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Developing 300°C Ceramic Circuit Boards

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Abstract:

This paper covers the development of a geothermal ceramic circuit board technology using 3D traces in a machinable ceramic. Test results showing the circuit board to be operational to at least 550°C. Discussion on producing this type of board is outlined along with areas needing improvement.

DEVELOPING 300°C CERAMIC CIRCUIT BOARDS

BY RANDY NORMANN, CTO, PERMA WORKS LLC

INTRODUCTION

High temperature circuit boards were a major effort under this grant. Conventional circuit boards use a nonconductive fiber board with a thin copper layer glued to each side. The fiber board is strong and inexpensive; however, at temperatures above 235°C, the glues start to break down, causing delamination of the copper and circuit board failure.

The development of a high temperature circuit board along with a high temperature solder enables all geothermal well monitoring and well logging tools to use new HT electronics. This technology has already been used elsewhere—for example, the aircraft industry builds their engine control systems on square co-fired ceramic circuit boards. Co-fired ceramic technology is limited to 4 X 4 inch dimensions due to ceramic-metal thermal expansion mismatch. Geothermal instrumentation is built into logging tools <2 inch in diameter. These tools require thick metal wall for withstanding geothermal pressures. The 2 inch limitation comes from the 2 inch inside diameter for many tool entry valves located on top of the well head. The geothermal circuit is normally limited to only 1 inch in width inside a geothermal logging tool. There is no hard limit on the length of the circuit board. In general, 1 inch wide by 10-18 inch long circuit boards are found inside a geothermal well logging or monitoring tool. Building complete circuits for geothermal tools using co-fired ceramic technology is not practical. A new means for placing metal on ceramic is needed and is, thus, developed under this grant.

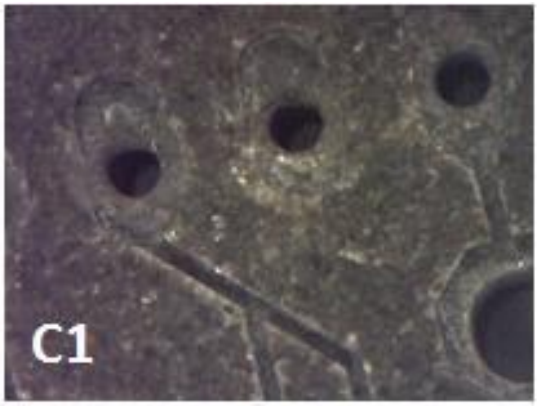
The image of the circuit board assembly below is from work performed in 1997 at Sandia National Labs,

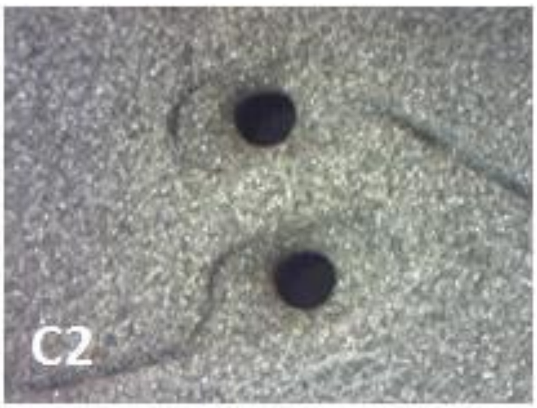
where some of the first HT SOI electronic devices from Honeywell SSEC were mounted on machinable ceramic. The devices were connected using simple Teflon-coated wire. No solder was used; instead, the wires were attached by laser welding. Clearly, average geothermal tool builders cannot afford to use laser welding; this was done simply to prove these circuits could run at 300°C. In fact, this circuit ran up to 317°C before the microprocessor locked up.

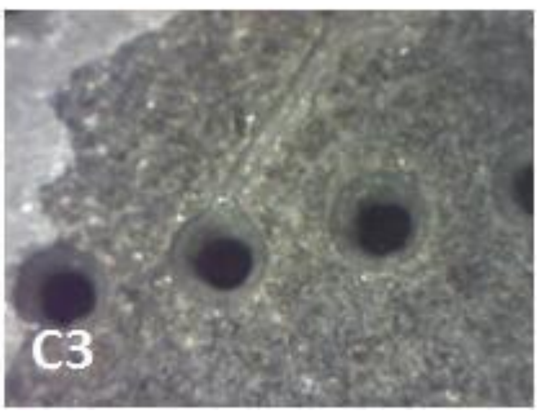
CONSTRUCTION OF A NEW TYPE OF CIRCUIT BOARD

Under this grant, a new means of placing metal onto ceramic was developed. Where co-fired uses the heat from the ceramic firing process to sinter metal on to the ceramic, Perma Works attempted to use ceramic which was already fully fired. Plasma (electrical arc) spray, flame spray, and high velocity impact processes were used to create a metal surface on the ceramic. As such, there were no organic glues or a need for high-temperature co-firing. This process allows for the use of a completely fired ceramic before the conductive traces are placed onto the board. Furthermore, this potentially allows for the use of any type of ceramic with a surface texture permitting the molten metal to adhere.

At Perma Works, we adapted a unique method for placing the metal into interconnecting circuit traces. Before the ceramic has been applied with a metal layer using a plasma spray, the future circuit traces are milled into the ceramic by a machining process using diamond cutters. After the stock ceramic board has







had circuit traces and solder pads milled into it, the metal layer can be applied across the board. Thereafter, unwanted metal can be removed by sanding the exposed top surface, leaving conductive metal circuit traces in milled sections.

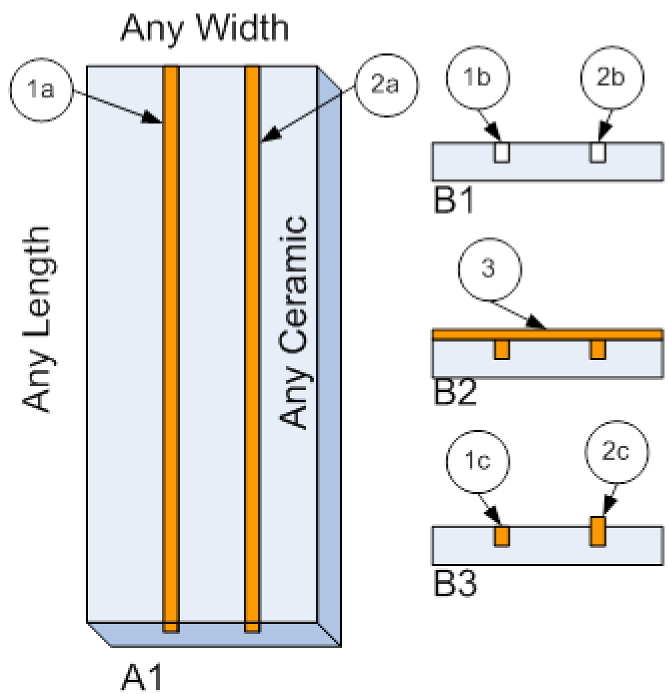
Perma Works purchased a computer-controlled mill capable of milling a 12 X 10 inch sheet of machinable ceramic. Alistair Black worked extensively on developing the software for converting conventional CAD drawings used to manufacture conventional copper circuit boards to mill instructions. This new process is both a negative process and a 3D process.

