SAND2022-7052C

GRC Transactions, Vol. 46, 2022

Evaluation of High Temperature Microcontrollers and Memory Chips for Geothermal Applications

Andrew A. Wright[1] and Avery Cashion[1]

Sandia National Laboratories, Albuquerque, New Mexico, USA

Keywords

Geothermal, Downhole Instrumentation, High Temperature, Microcontroller, Memory

ABSTRACT

The latest high temperature (HT) microcontrollers and memory technology have been investigated for the purpose of enhancing downhole instrumentation capabilities at temperatures above 210°C. As part of the effort, five microcontrollers (Honeywell HT83C51, RelChip RC10001, Texas Instruments SM470R1B1M-HT, SM320F2812-HT, SM320F28335-HT) and one memory chip (RelChip RC2110836) have been evaluated to its rated temperature for a period of one month to determine life expectancy and performance. Pulse rate of the integrated circuit and internal memory scan were performed during testing by remotely located axillary components. This paper will describe challenges encountered in the operation and HT testing of these components. Long-term HT tests results show the variation in power consumption and packaging degradation. The work described in this paper improves downhole instrumentation by enabling greater sensor counts and improving data accuracy and transfer rates at temperatures between 210°C and 300°C.

1. Introduction

Geothermal wells require an evaluation of their properties, including temperature and chemistry of the subsurface environment, before and after drilling. Using these well characteristics, the potential energy production from the well can be determined. This information can also be used for well maintenance and geothermal field management over the years of operation. The challenge in evaluating a geothermal well is the extreme temperatures and vast depths. Temperatures can exceed 200°C and reach up to 400°C in some cases. Considering the depth, a signal from a sensor that produces a millivolt signal would fall into the noise floor as the signal propagates through the cable. Thus, the sensor is required to be measured locally, which can be done with a microcontroller and other associated components, such as amplifiers and analog-to-digital (ADC) converters. There is a limited set of microcontroller options that can operate at temperatures exceeding 210°C. The method typically used for logging is placing low temperature electronics into a Dewar flask, which is essentially a heat shield to protect the electronics for a short period of time. With 150°C components, the Dewar tool can operate for 8–12 hours in a 250°C environment or for four hours at a 400°C.

Sandia National Laboratories (SNL) has done extensive research on high temperature (HT) logging tools in the past utilizing the HT83C51. The microcontroller was the only option on the market at the time capable of operating up to 300°C. This microcontroller and other HT components from Honeywell and Cissoid eliminated the need for a Dewar, which significantly reduced the cost of the tool. The issue with the HT83C51 is that it does not meet the standards of today's technology. The architecture is based on the 8051, which was developed back in 1980. As proven by Perma Works, using the HT83C51 and a Dewar, they developed a 300°C logging tool that can operate in a 400°C environment for six hours. This effort focuses on evaluating various contemporary microcontroller options that can operate above 200°C. The SNL Geothermal department will provide their recommendations for use in geothermal logging tools.

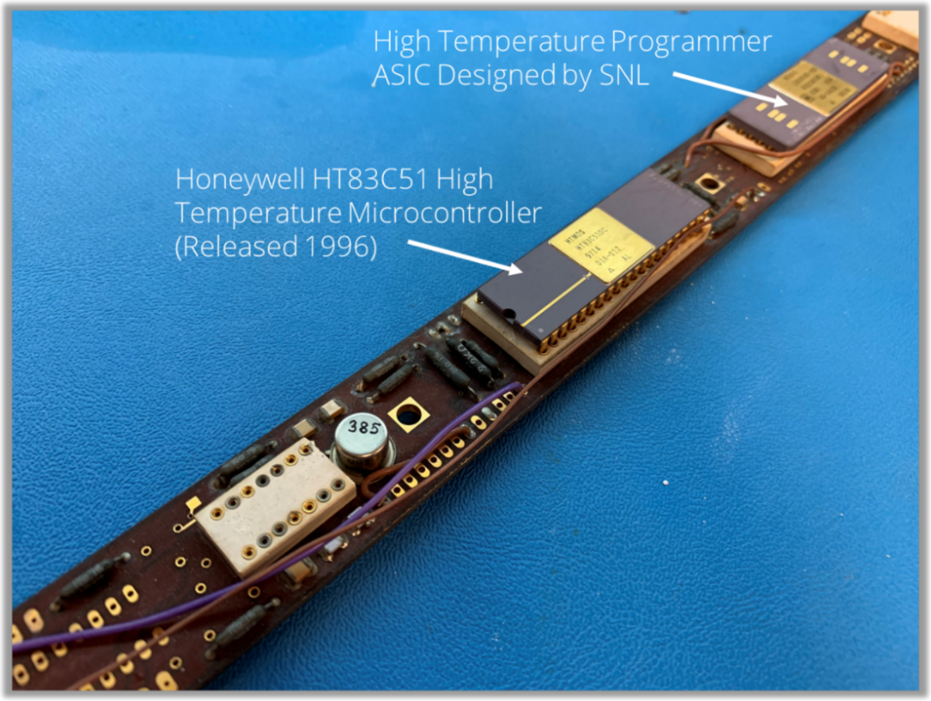

Figure 1: Sandia National Laboratory custom high temperature pressure temperature spinner tool.

