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Demonstration of Passive Fuel Cell Thermal Management Technology

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Abstract

The NASA Glenn Research Center is developing advanced passive thermal management technology to reduce the mass and improve the reliability of space fuel cell systems for the NASA Exploration program. The passive thermal management system relies on heat conduction within highly thermally conductive cooling plates to move the heat from the central portion of the cell stack out to the edges of the fuel cell stack. Using the passive approach eliminates the need for a coolant pump and other cooling loop components within the fuel cell system which reduces mass and improves overall system reliability. Previous development demonstrated the performance of suitable highly thermally conductive cooling plates and integrated heat exchanger technology to collect the heat from the cooling plates (Ref. 1). The next step in the development of this passive thermal approach was the demonstration of the control of the heat removal process and the demonstration of the passive thermal control technology in actual fuel cell stacks. Tests were run with a simulated fuel cell stack passive thermal management system outfitted with passive cooling plates, an integrated heat exchanger and two types of cooling flow control valves. The tests were run to demonstrate the controllability of the passive thermal control approach. Finally, successful demonstrations of passive thermal control technology were conducted with fuel cell stacks from two fuel cell stack vendors.

Nomenclature

A	Cooling plate cross sectional area, m^2
dT/dx	Temperature gradient, K/m
k	Thermal conductivity, W/m-K
Q	Applied heat, watts
T	Cooling plate temperature, K
x	Location of the temperature measurement on the cooling plate, m

1.0 Introduction

The purpose of this work was to test two different approaches to the control of the passive thermal management of fuel cell stacks. One approach used an electronically controlled valve to control the coolant flow through the heat exchanger which controlled the fuel cell temperature. The other approach used a thermostatic valve whose actuator opened and closed the valve through expansion and contraction in response to the temperature of the coolant flowing through the valve. This variation in the coolant flow in turn controlled the fuel cell stack temperature.

Another purpose of this work was to demonstrate two previously developed cooling plate technologies (Ref. 2) and previously developed passive fuel cell heat exchanger technology (Ref. 1) in actual fuel cell stacks. The first cooling plate technology was based on thin pyrolytic graphite plates to transmit the heat from the core of the fuel cell stack to the cooling fluid manifold. In a collaboration between NASA and Teledyne Energy Systems (Ref. 3), a demonstration fuel cell stack was built with pyrolytic graphite cooling plates integrated with a heat exchanger developed and built by NASA. The demonstration stack was assembled and tested at Teledyne Energy Systems, Inc. The other cooling plate technology was based on thin titanium heat pipes developed for NASA by Thermacore International, Inc. (Ref. 4). Infinity Fuel Cell and Hydrogen, LLC (Ref. 5) designed and built a demonstration fuel cell stack using titanium heat pipe cooling plates and heat exchanger technology supplied by NASA. The fuel cell stack was assembled and tested at Infinity Fuel Cell and Hydrogen.

2.0 Background

The heart of a fuel cell is an electrochemical "cell" where a fuel and an oxidizing agent react, converting the chemical energy directly into electrical power, water and waste heat. The fuel cells under development for future NASA missions for this project are acid-based Proton Exchange Membrane (PEM) hydrogen-oxygen fuel cells. An illustration of this type of cell is shown in Figure 1. A hydrogen molecule reacts at the anode to create a pair of protons and electrons. The proton ion exchange membrane conducts the protons, which were generated at the anode, from the anode to the cathode. The electrons which are also generated at the anode are conducted through the electrical load that is connected to the fuel cell and also reach the cathode. The hydrogen protons and the electrons react at the cathode with an oxygen atom to produce a molecule of water. An illustration of a "stack" of cells connected electrically in series is also shown in Figure 1.

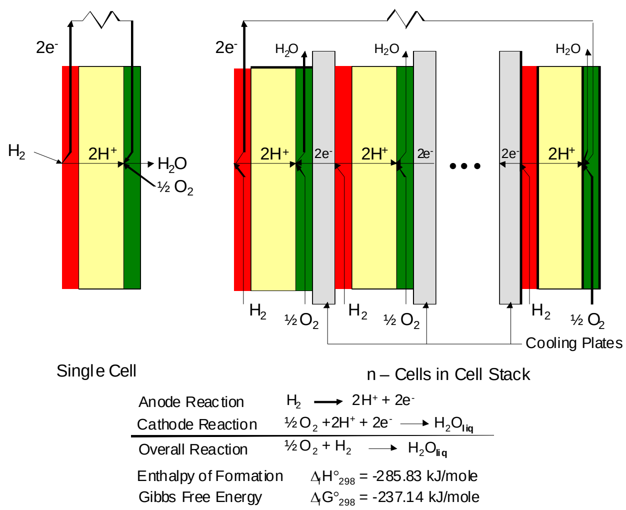

Figure 1.—Proton exchange membrane fuel cell.

Heat is a by-product and must be removed from the fuel cell stack to prevent the stack from overheating. Heat is typically removed from the fuel cells via a liquid coolant circulated through cooling plates located between the cells within the fuel cell stack (Fig. 1). Heat is removed convectively as the coolant passes through the plate and out of the fuel cell stack to a fuel cell system heat exchanger. A passive cooling plate must conduct the heat within the plane of the plate out to one or more of the edges of the plate so that the heat can be transferred to a heat exchanger external to the fuel cell stack. Figure 2 shows the difference between a conventional fuel cell thermal management system and a passive fuel cell thermal management system. Potential benefits of the passive approach include reductions in mass, system complexity, and parasitic power as well as improvements in system reliability.

Figure 3 plots the fuel cell heat generation density (the heat generated per unit of cell area) versus the fuel cell output current density. The fuel cells under development typically optimize in the lower current density range (≤400 mA/cm^2), so the heat generation expected is generally ≤0.3 W/cm^2.

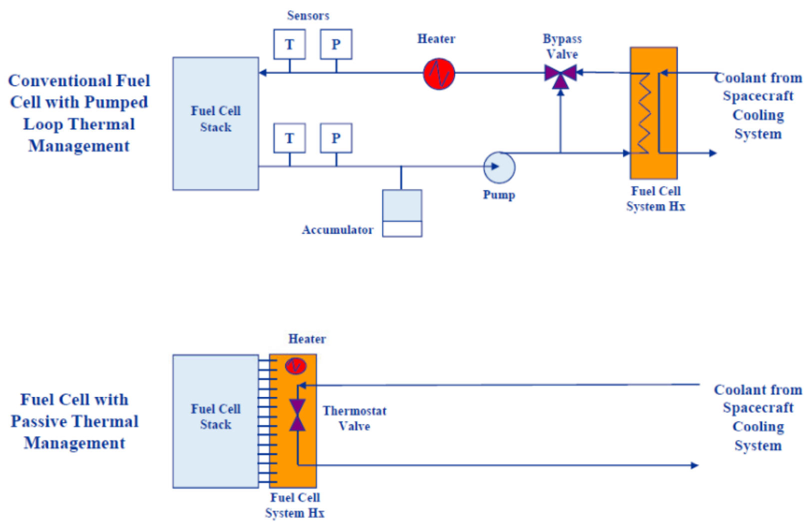

Figure 2.—Fuel cell thermal management systems.

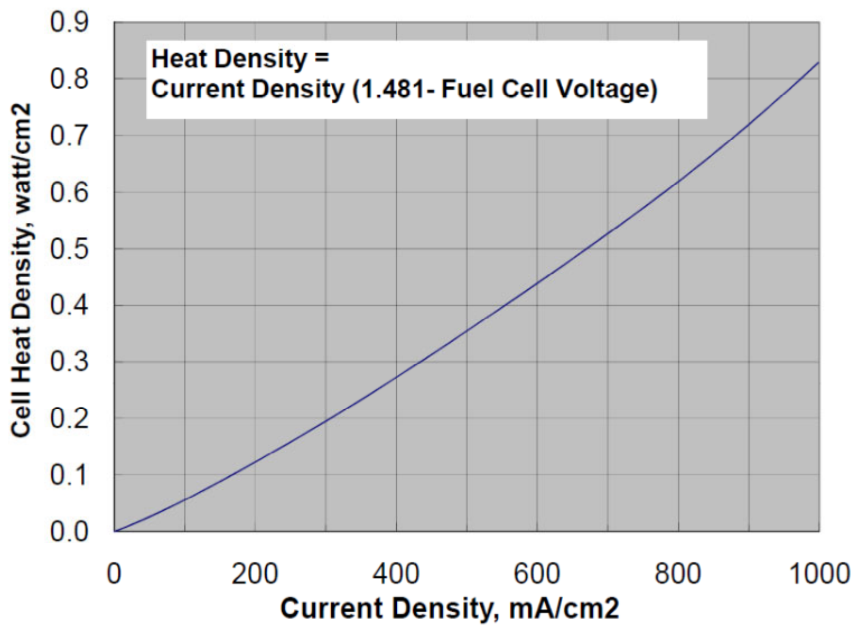

Figure 3.—Fuel cell heat generation.

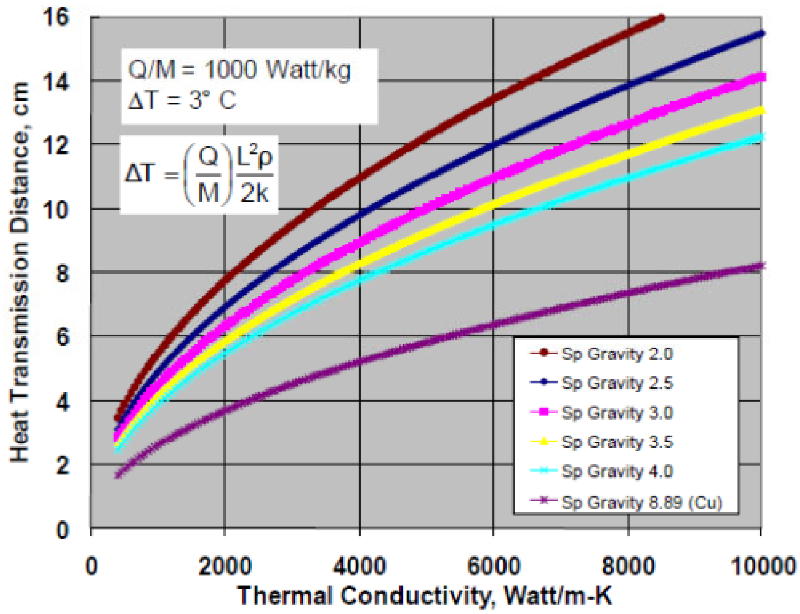

Figure 4.—Cooling plate heat transmission distance, thermal conductivity, and plate specific gravity.

