<u>THE THERMAL PROPERTIES OF HIGH TEMPERATURE CERAMIC COATINGS</u>

There are three modes of heat transfer which determine the thermal behavior of any object:

1) Conduction,
2) Convection, and
3) Radiation

When choosing a ceramic coating for high temperature use, each of these modes of heat transfer needs to be considered. For many applications, retention of heat, say in an exhaust gas, is a desirable characteristic. In other applications, for example a coating on a piston, removing as much heat from the piston surface as fast as possible is important.

The ability for a coating to transfer heat from its hotter surface through to its cooler surface is determined by its "Thermal Conductivity". A coating with a <u>high</u> "Thermal Conductivity" will quickly transfer heat from its hotter surface to its cooler surface, where it can be dissipated. Conversely, a coating with a <u>low</u> "Thermal Conductivity" will only slowly transfer heat from its hotter surface to its cooler surface. Such a coating is a thermal insulator.

Clearly, coatings that have high "Thermal Conductivity" and can quickly conduct heat are preferred in applications where it is important to remove as much heat as quickly as possible. Coatings that have low "Thermal Conductivity" are preferred in such applications where it is important to insulate the exhaust system to maximize power output.

It is in the dissipation of heat from a coating <u>surface</u> where "Convective" and "Radiative" heat transfer come into play. In typical situations, coated parts are used in environments where their outer surface encounters a gas such as air, or a liquid such as water. It is the motion of this fluid that will then tend to move any heat that is released from the surface of the coating away from the part. This makes intuitive sense. A motorcycle exhaust pipe will get hotter when stopped at a red light than when in operation at speeds where the air flow at the pipe surface quickly moves the heat away from the pipe. So "Convective" heat transfer in these instances comes into play.

But just <u>how</u> this heat is released from the coated surface, as well as how quickly this heat is released depends on a third mode of heat transfer – "Radiation". When a coating receives heat energy at one of its surfaces (inner or outer) that heat energy can either be absorbed or reflected. When the heat is reflected it simply reverses its direction of flow and is, more or less, directed back toward its source. Materials that are highly reflective of heat are typically those that we recognize as highly reflective of light – for instance, polished metals. On the other hand, there are other materials that don't reflect heat very well but, rather, tend to absorb it. Some common materials that have this property are encountered in every day life and include, for example, asphalt driveways that radiate quite a bit of heat in the evening after absorbing heat from the sun all day long, or the walls of brick buildings when you lean up against them after a long, hot day.

Of course, any material can only hold so much heat (it's "Heat Capacity"). After some time it gets to a point where it can no longer accept any more heat without releasing – "Emitting" – some of its stored up heat. This release of heat, most often into the air at the surface of a coating, occurs through "Radiation" of the heat (like a "radiator"). A material that will absorb and readily radiate heat to its surroundings is a material that is said to have <u>high</u> "Thermal Emissivity". These include the asphalt driveways and brick walls of the world as well as a variety of other highly emissive materials. On the other hand, things like polished metal surfaces have low "Thermal Emissivity". Of course, the direction that the heat is emitted will be primarily from the hotter side of the coating that is being heated and out the cooler side of the coating that is being heated– heat will flow from "hot" to "cold".

Various ceramic coatings are used in engines to improve performance. There are two basic types of thermal management coatings for under-the-hood applications:

1. Thermal Barrier Coatings

Thermal-barrier coatings (TBCs) are used to reduce heat migration, reflecting heat rather than absorbing it. They, therefore, must have have high "Thermal Reflectivity" as well as low "Thermal Conductivity" to prevent the absorption and transmission of heat into and through the coating. They should also have a high "Specific Heat" in order to have the capability of holding a predetermined quantity of heat to limit the release of waste heat to their environment, and be sufficiently thin or low enough in mass to limit the flow of any stored heat in a reverse direction to an incomring colder gas charge. They may be applied to piston-top surfaces and top ring grooves, combustion chambers, exhaust-valve heads and faces, exhaust manifolds and headers, and inside exhaust ports.

When applied to piston tops, TBCs reflect heat back into the combustion chamber. The additional heat translates into more energy to push the pistons down. To the extent coating the piston tops makes the top surface smoother and minimizes the development of local hot spots on the pistons' surfaces, TBCs may decrease detonation potential. On the other hand, TBCs may prevent heat from dissipating down into the pistons and rings, through the cylinder wall, and into the water jacket; this may actually increase detonation potential. The tilt point is related to whether the engine will be subjected to heat over a long period (as in an endurance motor) or in short bursts (like a drag-race car).

Setting up a thermal barrier in the combustion chamber also helps the chamber retain heat for more power potential. Again, assuming detonation does not become a problem, this can increase combustion efficiency while lowering engine-coolant temperatures. Aluminum heads, which are said to reject heat quicker than traditional cast iron, may see particular benefits from TBCs. Barriers can also be applied to valve heads to keep them cooler.

Highly efficient metal-based piston coatings have the following properties:

		FOR REFERENCE:	
	U.S. Patent 5,477,820 to Ford Motor Co.	*[C-186 Piston Coat] Tenneco Exhaust System Apparatus*	*[V-136 Piston Coat] Third-Party Analytical Lab*
Thermal Conductivity (k)	0 – 21 W/mK	*[0.14 W/mK]*	*[0.65 W/mK]*
Density (ρ)	5000 – 9000 kg/m^3	*[1730 kg/m^3]*	*[~1730 kg/m^3]*
Specific Heat (C_p)	> 500 J/kgK	*[2000 J/kgK]*	*[1150 J/kgK]*
Coating Thickness (d)	75 – 122 μm	*[120-200 μm]*	*[25-50 μm]*
Thermal Diffusivity (α)	0 – 62 m^2/s	*[4.0 x 10^{-8} m^2/s]*	*[3.3 x 10^{-7} m^2/s]*

Coating the inside and outside surfaces of exhaust parts with TBCs is said to increase exhaust-gas velocity, reducing backpressure and reversion. Coating the inside of a mild-steel header smoothes the surface by eliminating corrosion and scale, which can enhance flow. Coating the outside reduces the ambient temperature, which may result in an overall temperature decline within the engine compartment.

2. Thermal Dispersant Coatings

These are the opposite of heat barriers: They radiate or disperse heat and have the requirement of having high "Thermal Emissivity" rather than high "Thermal Reflectivity" (Emissivity = 1 – Reflectivity). As opposed to Thermal Barrier Coatings, for Thermal Dispersant Coatings a high "Thermal Conductivity" is preferred. As previously stated, keeping heat in a piston chamber is good, provided you don't get into detonation. But if there is a detonation problem, a thermal dispersant can be used. Often, ceramic-based thermal dispersants take the place of traditional black paint and can be applied to brakes, intake manifolds, cylinder heads, oil pans, radiators, and intercoolers.

To summarize, the following thermal attributes for engine coatings apply:

Thermal Barrier Coatings

Interior Exhaust Pipe Coating:	Low Thermal Conductivity	High Reflectivity
Piston Coating	Low Thermal Conductivity	High Reflectivity

Thermal Dispersant Coatings

Exterior Exhaust Pipe Coating:	High Thermal Conductivity	High Emissivity
Cylinder Head Coating	High Thermal Conductivity	High Emissivity