



Boiler Emission Control with Fuel Oil Emulsion (FOE) Technology

Abstract

In the early twenty-first century, emphasis on fossil fuel emission reductions was focused on gaseous emissions. NO_x emissions were recognized as precursors of smog and as such adversely affected the quality of life. Lately, emphasis on emission reductions has shifted to solid emissions. Particulates are recognized as health hazards that contribute to respiratory ailments. Fossil fuel combustion - so fundamental to the nation's economy - unfortunately produces both emissions. Thus, the development of after-treatment technologies to treat fossil fuel combustion was pursued. Imposition of after-treatment technology proved costly from both application and maintenance aspects. In some instances, introduction of after-treatment technology caused a decrease in fuel efficiency.

In view of the foregoing, it is important to note that there is a technology that REDUCES gaseous AND solid emissions of liquid fossil fuels. Furthermore, this technology can INCREASE fuel efficiency. The technology that can deliver this "triple-crown" of dual emission reduction and enhanced fuel efficiency is EMULSIFIED FUEL TECHNOLOGY (EFT). In this paper, we consider the constitution, production and characteristics of Emulsified Fuels. Then we consider their combustion and the environmental benefits that can accrue to their utilization. Finally, we consider past applications of EFT and the future markets for this intriguing technology.

Constitution of Emulsified Fuels

An emulsion is a mixture of two immiscible (i.e., not able to be blended) substances. In an emulsion, one substance - the dispersed phase - is uniformly distributed throughout the second substance - the continuous phase. For example, a fuel oil emulsion features water droplets - the dispersed phase - uniformly distributed throughout the fuel oil - the continuous phase. An emulsion takes on the characteristics of the continuous phase. Hence, fuel oil emulsions exhibit characteristics of fuel oil NOT water.

Emulsions are inherently unstable. Over time they tend to "separate" into the stable states of the dispersed and continuous phase materials. Thus, a volume of fuel oil emulsion over time will separate into distinct volumes of water and oil. In order to maintain the composition of an emulsion, surface active agents, i.e., surfactants, are incorporated into the production of an emulsion. In a fuel oil emulsion, these surfactant agents encase the droplets of water in the continuous oil phase and prevent the water droplets from coming together and coalescing into larger droplets and ultimately into a significant volume of "separated" water. Because of surface tension, the surfactants act to form a membrane that encases the water droplets within the fuel oil emulsion and forces the droplets into small spheroids of water that are distributed throughout the continuous fuel oil phase. A micrograph of such water spheroids contained within the light (diesel) oil continuous phase of a diesel oil emulsion is shown in Figure 1.

Production of Emulsified Fuels

The production of an emulsion involves both chemical and mechanical operations. As stated previously, a surfactant is incorporated into the production of an emulsion to preserve its stability. The chemical nature of this surfactant is such that it is amenable to both the dispersed and continuous phase materials. The formulation of an emulsion surfactant agent must take into account the need to preserve the stability of the emulsion in storage and pumping operations as well as the need to render harmless the emission products arising from the combustion of the emulsified fuel. In this regard, it is to be noted that both the additive and the light oil (diesel) emulsified fuel produced by Alternative Petroleum Technologies S.A. (APT) have been verified by the California Air Resources Board (CARB) and registered with the United States Environmental Protection agency (USEPA).

The mechanical operation involved in the production of emulsified fuels is that of a high value (HV) shearing operation. In conjunction with this HV shearing action, the proper amounts of water, surfactant and fuel oil must be metered into the shearing volume to preserve the homogeneity of the final emulsified fuel product. This HV shearing operation is accomplished in a computer-controlled Blending Unit that insures the dispersed phase (water) in an emulsified fuel is sufficiently shattered into micro-scale droplets that will react with a proprietary surfactant agent to produce a maximum dispersion of water spheroids within the surrounding fuel oil phase. Example of computer-controlled APT Blending Units - both stationary and mobile configurations - that produce light and heavy fuel oil emulsions are shown in Figure 2.

Characteristics of Emulsified Fuels

While emulsified fuels take on the primary characteristics of the continuous phase material, emulsified fuels differ significantly in some respects from their base constituents. For example, light (diesel) oil emulsions appear white in color as compared to the amber color of base diesel oil. However, diesel oil emulsions do feel "oily" to the touch thus preserving some of the base characteristics of the continuous phase. In contrast, heavy oil emulsions appear black in color - like their base oil - but flow liberally at a somewhat lower temperature than do their base (continuous phase) fuel oil. This lower viscosity aspect of fuel oil emulsions provides added savings in energy usage for their service as combustibles since less power is needed to pump fuel oil emulsions from storage tanks to burner fronts and less heat is also needed to preserve fuel oil emulsions in a proper pumping state within plant storage tank farms.