The key to making the passive fuel cell thermal management approach workable is by making the cooling plates light enough, yet highly thermally conductive, so that the heat can be effectively removed and also provide each cell in the fuel cell stack a thermally uniform heat sink. Analytical expressions were developed (Ref. 6) that relate the thermal performance of a passive cooling plate to its physical characteristics. There are two key metrics used in the evaluation of the thermal management system, the first is the maximum temperature difference, the ΔT, over the chemically active area of each cell in the fuel cell stack. Ideally, a uniform temperature over the active area is desired because this maximizes the electrochemical performance throughout the stack. In practice, a ΔT of zero is never achieved because the process of removing waste heat from the fuel cell always requires a temperature differential. A ΔT of 3 °C has been acceptable, and therefore was used as a driving requirement. A second key metric is the mass of the thermal management system. The waste heat managed per unit mass of the thermal management system was the defined metric for mass evaluation. Previous work (Ref. 6) identified 1000 W/kg as a target for this metric.

Using 1000 W/kg as the value of the metric and 3 °C as the ΔT, the relationship between heat transmission distance L, the specific gravity of the cooling plate ρ, and the thermal conductivity k of the cooling plate is plotted in Figure 4 using the analytical relationships developed previously (Ref. 6).

From the plot shown in Figure 4, it is apparent that for fuel cells which have to transmit the heat ≥4 cm, a thermal conductivity of ≥1000 W/(m-K) and a specific gravity of ≤4 gm/cc would be required to meet the metric targets. From previous testing of potential cooling plate technology, two candidate cooling plate technologies emerged, one based on pyrolytic graphite that has a conductivity of approximately 1100 to 1500 W/(m-K) and a density of 2 to 2.8 gm/cm^3, and the other candidate was a titanium heat pipe which has a conductivity of 20,000 W/(m-K) and a density of approximately 2.6 gm/cm^3.

3.0 Passive Thermal Management System Test Articles

Several test articles were developed to facilitate the investigation of the control of the passive thermal management approach and to demonstrate the cooling plate technologies in actual fuel cell stacks.

3.1 Passive Thermal Management System Simulator

Figure 5 is an illustration of the assembled thermal management simulator, showing four cooling plates inserted into a heat exchanger. Each cooling plate was instrumented with nine thermocouples as shown in Figure 6. A silicone pad heater was adhered to the other side of each plate, so that on one side of each plate were the thermocouples, and on the opposite side of each plate was the silicone pad heater. The pad heaters simulated both the amount of waste heat produced by the cells of a fuel cell stack as well as the area on the cooling plate expected to absorb the waste heat. The cooling plates were thin pyrolytic graphite plates coated with silver paint. They were identical to the cooling plates used in the fuel cell stack demonstration of the graphite plate cooling plate technology.

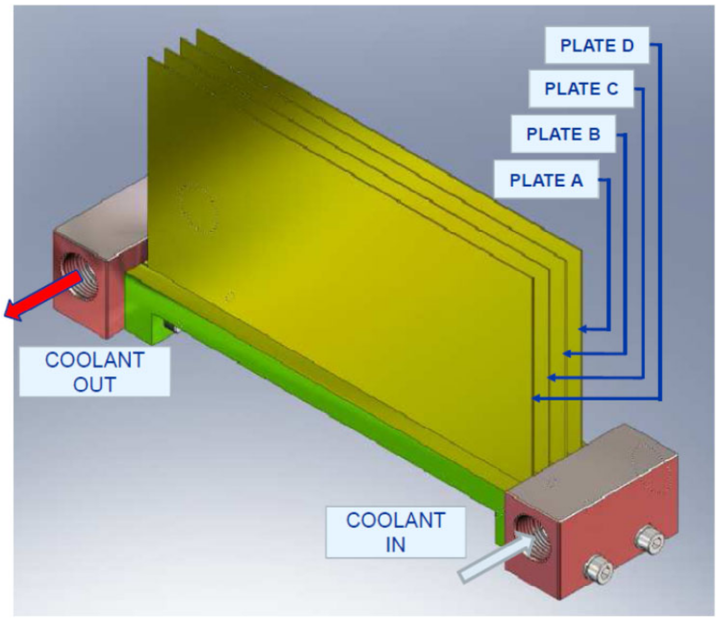

Figure 5.—Simulated fuel cell stack for testing thermal controls.

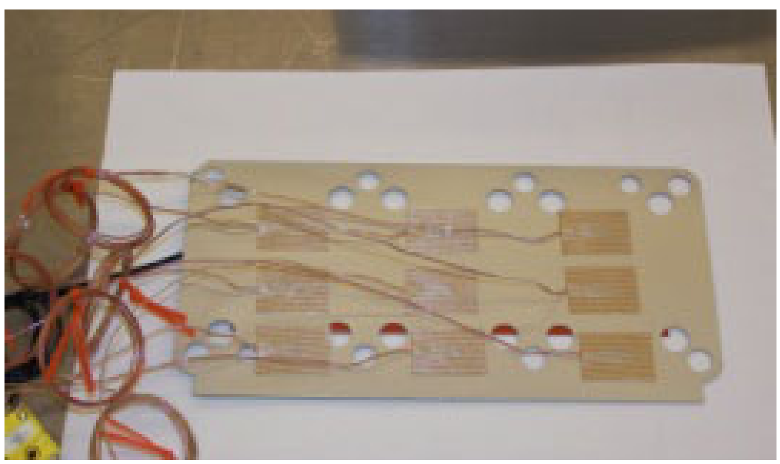

Figure 6.—Simulated fuel cell stack cooling plate with pad heater and thermocouples.

Figure 7 illustrates the geometry of the cooling plates used for the passive thermal management system simulator. Figure 7 also shows the location of the silicone pad heater. The pad heater mimicked the quantity of heat expected from each cell in the fuel cell stack. The area and placement of the heater similarly mimicked the area and location where the heat would be absorbed from the cells in the fuel cell stack. Figure 7 also shows the number and placement of the thermocouples used to measure the temperature of each cooling plate. The holes in the cooling plate at the top and bottom of the plate are for the hydrogen and oxygen manifolds within the fuel cell stack, and played no functional role in the experiment of the heat exchangers.

Figure 8 shows the fabricated heat exchanger. The cooling plates were inserted into the heat exchanger to a depth of approximately 6.4 mm. The heat exchanger was made of anodized aluminum. The anodized heat exchanger used five smaller diameter flow channels that carried coolant down the length of the heat exchanger and were connected in parallel to common manifold aluminum blocks.

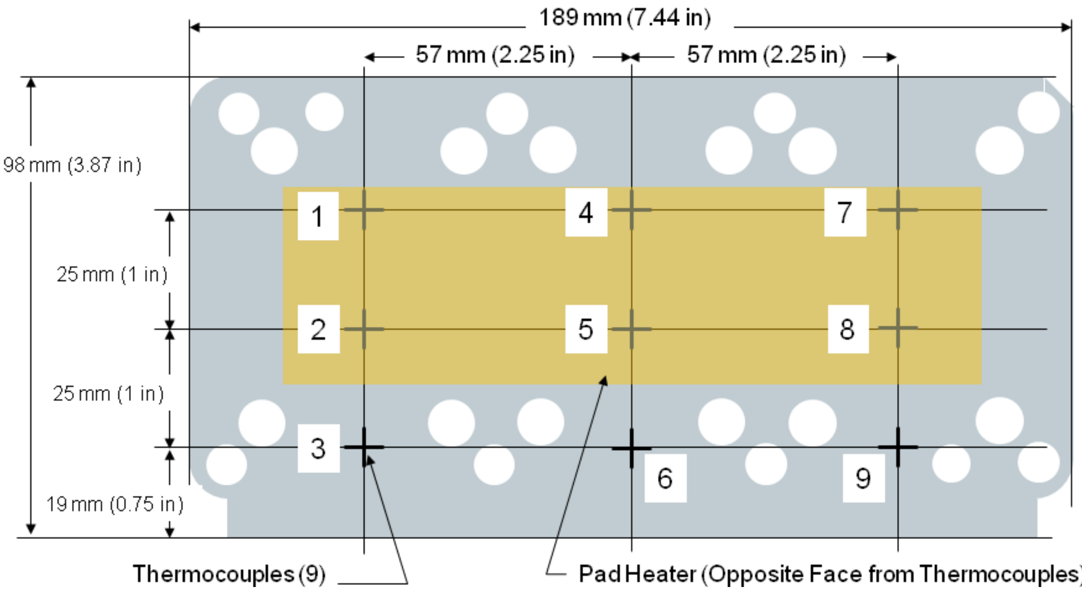

Figure 7.—Fuel cell cooling plate showing location of the pad heater and thermocouples.

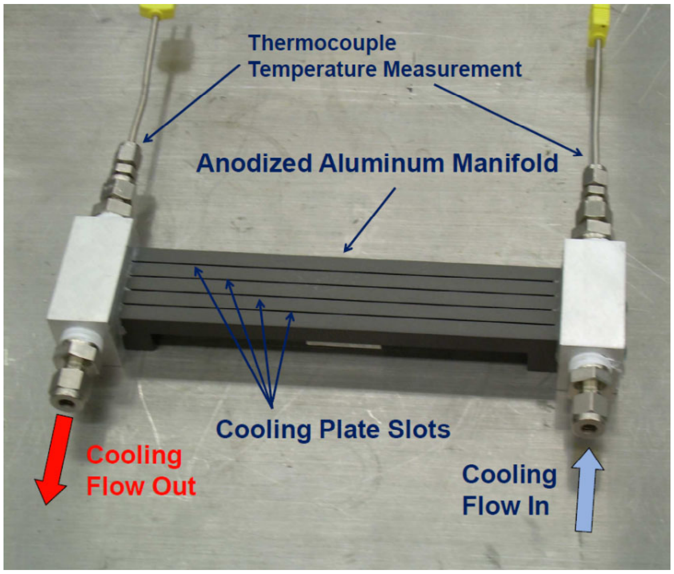

Figure 8.—Fabricated anodized aluminum heat exchanger.

3.2 Electronically-Controlled Proportional Valve

One of the passive thermal management control methods tested used an electronically-controlled valve to control the coolant flow through the heat exchanger which controlled the fuel cell temperature. The valve, produced by Kelly Pneumatics, Inc. (KPI) (Ref. 7), was a two-way proportional valve. The flow through the valve was roughly proportional to the electronic control signal used to control the valve. The valve actually consisted of two KPI proportional valves manifolded in parallel such that the flow through the two-valve assembly was twice the flow through a single valve. Figure 9 shows a table of valve characteristics and a drawing showing the valve assembly overall dimensions. Figure 10 shows a photograph of the valve assembly.

Valve Type	2-Way, Proportional
Electrical Connection	Wire Leads
Working Pressure	25 psig
Flow Range	0-1000 ml/min of water
Orifice Size	0.060 inches
Ports	#10-32 Manifold Mount, ¼ in Female NPT Ports
Seal Material	Viton
Operating Temp.	0-150 °F
Voltage Range	0-10 VDC
Power Usage	4.6 watts max
Maximum Hysteresis	8-10 % of full current
Response Time	10 - 15 ms

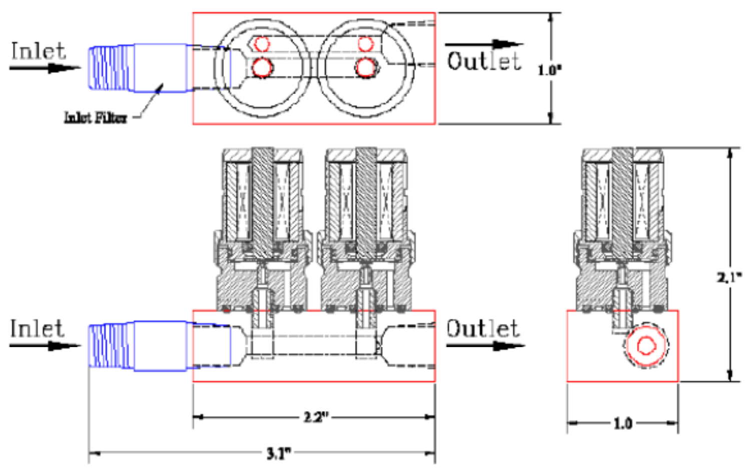

Figure 9.—Proportional valve assembly characteristics and overall dimensions.

