Assessment of Thermocouple Attachment Methods for Measuring Vehicle Exhaust Temperatures

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Preface

The work reported on herein was conducted for the Motor Vehicle Fire Research Institute and represents a deliverable for the contract signed and dated May 17, 2006.

The opinions expressed herein are those of Biokinetics and Associates Ltd. and do not necessarily reflect those of the Motor Vehicle Fire Research Institute.

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1. Introduction

Engine and exhaust temperature measurements were conducted, under previous work, on four 2004 model year vehicles representing different vehicle classes [Ref. 1]. Included in the testing were:

- Chevrolet Silverado
- Dodge Neon
- Dodge Caravan
- Ford Focus.

The objective of the testing was to determine if engine/exhaust surface temperatures under normal operating conditions exceed the hot surface ignition temperatures of the engine compartment fluids as reported by Santrock [Ref. 2] and presented in Table 1 below for reference.

Table 1: Lowest temperature resulting in 100% probability of auto ignition of engine compartment fluids tested on heated cast iron crucibles.

Fluid Type	**Auto Ignition Temperature [1, 2] (°C)**
Unused Motor Oil	320 to 335
Used Motor Oil	315 to 335
Unused Synthetic Motor Oil	320 to 370
Used Synthetic Motor Oil	335 to 365
Brake Fluid	280 to 340
Power Steering Fluid	325 to 345
Automatic Transmission Fluid	315 to 320
Antifreeze and Engine Coolant	550 to 675

Notes: 1- The temperature range indicates the upper and lower hot surface ignition temperatures, producing 100% probability of auto ignition, for the various brands and compositions of fluids tested on heated cast iron crucible.

2- These results are specific to the conditions of the test and may vary depending on surface geometry and airflow conditions. For example, tests on a cast iron hemisphere increased the lowest temperatures need for 100% probability of auto ignition to occur and an increase in airflow further increased the minimum temperature required..

The temperatures were recorded with the vehicle stationary and during level road and uphill driving at speeds ranging from 30 mph to 70 mph (48 km/h to 112 km/h). Once steady state temperatures were obtained during the driving tests, the vehicles were pulled to the side of the road and their engines turned off. Temperature measurements continued for an additional 20 minutes. This procedure represented the engine temperature conditions that may persist following a collision and the vehicle coming to a sudden halt.

The results of the testing indicated that the lowest hot surface ignition temperature of 280 °C, as indicated in Table 1, was exceeded by each vehicle under at least one of the driving conditions evaluated. The hottest temperatures were typically recorded on the exhaust manifold or the catalytic converter. Surprisingly, however the peak temperatures were recorded only after the engines were turned off. The removal of forced convective cooling, when the vehicles were stopped, was offered as an initial explanation for the phenomenon observed. A typical example of the increase in temperature observed is shown below.

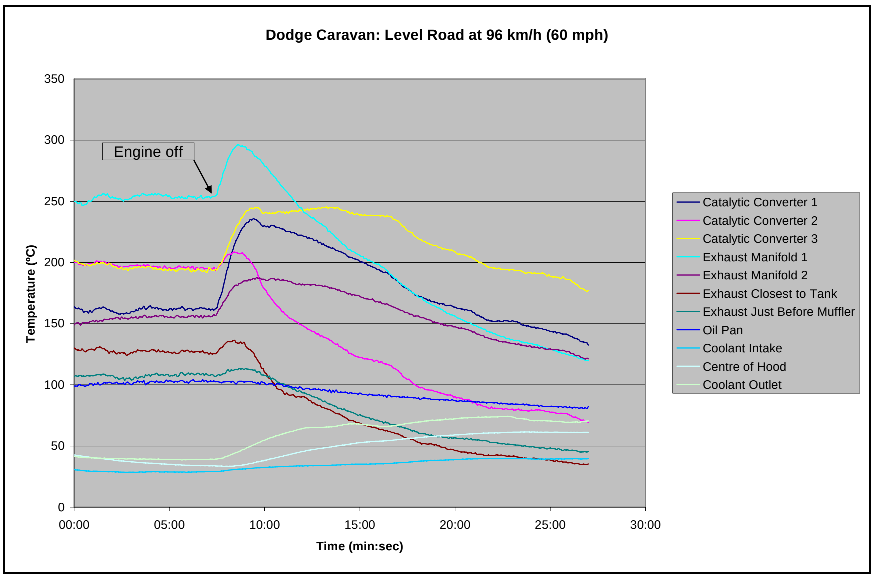

Figure 1: Dodge Caravan temperature time history showing the increase in temperature after the engine is turned off.

