AGING MODELS AND PARAMETERS OF QUARTZ CRYSTAL RESONATORS AND OSCILLATORS

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For practical applications of quartz crystal resonators, accurate estimation of the aging pattern and adoption of appropriate correction procedure will be important in ensuring the precise operating condition and maintaining their optimal performance. There are two generally accepted aging models for the prediction of long-term behavior of quartz crystal resonators. The Arrhenius model is universally accepted for aging of most materials in engineering applications under a physical process, while the Mattuschka model is an empirical formula from quartz crystal device industry based on the long-term measurement of quartz crystal resonators. In this study, quartz crystal samples from major producers in different countries are collected and a common testing standard was adopted. From the statistical analysis of measurement data, it is found that the Arrhenius model has a much better agreement. Different products and measurements are consistent with the general trend of aging patterns from the Arrhenius model but the key parameters are different from products.

Keywords: Aging; Quartz; Crystal; Resonator; Arrhenius

1. INTRODUCTION

The life cycle of products is an important indicator of product quality with vital applications in the evaluation and improvement of products through design, production, and applications. With proper models of life and aging, we can predict the life and behavior pattern of products to enhance the usability and grade of products and performance for critical and devices and components like quartz crystal resonators. In the product development process, the aging effect under room temperature is too small and its long term measurement is impractical and costly, making the accelerated testing under high temperature variations in a short duration of time is frequently conducted and results are converted to the aging under normal temperature for convenience and efficiency. The current aging models were proposed decades ago and the usability and conditions have changed considerably to cause further doubts about aging models and some of the existing parameters for validation. Particularly, the shrinkage of resonator sizes and packaging technology should be considered in the evaluation and estimation of the aging effect of acoustic wave devices. For this reason, an initiative on the renewed and broad examination of aging models and determination of aging parameters are proposed by the IEC/TC-49 as part of the efforts in standardization of quartz crystal resonator products and production process. A common aging model and validated parameters will enable a generally accepted evaluation and qualification standard needed in the comparison and specification of products. With a general agreement, the IEC/TC-49 decided to collect quartz crystal resonator samples with pre-defined specifications from selected producers in Japan and China for the measurement and analysis. The testing procedure was also discussed and agreed on the conditions and instruments to be used. Furthermore, measurements are to be done in Japan and Germany for comparison and validation. It was also agreed that the final data will be analyzed in a university laboratory separated from measurements. In addition, the aging models, such as the Arrhenius and Mattuschka models, have also been specified from the beginning to include the earlier studies on the aging of quartz crystal resonators by some other producers of the industry.

The quartz crystal samples are prepared with the following basic properties: 1) frequency at 40 MHz; 2) AT-cut with the angle around zero temperature coefficient at room temperature; 3) Packaging with ceramic base and metal lid plus seam welding; 4) The package size should be 3.2mm x 2.5mm x 0.6mm in the SMD style (as 3225 resonators hereafter).

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There were 100 pieces of resonator samples from leading manufacturers in China and Japan to represent the industry's capability and technology. The measurements were carried out in NDK and ES Quartz while the data analysis has been done at Ningbo University. The project is supported advised by AXTAL of Germany. This paper is the initial summary of the measurement and analysis.

2. SAMPLES AND MEASUREMENT PROCEDURE

For the measurement of resonators, the samples are 3225 AT-cut SMD type resonators with frequency of 40 MHz. The measurement was done at 25^{o}C, 85^{o}C, 105^{o}C, 125^{o}C, and 150^{o}C with 25 pieces of samples in each batch and a total duration of measurement of 2520 hours with weekly readings. The second set of data is obtained from oscillators of different sizes and frequencies. Again, four batches of samples were measured at25^{o}C, 85^{o}C, 105^{o}C, 125^{o}C, and 150^{o}C for 500 hours.

The frequency shift is measured and the average of each sample product is recorded with the frequency shift versus time and temperature. Then the data analysis is done with a regression process to obtain key parameters of Arrhenius and Mattuschka aging models.

3. COMPARISONS OF AGING MODELS AND PARAMETERS

3.1 Introduction of Two Aging Models

As explained by Vig [1], it is generally accepted that the frequency shift versus time for quartz crystal resonators is a logarithmic relation [2]. As for the frequency shift versus temperature, people usually use the Arrhenius relation in exponential form. As a result, both effects of ageing and temperature can be considered with the Arrhenius model as [3]

$$\frac{df}{f} = A\ln(1+Bt)\exp\left(-\frac{E_a}{kT}\right), \qquad (1)$$

where df/f is the frequency shift (ppm); A, B, and E_a are parameters to be decided; t and T are time and temperature in hour and K; and k=0.00008617eV/K is the Boltzmann's constant.

Similar to the Arrhenius model, and empirical model was proposed and adopted at Simens as the so-called Mattuschka model [4]

$$\frac{df}{f} = \mathrm{A}\ln(1+\mathrm{t})\exp\left(\frac{T}{100}\right), \qquad (2)$$

where t is time in hours, and T is the temperature in K.

