TEST SUMMARY REPORT

TITLE: **Zircotec Exhaust Manifold Test**

MIRA-07-1016994	

Project No:	1016994	**Client:**	Zircotec PLC
Test Date(s):	Week 40 & Week 44 2007	**Client Address:**	528.10 Unit 2, Rutherford Avenue, Harwell Science & Innovation Campus, Didcot, OX11 0QJ
		Client Liaison Engineer:	Terry Graham
Authority:	N/A	**Witnesses:**	N/A

Test Objective(s):
To compare the thermal insulation performance of a gasoline exhaust manifold with and without the Zircotec surface coating in terms of heat transfer rate, surface temperatures, and exhaust gas temperatures. The effect of surface smoothing of the coating was also investigated.

Specimen Description/Part No(s):
Range Rover, MY2002, V8 gasoline manifolds, Land Rover part number LKC102470.

Test Equipment:
1. MIRA Engine Test Cell 10 (dynamometer, instrumentation, and data acquisition). Calibration status: current.
2. Range Rover V8 gasoline engine: Serial No. 60D00037A
3. Auxiliary blower, ID No.P03EL075, instrumented with mass air flow meter ID H4VMAF1, calibrated to BS EN ISO 5167-1.

Test Preparation:
1. Two new exhaust manifolds were procured and instrumented with K-Type thermocouples in an identical way to enable measurement of gas temperatures and boundary layer surface temperatures. The locations of each thermocouple are shown in Figure 1.
2. One of the manifolds was sent to Zircotec to be treated with the Zircotec thermal insulation coating.
3. An exhaust manifold encapsulation was fabricated by MIRA with air entry and exit orifices instrumented for inlet and exit temperature measurement by PRT (Platinum Resistance Thermometer). The inlet orifice was designed to enable coupling to an auxiliary blower that would be used to convect cooling air around the manifold. The exit PRT was shielded from manifold radiation.
4. An air blower was configured and coupled to the encapsulation air inlet with a hot-film mass airflow (MAF) meter inserted in series.
5. Two mass airflow rates through the encapsulation (i.e. over the manifold) were estimated that corresponded nominally to vehicle speeds of 35 MPH (225 $kghr^{-1}$) and 70 MPH (450 $kghr^{-1}$) respectively. Simplified assumptions were made on the attenuation of the free stream air velocity by the cooling pack blockage and restriction.
6. The dynamometer controller was programmed to follow a 10-site steady state sequence with an initial warm up at the first site of 15 minutes (3,500 RPM, full load). The 10 sites comprised loads of 100%, 80%, 60%, 40%, and 20% at speeds of respectively 3500 RPM and 2500 RPM. Migration from one site to the next was designed to minimise the magnitude of the thermal disturbance and 5 minutes of thermal stabilisation was allowed prior to data acquisition. 60 data samples for each channel were acquired (@ ~ 1Hz) at each site and the results averaged.
7. The automated dynamometer sequence was to be run for 6 cases:
   (i) baseline manifold at 225 $kghr^{-1}$ and 450 $kghr^{-1}$ cooling flow rates,
   (ii) original surface Zircotec coated manifold at 225 $kghr^{-1}$ and 450 $kghr^{-1}$ cooling rates,
   (iii) smoothed surface Zircotec coated manifold at 225 $kghr^{-1}$ and 450 $kghr^{-1}$ cooling rates.

Test Preparation (cont.):

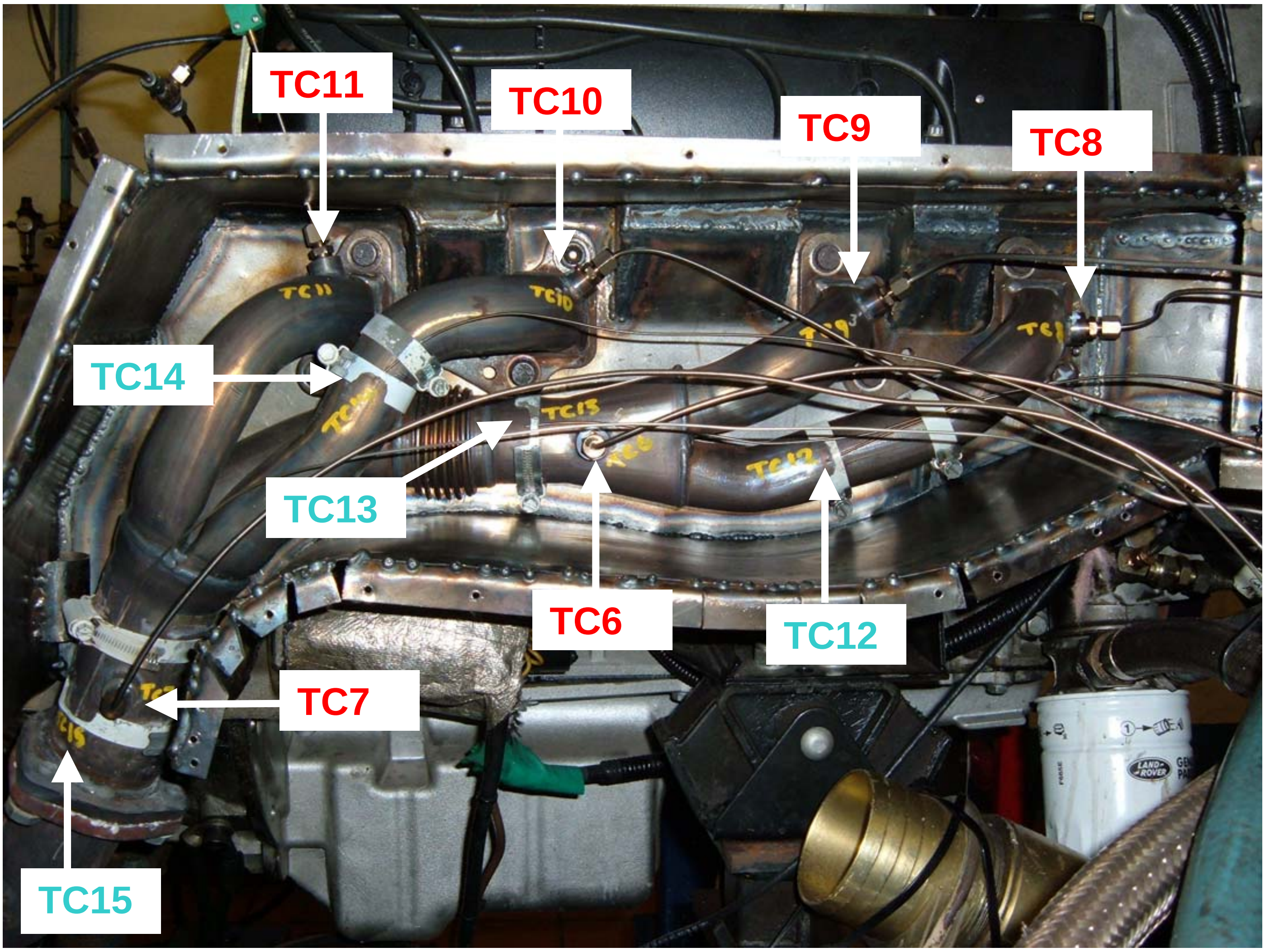

Figure 1 – Locations of Thermocouples (red=> gas, blue=> surface)

Test Procedure:

1. Instrument Baseline manifold with thermocouples. Positions of surface thermocouples and band torques to be recorded.
2. Mount instrumented Baseline manifold on engine inside exhaust encapsulation.
3. Seal encapsulation inspection cover, routing thermocouple leads appropriately, and wrap with rock wool insulation.
4. Set blower flow rate to 450 $kghr^{-1}$.
5. Run automated engine dynamometer sequence for warm up and 10- site mapping.
6. Remove inspection cover, check band torques and retighten if necessary, re-seal inspection cover and wrap with rock wool insulation.
7. Set blower rate to 225 kg hr^{-1}.
8. Run automated engine dynamometer sequence for warm up and 10- site mapping.
9. Remove thermocouples from Baseline manifold and remove manifold from engine.
10. Instrument Zircatec coated manifold with the same thermocouples in the same locations using positional and band torque settings from the Baseline case.
11. Mount instrumented Zircatec manifold on engine inside exhaust encapsulation (see Figure 2).
12. Seal encapsulation inspection cover, routing thermocouple leads appropriately, and wrap with rock wool.

Test Procedure (cont.):

13. Check blower rate still set to 225 kg hr^{-1}.
14. Run automated engine dynamometer sequence for warm up and 10- site mapping.
13. Remove inspection cover, check band torques and retighten if necessary, re-seal inspection cover and wrap with rock wool insulation.
14. Set blower rate to 450 kg hr^{-1}.
15. Run automated engine dynamometer sequence for warm up and 10- site mapping.
15. Export Data
16. Process data to calculate heat transfer rates and plot results. In the heat transfer calculation the specific heat of air was evaluated at the average of the encapsulation inlet and exit temperature.
17. Send Zircotec manifold back to Zircotec for surface smoothing and repeat Steps 11 to 16.

In practise the above procedure Steps 1 to 16 was not completed smoothly because of several abortive runs following thermocouple breakages. Runs were repeated until the required complete sets of data were obtained.

