SMART Modular Technologies

White Paper

What defines a true Industrial Grade Flash SSD?

An in-depth review on the building blocks of an Industrial Grade Flash SSD

Esther Spanjer
Director of Technical Marketing
Storage Products
SMART Modular Technologies

June 2008

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1 EXECUTIVE SUMMARY

With the year-over-year price decline of NAND flash technology, SSDs have become an affordable solution for additional applications and new markets. The explosive growth of the SSD market has led to a significant increase in new SSD vendors and products, which in turn has caused a lot of confusion with OEMs who are trying to decide which vendors and products are most suitable for their application.

Comparing product attributes alone is not enough to distinguish between the three emerging SSD categories: Consumer, Commercial or Industrial Grade. While Consumer Grade SSDs are more recognizable since they are optimized for the lowest cost per gigabyte, the distinction between Commercial and Industrial Grade SSD is less obvious. Comparing product specifications doesn't adequately uncover this distinction, and an in-depth review of the vendor's design, testing and manufacturing procedures is needed to assess the category into which the drive falls.

Industrial Grade SSDs set themselves apart from their Commercial Grade counterparts throughout all aspects of the product life cycle. During design phase, a vendor that provides Industrial Grade SSDs should implement Failure Mode and Effects Analysis (FMEA) procedures and qualify components for industrial standards. The design verification stage should include thorough design verification testing, margin testing, environmental testing on *operational* devices, Highly Accelerated Life Testing (HALT testing) and regulatory compliance certification. During manufacturing, each *individual* drive should be tested, including an 8-hour burn-in test to eliminate early device failure in the field. Finally, ongoing quality assurance methods, such as beta testing and closed loop corrective action through failure analysis procedures, should be standard business practices.

A vendor that sells Commercial Grade SSDs will most likely not include many of these practices. Typically, environmental testing is done on non-operational drives, burn-in testing is limited or non-existent, the design phase does not include HALT testing and margin testing, and manufacturing testing is done on lot samples.

Only by reviewing all the test reports and understanding how the design, testing, and manufacturing methods are implemented can an OEM validate whether the drive falls into the Industrial Grade or Commercial Grade category.

This white paper is meant to help the OEM understand the distinctiveness of an Industrial Grade SSD, and know what questions should be asked of their SSD vendor to determine the validity of a drive that is promoted as an Industrial Grade SSD.

2 INTRODUCTION

Since they were first introduced in the mid-1990s, flash-based solid state drives (SSDs) have been used predominantly in the military/aerospace and industrial markets. Their superior ruggedness and reliability over hard disk drives (HDDs) allowed them to perform in harsh environmental conditions, and their higher price was a minor concern in these types of embedded applications.

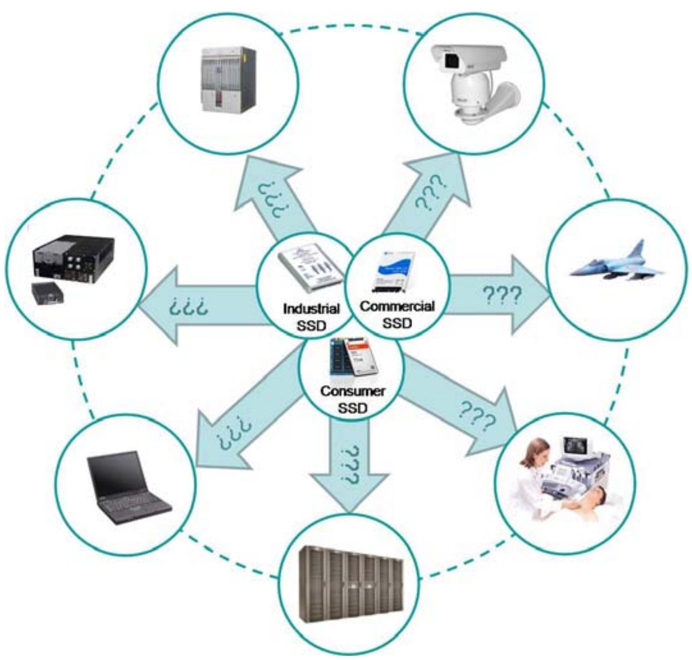
With the year-over-year price decline of NAND flash technology, SSDs have become an affordable solution for additional applications and new markets, such as the emerging consumer laptop and enterprise storage market.

Due to these large, new opportunities, industry analysts [1] are predicting exponential growth for the SSD market, and this growth has attracted many new SSD vendors. The market is literally being flooded with new SSD products, each designed for specific market or application segments.

At the highest level, the flash SSD market can be divided into 3 sub-segments:

- **Consumer Grade**, targeted at the consumer laptop market, primarily optimized for the lowest cost per gigabyte. Most products for this market will be offered with Multi-Level Cell (MLC) flash technology by the end of 2008.
- **Commercial Grade**, targeted at applications that require a drive that is more reliable than a standard HDD, but that do not have extremely demanding requirements for their storage device in terms of ruggedness and reliability. Typically these products will be offered with Single Level Cell (SLC) technology, although in the future they may also be offered with MLC technology.
- **Industrial Grade**, targeted at extremely demanding applications in terms of ruggedness and reliability. Products in this category will be offered with Single Level Cell (SLC) technology due to its superior performance, reliability and endurance.

Figure 1: Different applications demand different storage requirements



As illustrated in Figure 1 above, the wide variety of flash SSD choices is causing a lot of confusion with purchasers and engineers who are evaluating SSD drives for their applications. Flash SSD vendors all use the same product attributes to describe their products, but in many cases, products with similar performance and capacity attributes have other characteristics that are optimized for a specific market. Some are optimized for high volume, low cost consumer markets and others for the more demanding embedded markets. The confusion grows when SSD vendors deliver very similar market messages and blur the distinctions between consumer, commercial, and industrial products. In fact, this confusion benefits vendors of less robust products in the short term since it helps attract interest from those markets whose capacity (and possibly I/O throughput) they can meet. It is only later that these markets realize that the other product characteristics are also important.

This white paper is meant to precisely define what makes a flash solid state drive a true Industrial Grade solution. Customers can use this definition in evaluating flash SSD products for their application. It will explain that an Industrial Grade flash SSD is much more than the combination of industrial temperature and SLC flash technology. In fact, an Industrial Grade flash SSD is most distinguished by how the product is designed, tested and manufactured. Factors such as extensive burn-in testing on each shipped product and verification testing on *operational* devices are what set them apart from their commercial grade counterpart.

