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## EEPROM Endurance Tutorial

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### INTRODUCTION

The endurance of an EEPROM-based device will be quoted by a manufacturer in terms of the minimum number of erase/write cycles (write cycles) that the device is capable of sustaining before failure. A write cycle is generally considered to be the operation that changes data in a device from one value to the next.

There are several EEPROM-based devices available on the market. Microchip Technology Incorporated makes three general types of EEPROM-based product: Serial EEPROMs, Parallel EEPROMs, and EEPROM-based Microcontrollers. As a manufacturer of many EEPROM products, Microchip is concerned with endurance and continues to try to educate its customers on the importance of this topic.

There are many differences in the interpretation of "endurance" that can result in misleading or inaccurate information being used in design decisions. This paper hopes to clear up any questions that the customer may have in the subject of endurance, without becoming so technical that the information given is not helpful.

There is no widely used standard for any type of endurance test. Each manufacturer will use their own endurance testing methodology. This report will describe all the testing options, and which tests Microchip performs on its EEPROM-based products.

The MIL-STD cycling test (Method 1033) has not been updated since 1977 and is well out of date as applied to EEPROM non-volatile memories. The standard does not distinguish the difference between block cycling and byte cycling, and gives a very poor failure criteria. Microchip does not use this standard.

### BASIC TERMS

The definition of "endurance" (as applied to EEPROMs) in the first part of this introduction contains various words and phrases that require clear definition and understanding. As shown in the following paragraphs, different manufacturers will use different standards.

"Endurance cycling" is a test performed by all manufacturers (and some customers) to determine how many "write cycles" the product will achieve before failing.

The "minimum number of write cycles" is the least number of times that you can expect to subject the product to a "write cycle" before it fails.

"Failure" is a somewhat arbitrary definition, since a device only truly fails when it no longer meets the customer expectation, and does not operate in his system. A failure can be defined in this, the loosest of definitions, or the most stringent of definitions (whereby a device would fail if it did not meet any of the data sheet parameters), as well as a wide range in between.

For example, if the device did not correctly store data into a particular address that the customer was not using, then the device would work correctly for the customer but would fail a functional test set by the manufacturer. Likewise, if the device drew more current than the data sheet specified after some time, but the customer application could supply the current needed, the device would work in the customer application but would fail a parametric test set by the manufacturer.

Microchip uses the most stringent definition: **A failure occurs when the device fails to meet any data sheet condition under any guaranteed operating condition of temperature and voltage.**

The number of devices that can fail before a particular endurance criteria is not met is also somewhat flexible. Even the most quality conscious manufacturer will occasionally have a failure, so a failure level is defined. The industry standard conditions for many types of reliability tests are set by JEDEC (the Joint Electronic Device Engineering Council). JEDEC defines that if 5% or less of a given sample fails at a given endurance goal, then that goal has been met. For example, if a sample of 100 units are endurance cycled to 1 million cycles and 3 have failed at 100,000 cycles and a further 7 have failed at 1 million cycles, then the sample would have an endurance of 100,000 cycles.

Microchip uses a more stringent criteria for endurance: no more than 2.5% of devices can have failed for the given endurance goal to have been met.

A “write cycle” is also a somewhat flexible definition since almost every customer will write the device in a different way. For example, if the customer application uses only the first three bytes of the array to store variable data, and the remainder of the array is used as a lookup table, then a write cycle will be complete when the three data bytes have been re-written to their new data state.

A write cycle is often described as an erase/write cycle, since almost all technologies employ an “auto-erase” before the data is actually written to the array. This is also used by Microchip, but we will use the term “write cycle” since the auto-erase is invisible to, and cannot be suppressed by, the customer.

The term “data changes” is occasionally used in place of “write cycle” or “erase/write cycle.” A data change will occur when an auto-erase cycle is initiated, and a second data change will occur upon the write cycle, therefore, one “erase/write cycle” is equivalent to two “data changes.” The term “data change” also implies that a different type of cycling is being used than “erase/write cycle.” This will be described later.

The term “write cycle” does not define under what conditions the cycling was done (unless explicitly stated) nor does it define the type of cycling that was done. The endurance cycling can be done at any number of conditions of voltage and temperature (e.g., 85°C and 5.5V, or 25°C and 5.0V) that may or may not meet with a customer’s application. The cycling mode used in endurance cycling can affect the endurance of the product. All these effects will be described later.

Microchip uses the most stringent conditions that are reasonable for endurance cycling. We use byte or page mode cycling at a temperature of 85°C at 5.5V. All data not explicitly defined at other conditions is taken at these conditions.

A “read cycle” is completed when any number of bytes of data have been read from the device. For the FLOTOX-design EEPROM-based devices made by Microchip a read cycle does not affect endurance, since the data in the EEPROM is not changed. Other technologies, such as Ferroelectric technology, may have a limited number of read cycles since data is corrupted during a read.

## System Design Considerations

There are a number of design considerations that the system designer can use to maximize the endurance of an EEPROM-based device, if endurance is the application’s limiting factor.