3.2 Comparisons of Arrhenius and Mattuschka Models

3.2.1 The frequency shift versus time

Under the constant temperature and with time as the only variable, the two models can be simplified to $df/f = A\ln(1+Bt)$ and $df/f = A\ln(1+t)$, respectively. We now use the data from 40MHz quartz crystal resonators for the regression, and results are given in.

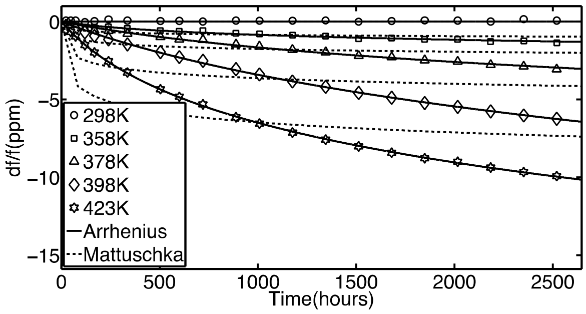

Fig. 1. Comparisons of two aging models at different temperatures

To measure the quality of regression, we need to calculate the correlation coefficients of the two models with the measurement data. The results are given in Table 1 below. Generally speaking, the correlation coefficient is between 0 and 1 and indicating better results if the value is closer to 1. If the correlation coefficient is above 0.95, we believe the regression results are quite reliable.

Table 1. Comparisons of correlation coefficient at different temperature

Temperature (K)	*298*	*358*	*378*	*398*	*423*	Average (Except 298K)
Arrhenius	-1.9	0.967	0.986	0.998	0.999	0.988
Mattuschka	-1.9	0.611	0.535	0.515	0.595	0.564

From both Fig. 1 and Table 1, it is clear that the results from temperature under 298K should be deleted due to inadequate time in the development of aging process. It is unlikely that the aging will be the major factor of frequency shift at this stage. For other temperatures, the correlation coefficient is above 0.95 and all data are better fitted to the curve with the Arrhenius model. In contrast, we do not obtain a good curve fitting with the Mattuschka model.

For all the oscillators measured, we calculated the correlation coefficients for both Arrhenius and Mattuschka models and results are listed in Table 2.

Table 2. Correlation coefficients of different products with both Arrhenius and Mattuschka models

Product Size	*QCR 3225*	*TCXO 2520*	*TCXO 3225*	*SPXO 2520*	*SPXO 3225*
Arrhenius	0.988	0.967	0.891	0.956	0.992
Mattuschka	0.564	0.465	0.359	0.661	0.708

It is clear that except the TCXO 3225 in Table 2, Arrhenius model is good with all products, while the Mattuschka model is not good for all products. From these regressions, we can draw the conclusion that without considering the temperature change, the pure aging, or the frequency shift versus time, is better represented by the Arrhenius model and parameters.

3.2.2 Frequency shift versus temperature with fixed time

With the time as a constant, the aging models for the temperature effects will be $df/f = A\exp(-E_a/kT)$ and $df/f = A\exp(T/100)$. As before, we did the curve fitting for 40MHz 3225 quartz crystal products and the results are shown in Fig. 2. The time duration of aging testing are done for 21, 42, 63, 84, and 105 days.

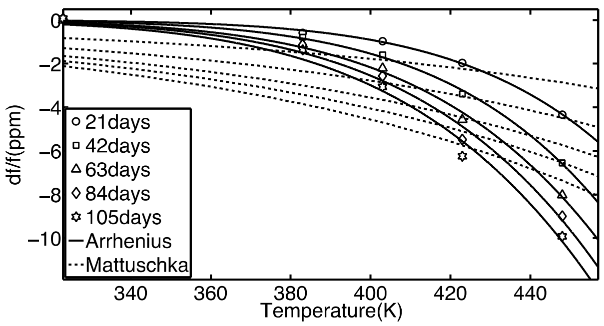

Fig. 2. Frequency shifts of 40MHz 3225quartz crystal resonators for different durations with Arrhenius and Mattsuchka models.

Again, we also calculated the correlation coefficients of different durations and it is clear that the Arrhenius model gives better results. For the calculation of the average correlation coefficients, we used all 21 time durations of all product tested.

Table 3. Correlation coefficients of 40MHz 3225 under different time duration with Arrhenius and Mattsuchka models

Time(days)	21	42	63	84	105	*Average*
Arrhenius	0.998	0.997	0.995	0.988	0.987	0.993
Mattuschka	0.612	0.632	0.665	0.667	0.683	0.652

Table 4. Correlation coefficients of different products for two models

Size	*40MHz 3225*	*TCXO 2520*	*TCXO 3225*	*SPXO 2520*	*SPXO 3225*
Arrhenius	0.987	0.904	0.857	0.846	0.952
Mattuschka	0.651	0.499	0.359	0.680	0.702

Once again, it is clear that the Arrhenius model has excellent correlation with measurement data in general. Even the data exhibited worse correlation is still much better than the Mattuschka model. Particularly, for aging effect under temperature variation, the Arrhenius model is very good for the products we have tested. We shall use the Arrhenius model for the analysis of products in our testing.