The topics covered in this white paper are meant to assist those evaluating SSD products in asking the right questions of their flash SSD vendor when searching for an Industrial Grade SSD.

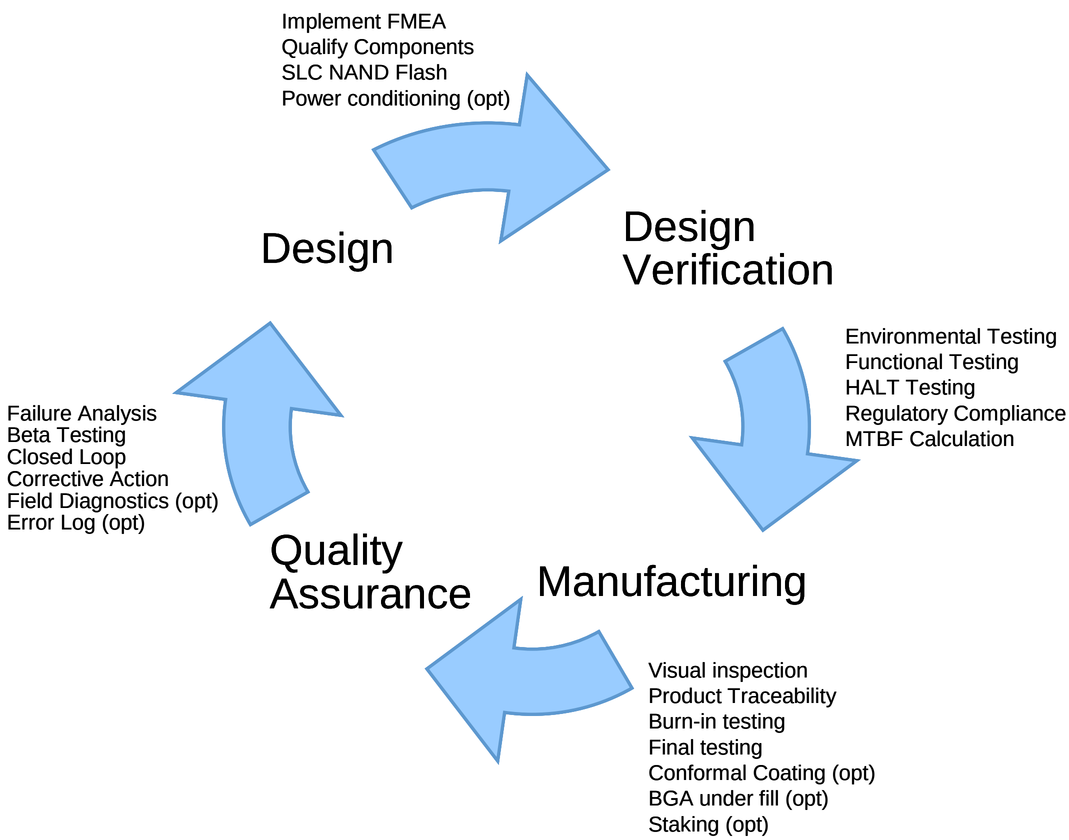
3 WHAT IS AN INDUSTRIAL GRADE FLASH SSD?

The term *industrial grade* for flash-based products was first introduced by SanDisk in 2002 [2] with the announcement of an Industrial Grade product line that was targeted at the telecom, factory automation, and aerospace markets. Since then, the term has been used loosely and has been increasingly associated with products that are offered with an industrial temperature (-40°C to 85°C) operating range.

An Industrial Grade SSD designed and manufactured to meet the needs of demanding applications requires much more than complying with specific product attributes – attributes such as industrial temperature, SLC flash components and high MTBF numbers. It is the combination of how the product is designed, tested and manufactured that results in the most reliable, highest quality product possible.

Figure 2 below shows how the combination of numerous steps during the product life cycle results in a product that can be rated as Industrial Grade.

Figure 2: Product life cycle results in true Industrial Grade SSD



Design Phase:

1. Implement FMEA (Failure Mode and Effects Analysis) practices (see section 4.1)
2. Use SLC NAND Flash components to ensure the highest reliability solid state drive (see section 4.2)
3. Select components that are qualified and/or screened for industrial standards (see section 4.3)

Design Verification Phase:

4. Perform thorough design verification testing, such as functional testing, margin testing, benchmark testing and burn-in testing (see section 4.4)
5. Perform environmental testing in independent labs on *operational* devices (see section 4.4.1 and section 4.4.2), according to an industry standard procedure, such as MIL-STD-810F [3]
6. Perform HALT testing to identify any weakness in the design and validate the margins of the design and, as such, its robustness (see section 4.4.4)
7. Calculate MTBF numbers based on common reliability prediction model (see section 4.5)
8. Obtain compliance certifications for all the regulatory standards (see section 4.4.5)

Manufacturing Phase:

9. Implement manufacturing procedures that allow for drive traceability, such that drive capacity, firmware version, serial number and manufacturing test results are recorded (see section 5.1)
10. Perform extensive testing during manufacturing on every *individual* product, including an 8-hour burn-in test to reduce early device failure in the field (see section 5.2)
11. Perform visual inspection throughout the manufacturing process and guarantee that each individual product passes a final test (see section 5.1)

Quality Assurance Phase:

12. Implement a beta test program that validates the drives in real-life applications at customers' sites (see section 6.1)
13. Implement closed loop corrective action, such that Failure Analysis procedures can be used as feedback for ongoing product and manufacturing procedures (see section 6.2)

Sections 4, 5 and 6 will explain in detail the procedures and methods that are required to deliver a final product that can be rated as Industrial Grade.

SMART Modular implements all of these best practices in order to offer its customers true Industrial Grade SSD products and meet the needs of the most demanding embedded and industrial applications.

3.1 Who needs Industrial Grade SSD?

Industrial Grade storage solutions are required by applications that:

- Operate in harsh environments in terms of shock, vibration, humidity and temperature
- Are located in remote locations with difficult, costly access by service engineers
- Have extremely high reliability demands (i.e., mission critical)

A true Industrial Grade SSD that is designed, tested and manufactured with these requirements in mind will be the product of choice for these applications.

