

Catalyst for Improving the Combustion Efficiency of Petroleum Fuels in Diesel Engines

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Abstract

In 1996 an oil-soluble organo-metallic iron combustion catalyst was developed for use in Siemens-Westinghouse 501 D-5 104 MW combustion turbine engines. The product also included oil-soluble magnesium to reduce vanadium deposits and corrosion. This product resulted in significant reduction of smoke in the exhaust of engines operating in steady state and non-equilibrium start-up conditions. The overall effects were greater than predicted from the literature.

We extended this work to steam boilers and compression-ignited reciprocating engines. We have found that the iron-magnesium catalyst when added to Diesel and heavy fuel oil supplies, promotes complete and more efficient combustion in the engine, resulting in increased power, improved fuel economy and radically reduced smoke emission. Certain metals, including Mn, Fe, Cu, Ba, Ce and Pt, are known to have catalytic activity in combustion processes. The iron-magnesium combination acts synergistically to give greater activity than expected.

This paper presents data from tests conducted by a combustion turbine engine manufacturer and customer, a government testing laboratory and independent fleet tests. A mechanism for the catalysis is proposed.

Earlier papers presented on this subject are available from the SFA International web site at www.SFAInternational.com.^{1,2}

Initial Application in Combustion Turbines

In 1996, Siemens Westinghouse began start-up of a new power plant at Hanwha Energy in Inchon, Korea. There were initially three model 501 D5 104 MW combustion turbines with nine more in process of installation. The economics of the plant were based on use

¹ May, W. R. and Ramdas, R., "Catalyst for Improving the Combustion Efficiency of Diesel Fuels", 9th Annual India Oil & Gas Review Symposium, Mumbai, India, Sept. 9-10, 2002.

² May, W. R., "Catalyst for Improving the Combustion Efficiency of Petroleum Fuels", Technical Exchange Meeting, Aramco Engineering Services, Research and Development Center, Dhahran, Saudi Arabia, April 28-30, 2003.

of low sulfur waxy residual (LSWR) fuel oil from the Hanwha refinery adjacent to the power plant. Particulate matter in the exhaust was 120 – 150 mg./cu. M. exceeding the 60 mg./cu. M. requirement at the time. This requirement was reduced to 40 mg./cu. M. in 1998. Westinghouse began an investigation into the use of fuel additives containing combustion catalysts to solve the problem. This work was reported by Rising in 1997.³ SFA International, Inc. was invited to participate in this work.

Several metals are known to catalyze combustion of hydrocarbon fuels. These metals include manganese, iron, copper, barium, cerium, calcium and platinum. Reports in the literature indicate that 50% reduction in carbonaceous matter in the exhaust is the limit of effectiveness of these catalysts.⁴ There are positives and negatives to using these various metals. Manganese, while an effective catalyst, interferes with inhibition of vanadium by magnesium.⁵ Iron is thought to catalyze formation of sulfur trioxide leading to sulfuric acid formation limiting use to low sulfur fuels. Copper, barium and calcium are less effective and water-soluble salts of barium are highly toxic. Cerium and platinum are very expensive. It was decided that iron was the best choice for the catalyst.

An oil-soluble iron carboxylate was developed that was miscible in the fuel and could be combined with oil-soluble over-based magnesium used to inhibit vanadium in the fuel. This was a 6.0% oil-soluble iron-napthenate product. Particulate matter was reduced from 120-150 mg./cu. M. to <60 which met the initial Korean Ministry of Environment requirement in 1996-98. Westinghouse and Hanwha measured the data summarized in Table 1.

The second set of turbines came on line later in 1996 and testing continued with the catalyst in six units. Table 2 presents data taken between October 31 and Dec. 26, 1996 under varying loads and percents distillate oil in the LSWR fuel. These data demonstrated that <60 mg./M.³ could be achieved with 0% distillate oil and less than full load – see unit 3 data. The data remained above 40 mg./M.³ in most cases.

This work demonstrated that (1) lower particulates are found at high load, (2) distillate fuel yielded significantly lower particulates than LSWR residual fuel, and blending small

³ Rising, B., “Particulate Emission Reduction Using Additives, Power-Gen ’97 International Exhibition, Dallas, Texas, Dec. 1997. This paper can be found on SFA International’s web site at www.SFAInternational.com on the Library page.

⁴ May, Walter R., et.al., “High-Temperature Corrosion in Gas Turbines and Steam Boilers by Fuel Impurities. Part VIII. Evaluation of the Effects of Manganese, Calcium and Several Heavy Metals on Corrosion and Slag Formation”, Presented to the American Chemical Society Division of Fuel Chemistry, Inc., Symposium on Heavy Fuel Oil Additives, New York, NY, April 5, 1976.

