Development of a Sheathed Miniature Aerothermal Reentry Thermocouple for Thermal Protection System Materials

Edward R. Martinez [*] and Carissa Tudryn Weber [†]
NASA Ames Research Center, Moffett Field, CA, 94035, USA

Tomo Oishi[‡]
Jacobs Technology, Moffett Field, CA, 94035, USA

and

Jose Santos [§] and Joseph Mach [**]
Sierra Lobo, Moffett Field, CA, 94035, USA

The Sheathed Miniature Aerothermal Reentry Thermocouple is a micro-miniature thermocouple for high temperature measurement in extreme environments. It is available for use in Thermal Protection System materials for ground testing and flight. This paper discusses the heritage, and design of the instrument. Experimental and analytical methods used to verify its performance and limitations are described.

I. Nomenclature

ARC   =   NASA Ames Research Center
MMTCP =   Micro Miniature Thermocouple Probe
OD   =   Outer Diameter
PAET   =   Planetary Atmosphere Experiments Test vehicle
RTD   =   Resistance Temperature Detector
SHARP   =   Slender Hypervelocity Aero-thermodynamic Research Probes
SMART   =   Sheathed Miniature Aerothermal Reentry Thermocouple
TC   =   Thermocouple
TPS   =   Thermal Protection System

II. Introduction

THERMOCOUPLE (TC) electromagnetic motive force was discovered in 1821 by Thomas Seebeck. Because of their comprehensive development, TCs have been used extensively on spacecraft to explore our solar system. Thermocouples are also the preferred choice to measure temperature in Thermal Protection Systems (TPS) due to their many advantages: cost-effectiveness, ease-of-use, small-size, reliability, stability, and, wide temperature range. Atmospheric reentry spacecraft have successfully used thermocouples in heat shields ranging from the Planetary Atmosphere Experiments Test Vehicle (PAET), Apollo, Shuttle, Mars Viking landers, to the impending Mars Science Laboratory (MSL). [1,2]

For certain aerothermal reentry applications, a sheathed MicroMiniature Thermocouple Probe (MMTCP) with fine wire diameters, developed by Paul Beckman in the 1960s, has been flown on over thirty Department of Energy ballistic reentry vehicles, including the NASA experimental Slender Hypervelocity Aero-thermodynamic Research Probes (SHARP) B1 & B2. [3,4] These MMTCPs were also the preferred sensor on rocket engine nozzles in order to

---

[*] Senior Research Engineer, Thermophysics Facilities Branch, NASA ARC, M/S 229-4. Ed.Martinez@NASA.gov
[†] General Engineer, Mission Design Center, NASA ARC, B202 RM201.
[‡] Senior Engineer, Aerospace Testing Operations/Maintenance, NASA ARC, N229-4.
[§] Mechanical Engineer, Thermophysics Facilities Branch, NASA ARC, M/S 229-4, AIAA Member.
[**] Mechanical Engineer, Thermophysics Facilities Branch, NASA ARC, M/S 229-4.

measure extreme temperature transients. The MMTCPs had advantages over the traditional TC implementation, such as reduced volume, minimal intrusion, and faster response time, compared to commercially available thermocouples.[5-8] Additional benefits include functionality over a wide range of temperatures up to 2300 ºC, higher survivability in oxidized environments due to the protective sheath, excellent resistance to thermal and mechanical shock, and design as a cohesive modular probe. These fast response MMTCPs are no longer commercially available, but the unique technology and processes have been transferred to NASA Ames Research Center in order to maintain their availability.

A. Thermocouples for Thermal Protection Systems

Instrumenting TPS materials, especially for flight vehicles, assists in the validation and verification (V&V) of TPS sizing tools that integrate state-of-the-art computational fluid dynamics (CFD) with material response modeling. Currently, TPS sizing V&V is incomplete because ground testing cannot simultaneously match all critical aerothermodynamic parameters with flight conditions. Flight data has been indispensible for improving our understanding of aerothermal phenomena, and the response of the TPS materials to such environments. For example, Analog Resistance Ablation Detectors installed on the Galileo Probe heat shield revealed that the measured recession was dramatically greater than expected, and the final frustum thickness was dangerously thin[8]. Thermocouple data in the aft heat shield of the Mars Pathfinder vehicle demonstrated that the TPS mass margins were overly conservative, due to the conservative assumption of turbulent afterbody flow. This knowledge led to a decrease in the TPS margin for the next mission, Mars Exploration Rover.