Figure 2– Zircotec Coated Manifold Prior to Test

Results:

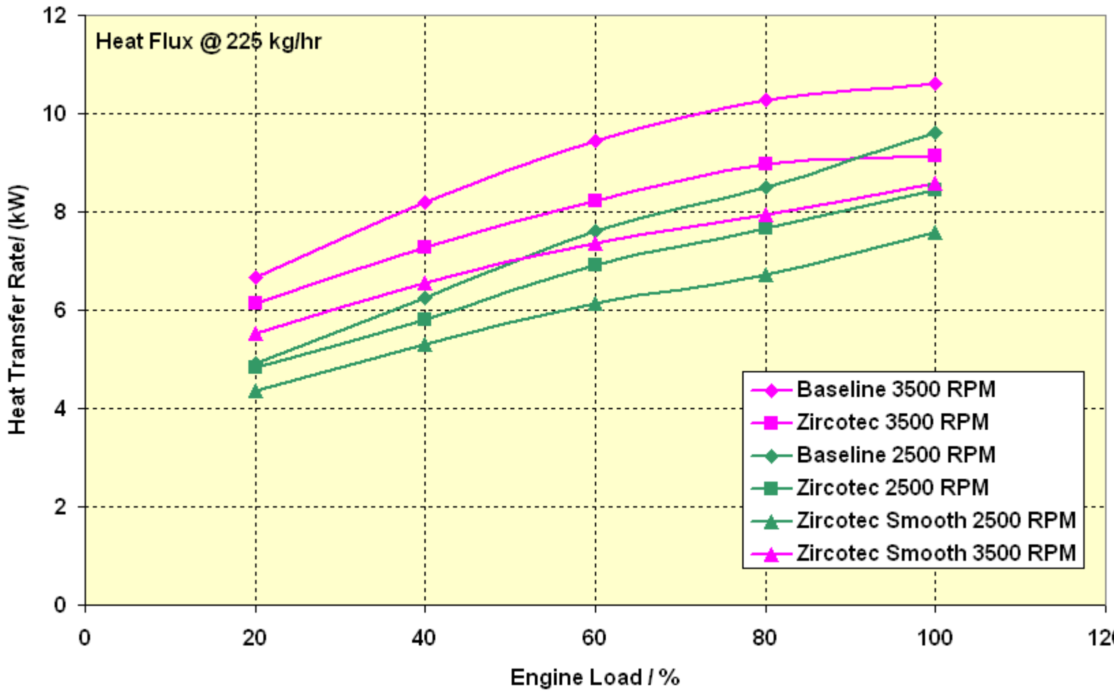

Figure 3 – Heat Transfer Rates to Encapsulation for Cooling Flow of 225 $kghr^{-1}$

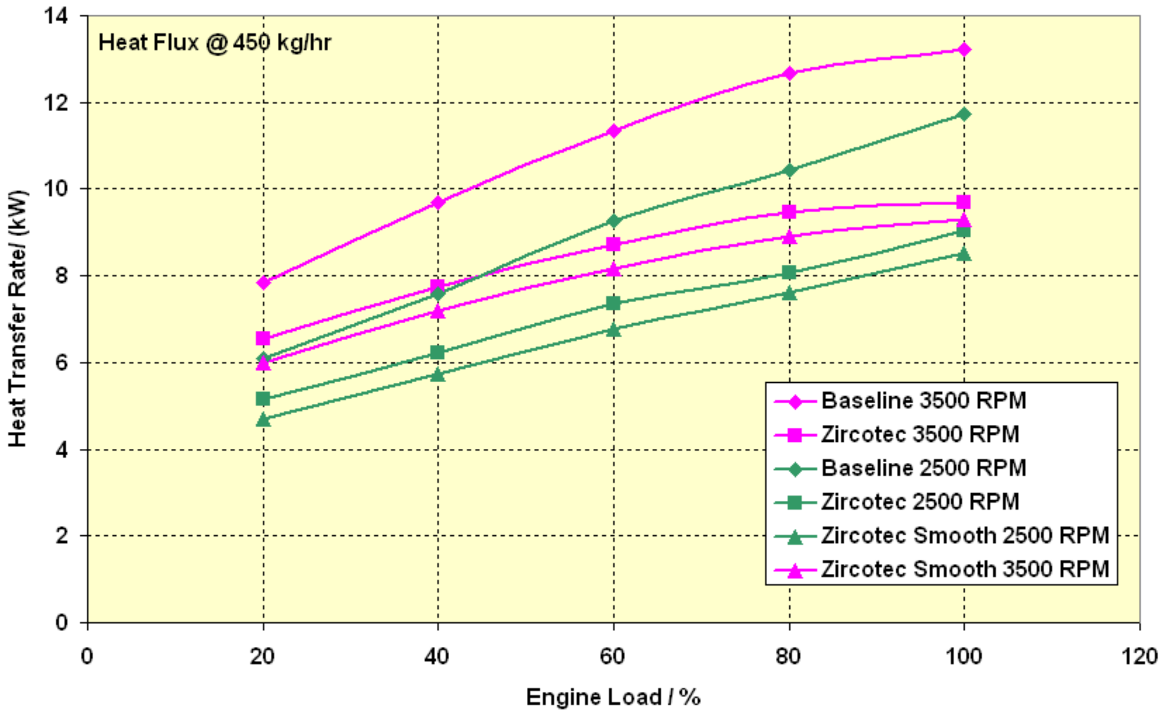

Figure 4 – Heat Transfer Rates to Encapsulation for Cooling Flow of 450 $kghr^{-1}$

Results (cont.):

Table 1a – Reduction in Convective Heat Transfer Rates with Zircotec Original Manifold

heat flux		225 kg/hr				450 kg/hr			
Eng. Spd	Engine	Baseline	Zircotec Rough	Change	Change	Baseline	Zircotec Rough	Change	Change
RPM	Load / %	kW	kW	kW	%	kW	kW	kW	%
3500	100	10.60	9.14	**1.46**	**13.8**	13.23	9.70	**3.5**	**26.7**
3500	80	10.28	8.98	**1.30**	**12.6**	12.69	9.47	**3.2**	**25.4**
3500	60	9.44	8.23	**1.21**	**12.8**	11.35	8.71	**2.6**	**23.3**
3500	40	8.18	7.27	**0.91**	**11.1**	9.68	7.76	**1.9**	**19.9**
3500	20	6.66	6.14	**0.53**	**7.9**	7.85	6.53	**1.3**	**16.8**
2500	100	9.62	8.44	**1.18**	**12.2**	11.72	9.04	**2.7**	**22.9**
2500	80	8.49	7.67	**0.82**	**9.7**	10.43	8.06	**2.4**	**22.7**
2500	60	7.61	6.90	**0.71**	**9.3**	9.25	7.37	**1.9**	**20.3**
2500	40	6.25	5.81	**0.44**	**7.1**	7.57	6.22	**1.4**	**17.9**
2500	20	4.93	4.83	**0.10**	**2.0**	6.11	5.16	**0.9**	**15.5**

Table 1b – Reduction in Convective Heat Transfer Rates with Zircotec Smooth Manifold

heat flux		225 kg/hr				450 kg/hr			
Eng. Spd	Engine	Baseline	Zircotec Smooth	Change	Change	Baseline	Zircotec Smooth	Change	Change
RPM	Load / %	kW	kW	kW	%	kW	kW	kW	%
3500	100	10.60	8.58	**2.02**	**19.1**	13.23	9.29	**3.9**	**29.8**
3500	80	10.28	7.95	**2.33**	**22.6**	12.69	8.92	**3.8**	**29.7**
3500	60	9.44	7.36	**2.08**	**22.1**	11.35	8.16	**3.2**	**28.1**
3500	40	8.18	6.54	**1.64**	**20.0**	9.68	7.20	**2.5**	**25.6**
3500	20	6.66	5.51	**1.15**	**17.3**	7.85	5.98	**1.9**	**23.8**
2500	100	9.62	7.59	**2.03**	**21.2**	11.72	8.52	**3.2**	**27.3**
2500	80	8.49	6.72	**1.77**	**20.8**	10.43	7.61	**2.8**	**27.0**
2500	60	7.61	6.14	**1.48**	**19.4**	9.25	6.78	**2.5**	**26.8**
2500	40	6.25	5.30	**0.95**	**15.2**	7.57	5.74	**1.8**	**24.1**
2500	20	4.93	4.36	**0.57**	**11.5**	6.11	4.70	**1.4**	**23.1**

Results (cont.):

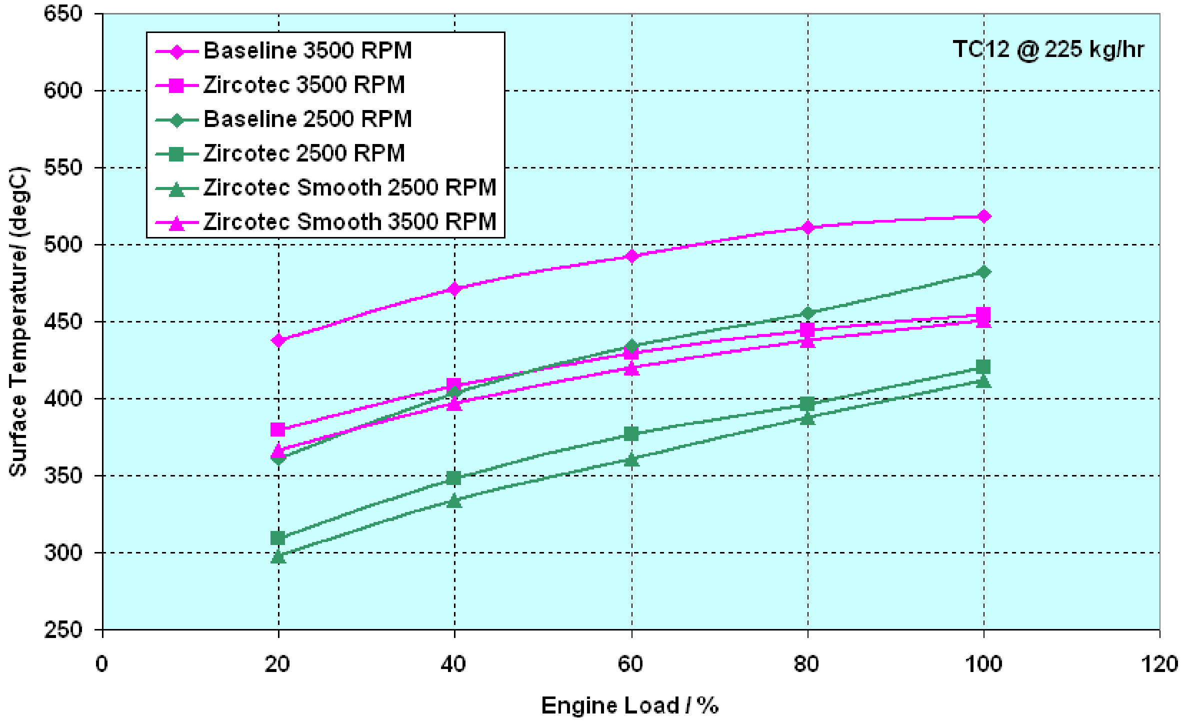

Figure 5 – Surface Temperatures at Location TC12 for Cooling Flow of 225 kghr^{-1}

