How to Estimate NAND Flash Retention Times Under Specified Mission Temperature Profiles

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Technical Article

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How to Estimate NAND Flash Retention Times Under Specified Mission Temperature Profiles

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In the industrial segment, particularly in the Automotive and Aerospace sub-segments, a great deal of emphasis is placed on system reliability.

For systems that include storage media based on NAND flash memory (which is almost all of them), one of the most critical parameters for overall system reliability is data retention time. This is defined as the maximum time period that data can be stored reliably, after which, the data read from a NAND generates a Raw Bit Error Rate (RBER) exceeding the correction limits of the adopted error correction code (ECC) algorithm.

The Role of Ambient Temperature in Data Retention

Given the extreme conditions in which storage media are required to operate, an accurate estimate of this parameter is sometimes necessary, based on the specific operating conditions. As is widely known, data retention time depends exponentially on temperature, and therefore, a precise estimate is required based on the exposure temperatures, especially when the storage media operate in environments with significant temperature fluctuations. This creates the need, for many system manufacturers, to record the ambient temperature exposure time distribution, throughout the system operational lifetime.

One of the most common methods for this purpose is the tabular approach, as shown in the example in Fig. 1, where the first column lists the temperatures and the second column shows the corresponding exposure times, expressed as a percentage of the system's operational life. Obviously, if the storage media loses data, meaning it reaches the maximum retention time for the given temperature profile, the system will stop functioning.

Temp [°C]: Ti	% Exposure Time: texp%(Ti)
50	0.0%
55	3.0%
60	7.0%
65	9.0%
70	13.0%
75	16.0%
80	17.0%
85	15.0%
90	11.0%
95	6.0%
100	2.7%
105	0.3%

FIG. 1

Computing Data Retention Time Based on Exposure Temperature

To clarify the dependency of retention time by the exposure temperature, let us assume that a NAND flash exposed to 328.15°K (55 °C) has a retention time of 5 years and we would like to know how the retention time will change if the NAND will be exposed to 356.15°K (83°C).

For this, we use the Arrhenius equation, which is a formula that mathematically expresses how a change in temperature can affect the rate of a particular reaction. An increase in temperature causes the reactions to accelerate or happen faster. In the semiconductor field, it is widely adopted as a life-stress model in accelerated life testing. It has been widely used when the stimulus or acceleration variable (or stress) is thermal (i.e., temperature).

In our example, it can be assumed that the retention time at 356.15°K will scale down from the one at 328.15°K simply by dividing it by the Arrhenius acceleration factor calculated between 328.15°K and 356.15°K.

$$\boldsymbol{t_R}(356.15\ °K) = \frac{\boldsymbol{t_R}(328.15\ °K)}{\boldsymbol{AF}(328.15\ °K, 356.15\ °K)} \qquad \text{Eq. 1}$$

Where $\boldsymbol{AF}(328.15°K, 330.15°K)$ is the acceleration factor calculated at 356.15°K with respect to 328.15 °K.

The next question is: how would it be possible to scale down the Retention Time, from $\boldsymbol{t_R}(328.15\ °K)$, to the Retention Time at a certain temperature profile (multiple temperatures and multiple exposure time intervals), like the one in Fig. 1?

So, let us first clarify the meaning of data in the second column of Fig.1. In the assumption that the whole exposure time would be $\boldsymbol{t_{exp\_tot}}$, then the exposure intervals are listed in the second column, named $\boldsymbol{t_{exp\%}}(T_i)$, in % of $\boldsymbol{t_{exp\_tot}}$, for each exposure temperature; then, it can be demonstrated (Appendix A) that:

$$\boldsymbol{t_{R\_C}} = \frac{\boldsymbol{t_R}(328.15\ °K)}{\sum_1^n \ \boldsymbol{t_{exp\%}}(T_i)\ \ \boldsymbol{AF}(328.15\ °K, T_i)} \qquad \text{Eq. 2}$$