Figure 1. TC installation in TPS and example plug design

Thermocouples are the traditional sensor of choice for in-situ measurements of temperature response for planetary atmospheric entry spacecraft and aeroshell reentry TPS. Resistance Temperature Detectors (RTD) have also been used for temperature measurement of the TPS substrate. [10] Generally, RTDs have better accuracy and higher sensor output than TCs. However, an RTD requires an excitation voltage or current for single output whereas TC output is self generating. The TC hot junction can be smaller in size than an RTD, providing a more discrete point of measurement.

Complexity of instrumenting TPS is caused by its widely transient physical properties experienced during aerothermal testing or atmospheric reentry. Typical TPS is thermally insulating. When instrumenting such material, a TC becomes intrusive to the surrounding thermal environment, which it attempts to measure. The much larger thermal mass of the TC, thermal conductance of the TC wires, and its components, can cause measurement error by acting as a heat sink to the surrounding environment. Those measurement errors are similar to those encountered in gas flow measurement. Proper placement of TC and miniaturization can minimize the error. Having a "land line", which is a section of TC perpendicular to the direction of heat flux, reduces the conduction error. This configuration makes TC shapes like upside down "L" or "U". Illustration of TC installation in TPS is shown in Figure 1. Single wire installation is the "U" shaped installation. A probe or paired insulated wire installation for TPS is typically "L" shaped to provide an isothermal environment for the TC hot junction. Proper land length dimension of thermocouples reduces the error due to conduction, but it does not remove the intrusiveness due to the thermal mass. Thermal mass can be reduced only by reducing the mass for a given sensor design. Miniaturization of the thermocouple mass is important when instrumenting TPS, however, miniaturization introduces fragility, and manufacturing challenges within practical limits.

Instrumenting TPS, especially for a large model or for a flight heatshield, means to fabricate a plug from the acreage TPS and then install instruments in the plug. The instrumented plug is then bonded into a mating counter bore in the heatshield. The use of plug-and-counter-bore technique is heritage heat shield "repair" process. When local anomalies, such as voids, are found in a heatshield, the section is repaired using the plug technique. The 3D model illustration of a typical TC plug is shown in Figure 1. This plug has single wire TCs at three different depths. Wires are routed at the bottom of the plug, and bundled into one for this design.
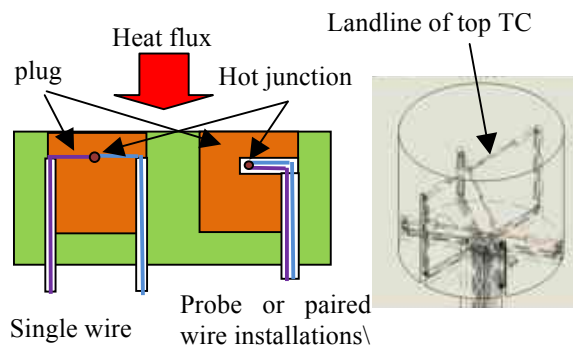
B. MMTCP and SMART

Paul Beckman developed the MMTCP to improve response time and minimize intrusiveness. Researchers used them for gas flow, rocket nozzle measurement, and for hypersonic flight tests. [8,14] MMTCPs were commercially available from the Paul Beckman Company until the 1980s when the company was downsized. After downsizing, they were still available in smaller quantities until 2010 when the company was dissolved. NASA Ames Research Center (ARC) acquired the details of the design and fabrication technologies through a NASA contract with the PBC. At ARC, MMTCP design and fabrication techniques are being modified for better performance and for easier fabrication. The probe was renamed to be the Sheathed Miniature Aerothermal Reentry Thermocouple (SMART) to distinguish its design improvements and manufacturing source from the original MMTCP.