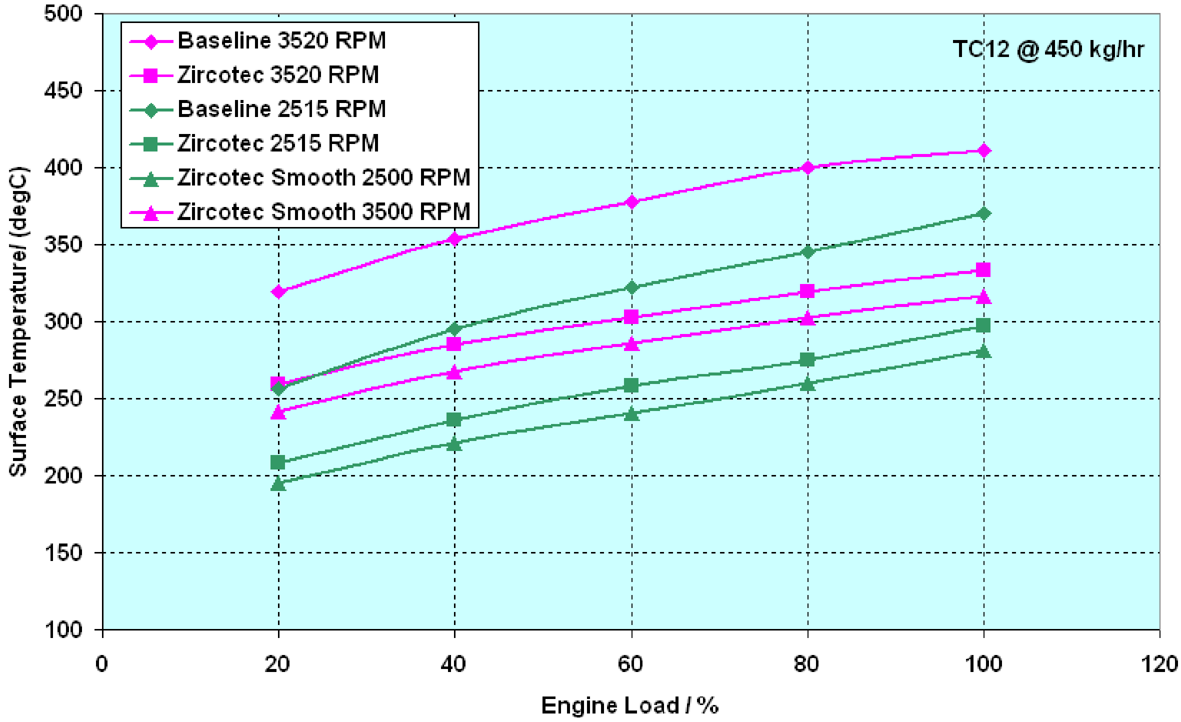

Figure 6 – Surface Temperatures at Location TC12 for Cooling Flow of 450 kghr^{-1}

Results (cont.):

Table 2a – Reduction in Surface Temperatures at Location TC12 with Original Finish Zircotec Manifold

TC12		225 kg/hr			450 kg/hr		
Eng. Spd	**Engine**	**Baseline**	**Zircotec Rough**	**Change**	**Baseline**	**Zircotec Rough**	**Change**
RPM	**Load / %**	**degC**	**degC**	**degC**	**degC**	**degC**	**degC**
3500	100	518	455	**63**	411	333	**78**
3500	80	512	445	**67**	400	319	**80**
3500	60	493	430	**63**	378	303	**75**
3500	40	471	408	**63**	354	285	**69**
3500	20	438	379	**59**	320	260	**60**
2500	100	482	421	**62**	370	297	**73**
2500	80	455	396	**59**	345	275	**70**
2500	60	435	377	**58**	323	259	**64**
2500	40	404	348	**55**	295	236	**59**
2500	20	361	309	**52**	257	208	**48**

Table 2b – Reduction in Surface Temperatures at Location TC12 with Smoothed Finish Zircotec Manifold

TC12		225 kg/hr			450 kg/hr		
Eng. Spd	**Engine**	**Baseline**	**Zircotec Smooth**	**Change**	**Baseline**	**Zircotec Smooth**	**Change**
RPM	**Load / %**	**degC**	**degC**	**degC**	**degC**	**degC**	**degC**
3500	100	518	451	**67**	411	317	**95**
3500	80	512	438	**73**	400	303	**97**
3500	60	493	420	**73**	378	286	**92**
3500	40	471	397	**74**	354	268	**86**
3500	20	438	367	**71**	320	241	**78**
2500	100	482	412	**70**	370	282	**88**
2500	80	455	388	**67**	345	260	**85**
2500	60	435	361	**73**	323	241	**82**
2500	40	404	335	**69**	295	221	**74**
2500	20	361	299	**63**	257	195	**62**

Results (cont.):

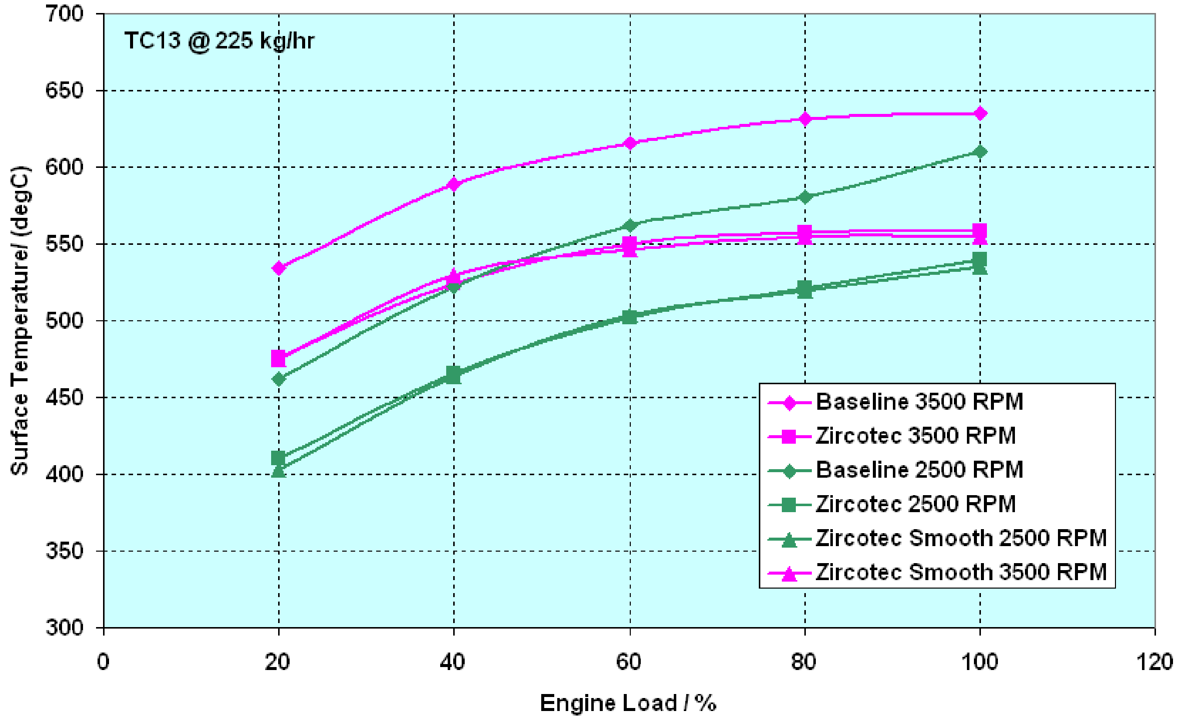

Figure 7 – Surface Temperatures at Location TC13 for Cooling Flow of 225 $kghr^{-1}$

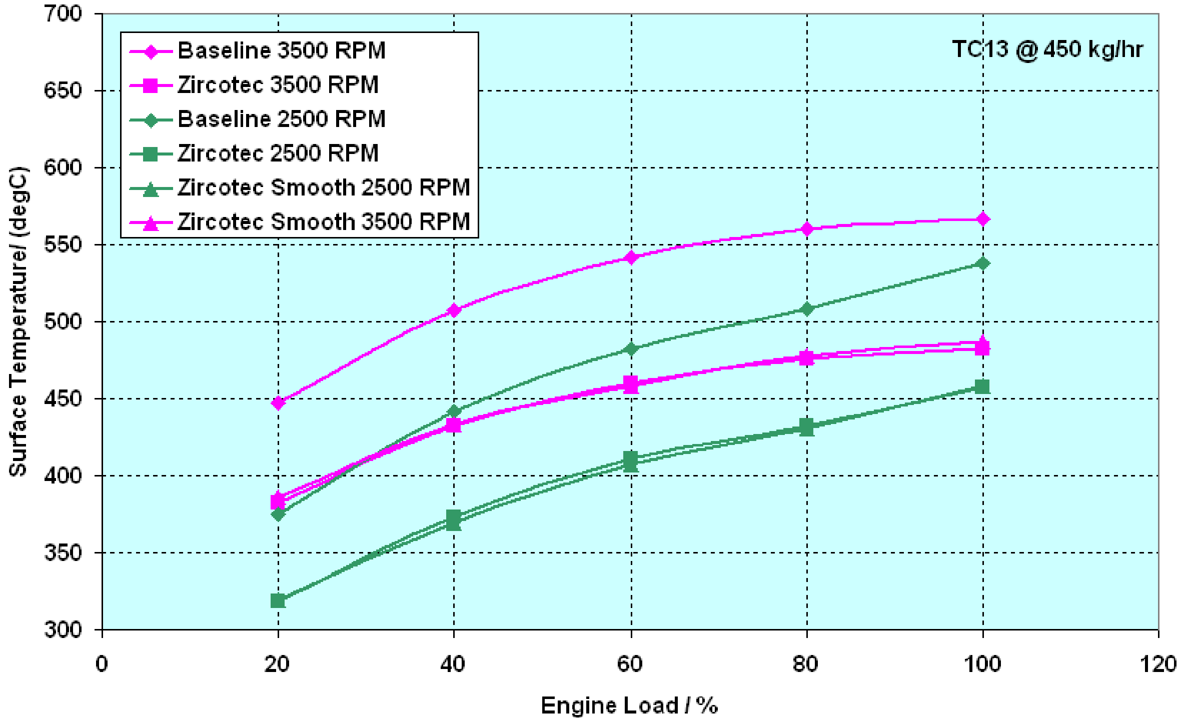

Figure 8 – Surface Temperatures at Location TC13 for Cooling Flow of 450 $kghr^{-1}$