2. Project Goals

The sensor needs to process data locally; therefore, we need to utilize HT microcontrollers, of which there are a limited number of options above 210°C. The HT83C51 has been around since 1996 and was a great option for the 300°C application, but it does not meet the standard of today's technology. The focus is to evaluate all microcontrollers on the market that can operate above 210°C and improve the performance of the subsurface tools. The microcontrollers we evaluated are compiled in Table 1. The two microcontrollers not evaluated are both from Tekmos. Although it does have more capabilities, such as the internal ADC, the TK89H51B was not evaluated because it uses the 8-bit 8051 architectures like the HT83C51. The TK8X51S was not evaluated because the chip has not been fabricated yet, but it can theoretically operate at 250°C. Future testing of this integrated circuit (IC) is under consideration.

Table 1: Selection of HT microcontrollers available on the market rated for 210˚C or higher.

DEVICE	MANUFACTURER	CPU	MAX OPERATION TEMPERATURE(°C)	MAXIMUM CLOCK FREQUENCY	INTERNAL MEMORY	ADC
SM320F2812-HT	Texas Instruments	32-bit C2000	220	150 MHz	128Kx16 Flash 128K×16 ROM	16-Channel, 12-bit
SM470R1B1M-HT	Texas Instruments	32-bit ARM7	220	60 MHz	1MB Flash, 64KB SRAM	12-Channel, 10-bit
SM320F28335-HT	Texas Instruments	32-bit C2000	210	150 MHz (125°C) 100 MHz (210°C)	256K×16 Flash 34K×16 SARAM	16-Channel, 12-bit
HT83C51	Honeywell	8-bit 8051	225 (300 derated)	16 MHz	8KB ROM	n/a
RC10001	RelChip	32-bit Cortex MO	300	4 MHz	4KB SRAM	n/a
TK89H51B	Tekmos	8-bit 8051	210	16 MHz	1024 Byte RAM 2K EEPROM	8-Channel, 8-bit
TK8X51S (Not Available)	Tekmos	n/a	250	n/a	n/a	n/a

Because the RC10001 requires external memory for downhole instrumentation, we also evaluated RelChip's RC2110836 (RC21) SRAM.

2.1 Device Packaging and Programming

Since the purpose of this program is solely to evaluate the microcontroller and memory, the project focused on simplifying the packaging with minimal components such as resistors, capacitors, and crystals. A printed circuit board (PCB) using Rogers 4003^{TM} material was designed and fabricated for each device for use in the evaluation. The glass transition temperature (Tg) and decomposition temperature (Td) of the material are shown in Table 2. Standard FR-4 cannot be utilized because it decomposes well below 300°C. Rogers 4003^{TM} was utilized because the Td was significantly higher than 300°C, and it is a common material option with the Advanced Circuits PCB foundry, which makes it a cost-effective option for testing. Tg is below the 300°C, which will make the material fall under a rubbery state. A dummy Rogers 4003^{TM} board was placed in the oven at 300°C for a week and was observed to hold its shape relatively well at those temperatures. Further review of the material is discussed in the evaluation section.

Table 2: List of PCB materials with Td much higher than 300˚C and common with PCB foundries.

Material	Layer Count	Company	Tg (˚C)	Td (°C)	Dielectric Constant
Rogers 3003	20	Rogers		500	3
Rogers 3035	20	Rogers		500	3.5
Rogers 3006	20	Rogers		500	6.15
Rogers 3010	20	Rogers		500	10.2
Rogers 4003C	20	Rogers	280	425	3.55
Rogers 5870	8	Rogers		500	2.33
Rogers 5880	8	Rogers		500	2.2
NF-30		Taconic		515	3
TLX-8		Taconic		535	
Rogers Cuclad 250	20	Rogers		500	2.97
Rogers CTLE	20	Rogers		487	3

The SM320F2812-HT (F2812) is a desirable microcontroller because it is the only digital signal processor (DSP) in this lineup of options. A DSP is designed for communications, audio processing, and sonar and is desirable for subsurface communications and efficient data processing. The SM470R1B1M-HT (SM470) is desirable for its small form factor. This is ideal for logging tools that will be installed in a small diameter borehole, for example the tool shown in Figure 1. Unfortunately, neither the F2812 nor the SM470 could be programmed for this project. Even though both devices are still active under Texas Instruments (TI), the TI Code Composer software no longer supports these devices. We attempted to go to the old version of Code Composer (matching the date of microcontroller release) without success. We also used the Spectrum Digital evaluation board for the TMS320F2812 to attempt programming but ran into the same issue and had no success programming the device. As such, the F2812 was not oven evaluated under this effort.