This aspect of emulsified fuel characteristics is especially pronounced with residual oil emulsions. Residual oil emulsions are made by emulsifying the very heavy liquid "bottom" oils from vacuum tower installations. Instead of "cutting" these vacuum tower "bottom" oils by blending them with lighter distillate oils to ultimately make #6 fuel oil, emulsifying these "bottoms" replaces the expensive "cutter" oils with water and an emulsifying surfactant to produce a residual oil emulsion that flows like water at an ambient temperature because the continuous phase is water. Again, these residual oil emulsions can be readily pumped from storage tanks to burner fronts to produce an inexpensive alternative to fuel oil #6 for plant power production.

Combustion of Emulsified Fuels

Traditional combustion of liquid hydrocarbon fuels in a power plant boiler requires the fuel to be first atomized (either mechanically or with steam or air) to breakup the fuel into small droplets that can be more readily ignited. Once these small fuel droplets enter the high temperature combustion zone of the boiler at the exit plane of the fuel nozzle, they begin to burn in a charring fashion, i.e., from the surface inward to the core of the droplet. Normally, this "char" burning of the fuel droplet is not completed within the high temperature combustion zone of the boiler. As a result, unburned fuel products (particulates) are expelled from the combustion zone and transported in the flow of exhaust gases from the combustion zone to the stack exit of the boiler.

Simultaneous with this generation of particulate emissions, the generation of gaseous emissions proceeds from the exposure of fuel-borne nitrogen and the nitrogen in combustion air to the high temperature refining atmosphere of the combustion zone. Depending upon the completion of the attending combustion, various concentrations of oxides of nitrogen (NO_x) as well as carbon oxides (CO and CO₂) exit the combustion zone and proceed to the stack exit plane. An illustration of this process is shown in Figure 3.

In contrast to this foregoing situation, the combustion of emulsified fuels features the introduction of water into the combustion zone along with the base fuel. Introduction of water into the combustion zone produces two profound effects upon the combustion of the emulsified fuel. First, upon expulsion from the exit plane of the burner nozzle, exposure of the droplets of water in the emulsified fuel to the high temperature of the combustion zone causes an immediate evaporation of the water in the droplets to steam - a phenomenon known in the literature as a "micro-explosion" [1] occurs. The introduction of water vapor into the combustion zone also tends to decrease the temperature of the combustion zone due to the high heat capacity of the water medium. This decrease in combustion zone temperature leads to a less energetic oxidation of both fuel borne and combustion air nitrogen contents and therefore leads to an overall decline in NO_x generation.

Each "micro-explosion" of a water droplet is accompanied by a significant increase in volume of the here-to-fore surfactant-encased water droplet and a subsequent shattering of the surrounding fuel oil medium into numerous auto-ignition centers of combustion. It is akin to the bursting of a balloon and the fracturing of the balloon surface into numerous pieces of balloon surface material. Each piece of balloon surface material immediately becomes a burning center and causes the surrounding medium to ignite. As such, the surface area of the surrounding material subject to burning is greatly increased and a more complete combustion of the surrounding material - the continuous fuel oil phase of the fuel emulsion - is generated. Hence, the chance of unburned particles of fuel oil escaping from this burning atmosphere is significantly decreased and thus the production of particulate emissions is stifled. An illustration of this process is shown in Figure 4.

Environmental Benefits

As we have seen, the introduction of water - via the fuel emulsification process - leads to a twofold environmental benefit. By fundamentally affecting the fuel combustion process [2], emulsification leads to the reduction of BOTH solid (particulate) AND gaseous (NO_x) emissions. Very rarely does a single technology have such a significant set of dual environmental benefits.

The introduction of water into the combustion process has an added benefit from an energy efficiency viewpoint. The added heat content of the water introduced into the combustion zone by an emulsified fuel means that the exhaust gases of the combustion process are more "energetic" than those of conventional fuels. Hence, as these more "energetic" combustion gases traverse the boiler heat transfer zones, they are able to transmit more heat by convection to the steam generating tubes resulting in an INCREASE in fuel efficiency.