Where in the Fig. 1 example “i“ ranges from 1 to 12, since there are 12 rows in the table. The cumulative retention time, $\boldsymbol{t_{R\_C}}$ **,** can be then easily calculated in a few steps:

1. Calculate for each temperature T_i, in the profile, the quantity:

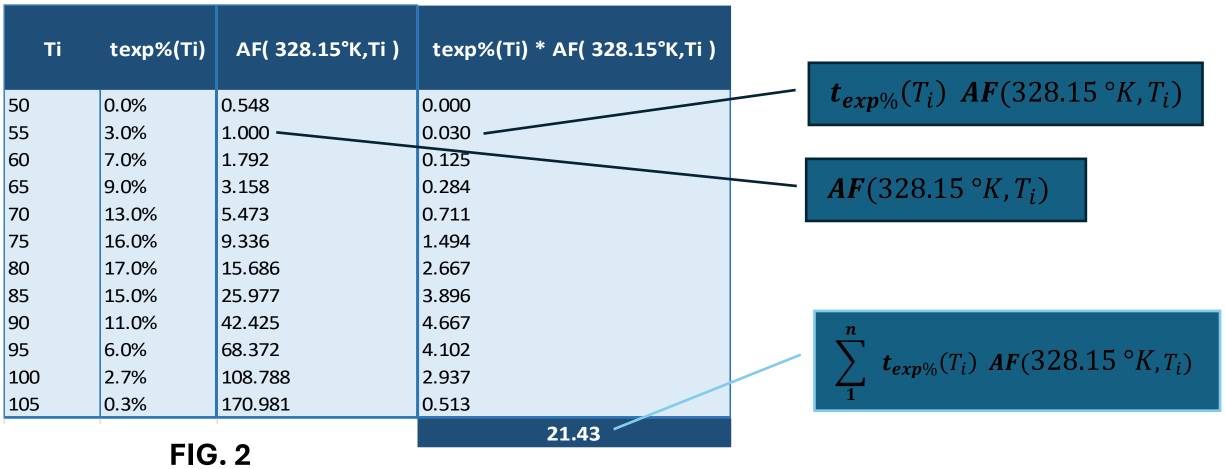
$$\boldsymbol{t_{exp\%}}(T_i)\ \ \boldsymbol{AF}(328.15\ °K, T_i)$$

2. Calculate the sum of values calculated in step 1, in the fraction denominator of Eq. 2, as shown in Fig. 2.

$$\sum_{\boldsymbol{1}}^{\boldsymbol{n}}\ \boldsymbol{t_{exp\%}}(T_i)\ \ \boldsymbol{AF}(328.15\ °K, T_i)\ =\ 21.43$$

3. Finally, calculate the $\boldsymbol{t_{R\_C}}$ by dividing $\boldsymbol{t_R}(328.15\ °K)$ by the value calculated in step 2.

$$\boldsymbol{t_{R\_C}}\ = \frac{5}{21.43} = \ 0.233\ years$$



Ti	texp%(Ti)	AF(328.15°K,Ti)	texp%(Ti) * AF(328.15°K,Ti)
50	0.0%	0.548	0.000
55	3.0%	1.000	0.030
60	7.0%	1.792	0.125
65	9.0%	3.158	0.284
70	13.0%	5.473	0.711
75	16.0%	9.336	1.494
80	17.0%	15.686	2.667
85	15.0%	25.977	3.896
90	11.0%	42.425	4.667
95	6.0%	68.372	4.102
100	2.7%	108.788	2.937
105	0.3%	170.981	0.513
			21.43

$\boldsymbol{t_{exp\%}}(T_i)\ \ \boldsymbol{AF}(328.15\ °K, T_i)$

$\boldsymbol{AF}(328.15\ °K, T_i)$

$\sum_{\boldsymbol{1}}^{\boldsymbol{n}}\ \boldsymbol{t_{exp\%}}(T_i)\ \ \boldsymbol{AF}(328.15\ °K, T_i)$

FIG. 2

Appendix A: Proving the Mission Profile Retention Time Calculation Method

The problem can be formulated as follows: find the retention time for the given temperature profile (as shown in the table in Fig. 1), knowing the retention time (named as t_{R_Ref}) at a reference temperature (referred to in the following calculations as T_{Ref}).