4. PARAMETERS OF ARRHENIUS MODEL

4.1 Activation Energy E_a and Life Prediction

In practical applications, it is impossible to determine the life of quartz crystal resonators through measurement under temperature due to the extraordinarily long life. It is always preferred to obtain the life from accelerated test and use the parameters to determine the life under room temperature. Of course, we shall use the Arrhenius model for the parameters and calculation.

Assuming the life at lower temperature T_L is t_L, and at temperature T_H is t_H, and assuming the frequency shift is the same, or

$$A\ln(1 + Bt_H)\exp\left(-\frac{E_a}{kT_H}\right) = A\ln(1 + Bt_L)\exp\left(-\frac{E_a}{kT_L}\right)$$

where B is a small number and t_H is about hundred hours.

Through Taylor series expansion, we can obtain

$$\ln(1 + Bt_L) = Bt_H\exp\left[-\frac{E_a}{k}\left(\frac{1}{T_H} - \frac{1}{T_L}\right)\right].$$

Since t_L is large, and $Bt_L >> 1$， we should have

$$\ln(1 + Bt_L) < Bt_L$$

and AFT is the acceleration factor, then

$$t_L > AFT\ t_H. \qquad (3)$$

For convenience, we choose $t_L = AFTt_H$ [5]. It is clear now that the activation energy E_a is an important parameter which determines the acceleration factor and links the high temperature aging with the room temperature aging.

4.2 The Determination of Activation Energy

Through calculating the activation energy of five different products we were testing, the activation versus time is given in Fig. 3.

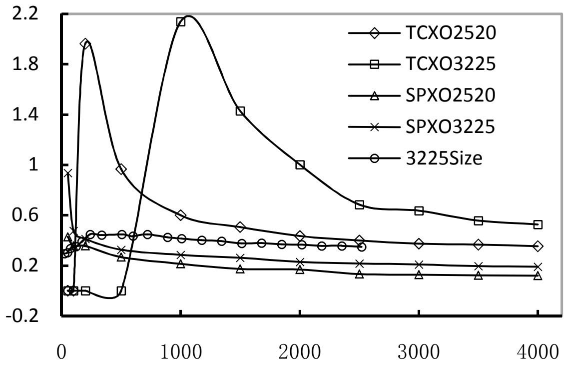

Fig. 3. E_a(eV) vs time(hours) with 5 resonators

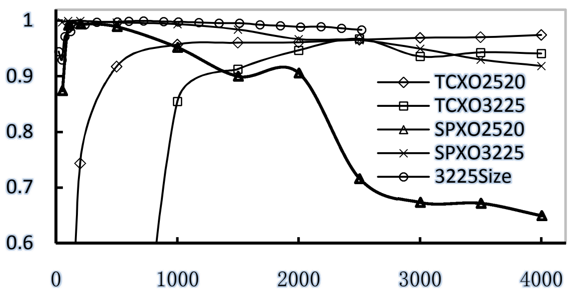

Fig.4. Correlation coefficients of five testing samples versus time

From Fig. 3, it is clear that the E_a increases with time but approaches to a stable value. The correlation coefficient also approaches to 1. It shows that the Arrhenius model is suitable for the aging pattern of quartz crystal resonators for longer time period. In other words, the Arrhenius model is good for the aging regression and we can obtain stable activation energy E_a. Since the measurement time is much smaller than the life of quartz crystal devices, we can safely ignore the short duration in which the activation energy varies significantly and the correlation coefficient is also very low. Consequently, the effect of activation energy on the life of a device can be neglected. Thus, we choose 2500 hours for oscillators and 2000 hours for quartz crystal resonators to obtain the activation energy with higher correlation coefficient and stable value. The values of activation energy based on this approach are listed in Table 5.

Table 5. Activation energy E_a of different products

Size	*40MHz 3225*	*TCXO 2520*	*TCXO 3225*	*SPXO 2520*	*SPXO 3225*
E_a	0.36	0.37	0.60	0.13	0.20

It is clear there are larger differences of activation energy for different products.

5. CONCLUSION AND DISCUSSION

From our analysis of measurement data, it is clear that the Arrhenius is better than the Mattuschka model for all products under all temperatures and measurement time. More specifically, Arrhenius model for aging with time is even better than aging with temperature. We need more measurements to confirm this phenomenon and obtain more parameters. We need to have more measurements to confirm our findings in this study. The activation energy varies with product significantly, showing strong needs for further researches on the vital factors and causes.

REFERENCES

[1] Vig JR, Meeker TR. The aging of bulk acoustic wave resonators, filters and oscillators. *Proceedings of the Annual Frequency Control Symposium*. pp. 77-101, 1991.

[2] Filler RL, Vig JR. Long-term aging of oscillators. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*. **40** (4): 387-394, 1993.

[3] Shen CN, Yang XW, Chang C, Chao MC. The study of activation energy (Ea) by aging and high temperature storage for quartz resonator's life evaluation. *Proceedings of the 2010 Symposium on Piezoelectricity, Acoustic Waves and Device Applications*. pp. 118-122.

[4] Neubig B, private communications, May, 2013.

[5] Nelson WB. Accelerated Testing-Statistical Models, Test Plans & Data Analysis. *John Wiley & Sons*. USA, 2004.