The images to the left show new machinable ceramic circuit board in the process of gaining the metal traces needed to support electronic circuits. C1 is an image of the board manufactured following a milling process that created holes, grooves (traces) needed to connect circuit elements and solder pads. C2 is an image of the board following a thermal spray of nickel. This is the same nickel spray used to protect steel aircraft parts. C3 is an image of the board following the use of a power sander to remove most of the nickel surface material. Traces of conductive nickel remain. Note, some nickel surface material still remains in the upper left-hand corner.

The placement of conductive metal traces in milled ceramic allows the metal to attach to the ceramic on three sides. Such a configuration creates for a stronger bond between the ceramic and the metal traces, allowing for improvements to operating lifetimes for applications with temperature cycling. Stronger bonding allows for heavier metallization, which improves the current-carrying capability. Traces on co-fired ceramic must be thin (1-2mils) to prevent the metal from separating from the ceramic due to the differences in thermal expansion.

The drawing to the right shows the flexibility of this process to create electrical traces. Placing the metal on the ceramic after the ceramic has fired allows for unlimited board, length and thicker metal traces, compared to co-fired ceramic processes.

A number of metal types were considered for this process. In fact, most any metal that can be purchased in a powder form is capable of being used. However, the two most common metals used in plasma spray operations are zinc and nickel. Both of these metals are used as protective coatings for aircraft and ships for which protection from the elements is required. In short, plasma spray is just like spray painting, except the spray temperature is hot enough to melt the metal powder.



Basic Properties of Potential Metal Layers
Zinc: Melting point 419°C, Resistivity = 59.0 nΩ·m at 20°C, Thermal conductivity = 116 $W \cdot m^{-1} \cdot K^{-1}$
Nickel: Melting point 1455°C, Resistivity = 69.3 nΩ·m at 20°C, Thermal conductivity = 90.9 $W \cdot m^{-1} \cdot K^{-1}$
Copper: Melting point 1085°C, Resistivity = 16.8 nΩ·m at 20°C, Thermal conductivity = 401 $W \cdot m^{-1} \cdot K^{-1}$

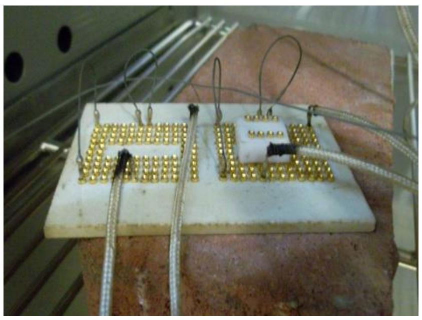
Above, the basic properties of zinc, nickel and copper are given. Copper is the most common metal used for the metal layer of commercial circuit boards. Clearly, copper is the better electrical conductor. Unfortunately, copper is not a metal commonly used with plasma spray processes. Additionally, copper has issues with intermetallic growth when combined at very low temperatures with other metals, such as tin, which is commonly found in solder. The tin-copper intermetallic compound growth is a solid-state transformation that occurs between the two metals at moderate temperatures near 200°C. The tin-copper intermetallic compound is a crystalline bronze which is non-conductive and easily broken.

Only nickel and zinc were tested using the plasma spray process. When tested by creating a metal layer on machinable ceramic, both nickel and zinc attached directly to the ceramic without issue. As such, this process is not dependent on organic glues to hold the metal in place.

TESTING THE NEW CIRCUIT BOARD

It was determined in solder testing at EWS that nickel actually worked better at holding to ceramic when it was repeatedly soldered. During testing a technician soldered a wire onto plasma sprayed traced on the ceramic circuit board, and then removed the same wire only to re-solder it again back on to the board at the same location. After about five additions and removals, the nickel layer would break away from the ceramic. This test indicates that the nickel metal layer plasma sprayed on to the ceramic withstands manual reworking or repair of high temperature geothermal electronic assemblies.

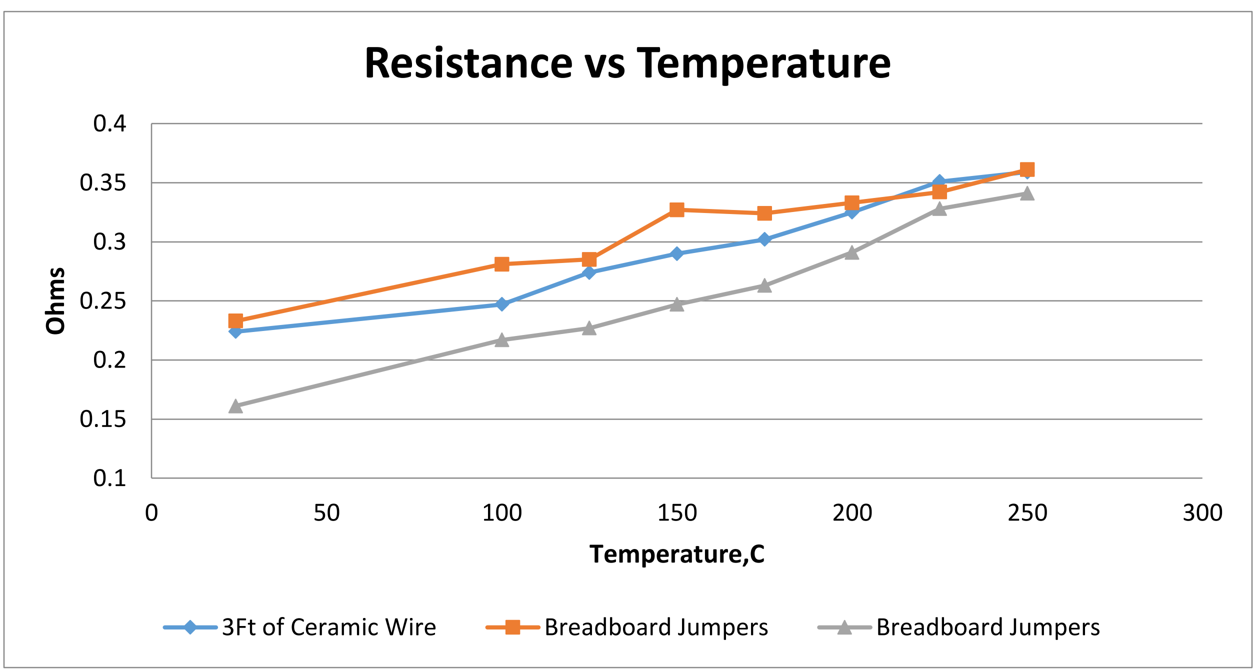
A common universal circuit board layout was created using machinable ceramic and a nickel plasma spray metallization layer. This universal circuit board was filled with gold-plated sockets for plugging 0.02 inch wire or other electrical leads in and out without soldering, which allows for easy testing of many electronic devices. One such test was conducted to compare the IC voltage references from two manufacturers, Honeywell and Cissoid. One of these test circuits was used in Perma Works' first YouTube video titled *High Temp High Rel Electronics*. In the video, the flame from a weed burner was used to heat the circuit board with a working HT SOI voltage reference on it. The heat actually turned the ceramic-coated high-temperature wire white-hot. After heating, the circuit was cooled down, and then was shown to still be working.