III. MMTCP

MMTCP was a commercial product with many configurations. The basic design is common to the all configurations. [7] Different protection or shrouds can be placed over the basic probe for easy mounting, pressure tight applications, radiation shielding, or other application requirements. The basic probe can be made using different TC type wires (K, S, R, C) and probe materials (steel, tantalum), catering to different measurement ranges. The basic MMTCP design is illustrated in Figure 2. The probe is divided into four sections: probe tip, sheath, probe body, and lead wire. The TC hot junction is located at the probe tip and a different tip termination is available for mechanical, thermal, and electrical performance requirement considerations. For example, a closed sheath end provides good mechanical protection of the hot junction but it results in slower thermal response. Exposed junction termination has the fastest time response and least intrusiveness. The sheathed section is the metal tube protecting the double bored quartz insulated tube. One leg of the TC is fed through one of the quartz bores. This is where the majority of temperature difference between the hot and cold junctions exists during use. The probe body consists of ceramic components and epoxy overglaze. It houses the transition joint from TC fine wires to lead wires. A fine wire is wrapped around a lead wire between ceramic ferrules and welded or soldered for joining. The remaining gap between ceramic ferrules is filled with ceramic cement to encapsulate the transition joints, and solidify the body section into one structural piece. The lead wire section has larger TC wires with flexible insulation for easier handling and connector termination. Figure 3 shows the photo of MMTCP with a 90-degree bend in the sheathed section. This "L" shaped probe has the "landline" portion, and is suited for TPS application.

Figure 2. MMTCP Illustration. (Probe tip configuration illustrations copied from Ref. 7.)

Figure 3. Photo of MMTCP

The following are the typical dimensions for MMTCP components. The fine wire diameter is 20 μm. Double bored quartz insulator has a 100 μm OD. The metal sheath has a 200 μm OD. The probe body is 2.2 mm in OD and 10 mm in length. The length of the sheathed section is made specific to the application and ranges from 10 mm to 130 mm.