Results (cont.):

Table 3a – Reduction in Surface Temperatures at Location TC13 with Original Finish Zircotec Manifold

TC13		225 kg/hr			450 kg/hr		
Eng. Spd	Engine	Baseline	Zircotec Rough	Change	Baseline	Zircotec Rough	Change
RPM	Load / %	degC	degC	degC	degC	degC	degC
3500	100	635	559	76	567	482	85
3500	80	632	557	74	560	476	85
3500	60	615	550	65	541	460	81
3500	40	589	524	65	508	432	75
3500	20	534	476	59	447	382	65
2500	100	611	540	71	538	458	80
2500	80	581	522	59	509	432	77
2500	60	562	502	60	482	411	71
2500	40	523	465	57	441	374	68
2500	20	462	410	52	375	319	56

Table 3b – Reduction in Surface Temperatures at Location TC13 with Smoothed Finish Zircotec Manifold

TC13		225 kg/hr			450 kg/hr		
Eng. Spd	Engine	Baseline	Zircotec Smooth	Change	Baseline	Zircotec Smooth	Change
RPM	Load / %	degC	degC	degC	degC	degC	degC
3500	100	635	555	80	567	487	80
3500	80	632	555	77	560	478	82
3500	60	615	546	69	541	459	83
3500	40	589	530	59	508	434	74
3500	20	534	475	59	447	386	61
2500	100	611	535	76	538	458	79
2500	80	581	519	62	509	430	78
2500	60	562	503	58	482	407	75
2500	40	523	464	59	441	370	72
2500	20	462	403	59	375	319	56

Results (cont.):

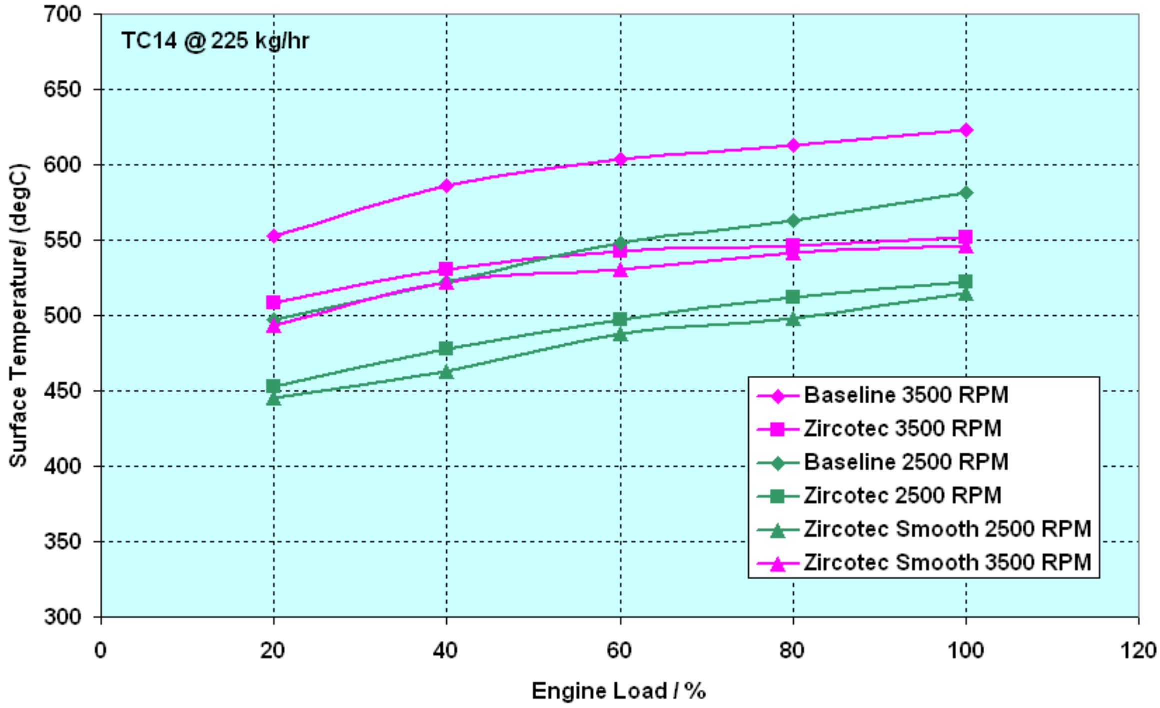

Figure 9 – Surface Temperatures at Location TC14 for Cooling Flow of 225 kghr^{-1}

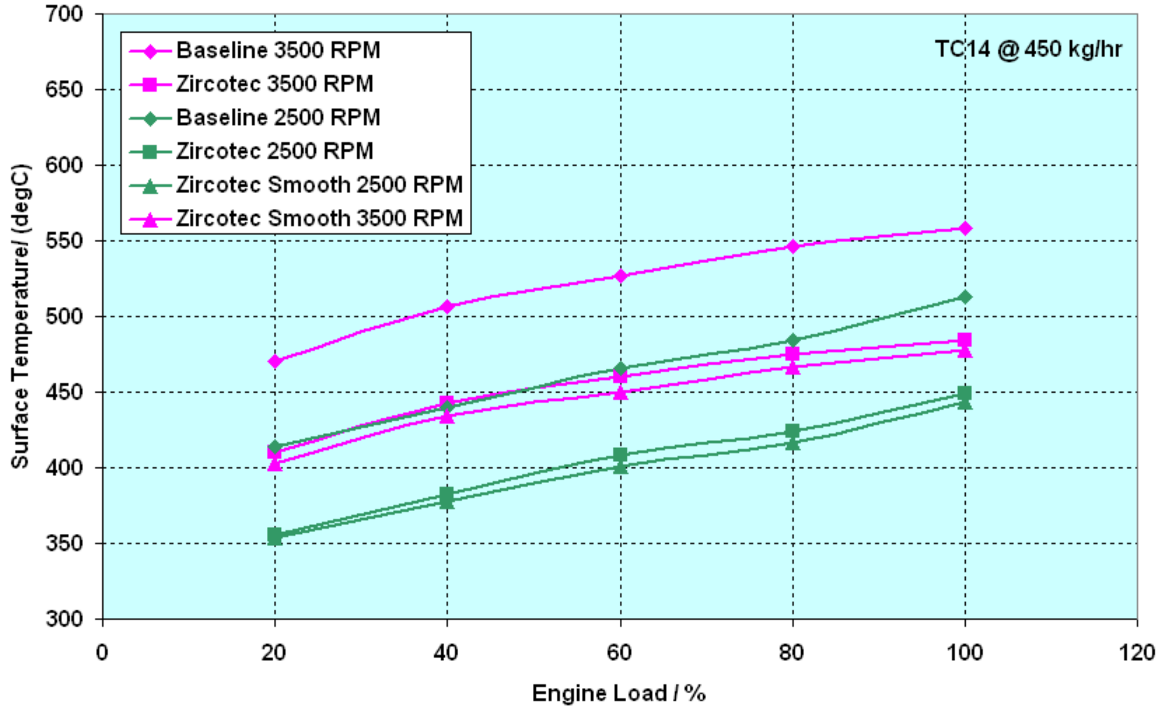

Figure 10 – Surface Temperatures at Location TC14 for Cooling Flow of 450 kghr^{-1}

Results (cont.):

Table 4a – Reduction in Surface Temperatures at Location TC14 with Original Finish Zircotec Manifold

TC14		225 kg/hr			450 kg/hr		
Eng. Spd	**Engine**	**Baseline**	**Zircotec Rough**	**Change**	**Baseline**	**Zircotec Rough**	**Change**
RPM	**Load / %**	**degC**	**degC**	**degC**	**degC**	**degC**	**degC**
3500	100	623	552	**71**	559	484	**75**
3500	80	613	546	**67**	546	475	**71**
3500	60	604	542	**61**	527	460	**67**
3500	40	587	531	**56**	506	443	**63**
3500	20	553	509	**44**	470	410	**60**
2500	100	581	523	**59**	513	450	**63**
2500	80	563	512	**51**	484	425	**59**
2500	60	548	497	**51**	466	408	**58**
2500	40	522	478	**44**	440	382	**57**
2500	20	497	453	**44**	414	355	**58**

Table 4b – Reduction in Surface Temperatures at Location TC14 with Smoothed Finish Zircotec Manifold

TC14		225 kg/hr			450 kg/hr		
Eng. Spd	**Engine**	**Baseline**	**Zircotec Smooth**	**Change**	**Baseline**	**Zircotec Smooth**	**Change**
RPM	**Load / %**	**degC**	**degC**	**degC**	**degC**	**degC**	**degC**
3500	100	623	546	**77**	559	478	**81**
3500	80	613	542	**71**	546	466	**80**
3500	60	604	531	**73**	527	450	**77**
3500	40	587	523	**64**	506	435	**71**
3500	20	553	493	**60**	470	403	**68**
2500	100	581	514	**67**	513	444	**69**
2500	80	563	498	**65**	484	417	**67**
2500	60	548	488	**60**	466	401	**65**
2500	40	522	463	**59**	440	378	**62**
2500	20	497	445	**52**	414	354	**60**

Results (cont.):

