Petroleum Coke Refueling
An Economic Alternative for Existing Oil-Fired Boilers

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***Abstract*— Air Products and Chemicals, Inc., a leading supplier of industrial gases worldwide, has developed an oxygen-enhanced combustion technology that allows conversion of existing high-cost oil-fired power plants to utilize pulverized petroleum coke ("pet coke"), a by-product of the oil refining process, as a replacement fuel with no other support fuels required. Conversion of these existing units includes the addition of pet coke receiving, storage and pulverizing equipment and flue gas treatment equipment. The resulting economics of burning pet coke transforms a previously high-cost, low-dispatch unit into a low-cost, baseload unit.**

Air Products completed commercial-scale demonstration of this process and is in various stages of development for the conversion of a number of units worldwide. In addition to conversion of a high-cost facility into a unit with dispatch costs similar to coal-fired plants, this technology is also compatible with a further oxy-fuel retrofit to allow post-combustion carbon capture and sequestration.

This paper describes Air Products' development of the technology and the benefits of conversion for a generic existing site. Actual economics are site dependent.

I. INTRODUCTION

Air Products has developed pet coke refueling, an oxygen-enriched combustion technology that converts existing oil-fired power facilities from high-priced heavy fuel oil to 100% pulverized pet coke without, in most cases, significant degradation of steaming capacity or boiler efficiency. The low cost of pet coke pays for the conversion of the units including the addition of emissions control equipment to remove sulphur generated by the combustion of high sulphur pet coke. The combustion technology employed is further convertible into full oxy-fuel to enable carbon capture at economically attractive costs relative to other pre- and post-combustion capture technologies. This paper will discuss the economic benefits of applying pet coke refuelling to a hypothetical facility as well as the potential to further convert the facility to full oxy-fuel operation with CO2 capture.

II. BACKGROUND

A. *Air Products and Chemicals, Inc.'s Combustion Experience*

Air Products and Chemicals, Inc. is an industrial gas company with main headquarters in Allentown, PA with operations in over 40 countries worldwide and annual sales exceeding $10Bn. Air Products supplies products and services in various energy markets, including being the leading on-purpose supplier of hydrogen to the oil refining industry, supplying the majority of process technology and heat exchangers to the LNG liquefaction market, and building, owning and operating numerous power generation facilities employing a variety of technologies. Air Products also has decades of experience in developing and supplying oxygen-assisted combustion technologies to numerous process industries to improve efficiency, productivity and/or emissions.

Pet coke refueling is an application of Air Products' oxygen-enhanced combustion technology expertise which allows conversion of high-cost power generation facilities into low-cost, baseload units. The concept of refueling has been discussed in a presentation at Power-Gen 2005 and in an article published in the August 2005 issue of the PACE Petroleum Coke Quarterly. Subsequent to those papers, a commercial-scale demonstration was completed in 2006. This paper discusses the potential economic opportunity of a commercial-scale refueling; a simplified process flow diagram of pet coke refueling is shown in Figure 1 below.