Figure 10.—KPI Two-way proportional valve.

3.3 Thermostatic Control Valve

The other approach for passive thermal management control used a thermostatic valve whose actuator expanded or contracted in response to the temperature of the coolant flowing through the valve, and the variation in the flow controlled the fuel cell stack temperature. The valve was a modification from a valve purchased from Rostra Vernatherm (Ref. 8). The valve purchased from Rostra Vernatherm exhibited too high of a bypass flow which prevented the temperature of the cooling plates from reaching the desired temperature. Only the valve piston, spring, and end fittings from the purchased valve were retained. The valve housing and valve itself were custom made by NASA to reduce the bypass flow. The valve was 5.74 cm in length, with a 5.0 cm flange diameter.

The valve actuator is a wax filled piston that expands as the wax melts and contracts as the wax resolidifies. The expansion of the piston moves a sliding valve element away from the valve seat allowing coolant flow through the valve. As the temperature of the coolant increases the valve responds by allowing more coolant flow through the valve which mitigates further rise in the coolant temperature. The simplicity and reliability of this type of actuator is an appealing characteristic, and if the control of the fuel cell stack temperature is adequate, then it would be preferable to use over more sophisticated control methods. Cutaway illustrations of the thermostatic valve are shown in Figure 11, and a photograph of the fabricated valve is shown in Figure 12.

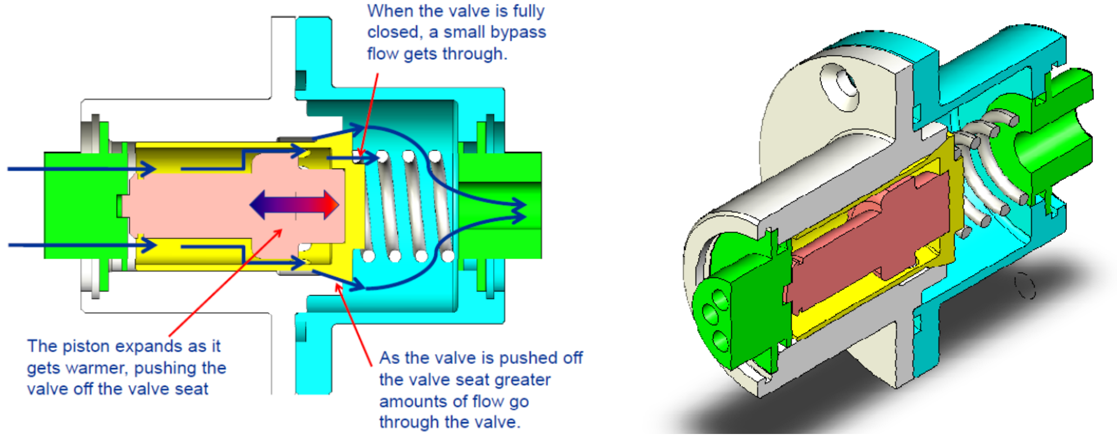

Figure 11.—Thermostatic valve cutaway view showing internal parts.

Figure 12.—Thermostatic valve.

3.4 Pyrolytic Graphite Cooling Plate Technology Demonstration Stack

In order to demonstrate the pyrolytic graphite cooling plate technology, a fuel cell demonstration stack was built. Teledyne Energy Systems, Inc. supplied the fuel cell hardware and NASA supplied the thermal management hardware. For cost reasons, the fuel cell design utilized a pre-existing Teledyne design that featured a fuel cell with an active area of 75 cm^2. NASA designed the thermal management hardware to mate with this existing fuel cell hardware. The thermal management hardware consisted of the pyrolytic graphite cooling plates, a cooling plate interface plate, an interface heat exchanger and associated brackets. An exploded illustrated view of the fuel cell stack and cooling plate interface plate is shown in Figure 13. An illustration of the fully assembled stack and thermal management hardware is shown in Figure 14, and an end view of the stack is shown in Figure 15. The cooling plate interface plate contained the slots into which the cooling plates were inserted. The interface plate was made from a thermally conductive plastic from Cool Polymers (Ref. 9). The plastic, in this case, provides the necessary electrical insulation between the cooling plates to keep the cooling plates from electrically shorting to one another. The plastic plate was epoxied onto an aluminum rectangular channel that the cooling flow passed

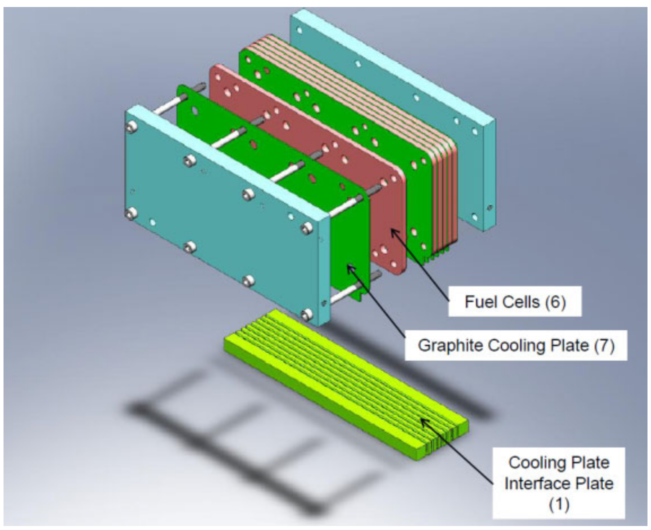

Figure 13.—Exploded view of pyrolytic graphite cooling plate technology demonstration stack.

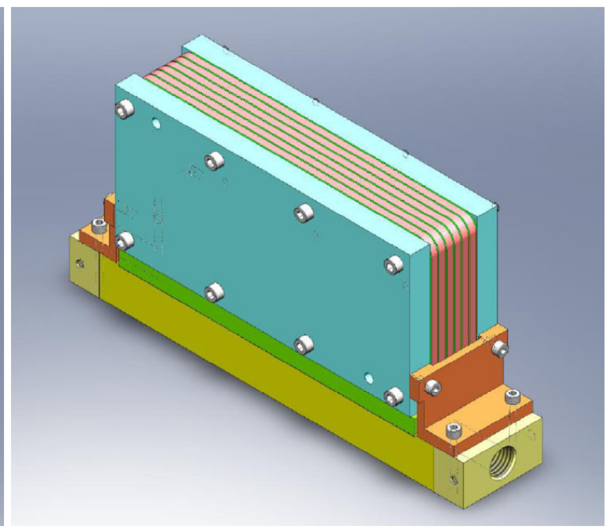

Figure 14.—Assembled view of pyrolytic graphite cooling plate demonstration stack.

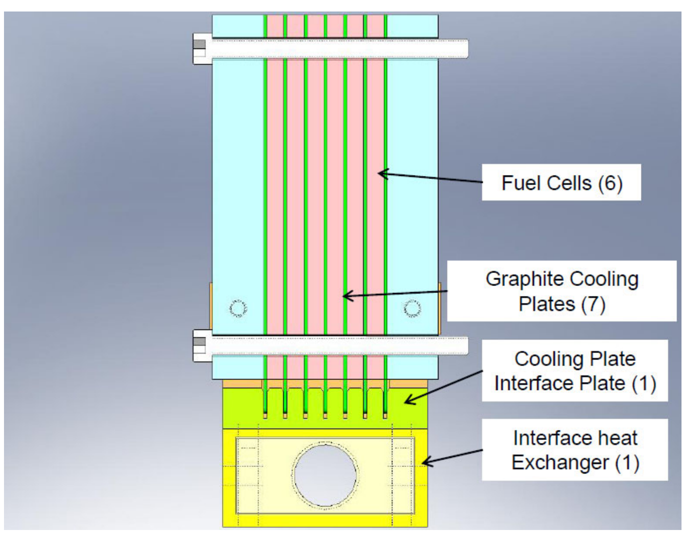

Figure 15.—End view of pyrolytic graphite cooling plate technology demonstration stack.

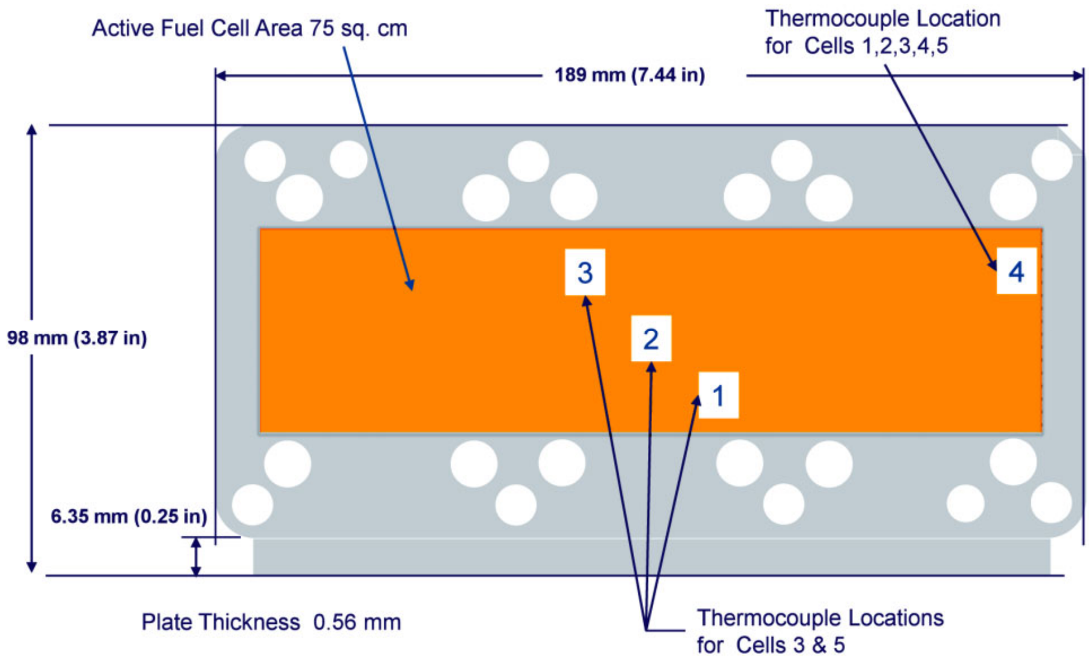

Figure 16.—Cooling plate geometry and thermocouple locations on fuel cells in demonstration stack.

through. The demonstration stack was originally intended to be a six cell stack, but the fabrication and assembly of the stack revealed a problem with one of the cells, so the number of cells in the stack was reduced to five cells.