The MMTCP is manually assembled using tweezers under a microscope. Many assembly steps require artistic skills of a specially trained technician. Completed MMTCPs are tested to verify functionality. With functionality checks, polarity and output range are verified by heating the probe tip with a low temperature source. Moving the heat source at the bend, and close to the body, can identify a short between the TC wires.
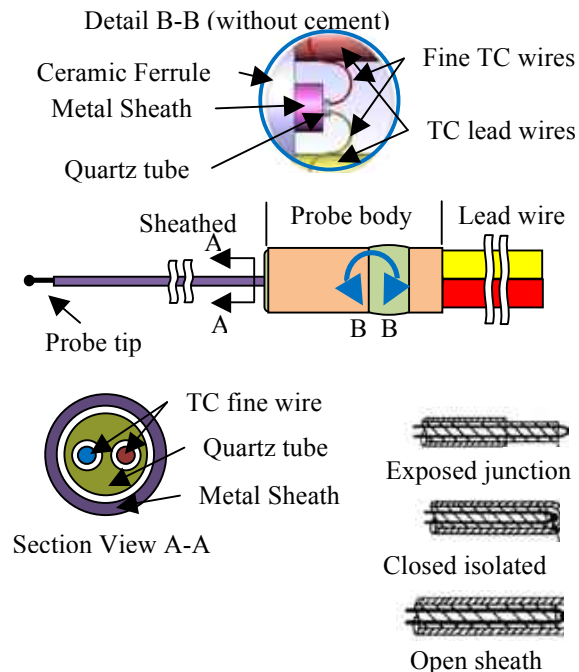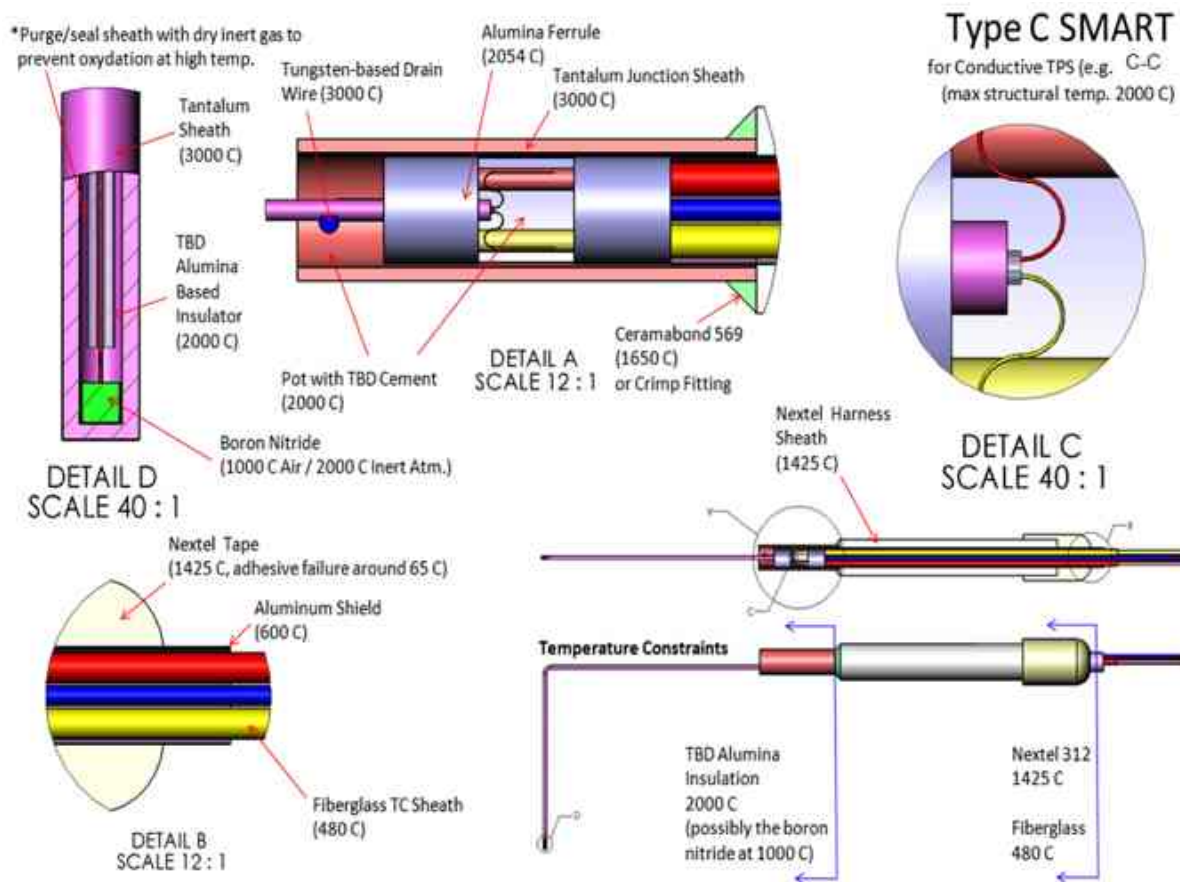
Figure 4. Illustration of SMART design

IV. SMART

The SMART was derived from the MMTCP, with the main design concept preserved. Figure 4 illustrates the SMART design. The changes were made for better probe performance, ease of fabrication, and improved quality control. Some of these changes are still under development.

The material of the component for the probe was changed to survive higher temperature. The SMART probe is purged with argon before being sealed to remove moisture and oxygen. The probe is entirely electrically shielded. The body section design was modified to minimize manufacturing time, and to provide a shielding shroud by accommodating the shielded lead wires.

Though not illustrated in Figure 4, other changes were made or are planned for SMART. Verification testing of samples will be performed for SMART. Junction fabrication and fine wire to lead wire joints will be changed to laser welding, where capacitance discharge arc welding was used for MMTCP. To minimize the size of the sheathed section, a process to coat the fine wires with ceramic is being investigated.