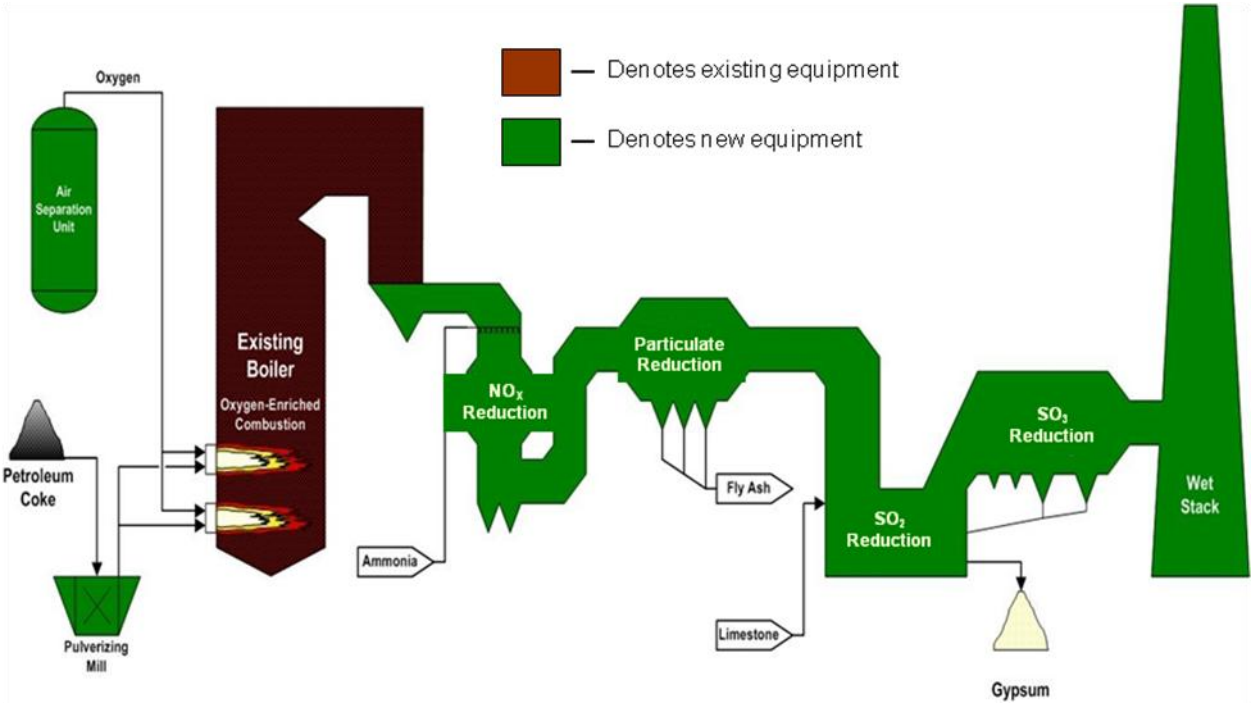

Fig. 1 Petroleum coke refueling illustrative depiction

B. Petroleum Coke

Pet coke is a by-product of the oil refining process. The majority of pet coke produced is high sulphur, with contents of 4% to 7% by weight. In addition, the majority of high-sulphur pet coke is produced in the U.S./Caribbean basin. Annual production capacity and actual production of pet coke has increased largely due to increasing demands for transportation fuels coupled with utilization of heavier, more sour crudes. Coking allows maximization of light fractions output while minimizing production of heavy fuel oil, especially as the crude feed slate becomes increasingly heavy. Pet Coke is produced as a by-product in the quest to maximize refinery profitability. This is important when considering relative impacts of the use of pet coke versus use of fossil fuels in power generation. Whereas coal, oil and natural gas are discretionary extracted fuels and every MMBtu extracted has a carbon footprint associated with that discretionary use, pet coke, as a by-product of the production of transportation fuels, is produced as the demand for transportation fuels, the crude feed slate and the refinery design dictates. Pet coke is neither produced on purpose nor to a specification.

Pet coke has a low volatile material content, which is the very idea of coking vacuum residuum in the refining process. This property causes combustion of pet coke to be difficult. Traditional technologies to burn pet coke include blending with fuels with high volatile content for combustion support or increasing combustion residence time by employing a technology such as circulating fluidized bed boilers. However, Pet coke refueling utilizes a proprietary oxygen enrichment process to efficiently combust pet coke with minimal combustion residence time and with heat release characteristics similar to oil firing.

C. Pet Coke Refueling Technology Development

Air Products tested a variety of burner configurations and oxygen enrichment strategies from 2000 to early 2002. A commercial-scale demonstration was conducted in 2006 on a commercial power plant to obtain necessary data for design of full-scale pet coke refuelling applications. The facility was converted to full pet coke firing under a limited duration testing permit and was subsequently converted back to coal firing. Analysis of the extensive data taken during the highly successful 30-day demonstration confirmed the viability of the technology and provided the bases for commercial applications.

III. Discussion

Pet coke refueling involves the conversion of a boiler designed for oil firing to utilize 100% pulverized pet coke. The basic design of an oil fired boiler utilizes the luminosity of the oil flame in the combustion zone to produce steam. Refueling had to mimic the characteristics of an oil flame while also fitting the flame within a tight space in order to be commercially practicable. In addition, the air emission characteristics had to be sufficiently within controllable parameters in order to be permittable. The unique oxygen enrichment strategy developed by Air Products meets all of these criteria creating a unique economic opportunity.

Because pet coke is difficult to burn, can be hard to grind (high HGI) and has high sulphur content, the amount of pet coke that may be burned with other fuels is generally limited. Pet coke sells as a substitute fuel for low-rank coals in the cement production industry and power generation industry. As such, the cost of pet coke is capped by the price of low-rank coals and has generally traded at a deep enough discount to coal to incent facilities burning coal to substitute some pet coke in their fuel slates. The effect of this economic relationship on a refueled facility will be that the converted unit will have an operating cost significantly lower than an oil or gas fired unit and comparable to or lower than a coal-fired unit with less pricing volatility than an oil or gas fired unit. The capital cost of the pet coke refuelling conversion is significantly lower than the investment in a new coal-fired unit or in re-powering an existing unit with other boiler technologies and it is this combination of low capital expense with similar or lower operating expense relative to coal that makes refueling especially attractive..