⁵ Eliot, R. C., ed., **Boiler Fuel Additives for Pollution Reduction and Energy Saving**, Noyes Data Corp., Park Ridge, NJ, 1978.

amounts of distillate into the LSWR significantly reduced particulates and (3) the reduction of particulates was proportional to the concentration of catalyst.

The remaining turbines came on line in 1997 raising the total to 12 units. Heat recovery steam generators (HRSG) units were installed and the plant capacity increased to 1,800 MW. Dust loadings as low as 20 mg./M.³ at 40 ppm Fe were measured indicating more than 80% reduction in particulate loading. The Korean Ministry of Environment reduced the particulate level requirement to 40 mg./cu. M. in 1998. We were able to meet this requirement until mid-1998 when the Korean Ministry of Environment proscribed use of the fuel in the Province of Seoul. This plant now operates on liquefied natural gas.

Combustion Turbines – Hyundai Heavy Industries, Ltd., Daeson, Korea

Hyundai Heavy Industries Petroleum Subsidiary built a new refinery at Daeson. This refinery included an on-site power plant for the refinery and local area with four Westinghouse 501 D-5 104 MW combustion turbines similar to those at Hanwha's Inchon Plant. The fuel was a similar LSWR material although derived from Chinese crude oil rather than Indonesian in the case of Hanwha. Both SFA International, Inc. and a competitor competed for this business. The competitor introduced a dispersion type product with 15% iron and 2% Mg that was extensively tested. The results were unusual as indicated in Figure 1. The product shows a minimum at 45 ppm Fe with strong peaks on both sides. These data are not consistent with classical laws of catalysis.

SFA developed a colloidal dispersion product with high iron concentration. We found a dosage curve similar to that at Hanwha Energy shown in Figure 1 that follows classical laws of catalysis. SFA's FuelSpec® 118-1502 has shown lower particulate matter over the dosage range than competitor's product. SFA's FuelSpec® 118-1502 has an unusually small average particle size of 0.007 µm compared with average particle size of 0.05 µm for the competitor's product shown in Figure 2. We believe that the smaller particle size results in higher activity. We do not have an explanation for the fact that the competitor's product activity is not proportional to concentration other than the particle size.

A summary of data for 2004 is presented in Table 3. We have successfully reduced emissions by 90 % at 50 ppm iron dosage rate for a two period from mid 2003.

Low Pressure Boiler Application

The Korean Ministry of Environment required that the additive was tested in a government operated laboratory at the Korean Institute for Energy Research (KIER) to verify that it would function as required and not create any additional environmental problems. This work was carried out in a low-pressure test boiler at 50% and 75% loads. LSWR fuel from the Hyundai Daeson Refinery was used in the test. The data are presented in Table 4. These data are averages of up to 10 tests under each condition. The data demonstrate that SFA's FuelSpec® 118-1502 combustion catalyst reduces emissions

by 84.3 and 89.1% respectively at 50% and 75% loads. This compares with tests presented in Table 5 for the competitor's product one year earlier. We have no explanation as to why FuelSpec® 118-1502 performed better than the competitor's product at 50% load and compared similarly at 75% load. The tests were carried out eleven months apart on different fuel samples.

The reductions were similar to those observed in combustion turbine exhausts at Hanwha and Hyundai. There are no data in the literature that give similar reductions of particulate matter in boiler emissions.

Application in Reciprocating Engines

Reciprocating engines, whether spark-ignited or compression-ignited, represent a different set of problems from combustion turbines, steam boilers and industrial process heaters. Reciprocating engines have a more complex system of pistons and valves subject to abrasive wear and problems with deposit build-up and corrosion. SFA International has treated Wärtsilla V 32 18-cylinder 8 MW engines at the Coastal Power Plant at Nejapa, El Salvador. That experience indicated that over-based oil-soluble magnesium fuel additives could be used to inhibit vanadium deposits and prevent corrosion on piston crowns and valve seats. It also reduced corrosion and failure of turbocharger power rotors. There were no examples to our knowledge of iron-magnesium fuel additives used in automotive high-speed (4,000 rpm) compression-ignited engines used in transportation applications.

In 2002, a KIA 1.6 liter Diesel truck used at the Emission Control Products WLL blend plant and warehouse in Bahrain had a severe emission problem. It would not pass inspection for annual renewal of registration. It was suggested that the oil-soluble iron combustion catalyst combined with oil-soluble over-based magnesium might alleviate the emission problem so that the vehicle would pass inspection. The product was introduced into fuel at the rate of 30 ppm iron. A reduction of emissions was noted visually. The dosage level was increased 50 ppm. Emissions were visually eliminated and the vehicle passed inspection. More surprisingly, the driver of the vehicle reported that it had the power of a new truck.

