DOE/PC 90360-48

ADVANCED IN-DUCT SORBENT INJECTION FOR SO_2 CONTROL

TOPICAL REPORT NO. 6
TASK 5: CONCEPTUAL COMMERCIAL PROCESS DESIGN AND ECONOMIC EVALUATION

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ADVANCED IN-DUCT SORBENT INJECTION FOR SO_2 CONTROL,
DOE CONTRACT DE-AC22-91PC90360,
TOPICAL REPORT NO. 6, TASK 5: CONCEPTUAL PROCESS DESIGN AND ECONOMIC EVALUATION

ABSTRACT

The objective of this research project is the development of a second generation in-duct sorbent injection technology as a cost-effective compliance option for the 1990 Clean Air Act Amendments. Research focused on the Advanced Coolside Process, which has shown the potential of exceeding the performance targets of 90% SO_2 removal and 60% sorbent utilization. In Task 5, Conceptual Process Design and Economic Evaluation, the economics of the CONSOL Advanced Coolside Process as a Clean Air Act compliance option were evaluated.

A conceptual process design for full-scale, coal-fired applications is described. Advanced Coolside is compared to conventional Limestone Forced Oxidation (LSFO) wet FGD technology. The process economics for coal sulfur levels ranging from 1.0% to 3.5% (as-received) and plant sizes ranging from 160 to 512 gross MW were investigated. In addition, the economics of on-site versus off-site lime hydration and the cost sensitivity to delivered pebble lime and hydrate prices are investigated.

Advanced in-duct sorbent injection enjoys a capital and levelized cost advantage relative to LSFO in all cases examined in this study. As a result of this study and others made during this contract, the following conclusions can be made:

- The capital cost of Advanced Coolside is 55% to 60% less than that of LSFO and varies slightly depending on coal sulfur content and plant size.

- The total levelized SO_2 control cost advantage relative to LSFO varies from 15% to 35% over the range of coal sulfur contents and plant sizes evaluated. This cost advantage is sensitive to sorbent transportation charges. As a result, the economics are site-specific.

- The experimental optimizations based on interim economic analyses were the key to capital and levelized cost reductions.

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INTRODUCTION

The Advanced Coolside Desulfurization Process was developed through 1000 acfm pilot plant testing, as reported in Topical Report Nos. 1 through 5.[1-5] This development work showed the technical feasibility of the process and demonstrated that the original process performance targets could be exceeded. The 90% SO_2 removal target was achieved at sorbent utilizations up to approximately 75%, exceeding the target of 60% utilization. SO_2 removals in excess of 99% were achieved at utilizations greater than 60%.

The objectives of Task 6, Conceptual Design and Economic Evaluation, were to develop a conceptual design for a utility-scale application of the Advanced Coolside process and to assess the economic attractiveness of the process. Additional objectives of CONSOL were to identify process areas for potential cost reductions and to guide research and development efforts in areas that would most impact the economics and commercial readiness of the process. As a result, CONSOL began engineering and economic evaluation early in the project, and this was an ongoing process. Part of this evaluation by CONSOL involved the development of a heat and mass balance computer model which was used as a tool to help estimate process costs.

In early 1993, an interim process economic evaluation was completed. The interim study was initiated in order to explore the feasibility of an intermediate scale-up test of the process. Results indicated that Advanced Coolside had an economic advantage relative to limestone wet scrubbing for a range of plant sizes and coal sulfur levels. The evaluation identified several areas for potential process improvement, including equipment design optimization and sorbent utilization optimization. Areas identified for design optimization included improvement of the gas/liquid contactor design, improvement of the sorbent recycle handling system, and improvement of the waste handling system. As a result, it was decided to continue process optimization in the 1000 acfm pilot plant to explore these further areas of cost reduction. Pilot plant development work in these areas is described in Topical Report 2. Sorbent utilization optimization work is described in Topical Report 3.

Based on the results of the interim economic study, economic targets were established for the process. These were to achieve a 20% levelized cost advantage and a 50% capital cost advantage over limestone wet scrubbing for a range of plant sizes and coal sulfur levels.

In late 1993, CONSOL conducted a second interim process economics study. The study confirmed that projected SO_2 removal costs for the Advanced Coolside process were substantially reduced by the process design improvements established during pilot plant development work. In addition, the study showed that the cost advantage applied to a range of plant sizes and coal sulfur levels.

