High-Temperature Component Evaluation of Commercial Flash Memory and Capacitors for Enhancement of Geothermal Tool Development

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Abstract

Environments relevant to geothermal energy exploration frequently exceed the temperatures and pressures commonly experienced by downhole tools in the oil and gas industry. As such, pushing the boundaries with geothermal tool development can often necessitate exceeding manufacturer specifications for temperature and pressure of individual circuit components. High-temperature circuit designers often must dedicate considerable time and resources to determine if a component exists that they may be able to knead performance out of to meet their requirements. In light of this difficulty, Sandia National Laboratories has initiated a program funded by the Geothermal Technologies Office at the US Department of Energy to compile and make available an empirically determined, practical dataset of select high-temperature component performances beyond specification. Detailed here are the efforts surrounding geothermal temperature characterization of commercially available HT-Flash memory modules made by Texas Instruments (SM28VLT32-HT) and preliminary results of 3 commercial solid tantalum capacitors. Flash evaluation boards were modified for high temperature application and read, write and erase functionality were tracked as well as prolonged data retention at various temperatures well beyond datasheet specifications. It was observed that each flash function has a different maximum operation temperature above specification. As temperature increases, erase, write, and then read functions successively fail. Within duration and temperature limits, functionality of each operation returns after cooling back below its threshold value. Importantly for logging tools, after cooling the flash modules in this study still retain all memory previously written. Flash lifetime at temperature was examined at several temperatures by 1000hr duration tests in the oven with new writes and periodic full memory reads throughout the test. To test the capacitors, capacitance and equivalent series resistance were tracked over a 1000hr test at 260°C. Results of MatLab fault analyses are described for each aspect of this study to facilitate out-of-spec high temperature tool design.

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Introduction

As geothermal energy exploration continues to rise and oil and gas companies pursue deeper and hotter resources, downhole tool developers will be designing for the absolute limits of available components. The high temperature component evaluation program at Sandia National Laboratories aims in part to address the paucity of COTS components rated for geothermal temperatures through publication of expected performances and failure modes of commercial components beyond manufacturer specifications. In some cases, specific functions of a COTS component are operational to higher temperatures than others and circuit designers may need only those functions for their intended application. It is important to note that the data presented is for designer reference only and is not to be considered complete. No intent is made to endorse any components tested in this program.

The length and limited bandwidth of logging cables often make “smart” systems a necessity for advanced downhole sensor packages. Downhole digitization and data processing has become standard practice in many logging applications to reduce noise and increase sample rates. Non-volatile memory is a critical element of digital logging tools that require storage for data recording and/or program storage for processors. The convenience and reliability of flash memory has made it ubiquitous in modern consumer electronics but few commercial flash options are available for extreme temperature environments (>200°C). Described in this paper is a characterization study of 10 SM28VLT32-HT 32Mb bulk CMOS NAND flash memory modules manufactured by Texas Instruments. The manufacturer describes that the module is packaged in ceramic HKN with a silver-glass die attach material. The published maximum temperature is 210°C. The study presented here tests the performance of these modules as high as 300°C. Duration tests are also performed at temperatures above specification.

Also described in this study is a capacitor test station designed for high temperature evaluation of capacitors. There exists a void in availability of capacitors rated above 200°C which can be used in construction of downhole power supplies, sample and hold circuits, and power distribution networks within tools. Where ceramic capacitors using specialized dielectrics partially fill this void, they are usually limited in value to below 1uF. This paper will describe the efforts to evaluate three models of capacitors with seven samples of each: TH5E106K021A1000 by Vishay, *THJD226K035RJN by AVX, and T499X226K035ATE700 by Kemet.* Each set of capacitors is evaluated for 1000 hours at 260°C which is well above their manufacturer specifications for all 3 capacitors. Capacitance and equivalent series resistance (ESR) are monitored throughout the test. Results of the testing are presented to aid the design of next generation of high-temperature tools.

Test Procedure

Flash Hardware Modification and Oven Mounting

High temperature flash evaluation modules were acquired and modified for temperature exposures as high as 300°C. The out-of-the-box EVMs consist of a high temperature substrate with gold-plated traces and come populated with low temperature capacitors and solder with a melting point lower than the temperatures of the planned tests.