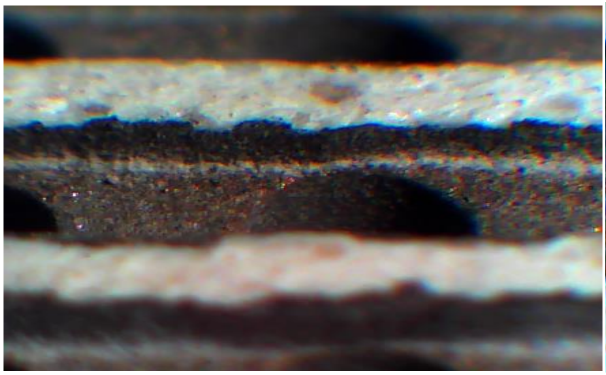
Other tests of the circuit board were conducted. In one test, two circuits composed of high temperature wire and circuit board traces, of equal length, are created. A third circuit of nothing but wire, approximately 3 ft., was also used. The resistance for the three circuits was made and then heated in an oven. The photo on the left shows the circuit board and wire resting on a brick inside the oven.

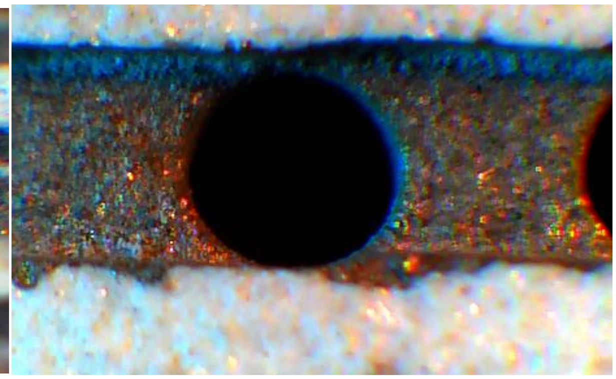
The wires used were very high temperature ceramic-coated nickel wire. They are only 28 AWG or about 0.01 inch in diameter, which was too small for the sockets, so the nickel wire was brazed (~700°C) with silver solder into 0.02 inch diameter pins. The larger wire was also brazed, which caused the glass insulation to blacken as seen in the image.

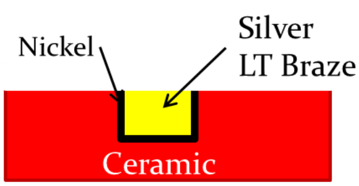
Below are the resistance measurements of the three circuits versus temperature. The resistance of metal circuits normally increases as a function of temperature. What is important here is that the two circuits, which included the Perma Works circuit board, increase at the same rate as the circuit that was made up of only 3 feet of high-temperature wire. This demonstrates that the circuit board works with all those connections.



Below are two close-up images of a circuit trace milled and coated in nickel metal. The benefit of thermal spray is that more than the bottom of the machined groove is covered. These photos clearly show that the side walls are also covered with nickel. This has a huge impact on the thermal stability of the metal with regard to thermal cycling. We believe that the thermal expansion difference between the ceramic and metal trace is held in check. The expansion along the trace that wants to lift the metal off the ceramic is offset by the expansion across the trace that is pinching the metal down on to the ceramic.







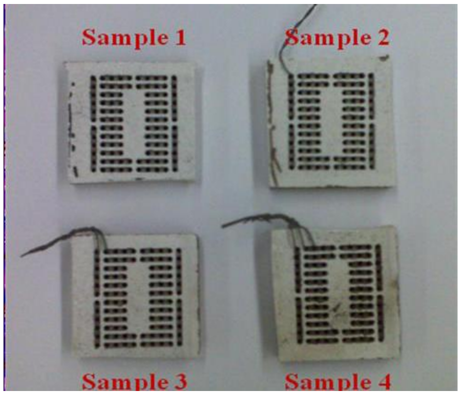
The plasma strayed metal coats all three sides of the machined circuit trace and forms a channel of metal. It is clear that this channel can be filled with more metal or conductive epoxy. This is a clear advantage of this technology, as shown in the drawing on the left. Such a heavy circuit board trace cannot be built at geothermal temperatures using any known commercial method.

In the next test, a 4-wire bridge circuit was built using traces filled with silver following a low temperature (~700°C) brazing process, as shown in the drawing. By using a 4-wire bridge circuit, we were able to run high currents through 30 Mil wide traces to measure the voltage drop and calculate the resistance. A photo of the test board and silver-filled traces is to the right.

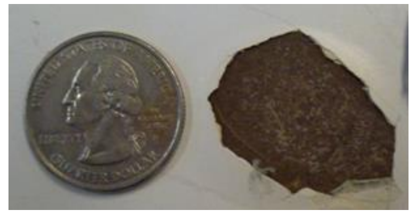
To test the resistance of the silver-filled, nickel-coated traces, 1 amp was run through the circuit from room temperature to 300°C. The test trace was 4.2 inches long. The resistance remained < 0.01 Ω/inch in all temperatures. That is approximately 0.005 Ω/inch lower than a 2 oz copper trace 30 Mil wide on a conventional circuit board.

NEW CIRCUIT BOARDS TESTED UP TO 550°C

A set of 4 small general purpose ceramic circuit boards were built on the Perma Works CNC mill and were plasma sprayed with a layer of nickel. The surface nickel was removed by sanding with a power sander. In short, these steps followed the same previously tested process. The 4 small circuit boards are shown below.