Following this observation, an owner of a bus fleet in Bahrain agreed to test in six vehicles over a period of about 8 weeks. We reformulated the fuel additive so that 500 ml. of additive achieved 50 ppm iron and 10 ppm magnesium in 100 liters fuel. This additive was a combination of iron salts of 200-240 molecular weight highly oil soluble carboxylic acid and over-based magnesium oxide suspended in a carboxylic acid and sulfonic acid surfactant system. The product concentration was adjusted with Solvent 150, a highly aromatic solvent with a flash point >60° C. The fuel additive closely duplicated density and viscosity of the fuel so that mixing and distribution of the metals in the fuel in a homogeneous manner could be easily attained by agitation caused during normal driving conditions.

There was no attempt to control driving conditions or duplicate traffic conditions. The results of this test are given in Table 6. The six vehicles gave a range of 2.9% to +19.7 % reduction in fuel consumption. The vehicle with the lowest result was badly in need of major engine maintenance and was using oil heavily. The other vehicles had 200,000 km or more on the odometer. All drivers with positive results reported a noted increase in power from the engine.

Further tests were carried out on a single vehicle under the auspices of the Automotive Research Association of India (ARAI). The vehicle was a small Padmini Premier 137D sedan. The fuel line was attached to a calibrated measuring device so that the fuel use could be accurately measured. In a relatively short test, a total of some 1,500 km., fuel consumption was decreased 16.1% and 18.7% under city and highway conditions respectively. These data are presented in Table 7. The driver also noted an increase in power from the engine.

ARAI measured fuel consumption alternatively from carbon dioxide measurements in the exhaust. They discovered that with catalyst, the same amount of carbon dioxide was in the exhaust (at similar rpm and loads) with and without catalyst although 10% less fuel was passing through the engine. This test demonstrated that the catalyst promoted much more efficient combustion of the fuel.

Observations of Catalysis

Hydrocarbon fuels contain a mixture of molecules with varying hydrogen to carbon ratio. Three examples of combustion reactions are:



The exact chemical reaction in the combustion process depends on the molecular structure and distribution of the fuel.

In the combustion-ignited reciprocating engine, oxygen present in air is compressed to ignition temperature and fuel is injected. While the air is in slight excess, it can be safely assumed that a discreet 2nd order reaction is occurring with two distinct reactants, hydrocarbon fuel and oxygen.

The activation energy and temperature relationship is defined by the equation^{6,7}:

⁶ Dykstra, C. E., **Physical Chemistry**, Prentice Hall, Upper Saddle River, NJ 07458, 1997.

⁷ E. A. Moelwyn-Hughes, **Physical Chemistry**, Pergamon Press, New York, 1957.

$$K = s e^{-\Delta H_a/RT}$$

Where s is a constant and ΔH_a is the heat of activation. Set in logarithmic form, the equation becomes:

$$\ln k = \frac{-\Delta H_a}{R T} + \ln c$$

Differentiating this equation and integrating between limits yields:

$$\ln k_1 / k_2 = \frac{\Delta H_a(T_2 - T_1)}{R T} + \ln c$$

The Heat of Activation (ΔH_a) is the slope of the plot of $\ln k$ versus $1/T$ ($^{\circ}\text{K}$). The slope of the line for the combustion reaction is very steep indicating high activation energy is required to ignite the fuel. With the catalyst, the reaction appears to continue at lower temperatures. This leads to a lower slope of the line indicating that the catalyst lowers the activation energy for the reaction. This is illustrated in Figure 3.

The next problem is the ramification of reducing the reaction order by one. The rate expression for a classic second order reaction is:

$$dx / dt = k_2(a - x)(b - x)$$

The integrated form of this equation is:

$$k_2 t = 1/(a - b) \ln (b(a - x)) / a(b - x))$$

The reaction rate will follow a logarithmic decay as the reactants are consumed. The combustion process has a high activation energy indicated by the temperature required to cause combustion. The immediate reaction of fuel and oxygen results in an increase in temperature of the gaseous phase reactants and products. High pressure in the piston chamber resulting from the heat of combustion is converted to kinetic energy as the hot gasses expand, reduce temperature and provide work that causes the piston to move transferring kinetic energy to the crankshaft. This is followed by an immediate reduction in temperature in the piston chamber.

If the chemical reactants are of sufficient molecular weight and structural complexity to reduce the rate of reaction, the temperature can drop below the level for the activation

energy allow reaction to continue before reaction is complete. The result is unreacted hydrocarbon resulting in smoke and unburned fuel in the exhaust.