This increase in fuel efficiency leads to the final benefit attributable to emulsified fuels - a reduction in hydrocarbon emissions. If indeed emulsified fuels can produce more steam output per fuel input, then the total amount of base (hydrocarbon) fuel input required to produce a required power output is less. If base (hydrocarbon) fuel usage is decrease, the oxides of Carbon resulting from this lessened requirement for base fuel combustion are LESS. Emulsified fuels can thus contribute significantly to the lessening of greenhouse gases generation resulting from existent hydrocarbon fuel combustion.

In summary, the introduction of water into the combustion process by the use of emulsified fuels results in the generation of an enhanced "triple crown" of benefits - the reduction of BOTH gaseous (NO_x) and solid (Particulate) emissions, an increase in fuel efficiency AND the reduction of greenhouse gases. As such, emulsified fuel technology is one of the most effective - and cost-beneficial technologies - available to accommodate future requirements for hydrocarbon emission reductions, energy efficiency enhancement and greenhouse gas diminution.

PAST APPLICATIONS OF EMULSIFIED FUELS

Past applications of Emulsified Fuel Technology (EFT) are now reviewed to validate the foregoing assertions on emissions and efficiency. These applications include:

1. EPA Test of Fuel Oil Emulsion (FOE) in a Package Boiler ETV
2. EER Test of Fuel Oil Emulsion (FOE) in a Coal Re-burn Boiler
3. EPT Test of Fuel Oil Emulsion (FOE) in a Tangential-Fire Boiler

Each of these applications is now presented in a summary exposition.

1. The Environmental Protection Agency (EPA) tested FOE in a Package Boiler as part of the Environmental Technology Verification (ETV) Program [3]. The Package Boiler was capable of firing natural gas or #2 through #6 fuel oils. It is a three-pass "Scotch" marine design boiler built in 1967. The burner was rated at 2.5M BTU/HR and featured an air atomizing center nozzle. The boiler has 300 square feet of heating surface and generates 2400 LB/HR of saturated steam at 15 PSIG. Heat is extracted from the steam

through a heat exchanger to an industrial cooling water system that provides the boiler load. Fuel temperature can be adjusted using an electric heater to maintain oil viscosity and both fuel and atomizing air pressures are variable to ensure adequate oil atomization. The test fuels consisted of water emulsions of #2 fuel oil (FOE) and of petroleum naphtha (NAPE). Performance of these emulsified fuels was compared to the performance of regular #2 fuel oil (FO).

Of particular interest in this test was the NO levels measured for each fuel under high, medium and low LOAD conditions on the boiler. NO levels were measured with a Rosemount Model 951A Unit using the chemiluminescence method of analysis. As shown in Figure 5, NO emissions (PPM) from the emulsified fuels showed significant reductions compared to the base #2 oil. As noted in the EPA report, at medium loads where the O₂ level of combustion air remained nearly constant for the three fuels, NO emissions fell 17% for the emulsified #2 oil (FOE) and 35% for the emulsified naphtha fuel (NAPE) compared to the #2 base oil (FO).

2. The Energy and Environmental Research (EER) Company of Irvine, CA tested the effectiveness of a #6 Fuel Oil Emulsion (with 30% water content) as a reburning fuel [4] in its Tower Furnace Facility in Irvine, CA. The tests were conducted over a range of conditions to optimize NO_x reduction performance. The Tennessee Valley Authority (TVA) Allen Station Unit #1 in Memphis, TN served as the basis for the projection of these pilot-scale tests to full-scale projections. The main fuel used in the test facility was natural gas or coal and the reburning fuel was an emulsified #6 fuel oil. At the baseline firing rate of 10 MMBTU/HR, tests were conducted in which reburn heat input was varied from 10% to 23% of the total heat input. NO_x reduction increased progressively with increasing reburn heat input until reburn heat input reached a 20% level whereupon NO_x reduction appeared to level off. As such, NO_x reduction increased until the stoichiometry in the reburn zone reached a slightly fuel-rich condition. Further increase in reburn fuel flow resulted in no further NO_x reduction and in some cases, lowered NO reduction.

When coal was fired in the test facility as the primary fuel, the baseline NO concentration was 1020 ppm. Therefore, this was the lowest baseline NO level that was utilized for the coal fired testing. When natural gas was fired in the test facility as the primary fuel, ammonia was added to adjust the baseline NO level to 1020 ppm.