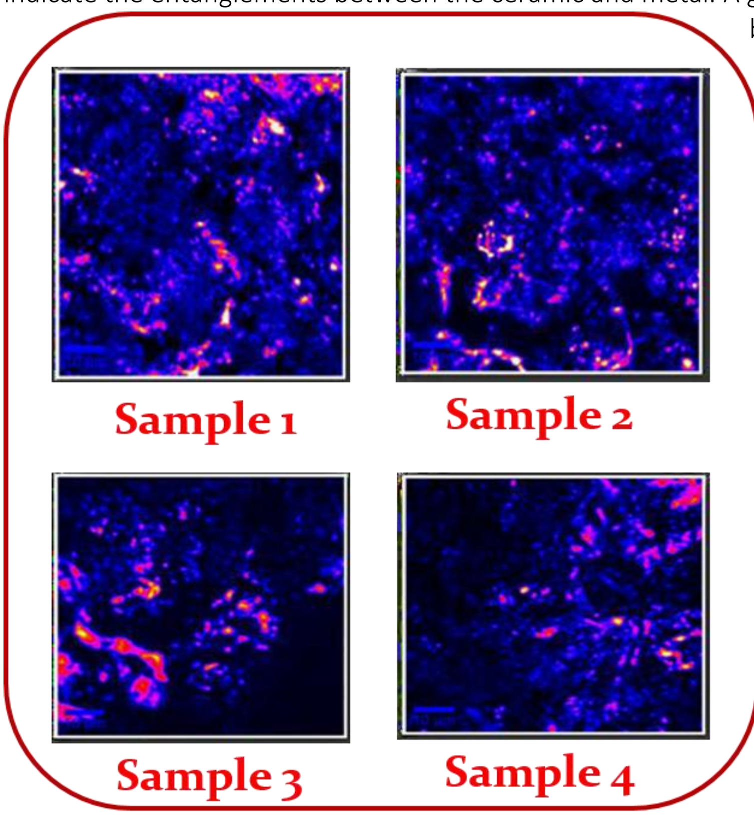


Sample 1 was our control sample. Sample 2 had one wire tied to the board and was heated to 300°C. Sample 3 had two wires and was heated to 400°C. Sample 4 had three wires and was heated to 550°C. The wires were used to mark the boards as the most common marking methods would simply burn off.



When sample 4 came out of the oven, it was so hot it was burning the oven cloves worn by James Parker, so he placed it on a table, on which it burned a quarter-sized hole in the Formica table top.

These four samples were sent to Professor Yuhang Ren's group at Hunter College of the City University of New York. (Dr. Ren receives some small funding from NASA to test materials that might benefit space exploration.) Dr. Ren took nondestructive confocal optical images of the ceramic-metal entanglements of the four samples. The experiments were conducted by using an Nd-YAG laser. The entangled boundaries between the metal and the ceramic phases can be well identified. In the images below, the mix of colors indicate the entanglements between the ceramic and metal. A greater mix implies a greater mechanical bonding between the ceramic and plasma-sprayed metal.



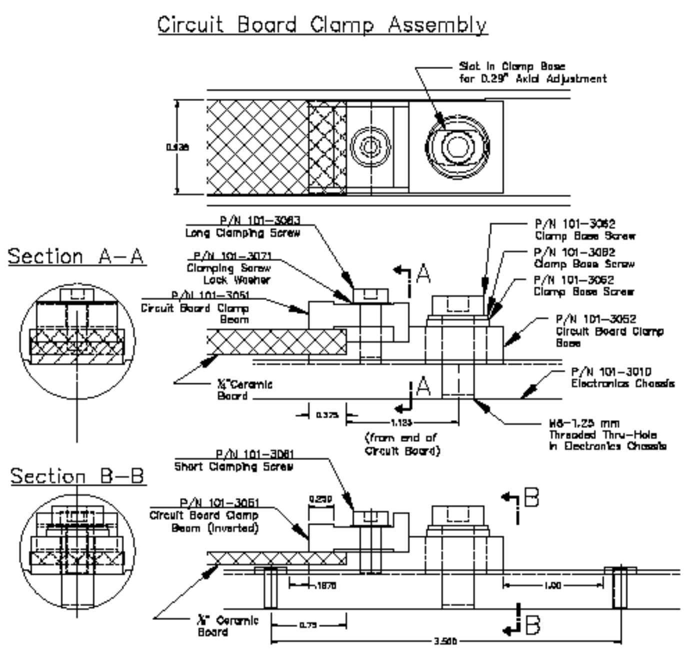
As can be seen, there is some loss of entanglements at elevated temperatures. However, it was the general opinion that this process held up very well, even at 550°C.

In the Perma Works YouTube video, *Perma Works: Circuit Board Comparison*, the Perma Works ceramic circuit board with plasma sprayed nickel traces was placed in a fire with other circuit boards. At the end of the video, the other circuit boards were durned up while the Perma Works board survived, even with a heavy bolt hanging on a wire attached to metal trace. The actual temperature of the test was unknown; however, it clearly exceeded 550°C.

MOUNTING CERAMIC CIRCUIT BOARDS INSIDE THE GEOTHERMAL TOOL

Ceramic is a useful material for handling geothermal temperatures. However, using it for circuit board material creates a problem inside the geothermal tool. The circuit board must be mounted inside the tool using a metal carrier. Under vibration and shock, metals can bend, whereas ceramic tends to break. Additionally, most common metals have a much larger thermal expansion coefficient than our machinable ceramic. The length of a ceramic circuit board is 10 to 14 inches long. Simply bolting the ceramic circuit board to a metal board carrier inside a geothermal tool would result in breaking the board via shock or thermal expansion.

Dave Glowka presented a report at the HiTEC on a clamping system used to mount the ceramic circuit board inside a geothermal logging or well monitoring tool. A short version of his report is presented here. Dave's clamp is shown below. The clamp fixes the lower end of the circuit board to the aluminum board carrier in such a way that it allows the board some ability to slide. This allows some room for the ceramic board and board carrier to undergo differential thermal expansion and slight bending through a sliding board clamp. When the clamp shown below is torqued to 30 lb.-in, it should securely hold a 3 lb. circuit board undergoing vibration and shock accelerations typical of wireline deployment without creating unacceptable stress levels in the circuit board, clamp components, or screws.



The clamp consists of two parts, plus two screws and three washers. The circuit board clamp base is screwed to the electronics chassis using a metric M8 screw, a flat washer, and an external tooth lock washer. The hole through the base is a slot that gives of the base an axial adjustment range of about 0.29 inch.