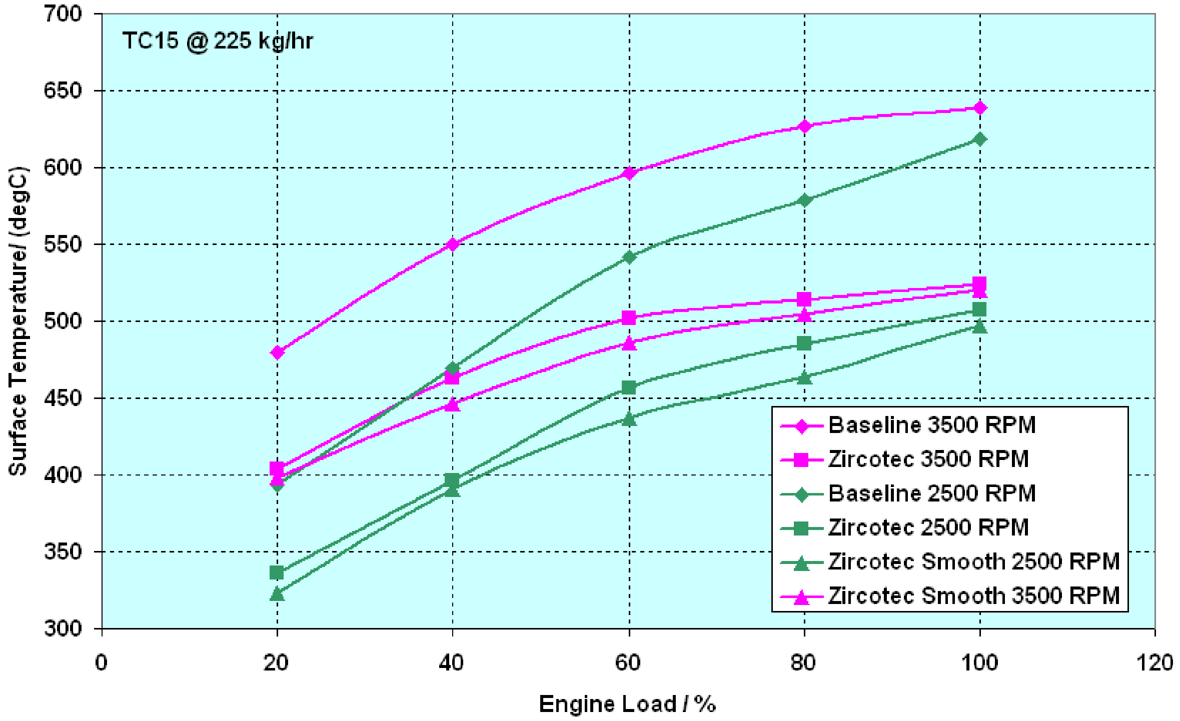

Figure 11 – Surface Temperatures at Location TC15 for Cooling Flow of 225 kghr^{-1}

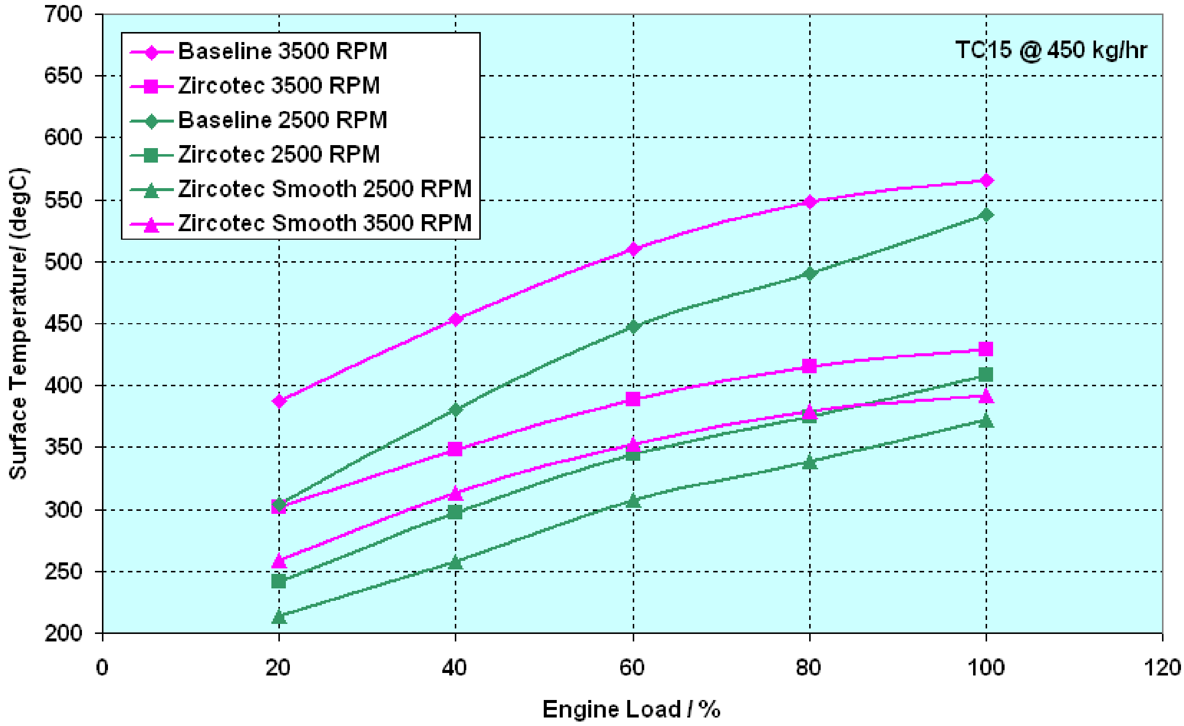

Figure 12 – Surface Temperatures at Location TC15 for Cooling Flow of 450 kghr^{-1}

Results (cont.):

Table 5a – Reduction in Surface Temperatures at Location TC15 with Original Finish Zircotec Manifold

TC15		225 kg/hr			450 kg/hr		
Eng. Spd	**Engine**	**Baseline**	**Zircotec Rough**	**Change**	**Baseline**	**Zircotec Rough**	**Change**
RPM	**Load / %**	**degC**	**degC**	**degC**	**degC**	**degC**	**degC**
3500	100	639	524	**115**	565	429	**136**
3500	80	627	514	**113**	548	416	**133**
3500	60	597	502	**95**	510	388	**121**
3500	40	550	463	**86**	454	349	**105**
3500	20	479	403	**76**	388	302	**86**
2500	100	619	508	**111**	538	409	**129**
2500	80	579	485	**94**	491	374	**116**
2500	60	542	457	**85**	447	344	**103**
2500	40	470	397	**73**	381	297	**84**
2500	20	393	337	**57**	304	242	**62**

Table 5b – Reduction in Surface Temperatures at Location TC15 with Smoothed Finish Zircotec Manifold

TC15		225 kg/hr			450 kg/hr		
Eng. Spd	**Engine**	**Baseline**	**Zircotec Smooth**	**Change**	**Baseline**	**Zircotec Smooth**	**Change**
RPM	**Load / %**	**degC**	**degC**	**degC**	**degC**	**degC**	**degC**
3500	100	639	520	**119**	565	392	**173**
3500	80	627	505	**122**	548	380	**169**
3500	60	597	486	**111**	510	353	**157**
3500	40	550	447	**103**	454	314	**141**
3500	20	479	398	**81**	388	260	**128**
2500	100	619	497	**121**	538	372	**166**
2500	80	579	464	**115**	491	339	**152**
2500	60	542	437	**104**	447	307	**140**
2500	40	470	391	**79**	381	258	**123**
2500	20	393	323	**70**	304	214	**90**

Results (cont.):