Transport media for the reburn fuel included bottled nitrogen (NT) and air (AT). The nitrogen was used to simulate the low oxygen content of recirculated flue gas which is used as a transport medium for reburn fuel in some installations. Flue gas features a very low oxygen content - usually 3% compared to 21% for combustion air - and thus minimizes the required reburn fuel flowrate. The NO_x reduction achieved at a given reburn fuel flowrate was consistently better with NITROGEN transport (NT) than with AIR transport (AT) by 5 to 10 percentage points. As shown in Figure 6, NO_x reduction (%) from Emulsified #6 Fuel reburning was similar for primary firing with coal as well as with natural gas.

3. Electric Power Technologies (EPT) tested a #6 Fuel Oil Emulsion (20% water content) in a tangentially-fired 100 MW boiler [5] at a paper mill in West Point, VA for the purposes of reducing NO_x emissions while firing a combination of liquid and solid (coal) fuels. The boiler was manufactured by ABB/CE and had a rated steam flow of 350 KLB/Hr on oil and 420 KLB/HR on coal. It featured eight oil burners located at two levels in each corner of the combustion chamber and twelve coal nozzles located above, below and in-between each oil burner set. Auxiliary air nozzles were located at the top and bottom of each burner-nozzle array. All of the compartment nozzles can be tilted in unison from -30 degrees to +30 degrees (off horizontal) to control steam temperature.

Historically, NO_x emissions were reported to be 0.70 LB/MBTU for 100% coal firing at high loads (420 KLB/HR). Co-firing coal plus a #6 Fuel Oil Emulsion resulted in NO_x levels of 0.35 LB/MBTU - a 50% reduction in harmful emissions. The effect on NO_x emissions of using simulated overfire air when cofiring coal and #6 Fuel Oil Emulsion was evaluated on a short-term basis. The data showed that NO_x emissions were reduced 13% by using simulated overfire air. Further, the minimum NO_x value obtained (0.27 LB/MBTU) with simulated overfire air was comparable to NO_x emissions obtained when firing with 100% oil fuel (i.e., 0.25 LB/MBTU). Accordingly, the NO_x reduction afforded by using #6 Fuel Oil Emulsion in cofiring permitted the burning of nearly 32% more coal with no added impact on total NO_x emission levels.

Two notable operational actions were also recorded in these tests. First, the pressure differential between the atomizing steam and fuel was reduced from 20 psid to 3 psid without any deleterious effect upon Fuel Oil Emulsion atomization quality. Second, the fuel temperature at the outlet of the suction heater was able to be reduced from 220F (for oil) to 165F (for emulsified fuel) while sufficient fuel flow was delivered to maintain boiler load. Both actions serve to illustrate the potential operational savings that can accrue to the use of emulsified fuels in an industrial power plant.

Future Markets for Emulsified Fuels

Considering the many benefits of Emulsified Fuel Technology (EFT), the future markets for this technology are vast. One of the best ways of viewing the potential for EFT is to consider the existent markets for various petroleum products and then consider the application of EFT involving these "base" petroleum products. An example of this approach is shown in Figure 7. This figure portrays the Heavy Fuel Oil Market for Asia as compiled by the Energy Information Agency (EIA) of the United States. For each country listed, the total consumption of heavy fuel oil (in liters) for the year 2004 is registered in the first column. Assuming a 5% market penetration, the resulting production of emulsified fuel - using this 5% market penetration factor as the "base" fuel equivalent for expected emulsified fuel production - gives the figures shown in the second column of Figure 7 i.e., a total of 9.6 billion liters = 2.54 billion gallons. Making the same determinations for a 6% market penetration produces the figures in the third column of Figure 7 i.e., a total of 11.5 billion liters = 3.04 billion gallons. Finally, making the same determinations for a 7% market penetration produces the figures shown in the fourth column of Figure 7 i.e. a total of 13.4 billion liters = 3.54 billion gallons.

The reason for choosing this market segment - the Asian market - as an example for application of Emulsified Fuel Technology is because this segment of the global economy has the two fastest growing economies - China and India. As such, the introduction of EFT into these

economies could provide significant environmental benefits. Furthermore, the energy efficiency to be wrought by incorporating EFT into these growing economies could also contribute to the sustenance and extension of these economies at a most cost-effective basis. Finally, the utilization of EFT within these economies could be accomplished with equally significant reduction of greenhouse gases as compared to the utilization of traditional hydrocarbon power generation technology.