The circuit board clamp beam is screwed into the base with a metric M5 screw and external tooth lock washer. The bottom 3/8 inch of the circuit board is clamped between the base and the beam. The clamping screw is torqued to a specific level to ensure that the board is held tightly without being crushed.

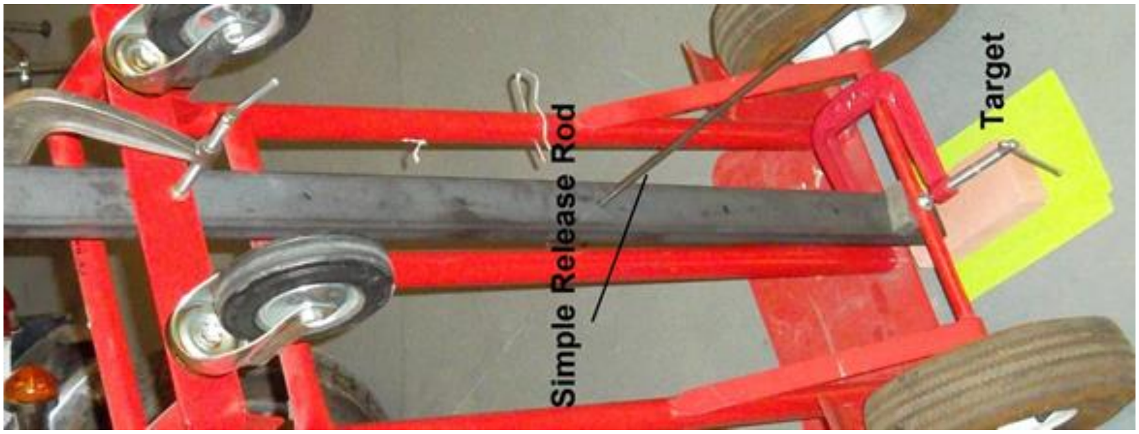
The clamp beam is designed so that it can be used with either 1/4 inch- or 1/8 inch-thick circuit board. The beam is used in one position for one thickness and flipped over for the other thickness. The clamp should also work fine with other thicknesses in or below this range.

The clamp base and screws are made of stainless steel, while the clamp beam is made of aluminum. This mixture of materials, with their particular thermal expansion coefficients, ensures that the clamp tightens, rather than loosens, at elevated temperatures.

Above is a photo of the actual clamp and a ceramic that is a nominal length for a circuit board used in a geothermal well monitoring or logging tool. At the other end is a mounting screw and spacer. The ceramic board is elevated off the aluminum board carrier as it would be in the tool to prevent shorting solder leads located on the bottom side of the board. The test fixture was temperature cycled 20 times up to 250°C, and after every two cycles, the board was tested to ensure that it was not cracked or broken and that the clamp was still tight.

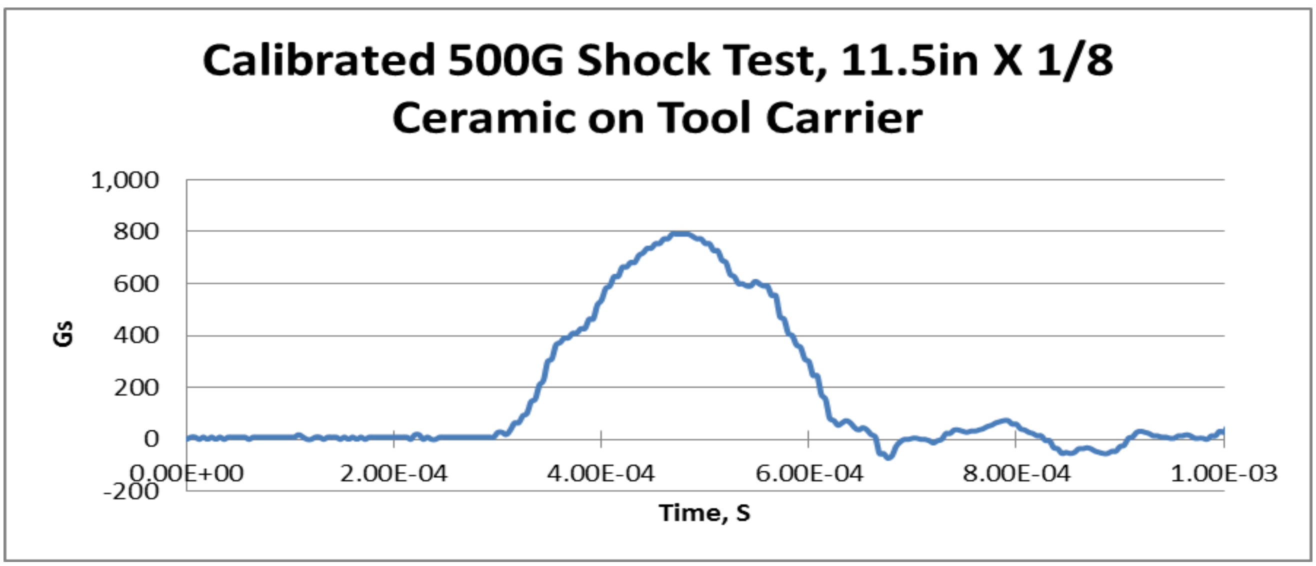
The clamp worked without an issue. The next test was to shock test the ceramic clamped to the aluminum carrier. For shock testing, Joe Henfling built a simple drop tester. An accelerometer was attached to the top of the aluminum carrier and connected to a digital scope. The same ceramic board and clamp used in the drop test was also used in the temperature cycle tests.

The aluminum carrier and board was placed inside a rectangular tube with a set of holes drilled through the tubing to hold a rod in place. When the rod was removed, the aluminum carrier and board were free to fall inside the rectangle tube, striking the brick below. The acceleration response of the test fixture was monitored. The shock pulse was lengthened or shorten with the use of more thin foam sheet(s) below the brick.



The aluminum board carrier, clamp, and ceramic board passed shocks exceeding the 500 Gs that the accelerometer was rated for. In all of the tests of the board clamp, there were no failures. There was some wear from the clamp rubbing on the ceramic, but that was to be expected.

Below is the final shock test, as recorded by the oscilloscope.



MANUFACTURING ISSUES WITH PERMA WORKS CERAMIC CIRCUIT BOARDS

Up to this point, most of our testing and data has been extremely encouraging. Perma Works had developed the basic universal circuit board to support testing. The goal moved to making this system more reproducible and to building real geothermal well monitoring systems.