Catalytic controlled reactions follow two laws. The order of the reaction is reduced by an order of one, and the rate of reaction is proportional to the concentration of the catalyst. Our field observations indicate a catalytic effect on emissions and energy from the fuel as indicated from increased “power” and fuel efficiency.

The rate expression for a classic first order reaction is:

$$-d(a - x) / dt = k_1(a - x)$$

The integrated form of this equation is:

$$k_1t = \ln (a / (a - x))$$

Therefore, with catalysis the reaction will follow the decay of the concentration limiting reactant, generally the fuel in steady state conditions. Under accelerating conditions the reaction will follow the oxygen level when excess fuel is injected into the piston chamber. This is observed as smoke not entirely eliminated during acceleration.

The second law of catalysis requires that the effect is proportional to concentration of the catalyst. We found that the effect is directly proportional to the catalyst concentration. The smoke reduction follows an asymptotic curve up to 50 ppm catalyst. This follows the same observation as seen with combustion turbines illustrated in Figure 2. Above that level, the effect appears to be minimal. Since the catalytic effect (under steady state conditions) is the only observation beyond the fact that fuel and oxygen remain in 2nd order reaction supply in the combustion chamber, the system appears to have reduced to a first-order reaction.

Particulate Matter

In Table 8 we have examined the particulate matter in Diesel exhaust as a proportion of fuel. While we evaluated three combustion reactions, methane (CH₄), aliphatic hydrocarbon (CH₂) and aromatic hydrocarbon (CH), we took an average of moles of reactant for the latter two as an average for the combustion reaction in Diesel fuel. From that we calculated the gas volume at STP per gram mole of fuel.

We then calculated the fuel consumption for a 1,000 HP (745.7 Kw) engine. We made the following assumptions concerning gravimetric collection of “dust” or “soot” on a collection filter in a typical particulate matter test such as EPA Method 5:

1. Particulate matter measured >2μ is equal to particulate matter <2μ.
2. Unburned fuel is equal to total particulate matter.
3. Exhaust temperature at time of measurement is 200° C. (392° F.)

4. Engine efficiency is 20% based on fuel converted to mechanical or electrical power.

At 1,000 milligrams per cubic meter of dust, the equivalent fuel is 17.5 percent of that required to produce the desired power. A 90% reduction in emissions is equivalent to 13.4% reduction in fuel consumption by the engine. Therefore, the fuel savings we have observed with use of the catalyst is justified by the amount of particulate matter reduction measured.

Mechanism of Catalysis

The fuel additive developed for Hanwha Energy combustion turbines was designed to treat vanadium at 2 ppm and provide combustion catalysis at 30 ppm in the fuel. The product is bimetallic containing a solution of iron naphthenate and over-based magnesium carboxylate and sulfonate mixture. The combination yield far more activity than has been predicted from the literature. Magnesium has no catalytic effect on combustion and iron is known to reduce carbon matter in exhausts by about 50%.

Later work at the Hyundai Daeson Refinery Power Plant led to 50 ppm Fe dosage with a 5/1 to 7/1 ratio of iron to magnesium in the additive. Particulate emissions were reduced by 90% over a lengthy period (two years and continuing). This is far larger than the expected 50% reduction from the literature and has led us to postulate a mechanism of synergy between iron and magnesium in this catalyst.

We believe that the catalytic effect of iron and magnesium comes about from excitement of outer shell electrons into higher energy states. As these electrons decay to degeneracy, energy is released that maintains the activation energy for reaction even though the temperature is below that required to maintain reaction from that source. Two factors should be considered. The catalyst, while in solution in the fuel and considered homogeneous in that state, is a heterogeneous catalyst in the combustion phase. The bimetallic catalyst converts to metal oxides that are intimate with the fuel and oxygen reactants but not homogeneous. The second is that the catalyst does not reduce the activation energy of the reaction. The more likely effect is that the catalyst releases energy to maintain the activation energy during reducing ambient temperature conditions in the combustion system so that the reaction continues to completion. Therefore, the apparent reduction in Activation Energy illustrated in Figure 5 does not actually occur. We believe that energy released by the catalyst during as electrons decay to the degenerate state replaces that lost by quenching continuing the reaction along the same Activation Energy path as without catalyst.

Iron has the electron structure $1s^2, 2s^2, 2p^6, 3s^2, 4s^2, 3d^6$. Iron is found in three valence states, Fe^0 , Fe^{+2} and Fe^{+3} . Under conditions of the combustion reaction and minimal excess oxygen, the ferric ion is the only likely species to be available. The most likely degenerate electron configuration of the ferric ion is $1s^2, 2s^2, 2p^6, 3s^2, 4s^0, 3d^5$. There are

a large number of electron orbitals available as electrons move to higher energy levels. The result is a large number of emission spectra lines with relative low energies.