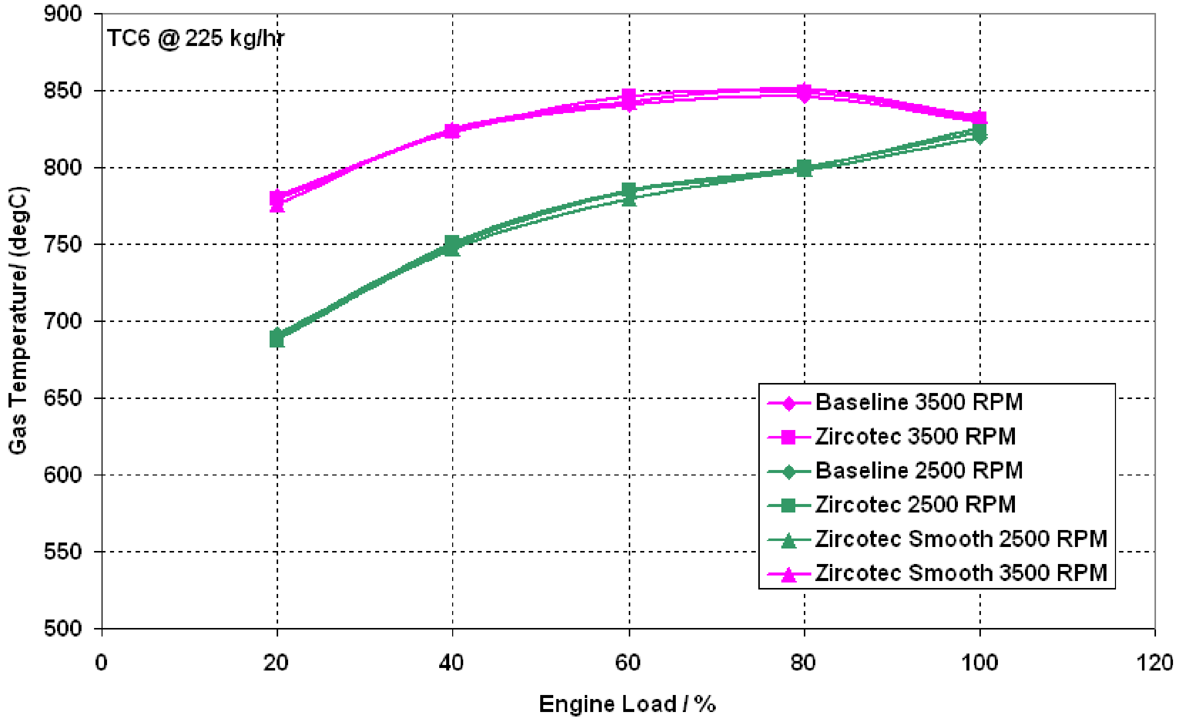

Figure 13 – Gas Temperatures at Location TC6 for Cooling Flow of 225 kghr^{-1}

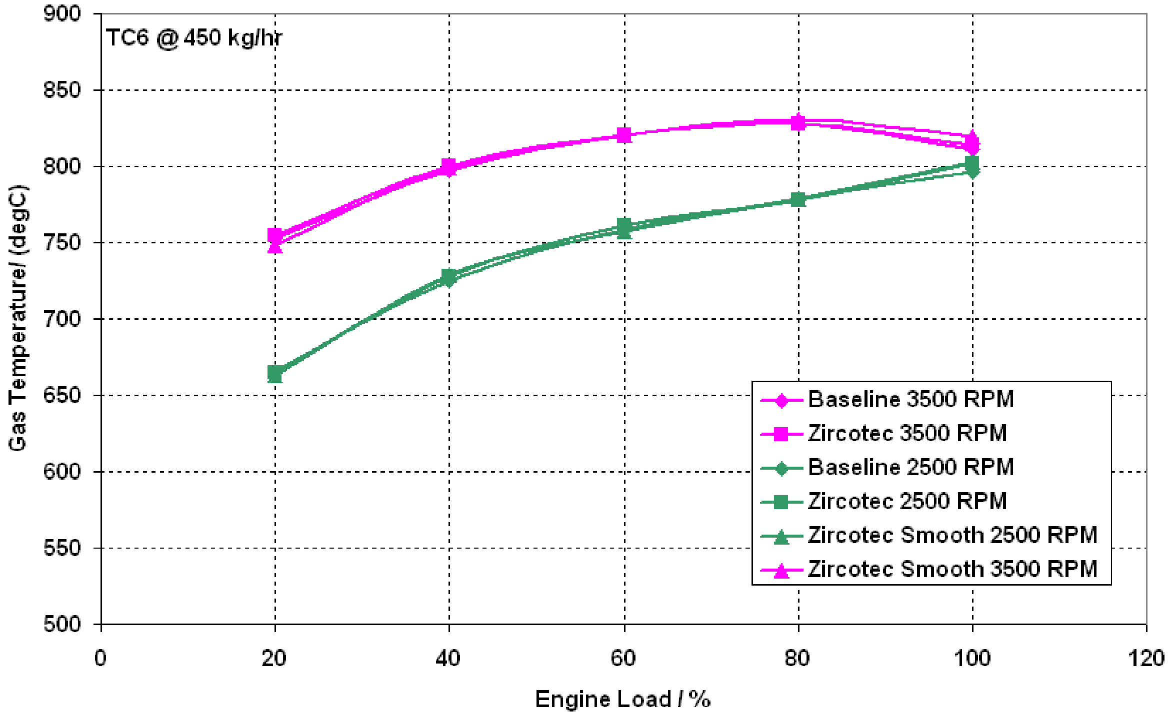

Figure 14 – Gas Temperatures at Location TC6 for Cooling Flow of 450 kghr^{-1}

Results (cont.):

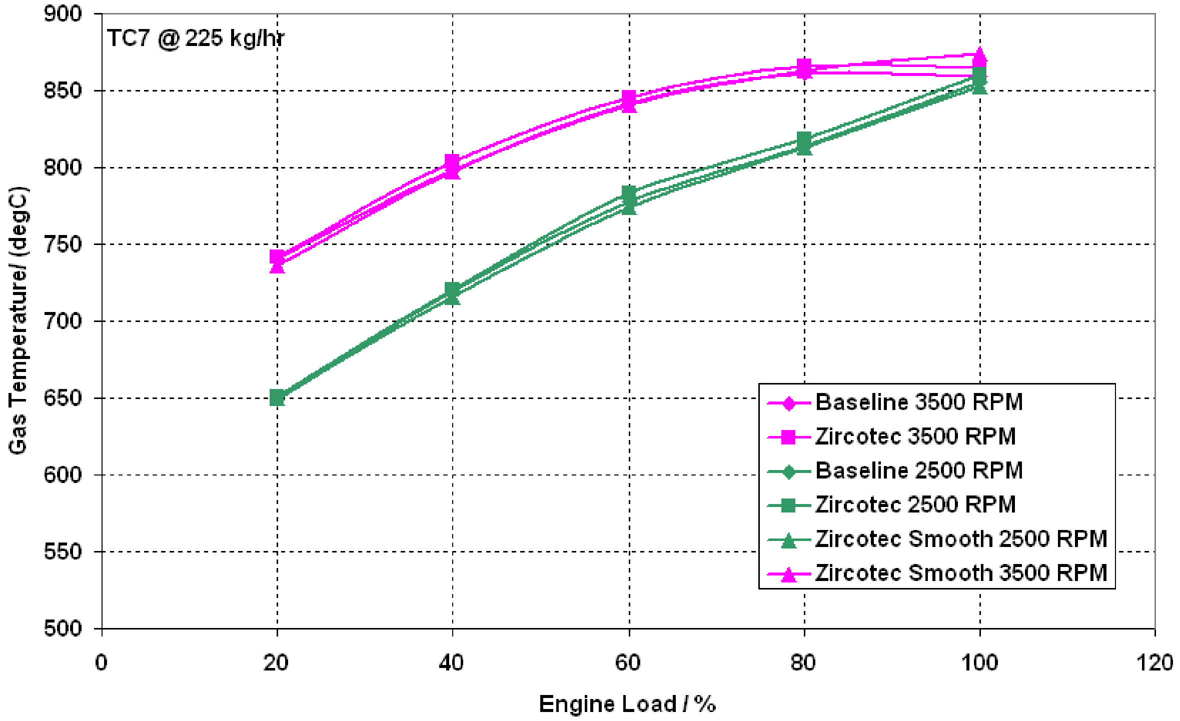

Figure 15 – Gas Temperatures at Location TC7 for Cooling Flow of 225 kghr^{-1}

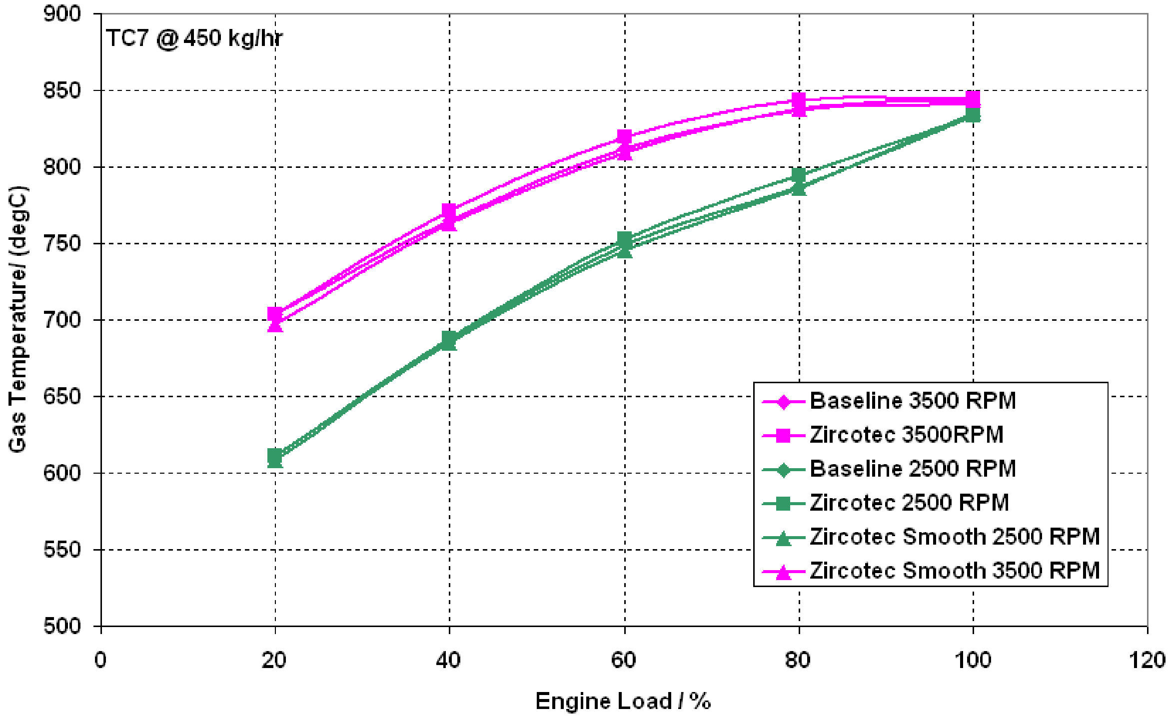

Figure 16 – Gas Temperatures at Location TC7 for Cooling Flow of 450 kghr^{-1}

Results (cont.):