This report presents the results of a final process economic study for the Advanced Coolside process, under DOE Contract DE-AC22-91PC90360. It incorporates the results of recent pilot plant development work. It also includes results of the engineering studies aimed at design improvement.

The Advanced Coolside process was compared to the commercial technology of limestone forced oxidation (LSFO) for retrofit applications. The SO_2 abatement processes were evaluated at three plant sizes (160 MW, 262 MW, and 512 MW, gross) and four coal-sulfur levels (1.0%, 1.5%, 2.5%, and 3.5%, as-received).

The performance and economics of the technologies were assessed using the CONSOL Coal Quality Cost Model (CQCM), developed by CONSOL in the 1980s.[6] A process inlet flue gas flow rate and composition were estimated for each coal and plant size using the power plant module of the CQCM. These values were incorporated into an Advanced Coolside Cost Model (ACCM) and a LSFO model to provide the final process economics. The LSFO model was developed by CONSOL in the 1980s[6] and is regularly updated. Economic assumptions were based on EPRI technical assessment guidelines.

Capital costs for the two processes were compared and expressed as \$/net kW. In addition, detailed total compliance costs were determined for all scenarios investigated, in total levelized dollars and \$/ton SO_2 removed.

To achieve consistency for a comparative evaluation, similar design philosophies, equipment cost algorithms, and financial assumptions were used for the evaluation of both technologies.

CONCEPTUAL PROCESS DESIGN—ADVANCED COOLSIDE

The process flow for the Advanced Coolside process is categorized into fresh sorbent handling, sorbent preparation, flue gas flow, ash dewatering, and ESP waste handling sections.

FRESH SORBENT HANDLING

The hydrated lime handling area for the off-site hydration scenario is designed for rail delivery of hydrated lime. The hydrate is conveyed pneumatically from the railcars to the hydrate storage silo. The hydrate then is transferred from the storage silo to the duct injection point via the pneumatic injection blowers.

SORBENT PREPARATION

The pebble (quick) lime handling and preparation area for the on-site hydration scenario is similar to the off-site hydration area, except for the addition of hydrators. Pebble lime is pneumatically transferred from the unloading section to a day bin and hydrator feed bin. The pebble lime then is fed to the hydrator where water is added. The fresh hydrate is conveyed to the hydrate day bin while the grits, or insoluble residue, are fed to the grits bin. The hydrator is equipped with a vent scrubber and fan package for vent gas cleanup.

FLUE GAS FLOW

The flue gas flow area consists primarily of a venturi contactor, sorbent injection ports, and new duct run. It is assumed that the existing duct from the boiler splits into two trains each containing air heater and ESP modules.

To remove fly ash and humidify to saturation, the flue gas passes through the venturi contactor and contacts with coarse water sprays at the venturi throat. Pressure-drop-induced turbulence in the venturi throat breaks up the water droplets improving contact and vaporization. Total pressure drop across the venturi contactor is five inches of water. The water injection system in the venturi uses low-pressure, low-erosion nozzles. The system does not require a second fluid, such as air, and an associated compressor. Excess water and most of the fly ash are separated from the flue gas in the cyclone section of the venturi contactor and collect in the bottom. Once collected, the ash slurry is pumped to the dewatering section.

Prior commercial operating experience shows that the ESP can be successfully operated at an 18 °F approach to saturation. This study assumes that operation at a 10 °F minimum approach is possible; however, a reheat system is included in the design as a contingency. Like the return duct, the ESP is heat traced.

Once the flue gas passes through the ESP, it enters the existing ID fan and a new booster fan. A booster fan will not be required if the existing ID fan has sufficient excess capacity to cover the additional power requirement resulting from the Advanced Coolside process pressure drop. However, it is assumed that the existing ID fan is sized exactly for the existing (i.e., pre-retrofit) flue gas conditions. The booster fan is sized for the additional process pressure drop after correcting for the new process conditions. A steam reheater is included at the ID fan exit to assure sufficient stack buoyancy. It is designed to give a 30 °F approach to saturation.

ESP WASTE/RECYCLE SOLIDS HANDLING

Solids that are collected by the ESP are conveyed continuously from the ash hoppers to the recycle solids bin and the waste silo. Water is added to the recycle sorbent using a mixer. Once the water is added, the wetted sorbent is injected into the duct.

