aging rates per day for passive and active aging are compared. While the measured 30 day aging data for passive aging are comparable (columns 4 and 5), the extrapolated (predicted) aging rate after 240 days (column 7) is only one third of that determined from the data of 240 days (col. 8).

TABLE 4: Computed aging rates [ppb/day]

freq	cut	xtal #	passive aging	active aging after 30 days		active aging after 240 days	
MHz			30day data	30d data	240d data	30d data	240d data
16,384	AT3	25946	0,58	0,53	0,91	0,07	0,20
16,384	SC3	513	-0,14	-0,12	-0,19	-0,04	-0,11
10,000	AT1	25336	0,09	0,18	0,87	0,05	0,14
13,000	AT1	26594	0,85	0,40	1,66	0,10	0,36

This means that the uncertainity of long-term prediction is much larger than the observed difference between passive and active aging

7. CONCLUSIONS

- Within the limits of these tests it was proofed, that the passive aging of OCXO crystals correlates well with active aging. The correlation is at least better than the uncertainity of aging predictions based on logarithmic curve fitting.
- Passive pre-aging is a powerful tool for selecting well-aging OCXO crystals before assembling them into the oscillator.
- No correlation between aging rate and drive level was found over the test periods.

- Crystals with strong DLD did not show higher aging rates than others.
- Aging predictions computed by log-fitting of aging data over 30 days have shown an uncertainity of -50%/+100%.
- Further verification tests on different kinds of OCXO crystals are necessary to proof these statements.

8. ACKNOWLEDGEMENT

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16.384MHz AT/3.OT BtNr.25942