Magnesium in the +2 valence state has a much simpler electron structure, $1s^2, 2s^2, 2p^6, 3s^0$ and much less complicated emission spectra. On the other hand, the peaks are much stronger than the iron peaks indicating that the electron energy adsorptions are between principal quantum numbers rather than orbital quantum numbers.

Major peaks in the emission spectra of magnesium and iron (III) are given in Table 8. It is noted that the five major peaks of magnesium fall in areas where iron does not have spectra lines. It is also noted that the magnesium lines are stronger by a factor of 10 to 100 than the iron lines. We suggest that the synergistic effect of magnesium on iron is caused by a small number of complimentary spectra lines of magnesium combined with the many more numerous iron lines over a much wider frequency range.

Conclusion

The results presented in this paper are those that have been carried out by sources independent from SFA International to demonstrate unbiased evaluation of the catalyst. SFA has carried out a number of other tests with customers under proprietary conditions that have given similar results. The product has been in commercial use in combustion turbines since 1996 and in boilers since 2002. We have yet to find a case in which emissions have not been reduced and/or power increases from the equipment observed.

Significant reductions in emissions and the simultaneous increase in fuel efficiency have obvious implications for environmental conditions and fuel economy. We hope that this paper stimulates interest in pursuing further evaluations of this system. Initial evaluation indicates that the catalyst does not contribute to emissions in a material manner and the ash produced from these metals is benign. Iron oxide is in the environment as rust and magnesium oxide is ingested into the body as a treatment for stomach acid.

Reductions in emissions have been well beyond anything seen in the literature and indicate an unusual and unexpected catalytic effect.

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Figure 1
Particulate Matter and Catalyst Concentration
SFA's FuelSpec 118-1502 (Blue) and Competitive Product A (Red)