The stock bypass capacitors on the HTFlashEVM were replaced with stacks of high temperature ceramic capacitors and all solder connections were removed and re-soldered with High-Melting-Point (HMP) solder (melting point 309°C). The header pins for power, ground, clock and SPI communication were removed and replaced with Teflon insulated nickel wire. Figure 1 inlay shows the modified evaluation module.

Initial tests of the module showed issues with mechanical preloads and/or thermal expansion overpowering the solder connections which caused the chip to disconnect from the solder pads at temperatures above 240°C. Additionally, as these PCBs are not designed for temperatures above 200°C, trace work was observed to delaminate from the substrate which could lead to breakage and/or shorting. To address these issues, the pads were more carefully soldered to improve mechanical connection of components and c-clamps were put in place to secure the chips to the circuit boards. Kapton tape was wrapped around the chip and traces to prevent trace delamination and to prevent the clamp from shorting the leads. The modified and wrapped modules were placed in a ceramic tray and gently secured in place with the c-clamps (Figure 1).

Figure 1. Technique for securing the flash modules in the oven. (Inlay) Modified flash module with HMP solder, high temperature ceramic capacitors and Teflon coated nickel wire.

Flash Temperature Evaluation

A total of 10 flash modules were evaluated in this study (Labeled Chip 1 – Chip 10) for performance in a temperature range above manufacturer specifications. Some of the manufacturer specifications for this device are shown in Table 1.

Table 1. Some of the manufacturer published SM28VLT32-HT specifications [1].

Parameter	Descriptor/Condition	Specification
I/O Voltage	VIO	3.1V to 3.6V
Core Voltage	VCORE	1.8V to 1.98V
Junction Temperature	TJ	-55C to 210C
Package		Ceramic HKN
Communication	Serial Peripheral Interface	Max 10MHz
Flash Clock	Fclk	Max 12MHz
Life Time	@210C	1000 hours
Write/Erase cycles	@30C	1000 cycles
Memory Capacity	2-M X 16-Bit Word Access	32Mb

All temperature tests were performed in a Blue-M industrial oven and with a core voltage setting of 1.92V and an I/O voltage setting of 3.5V unless otherwise specified. The clock frequency was set to 12MHz using a waveform generator external to the oven. The SPI bit rate was set to the maximum of 10MHz for all tests unless otherwise specified. Data was recorded using a Cheetah SPI USB adapter and a LabView interface program made publicly available by Texas Instruments [2].

Eight of the modules (Chip 1 through Chip 8) were examined at increasing temperatures until each of the primary flash functions (read, write, erase) ceased to operate properly. Exact values were recorded of the maximum temperatures for write and read functionality with zero bit errors. Erase functionality was confirmed up to the maximum specification of 125°C but was not tested above this temperature because of the possibility of permanent damage caused by over depletion of the floating gate transistors in the flash memory.

The minimum delay necessary between program commands to yield zero errors (after a write to every address in memory) was tracked with temperature. The data, 0xAAAA was written to every address of the fully erased module with a set delay between writes. The number of errors over the full memory write was recorded by reading the module's quick status register during each write command. The errors were counted in software. To test at temperatures above 125°C, the modules were cooled back below 125°C for a full erase and then brought back up to the test temperature for the next full write.

The core current was tracked for five modules (Chip 4 – Chip 8) over a temperature range of 25°C to 250°C using BK Precision DC power supplies. The core current was measured with all 1's in memory (all 0xFFFF) and also with all 0's in memory (all 0x0000). The difference between the 0xFFFF current and the 0x0000 current is considered here to be the bit maintenance current because it is the excess current drawn by having all 1's in memory.

Flash Lifetime at Temperature Evaluation

Modules were tested for 1000hrs+ at temperatures of 225°C, 240°C and 253°C. The modules under test were placed in the oven as described above and read and write functionality was tracked periodically for the duration of each test. Tests to failure are on-going for 3 modules at 250°C and 4 modules at 265°C. Further description of lifetime testing is in the test results section below.