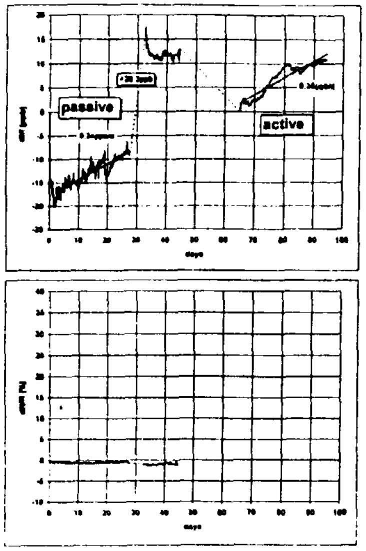

Fig 1 passive and active aging

16.384MHz AT-Schnitt/3.OT BtNr.25945

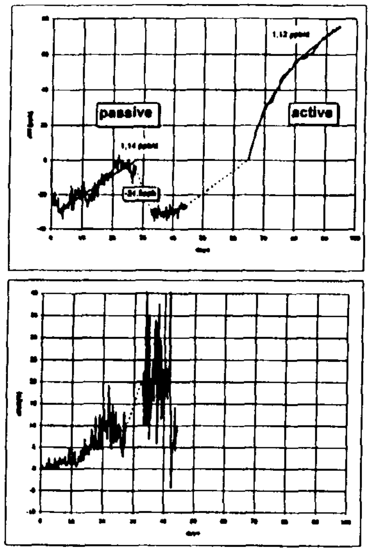

Fig 2: passive and active aging

16.384Mhz AT/3.OT BtNr. 25946

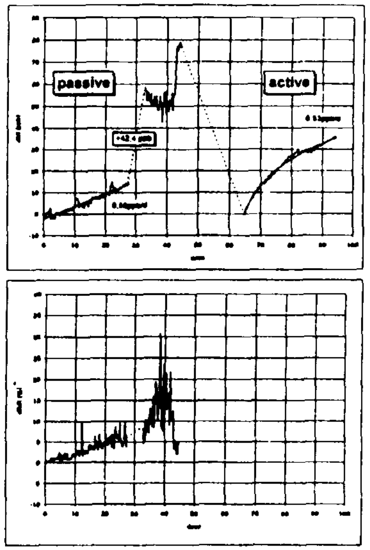

Fig 3: passive and active aging

16.384 MHz SC/3.OT Btnr. 488

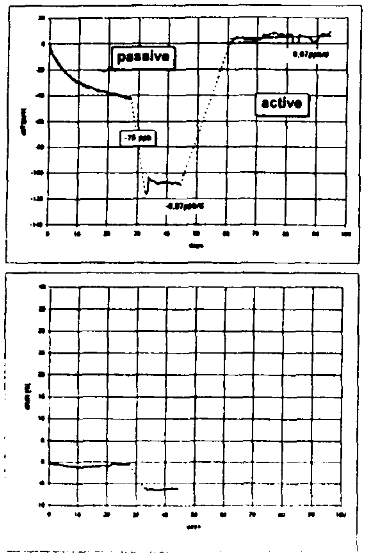

Fig 4 passive and active aging

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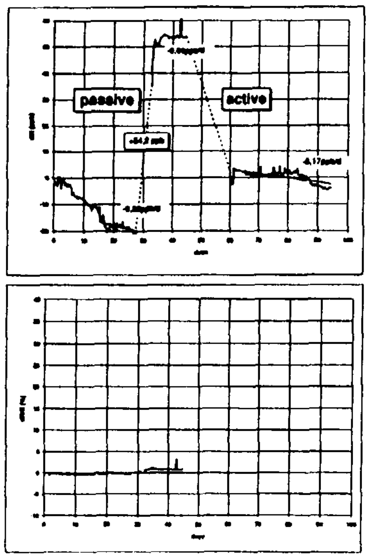

Fig 5 passive and active aging

16.384 MHz SC/3.OT BtNr 513

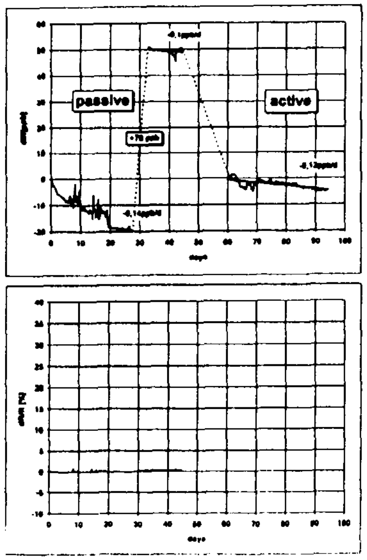

Fig 6 passive and active aging

10.000 MHz AT/1.OT Btnr. 25334

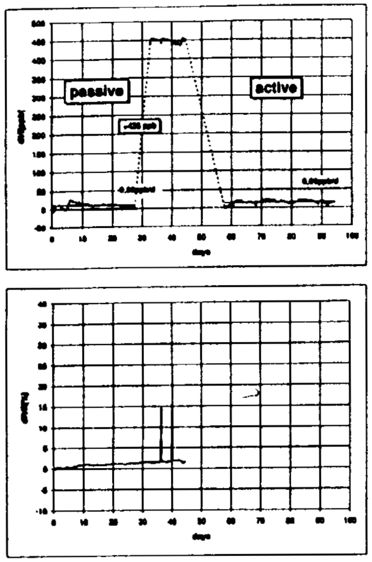

Fig 7. passive and active aging

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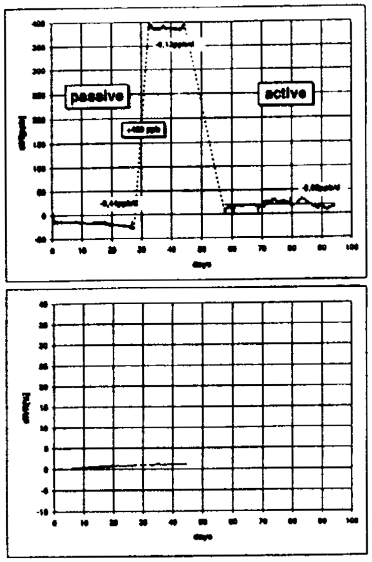