Table 1 summarizes the difference between SMART and MMTCP.

V. Numerical Modeling of MMTCP and SMART Probe Tip

The advantages of both MMTCP and SMART are fast response and small intrusiveness due to its miniaturized size. The disadvantage is fragility during tedious manual

Table 1. Summary of changes between SMART and MMTCP

SMART	Implemented	MMTCP
Cavity is purged with Ar	planned	Air
Ceramic body is one piece	yes	Two ferrules
Ceramic insulator	planned	Quartz
Electrical shielding	planned	No shielding
No low temperature component	planned	Epoxy and Teflon present
Verification testing of lot samples	yes	Sanity check testing
Laser welding	planned	Arc welding
Ceramic wire coating	planned	No coating

4

fabrication. Methods are being examined to streamline this process.

To evaluate the basic SMART design, a parametric study was performed using 2D numerical models of the probe tip section using commercial Finite Element Model analysis. Tip configuration of a closed sheath with an isolated hot junction was analyzed. Probe geometry was simplified to avoid modeling in 3D. Three parameters were chosen for evaluation: wire size; hot junction bead diameter; and the hot junction bead location from the tip inner wall.

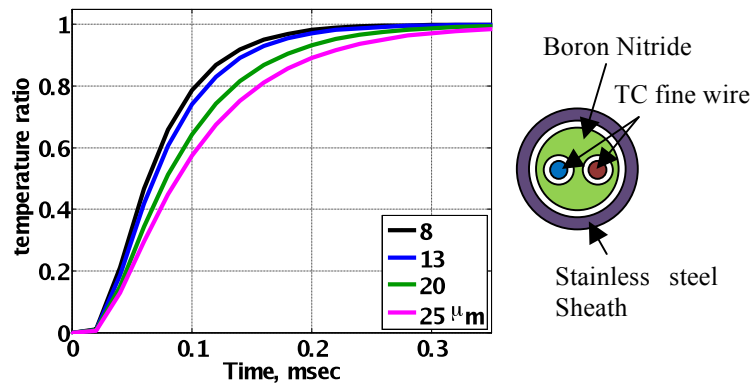For the wire size study, Figure 5 shows the 2D model illustration and

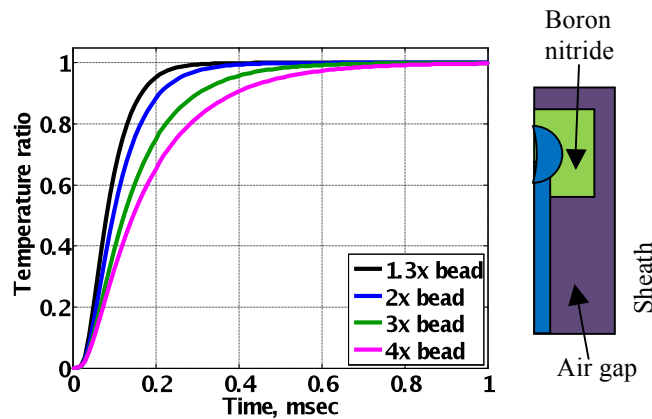**Figure 5. Wire size study model and time response to step temperature change**

Figure 6. Bead size study model and time response to step temperature change

result. It models the wires close to the hot junction. The sheath OD is kept at 200 μm and the gap was filled with boron nitride. Only the wire size was changed from 8 μm to 25 μm and all other parameters were kept constant. Step temperature change from room temperature to 1000 °C was applied at the sheath outer wall and temperature at the center of sheath were computed. As shown, the time response was less than a millisecond, and has a weak dependency on the wire size. Wire size affects ease of fabrication significantly due to handling of stiff versus soft wires – which is challenging when feeding through small holes or forming welds.