The SM470 is also no longer supported under the TI Code Composer software, but the Keil software supports the TMS470R1B1M (TMS470) sister microcontroller. We successfully programmed a TMS470R1B512 (similar to the TMS470R1B1M) evaluation board. With that, we expanded to the SM470 and confirmed proper joint test action group (JTAG) communications. Next, we attempted to program the device with the example program written for the TMS470. Unfortunately, the two ICs are not made the same way, and a new library set was needed to program the device. After researching this, we determined that IAR Systems software supports the SM470. Forums also suggest the community was successfully programming the device in late 2021. This project could not support the purchase of the IAR Systems software, so the IC was not oven tested, although we hope to test the device in the future.

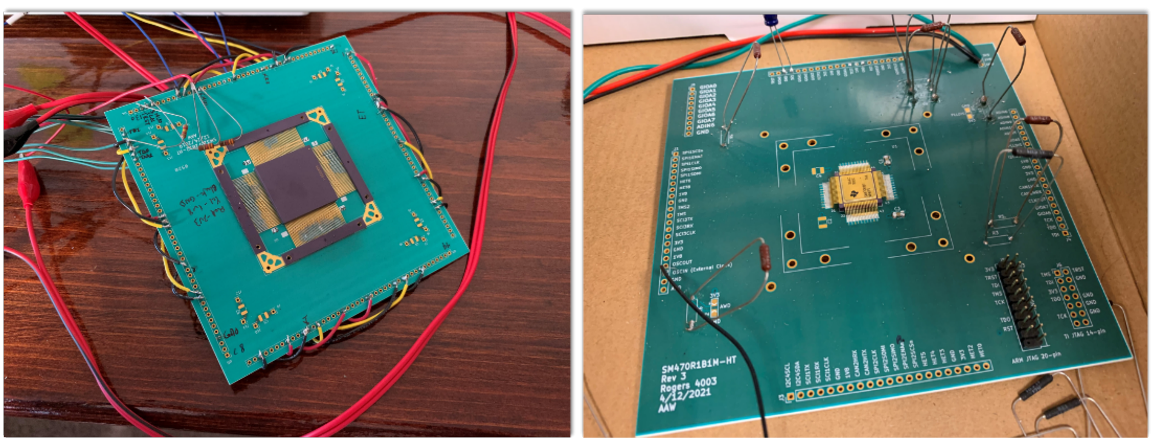

Figure 2: SM320F2812-HT (left) and SM470R1B1M-HT (right) microcontrollers packaged on to a custom Rogers 4003™ PCB.

The HT83C51 (HT83) is a well-known microcontroller in the HT logging tool community considering it has been around since 1996. This device is well characterized and proven to operate at 300°C, but as noted earlier, the device's architecture is severely outdated with limited input/ouput (I/O) ports, no analog-to-digital converter (ADC), no floating-point function, low memory, no serial communications, and other issues. Thus, many more external components are required, making the required PCB much larger and allowing more points of failure. The device does not utilize a common JTAG protocol, making it complicated to program. External electronic circuitry is required to upload the .hex file to the device. SNL's FPGA allows the device to be programmed, and their efforts with Honeywell resulted in an HT ASIC to program the HT83 under high temperatures. Despite this, neither of these components are available outside of SNL, making it challenging to first program the device. We are evaluating this microcontroller because it is a good reference for performance in comparison to the other microcontrollers being evaluated under this effort. The code written to evaluate the HT83 is a simple "hello world" code. The microcontroller sends a serial command "Hello World," until it fails.

The RC10001 microcontroller is desirable because of its ability to operate at 300˚C, its internal serial communications, high I/O count, JTAG, and updated 32-bit architecture. The IC does not have an ADC or floating-point functionality. Because the microcontroller was recently released to the public, it is still a supported device, and Keil software has the latest library to program the device. The RelChip also offers an evaluation board with the microcontroller and SRAM to easily start programming. Unfortunately, the owner is in the process of selling the company. Currently, the future of the microcontroller is unknown, but for this project, the microcontroller was still evaluated. For future efforts, SNL has purchased a stock of both the RC10001 and RC2110836 microcontrollers. Code written for the RC10001 simply pulses one of the I/O ports indefinitely.