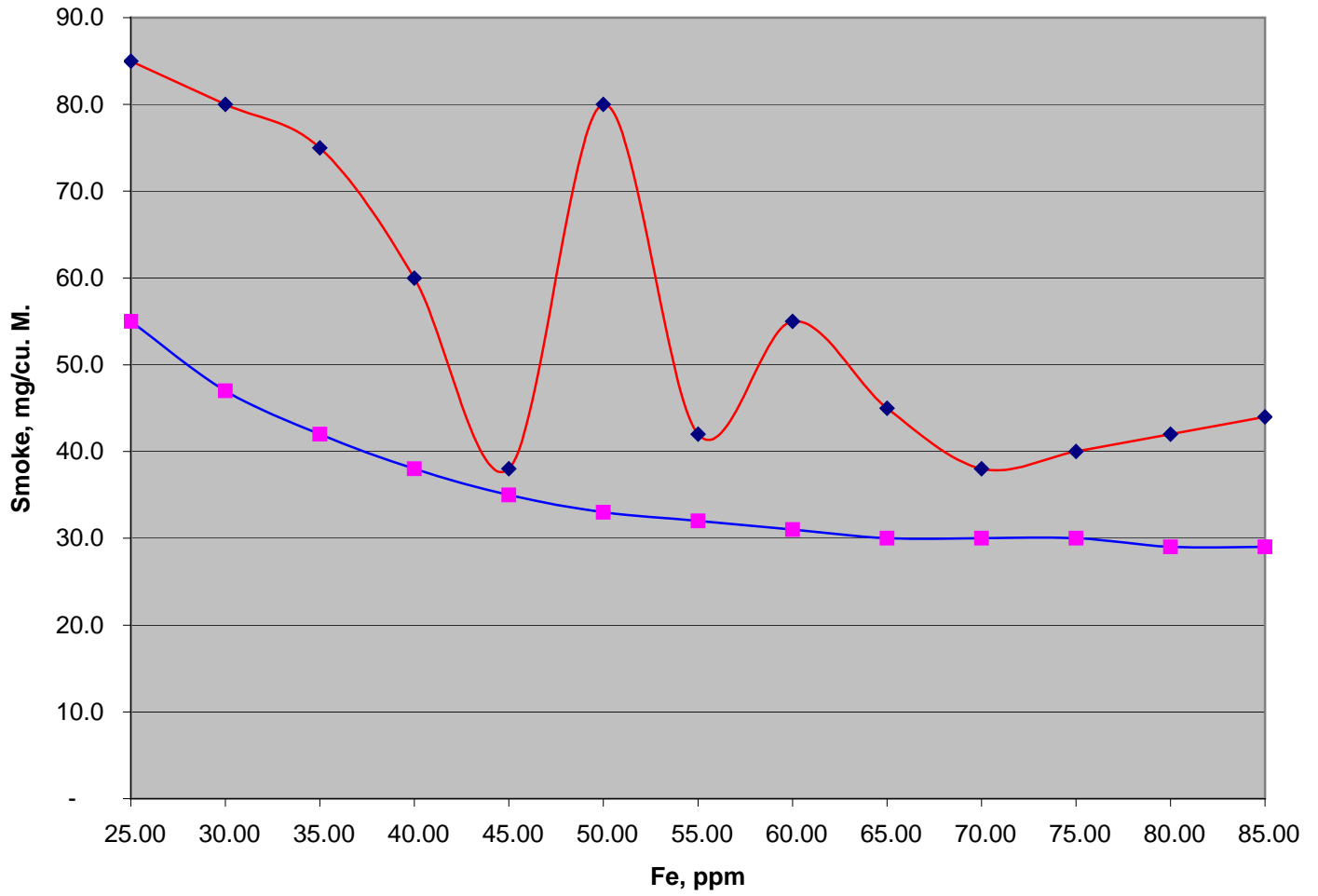


Figure 2
SFA's FuelSpec 118-1502 (Red) and Competitive Product A (Yellow)