The vehicles of the initial test program were obtained from rental agencies which precluded the use of welding as a means of affixing thermocouples to the vehicle components to be measured. In discussions with a thermocouple manufacturer, a clamp-on style of thermocouple was selected. These thermocouples were affixed to the engine/exhaust components with stainless steel hose clamps. Upon further consideration of the increase in temperature phenomena observed, the clamps and the thermocouple housing were believed to be acting like cooling fins, thereby reducing the observed temperature at the thermocouple bead location while the vehicles were in motion. When the vehicles were stopped the added cooling effect from the clamp was reduced and the temperature increased to be closer to the surrounding surface temperature.

Discussions with expert vehicle fire investigators suggested that the increase in temperature was a physical phenomenon that may occur when an engine is turned off. A reference to this phenomenon was even found in the National Fire Protection Association's guide for fire investigation [Ref. 3]. Vehicle manufacturers' representatives however, suggested thermocouple attachment method was likely the cause of the temperature increase. A further literature review revealed that in fact there was no published data supporting either position. The proposition was then made that, in the absence of any published data, the results would at the very least be conservative in nature (i.e. lower than actual) because the thermocouples can not read a temperature higher than actual. Therefore, the general finding indicating hot surface ignition temperatures are achieved under normal vehicle operating conditions is still valid.

The testing reported on herein assesses various thermocouple styles and attachment methods and their effect on measured surface temperature. The results of these tests will help to clarify the original results. The tests were only conducted on one vehicle at one speed during level road and uphill driving.

2. Vehicle Temperature Measurements

The additional vehicle temperature measurements are described in the following sections. Where applicable the same procedures as those used in the initial testing of four vehicles were followed [Ref. 1]. The results of a simplified heat transfer calculation examining the effects of air space on a clamp's surface temperature is presented prior to the presentation of the vehicle test results.

2.1 Test Vehicle

A 1996 Ford F150 V8 pickup truck was selected as the test vehicle. Unlike the vehicles used in the initial testing, there were no limitations on the methods that could be used to attach the thermocouples.

2.2 Thermocouple Selection and Placement

Five different K-type thermocouple and attachment methods were selected for the additional temperature measurements and they are listed in Table 2 below.

Table 2: Thermocouple type and attachment method.

Thermocouple Type	**Thermocouple make/model**	**Attachment Method**
Surface Temperature (same as recommended for initial testing)	Omega Hi Temperature XCIB Style 4	Clamped
Thin Film Surface Temperature	Omega Cement-on Style 2, CO2-K	Cemented
Bead	Omega Ready Made 5SRTC-GG-K	Brazed
Bead		Cemented
Surface Temperature Probe	Omega Weld Pad Probe PDR	Welded

Of the thermocouples listed in Table 2, the cemented on thin film thermocouple required the most effort and preparation to install and it was the least robust during testing as the thermocouple leads were fragile.

The five types of thermocouples measured the temperatures at each of two locations along the exhaust system. The first was located at the union of the driver side exhaust manifold with the catalytic converter pipe section. The catalytic pipe was comprised of two catalytic converter modules joined by a short section of pipe. This short pipe was selected as the second location for measuring surface temperatures. These exhaust components were mirrored on the passenger side of the vehicle however, measurements were only recorded on the driver's side. In both locations the thermocouples were placed on the surface of the pipe along the circumference defined by a cross sectional plane perpendicular to the axis of the pipe. The thermocouples were installed on a new section of exhaust pipe prior to being installed in the vehicle. The placement of the thermocouples are shown in Figure 2.