ASH DEWATERING

Dewatering of the venturi contactor bottoms is carried out with hydroclones. Use of hydroclones instead of a thickener results in a smaller footprint and lower capital cost.

Holding tanks are placed at the venturi contactor exit, hydroclone bank overflow, and hydroclone bank underflow. Pumps move the venturi contactor bottoms to the hydroclones and various other points in the process.

The fly ash and spent sorbent are disposed of by trucking to a land fill.

PROCESS DESCRIPTION—LIMESTONE FORCED OXIDATION

The limestone forced oxidation (LSFO) process is a standard post-ESP wet FGD process. The LSFO process uses the current state-of-the-art design for commercial operation. A single absorber module with no spare is assumed.

PROCESS DESIGN CONDITIONS

ADVANCED COOLSIDE

The Advanced Coolside process is assumed to operate at 90% total SO_2 removal and a fresh Ca/S ratio of 1.2, to yield a calcium utilization of 75%. SO_2 removal in the ESP is assumed to be 4% (absolute).

The pebble lime or hydrate storage silo has a capacity of 30 days while the silo feed blowers are sized for six times the required fresh lime feed rate. The recycle solids bin has a four-hour capacity.

For the on-site hydration scenarios, the commercially available hydrators are sized at either 10 or 15 tons per hour of product. One spare hydrator is supplied for each plant.

A pressure drop of 5" H_2O is estimated for the venturi contactor. Although the pilot plant venturi was operated at 6-8" H_2O, less pressure drop is expected in a commercial unit designed with a more gradual expansion after the throat. At these conditions, it is assumed that the venturi contactor removes 85% of the incoming fly ash and humidifies the flue gas to saturation. The contactor is designed to resist acid corrosion.

Corrosion-resistant material is used for the duct between the venturi contactor and the injection point. Since the presence of the alkaline solids eliminates acid corrosion, the new duct after solids injection is constructed of carbon steel.

The post-injection duct layout is configured to yield a total flue gas residence time of three seconds at 50 fps average velocity after lime injection. Half of the total residence time, or 1.5 seconds, is obtained in the new duct run while the remaining 1.5 seconds is obtained in the existing dual ducts. Process equipment layout considerations require much of this new duct length to provide reasonable access for maintenance. The total reaction duct requirement of three seconds is based upon engineering judgment of mixing conditions in the large ducts. The additional pressure drop resulting from the new duct run is estimated to be 1.5" H_2O.

Heat tracing of the ESP is included to insure that condensation does not occur on the walls. Ductwork from the venturi contactor through the ID fan is also heat traced. The electric costs correspond to operating the heat tracing at an annual average of 70% of design capacity.

Staffing of the Advanced Coolside process is set at an average of 3.25 operators per shift. This consists of three operators per shift, seven days a week, plus one operator on daylight during the five-day work week for waste disposal.

LIMESTONE FORCED OXIDATION

The LSFO Process is designed for 90% SO_2 removal and operates at a 1.05 available fresh Ca/S ratio. No additives are utilized in the system. A single absorber design philosophy is assumed for all plant sizes. Hydroclones are used for primary dewatering of absorber slurry. A new 350-ft high stack is assumed. Staffing for the LSFO Process is averaged at 4.2 operators/shift.

TECHNICAL AND ECONOMIC CRITERIA

The prices of consumables are listed in Table 1. Both lime and limestone prices are a function of site-specific delivery factors and may vary with location. A significant change in the delivered pebble lime or hydrate price will affect the economics of the technologies. For this report, the economics for generic delivered prices of pebble lime and hydrate for river (barge transport) and inland (barge plus rail/truck transport) locations were generated. Lime plant fob prices were set at \$50/ton for pebble lime and \$54/ton for hydrate. Barge transport rates were set at \$4/ton for pebble lime and \$5/ton for hydrate while truck/short rail rates were set at \$3/ton and \$6/ton, respectively. The difference in the transport rates for pebble lime and hydrate reflect truck/car capacities for the different bulk densities (60 lb/cf for pebble lime versus 35 lb/cf for hydrate).

Specifications for the 2.5% sulfur coal are listed in Table 2. The coal represents a cleaned, eastern bituminous product.