Take for example a pipeline inspection gauge (PIG) device that runs through an oil pipeline to inspect the conditions of the pipeline walls and capture and record geometric information (i.e., size and position). The storage device recording the sensor data must be able to withstand conditions of high shock, vibration and perhaps temperature, while running without failure. Running a PIG device through a pipeline is a very costly operation, and a failed storage device could cause the loss of millions of dollars, expensive man hours, and company reputation. Knowing that the solid state drive was tested in *operational mode* while undergoing environmental shock and vibration testing, as specified in MIL-STD-810F, substantially increases the level of confidence that the device will perform equally well while running through the pipeline.

Figure 3: Various applications requiring Industrial Grade SSD

Another example of an application that has high demands for a storage device would be a data recorder in a jet fighter. The storage device inside the recorder would not only have to be able to withstand operational conditions of high shock, vibration and possibly extreme temperature, it also would have to have high write throughput, 100% duty cycle and perform reliably. If the SSD vendor can prove that the Industrial Grade SSD can withstand *operational* conditions of shock and vibration, according to the jet profile of MIL-STD-810F (Section 514.5, procedure 1), the chances that it will perform equally well inside a real jet fighter increase dramatically. In addition, simulated testing for altitudes up to 80,000 ft (per MIL-STD-810F, Method 500.4) will ensure that the device will continue to record data when the jet fighter is flying at high altitudes.

Finally, let's look at a medical device that is used for diagnostic purposes in a hospital where it will record the results of patient tests. Data integrity, security and device reliability are absolute necessities for storing medical information. Any single piece of information, whether it is the system code or patient information, cannot afford even the slightest bit of data loss. A thorough burn-in of the solid state drive over multiple hours prior to shipment will ensure that early device failures in the field are reduced to an absolute minimum. In addition, strong error detection and correction and flash management algorithms will substantially reduce the risk of failures during operation. Finally, *operational* shock and vibration testing during design verification will increase the confidence that the device will work without failure while being pushed around the hospital floor.

4 DESIGN AND DESIGN VERIFICATION

Product quality is defined by customer expectations and achieved by the combination of the component selection, component qualification, design methods and design verification.

A single weak component or process echoes throughout the entire product lifecycle, from design engineering to field support. To ensure the highest quality product, an Industrial Grade SSD vendor should:

- Implement Failure Mode and Effects Analysis (FMEA) procedures
- Choose the highest quality components and qualify them
- Perform design verification testing, both in-house as well as by independent labs, to ensure that the products are tested to real world operating conditions (shock, vibration, temperature, humidity and altitude)
- Include HALT testing to identify any flaws in the product design and validate the margins of the design

This section will explain in detail all the steps that are required during the design and design verification stages, and what a prospective customer can expect from the SSD vendor in terms of reports and validation.

4.1 Failure Mode and Effects Analysis (FMEA)

The FMEA process was originally developed by the US military in 1949 to classify failures "according to their impact on mission success and personnel/equipment safety", and was implemented commercially in the 1980s by Ford to reduce risks after the Ford Pinto suffered a design flaw that could potentially result in an exploding gas tank.

Failure Mode and Effects Analysis (FMEA) is a method [4] that helps to identify potential failure modes within a product or system and classifies the severity of them. Failure causes are any errors or defects in process, design, or items that can affect the customer. The purpose of the FMEA is to take preventive actions to eliminate or reduce failures in a design or manufacturing process, resulting in a better quality product.

By implementing well-defined FMEA methods and procedures, an SSD vendor can detect the weaknesses in an SSD design, improve the overall quality of its products and use the acquired knowledge to continually improve its product design and manufacturing procedures. Implementation of FMEA from the earliest conceptual stages of design throughout the life of the product is one of the steps an SSD vendor should take to provide a true Industrial Grade SSD to its customers.

4.2 SLC NAND Flash Components

Multi-Level Cell (MLC) NAND and Single-Level Cell (SLC) NAND offer capabilities that serve two very different classes of applications – those requiring the lowest cost-per-bit, and those demanding higher performance and reliability.

MLC NAND flash allows each memory cell to store multiple bits of information, compared to the one bit per cell for SLC NAND flash. As a result, MLC NAND offers a larger capacity, twice the density of SLC, at a lower cost. The higher density comes however with a price: MLC NAND flash provides slower performance, higher error rates and substantially shorter write endurance parameters when compared to SLC NAND flash.

As a result, SLC NAND is better suited for applications that require high reliability, performance, and viability in multi-year service life. Industrial Grade SSD vendors should not use anything less than SLC flash within their product designs.

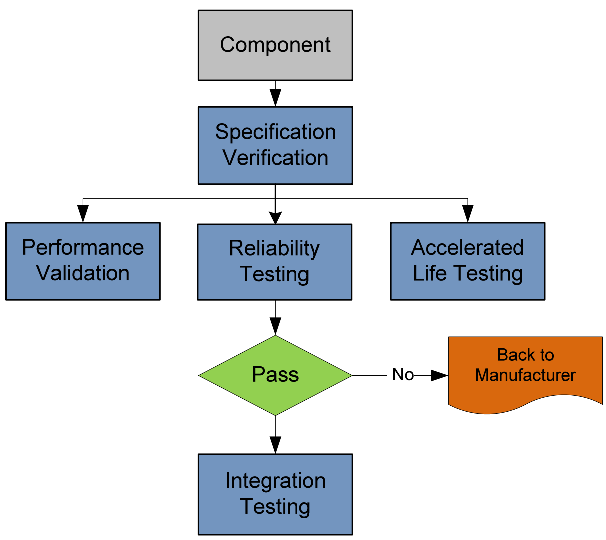
4.3 Component Qualification

Careful attention must be given to selecting, evaluating, characterizing, and testing the components for an Industrial Grade SSD, from the chip sets used on the printed circuit board assemblies to the NAND flash media that populate the drive. Since the Bill-Of-Material of a solid state drive consists of many NAND flash components, thorough media selection and testing are critical.