Fig 8: passive and active aging

10.000MHz AT/1.OT Btnr. 25336

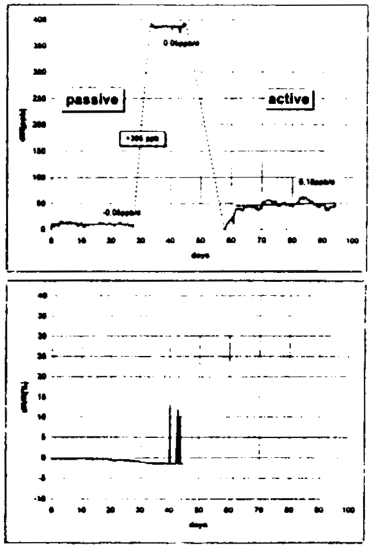

Fig 9: passive and active aging

13.000 MHz AT/1.OT Btnr. 26594

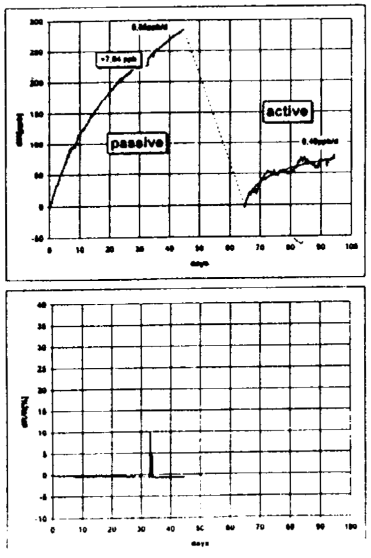

Fig 10 passive and active aging

13.000 MHs AT/1.OT Btnr. 26595

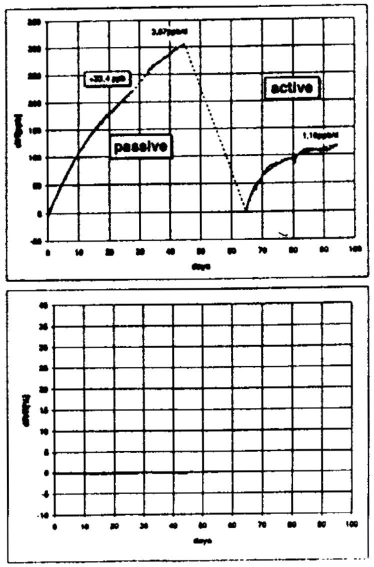

Fig 11 passive and active aging

13.000 MHz AT/1.OT Btnr. 26596

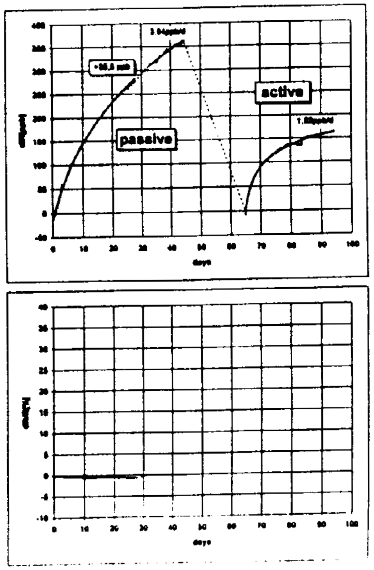