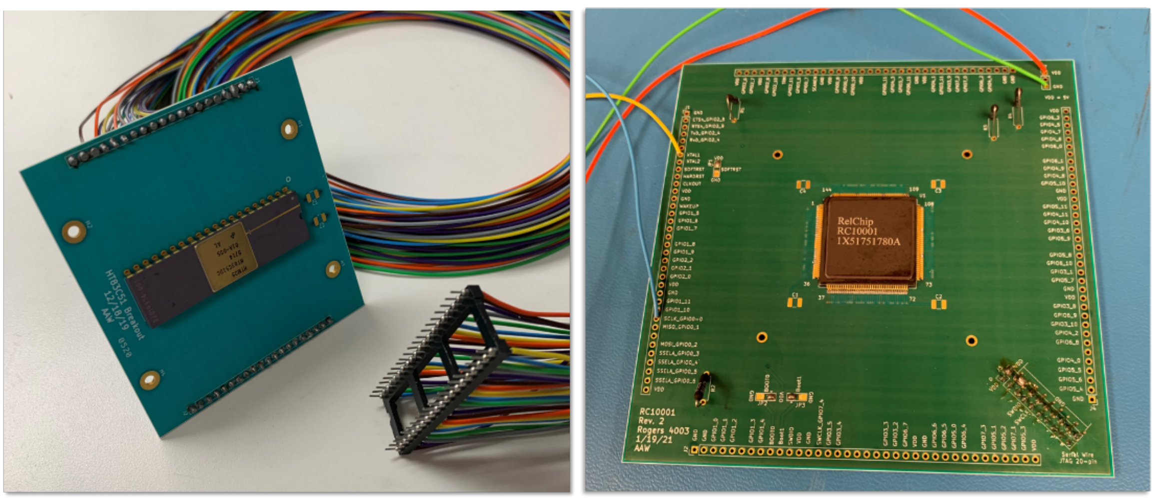

Figure 3: HT83C51 (left) and RC10001 (right) microcontrollers packaged on to a custom Rogers 4003™ PCB.

Before designing the SM320F28335 (F28335) board, the low temperature sister microcontroller was utilized, TMS320F28335, to confirm proper programming. TI Code Composer still supports the F28335 and can successfully program TI's low temperature evaluation board. Using this information, a custom PCB for the F28335 was developed, as shown in Figure 4. The board has many components, unlike the other HT evaluation boards. This board is also being used in a parallel effort, demonstrating an HT datalink; however, this paper's focus is only on the microcontroller. A major benefit to the F28335, is that it is a through-hole device, which is ideal for a coefficient of thermal expansion (CTE) mismatch. Code written for the F28335 is more complicated compared to the other devices, but ultimately the IC sends a string of serial characters through twelve I/O ports which is converted to a two-wire output on the PCB. An oscilloscope and MATLAB code then converts the serial string back to, "Live Long and prosper, from the Communications Toolbox Team at MathWorks!"

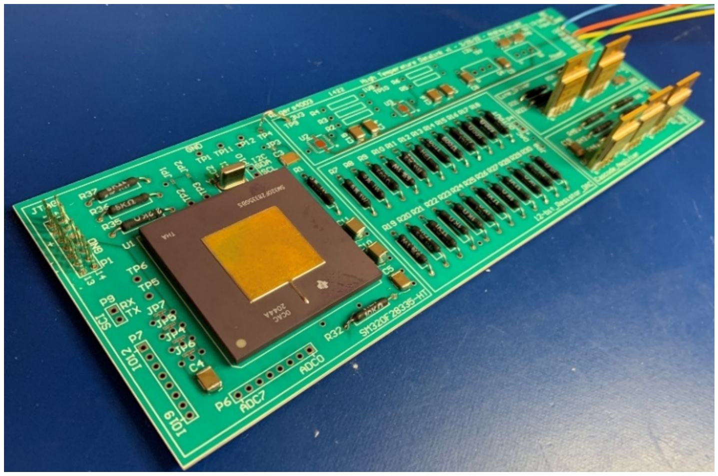

Figure 4: SM320F28335-HT microcontroller packaged on a custom Roger 4003™ PCB for a datalink application.

The RC2110836 SRAM is designed specifically for the RC10001 to effectively use the I/O pins between the two ICs. Just like the RC10001, it is a surface mount device (SMD). This IC was packaged on Rogers 3003 material, unlike the other board discussed above. The Td is shown in Table 2. The PCB was originally designed for a different project but was reused for this project with a different material than its predecessor. The trace width and clearance are 10 mils with no copper fill. As shown in Figure 5, the SRAM is packaged onto the PCB. Unfortunately, no pictures were taken before the oven testing; thus, only the severely damaged PCB is shown here. The code written for the SRAM continuously cycles all the registers to check if any registers begin to fail.