Capacitor Test Station

To facilitate the testing of the tantalum capacitors, a test station was developed incorporating B&K Precision Model 889B LCR Meter with a switch matrix and a forced air oven allowing for simultaneous testing of three sets of 7 capacitors at various temperatures. The test station uses a 4-wire measurement approach to mitigate lead resistance. The capacitance and the ESR of each capacitor are measured and recorded in fixed time intervals at three frequencies.

Table 2. Capacitor specifications [3-5]

Manufacturer	*Model*	*Value*	*Rated Temperature*	*Maximum ESR*	*Rated Voltage*
Vishay	*TH5E106K021A1000*	*10uF*	*200°C*	*1.0*	*21V@200°C*
AVX	*THJD226K035RJN*	*22uF*	*175°C*	*0.6*	*17.5V@175°C*
Kemet	*T499X226K035ATE700*	*22uF*	*175°C*	*0.7*	*17.5V@175°C*

Capacitor Test Procedure

Seven capacitors of each model shown in Table 2 were tested. The capacitors were soldered to custom high temperature breakout boards and placed in ceramic zero insertion force sockets mounted in the forced air oven. The solder used is a specialized HT eutectic solder with melting point of 309°C. The capacitors were tested at a constant temperature of 260°C which is significantly exceeds manufacturer specifications for a duration of 1000 hours. The capacitance and ESR were measured and recorded every hour at 100 Hz, 1 kHz, and 10 kHz. When not being measured, the capacitors were soaked at 5V. The de-rated soak voltage was in part chosen due to fact that 5V is commonly used in geothermal tools and also to increase chances of parts survival.

Test Results

Flash Temperature Effects

The results of the test for determination of absolute maximum temperatures of each function of the flash memory are presented in Figure 2. The read and write maximum temperatures shown are the maximum temperature the data was written or read on each chip without errors. The 240°C max write temperature result in Chip 1 was the only module with a max write temperature below 250°C. Chip 1 was the first module tested in this study and we have reason to believe the failure may have in the PCB rather than the chip itself. With the exception of Chip 1, while cooling from the maximum read temperature, functionality of the write and erase commands returned as the respective temperature thresholds were crossed for all chips. Lowering the bit rate of the SPI communication had no observable effect on the maximum write temperature in this study. The datasheet indicates that the erase command can cause permanent damage by over depletion of the memory at temperatures above 125°C. This depletion was observed in some modules at temperatures just over 125°C so no further tests were performed above 125°C for the erase function. Figure 3 shows the minimum necessary delay between write commands versus temperature for a write to every address in the memory with zero errors over a range of 25°C to 225°C. The data in Figure 3 indicates a temperature dependence on write command frequency. Figure 4 depicts the temperature dependence of the core current with all 1's in memory over a temperature range of 25°C to 250°C. Figure 4 also depicts the bit maintenance current versus temperature. The bit maintenance current is the difference in core current between all 1's and all 0's in memory.