Summary

As portrayed herein, Emulsified Fuel Technology (EFT) is a proven technology that summarily delivers on the promises of emissions reductions - BOTH gaseous AND solid emissions reductions - plus an increase in operational efficiency. Moreover, in addition to operational efficiency enhancements, EFT can contribute significantly to the ultimate lessening of overall system maintenance costs. This last advantage arises from the fact that emulsified fuels generate energetic steam gases in the combustion zone that sweeps through the combustion and exhaust chambers of a boiler and effectively clean the heat transfer surfaces therein. Such "steam cleaning" actions give rise not only to a more immediate efficient operation but ultimately contribute the diminishment of the time and effort that needs to be devoted to cleaning these surfaces in normal outage situations. Furthermore, as seen from the last application cited in this paper, the ability to lower fuel heating temperatures and atomizing steam pressures when using emulsified fuels also contributes to an increase in overall plant operational efficiency and thus directly to the enhancement of the bottom line of a power generation activity.

The applications of EFT are widespread. In addition to the fuel oil emulsion applications portrayed in this paper that are focused on boilers, EFT can be readily applied to light distillate oils - like diesel oils - to operate in internal combustion engines. At the other end of the spectrum, EFT can be applied to residual oils to produce usable combustion products from such diverse stocks as vacuum tower bottom oils and pitch blends. In all instances, EFT presents a significant opportunity to fully utilize hydrocarbon fuels - in all "flavors" - to their maximum operational potential without fear of contributing exceptionally to harmful emission levels. As such, EFT is an enabling technology that has a significant market potential as well as an enviable position in the quiver of modern technologies that are able to deliver an immediate impact on global warming and community health.

References

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3. Miller, C. Andrew, 1998, "Verification Testing of Emissions from A-55 Clean Fuels in a Firetube Boiler", Technical Report No. EPA-600/R-98-033, Research Triangle Part, Durham, NC.
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Figure 1. Photomicrograph of Diesel Oil Emulsion



Figure 2a. Stationary Emulsified Fuel Blending Unit Located at Iplom Refinery, Busala, Italy



Figure 2b. Mobile Emulsified Fuel Blending Unit Located at Daesang Food Processing Plant, Ganchon, Korea