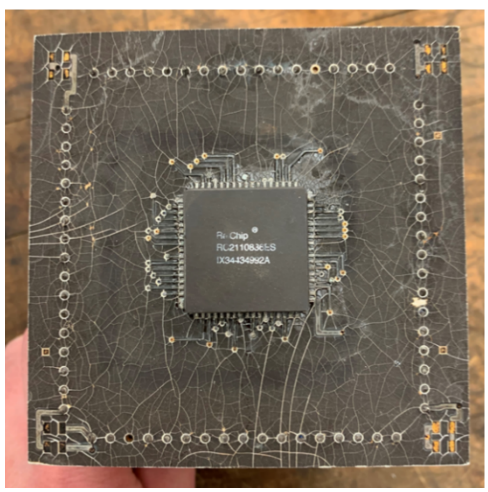

Figure 5: RC2110836 SRAM packaged on a custom Rogers 3003 PCB. The board was initially green before it was exposed to temperatures above 300°C.

2.2 High Temperature Component Evaluation

The HT83, RC10001, and SRAM were stressed between 200 and 300°C. As for the F28335, it is planned to be evaluated at 210°C. The four packaged devices are shown in Figure 6. An additional packaged RC10001 is there because it had failed an earlier test.

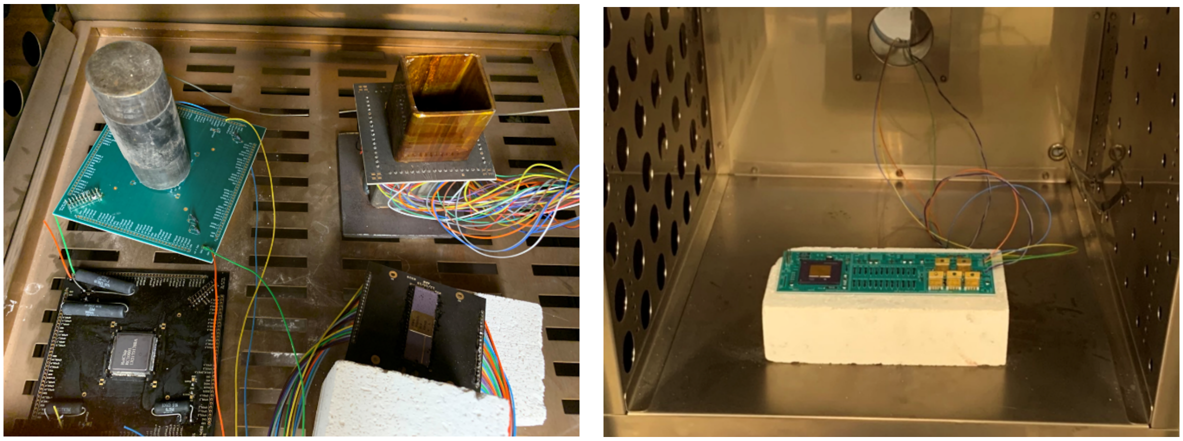

Figure 6: RC10001, HT83C51, and RC2110836 (left) and SM320F28335 (right) oven evaluation.

2.2.1 Packaging Issues

Multiple issues, including bulging of the PCB, CTE mismatch, degradation of the solder, trace shorting, and delamination of the IC away from the PCB, occurred during testing of the packaged device preventing full evaluation of some components to 300˚C. As shown in Figure 7, a bulge in the center of the Rogers 4003™ PCB had formed, which was caused by moisture in the board and CTE mismatch. The PCB is a four-layer board; hence, two Rogers 4003™ panels are bonded by a PCB core with similar properties to the Rogers 4003™. Separation had formed at the PCB core, likely due to CTE mismatch. The moisture in the board also caused an increase in pressure, allowing the bulge to form. Bulging then created strain on the IC, causing debonding of the pins from the PCB pads. To mitigate this issue, the PCBs were baked at 100°C for 24 hours to remove most of the moisture.

During testing of the RC10001 board, two boards failed due to shorting between the supply line and the ground. Despite an apparent short on the PCB, no cause was found after inspecting the top and bottom surfaces as well as the degraded solder on the IC pads. Possible causes of the short are from the few through-hole devices and the solder to copper fill. Each layer had a copper fill; the top and bottom layers are ground, and the inner layers are 3.3 V planes. Copper fill is desired because it helps prevent coupling between traces, which reduces noise on data lines. The PCB used 8 mil trace width and a trace clearance of 5 mils. The solder mask protecting the copper may have degraded allowing the nearby solder to short with the copper fill. Information gained from the PCBs helped to improve the F28335 PCB, which used 10 mil trace width and spacing with no copper fill.

Figure 7: Rogers 4003™ PCB bulging in the center due to the moisture expanding as well as CTE mismatch between layers.