In general, the best applications of pet coke refueling technology will be at sites with enough generating capacity to effectively utilize the investment in solids receiving, storage, handling and grinding. As such, sites with oil-fired capacity of 500MW or greater are best suited to refueling conversions although sites with existing coal handling capabilities create specific opportunities for refueling effectively at a smaller scale. In order to be a good candidate for refueling, a site also has to have sufficient space available to fit the solids storage as well as the new desulphurizing unit required to treat the flue gas from the combustion of high sulphur pet coke. In general, the best boiler candidates are those boilers which were originally designed for full output with oil firing. Finally, the site has to be able to receive large quantities of solid fuel and, if employing wet limestone flue gas desulphurization, limestone as well as allowing for shipment of gypsum produced by the FGD. As such, sites with good water access for barge or vessel logistics are more attractive owing to better freight economics for pet coke and limestone deliveries as well as gypsum shipments.

An illustrative economic opportunity analysis for a hypothetical existing oil-fired 1,000MWnet facility consisting of 2 separate 500MWnet boilers located in the U.S. Gulf Coast region with water access for barge receipt/shipment of solids is presented below in Figure 2. As shown, the economic benefit of refueling relative to other options is significant, both on a dispatch cost basis and on a full cost basis with a 12% return on capital.

[2008 $'s]	**Existing**	**Co-Fire Oil/Pet Coke**	**New SCPC**	**Repower with CFB's**	**Pet Coke Refueling**
Fuel Type	HSFO	80/20 Oil/Pet Coke	Coal	Pet Coke/Coal	Pet Coke
Gross Power Output (mw)	1,000	900	1,026	1,000	900
Auxiliary Power (mw)	30	50	56	75	113
Net Output (mw)	970	851	970	925	788
Heat Rate (btu/kwh-gross)	10,500	10,500	8,600	9,500	10,500
Availability Factor	90%	90%	90%	90%	90%
Capacity Factor	90%	90%	90%	90%	90%
Fuel Price (US$/mmbtu)	**$13.00**	**$11.10**	**$6.00**	**$3.50**	**$3.50**
Total Incremental Capital (US$mm)	**$0**	**$315**	**$3,248**	**$2,950**	**$1,569**
Fuel Cost (US$mm/yr)	$969	$744	$376	$236	$235
OPEX (US$mm/yr)	$185	$186	$233	$239	$190
Fuel Cost (US$/mwh)	$141	$123	$55	$36	$42
OPEX Recovery (US$/mwh)	$27	$31	$34	$36	$34
Capital Recovery @12%IRR (US$/mwh)	$0	$7	$63	$60	$38
Total Cost of Power (US$/mwh)	$168	$161	$152	$133	$114
Annual Savings v. Existing (US$mm)		$39	$110	$230	$302

Fig. 2 Illustrative economic comparison for refueling

The cost of power generated from a refueled unit is lower than all options other than a re-powering with circulating fluidized bed (CFB) boilers and is lower than all other options on a full-cost basis. The main reason that the CFB option in the illustrative example below is slightly lower on a variable cost basis is that the heat rate for the re-powering is assumed to be significantly lower, at 9,200 Btu/kWh, than the existing unit. To the extent this is not deliverable by a re-powering, the variable cost of refueling would become better than all options. It should also be noted that the comparison is not consistent across net output and is based on the same size existing 1,000MW facility with the exception of the super-critical pulverized coal unit, which was assumed to produce the same net output as the existing facility.

Although the dispatch cost of refueled units justify their operation as baseload generation, it should also be noted that the oxygen-enriched combustion technology employed allows for stable combustion even at low output, thereby allowing the unit to be turned down for reasons other than economic dispatch such as system stability.

Pet coke is a high-carbon content fuel and the relative carbon dioxide emission footprint of a refueled unit is compared to other fuels in Figure 3.

Generation Mode/Fuel	**lb CO2/MWHnet**
Combined cycle/Natural gas	990
Subcritical boiler/HSFO	1,640
Supercritical boiler/Coal	1,750-1,800
Subcritical boiler/Pet coke refueled	1,955
Subcritical/Pet coke refueled with subsequent oxy-fuel conversion	**<300**

Fig. 3 Approximate carbon footprint comparison

As shown in Figure 3, the net effect of refueling the existing oil-fired boiler with pet coke using Air Products' proprietary technology is to increase the carbon output per net megawatt generated. However, pet coke refueling represents a partial investment towards a full oxy-fuel conversion of the existing boiler, which allows carbon capture utilizing a variety of technologies.