Component validation should include verification of manufacturing specifications, performance validation and endurance testing, based upon the solid state drive design criteria:

- *Specification verification*: each relevant element of the specification is reviewed, and actual product test results are compared with the published values
- *Performance test validation* is required for NAND flash components and is used to substantiate the data performance read/write claims
- *Reliability testing* is a critical part of determining whether a component derates over time. For example, durability testing on NAND flash media involves millions of read and write operations to each flash cell to verify cell life and the spare sectoring qualities
- *Accelerated life testing* is required for NAND flash and focuses on silicon aging that causes component failures typically referred to as device wear-out. Intense write testing at high temperatures for extended periods of times (months, even years) is required to verify the endurance specification of the media

Figure 4: Component qualification



As illustrated in Figure 4 above, only components that pass the multi-phase qualification process are eligible for implementation in an Industrial Grade SSD. Component qualification is a continuous process that influences the design and development of new and existing generations of solid state drives.

4.4 Design Verification

Design verification testing is performed on a fully functioning prototype and includes environmental, shock and vibration, functional, margin, performance and HALT testing.

It should be noted that many SSD vendors perform environmental and shock/vibration testing on non-operational devices, whereby the drives are tested (sometimes only by visual inspection) *before* and *after* the test, but not *during* the test. In addition, test reports can state that the drive was tested in operational mode, but if no pictures were shown or if there is no mention in the text of a computer connection, then it is questionable whether the drives were powered on and operating during the test. Testing a device in this mode does not reflect a true working environment and reduces the guaranteed reliability of the drive in similar working conditions.

4.4.1 Environmental Testing

Environmental testing determines the ability of a solid state drive to perform in harsh and extreme environments without failures, and will truly verify the ruggedness and the durability of the design or will reveal any flaws. It should include the following tests:

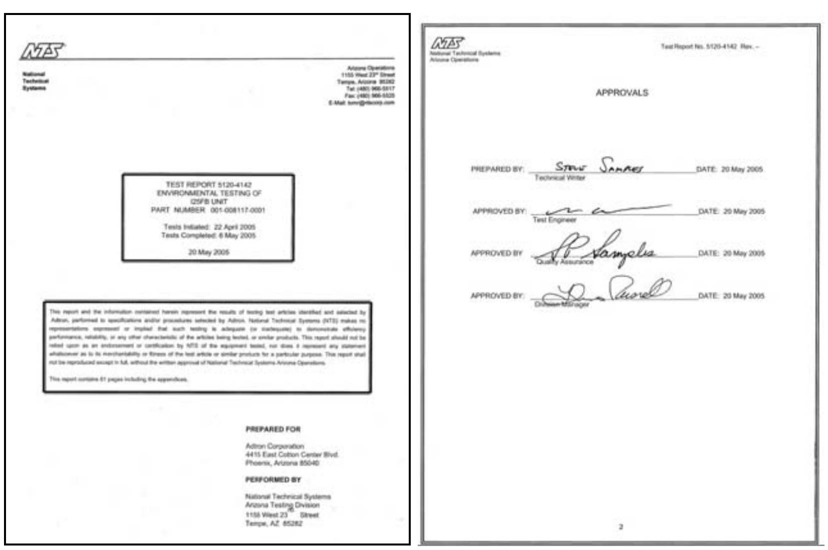
- **Operational and Storage Temperature** as specified in one of the accepted industry standards, such as MIL-STD-810F (Method 501.4, Procedure I and II, and Method 502.4, Procedure I and II), and JESD22-A104B. The design verification test should be performed on an *operational* device while temperature ranges and ramp times (the time it takes to move from low temperature to the high temperature) are varied to simulate real world environments. During the test, data is written to random address locations and with random file sizes, then read back to verify its integrity. Special write disturb patterns are used to purposely create errors in order to validate the effect of the implemented error correction/detection mechanism and flash management algorithms. At specific intervals a power cycle test is conducted, where the drive is powered down and then powered up to make sure that data and flash integrity have been maintained throughout the test.

  Beyond testing for compliance with an industry standard, the drive should be submitted for additional margin testing to further validate the reliability of the design. It is recommended to submit the drive for hundreds of hours of testing at the extreme temperature ranges (i.e., 85°C), as well as temperatures that go beyond the specified range, with multiple power cycles throughout that period. For example, an industrial temperature SSD would be submitted for operational testing at -50°C and 95°C for multiple hours (8 hours at each extreme of the temperature range), while being power cycled at least 3 times at both temperature extremes.

- **Altitude and humidity** should be tested in a controlled laboratory environment, following the specifications and industry accepted standards, such as MIL-STD-810F, Method 507.4-1 (Humidity) and Method 500.4 (Altitude). In altitude testing, the solid state drive is put into a chamber, and air pressure is reduced until a simulated altitude of 80,000 feet is reached. The altitude is reduced at a predetermined rate. Humidity testing is done in a chamber that creates non-condensing humidity, ranging from 5% to 95%. During the tests, the drives should undergo ongoing read/write operations to uncover failure events in the flash media.

Detailed test reports from known labs, such as National Technical Systems (NTS), of the above testing should be made available to customers to validate the reliability and durability of the Industrial Grade SSDs in extreme environments. Figure 5 below shows an example of such a report.

Figure 5: Example of an environmental test report



NTS
National Technical Systems

Arizona Operations
1155 West 23rd Street
Tempe, Arizona 85282

TEST REPORT 5120-4142
ENVIRONMENTAL TESTING OF
I25FB UNIT
PART NUMBER 001-008117-0001

Tests Initiated: 22 April 2005
Tests Completed: 6 May 2005

20 May 2005

This report and the information contained herein represent the results of testing test articles identified and selected by Adtron, performed to specifications and/or procedures selected by Adtron. National Technical Systems (NTS) makes no representations expressed or implied that such testing is adequate (or inadequate) to demonstrate efficiency performance, reliability, or any other characteristic of the articles being tested, or similar products. This report should not be relied upon as an endorsement or certification by NTS of the equipment tested, nor does it represent any statement whatsoever as to its merchantability or fitness of the test article or similar products for a particular purpose. This report shall not be reproduced except in full, without the written approval of National Technical Systems Arizona Operations.

This report contains 61 pages including the appendices.