Another observable issue was the degradation of solder bonding the IC to the PCB. Standard 60/40 (tin/lead) solder was used, which has a melting point of 190°C. Initially, it was decided to use standard solder because it is significantly easier to work with compared to HT solder. Even though the solder is in a liquid state at 300°C, it still conducts current, and the method does work for a short period of time. Over time, the solder degrades from the high temperatures and as it consumes the gold on the traces and the IC pins. As shown in Figure 8, two pins were soldered to the PCB, while the remaining pins were not. The two pins no longer have a gold plating, because the gold slowly wicks into the solder, changing its chemistry. The CTE mismatch between the IC and PCB, the liquid state of the solder, and the degradation of the solder all assist in the debonding of the IC from the PCB. Ultimately, the RC10001 was soldered with HT solder to avoid delamination. Surprisingly, the SRAM chip with standard solder is still operating at 300°C.

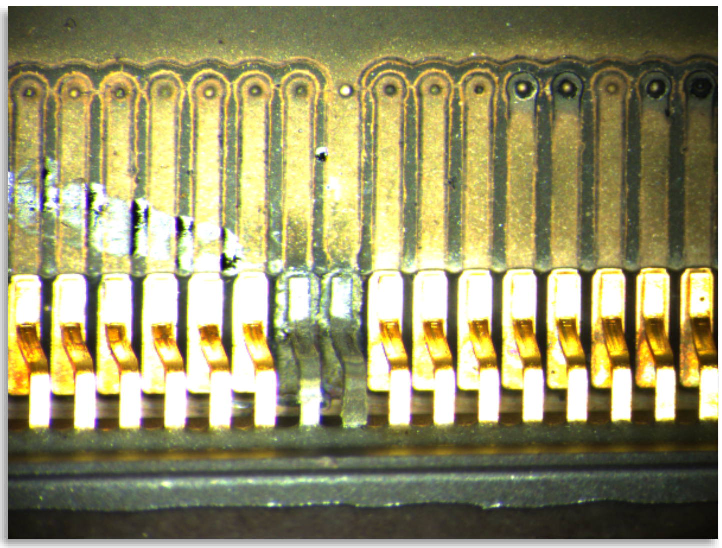

Figure 8: Solder consumes the gold plating on the SMD pads and IC leads. Two pins in the picture have been soldered. The other pins were left untouched.

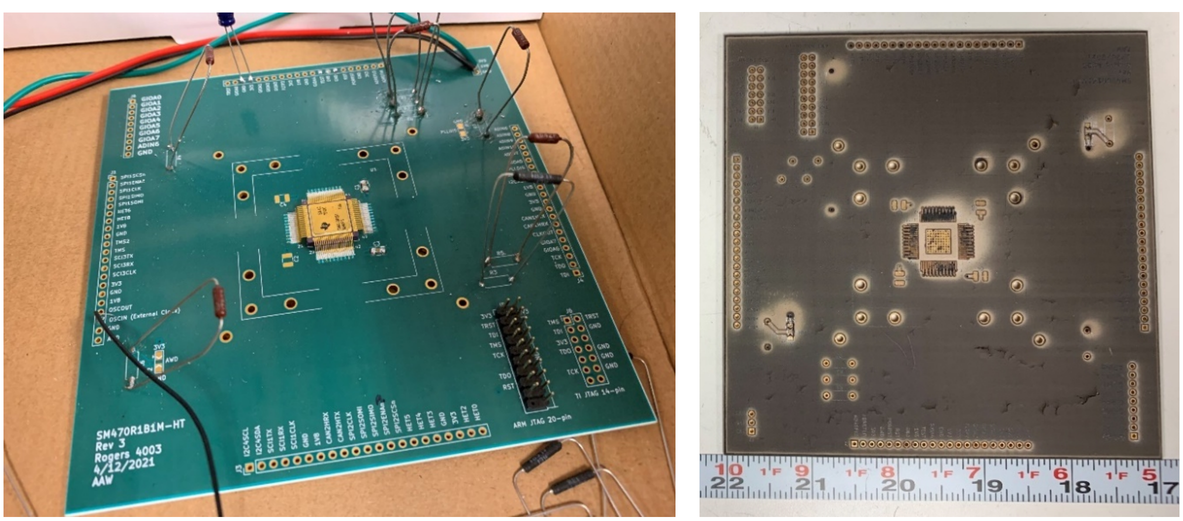

Figure 9: Rogers 4003™ PCB before testing in the oven (left) and after testing in the oven at 300°C for one week (right).

As shown in Figure 9, the solder mask changed from green to grey in the open regions and white near each exposed trace. This degradation may have led to the potential shorting between the solder and copper fill layers noted earlier that could have formed between the solder and copper fill layers. The solder mask was also observed flaking off, exposing the copper layer. At 210°C, the solder mask changes to black with no visual degradation of the solder mask, and thus, the board is ideal for the F28335.