Oxy-fuel technology is still in a phase of technology development, both on the combustion side of the boiler and on the flue gas carbon capture and clean-up side of the boiler. There are several technology demonstration projects underway to address the oxy-fuel combustion and also to address the capture and purification of the carbon dioxide produced from an oxy-fuel boiler. A general process overview depiction for a pet coke refueled unit that has subsequently been converted to oxy-fuel with carbon capture is shown in Figure 4. Oxy-fuel conversion consists of adding additional oxygen production capacity to the capacity already installed for refueling, adding flue gas recycle and adding carbon capture and purification equipment. By eliminating the introduction of air as the source for combustion oxygen and instead introducing pure oxygen into the recycled flue gas stream, a synthetic combustion atmosphere is created with little or no atmospheric nitrogen. The combustion gases are therefore high in carbon dioxide making purification of the flue gas stream more economical and more amenable to a variety of technologies. Air Products is developing technologies on the combustion side as well as developing a novel carbon capture and purification technology. Because commercial scale demonstrations have yet to take place, an oxy-fuel option to further convert a pet coke refueling opportunity is not yet offered. However, the choice of refueling in the short-term provides the opportunity to take advantage of the attractive economics of refueling with a subsequent conversion to oxy-fuel as that technology matures and also as carbon sequestration options and regulations mature.

IV. CONCLUSIONS

Air Products has developed a commercially combustion technology which allows conversion of existing high-cost, low-value oil-fired power generation facilities to utilize 100% pet coke with minimal de-rate thereby creating a low-cost, baseload unit. The pet coke refueling conversion is further amenable to future oxy-fuel conversions to achieve economically advantaged carbon capture solid-fuelled units.

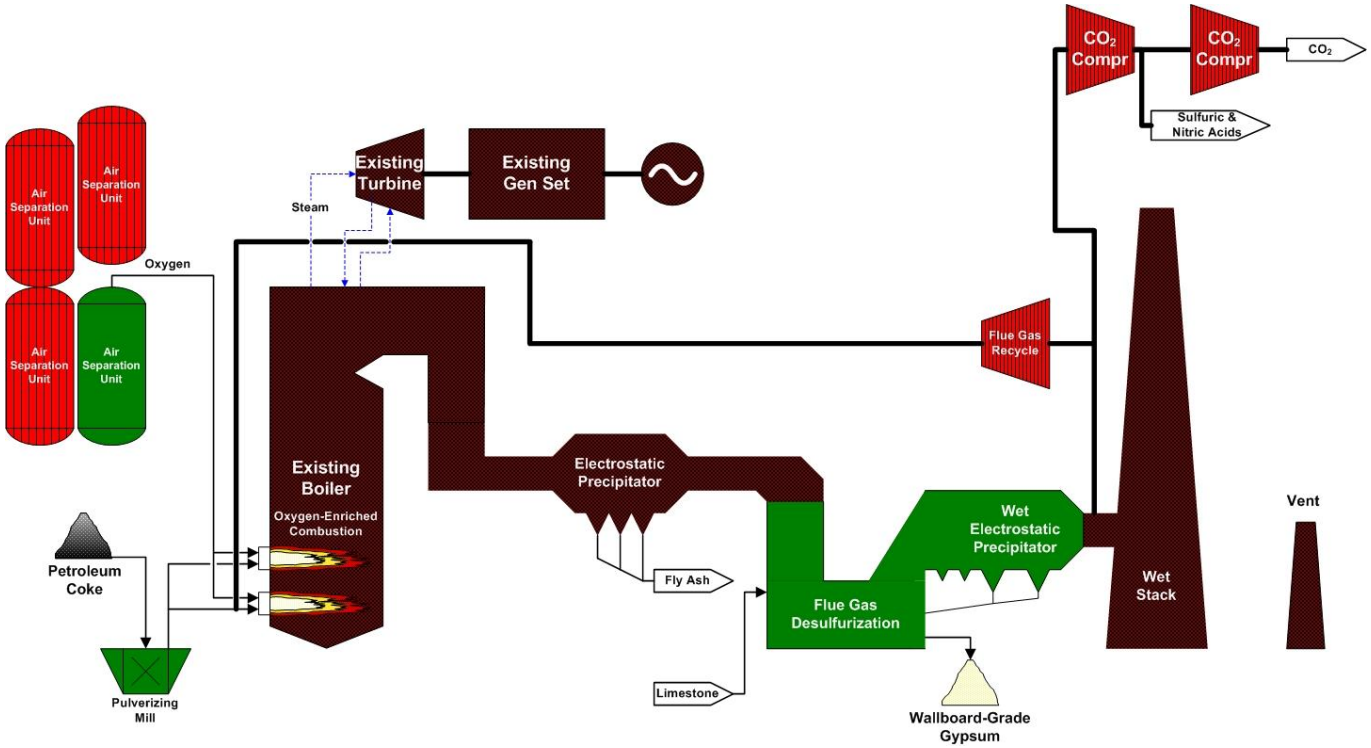

Fig. 4 Pet coke refueled unit with subsequent oxy-fuel conversion