PREPARED FOR

Adtron Corporation
4415 East Cotton Center Blvd.
Phoenix, Arizona 85040

PERFORMED BY

National Technical Systems
Arizona Testing Division
1155 West 23rd Street
Tempe, AZ 85282

NTS
National Technical Systems
Arizona Operations

Test Report No. 5120-4142 Rev. –

APPROVALS

PREPARED BY: Technical Writer DATE: 20 May 2005

APPROVED BY: Test Engineer DATE: 20 May 2005

APPROVED BY: Quality Assurance DATE: 20 May 2005

APPROVED BY: Division Manager DATE: 20 May 2005

2

4.4.2 Shock and Vibration Testing

An average earthquake registers shock at 1 to 2*g*, while the most hair-raising roller coaster ride registers at 1*g*. Although one of the most commonly used standards, MIL-STD-810F (Method 516.5, Procedure I, Figure 516.5-10), calls out for shock testing up to 20*g* for flight vehicles and 40*g* for 11ms for ground vehicles, a true Industrial Grade SSD should undergo shock testing of 50*g* for 11ms while read/write operations are conducted. The success of shock testing determines the type of environments in which the drives can operate.

Figure 6: Unholtz Dixie Shaker Table

Vibration testing is conducted by mounting a drive on a vibration table, as shown in Figure 6 above. While the drive is undergoing read/write operation, various vibration profiles are simulated on the table. For example, to pass a vibration test for a helicopter, the solid state drive must perform read/write operations without error at 3*g*, using random frequencies for 1 hour per axis. The drive is rotated on the x, y, and z axes. Test for aircraft vibration may exceed 16*g* on each axis.

When testing according to an industry-accepted standard, it should be confirmed that *all* test requirements are followed. For example, MIL-STD-810F calls out for various profiles, to ensure that all real-world situations are covered:

- Method 514.5A, Procedure I, Category 12, Figure 514.5C-III, 514.5C-8 for jets
- Method 514.5A 2.3.2, Procedure I, Category 13, Figure 514.5C-II, 514.5C-9 for propellers
- Method 514.5A 2.3.3, Procedure I, Category 14, Figure 514.5C-IV, 514.5C-10&11 for helicopters
- Method 514.5A 2.3.9, Procedure I, Category 20, Figure 514.5C1&2&3&4 for ground vehicles
- Method 514.5A 2.3.12, Procedure I, Category 23 for other

Once the drive successfully passes the test, the SSD vendor should be able to provide a full test report that includes test setup photos, test logs, and photos of actual shocks from the transient recorder or storage oscilloscope, as per the requirements in the followed industry standard.

4.4.3 Functional Testing

The purpose of functional testing is to verify the compatibility of the drive in various host environments and whether the drive meets the requirements of the published specification. Functional testing should include:

1. **Electrical hardware testing:** this test should validate all electrical specifications, such as power-up sequence and timing, power supply step load, power supply voltage protection, power supply overload, power supply temperature, behavior in brown-out conditions, reset circuitry, and bus signaling and timing
2. **Host compatibility testing:** this test should verify the compatibility of the drive in different host environments running different operating systems, such as UNIX, Solaris, Windows, and Linux. In addition, all of the supported interface commands (SCSI, ATA, SATA, etc) should be validated for operation and correctness in behavior

3. **Performance testing:** this test should validate the published performance numbers in the product specification. The test should be run for different capacities, and block sizes, and measure burst, sustained, and I/O performance. It should use at least 2 different benchmark software programs to validate the results
4. **Validating product features:** Each solid state drive has different product features that need to be validated. In the functional test report, the vendor should include test results of jumpers operation, LED functionality, security and encryption features, firmware upgrade possibilities, and S.M.A.R.T. features
5. **Mechanical testing:** this test should validate the published mechanical dimensions, weight, location of mounting holes, etc. In addition, the drive should be assembled and connected as described in the product manual to validate the ease-of-use for the customer

The SSD vendor should be able to provide a full test report that includes test setup photos, description of the procedures, and results of all the above mentioned tests. These reports should be available upon request for any prospective customer.

4.4.4 HALT Testing

Although HALT (Highly Accelerated Life Testing) appears to be similar to Design Verification Testing (DVT), it has different goals, uses different stresses and provides different results [5]. The goal of DVT is to demonstrate whether the solid state drive will function properly in its intended environment and meet its specifications. The purpose of HALT, however, is to subject the drive to environmental overstress, effectively forcing failure modes to emerge by accelerating mechanical fatigue. With tests performed at elevated stress levels, HALT can more quickly identify design weaknesses. DVT testing can sometimes identify those failures, but the required time and number of units in test would be extreme.

HALT testing on a solid state drive requires submitting the drive for an extended period of time (i.e., months) to extreme temperatures, at both sides of the temperature spectrum, while undergoing power cycling. During the test, data is written to random address locations using random file sizes. The data is then read back to verify its integrity. Special write disturb patterns should be used to purposely create errors on the NAND flash media. The device is brought to Last Operating Point (LOP) and even further to Last Operating Failure (LOF) to demonstrate and validate the margins of the design.

A final HALT test report should include detailed data on the product's operating margin, destruct margin and design flaws, along with what the new margins would be if each of the design flaws were eliminated.

4.4.5 Regulatory Compliance

In order to obtain a CE (Conformité Européenne) mark, the drive must undergo Electromagnetic Compatibility (EMC) testing. This is typically done by an outside lab, in order to verify compliance with EN55022:1998, EN 550241998, CIPSR 22:1997 and CIPS 24: 1997 standards [6] [7].

Further regulatory compliances that should be obtained through outside labs are UL (Underwriters Laboratory), CSA (Canadian Standards Association), and RoHS (Restriction of use of certain Hazardous Substances). It should be noted that a RoHS certificate for the drive is only valid if RoHS compliance statements are available from all the vendors that supply the components used in the drive.

Reports or statements of these compliances should be made available to customers.

4.5 Mean Time Between Failure (MTBF) Calculation

Reliability models are used to predict system failure rate (Mean Time Between Failure) based on component information. The two most popular models are MIL-HDBK-217 [8] and Telcordia (formerly Bellcore) SR332, Issue 1 [9].

The best commercial practice is to provide detailed information on how the numbers were calculated. It is important to understand this, as the results may vary dramatically depending on environmental and operational assumptions. Changing the operating temperature parameter by 5°C may change the result by 20-25%. Changing the environment parameter for the test from Ground Fixed Controlled to Ground Fixed Uncontrolled may change the results by 100% [10]. Table 1 below illustrates the wide variety of

MTBF numbers that can be calculated for the same XceedUltraX 2.5" IDE 8GB drive using different environmental parameters.