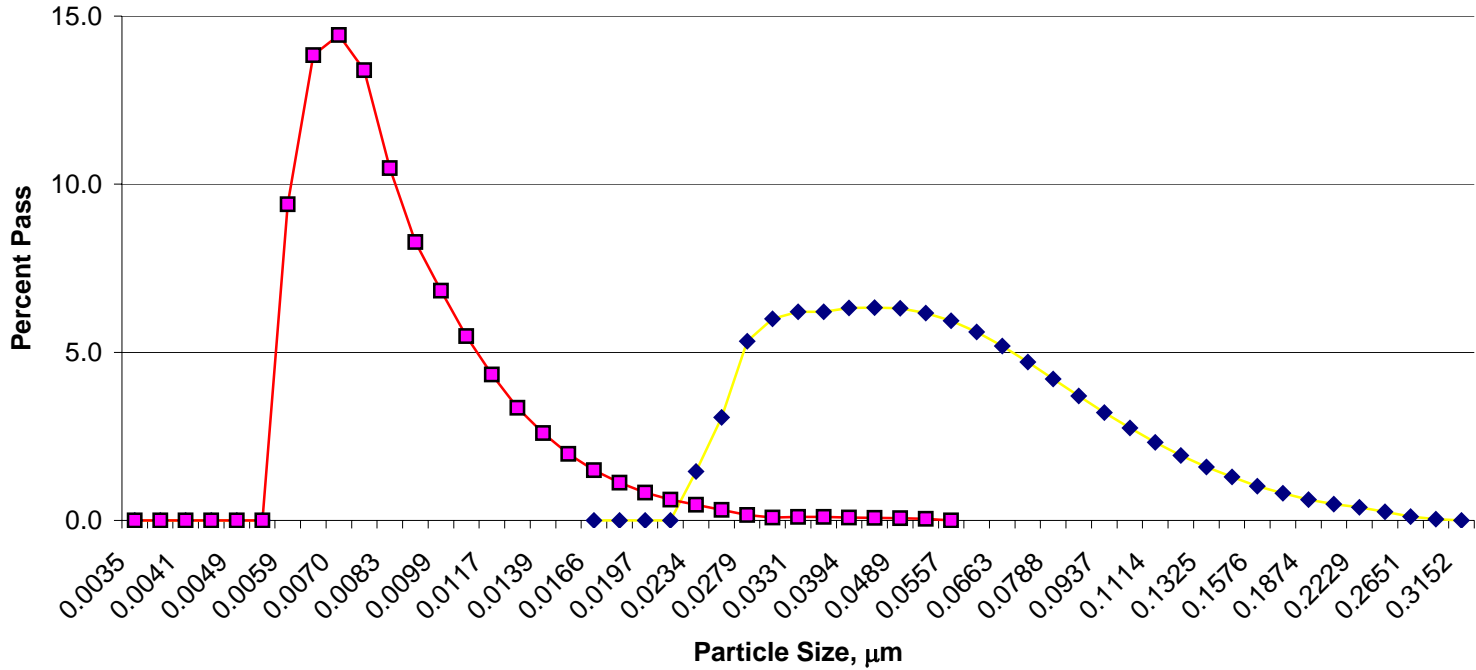


Figure 3.
Activation Energy for Combustion Catalysis Reaction

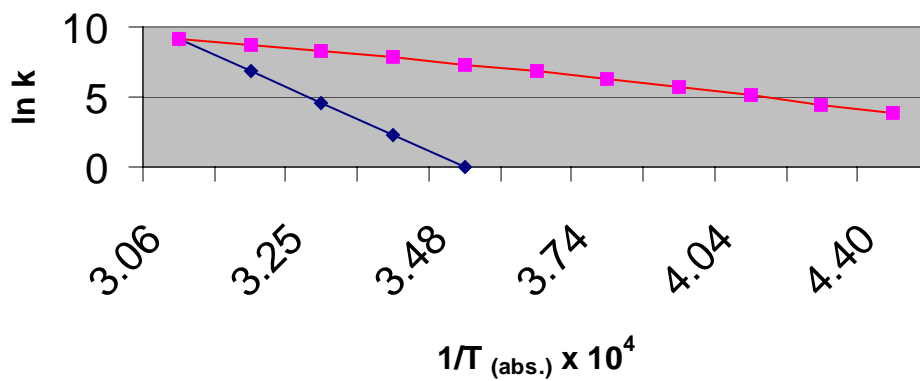


Table 1

**Hanwha Energy Ltd.
Inchon Plant**

Westinghouse 501 D-5 104 MW Combustion Turbines

Unit	Load MW	Fe ppm	Exhaust O ₂ , %		Particulates 4% O ₂		Fuel
			M-5	HEC	M-5	HEC	
1	90	0.0	15.6	15.3	122.4	108.2	LSWR
2	87	0.0	15.6	15.3	93.9	92.4	
2	88	7.5			123.7		
2	85	14.9	15.6	15.2	76.7	79.2	
1	87	14.9	15.4	15.6	80.5	87.1	
1	88	29.9	15.6	15.6	62.9	78.6	
2	84	31.3	15.8	15.2	61.1	73.9	
1	88	35.8	15.6	15.6	61.1	76.7	
2	88	44.87	15.8	15.1		74.2	
1	89	29.9	15.8		61.1		LSWR Blend with 20% DO
2	90	29.9	15.8		54.2		
1	88	0.0	18.8		58.2		DO Only
2	85	29.9	15.6		29.1		

M-5 EPA Method 5 (Westinghouse Measurements)
HEC Hanwha Energy Corporation

Data received from Westinghouse Electric Corporation Sept. 23, 1996.

Table 2
Hanwha Particulate Emission Data
Operating Data from Units 1 – 6

Unit	Load MW	Date	% DO	Dust Mg./M. ³	Fe ppm
1	90	18-Dec-96	5	94	30
2	105	16-Dec-96	5	51	30
3	95	31-Oct-96	5	37	30
3	95	31-Oct-96	5	38	30
3	100	06-Nov-96	5	49	30
3	99	20-Dec-96	0	74	30
3	99	20-Dec-96	0	49	36
3	80	24-Dec-96	0	57	36
3	80	24-Dec-96	0	62	36
3	95	26-Dec-96	15	51	36
3	95	26-Dec-96	15	40	36
3	90	26-Dec-96	15	46	36
4	100	02-Nov-96	5	46	30
4	100	02-Nov-96	5	49	30.3
5	97	04-Nov-96	5	63	27.6
5	100	04-Nov-96	5	50	27.6
5	60	16-Dec-96	5	79	30
5	100	20-Dec-96	0	73	30
5	100	20-Dec-96	0	60	36
6	100	06-Nov-96	5	50	30
6	90	18-Dec-96	5	58	30

Table 3

Hyundai Heavy Industries Daeson Refinery Power Plant

Combustion Catalyst Data – 2004 Summary

Westinghouse 501 D5 104 MW Turbines
 SFA FuelSpec® 118-1502, 50 ppm Fe Dosage
 Korean Ministry of Environment Requirement: <40 mg./M³
 Particulate Level without Catalyst: >160 mg./M³

Particulate Level with Catalyst –

Turbine	#1	#2	#3	#4
High	18.1	18.2	22.7	22.0
Low	10.3	8.1	5.4	9.5
Average	13.8	12.4	13.4	14.4

Table 4

Korean Institute of Energy Research

Low Pressure Boiler Tests – Low Sulfur Waxy Residual Fuel

Load		75%	75%	Difference
Catalyst, ppm Fe		0	50	
Date		10-Oct-02	10-Oct-02	
Smoke No.	Bach. No.	3.1	2.1	-1.1
Dust	Mg./M ³	306.2	33.4	-272.9
Dust, O ₂ , 4%	Mg./M ³	268.8	29.3	-239.6
Improvement				89.1%