2.2.2 Microcontroller Results

Starting with the RC10001, three sets were packaged and tested in the oven. The first set was soldered with standard solder. It failed at 276°C due to the chip debonding from the PCB. Before failure, it was the current rose from 20 mA on the 3.3 V line to 24 mA. The set was in the oven above 100°C for 47.5 hours before the failure, of which 42.5 hours were spent above 200°C. The second set also used standard solder but with a weight on top of the IC as seen in Figure 6. Before pushing for higher temperatures, the board was baked at 100°C for four hours. Failure occurred at 256°C after sitting at that temperature for 2.4 hours. Electric current had increased from 18 mA to 21 mA, from room temperature to 256°C, respectively. Even after the failure, the oven temperature was increased to 300°C, where shortly afterward the set had formed a short. The set was in the oven above 100°C for 28.75 hours before the failure. The third set used HT solder and was baked at 100–110°C for 41 hours to ensure there was no moisture to minimize bulging on the board. The RC10001 microcontroller was recycled from the second set. Failure ultimately occurred at 234°C when the PCB had shorted again. The set was tested with no issues at 200°C for 117 hours and at 220–234°C for 157 hours. Unfortunately, we could not test the active device at 300°C, but the recycled chip was exposed to 300°C in an off state for 19 hours.

Testing of the HT83 was conducted with the HT PCB and microcontroller that interfaced with a low temperature board (placed outside the oven) that contained the FPGA, power regulation, and memory. Electric current measured when the microcontroller was exposed to temperatures from room temperature to high temperatures transitioned from 38 mA to 30 mA. The current decreased as the temperature increased. Two HT83s were packaged and tested in the oven. The first set failed after being exposed to 301°C temperatures for six hours. Before the failure, the chip was exposed to temperatures above 200°C for 67 hours. After the temperature was brought back down, the device was still functioning but only at room temperature. The second HT83 set failed at 277°C after being exposed to ~275°C for 12.8 hours, 255–265°C for 50 hours, 250°C for 118 hours, 225–235°C for 206 hours, and 200–215°C for 125 hours for a total of 585 hours at temperatures above 100°C. Cause for the failure is under investigation.

F28335 was a late addition to the effort. As such, it was not tested to the same extent as the other microcontrollers. After the microcontroller is programmed, the current level for each supply line is 221 mA, 200 mA, and 75 mA, for 1.9 V, 3.3 V, and 12 V, respectively. With the onboard HT crystal, the board operated up to 110°C before the message transmitted became corrupted. It was determined the error occurred due to operating the chip at 150 MHz instead of the derated operating frequency, at high temperatures, of 100 MHz. To fix the issue, the 30 MHz crystal was replaced with an external 20 MHz source and change the software settings of the IC to operate at 100 MHz. With the new setup, the IC current level for each supply line observed is 176 mA, 185 mA, and 80 mA, for 1.9 V, 3.3 V, and 12 V, respectively. Proper operation of the microcontroller was observed up to 210°C. At this point in time, the microcontroller had no issues at that temperature for 288 hours of operation.

The final IC, the RC2110836 SRAM, was soldered to the Rogers 3003 PCB with standard solder. An external microprocessor sweeps all the registers on the SRAM and constantly flips the registers from 0 and 1. At low temperature, the current is 2.5 mA. At 200°C the current increases to 3.5 mA and at 300°C the current increases to ~21mA. SRAM and PCB were still operating after more than 528 hours at 300°C as shown in Figure 10. Pushing the SRAM even further, the temperature of the oven was brought up to 305°C, with 552 hours operating at that temperature, the SRAM is surprisingly still in operation. The SRAM has a metal weight on top and second metal weight box (wrapped in Kapton tape) sitting on the PCB. A small metal table is below the PCB. As shown in Figure 10, the board changed to a white color and is starting to warp along the edges. Testing of the device will continue until failure.

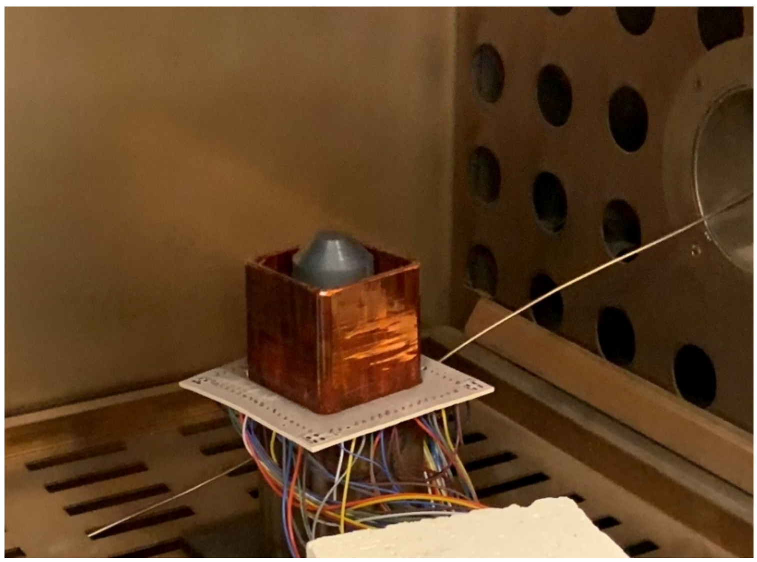

Figure 10: RC2110836 SRAM with Rogers 3003 PCB operating at 300°C.