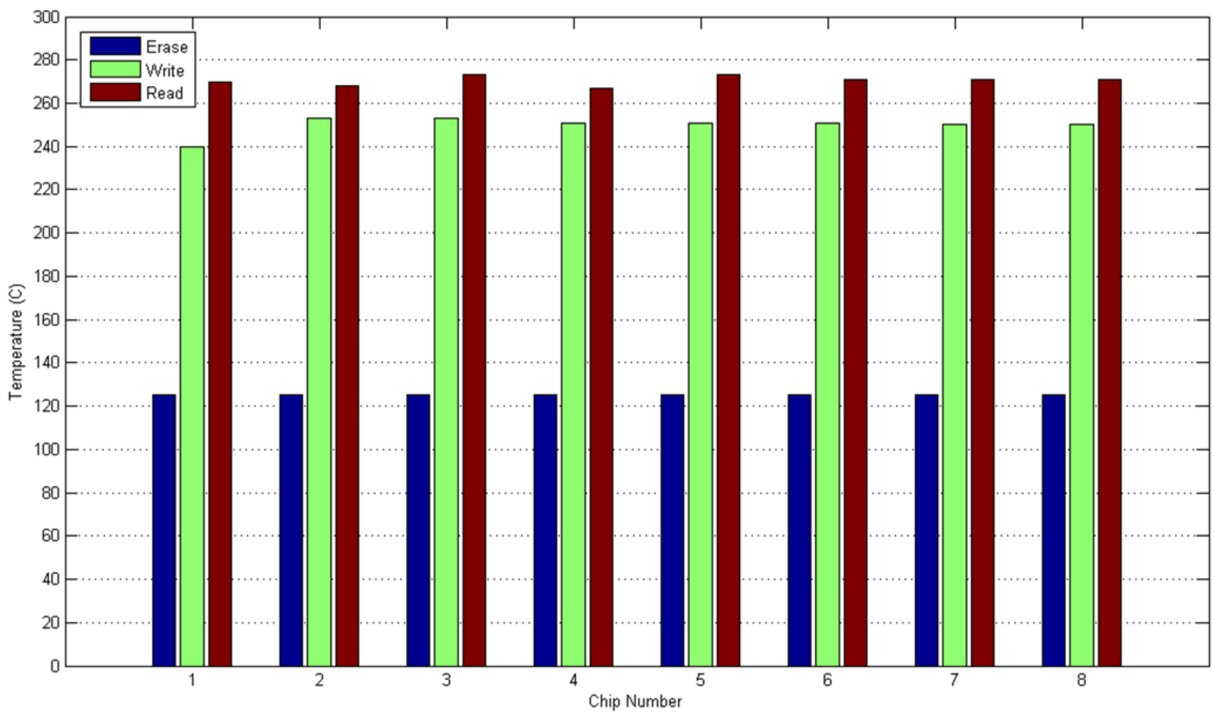

Figure 2. Maximum temperature of each function. The maximum read temperatures in these 8 modules range from 267°C to 273°C with an average of 270.5°C. The maximum write temperatures range from 240°C to 253°C with an average of 249.9°C. To avoid depletion faults, the maximum erase temperature shown (125°C for all) is the highest temperature the erase function was tested.

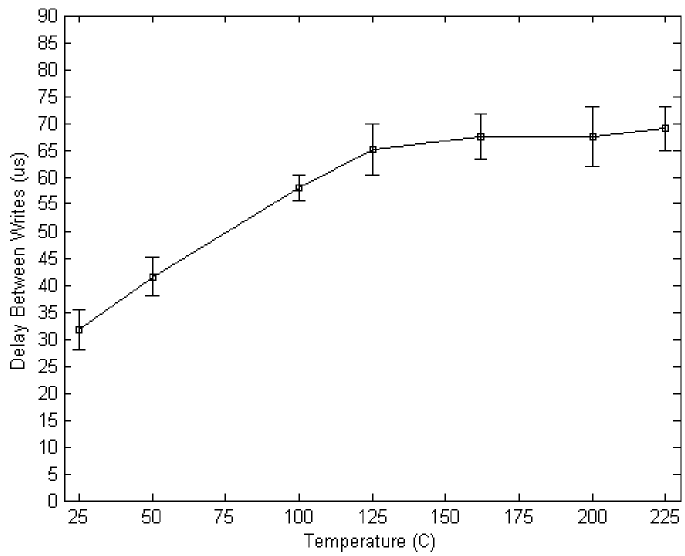

Figure 3. Minimum delay between program commands necessary for successful writes to every address in memory with zero errors. Results are shown from 25°C to 225°C. The data is from Chips 5, 6, 7, 8. Error bars depict standard error.