For the bead size study an axisymmetric model was used by lumping two wires into one, and averaging material properties. The model illustration and the time response plot are shown in Figure 6. The bead size varied from 1.3 to 4 times the wire diameter. For the wire size study, a step temperature change was applied at the sheath outer wall including the closed tip section. Changing the bead size from 1.3 to 4 changes the time constant by a factor of ~2. This shows that tight tolerance on bead size is unnecessary to maintain the fast time response.

For the bead location study, the same axisymmetric model was used. The bead size was kept constant at 2 times the wire diameter, except for one case. The location of the bead was changed from 0.025 to 3 mm from the inner wall of the closed sheath tip. The boundary condition was convective with a coefficient of 2000 W/(m^2·K) and only applied at probe the tip. The sheath outer wall at the side was insulated. This boundary condition was chosen to study the bead location dependency in a worst-case scenario, although it is unlikely to be encountered in TPS instrumentation. Proper installation of the probe with a "landline" minimizes temperature discrepancy along the sheath close to the tip. Nevertheless, it can be considered as a performance indicator when the probe is used in other applications, such as a "bayonet" installation, that does not have any landline section, or a "tip touching mode", where only the tip is in contact with the object of interest. As seen in Figure 7, the response time is tens of seconds. The orders change from two previous analyses due to the
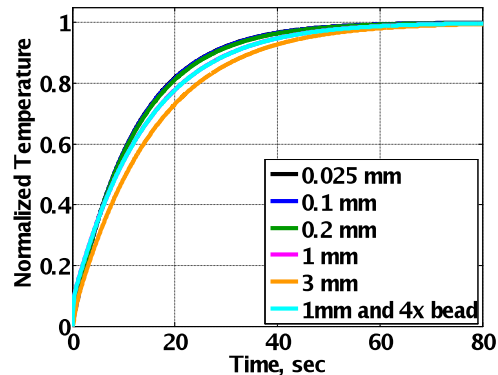

Figure 7. Bead location study time response to step convective boundary condition

5

change of the boundary condition from temperature specified to convective. Even though the bead location changes drastically, the time response remains consistent. The conclusion is that boron nitride filler is providing excellent thermal contact between the probe tip and the hot junction, without adding significant thermal mass. The bead location study shows that exact placement is not critical when boron nitride filler is used.

VI. Verification Testing Apparatus

There are several performance parameters of the TC probes that should be verified for quality control. However, without a reference probe with equivalent or better performance, it is impossible to test the probe for important performance parameters at the same condition as the actual application. It was decided to verify temperature and voltage relation and time response of the probes at controlled environments different from the actual usage.
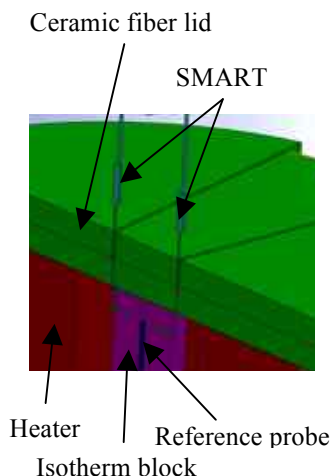

Figure 8. Section view and entire view illustration and photo of temperature verification apparatus.

C. Temperature and voltage output verification

For TPS applications, and especially flight, the probe usage is limited to a short period of time, up to a few minutes. Long term de-calibration of the probe in service is not a concern for the SMART and MMTCP. There are several ASTM standards for TC wires and mineral insulated TC probes. [11,12] There are many off-the-shelf TC calibrators available, and many vendors providing calibration services. However, they are typically not suited for small probe sizes, and wide temperature ranges seen for these specific applications. The difficulty in temperature versus voltage verification of the SMART and MMTCP are their small size and high temperature measurement range. For 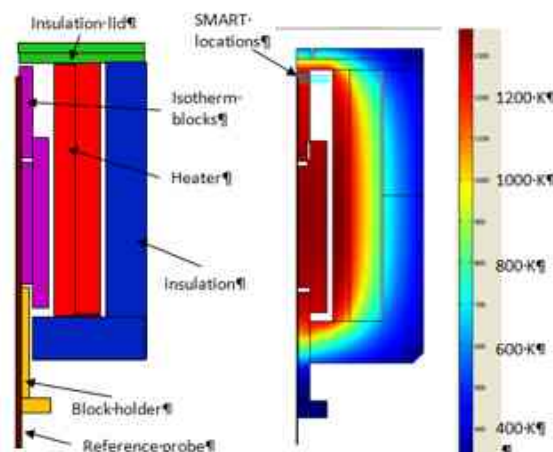proper verification of the probes, the majority of the temperature difference needs to be contained within the sheathed section. Otherwise, the effort is ineffective because it tests the lead wires and not the sheathed section where temperature difference is present in actual application. Besides, the body section of the MMTCP cannot survive extreme high temperatures. The use of off-the-shelf calibrators would result in large spatial temperature uncertainties, or unacceptable heating levels of the probe body section.