Table 1: MTBF Calculation for different environmental parameters

Reliability Model	Environmental Parameters	MTBF (hours)
Telcordia	25°C, Ground Benign, Controlled	1,261,419
MIL-HDBK-217	25°C, Ground Benign, Controlled	1,284,016
MIL-HDBK-217	25°C, Ground Benign, Uncontrolled	354,710
MIL-HDBK-217	45°C, Naval Sheltered	214,486

Drive capacity is also an important parameter in any MTBF calculation. The number of NAND flash components used on the board will increase with drive capacity, thereby lowering the MTBF. In general, when providing the MTBF numbers for a solid state drive, the vendor should specify the basis for the calculation including reliability prediction model used, model parameters and drive capacity.

5 MANUFACTURING AND TESTING

5.1 Manufacturing

A very important part of what makes up an Industrial Grade SSD is how it is manufactured and tested. In fact, without a stringent manufacturing process, thorough testing procedures, and the ability to log the manufacturing and test data of each *individual* device, a solid state drive cannot be promoted as being Industrial Grade. It should be noted that many SSD vendors do not perform operational testing on each shipped product, and instead settle for lot sampling and/or very minimal and short test procedures.

In order to fully qualify for an Industrial Grade rating, a solid state drive should be manufactured with the following in mind:

1. **Quality Assurance:** All materials and components used to build the drive must come from qualified vendors and successfully go through rigorous incoming inspection and tests before the start of the manufacturing process. When being put into assemblies, stringent process controls and tests must be used to eliminate manufacturing variation to achieve product uniformity. Workmanship must be constantly challenged, using the latest industry standards such as IPC. A final inspection of the finished product should include a full verification of firmware version, customer-specific settings, and serial and model number verification. All of these activities must be performed in an ISO-certified environment that includes a continuous improvement process.
2. **Testing:** Thorough testing on each *individual* device should be conducted and should include initial testing to confirm assurance to design parameters and initial operation, extensive burn-in testing to reduce early device failure, and final testing to assure that the product is 100% fully functional and contains enough spare blocks before it is shipped to the customer. See section 5.2 for further details on manufacturing test procedures.
3. **Drive Traceability:** Manufacturing and test data for each individual drive should be logged as the drive goes through the manufacturing process. Data such as serial number, firmware version, capacity, and manufacturing test results should all be collected. This information is critical for a failure analysis, should it be necessary. Also, this data will be used in any continuous improvement process relating to product design and manufacturing procedures.

In order to verify that the above manufacturing and testing procedures are followed, the prospective customer should ask the SSD vendor to provide detailed documentation on the implemented procedures. For more information on SMART Modular's manufacturing procedures, please refer to the *Solid State Drive Manufacturing Process* document.

5.2 Manufacturing Testing

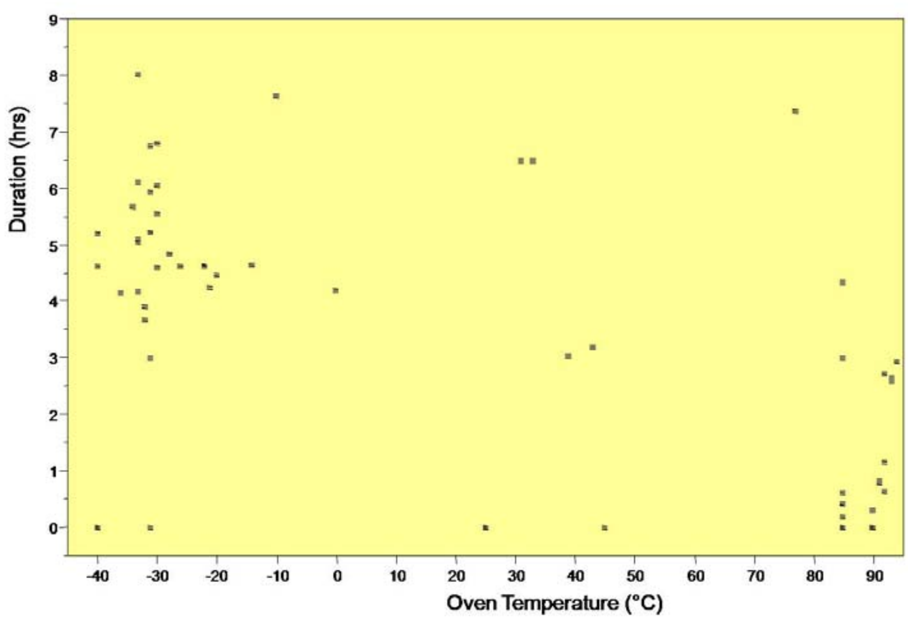
To ensure the delivery of the highest reliability and quality solid state drive to a customer, an Industrial Grade SSD should pass the following three test stages during manufacturing:

1. **Initial testing:** During this test, it should be verified that the correct configuration is loaded based on the model number, and that the drive has the right capacity. On-board electronic components are programmed at this time, while the media is verified with a read/write test. Finally, a serial number is programmed into the device, and various electrical tests should be performed to ensure proper operation of the device.
2. **Burn-in testing:** During this test, the drive is placed into an oven for an extended period of time and subjected to different burn-in profiles, depending on whether the drive is rated for commercial or industrial temperature. See section 5.3 for more details.
3. **Final testing:** This test should be very similar to the initial testing, whereby the serial number, firmware, media integrity and electrical operation are verified. The test should include a validation of the minimum amount of spare blocks that the drive is shipped with, in order to guarantee the specified life time of the drive.

5.3 Burn-in Testing

Executing burn-in tests for an extended period of time on an *operational* drive will result in more reliable products, due to the fact that drives that contain weaker components will surely fail during the test. During empirical testing[1] within SMART Modular's manufacturing facility over a period of a few months, it was concluded that the burn-in test should be conducted for a minimum of 8 hours. As can be seen in Figure 7 below not all drives failed in the first few hours of the test, but still showed a consistent failure rate throughout the 8-hour test time.