There were six cooling plates along with five fuel cells in the demonstration stack with a cooling plate on either side of each cell in the stack. The cooling plates were inserted into the cooling plate interface plate to approximately 6.4 mm depth. A silver-filled grease was used to fill the clearance between the cooling plates and the walls of the slots into which cooling plates were inserted. Figure 16 shows the geometry of the cooling plates. Each of the cells was instrumented with thermocouples to measure the temperature distribution throughout the stack. Figure 16 shows the location of the thermocouples on each cell in the fuel cell stack.

3.5 Titanium Planar Heat Pipe Cooling Plate Technology Demonstration Stack

As a demonstration of the titanium planar heat pipe cooling plate technology, a fuel cell demonstration stack was built utilizing Infinity Fuel Cells and Hydrogen, LLC supplied fuel cell hardware and NASA supplied the thermal management hardware. The fuel cell stack design used four cells. Each cell had a cooling plate on either side, for a total of five cooling plates. Each fuel cell had an active area of 50 cm^2. Portions of the fuel cell stack's stainless steel bipolar plates required machining to create a pocket for the cooling plate. Also a thin rubber pad was added to one face of the cooling plate. The rubber pad pushed the cooling plate against the adjoining fuel cell bipolar plate for good thermal conduction. The rubber pad also made up for the slight non-uniform thickness of the cooling plate. NASA designed the thermal management hardware to mate with this fuel cell hardware. The thermal management hardware consisted of the cooling plates, cooling plate interface plates, an interface heat exchanger and other associated hardware. Thermacore International, Inc. designed and fabricated the cooling plates. A photograph of the fuel cell stack is shown in Figure 17. On the left side of the fuel cell stack, as shown in the photograph, the edges of the cooling plates can be seen protruding out the side of the stack. An illustration of the fully assembled stack and thermal management hardware is shown in Figure 18, and an exploded view of the stack and associated thermal hardware is shown in Figure 19. The cooling plate interface plates contained the slots into which the cooling plates were inserted. The interface plates were made from aluminum, anodized on the surface to provide the necessary electrical insulation between the cooling plates to keep the cooling plates from electrically shorting to one another. A flat plate heat exchanger with an internal serpentine cooling channel was designed and fabricated. The heat exchanger was attached to each cooling plate.

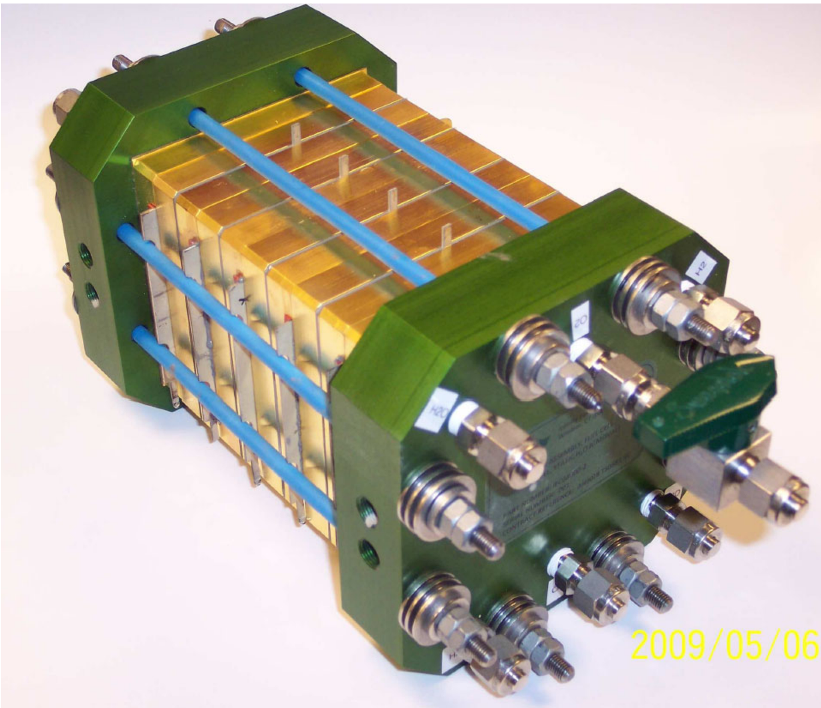

Figure 17.—Titanium planar heat pipe cooling plate demonstration fuel cell stack.

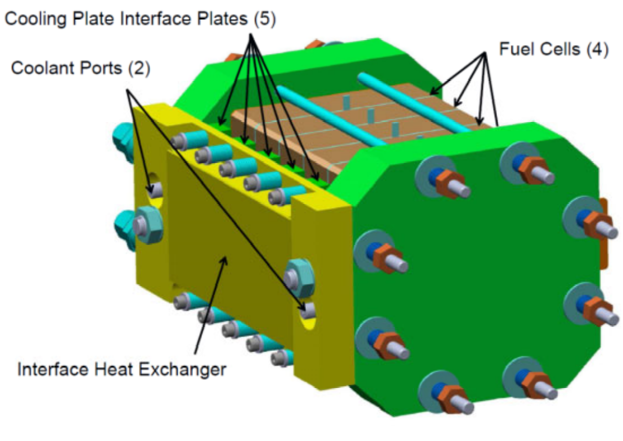

Figure 18.—Assembled demonstration hardware.

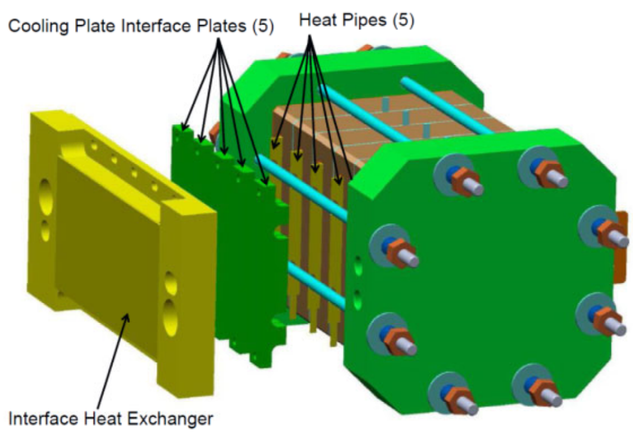

Figure 19.—Separated view of demonstration hardware.

One of the planar heat pipes used in the demonstration is shown in Figure 20. The heat pipes were made from titanium, but were plated with platinum on the exterior to reduce the electrical contact resistance between the cooling plate and the fuel cell bipolar plate. The heat pipe working fluid within the cooling plates was water. The pressure inside the heat pipe was sub-atmospheric so that the water inside the heat pipe started to vaporize well below its normal 100 °C boiling point. The cooling plates were designed to absorb the heat produced on the 50 cm^2 active area of the fuel cells. The evaporator section of the cooling plate measured 6.8 cm in length by 6.6 cm in width. The condenser section of the heat pipe was approximately 0.64 cm wide by 7.6 cm in length. Two semicircular notches provided clearance around the fuel cell stack tie rods. The slot in each cooling plate interface plate slipped over the edge of the cooling plate. The slot was designed for a slight interference fit over the condenser. A silver-filled thermal grease inside the slot was used to improve thermal conductance between the cooling plate and the cooling plate interface plate. The cooling plates were instrumented with thin surface mount thermo-couples to measure the temperature distribution throughout the fuel cell stack, and determine the effectiveness of the cooling plates in removing heat and providing a uniform heat sink for the fuel cells. Figure 21 shows the placement of the thermocouples on the cooling plates.

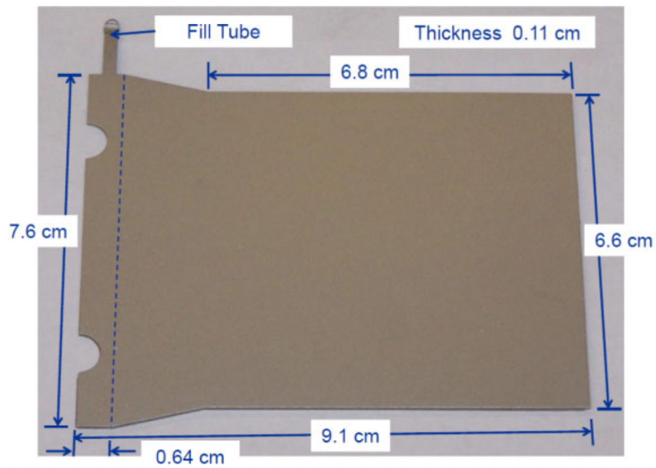

Figure 20.—Titanium planar heat pipe cooling plate.

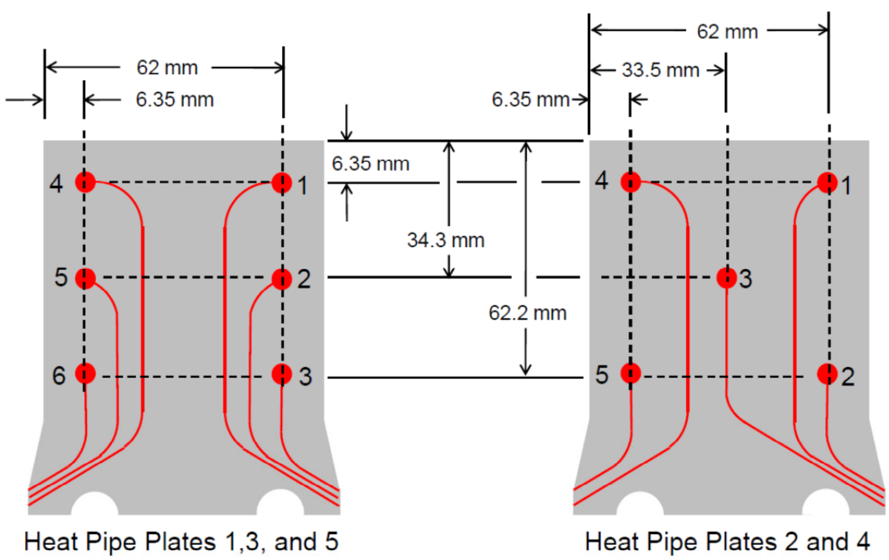

Figure 21.—Thermocouple locations on the titanium planar heat pipe cooling plates.

4.0 Fuel Cell Stack Test Facilities

The testing work described below was conducted at several different test facilities. The testing of the proportional valve and thermostatic thermal control valves was performed at the NASA Glenn Research Center in one of the vacuum tanks onsite. Previous testing of advanced cooling plate and heat exchanger technology for fuel cell cooling used this same vacuum facility. The testing of the cooling plate technology in the fuel cell demonstration stacks was performed by Teledyne Energy Systems, Inc. and by Infinity Fuel Cells and Hydrogen in their respective fuel cell testing laboratories. Teledyne tested the graphite cooling plate technology fuel cell demonstration stack and Infinity tested the heat pipe cooling plate technology fuel cell demonstration stack.