The SMART temperature verification apparatus was designed and fabricated to overcome the probe size difficulty. However, the temperature range is still limited to moderate at 1000 °C. It is a tube furnace with a ceramic heater and an alumina insert as isotherm block. The isotherm block has blank holes machined to house the SMART probe tip. High temperature ceramic fiber insulation is used as a furnace lid to minimize heat loss, which provides for better temperature spatial uniformity. Figure 8 shows the section view of the heater and the isotherm block. An entire view of the apparatus with probe holders and the frame housing the furnace is shown in the photo. The reference probe was inserted in the isotherm, opposite from SMART, to minimize heat loss by the large reference probe. Figure 9 shows the numerical prediction of temperature distribution when the apparatus is operating at its maximum temperature of 1000 °C. The numerical model shows that there is 4 °C discrepancy within the 5 mm by 5 mm region where the

Figure 9. Numerical prediction temperature distribution in the verification oven operating at the maximum temperature.

probe tips are located. The apparatus was completed but its heater parameters and ramping rate are being adjusted for best testing conditions. Type K MMTCP was tested in the verification apparatus as a trial to 800 °C, during a furnace dry run. The probe stopped functioning during a cooling cycle after heating and dwell at 800 °C, for an unknown cause. The difference in temperature between the MMTCP obtained by using the standard TC conversion equation, and that of the reference is within ± 10 °C, plotted in Figure 10. This plot excludes the time when the temperature was unstable, and when the probe was inoperative.
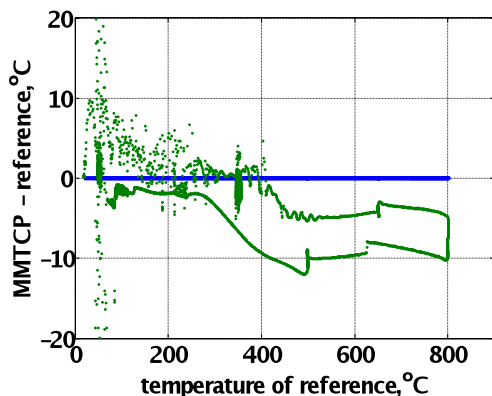
Figure 10. Temperature difference between MMTCP and reference when tested in verification apparatus.