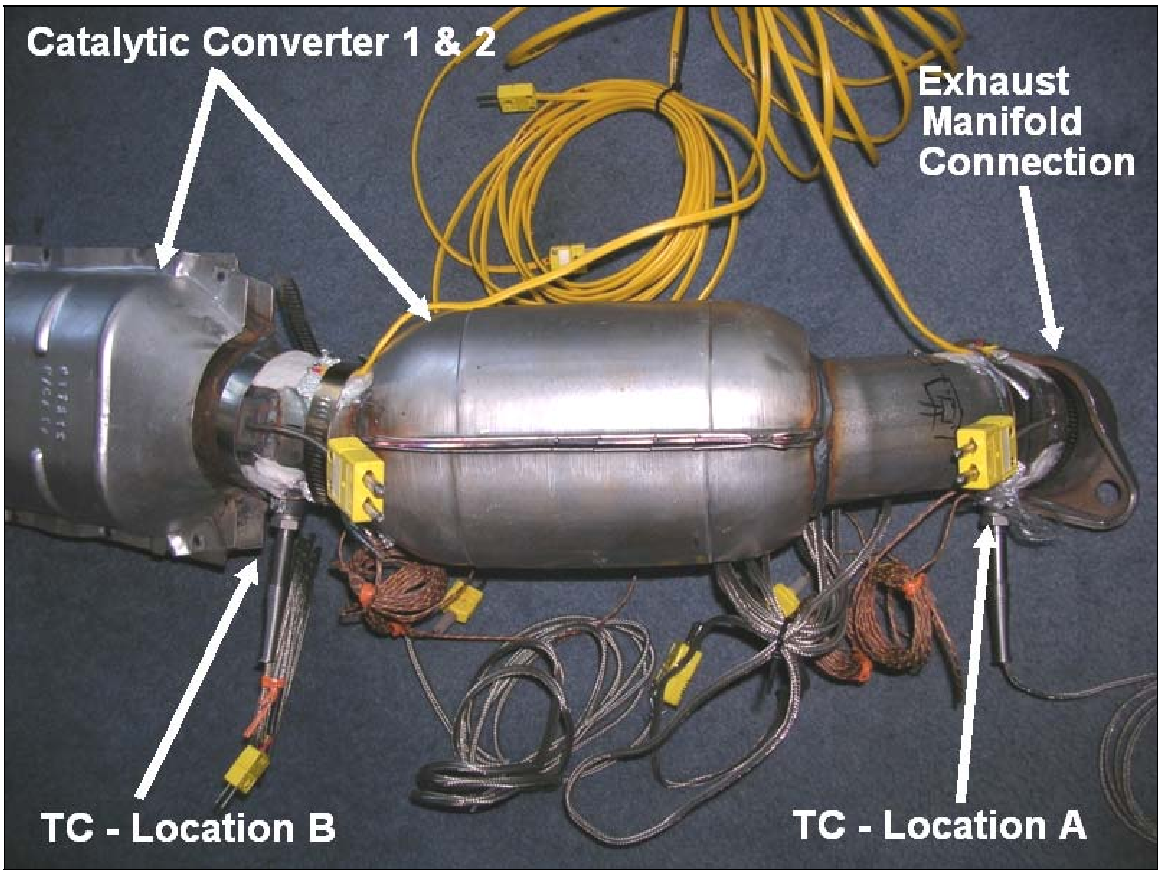

Figure 2: Thermocouple placement on driver side exhaust pipe.

The thermocouple cabling was routed through the driver side window and connected to two data loggers. The thermocouple data loggers were synchronized and recorded the measured temperatures at 5 sec intervals.

2.3 Test Matrix and Procedure

The temperatures at the two locations on the exhaust system were measured under two loading conditions that were achieved by level road driving and uphill driving. For both driving conditions the vehicle was loaded with 955 lbs (433 kg) of additional mass which included the driver and the instrumentation technician. The driving tests were only conducted at 60 mph (96 km/h). The test conditions are summarized in Table 3.

Table 3: Test conditions for under hood temperature measurements.

Test Condition	Speed
Level road	96 km/h (60 mph)
Driving uphill	96 km/h (60 mph)

All the testing was performed with a minimum ambient temperature of 23 °C.

For the level road driving the pickup truck was driven at a constant speed until the temperature readings stabilized, at which point the vehicle was brought to a stop and the engine turned off. Temperature measurements continued for a period of 20 minutes or until the maximum temperature recorded by any of the temperature transducers dropped below 200 °C.

As in the first test series a stretch of highway approximately 1.6 km (1 mile) in length with a 7% grade was selected for the uphill driving tests. The length of the hill was insufficient to allow the vehicle temperatures to stabilize, consequently the same procedure as used previously was used and is repeated below:

1. Ascend hill at steady state speed.
2. Continue over crest off hill and descend the back side for 0.7 km to the stop at the bottom.
3. At the bottom, turn around and accelerate to steady state speed up the back side of the hill (also 7% grade).
4. Continue over crest to the bottom of the test hill.
5. Turn around, accelerate to steady state speed and repeat.

Steps 1 through 5 were repeated 3 times. On the third ascension of the test hill the vehicle was pulled off to the side of the road and the engine was turned off. The repeated process of ascending and descending the hill several times stabilized the peak temperatures achieved at the crest of the hill prior to the engine being turned off. Similarly to the level road testing, the temperature measurements were continued for a period of 20 minutes or until the maximum temperature dropped below 200 ºC.

2.4 Theoretical Effect of Air Space on Temperature Measurement

Prior to the physical tests on the Ford F150, a simplified heat transfer calculation was conducted to investigate the effect of an air space on the temperature that would be expected on the clamp used to secure a thermocouple. The simplified case is depicted in Figure 3.