4.1 Fuel Cell Stack Test Facilities—Glenn Research Center

The simulated fuel cell stack was placed inside the vacuum test chamber shown in Figure 22. Figure 23 shows the interior of the chamber and the simulated fuel cell stack mounted in its test position. The tests were run at vacuum conditions (~1 millitorr) to minimize convective heat transfer between cooling plates and from the simulated fuel cell stack to ensure that heat conduction from the cooling plates to the heat exchanger was the predominant heat transfer mechanism. This approach simplified the analysis of the data. Radiative heat losses from the samples during the test were negligibly small in comparison to the heat being conducted through the plane of the cooling plate.

Coolant plumbing lines were run from the test article to a feed-through in the vacuum tank wall, and from there to a temperature controlled chiller bath located outside of the vacuum chamber. Power lines to the pad heaters on the cooling plates were run to a feed-through in the vacuum tank wall and from there to a DC power supply located outside of the vacuum chamber. Leads for thermocouples were similarly run to a feed-through and from there to a computer to record the temperature data. During the testing of the thermal control utilizing the proportional valve, the proportional valve was connected to the coolant line on the outside of the vacuum chamber because the electronics associated with the valve were not compatible with a vacuum environment. Figure 24 illustrates the overall test rig configuration during testing with the proportional valve. When testing with the thermostatic valve, it was essential, in order to minimize the response time, that the valve be in close proximity to the simulated fuel cell stack so that the heat absorbed by the coolant could go through the thermostatic valve before losing heat to plumbing lines, supporting brackets, and other potential heat sinks. For this reason the thermostatic valve was mounted inside the vacuum test chamber, immediately downstream of the simulated fuel cell stack. Figure 25 illustrates the overall test rig configuration during testing with the thermostatic valve.

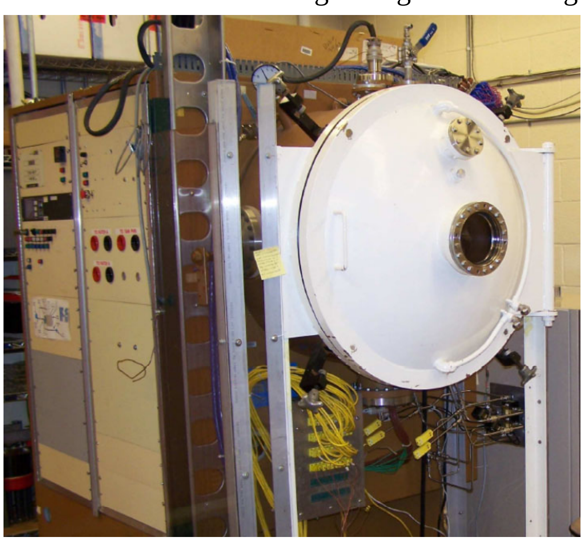

Figure 22.—Heat exchanger vacuum test chamber.

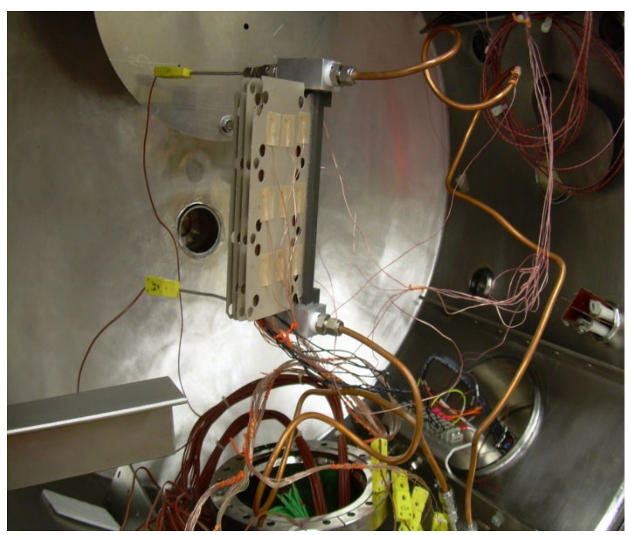

Figure 23.—Vacuum chamber interior with simulated fuel cell.

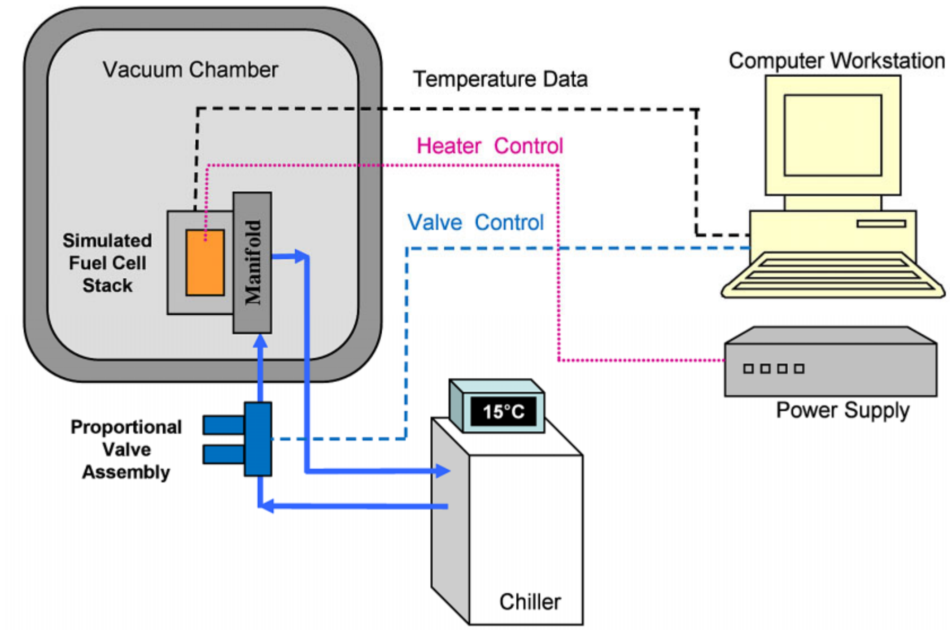

Figure 24.—Overall test rig configuration with proportional valve control.

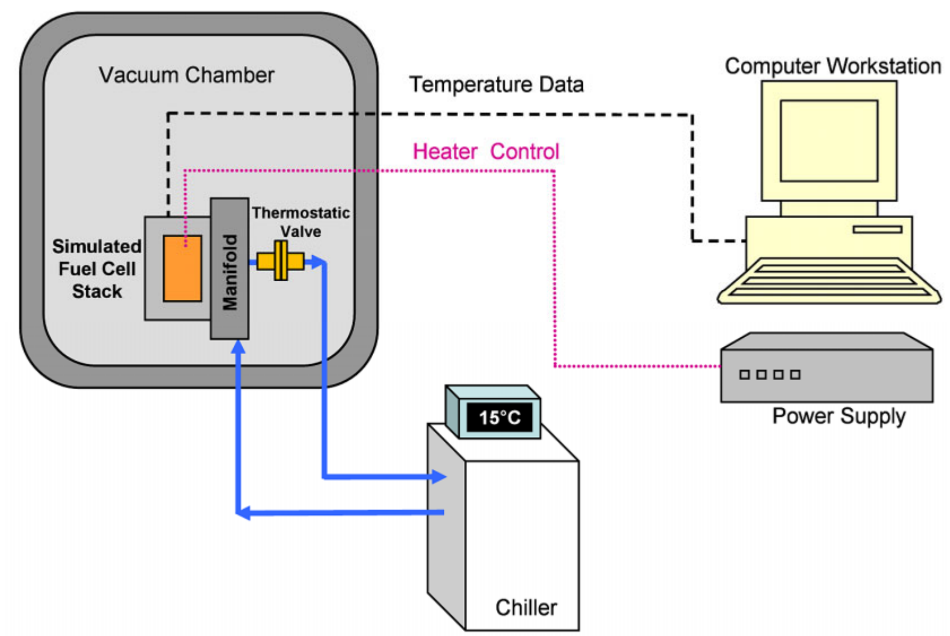

Figure 25.—Overall test rig configuration with thermostatic valve control.

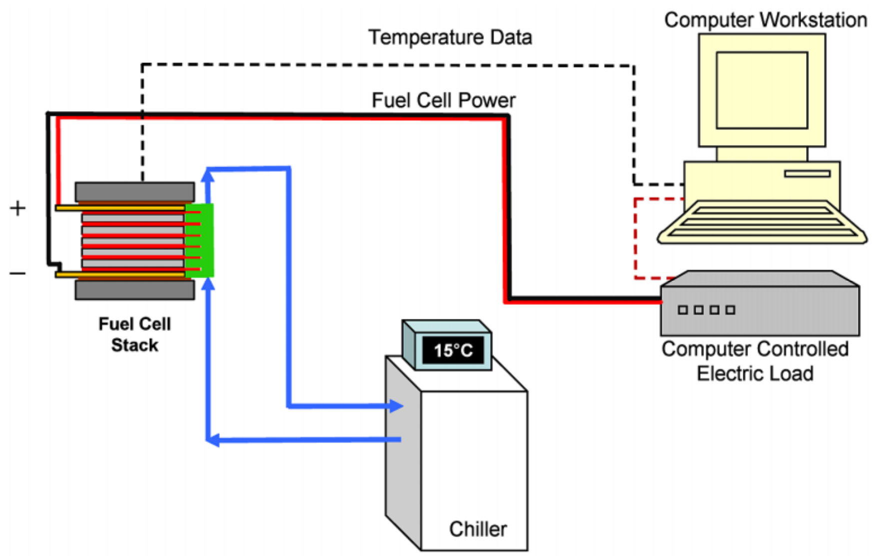

Figure 26.—Overall fuel cell stack demonstration test rig configuration.

4.2 Fuel Cell Stack Test Facilities—Teledyne Energy Systems and Infinity Fuel Cells

The operation of the thermal control system of the two passive thermal management systems was very similar. The fuel cell stacks were operated in a room-temperature laboratory environment. The coolant flow through the heat exchanger attached to the fuel cell stack was deliberately kept very high so that the coolant increased very little in temperature as it went through the heat exchanger. This kept the heat exchanger essentially isothermal. The temperature of the heat exchanger was adjusted manually using the controls on the heat exchanger. At the start of the test when the fuel cell stack was cold, the temperature of the coolant was kept high, and heat actually was transferred into the fuel cell stack to assist in warming the stacks up. During the testing when the waste heat from the fuel cell was not sufficient to maintain the fuel cell stack temperature, the coolant was used to provide additional heat. At some point during each test the stack temperature started to exceed the desired control value because of the waste heat produced by the fuel cell stack. At this point the temperature of the coolant was manually lowered, which was sufficient to keep the fuel cell stack at the desired temperature. Figure 26 illustrates the overall test configuration of the fuel cell stack demonstrations.

5.0 Fuel Cell Stack Test Results

5.1 Control of Passive Thermal Management Process Results—NASA Glenn Research Center

Tests were done to examine the effectiveness of using two different flow control valves to control the flow of coolant through the heat exchanger which in turn would control the temperature of the fuel cell stack to which the heat exchanger was attached.