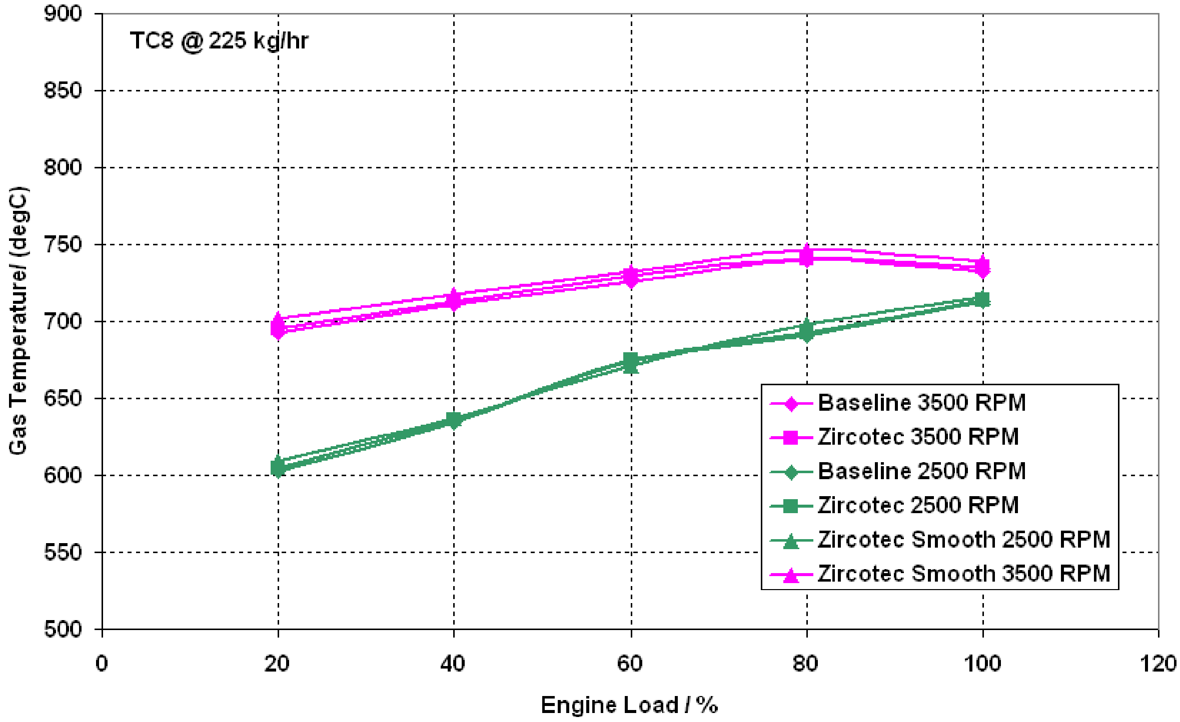

Figure 17 – Gas Temperatures at Location TC8 for Cooling Flow of 225 kghr^{-1}

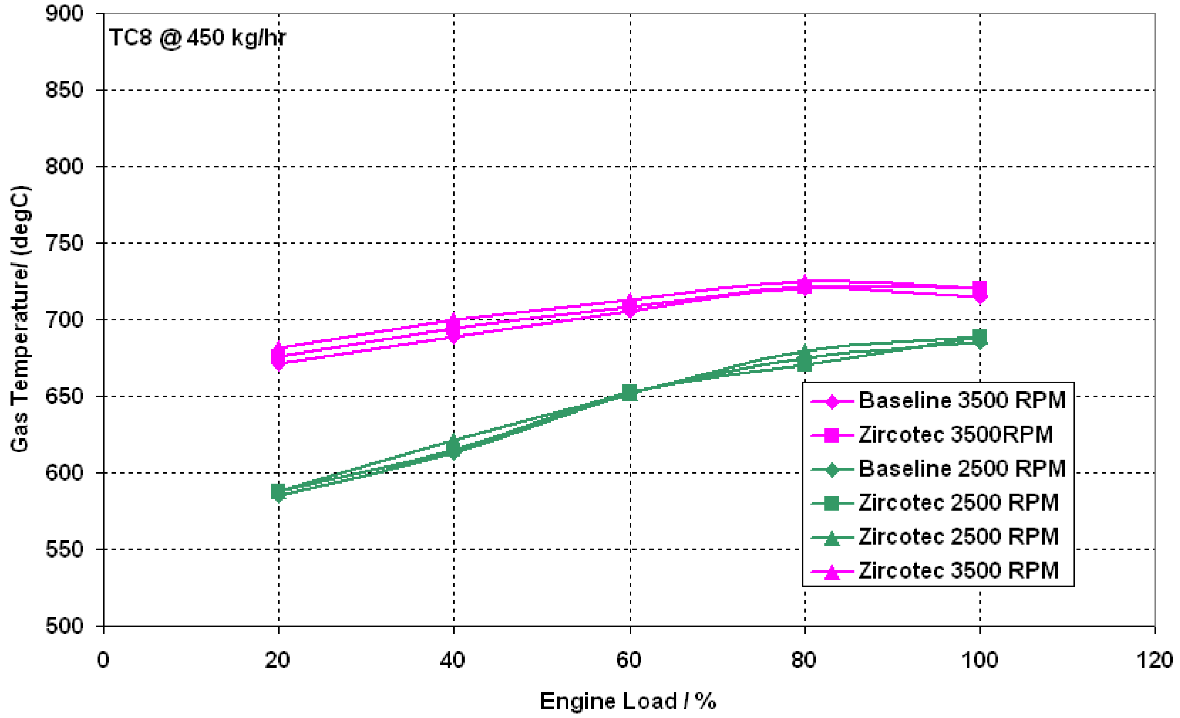

Figure 18 – Gas Temperatures at Location TC8 for Cooling Flow of 450 kghr^{-1}

Results (cont.):

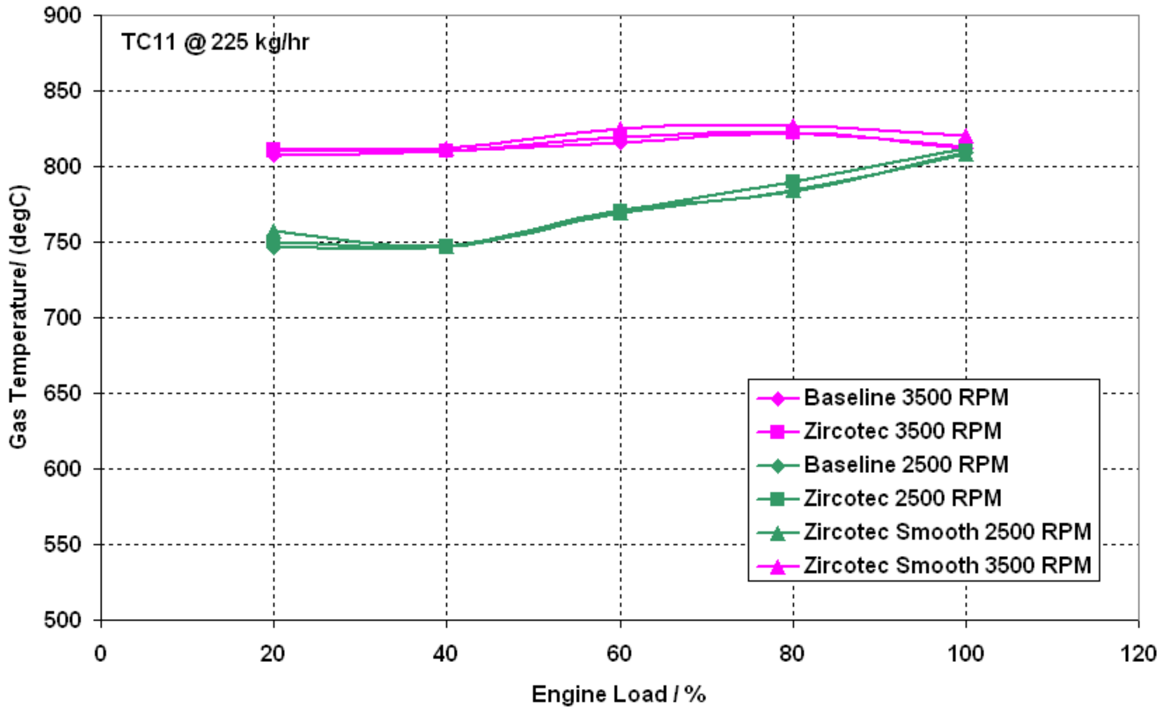

Figure 19 – Gas Temperatures at Location TC11 for Cooling Flow of 225 kghr^{-1}

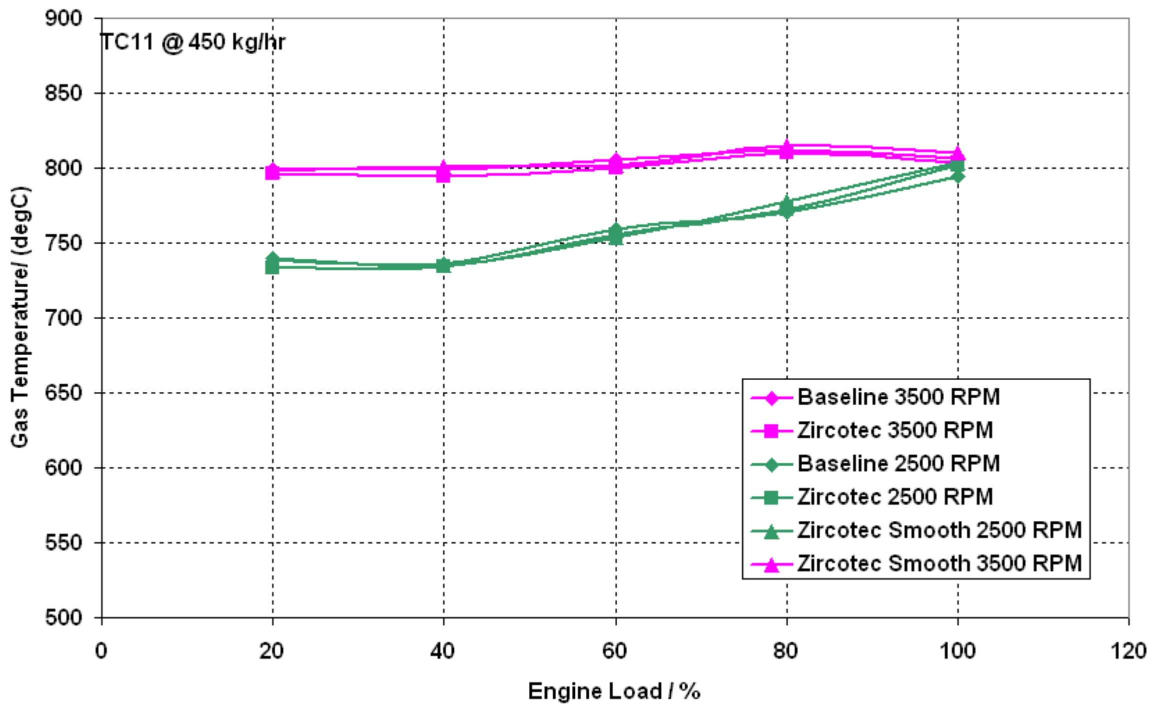

Figure 20 – Gas Temperatures at Location TC11 for Cooling Flow of 450 kghr^{-1}

Results (cont.):