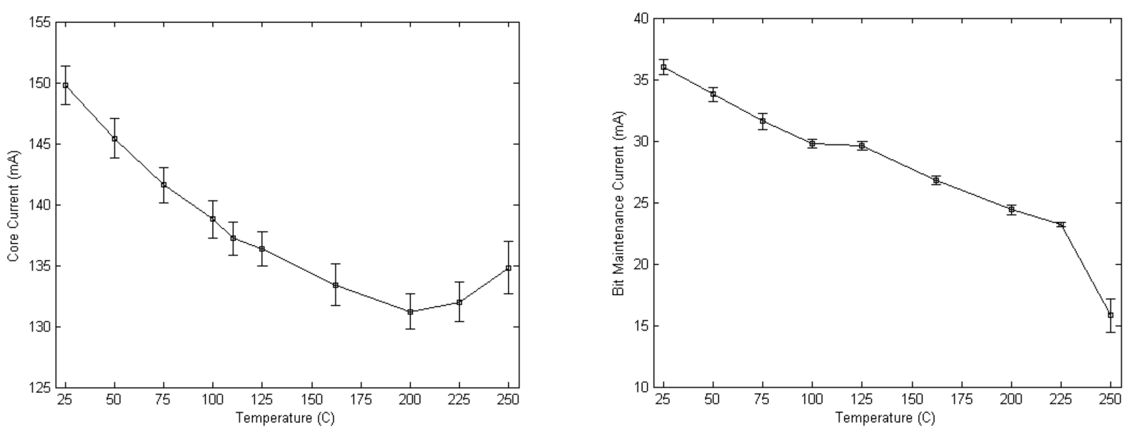

Figure 4. (Left) Core current with all data at 0xFFFF versus Temperature. The data is from Chips 4, 5, 6, 7, 8. Error bars depict standard error. **(Right)** Bit maintenance current is calculated by the difference between the core current with all data at 0xFFFF and the core current with all data at 0x0000. This is an estimate of the maximum amount of current used by maintaining all 1's in memory. The data is from Chips 4, 5, 6, 7, 8. Error bars depict standard error.

Flash Lifetime Duration Results

One of these modules (Chip 2) was tested and verified for functionality at 225°C for 1000 hours, then at its maximum write temperature of 253°C for 2000 hours, and finally at 240°C for approximately 700 hours before it failed. While operational, all memory was valid and data from new writes were confirmed. When the device failed, the device could no longer be written to; data could still be read but it was corrupt.

Two of these modules (Chip 3 and Chip 4) were successfully tested for 1000 hours at 240°C. Write and read functionality was confirmed periodically throughout the test. Tests to failure of three modules at 250°C (Chip 4, Chip 9, Chip 10) are currently on-going. Tests to failure at 265°C are on-going for four modules (Chip 5, Chip 6, Chip 7, Chip 8). Only read functionality is tracked in the 265°C test as this is above the maximum possible write temperature for all of the modules.

One module (Chip 1) was held for 16 hours at 300°C. Neither write nor read functions operated at 300°C but when the module was cooled back below the read threshold (270°C), read functionality returned and all data was still correct. The module was then left at 300°C for 100 hours and after cooling, no functionality was restored.

Preliminary Capacitor Test Results

The results of the capacitor testing are shown in (Figures 5-8). The capacitance reported was measured at 100Hz while the ESR at 10kHz which is consistent with the approach taken by the manufacturers, however manufactures report capacitance measured at 120Hz and ESR measured at 100kHz. Due to the limitations of the current setup we were unable to measure the ESR at 100kHz.

At 260°C all capacitors exhibit increased capacitance (up to ~140% of rated value) which decays with time over the duration of the test. However, the ESR shows different trends for each manufacturer. The ESR increases almost linearly with time for the Vishay capacitors. The AVX capacitors show a sublinear increase in ESR with time while the Kemet capacitors show a significant change in trend at about 600 hour mark. Up to the 600 hour mark, the ESR of the Kemet capacitors increases linearly and after that point the increase appears exponential.

At the end of the test, close evaluation of capacitor packaging was performed. Significant cracks were found in both the Kemet and AVX packaging which could explain the sudden increase in the ESR results for Kemet capacitors (Figure 8). The cracks in packaging are not necessarily due to temperature effects but could also be related to the mounting method chosen for this test. We are currently repeating the tests using an alternative mounting method.