5.2 Electronically-Controlled Proportional Valve

The first type of flow control valve examined was an electronically controlled proportional flow control valve. The valve was installed upstream of the heat exchanger as previously described. Valve control software was written in LabView which was run on a desktop computer. The software implemented a commonly used Proportional, Integral, Derivative (PID) control loop technique.

Two types of tests were run. The first type of test was to apply a constant power level to each plate and use the proportional valve and its control to adjust and control the temperature of the plates. The control feedback signal used for these tests was the average of all the temperatures measured on Plate B (Fig. 5). The thermal performance of plates A, C, and D was very similar to Plate B and any of the other plates could have been used instead. The uniformity of temperatures on each of the plates was also very good, so a single temperature signal from Plate B, rather than an average could also have been used. Figures 27 to 31 show the results of that testing.

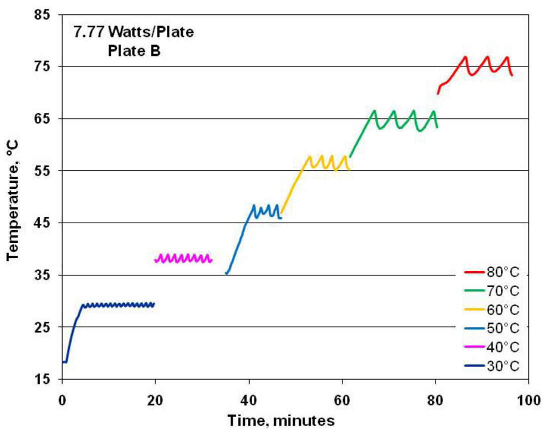

Figure 27.—Thermal control performance at 7.7 W/plate.

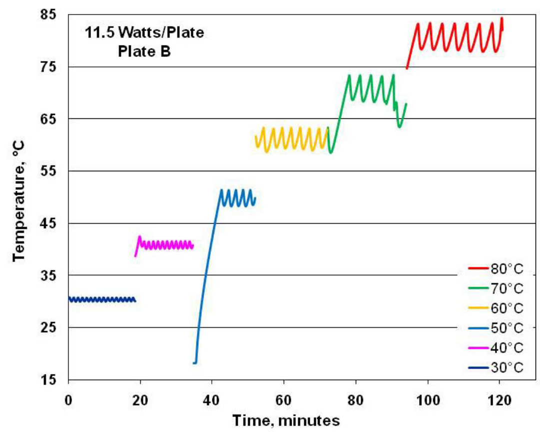

Figure 28.—Thermal control performance at 11.5 W/plate.

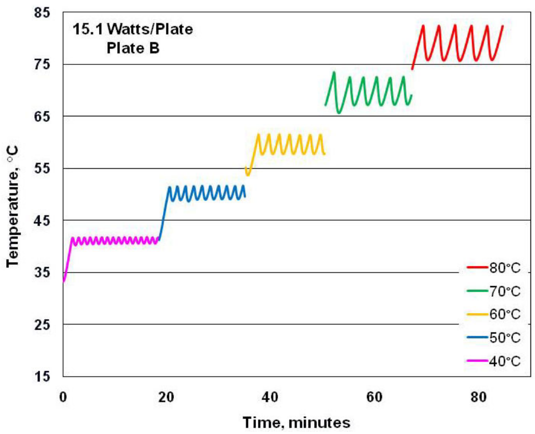

Figure 29.—Thermal control performance at 15.1 W/plate.

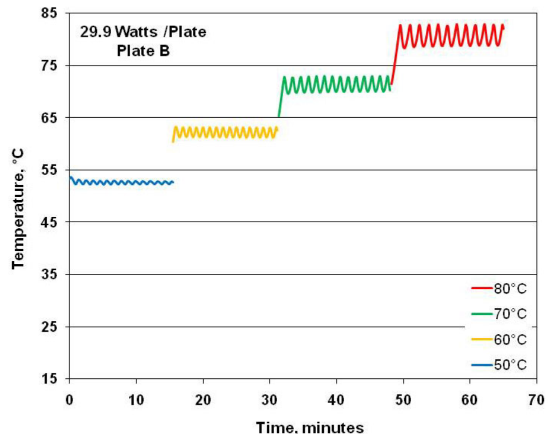

Figure 30.—Thermal control performance at 29.9 W/plate.

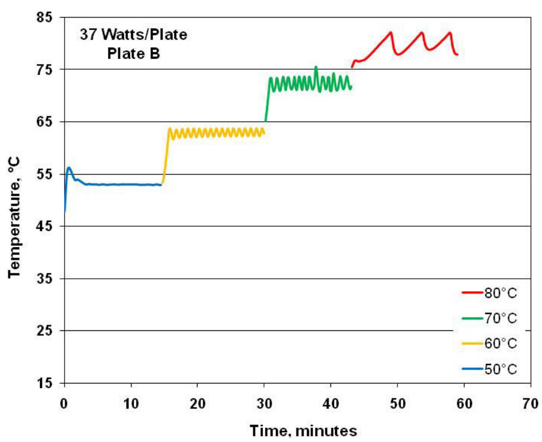

Figure 31.—Thermal control performance at 37 W/plate.

The proportional control maintained the plate temperature within a small temperature band at all power levels tested. At most, the observed temperature oscillated a few degrees above or below a nominal temperature at or near the setpoint. The nominal temperature in some cases was a few degrees below the entered setpoint. The reason for this was not found or corrected, but it was felt that its presence did not negate the conclusion of this approach's effectiveness of thermal control. Given the time, this could have been corrected.

The next test with the proportional valve thermal control was to fix the setpoint and vary the power level and duration at a given power according to a defined power profile that represented a simulated mission. This type of test was designed to more realistically mimic the operating conditions within the fuel cell to more accurately evaluate the operation of the fuel cell thermal control system. Figures 32 to 35 show the results where the same power profile was run, but the control setpoint was changed. For each of these tests the plate temperature quickly rose to the control level and then oscillated within a few degrees of that temperature despite the power level variation. The only instance where this was not the case was when the power level dropped instantly from approximately 23 W per plate to about 3 W per plate. In this instance the plate temperature dropped 10° to 15° before it stabilized and started to rise back to the setpoint. A real fuel cell stack would have much greater mass than the collection of cooling plates that represented our simulated fuel cell. The relatively low mass of the simulated fuel cell stack made this system respond very fast to power changes, much more so than an actual stack whose thermal mass would slow down any temperature change. The thermal control system did well controlling this fast acting system, and it is expected that it would provide better control with an actual fuel cell stack.

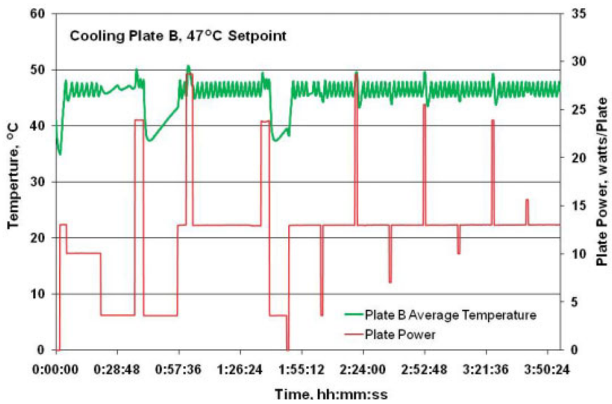

Figure 32.—Thermal control performance at 47 °C.

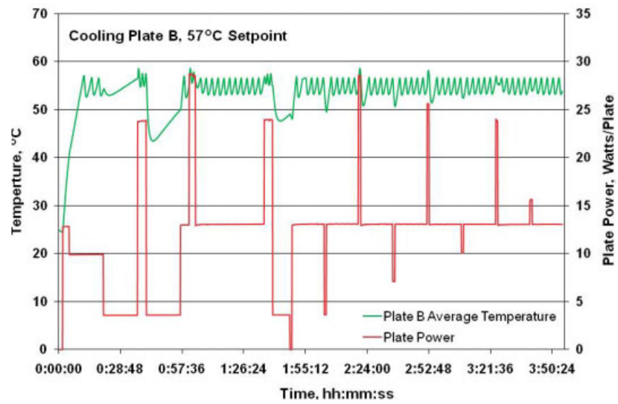

Figure 33.—Thermal control performance at 57 °C.

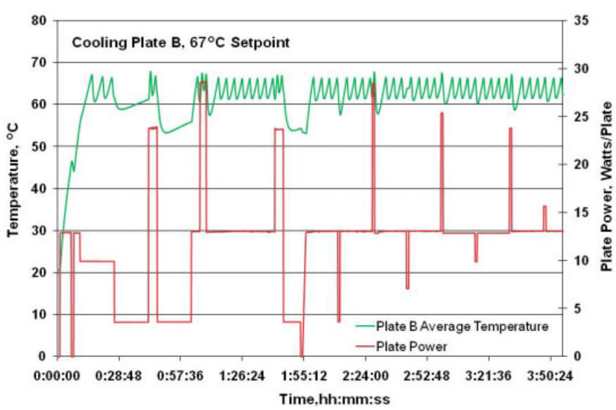

Figure 34.—Thermal control performance at 67 °C.

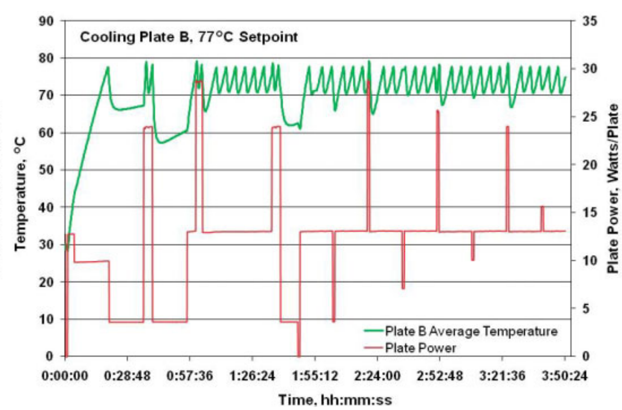

Figure 35.—Thermal control performance at 77 °C.

5.3 Thermostatic Control Valve

The second type of flow control valve examined was the thermostatic valve described previously. While this type of flow control is much simpler than the proportional valve control approach, it is less flexible. Greater heat removal from the plates requires either greater heat put into the same flow rate of coolant (which increases the temperature of the coolant) or an increase in the flow of the coolant, or both. The thermostatic valve increases the flow as a result of an increase in coolant temperature so in response to an increase in the heat, both the coolant temperature and the coolant flow rate increase. The thermostatic valve, in response to higher heat loads, only mitigates the rise in plate temperature by increasing the coolant flow.

The first test of the thermostatic approach was to vary the heat load and observe the resultant increase in plate temperature, coolant flow rate, and the time required to establish the new equilibrium. The commercial thermostatic valve purchased had a very high bypass flow through the valve. The valve requires some bypass flow so that the heat absorbed by the coolant can effectively reach the valve's interior. The high bypass flow of the as-purchased valve posed a problem because the power levels of the tests could not raise the temperature of the coolant high enough to have the valve respond. The valve's design was modified to reduce the bypass flow to 10 cc/min initially. Later the design was modified a second time to reduce the bypass flow to 5 cc/min. These lower bypass flows allowed the coolant to become warm enough to get the valve to respond. Figures 36 to 39 show the data from the tests run.