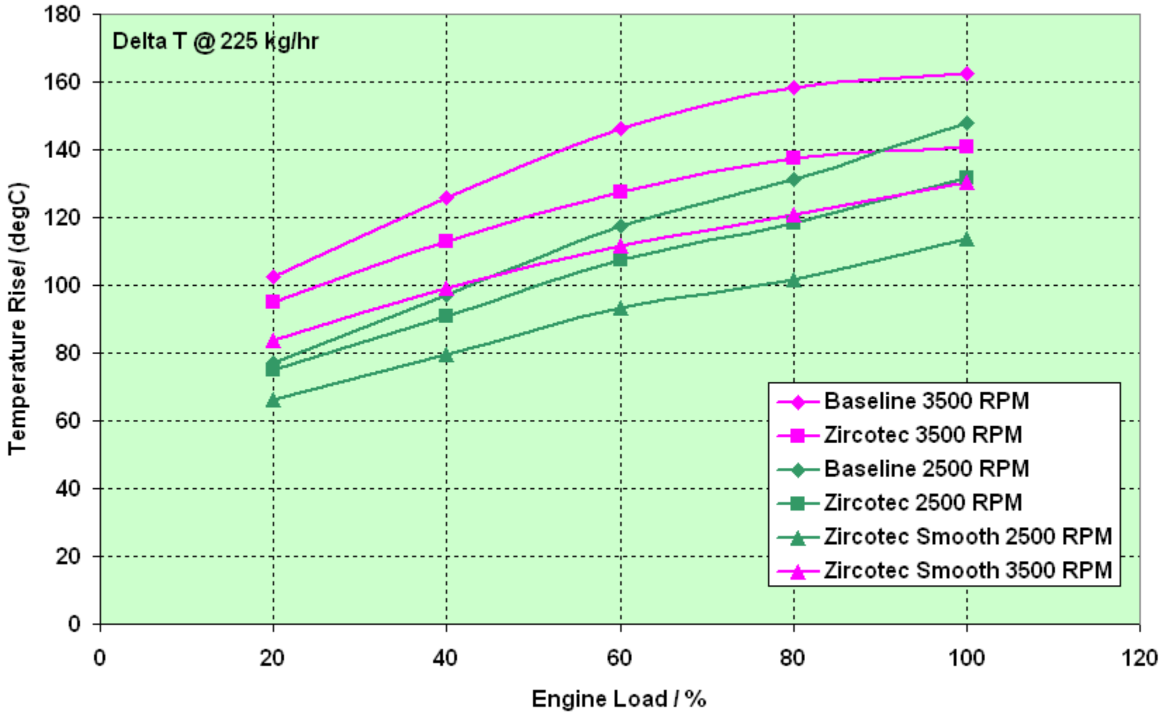

Figure 21 – Air Temperature Rise Across Encapsulation for Cooling Flow of 225 kghr^{-1}

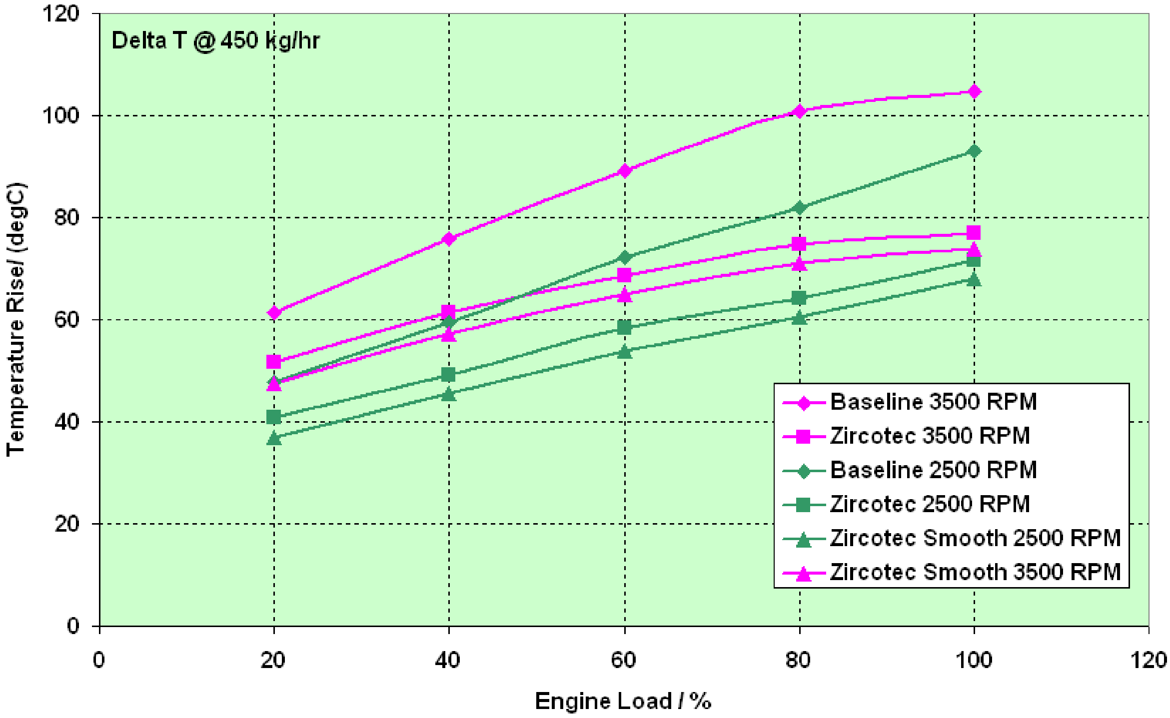

Figure 22 – Air Temperature Rise Across Encapsulation for Cooling Flow of 450 kghr^{-1}

Results (cont.):

Gas temperatures for location TC9 – data suspect, not presented.

Gas temperatures for location TC10 – data suspect, not presented.

Discussion of Results:

Heat Transfer Rates

Figures 3 and 4 show the heat transfer rates to the cooling air convected through the exhaust manifold encapsulation. Heat transfer increases with cooling flow rate. The plot data are also presented in Table 1a and 1b with an analysis of the difference in rates between respectively the Baseline and the original finish and smooth finish Zircotec coated manifolds. Absolute differences and percentage changes are presented. In general, heat transfer rates are lower for the Zircotec coated manifold and lowest for the smoothed surface Zircotec manifold. Differences are greatest at highest engine loads for a given engine speed. Temperature differentials across the encapsulation are shown in Figures 21 and 22.

Surface Boundary Layer Temperatures

Figures 5 to12 inclusive show the surface temperatures at locations TC12 to TC15. These thermocouples are measuring the temperature at the boundary layer interface between the bead and the surface. Tables 2 to 5 present the data with an analysis of the absolute differences between the Baseline and Zircotec coated manifolds. In all cases the surface temperature of the Zircotec manifolds is significantly lower than the Baseline.

In the case of TC13 there appears to be little difference in the surface temperature of the original finish and smoothed finish Zircatec manifolds. However, in the cases of TC12, TC14, and TC15 there is a noticeable reduction in measured surface temperature. Logically, one would expect all of the surface measurements to behave as TC13, i.e. little or no change in temperature between the original and smoothed finish, since the smoothing of the surface reduces the heat transfer area but will have little impact on the temperature differential driving the heat flux. A lower surface temperature suggests that the smoothing process (working of the surface) has in some way influenced (i.e. reduced) the conductivity of the Zircotec coating and is contributing to a further reduction of the heat flux magnitude by reducing the manifold surface temperature.

Exhaust Gas Temperatures

Before considering the measured gas temperature results it is important to note that with use of thermocouples at elevated temperature in an engine exhaust there is an uncertainty in measurement typically of the order of ± 5 degC.

Figures 17 to 20 inclusive show the exhaust gas temperatures at exhaust port exit locations TC8 and TC11 (results for TC9 and TC10 were suspect and are not presented in this report). Within the bounds of measurement uncertainty the data show that the engine-out boundary condition is repeatable.

Figures 13 and 14 show the exhaust gas temperatures at location TC6. This is the junction between the down pipes from two adjacent cylinders. Within the bounds of measurement uncertainty no significant difference in gas temperature is observed.

Figures 15 and 16 show the exhaust gas temperatures at location TC7. This is close to the exit of the manifold and any impact of reduced heat transfer should be most pronounced at this location. Strictly, within the bounds of measurement uncertainty no significant difference in gas temperature is observed, however, there does appear to be an increase in the underlying trend value with the Zircotec coated manifold. This result would be consistent with a reduced heat transfer rates to the encapsulation i.e. more heat retained by the exhaust gas. The difference in heat transfer between the Baseline and Zircotec manifolds when expressed as a fraction of the sensible enthalpy flux convected in the exhaust gas stream is small. Simple estimations of the resultant temperature rise of the exhaust gas by virtue of the measured reduction in heat losses through the manifold walls suggest magnitudes of a similar order to the measurement uncertainty.

Effect on Underbonnet Gas Temperatures

It is reasonable to infer that under bonnet temperatures will be reduced with the Zircotec manifold but it is not possible to quantify this reduction without performing in-vehicle tests since the engine compartment flow regime will be a strong function of the cooling pack blockage, engine orientation, detailed bay geometry, and so on.

Conclusions:

1. The Zircotec coated engine exhaust manifold was found to reject significantly less heat to its surroundings under conditions of forced convection when compared to an identical but uncoated Baseline manifold.
2. Smoothing of the Zircotec coating resulted in a further significant reduction in heat rejection.
3. Within the specified range of test conditions, the Zircotec manifold reduced convective heat transfer by up to 26.7% for the original surface finish and 29.8% for the smoothed finish.
4. Manifold surface boundary layer temperatures were found to be significantly lower with the Zircotec manifolds when compared to the uncoated Baseline manifold.
5. At 3 of the 4 measurement locations the surface temperatures of the Zircotec coated manifold were found to be significantly lower in the smoothed case. It is speculated that the smoothing process reduces the conductivity of the coating, though the mechanism is not understood.
6. Within the specified range of test conditions, the Zircotec manifold displayed surface temperature reductions of up to 136 degC (original finish) and 173 degC (smoothed finish) when compared to the uncoated Baseline manifold.
7. With reduced exhaust manifold heat transfer exhaust gas temperature will be expected to increase. The magnitude of this increase was found to be small and confined to the uncertainty limits of the thermocouple measurements
8. It is reasonable to infer that under bonnet temperatures will be reduced with the Zircotec manifold but it is not possible to quantify this reduction without performing in-vehicle tests since the engine compartment flow regime will be a strong function of the cooling pack blockage, engine orientation, detailed bay geometry, and so on.

Recommendations:

1. Investigate the possible benefits of using Zircotec coated manifolds to lower under bonnet component temperatures in-vehicle.
2. Following smoothing, investigate the changes in coating uniformity and thickness that appear to have reduced the thermal conductivity of the surface.
3. Investigate the possible benefits to reduced catalyst light-off times during cold start with a Zircotec coated manifold/ full exhaust. These tests should be carried out on a chassis dynamometer with cooling fan flow set to replicate the air speed of a moving vehicle.

Attachments/Notes:

None.

	Name	Position	Signature	Date
Prepared By	Dr Les Smith	Senior Consultant, Powertrain Engineering	[signature]	6/11/07
Concurred By	Dr Anthony Baxendale	Manager, Powertrain Engineering	A H Baxendale [signature]	6/11/07