As will be described in more detail later, if the designer has any control over certain environmental or operation conditions he should observe the following basic guidelines:

- Keep the application temperature as low as possible
- Keep the application voltage (or the Vcc voltage on the EEPROM-based device) as low as possible
- Write as few bytes as possible
- Use page write features wherever possible
- Write data as infrequently as possible

With these basic guidelines applied to the fullest extent, the endurance of EEPROM-based devices can be extended well beyond the guaranteed minimum endurance. Under certain very specific conditions, Microchip Serial EEPROMs have been shown to last for well over 100 million cycles.

## WRITE MODES IN EEPROMS

There are three ways that EEPROM-based devices can have the entire array data contents changed. These are: byte mode, page mode, and block (or bulk) mode. Some types of devices support all three modes, others may only support one or two modes. The mode that you use to write an EEPROM-based device will affect the long term endurance of the product.

Byte mode writing is used when the contents of the array are changed one byte at a time. For many devices this is the only user-accessible write mode available. To change the entire contents of a Serial EEPROM in this way would take up to 10 seconds (using 10 ms per page on a 64K Serial EEPROM). Parallel EEPROMs such as a 28C64, which have a faster byte write time (1 ms rather than 10 ms), but no page mode would also take up to 10 seconds.

Page mode writing is a popular feature on many new designs of EEPROM memory products. This feature allows up to 8 bytes of data to be written to the memory in the same time that one byte would normally take. In this mode, the write time for a 64K Serial EEPROM can be cut from eight seconds to one second.

Block cycle is generally a test mode used by EEPROM manufacturers to make it easier to test the products. Some types of EEPROM-based products have these modes as user options (such as the ERAL and WRAL mode in 93CXX products, or the Chip Clear mode in 28CXXX products) but generally this mode is not user accessible. A block write can be done in as little as 1 ms, allowing millions of write cycles to be completed in a few hours.

A general rule to follow in choosing write modes is that the larger the number of bytes being written in a single instruction, the longer the device will last. For example, in byte mode a device might start to fail after 300,000 cycles under a particular set of conditions, but the device may last 600,000 cycles in page mode under the same conditions. In block mode the device might last 1 million cycles, under the same conditions.

The reason for this is related to the internal design of any FLOTOX EEPROM-based product. In these devices, an internal "charge pump" takes the applied Vcc voltage (typically 2.5 to 5.5V) and increases it to 15 to 25V. This voltage is required to induce the "Fowler-Nordheim Tunneling" or "Enhanced Emission" effects that are used to program and erase EEPROM-based devices. The specific effect that is used is manufacturer-dependent. Microchip EEPROMs program by Fowler-Nordheim Tunneling.

The charge pump voltage is used to program however many EEPROM-cells are being programmed. For example, in byte mode, all the cells in a byte (8 to 16) are biased with the charge pump voltage. In block mode, all the cells in the array (up to 100,000, depending on the device) are biased with the charge pump voltage. The charge pump is like a current source during conditions of high load, so the voltage put out by the charge pump will be reduced slightly if more bytes are being written. If the whole array is being programmed then the charge pump voltage will be significantly reduced, but the programming current Ipp will be very high.

Generally, the lower the charge pump voltage the better the endurance (there is a limit since the charge pump voltage needs to be high enough to program the cell) and so the best endurance is generally achieved by using block mode cycling. Page mode is worse than block mode, but better than byte mode. Block mode is generally not a very useful cycling mode to the end user, since the data contents in the whole array will be changed to the same value (generally 00 or FF).

When Microchip tests EEPROM-based products we use byte mode cycling on devices which do not have a page mode, and page mode cycling for those that do. We encourage our customers to use page mode writing on all products which have page mode, to ensure high endurance.

## ENDURANCE TESTING METHODOLOGIES

Different manufacturers use different ways to both endurance cycle and test EEPROM-based products. There is no standard for endurance cycling, or testing devices after cycling.

There are two groups of testing that Microchip performs on all products: qualification and production. Qualification testing is done for all new products, and major changes to a product or manufacturing process. Production testing is done on all devices shipped to customers.

Qualification testing at Microchip is used to test the reliability of new products, and to guarantee that the device is reliable. A great deal of testing is done, including endurance testing on all EEPROM-based products. Endurance cycling is done at the maximum rated data book value, generally 85°C or 125°C. After the rated number of cycles (10,000, 100,000, or 1,000,000) the sample (around 300 from multiple wafer lots) is tested to a full production test program. After endurance, the units are subject to "data retention" to guarantee that the required 40 years of data retention will be achieved, after the maximum number of cycles has been completed.

Endurance cycling is done under the conditions previously described, and the data retention test is performed after this. After the data retention stress is completed (which takes six weeks) the devices are tested again, to confirm the functionality of the device to all data sheet parameters.

No more than 2.5% failures are allowed after endurance, and a failure rate higher than 100 FITs after 1000 hours of data retention stress (equivalent to more than 10 years at 55°C) is unacceptable.

Production testing is done by Microchip on all devices shipped to a customer. Production testing begins immediately after a wafer lot is finished being processed, continuing in various stages until the devices are shipped to a customer.