Figures 36 and 37 were run with the valve modified to make the bypass flow 10 cc/min. Figure 36 shows that as the power level was increased stepwise, the temperature of each plate likewise increased in discrete steps. Note that the plate temperatures of plates A and D were lowest. It is believed this occurred because plates A and D are on the outside of the stack, and therefore only have one other plate next to them, whereas plates B and C have plates on either side of them. Figure 37 shows the change in the coolant flow and outlet coolant temperature during the same test. Figure 37 shows the coolant flow and outlet temperature responding in a somewhat well defined staircase. The coolant flow rate in particular shows a high frequency oscillation. This is because when the valve opens quickly the in-rush of coolant cools the wax piston causing it to contract quickly which causes a quick rise in the coolant temperature. Large changes in flow from small changes in coolant outlet temperature makes for a fast responding valve, but one prone to oscillatory instability.

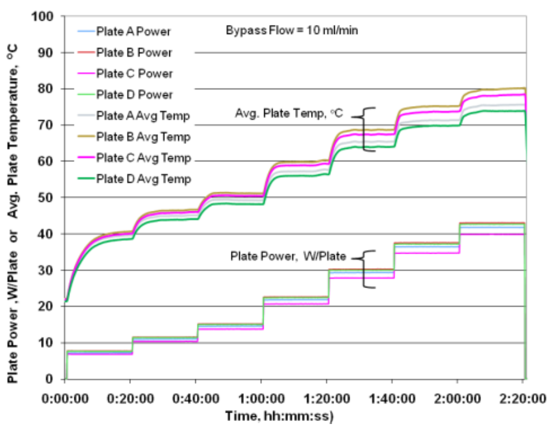

Figure 36.—Thermostatic valve performance, plate temperatures.

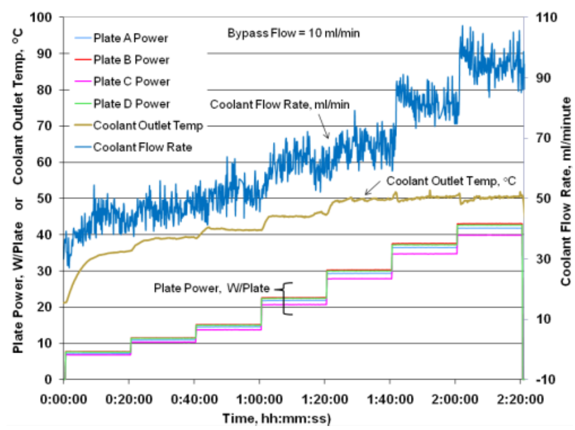

Figure 37.—Thermostatic valve performance, coolant flow and temperatures.

A similar test was run after the valve was modified to reduce the bypass flow from 10 to 5 cc/min. Figures 38 and 39 show the results from this test. Similar to the results shown in Figure 36, the results shown in Figure 38 have the same stepwise increase in power level and a stepwise response in plate temperature. Note the faster response of the plate temperature at the lowest power levels and the higher steady-state temperatures associated with the power levels. This higher steady-state temperature is most prominent at the lowest power levels where the effect of the magnitude of the bypass flow is a greater percentage of the overall flow through the valve. Figure 39 shows the coolant flow and outlet temperature during this same test. Note the more rapid rise in coolant temperature compared to the data in Figure 37. Also note that at 30 W and above the valve flow oscillates over a much wider range of flow rates, essentially becoming an ON-OFF flow controller. Despite the wide flow variations, the plate temperatues showed very little variation.

The other test performed with the thermostatic valve control was the power profile test test, where the power profile was identical to the 4 hr power profile test completed with the proportional valve control. This permitted a direct comparison of the two different control methods. Figures 40 and 41 show the results from the power profile test conducted with the thermostatic valve with the 10 ccc/min bypass flow. Figure 40 shows the average temperature of plate B during the test. Like the power profile test conducted with the proportional valve, the largest variation in plate temperature during the thermostatic valve test occurs when the power level drops from 23 to 3 W. In addition to these instances, the temperature spiked during the large increases in power level. In general, the control observed with the thermostatic valve was not as good as with the proportional valve.

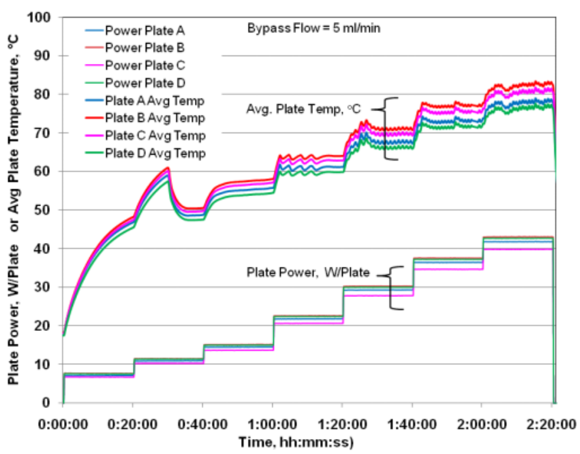

Figure 38.—Thermostatic valve performance, 5 cc/min bypass, plate temperatures.

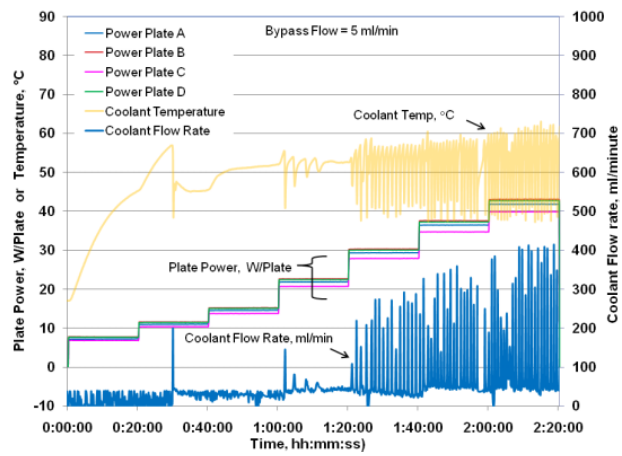

Figure 39.—Thermostatic valve performance, 5 cc/min bypass, coolant flow and temperature.

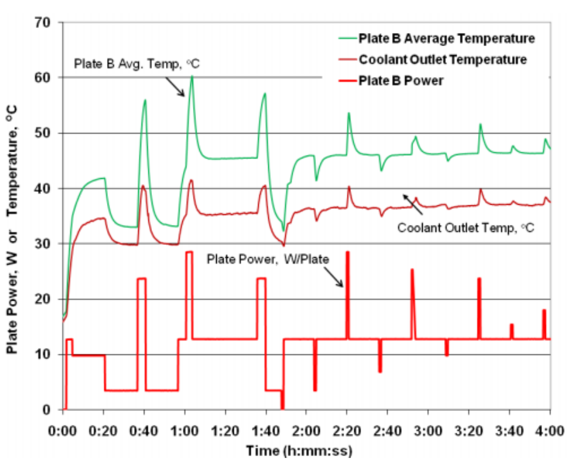

Figure 40.—Thermostatic valve performance, average plate temperature during power profile test.

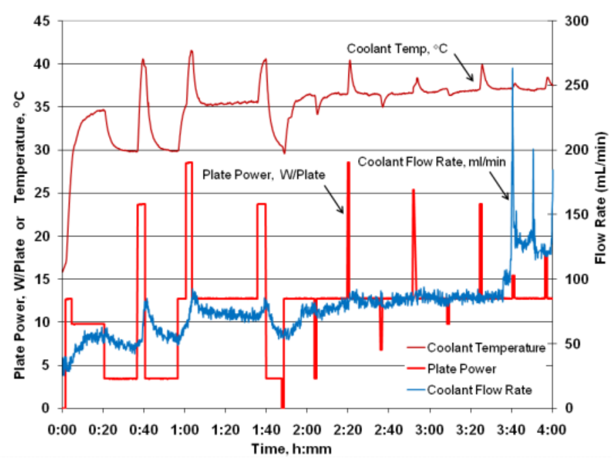

Figure 41.—Thermostatic valve performance, coolant flow during power profile test.

5.4 Pyrolytic Graphite Cooling Plate Technology Demonstration Results—Teledyne Energy Systems

The objective of this demonstration testing was to provide direct evidence with an operational fuel cell stack of the ability of the pyrolytic graphite cooling plates to remove the heat generated in the fuel cell stack, and also to provide a uniform thermal enviroment for the fuel cell chemical reaction. Figures 42 and 43 show the results of the demonstration test. Figure 42 shows that at the start of the test the cooling plates actually moved heat into the stack, allowing the cells of the stack to heat up uniformly. As the power was increased during the test, the cell temperatures reach their desired setting. As the power is increased further, the coolant temperature is reduced to maintain the cell temperatures at the desired level. The difference between the highest temperature reading and the lowest temperature reading of the eleven thermocouples in the stack never exceeded 3 °C. This is excellent uniformity throughout the stack. Figure 43 shows the voltage performance of the five cells in the stack. The average cell voltage dropped as the current was increased but remained steady after the current was left unchanged.

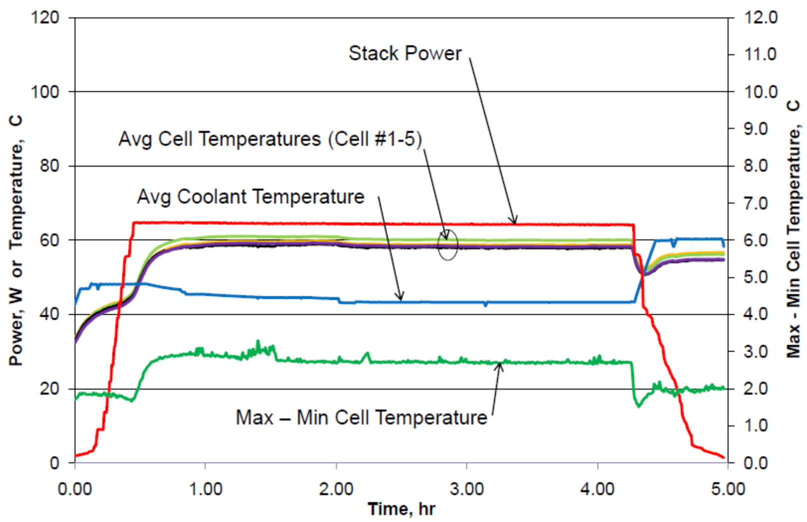

Figure 42.—Pyrolytic graphite cooling plate performance.