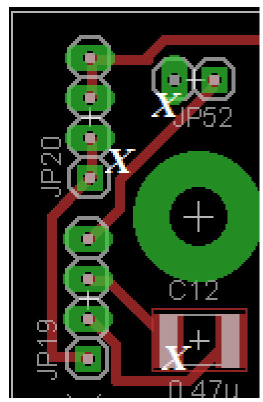
Alistair Black, provided with actual tool circuit designs, worked with the CNC mill to develop software for converting Eagle CAD electrical designs to ceramic milled designs. Meanwhile, the work was continued to find lower cost external suppliers of the plasma spray process.

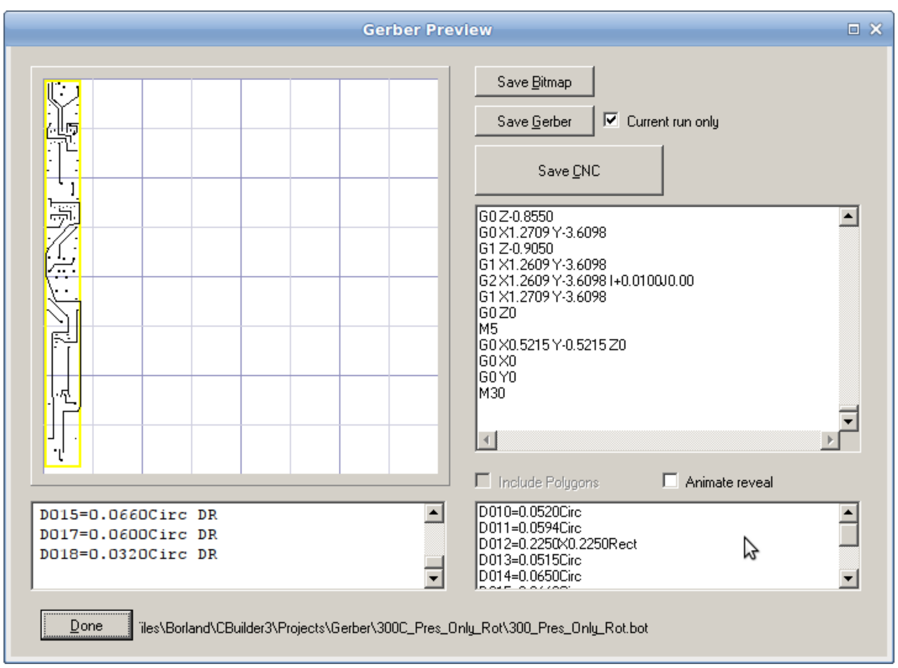
SOFTWARE DEVELOPMENT NEEDED TO MANUFACTURE

The first task was to learn how to interpret the Eagle CAD board instructions and convert them to mechanical CNC mill instructions. The second task was to produce a two-sided circuit board, which entails that once one side is completely milled, the ceramic must be flipped, and the backside must be milled with all the circuits and interconnections matching both sides of the board. Flipping the board requires that the circuit feedthrough holes must line up within 0.005 of an inch. Unfortunately, the Perma Works mill could not hold this tolerance across the entire operating plain of 8 X 10 inch; though it did well with smaller designs, about 5 X 5 inch. There are more costly mills capable of this tolerance. They generally cost upwards of $35K. Our mill is roughly a $13K mill.

A solution was to design the tool circuits with a component layout within 4 quadrants on a 10 x 1 inch double-sided circuit board. In short, the mill would run 4 milling operations, two for each side. Now the circuit traces connection between the top two and bottom two circuits could be made using simple straight traces, allowing for increased error.

Under this grant, Perma Works personnel took a short class on CNC programming held by instructors at the local community college. With this training, we worked back and forth to understand the Eagle CAD files and when our layouts would create circuit constructs that were difficult to reproduce in a 3D milling process. This back and forth went on for two years, with the end result that we can now create our tool electronics using the CNC mill by limiting the circuit board layout options. There are still a number of issues, given the large library of possible board layout options. To the right is an image of the Eagle CAD circuit board layout for the signal (pressure and temperature) wire solder connections: JP19, JP20, and JP52. At Perma Works, the layout of the pin 1 solder pads on these connectors is square, while the remaining pads are oval as seen in the image. This reduces errors made during hand soldering. However, the CNC mill can only work with round end mill cutters. Making a square is not practical. So, all the Eagle CAD drawings must be recreated with all solder joints with oval solder pads. Doing so creates at the milling point in board fabrication creates other issues. For example, note where the “X”s have been placed in the image. Near the “X”s there are a signal traces which must be moved if the square solder pads are changed to oval or there is a potential short circuit.





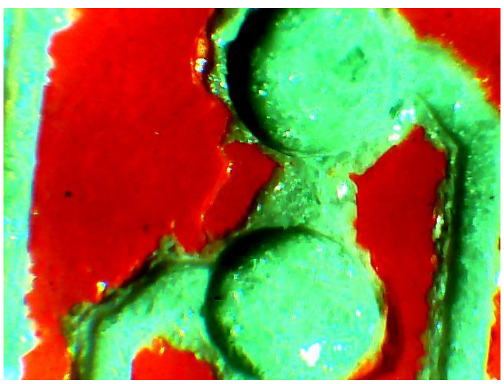
Above is a screen shot of the software developed to convert the Eagle CAD layouts (Gerber Preview) to CNC milling instructions are called G-codes.

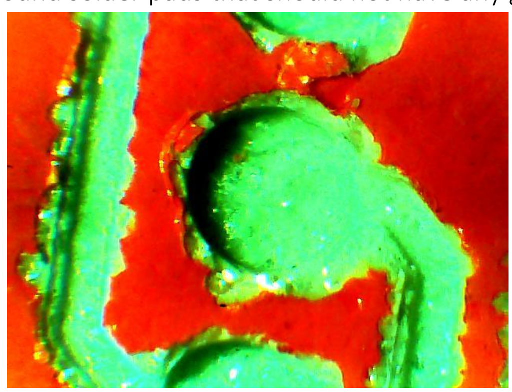
YIELD PROBLEMS

The milling process can take an entire day for only one geothermal well monitoring circuit. Cutting traces in even machinable ceramic is hard on equipment and bits. Our CNC machine did not come with water jets for cleaning the ceramic dust or for cooling the end mill cutter. With the grant, a simple water jet was added to the mill, but this failed to greatly extend the bit life. Bit replacement takes operator time. As a bit might break at any time, an operator has to stay near the machine all day. During a day of milling, three to five bits might be used at a cost of $7.50/ea. All in all, these circuit boards are expensive to depend on for milling. In the future, an effort should be taken to mold the circuit traces when making the ceramic. Even as expensive as they are, it is still worth the cost if each milled board were usable. However, most boards would have manufacturing issues with short circuits between signal traces caused by ceramic breakouts.