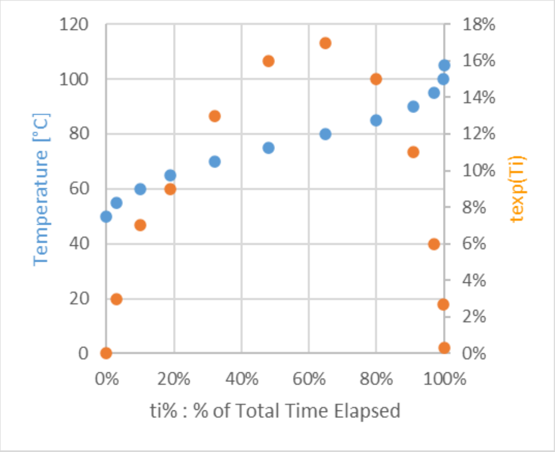


FIG. 3

Since the effect of temperature on retention time does not depend on the exposure order, the table in Fig. 1 can be rewritten using a progressive time scale (instead of intervals), which respects the duration of exposure intervals at different temperatures, as shown in the graph in Fig. 3.

Here, the x-axis represents the elapsed time, as a percentage of the retention time (for the given profile), while the y-axis (primary axis) represents the exposure temperature T_i at the time $t_{exp\%}(T_i)$.

For clarity, we can write that:

$$t_j = t_R \; t_{j\%} \qquad \text{Eq. 3}$$

$$t_{j\%} = \sum_{1}^{j} t_{exp\%}(T_i) \qquad \text{Eq. 4}$$

Having completed these preliminary considerations on the transformation of the temperature profile table format, we return to the original problem.

Here are a few well-known facts to consider:

- **<u>How data is stored</u>**: Data is stored in storage media as electric charges trapped in a layer within the flash memory cells that constitute them.
- **<u>How leakage occurs</u>**: Unfortunately, due to leakage phenomena, which are temperature-dependent, these charges can escape from the trapping layer.
- **<u>How charge loss leads to data corruption</u>**: If the charge loss is significant, it can lead to the complete corruption of the data stored in the media, based on the amount of charge contained in the storage layer.

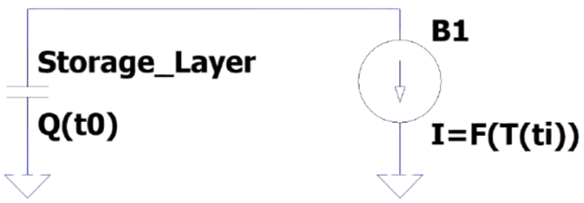


FIG. 4

Given these facts, an approximate model for the charge loss phenomenon can involve a charge capacitance representing the flash memory cell, connected to a discharge current generator, the leakage, which is temperature dependent.

So, assuming that the discharge current depends solely on the temperature and not on the voltage across the capacitance (storage layer), the circuit shown in Fig. 3 can represent a good approximation of the charge loss phenomenon in the flash cell.

Using this model, the capacitor discharge equation can be written as follows, considering that the current generator changes its value over time (and consequently with temperature):

$$\boldsymbol{Q}(t_{R\_C}) = \boldsymbol{Q}(t_0) - \sum_{1}^{n} \boldsymbol{I}(t_j)\ [\boldsymbol{t_j} - \boldsymbol{t_{j-1}}] \qquad \text{Eq. 5}$$

Where:

$\boldsymbol{Q}(t_{R\_C})$ is the residual charge at the end of the retention time
$\boldsymbol{t_{R\_C}}$, $\boldsymbol{Q}(t_0)$ is the charge at the initial time $\boldsymbol{t_0}$
n is the total number of a given temperature $\boldsymbol{T_i}$ in the profile