D. Time response verification

Originally, the time response test was to be performed in a convective gas flow using a mechanical shutter to expose or isolate the probe from high temperature flow. This option makes analysis much simpler, but designing and assembling the apparatus is more complex than the tube furnace design. A laser welder is available for large size TC fabrication purposes. Using this laser welder for the time response verification test removes the necessity to fabricate a convective apparatus. Analysis might be more involved since the laser has limit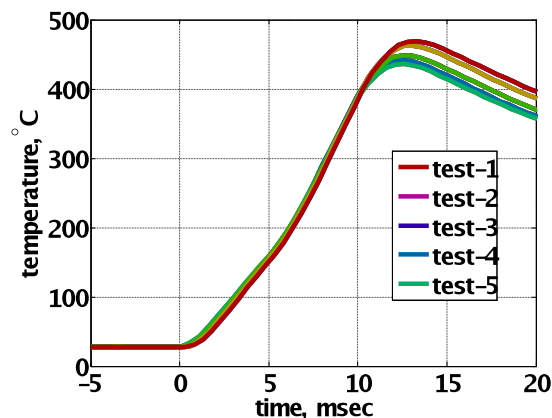ations in firing duration, number of shots, and time intervals. The absorbed heat flux is probably influenced by the surface condition of the probe tip. Using quantitative analysis, such as time to reach certain temperature for a certain incident flux may not be adequate. Modifying the probe tip for controlling its absorptivity does not work for open probe tip configurations, and is too intrusive to the testing objectives because of the small tip size. Laser test dry runs were performed to adjust laser parameters, such as firing duration, focal distance, and power. During the dry runs, a SMART was placed and temperature measurements recorded. Figure 11 shows the SMART temperatures as function of time. The consistency between runs is excellent, but all the data is from one individual SMART probe.

Figure 11. laser test preliminary data

VII. Future work

Design changes for SMART are left as future work to expand the range of peak temperature, measurement duration, and reliability beyond the documented traditional values. The verification testing apparatuses needed to start screening SMART modifications are available. Several arc jet tests are planned to use SMART for TPS instrumentation replacing the traditional single bare wire "U" installation TCs.

VIII. Conclusion

A micro-miniature thermocouple, called 'SMART', has been maintained and improved from the original Paul Beckman Co design. This sensor represents the current state-of-the-art for extreme environment thermal protection systems temperature measurement with respect to response time and minimal mass intrusiveness.

References

[1] Seiff, A., Reese, D., Sommer, S., Kirk, D., Whiting, E. and Niemann, H., "PAET, 'An Entry Probe Experiment in the Earth's Atmosphere,'" ICARUS, 18, 525–563, 1973.

[2] Santos, Jose, et al., "Thermal Modeling of In-Depth Thermocouple Response in Ablative Heat Shield Materials." 26th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, Seattle, Washington, June 2008.

[3] P. Kolodziej et al., "First Flight Demonstration of a Sharp Ultra-High Temperature Ceramic Nose-tip." NASA Technical Memorandum 112215, Dec. 1997.

[4] Kuntz, D.W., Potter, D.L., "Boundary-Layer Transition and Hypersonic Flight Testing." J. of Spacecraft and Rockets. 45, 184 (2008)

[5] Beckman, A., 300 Series Microminiature Thermocouple Probe (MMTP) Manufacturing Procedures Manual (MPM) Prepared for NASA Ames Research Center, 2009.

[6] Paul Beckman Company Internal Report, "Millisecond Response Thermocouples Basic Theory."

[7] Paul Beckman Company Product Catalog, "300 Series Microminiature Thermocouple Probes".

[8] Beckman, P. and R.P. Roy, "An Improved Fast Response Microthermocouple." Rev. Sci. Instrum. 66, 4731 (1995)

[9] Milos, F. S., "Galileo Probe Heah Shield Ablation Experiment", Journal of Spacecraft and Rockets, Vol. 34 No. 6, November-December 1997

[10] Talley, R. N., "Galileo Probe Deceleration Module Final Report," Reentry System Operations, General Electric Co., Rept. 84SDS2020, Jan 1984.

[11] Hoersch, H., and Park, R.M. ASTM Manual on the Use of Thermocouples in Temperature Measurements. 4th ed.

[12] ASTM Standard ASTM E230-03

[13] Benedict, Robert. Fundamentals of Temperature, Pressure, and Flow Measurements. New York: John Wiley & Sons, Inc., 1969.

[14] Lanius, S.J., Kerrigan, B.E., "Instrumentation Techniques and Results for a Highly Instrumented Carbon-Carbon Nozzle Static Test." JANNAF Rocket Nozzle Technology Subcommittee Annual Meeting, Alabama (1988)

[15] Oishi, T., Martinez, E. R., and Santos J., "Development and Application of a TPS Ablation Sensor for Flight." AIAA 2008-1219.