Below is an image of a ceramic board on which a bright red paint was used to cover the board prior to milling. The milled sections appear greenish in the microscope lighting for the photo.

In the first image to the left, there are two round solder pads that should not have any green showing between them. A small shallow fragment of ceramic has broken out between the two round pads. Following metallization, these pads would be electrically shorted. The image on the right shows two pads that are very close to being connected. This image also shows a straight trace with small breakouts along both sides.





A number of ideas were attempted to reduce the size and frequency of breakouts. First was simply to use a smaller end mill cutter at 0.01 inch. The images above are milled with 0.015 inch cutters. However, machinable ceramics are simply too tough to cut consistently with such a small cutter. Switching to a 0.015 inch or larger cutter improves bit life but reduces the clearance between solder pads and traces, increasing the likelihood of small breakouts shorting between signal traces.

Other attempts were made to place a thin bonding agent, such as glue or epoxy, on top of the ceramic prior to milling. The hope was to hold the ceramic and prevent it from breaking out. However, these methods did not work. It is possible the problem lies in the manufacturing of machinable ceramic. The particle size used in the manufacturing of machinable ceramic is too large. We estimate them to be ~0.005 inch; this size is why the 0.01 inch bits are easily broken.

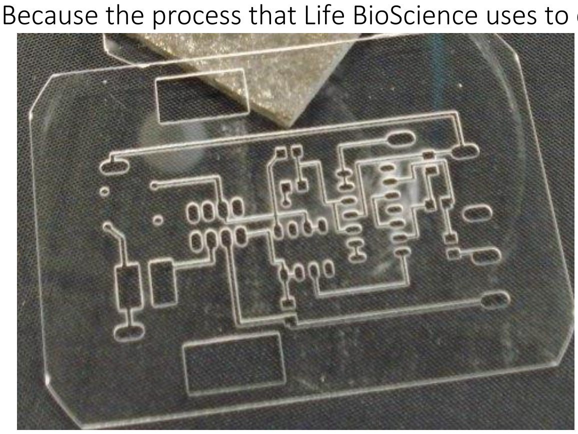
In our building and testing of the universal circuit boards, Perma Works used a manually operated mill with larger 0.03 inch bits. Although manual mills and larger bits can be used for small test fixtures, this is not practical for real geothermal logging tools.

Life BioScience Inc.

Life BioScience is a startup technology company in Albuquerque with an interesting technology. They have a method of etching through thin layers of APEX™ glass and then converting the glass to a ceramic. They can produce holes and open groves in ceramic at dimensions too small for the human eye to see. In short, they can make circuit-like traces and solder pads even smaller than existing circuit board technology. So we asked them to help us.

However, their technology does not work on machinable ceramic. Additionally, they normally etch all the way through the thin glass as they do not have good control on the depth of etching. So the plan was to use their technology to either make a mask for our plasma flame process or attach their thin ceramic to our machinable ceramic. Masking would create flat metal traces on top of the machinable ceramic. On the other hand attaching their ceramic to the machinable ceramic would keep the 3D traces already demonstrated.

With a contract in place, Life BioScience went to work. Perma Works provided Eagle CAD test circuits. Because the process that Life BioScience uses to create patterns in their ceramic is the same as the process used for laying out printed circuits, they were able to work directly with our Eagle CAD drawings, which was a huge benefit.



The photo on the left is of a circuit pattern etched in clear APEX™ glass. Note the clean lines and solder pads cut in the glass. Within the image to the right, a signal trace is actually running between two solder pads of a small surface mounted capacitor. This is not possible with a milling process. An additional benefit is that the etching process can be done in bulk. However, as a new technology, the cost of the materials and equipment is quite high.

Using the Life BioScience process to create a metallization mask for the plasma spray of metal might work, but it was not tried. After some discussion, it appears to engineers on both sides that the mask would not hold up to the pressure created by the plasma spray gun. So, the thin ceramic would need to be physically mounted to the large, thicker machinable ceramic that Perma Works has been testing.

The basic plan was to find a means to attach the Life BioScience ceramic containing circuit traces to machinable ceramic. Once the two ceramics were bonded, the process used by Perma Works for metallizing the circuits and removing the excess metal would be unchanged.

Life BioScience provided a report on their work, which is available from Perma Works with some limitations. A non-proprietary review of this effort is given in this report.

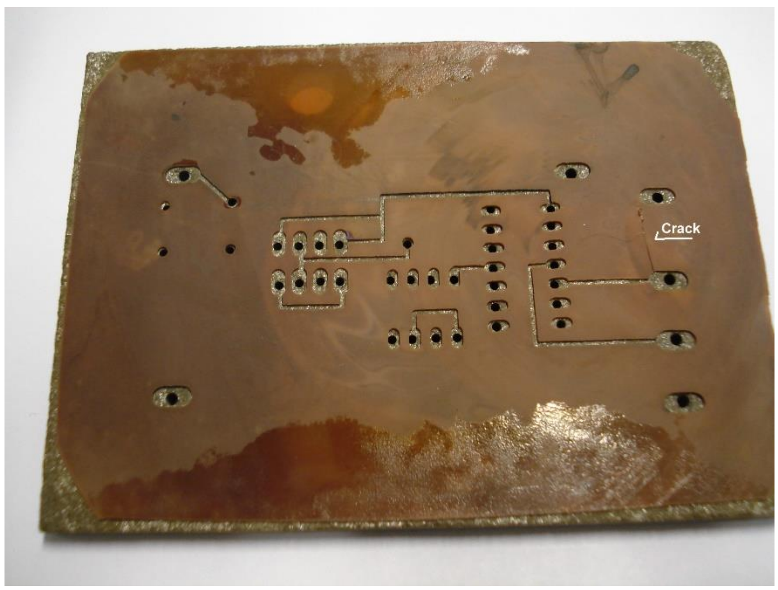
CERAMIC CEMENT

A ceramic cement was used as a simple first attempt to attach the thin ceramic containing the circuit layout produced from APEX™ glass. This process did work to bond the thin circuit ceramic to a heavier machinable ceramic. However, great care is needed to prevent the ceramic cement from flowing in the grooves needed for the metal traces.