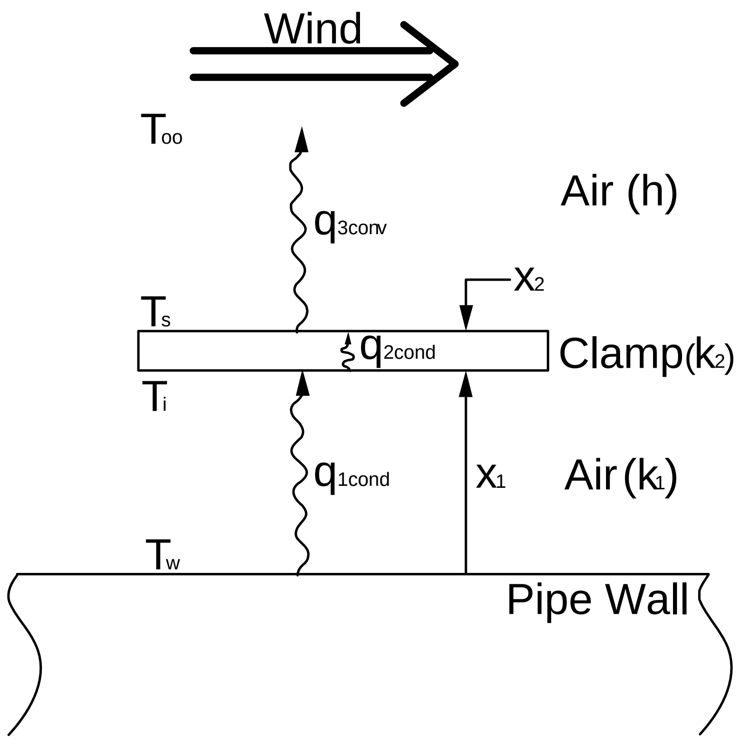

Figure 3: Simplified heat transfer scenario.

Assumptions and definitions:

- For the purpose of the calculations, the temperature of the surface of the clamp will be investigated.
- The air is stationary in the space between the pipe and clamp surfaces.
- The airflow is parallel to the axis of the pipe.
- Radiation heat transfer is not included. Radiation heat transfer calculations can be extremely complex and are best suited to finite element analysis.
- A = area of clamp coverage (m^2 assume unit depth).
- ρ = density air at ambient conditions (kg/m^3).
- μ = dynamic viscosity
- u = air velocity (m/s).
- T_w = temperature of the pipe outer wall (assumed constant at 500 °C).

- T_i = temperature of the clamp inner surface.
- T_s = temperature of the clamp outer surface.
- T_∞ = ambient air temperature in the engine compartment (100°C)
- $T_f = (T_\infty + T_w)/2$: film temperature - used for determining heat transfer properties of free streem air.
- q = heat flow.
- X_1 = air gap.
- X_2 = clamp thickness (0.7 mm).
- K_1 = thermal conductivity of air (0.0564 W/m*°C @ 500 °C).
- K_2 = thermal conductivity of clamp (22 W/m*°C).
- Nu = Nusselt number (average)= $0.664 * Re^{1/2} * Pr^{1/3}$.

  $Re = \rho u L/\mu$ – Reynold's number

  Pr – Prandtl (0.673 @ 300°C)
- L = clamp width (12.75 mm).
- h = convective heat transfer coefficient ($h = Nu * k_{air}/L$).

Equations:

Between the pipe wall and the inner surface of the clamp:

$$T_w - T_i = qX_1/k_1A \qquad (1)$$

Through the clamp:

$$T_i - T_s = qX_2/k_2A \qquad (2)$$

Off the outer surface of the clamp:

$$q = hA(T_s - T_\infty) \qquad (3)$$

Adding the equation (1) and (2) and substituting the q with equation (3) and solving for t_s,the following equation for t_s is obtained.

$$T_s = (T_w + hBT_\infty)/(1 + hB) \qquad (4)$$

where $B = (X_1/k_1 + X_2/k_2)$

The clamp surface temperature was calculated as a function of airflow velocity for different air gaps and is plotted in Figure 4.