Figure 7: Failure of drives at varying temperatures and duration



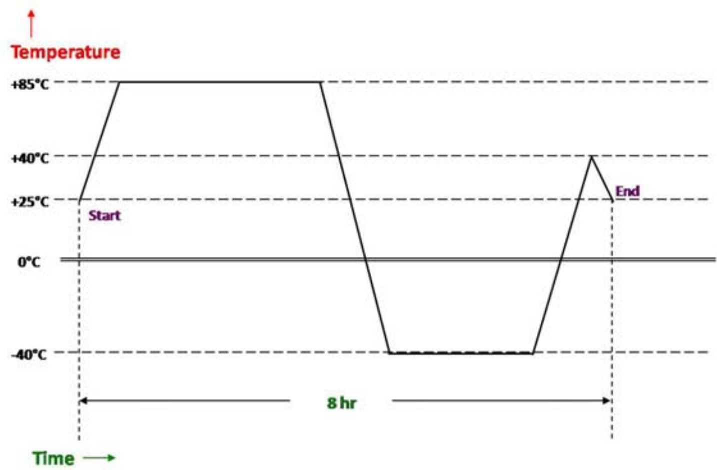
From this it can be concluded that performing a burn-in test for only a few hours would increase manufacturing yield, but would result in a higher infant mortality rate in the field. An SSD vendor that manufactures an Industrial Grade SSD is committed to minimize the infant mortality rate in the field and should therefore conduct burn-in tests for a minimum period of 8 hours.

[1] For detailed information on SMART Modular's empirical burn-in testing, refer to *Burn-in Test Data Analysis Report, Temperature & Duration*

Depending on whether the solid state drive is rated for commercial (0-70°C) or industrial temperature (-40°C to 85°C), two separate burn-in tests[2] can be performed:

- **Commercial Burn-In:** As can be seen in Figure , the majority of failures occur at the extreme ends of the temperature range. Therefore, in this test, the drive should be inserted into an oven at the maximum temperature for which it is rated (70°C) for a minimum of 8 hours. During the test, a test script is running that writes/reads to/from the drive continuously to random address locations and with random file sizes.
- **Industrial Burn-In:** To minimize fallout in the field and optimize the amount of captured drives that contain weak components, the drive should be inserted into an oven that is temperature cycled from -40°C to +85°C for a minimum of 8 hours. Figure 8 below shows an example of such an oven profile. Throughout the test, a test script read/writes from/to the drive continuously to random address locations and with random file sizes and data patterns. At specific intervals throughout the test, multiple power cycling procedures should be performed to ensure complete data integrity of the media.

Figure 8: Oven profile for industrial temperature solid state drive



[2] For more details on SMART Modular's burn-in test procedure, refer to the *Solid State Drive Manufacturing Process* document.

6 ONGOING QUALITY ASSURANCE

Ongoing quality assurance occurs through a variety of business practices. Beta testing helps to gain a better understanding of the operation of the drives in the field, whereas thorough failure analysis will help to substantiate a closed loop corrective action plan.

6.1 Application Validation through Beta Testing

System level validation testing occurs both inside the SSD vendor's test lab, as well as at a customer's site. Beta testing should be conducted by one or more customers whose applications fall in the target market(s) for which the product was designed and built. The beta testing program should be very closely monitored by the customer's account manager and field application engineer to make sure that customers receive optimal support. During the beta test stage, the customer validates the hardware and software functionality, mechanical requirements, and media integration, as well as any other tailoring that may be required by the customer. Beta test results can influence product release schedules, current engineering and manufacturing priorities, and future product enhancements.

6.2 Failure Analysis

The ability of an SSD vendor to perform root cause analysis on returned parts is an integral part of an ongoing quality assurance program. Customers using Industrial Grade SSDs in their product should demand that their vendor have a thorough, well documented failure analysis procedure in place.

Returned parts should be inspected for mechanical, electrical and manufacturing defects, and submitted to the same test procedures that are used during the manufacturing stage (including 8 hour burn-in). A very important aspect of the failure analysis procedure is the ability of the vendor to look-up the history of the drive from the moment it was manufactured. The availability of data such as original serial number, firmware version, capacity, and manufacturing test results can help determine the root cause of the failure and be used for improving procedures in the future.

A complete system level analysis may be required if the drive does not fail inside the manufacturer's standard test setup, but does fail inside the customer's application. The ability of the SSD vendor to perform failure analysis at the system level can be extremely valuable in determining the root cause of the problem.

Once the root cause has been determined and linked to the product itself or to manufacturing procedures, the SSD vendor should commit to implementation of a corrective action procedure. A full report with details on the failure analysis investigation and corrective actions should be made available to the customer.

7 EXTENDED INDUSTRIAL GRADE OFFERING

This white paper describes the methods and procedures that an SSD vendor should implement to ensure that a true Industrial Grade SSD is delivered. The described set of requirements is the minimum that should be delivered, and can be extended to ensure an even more robust product and design. This section describes additional features that an Industrial Grade SSD vendor can offer to its OEM customers to provide enhanced Industrial Grade offering.

7.1 BGA Underfill and Staking

Some applications require additional strengthening of the solder joints on BGA components or other components (i.e. capacitors, etc) in order to improve mechanical stresses that result from shock, vibration and thermal cycling. An Industrial Grade SSD vendor should be able to address those concerns by providing the possibility to manufacturing the solid state drive with BGA Underfill (encapsulating the solder joints of BGA components with an epoxy) or staking (silicon glue for other components).

SMART Modular provides this manufacturing option for its XceedUltraX and XceedSecure solid state drives. For more information, please refer to the document *BGA Underfill Process* [12], available through your Smart Modular contact person.

7.2 Conformal Coating

Conformal coating material is applied to electronic circuitry to act as protection against moisture, dust, chemicals, and temperature extremes that if uncoated (non-protected) could result in a complete failure of the electronic system. Since Industrial Grade solid state drives can be deployed in environments that have are subject to such conditions, an Industrial Grade SSD vendor should provide the option for conformal coating with either HumiSeal 1A33 Polyurethane or HumiSeal 1B31 Acrylic Resin.

7.3 Field diagnostics

The ability to perform field diagnostics on a storage device provides the OEM designer with a tool to predict drive degradation to allow for data back-up prior to an operational failure. It can therefore proactively schedule maintenance and/or drive replacement. The best vehicle for this is to use the industry standard S.M.A.R.T. (Self-Monitoring Analysis and Reporting Technology) attributes.

Many S.M.A.R.T. attributes that are used with hard disk drives (i.e. all of those that are related to the mechanical nature of a HDD, such as such as Seek Error Rate, Spin-up time, etc) are not relevant for solid state drives. Drive degradation and potential causes of failures within solid state drives are related to the wear out of the flash blocks inside the drive.