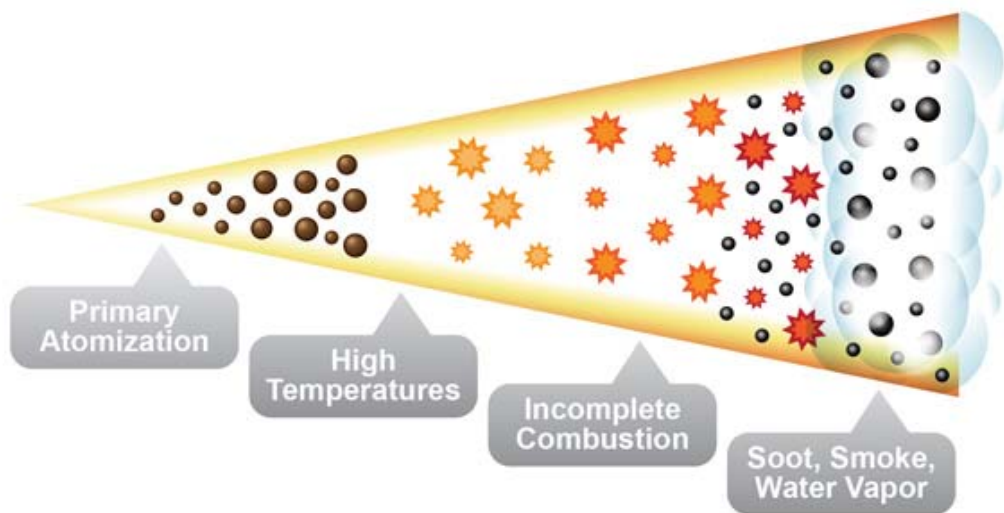


Figure 3. Tradition Fuel Combustion

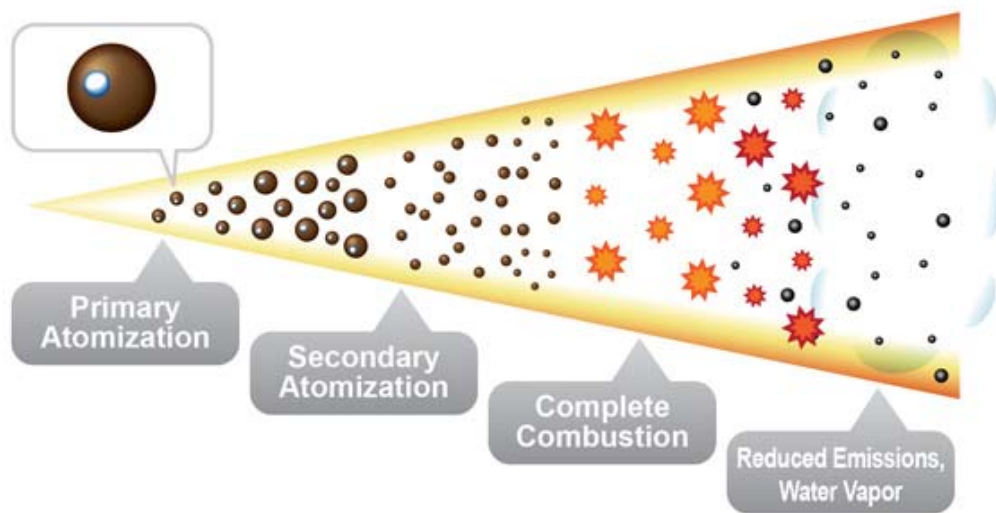


Figure 4. Emulsified Fuel Combustion

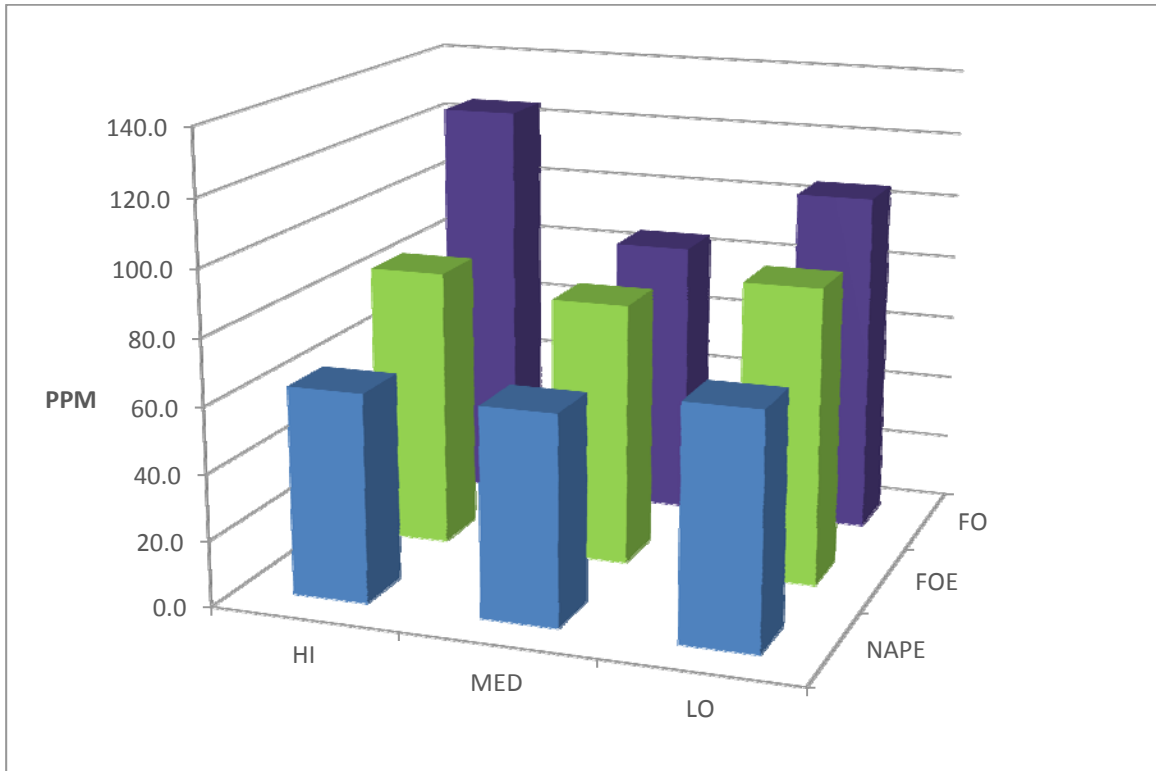


Figure 5. EPA Boiler Emissions

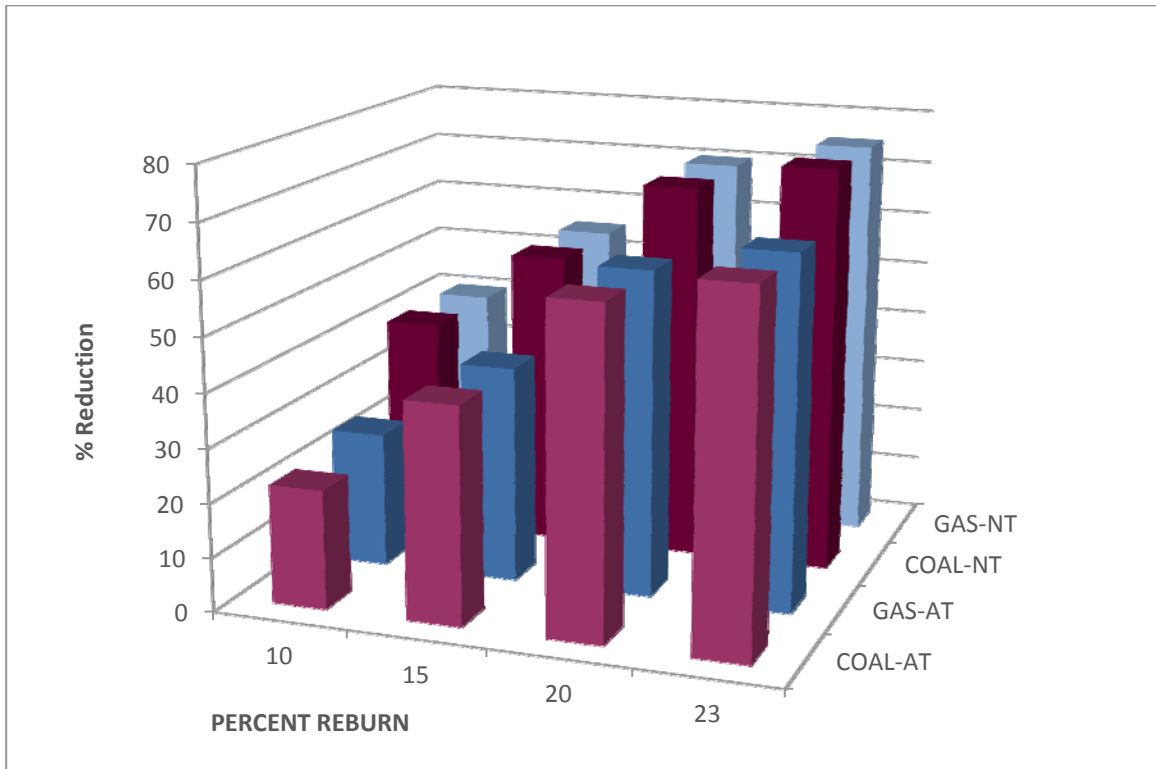


Figure 6. Re-Burning NO_x Reduction

Residual Fuel Oil litres Region/Country	Total per year	5% Market (litres)	6% Market (litres)	7% Market (litres)
China	41,988,686,040	2,099,434,302	2,519,321,162	2,939,208,023
Hong Kong	2,885,780,520	144,289,026	173,146,831	202,004,636
India	13,930,554,960	696,527,748	835,833,298	975,138,847
Indonesia	6,918,919,560	345,945,978	415,135,174	484,324,369
Japan	34,646,750,460	1,732,337,523	2,078,805,028	2,425,272,532
Korea, South	28,098,694,260	1,404,934,713	1,685,921,656	1,966,908,598
Malaysia	2,700,348,840	135,017,442	162,020,930	189,024,419
Pakistan	8,495,088,840	424,754,442	509,705,330	594,656,219
Philippines	5,041,423,800	252,071,190	302,485,428	352,899,666
Singapore	23,833,765,620	1,191,688,281	1,430,025,937	1,668,363,593
Sri Lanka	909,774,180	45,488,709	54,586,451	63,684,193
Taiwan	14,834,534,400	741,726,720	890,072,064	1,038,417,408
Thailand	5,192,087,040	259,604,352	311,525,222	363,446,093
Vietnam	1,657,295,640	82,864,782	99,437,738	116,010,695
Totals	191,133,704,160	9,556,685,208	11,468,022,250	13,379,359,291

Figure 7. Heavy Fuel Oil Asia Market EIA Report, 2004