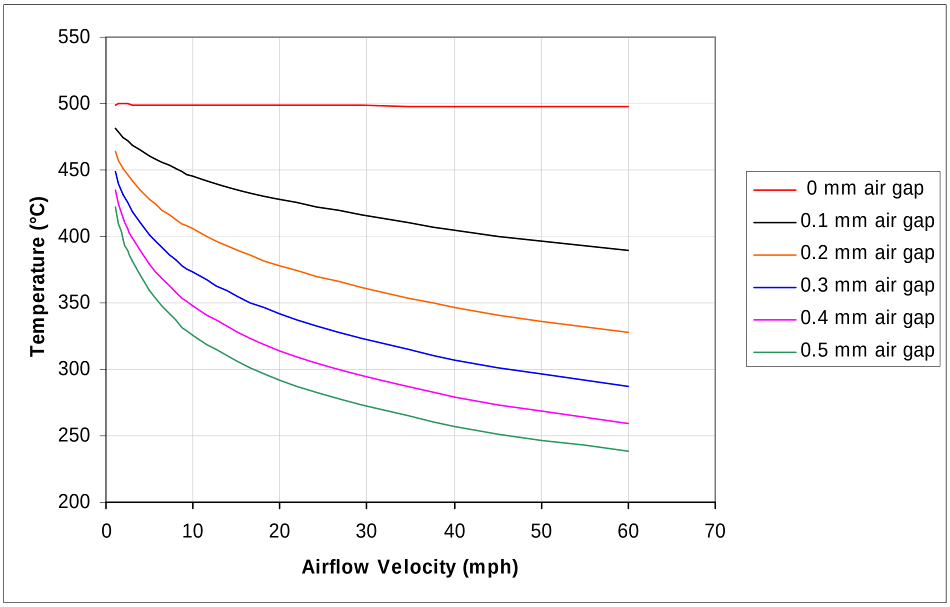

Figure 4: Theoretical clamp/bead surface temperature as a function of airflow velocity and air gap.

Referring to Figure 4 the effect of an air gap can clearly be seen. As would be expected, an increase in air gap results in a decrease in measured surface temperature. Similarly the measured surface temperature would decrease as the airflow increases.

If the airflow is suddenly removed it would be expected, according to the plots shown in Figure 4, for the measured temperatures to increase. For a given air gap the temperature is decreased further by forced convection as the airflow velocity over the clamp increases. With an air gap of 0.1 mm and an airflow velocity of 60 mph (96 km/h) the measured clamp surface temperature is reduced by approximately 90 °C from a no airflow condition. With an air gap of 0.5 mm the reduction is approximately 180 °C. The lower temperature on the clamp would act to reduce the measured temperature on the thermocouple. This offers a possible explanation for the increase in temperatures that were recorded during the vehicle tests when the vehicles were stopped and the engines turned off.

In practise the thermocouple would be placed under the clamp and would measure an average temperature between T_w and T_i. T_i is essentially the same as T_s because of the thinness of the clamp.

2.5 In Vehicle Temperature Measurement - Results and Discussion

The time histories of the thermocouple measurements for the level road and uphill driving tests are shown in Figure 5 to Figure 8.

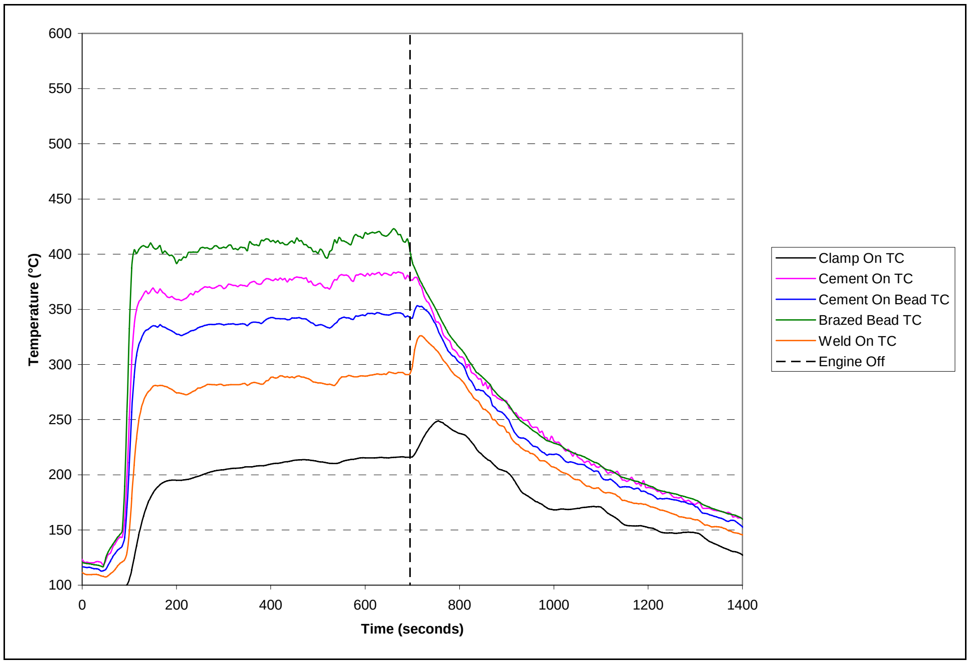

Figure 5: Level road - temperature time history at the connection to the manifold (TC – location A).