Fig 12 passive and active aging

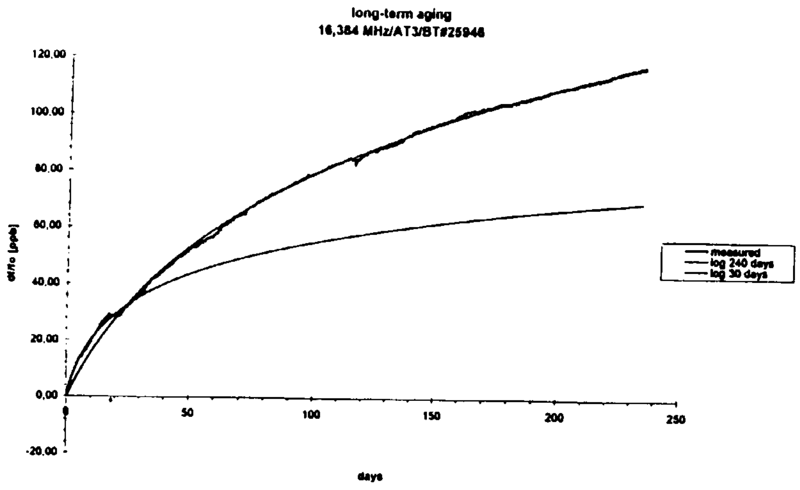

Fig 13: predicted and measured long term aging

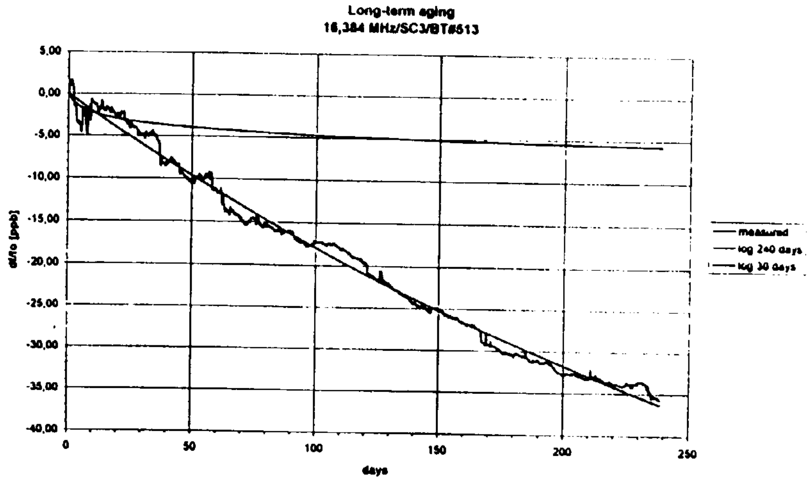

Fig. 14: predicted and measured long term aging

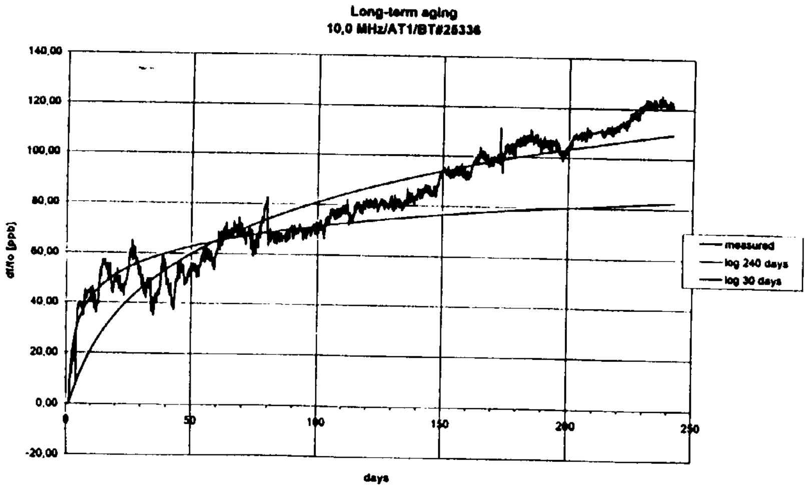

Fig 15 predicted and measured long term aging

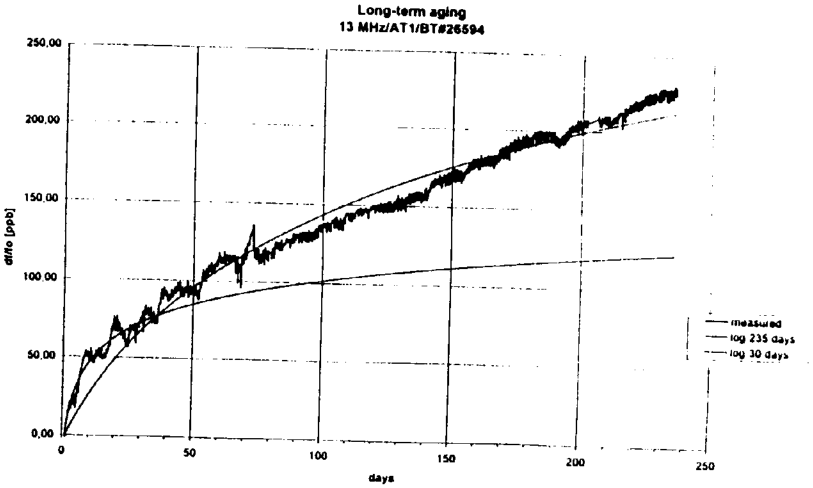

Fig. 16: predicted and measured long term aging