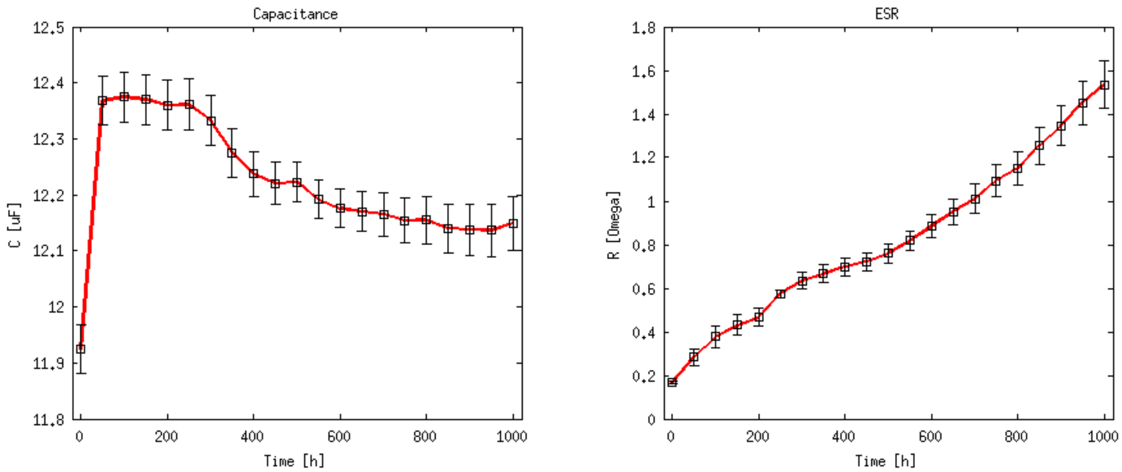

Figure 5. Results of Vishay *TH5E106K021A1000* **(Left)** capacitance and **(Right)** ESR over time at 260°C. Error bars depict standard error.

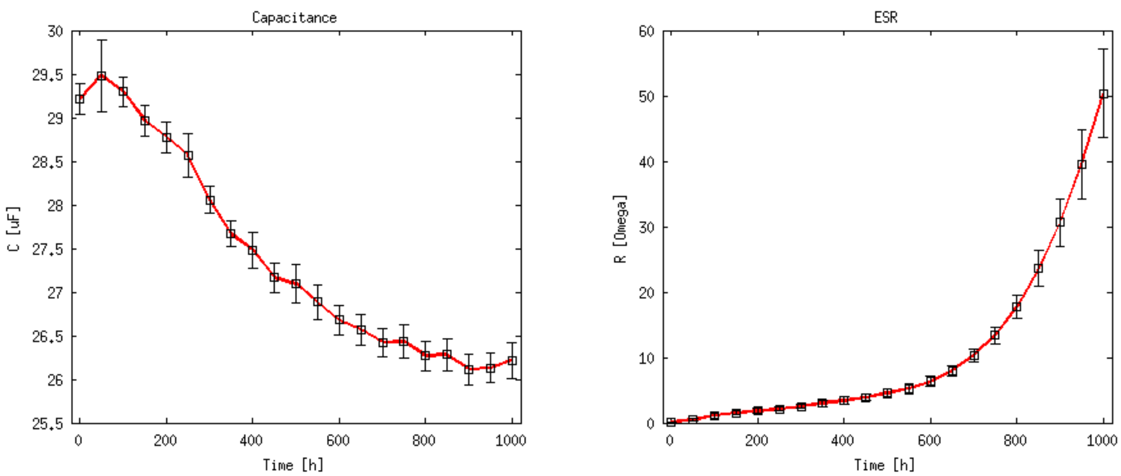

Figure 6. Results of Kemet *T499X226K035ATE700* **(Left)** capacitance and **(Right)** ESR over time at 260°C. Error bars depict standard error.