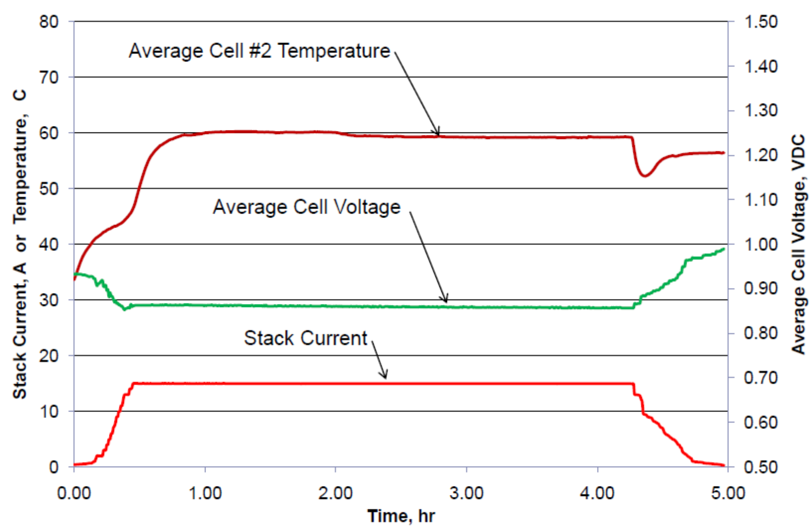

Figure 43.—Pyrolytic graphite cooling plate demonstration stack performance.

5.5 Titanium Planar Heat Pipe Cooling Plate Technology Demonstration Results—Infinity Fuel Cells

The objective of this demonstration testing was to provide direct evidence with an operational fuel cell stack of the ability of the titanium heat pipe cooling plates to remove the heat generated in the fuel cell stack, and to provide a uniform thermal enviroment for the fuel cell chemical reaction. Figures 44 to 47 show the results of the demonstration test. Figure 44 shows that at the start of the test the cooling plates moved heat into the stack, allowing the cells of the stack to heat up uniformly. As the power was increased during the test, the cell temperatures reach their desired setting. As the power was increased further, the coolant temperature was reduced to maintain the cell temperatures at the desired level. The coolant inlet and outlet temperatures were nearly identical because the flow rate of coolant through the fuel cell stack was very high. The difference in cooling plate temperatures was about 10 °C. The temperature of heat pipes 1 and 5 were lower than heat pipes 2, 3, and 4. This is probably because heat pipes 1 and 5 were on the outside cells with only one other cell next to them. Heat pipes 2, 3, and 4 had cells on either side. The temperature of heat pipes 2, 3, and 4 were within 3 °C of each other. This is excellent uniformity throughout the stack. Figure 45 shows the voltage performance of the four cells in the stack. The cell voltages dropped initially as the current was increased but remained steady between 0.6 and 0.7 VDC after the current was left unchanged.

Figures 46 and 47 show the distribution of temperatures on heat pipes 3 and 5. These results show a high degree of thermal uniformity on a given heat pipe. The uniformity generally got better after the cells reached their nominal operating temperature.

5.6 Future Fuel Cell System Using Passive Thermal Management Technology

Figure 48 shows a concept of an advanced NASA fuel cell system. This fuel cell system incorporates several passive operational technologies, including the passive thermal technology. Figure 48 shows the passive cooling plates and the heat exchanger. The thermal control valve is not shown in the illustration. The elimination of components that use significant amounts of power (such as the cooling pump) helps to increase the overall net power and efficiency of the fuel cell system.

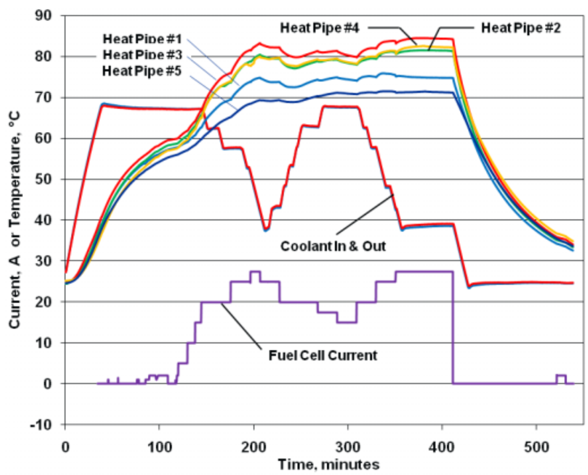

Figure 44.—Heat pipe cooling plate performance.

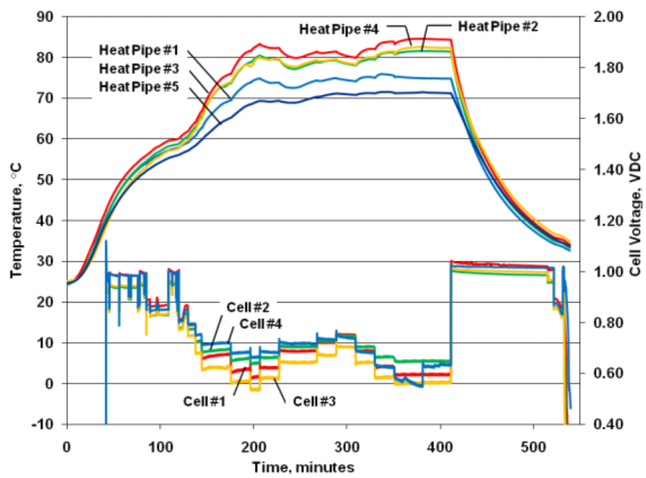

Figure 45.—Heat pipe cooling plate stack performance.

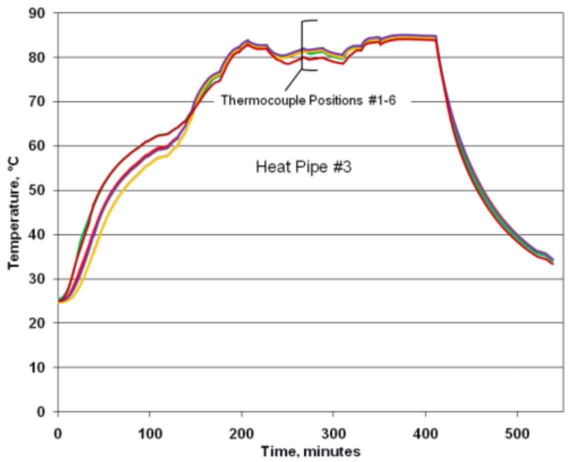

Figure 46.— Heat pipe cooling plate #3 temperature uniformity.

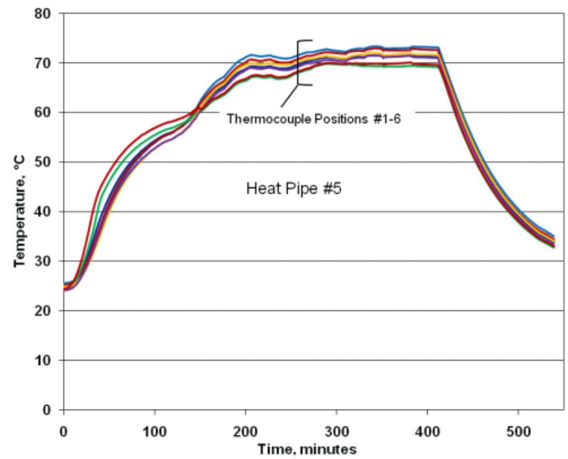

Figure 47.—Heat pipe cooling plate #5 temperature uniformity.

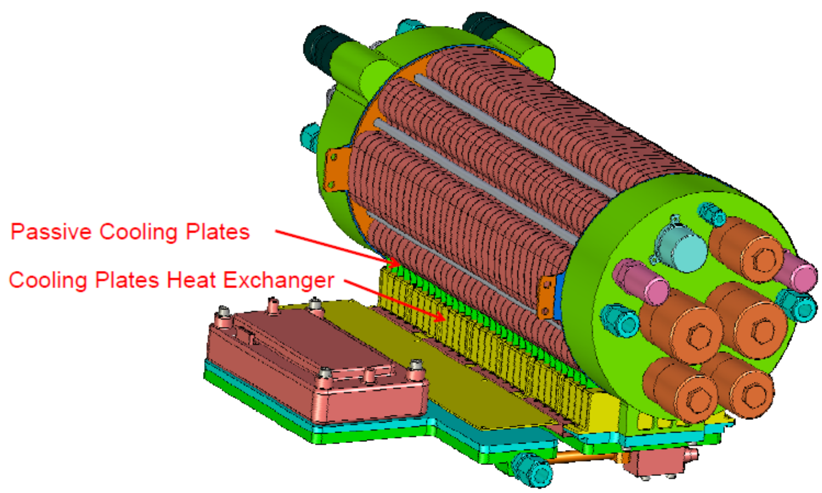

Figure 48.—Flight fuel cell system with passive thermal technology.

6.0 Conclusions

The results demonstrate that passive thermal control of fuel cell stacks is feasible, and that passive removal of heat is controllable and provides the highly uniform thermal environment desired for fuel cell operation. This revolutionary thermal control approach reduces the components and parasitic power compared to the traditional pumped loop thermal control approach.

The two different types of controls used for altering the coolant flow to control the stack temperature proved to be effective. The proportional valve approach is very flexible. It permits the temperature control setpoint to be adjusted independent of the power produced by the fuel cell stack. It provides very responsive control and is capable of maintaining the fuel cell stack temperature within a small control band. The mass of the valve is very small relative to the balance of the fuel cell system, and its power requirements are also quite small. In general, this approach provides excellent thermal control. The thermostatic valve is an extremely simple approach since it requires no electrical power, no feedback sensors, no software, and no computer to make it operate. This simplicity comes at the price of reduced flexibility. Using the thermostatic valve the power level and the operating temperature of the fuel cell stack rise or fall together, but the thermostatic valve mitigates how much the temperature rises as the power increases. Properly optimized for the fuel cell stack, it could provide an acceptable level of thermal control.

Both the pyrolytic graphite and titanium heat pipe cooling plate technologies were tested for their thermal conductivity and showed that their use in fuel cell stacks is feasible. The performance of both these technologies in fuel cell stacks is unequivocal proof of the feasibility of either style cooling plate. Both technologies can be adapted for integration in fuel cell stacks and both produce uniform thermal environments for fuel cell operation, both cell-to-cell and within any one cell.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NASA Glenn Research Center is developing advanced passive thermal management technology to reduce the mass and improve the reliability of space fuel cell systems for the NASA Exploration program. The passive thermal management system relies on heat conduction within highly thermally conductive cooling plates to move the heat from the central portion of the cell stack out to the edges of the fuel cell stack. Using the passive approach eliminates the need for a coolant pump and other cooling loop components within the fuel cell system which reduces mass and improves overall system reliability. Previous development demonstrated the performance of suitable highly thermally conductive cooling plates and integrated heat exchanger technology to collect the heat from the cooling plates (Ref. 1). The next step in the development of this passive thermal approach was the demonstration of the control of the heat removal process and the demonstration of the passive thermal control technology in actual fuel cell stacks. Tests were run with a simulated fuel cell stack passive thermal management system outfitted with passive cooling plates, an integrated heat exchanger and two types of cooling flow control valves. The tests were run to demonstrate the controllability of the passive thermal control approach. Finally, successful demonstrations of passive thermal control technology were conducted with fuel cell stacks from two fuel cell stack vendors.

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