HIGH PRESSURE, HIGH HEAT

The machinable ceramic used by Perma Works is not a true ceramic. It is a glass ceramic composite of ceramic materials. Whereas true ceramics are rated for 1000s of degrees Celsius, machinable ceramics used by Perma Works are rated for lower temperatures. For example, Contronics 914 is only rated to 540°C.

Life BioScience built a steel heating plate to heat the machinable ceramic to a point where it could be physically deformed under a 10 ton press. Using heat and pressure, they were able to mate the two materials without using glues or adhesives. The two ceramics had to be truly flat, however; any manufacturing irregularities on either surface causes the thin circuit ceramic to break. Thus the surface of the machinable ceramic was first ground true to 1/10,000 of an inch. The two ceramics were then centered on top of one another and placed in the press. Heat was then applied as the press squeezed them together.



A photo of the end product is shown on the right. The APEX™ glass changes color when converted from glass to ceramic. This example is not of a real operating circuit. It is too simple (use of such a simple circuit will be explained later). In the photo, circuit traces and solder pads can clearly be seen. This is an example of a nearly perfect result; however, even this attempt has a small crack. Despite best efforts to work with truly flat surfaces and controlled heating in the press, avoiding cracks was challenging, even with this simple test circuit.

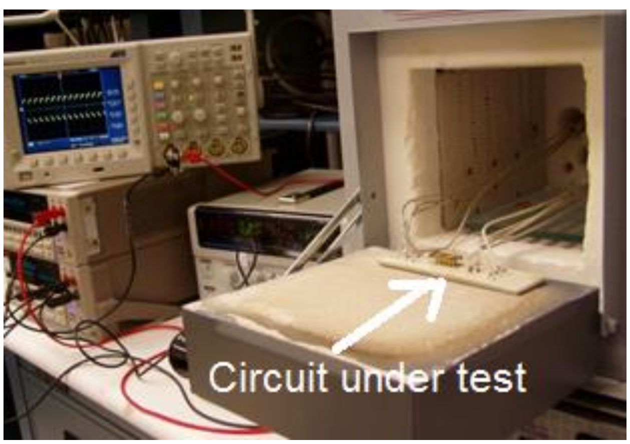
Working with real circuit designs created additional problems. To cut circuit traces through the thin APEX™ glass would result in small sections simply falling out. It is normal for power and ground circuit traces to be interconnected; thus, a section of the board would fall out. These sections required being manually placed in the right orientation back on to the machinable circuit prior to being pressed together. Additionally, in a real geothermal circuit, the circuit boards are narrow and long; for example, 1 X 12 inches. As such, most signal traces run along the long axis of the circuit board in parallel. It is not uncommon to have two signal traces running for 5 or 6 inches with only a 0.02 inch separation. This leaves a very narrow strip of APEX™ ceramic to be pressed onto the supporting ceramic using heat and high pressure. These sections would deform or, more likely, simply break.

Life BioScience attempted to use just the APEX™ material where the APEX™ circuit was pressed onto a blank or solid sheet of APEX™. This process actually worked well. However, the metallization using plasma spray would not work. Life BioScience was able to fill the circuit traces and pads with HT conductive epoxy. This was effective for signal traces, but not for solder pads. The application of HT conductive epoxy requires mounting the electronic components at the same time that the traces and pads are filled. As discussed in PW01085-1, “Efforts to Develop a 300°C Solder”, HT conductive epoxies are difficult to work with and to complete logging tool circuits. This technique is just not practical.

CONCLUSION OF 300°C CERAMIC CIRCUIT BOARD DEVELOPMENT

Perma Works successfully demonstrated a circuit board technology for geothermal temperatures up to 550°C. This technology is based on a machinable ceramic and plasma spray metallization. We believe the technology has virtually unlimited operating time inside a geothermal well and the capability to go to even higher temperatures. This technology uses 3D-like signal traces and solder pads, which creates opposing forces of thermal expansion to prevent separation of the conductive metal and the ceramic foundation under thermal cycling. The 3D traces allow for the production of very thick board traces for high current and high temperature circuits. This technology is well suited for use in future downhole motor control circuits or for future EGS flow control valves.

Perma Works purchased a CNC mill and created software designed to convert Eagle CAD circuit board layout drawings to G codes needed by the mill. This allowed Perma Works to build test circuit boards and to develop a complete circuit board design and manufacturing process. Perma Works has supplied high temperature test fixtures to third parties to test their geothermal electronics. One example was a project for a GE project developing 500°C geothermal well pressure amplifiers out of silicon carbide (SiC) electronics. The photo of the test circuit shown below was taken by GE engineers.



Nickel plasma spray was chosen over other metal options to create the metalized traces and solder pads on the ceramic board. Nickel is commonly used in plasma spray processes and is a tough metal with few intermetallic issues at 300°C. EWS was able to solder to the nickel using high lead solder, and demonstrated that these ceramic-based circuit boards could be reworked up to five times. Perma Works also showed that this circuit board technology can be brazed up to 700°C. Several YouTube videos were released showing these circuit boards surviving extreme heat and boiling brine.

A significant effort was taken to reduce production costs and to increase the yield for building geothermal circuit boards, and for geothermal well monitoring and well logging tools. Our efforts were hampered, however, because of the large particle size of commercially available machinable ceramic. Perma Works was unable to reduce circuit traces to less than 0.015 inch, and ceramic breakouts sometimes shorted signal paths that were 0.020 inch away from one another. A possible solution is to fabricate the machinable ceramic in a mold, which would remove the need for machining circuit traces and solder pads.

The local startup company Life BioScience LLC has the unique capability to etch very fine details into APEX™ glass. The glass is then transformed into a ceramic. Perma Works attempted to use this process to replace the current machining process. Using actual test circuits from Eagle CAD circuit board layout software, Life BioScience was able to bond a thin ceramic containing simple circuits to very flat machinable ceramic using a combination of heat and pressure. The end product was 100% ceramic without any organic glues or adhesives.

However, the test circuited used by Life BioScence were very simple. Effort is still needed move this technology for to real world circuits. Etching through the thin glass resulted in completely cutting small glass sections free. These sections have to be manually returned to the correct location. Additionally, in geothermal tool circuits, many signal traces run in parallel on 1 inch wide, 12 to 14 inch long circuit boards. With only a 0.02 inch separation between traces, the pressure used to bond the thin, circuit-containing ceramic to the machinable ceramic would deform or break the traces. Thus, the effort to use this novel process was dropped.

Despite the setbacks to make machinable ceramic circuit boards a commercially viable technology for geothermal well monitoring tools at 300°C and above, Perma Works is continuing to develop this technology. The 3D traces in ceramic offers too many advantages over existing technology at geothermal temperatures to be ignored.