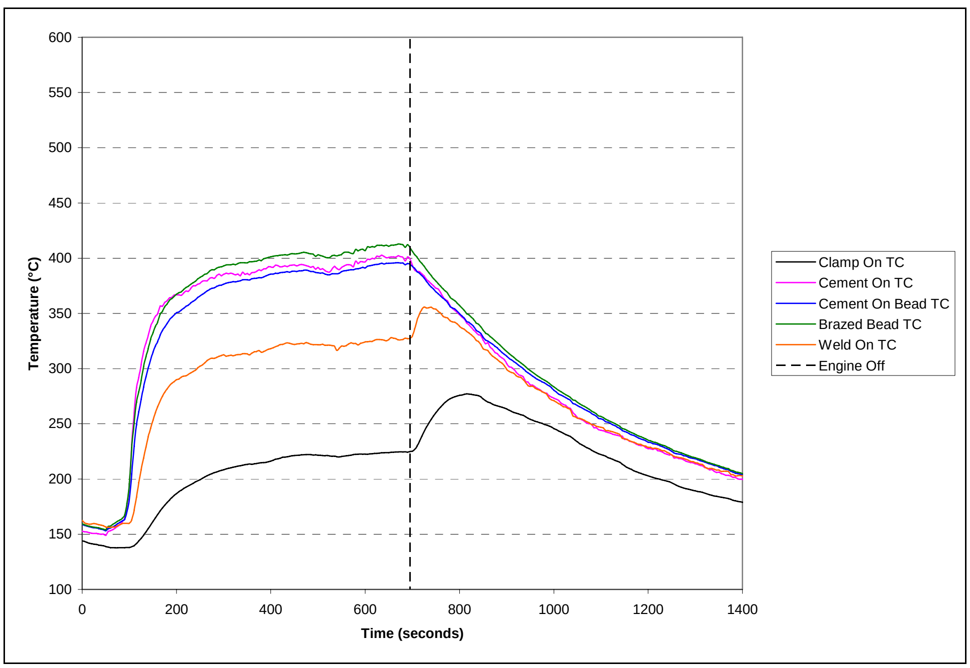

Figure 6: Level road - temperature time history on the short section of pipe between the two catalytic converter modules (TC - location B).

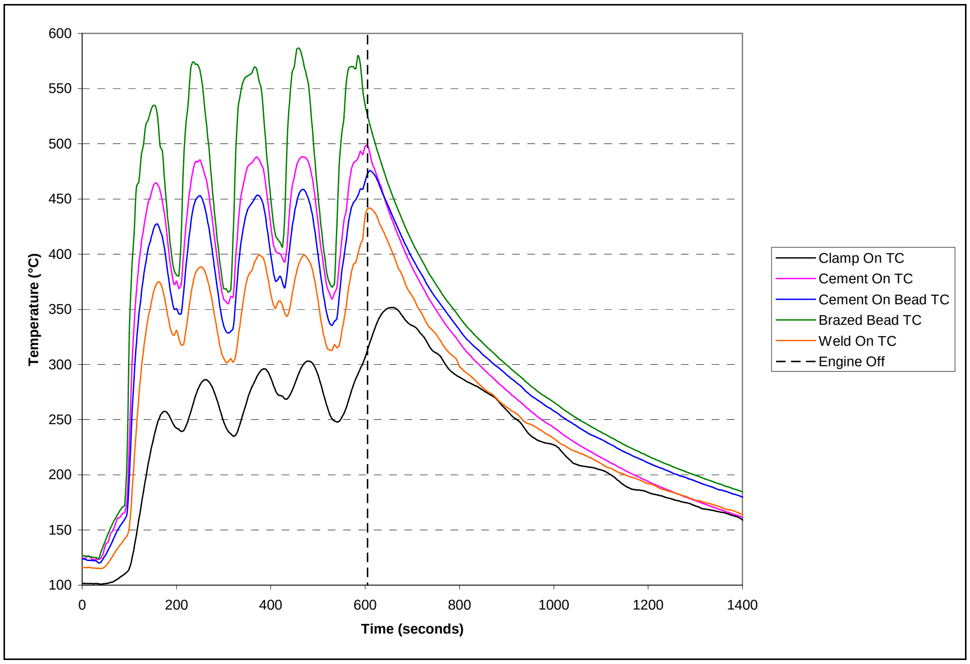

Figure 7: Uphill - temperature time history at the connection to the manifold (TC – location A).