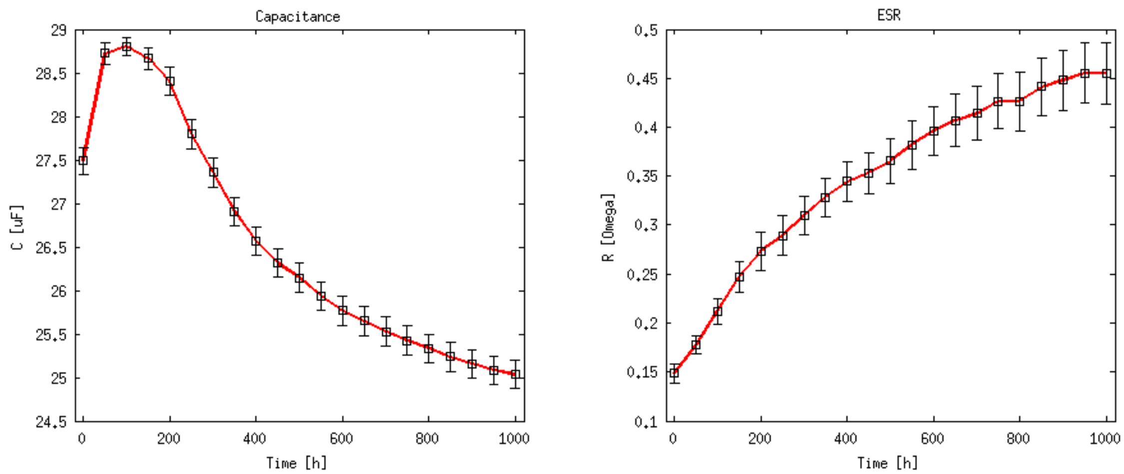

Figure 7. Results of AVX *THJD226K035RJN* **(Left)** capacitance and **(Right)** ESR over time at 260°C. Error bars depict standard error.

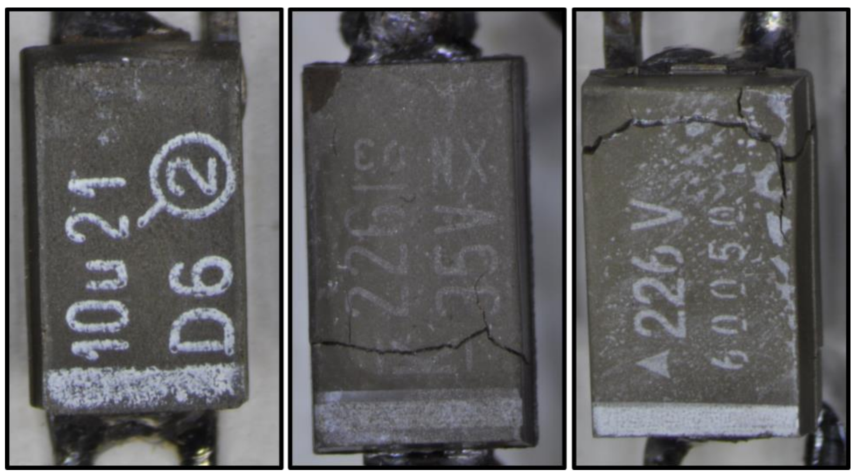

Figure 8. Package images of **(Left)** Vishay, **(Center)** Kemet and **(Right)** AVX capacitors after the 1000hr test at 260°C

Conclusion

Ten flash modules and 3 commercial capacitors were evaluated at temperatures beyond manufacturer specifications in this study. Maximum temperature of erase, write, and read flash commands were determined and reported. The flash modules studied demonstrate read functionality at temperatures above 267°C but with returning write and erase functionality at lower temperatures. 1000hr+ tests were performed on subsets of these modules at temperatures of 225°C, 240°C, and 253°C with write and read functionality confirmed throughout the test duration.   The capacitors tested in this study may have applicability to development of HT geothermal tools where higher values of capacitance are desired, however further is necessary to address the packaging and test fixture issues. Ongoing and future capacitor studies will also include a measurement of leakage current over time at temperature. The data described in this study and others from this test program can assist high temperature circuit designers with out-of-temperature-spec circuit design as can be necessary with geothermal resource exploration tools.

References

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[2] HTFLASHEVM User's Guide. *Texas Instruments SLVU805.* November 2012

[3] Tantalum Surface Mount Capacitors-Automotive Grade. KEMET - T499 MnO2 175C Data Sheet. Kemet Electronics Corporation. 2015

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[5] Solid Tantalum Surface Mount Chip Capacitors Tantamount Molded case, Hi-TMP, Very High Temperature 200C. Vishay Sprague Data Sheet. Document Number 40146. Revision Jan-2015.