Eq. 5 can be rewritten as:

$$\boldsymbol{Q}(t_{R\_C}) = \boldsymbol{Q}(t_0) - \sum_{1}^{n} \boldsymbol{I}(t_j^{\%})\ \boldsymbol{t_{R\_C}}\ [\boldsymbol{t_j^{\%}} - \boldsymbol{t_{j-1}^{\%}}] \qquad \text{Eq. 6}$$

But $[\boldsymbol{t_j^{\%}} - \boldsymbol{t_{j-1}^{\%}}] = \boldsymbol{t_{exp\%}}(\boldsymbol{T_i})$, hence the Eq. 6 will convert in:

$$\boldsymbol{Q}(t_{R\_C}) = \boldsymbol{Q}(t_0) - \boldsymbol{t_{R\_C}} \sum_{1}^{n} \boldsymbol{I}(T_i)\ \ \boldsymbol{t_{exp\%}}(T_i) \qquad \text{Eq. 7}$$

Let us assume that the retention time $\boldsymbol{t_{R\_ref}}$ is known at a fixed Temperature $\boldsymbol{T_{ref}}$, then

$$\boldsymbol{Q}\left(t_{R\_Ref}\right) = \boldsymbol{Q}(t_0) - \boldsymbol{t_{R\_Ref}}\ \ \boldsymbol{I_{Ref}} \qquad \text{Eq. 8}$$

Since the maximum acceptable charge loss for the retention time must be the same irrespective of the arrangement of current source leakage, then we can impose:

$$\boldsymbol{Q}(t_0) - \boldsymbol{Q}(t_{R\_Ref}) = \boldsymbol{Q}(t_0) - \boldsymbol{Q}(t_{R\_C}), \qquad \text{Eq. 9}$$

Adopting the Arrhenius equation is also possible to convert all the $\boldsymbol{I}(T_i)$ to $\boldsymbol{I_{Ref}}$ as follows, (see Appendix B).

$$\boldsymbol{I}(T_i) = \boldsymbol{I_{Ref}}\ \ \boldsymbol{AF}(T_{Ref}, T_i) \qquad \text{Eq. 10}$$

Combining the Eq.7, Eq. 8, Eq. 9, Eq. 10, we can therefore obtain:

$$\boldsymbol{t_{R\_Ref}}\ \boldsymbol{I_{Ref}} = \quad \boldsymbol{t_{R\_C}}\ \ \boldsymbol{I_{Ref}}\ \ \sum_{1}^{N} \boldsymbol{AF}(T_{Ref}, T_i)\ \ \boldsymbol{t_{exp\%}}(T_i) \qquad \text{Eq. 11}$$

Then:

$$\boldsymbol{t_{R\_C}} = \boldsymbol{t_{R\_Ref}} \cdot \frac{1}{\sum_{1}^{N} \boldsymbol{AF}(T_{Ref}, T_i)\ \ \boldsymbol{t_{exp\%}}(T_i)} \qquad \text{Eq. 12}$$

Appendix B: Arrhenius Equation

$$\boldsymbol{AF}(T_{use}, T_{stress}) = e^{\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)}$$

Where:

$\boldsymbol{AF}(T_{use}, T_{stress})$ is the acceleration factor due to changes in temperature;
E_a is the apparent activation energy (eV, for silicon 1.1eV);
k is Boltzmann's constant (8.62 × 10-5 eV/K);
T_{use} is the absolute temperature of the refence test (K);
T_{stress} is the absolute temperature of the stressed media (K).

Conclusion

Data retention time is a critical parameter for system reliability in industrial systems, particularly in the Automotive and Aerospace sub-segments.

When the maximum time interval for reading data is reached, generated raw bit errors exceed the correction limits of the ECC algorithm. This leads to data corruption, which compromises the integrity of the stored data.

As data retention time depends exponentially on temperature, it is important to make precise estimates based on exposure temperatures.

For more information on calculating the data retention times of ATP NAND flash solutions, please contact an ATP Representative in your area.