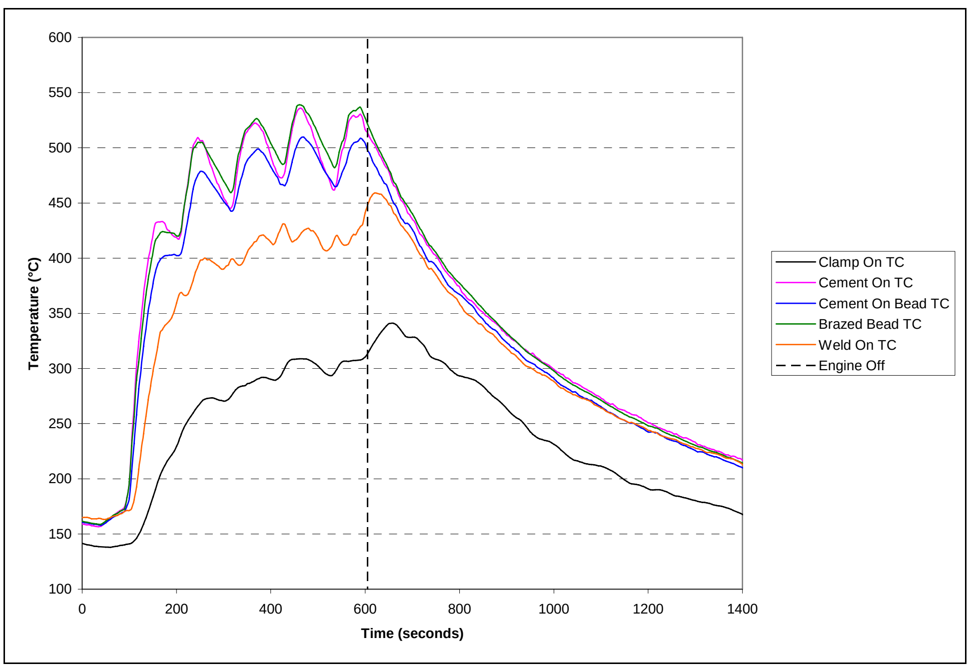

Figure 8: Uphill - temperature time history on the short section of pipe between the two catalytic converter modules (TC - location B).

Referring to the uphill driving test procedure described earlier (Section 2.3), the undulations in the temperature measurements seen in the uphill driving temperature time histories (Figure 7 and Figure 8) are directly linked to ascending or descending of the hill.

At both temperature measurement locations and under both driving conditions the brazed on thermocouple bead registered the highest surface temperature measurements and the clamp on surface temperature thermocouple measured the lowest. The remaining thermocouples measured temperatures somewhere in between the two. However, the temperatures recorded by the brazed on, the cemented thin film and the cemented bead thermocouples located on the short section of pipe between the catalytic converted modules (location B) were within approximately 30 °C of each other compared to a range of almost 100 °C near the connection to the manifold (location A). The difference in the temperature range between the two thermocouple locations may be due to the turbulence of the exhaust gas flow at the union of the four manifold pipes and the connection with the catalytic converter pipe. At this location the exhaust gases in the four manifold pipes have travelled different distances from the piston exhaust valves, thereby producing an uneven temperature distribution. Additionally, the exhaust manifold clamp introduced an uneven distribution of thermal mass (see Figure 2) at location A which was less exposed to airflow than location B. At location B, after having passed through the first catalytic converter module, the exhaust gas temperature has stabilized. The smaller differences observed in this location could be due to the differences in convective cooling occurring around the circumference of the pipe at the measurement location.

The response times of the clamped on surface temperature thermocouple and the welded on surface temperature probe are noticeably slower than the other thermocouples used. This is likely due to the thermal mass associated with these thermocouples' exterior sheathing which may have acted like heat sinks delaying the discernment of temperature changes. Diminished thermal conductivity between the pipe surface and the clamped thermocouple would have also contributed to the slower response time of the clamped on thermocouple. This, in conjunction with the additional forced convective cooling that may be associated with the thermocouples additional sheathing or clamp may be responsible for the 75 °C to 175 °C lower temperatures measured when compared to the brazed on bead thermocouple.

Instances where a temperature increase was recorded after the engine was turned off were observed with the clamped on, the welded surface temperature probe and the cemented thermocouple bead and are summarized in Table 4.

Table 4: Summary of observed temperature increases after the vehicle engine was turned off.