The first tests that are done on EEPROM-based products at Microchip are called wafersort. They are done before the wafer is cut up into dice for assembly. There is a series of tests which include large numbers of write cycles (up to 5000) to ensure reliability by weeding out weak devices so they never get shipped.

After assembly full testing is done which includes further write cycles across the guaranteed temperature range, to ensure device functionality at the temperature extremes. After the normal production testing a sample of 128 units is taken from every wafer lot, and cycled to 10,000 cycles (Parallel EEPROMs) or 1,000,000 cycles (Serial EEPROMs and EEPROM microcontrollers) at 85°C using the conditions already described. After endurance testing the devices are tested for functionality at 85°C.

Any sample of Parallel EEPROMs which shows significant failures at the end of cycling causes the entire wafer lot to be pre-cycled prior to production testing. Serial EEPROMs and EEPROM-based microcontrollers do not receive the same disposition. Lots with significant failures come under scrutiny and full failure analysis with corrective actions is done. This is, however, a rare occurrence.

The testing that Microchip does is unique. Manufacturers will generally do different testing from each other. Microchip firmly believes that our testing ensures excellent quality and reliability.

## THE EFFECT OF TEMPERATURE ON EEPROM ENDURANCE

The temperature at which cycling is done will affect the number of write cycles that can be executed before the device fails. The higher the temperature, the worse the endurance will be. Generally, and approximately, a device which fails at 10 million cycles at 25°C will fail at 2 million cycles at 85°C and 1 million cycles at 125°C. The reasons for this are not conclusive (although there is much technical literature supporting one theory or another) but it is apparent that the failure mode of EEPROM cells (generally considered to be electron trapping in the tunnel dielectric causing shielding and dielectric breakdown) is strongly dependent on temperature.

Data taken by Microchip suggests that if the typical failure of an EEPROM-based device is 10 million cycles at 25°C, the mean failure will occur at other temperatures according to the following table:

**TABLE 1: TEMPERATURE MEAN FAILURE**

Write Cycle Temperature	Mean Failure (Cycles)
-40°C	37.1 million
0°C	16.7 million
25°C	10.0 million
40°C	7.4 million
55°C	5.4 million
70°C	4.0 million
85°C	2.9 million
100°C	2.2 million
125°C	1.3 million

This data was taken on Microchip FLOTOX Fowler-Nordhiem Tunneling EEPROMs and formed a part of the data set used to create the Total Endurance™ disk. Other technologies (such as FLOTOX Enhanced Emission or Ferroelectric technologies) may have different characteristics.

As is clearly seen, any cycling done at 25°C can be misleading in the extreme if the application requires a device that can be cycled 10 million times at, say, 55°C.

## THE EFFECT OF VOLTAGE ON EEPROM ENDURANCE

The voltage at which a device is written can also affect the endurance. This is simply because the charge pump (used to program and erase EEPROM cells) is more powerful at higher voltages. As has already been described, a higher programming voltage will reduce the endurance of an EEPROM cell, and a stronger charge pump will produce a higher voltage.

Data taken by Microchip suggests that if typical failure of an EEPROM-based device is 1 million cycles when endurance cycling is done at 5.5V, mean failure occurs at other temperatures according to the following table:

**TABLE 2: VOLTAGE MEAN FAILURE**

Endurance Cycling Voltage	Mean Failure (Cycles)
5.5V	1.0 Million
5.0V	1.2 Million
4.5V	1.4 Million
4.0V	1.7 Million
3.5V	2.0 Million
3.0V	2.4 Million
2.5V	2.8 Million
2.0V	3.3 Million

This data was taken on Microchip FLOTOX Fowler-Nordhiem Tunneling EEPROMs and formed a part of the data set used to create the Total Endurance disk. Other technologies (such as FLOTOX Enhanced Emission or Ferroelectric technologies) may have different characteristics.

## THE EFFECT OF WRITE MODE ON EEPROM ENDURANCE

As has been discussed there are three basic ways of writing data to an EEPROM-based device:

- Byte mode
- Page mode
- Block mode

This is related to the strength of the charge pump in applying the required programming voltages to the EEPROM cells.

Data taken by Microchip suggests that if the typical failure of an EEPROM-based device is 1 million cycles when the endurance cycling is done in byte mode, the mean failure will occur in other modes according to the following table:

**TABLE 3: ENDURANCE MEAN FAILURE**

Endurance Cycling Mode	Mean Failure (Cycles)
Byte	1.0 Million
Page	4.6 Million
Block	13.2 Million

This data was taken on Microchip FLOTOX Fowler-Nordhiem Tunneling EEPROMs and formed a part of the data set used to create the Total Endurance disk. Other technologies (such as FLOTOX Enhanced Emission or Ferroelectric technologies) may have different characteristics. This data was taken from a Microchip 24LC16.

As you can see, the use of the block cycle data to guarantee endurance can be misleading.

## THE TOTAL ENDURANCE PREDICTIVE SOFTWARE

Microchip has a Windows<sup>®</sup>-based software model called Total Endurance. This program, based on all of the customers endurance parameters, will predict the failure level at the expected end of application life. This tool is invaluable for system designers who would like to fine-tune their application in favor of endurance. It is available now from your local Microchip distributor.

NOTES:

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