SMART Modular provides the following S.M.A.R.T. attributes on the XceedUltraX and XceedUltra solid state drives.

- Minimum Spares – the number of spare blocks remaining as a value from 1% to 100%
- Power-On Hours[3] – the amount of time the drive has been in operation in seconds
- Temperature[4] – the temperature of the drive in degrees Celsius

In addition, it can be very useful if the drive is equipped with the ability to have an internal error log that can be extracted and read for diagnostic purposes. Such a log can log can contain information on power on reset events, host command errors, secure erase events, etc. SMART Modular provides an error log option on its XceedUltraX and XceedSecure solid state drives.

[3,4] This S.M.A.R.T. attribute is offered on XceedUltraX only

8 WHAT SHOULD YOU ASK YOUR SSD VENDOR?

This white paper describes all of the methods and procedures that an SSD vendor should implement within its design, manufacturing and test stages to ensure that a true Industrial Grade SSD is delivered. Prospective customers can verify whether their vendor is implementing these methods and procedures by asking for the following reports:

- **Design Verification Testing:** This report, also known as the product qualification report, should include descriptions of all testing, including functional testing of all the product features, electrical and mechanical testing, performance testing and host compatibility testing
- **Environmental testing:** This report should include a detailed description and photos illustrating how the tests were done, and whether the tests were performed on electrically *operational* drives rather than as visual inspections *before* and *after* the tests
- **MTBF Calculation:** This report should clearly identity the reliability prediction model, model parameters and drive capacity used as the basis for the calculation
- **Regulatory Compliance**: such as RoHS, CE, UL and CSA
- **Manufacturing Procedures Manual:** Also known as quality system manual, it should include a description of the burn-in procedures, as well as the procedures the manufacturer has implemented to log data and trace the history of the drive

In addition to requesting these reports, customers should verify whether the SSD vendor is incorporating the following practices:

- **FMEA method** for improvement of design and manufacturing procedures
- **Beta testing program** to validate the operation of the drive at customer sites
- **Failure Analysis and Quality Assurance** procedures to validate how failures in the field are used for ongoing product and manufacturing improvements. This is important for implementation of closed loop, corrective action practices.

Finally, a comprehensive review of the vendor's customer base and the number of years the company has been servicing the SSD market are good indicators of the quality level of the vendor and its products.

9 CONCLUSION

The explosive growth of the SSD market has led to a significant increase in new SSD vendors. In 2002 there were less than 10 SSD vendors; today there are over 50 vendors, and this number is expected to exceed 100 by the end of 2008 [11]. The vast choice of SSD products that are offered by these vendors is causing considerable confusion with customers who are trying to decide which product is most suitable for their application. Comparing product attributes alone is not enough to distinguish which of the three emerging SSD categories the product belongs to: Consumer, Commercial or Industrial Grade.

Consumer Grade SSDs are the most visible in the market since they are optimized for the high-volume, low-cost per gigabyte applications such as laptop computing. Increasingly, Consumer Grade SSDs are being based on MLC flash technology, lowering the cost per gigabyte while sacrificing durability.

The distinction between Commercial and Industrial Grade drives is far less clear since SSD vendors can deliver very similar market messages, and comparing product attributes does not sufficiently distinguish the differences between these two grades.

A good way to understand whether an SSD is truly Industrial Grade is by comparing the design, testing and manufacturing processes used by the vendors being evaluated. Thorough design verification on *operational* devices, extensive burn-in testing during manufacturing on every single device (vs. lot sampling), and comprehensive quality assurance procedures will lead to the highest quality solid state drive possible. The SSD vendor should be able to provide all the test reports described in this white paper to backup their Industrial Grade claims. The test reports should be carefully scrutinized to understand whether the tests were performed on operational drives or not. If no pictures were shown or if there is no mention of a computer hookup in the text, then it is questionable whether the drives were powered on during the test. Testing a non-operational device does not reflect a true working environment and reduces the potential reliability of the drive in similar working conditions.

SMART Modular is committed to providing Industrial Grade SSD products to its customers, and as such designs, manufactures and tests its solid state drives to the highest standards available. The procedures and methods described in this white paper are implemented within the organization. SMART Modular's quality system permeates every aspect of our business and is an inherent attribute throughout the entire product lifecycle. ISO 9001 certification is the foundation of the SMART Modular quality system. SMART Modular strives to ensure that customer quality expectations are met by providing true Industrial Grade products for demanding applications.

10 REFERENCES

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About the Author

Esther Spanjer is Director of Technical Marketing at SMART Modular. With more than 10 years of experience with flash-based solutions, Ms. Spanjer has gained valuable insight into the use of this rapidly evolving technology in a wide range of embedded applications in the military, aerospace, communications and industrial markets. She joined SMART Modular to help evangelize the use of flash technology for new types of applications in both the traditional markets and the emerging enterprise market. As users become more familiar with the full range of benefits of flash technology, she believes that flash-based storage will be adopted in a broader range of what have typically been thought of as hard-disk applications.

Ms. Spanjer received a B.Sc. degree in Electronic Engineering from the Technical University Amsterdam (Netherlands) in 1991. She can be reached at esther.spanjer@smartm.com.

About SMART

SMART is a leading independent designer, manufacturer and supplier of electronic subsystems to original equipment manufacturers, or OEMs. SMART offers more than 500 standard and custom products to OEMs engaged in the computer, industrial, networking, gaming, telecommunications, and embedded application markets. Taking innovations from the design stage through manufacturing and delivery, SMART has developed a comprehensive memory product line that includes DRAM, SRAM, and Flash memory in various form factors. Through its subsidiary, Adtron Corporation, SMART offers high performance, high-capacity solid state drives for enterprise, defense/aerospace, industrial automation, medical, and transportation markets. Its Embedded Products Division develops embedded computing subsystems, backed by design and manufacturing, for markets supporting test equipment, 3G infrastructure, and network processing applications. SMART's Display Products Group designs, manufactures, and sells thin film transistors (TFT) liquid crystal display (LCD) solutions to customers developing casino gaming systems as well as embedded applications such as kiosk, ATM, point-of-service, and industrial control systems. SMART's presence in the U.S., Europe, Asia, and Latin America enables it to provide customers with proven expertise in international logistics, asset management, and supply-chain management worldwide.

See http://www.smartm.com for more information.
See http://www.adtron.com for more information on SMART's SSD products.

IndGrade-R2-062508