Table 5**Korean Institute of Energy Research****Comparison of Results with Two Combustion Catalysts**

Additive	Catalyst ppm Fe	50% Load Mg./M ³	75% Load Mg./M ³	O ₂ Exhaust Gas
SFA International, Inc. FuelSpec® 118-1502 October, 2002	0	215	270.5	2.5%
	50	32.2	34.4	1.6%
		84.3%	89.1%	
Competitive Product November, 2001	0	222.7	221.4	6.0
	50	77.8	21.9	6.0
		65.1%	90.1%	

Table 6**Emission Control Products WLL****Bahrain Fleet Tests**

Manufacturer	Ashok Leyland	Ashok Leyland	Ashok Leyland	Mitsubishi	Mitsubishi	Toyoto
Year	1991	1996	1997	1996	1997	1995
Vehicle No.	4059	4394	4402	4038	4068	4374
Without Catalyst						
Kilometers	3,267	3,488	3,281	3,615	5,034	3,201
Km./Lit	3.209	3.566	3.249	6.537	6.000	5.041
With Catalyst						
Kilometers	3,521	3,913	4,607	2,710	5,311	3,528
Km./Lit.	3.510	4.005	3.888	6.725	6.445	6.010
Improvement	9.38%	12.31%	19.67%	2.88%	7.42%	19.22%

Table 7

Automotive Research Association of India (ARAI)

Calibrated Fuel Measurement Test

Premier Padmini 137D 1.6 Liter Diesel Engine

Conditions	Km	Without Catalyst		Improvement
		Liters	Km/Liter	
City	256	26	9.85	
Highway	389	28	13.89	
		With Catalyst		
City	480	42	11.43	16.1%
Highway	531	32.2	16.49	18.7%

Table 8. Diesel Exhaust Particulate Matter as Proportion of Fuel

					Component to Fuel Weight Ratio					Total	Gas Vol STP per Gram Mole Fuel					
					O ₂	Air	CO ₂	H ₂ O	Air less O ₂							
1	CH ₄ + 16.043	2	O ₂ 64.000	8.517 Air 305.548	→	1	CO ₂ + 44.011	2	H ₂ O 36.032	3.989	18.203	2.743	2.246	14.213	19.20	258.1
1	CH ₂ + 14.027	1.5	O ₂ 48.000	6.388 Air 229.161	→	1	CO ₂ + 44.011	1	H ₂ O 18.016	3.422	15.614	3.138	1.284	12.192	16.61	188.0
1	CH + 13.019	1.25	O ₂ 40.000	5.323 Air 190.967	→	1	CO ₂ + 44.011	0.5	H ₂ O 9.008	3.072	14.019	3.381	0.692	10.947	15.02	152.9

Average Liters/Gm Mole 170.46

Engine Horsepower = 1,000 Engine Kilowatts = 745.70
 BTU/Lb. 18,000
 Engine efficiency 20%
 BTU/Kw Hr. 17,050

Element	Mol. Wt.
C	12.011
H	1.008
O	16.000
N ₂	28.013

BTU/Hr 12,714,185
 Fuel/Hr 706 Lbs./Hr 320.4 Kg./Hr
 Gram Moles Fuel/Hr 23,693
 Exhaust STP/Hr. 4,038,758 Liters
 4,039 Cu. Meters
 Exhaust Temp. 200 ° C. 392 ° F.
 Exhaust Volume/Hr. 6,996 Cu. Meters

Composition of Atmosphere

O ₂	20.946%	0.0065
N ₂	78.084%	0.0279
Ar	0.934%	

Particulate Matter, > 2μ 2,000
 Particulate Matter, < 2μ 2,000 Assumption: <2μ particulate matter = >2μ particulate Matter
 Unburned Fuel 4,000 Assumption: Weight unburned fuel = total particulate matter
 Total 8,000 Milligrams/Cu. Meter
 55.97 Kg/Hour
 17.5% Fuel Requirement
 90 % Reduction in Emission equals 13.4%

Table 9

Major Atomic Spectra Lines for Iron(III) and Magnesium(II)

Iron		Magnesium	
Wavelength	Intensity	Wavelength	Intensity
2,151.78	15		
2,174.66	15		
		2,795.53	1,000
		2,825.70	600
		2,852.13	6,000
3,013.17	15		
		3,832.30	300
		3,838.29	50
3,954.33	16		
4,164.73	18		
4,296.85	16		
4,304.78	18		
4,310.36	20		
4,372.81	18		
5,243.31	18		
5,276.48	15		
5,282.30	16		
5,833.93	18		
5,891.91	15		
5,929.69	18		
5,999.54	18		
6,032.59	16		