2.2.3 Future Packaging

As observed in the experiment, there are several issues associated with packaging, and in the future, SNL will investigate alternative materials, such as replacing the Rogers material with alumina PCBs. Ozark Integrated Circuits, Inc offers alumina substrates that operate <500°C. SNL will also investigate alternative methods to bond the IC to the substrate, including gold/tin soldering and wire bonding. An additional research effort will be an HT conformal coating to protect from oxidation and strengthen the bonds (assuming the CTE is a match).

3 Conclusion

Five microcontrollers and one SRAM chip were evaluated. The F2812 and SM470 could not be programmed, but the SM470 may be programmable using alternative software. The RelChip SRAM is still operational after over 528 hours at 300°C and additional 552 hours at 305°C. The RelChip RC10001 experienced multiple packaging failures, preventing it from being tested up to 300°C, but the same MOSFET technology in the SRAM is used in the RC10001, suggesting the device would operate at those temperatures. After improving the packaging, the RC10001 will be reevaluated at 300°C. The HT83 microcontroller failed prematurely even though Honeywell claims it will operate for one year at 300°C. Both of the HT83 microcontrollers tested are old stock from 10–20 years ago. Further investigation is required on the HT83. Finally, the F28335, has shown proper operation up to 210°C for 288 hours. As of the date of publication, SNL makes the recommendations in Table 3. Later this year, SNL will release a SAND report reviewing all these results as well as the steps to program the newer microcontrollers.

Table 3: Recommendations for the high temperature microcontrollers and SRAM as of April 2022.

DEVICE	ISSUES	RECOMMENDATIONS
SM320F2812-HT	Outdated microcontroller. Was not able to detect device with TI software, thus cannot program the device	Not recommended
SM470R1B1M-HT	Outdated microcontroller. Successfully detected the device with KEIL software, but could not program. Requires purchase of $7k software that *might* be able to interface with it.	Possibly usable, more research required
SM320F28335	Recently added to the effort. In the process of designing PCB board. Successfully programmed the low temperature version.	Recommended for use
HT83C51	Outdated microcontroller with minimal features. Successfully programmed and tested at high temperatures.	Not recommended
RC10001	Successfully programmed and tested at high temperatures for short period of time. Issues with device delaminating from PCB board and internal PCB shorting. RelChip is currently in the process of selling to a new company, device maybe discontinued.	Recommended if component available in hand

REFERENCES

Burroughs, C. "Hot Research at Sandia may Make Producing Electricity from Geothermal Energy More Cost Competitive." Sandia National Laboratories News, Albuquerque, NM (1998).

Demeus, L., Delatte, P., Dessard, V., Adriaensen, S., Viviani, A., Renaux, C., and Flandre, D. "The Art of High Temperature FD-SOI CMOS." IEEE (1999).

Henfling, J., and Norman, R. "Dewarless Logging Tool – 1st Generation." SAND2000-1680, Sandia National Laboratories, Albuquerque, NM (2000).

Normann, R., and Henfling, J. "Elimination of Heat-Shielding for Geothermal Tools Operating up to 300 Degrees Celsius." Proceedings World Geothermal Congress, Kyushu – Tohoku, Japan (2000).

Henfling, J., Normann, R. "High Temperature Downhole Reservoir Monitoring System." Proceedings Twenty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, California (2004).

Rogers, J., Ohme, B., and Normann, R. "New Paradigm in Electronics Needed to Take the Heat of Deep Gas Drilling." The American Oil & Gas Reporter (2005)

Swenson, G., and Ohme, B. "HTMOS™: Affordable High Temperature Product Line." Aerospace Honeywell.

Reed, L. "A 250˚C ASIC Technology" HiTEN (2013)

Normann, R., and Glowka, D. “Designing Logging Tools for Future High Entropy Geothermal Power.” GRC Transactions, Vol. 38 (2014).

Soares, M., Durham, W., and Behbahani, A. “A 0.15um SOI High Temperature ARM Microcontroller for Local Control Nodes: Status of the Next Step.” AIAA Propulsion and Energy Forum, Cincinnati, Ohio (2018).

FUNDING STATEMENT

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.