Measurement Condition	TC Type	Temp. at Engine Shut-off (°C)	Peak Temp (°C)	Temp. Increase (°C)	Time of Peak After Engine Turned Off (s)
Level Road TC location A	Clamped	215	249	34	60
	Welded Probe	292	326	34	25
	Cemented Bead	342	353	11	15
Level Road TC location B	Clamped	225	277	52	120
	Welded Probe	327	356	29	30
Uphill TC location A	Clamped	313	352	39	50
	Welded Probe	441	442	1	5
	Cemented Bead	473	475	2	5
Uphill TC location B	Clamped	313	341	28	50
	Welded Probe	447	459	12	15

The additional forced convective cooling associated with the sheathing of the clamped on and the welded probe thermocouple likely contributed to the lower temperature measurements. With the vehicle stopped and the engine turned off the forced convective cooling would cease, allowing the measured temperature to increase and approach the measured temperatures of the bead and thin film thermocouples. The higher temperatures, however, were never actually reached by the clamped on or welded probe thermocouples. Both these thermocouples therefore are conservative in their measurement of the exhaust surface temperatures.

Comparatively small temperature increases were seen in two instances with the cemented bead thermocouple at location A. As indicated previously there appeared to be a temperature gradient around the circumference of the pipe at this location. When the engine was turned off the immediate response would be for the local low temperature location to equalize with an adjacent higher temperature. This may result in a brief temperature increase. At location B, where the temperature gradient was not as apparent, such a temperature equalization effect would not be as apparent.

After the peak temperatures were reached the thermocouples all cooled at approximately the same rate.

3. Summary and Recommendations

Previous testing on four vehicles to measure the under hood engine and exhaust system temperatures during and immediately after vehicle operation identified component temperatures that increased after the vehicle's engine was turned off. Various explanations were offered as to possible reasons for the observed phenomenon. Additional tests were conducted on a single vehicle to investigate the effect of 5 different thermocouple types and attachment methods on surface temperature measurements. Brazed on, welded on, clamped on and cemented on thermocouple attachment methods were employed to measured surface temperatures at two locations on the exhaust system during level road and uphill driving at 60 mph (96 km/h).

At both measurement locations and under both driving conditions the brazed on thermocouple bead registered the highest temperatures whereas the clamp on thermocouple, similar to that used in the initial testing registered the lowest temperatures.

The two thermocouples with thermal mass associated with their construction, namely the clamp on and the welded on probe thermocouple registered lower temperatures, due to the forced convective cooling acting on the thermocouple sheathing, than the thermocouples that consisted only of the sensing bead. These two thermocouples also exhibited a delay in response compared with the bead thermocouples and exhibited a significant temperature increase after the vehicle engine was turned off. The delay in response was associated with the thermal mass of the thermocouple construction. The measured increase in surface temperature was believed to be associated with the cessation of forced convective cooling acting on the thermocouples housing and where applicable on the clamp attachment method. Consequently, these types of thermocouple may not be the most appropriate for surface temperature measurements where forced convection or quickly changing temperatures may be experienced. If used, these thermocouples would provide conservative estimates of the surface temperatures that are attained. This suggests that the initial study of in vehicle surface temperature measurements conducted on four vehicles are conservative in nature and are lower than the temperatures that were attained. Furthermore, the increase in temperature after the engine was turned off was likely a phenomenon associated with the specific thermocouple and attachment method.

The effect of cooling due to the use of a clamp to secure the thermocouple was investigated with a simplified heat transfer configuration. The numerical computations supported the fact that cooling on a clamp, offset from the surface of the exhaust pipe, would result in temperatures that are lower than those on the surface of the pipe. Although the configuration modeled was simplified from the actual, the numerical results do offer supporting explanation for the temperature increases that were observed with the clamped on thermocouple.

For the most part, the results of the current work suggest that the temperature increases previously recorded are likely an artefact of the thermocouple type and attachment method. Nevertheless, there was some indication that a slight, temperature increase may be possible in areas where localized thermal gradients exist. When the source of heat is removed the region of lower temperature would increase to equalize with a decreasing higher temperature region.

In consideration of possible thermal gradients around the circumference of the pipe at the measurement locations, the brazed on thermocouple bead and the cemented on thin film thermocouple produced similar results. However, the thin film thermocouple required more effort and preparation to install. Generally, the brazed on thermocouple bead would be recommended for further measurements under similar condition to those discussed in this report.

4. References

Ref. 1 Fournier, E., “Under Hood Temperature Measurements of Four Vehicles”, Biokinetics Report to the Motor Vehicle Fire Research Institute, Report No. R04-13b, September 7, 2004.

Ref. 2 Santrock, J., Kononen, D. W., “Project B.10 – Study of Flammability of Materials: Flammability Properties of Engine Compartment Fluids Other than Gasoline; Auto Ignition Characteristics of Non-Gasoline Motor Vehicle Fluids on Heated Surfaces”, National Highway Traffic Safety Administration Docket No. NHTSA-98-3588-193.

Ref. 3 “NFPA 921: Guide for Fire and Explosion Investigations”, National Fire Protection Association, 2004 Edition.