Design assumptions for the processes are 90% SO_2 removal, 65% net capacity factor, and 30-year capital life. Indirect costs, expressed as a percentage of direct costs, consist of 13.8% field costs, 22.4% home office, and 1% bonds, all-risk insurance, and tax. An 18% contingency is used for all technologies.

A medium-difficulty retrofit level and a standard 1.06 location factor are assumed for all technologies. A two-year construction life is used for Advanced Coolside while LSFO is based on a three-year construction life. Other assumptions are a 4.5% inflation rate, 45% debt, and a 38% income tax rate. All costs are in 1992 dollars.

ECONOMIC RESULTS

Predicted capital costs and total annual levelized costs for the Advanced Coolside process are listed in Tables 3 and 4. The capital costs are expressed in \$/net kW of capacity while the total annual levelized costs are expressed in \$/ton SO_2 removed. Note that these costs do not include coal or other boiler-related expenses. As a result, the costs in Table 3 represent the total additional SO_2 control cost that results from the capital expenditure costs, operating costs, maintenance costs, and variable costs attributed solely to the FGD process. Plots comparing the capital and levelized compliance costs for Advanced Coolside and wet FGD (LSFO) for the 262 MW plant cases are shown as Figures 1 and 2.

Advanced Coolside has significantly lower capital cost requirement than LSFO for all cases investigated. The capital cost advantage for the Advanced Coolside process over LSFO ranges from 50% for the 1.0% sulfur coal, 160 MW plant, on-site hydration case up to 62% for the 2.5% sulfur, 160 MW plant, off-site hydration case. For the 512 MW plant cases, the capital cost advantage ranges from 53% for the 1.0% sulfur coal, on-site hydration case up to 59% for the 3.5% sulfur coal, off-site hydration case.

Advanced Coolside enjoys a total levelized cost advantage relative to LSFO for all cases. The total removal cost advantage for the Advanced Coolside process, at a river location, relative to LSFO, on a \$/ton SO_2 removed basis, ranges from 17% for the 3.5% sulfur coal, 512 MW plant, on-site hydration case to 35% for the 1.0% sulfur, 160 MW plant, off-site hydration case. For the 262 MW plant burning a 2.5% sulfur coal and employing on-site hydration, the Advanced Coolside compliance cost advantage is 26%.

For the 262 MW plant burning a 2.5% sulfur coal, adding the hydrator to the Advanced Coolside process increases the required capital by \$12/kW but decreases the overall removal cost by \$12-17/ton of SO_2 removed, depending on the reagent delivered prices.

PROCESS IMPROVEMENTS

A number of key process improvements have been added to the Advanced Coolside process since the initial interim economic study. For the 262 MW plant size burning a 2.5% sulfur coal, total process capital was reduced by approximately \$6.8 MM, which translates to over \$62/ton SO_2 removed. Since these are capital cost savings, the levelized cost, \$/ton SO_2 removed, is much higher for the low-sulfur coals. For the 1% sulfur coal, the savings is 2.5 times the previously mentioned \$62/ton SO_2 removed. This reduction was a result primarily of switching to a venturi contactor for fly ash removal and humidification (~\$4.0 MM), using hydroclones in place of a thickener for ash dewatering (~\$2.0 MM), and improving the recycle handling system (~\$0.8 MM). The process improvements were corroborated by either pilot plant tests or by engineering studies and vendor recommendations.[2]

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6. Bissel, P. E.; Fink, C. E.; Koch, B. J.; Rutledge, G. D. "Scrubbers: A Popular Phase I Compliance Strategy", Presented, EPRI-EPA-DOE 1991 SO_2 Control Symposium, Washington, DC, December 1991.

TABLE 1

PRICES

	Price
Pebble Lime, River/Inland	$54/$60/ton
Hydrate Lime, River/Inland	$57/$65/ton
Limestone	$15/ton
Water	$0.60/Mgal
Fly Ash Credit	$8/ton
FGD Waste Disposal	$6.50/ton
Replacement Power	$30/MW
Operating Labor	$22/hr
Maintenance Labor	$18.90/hr
Administration	$16.87/hr

TABLE 2

COAL SPECIFICATIONS

Coal Sulfur Level	2.5% S
<u>Proximate Analysis, wt %</u>	
Moisture	5.5
Volatile Matter	36.5
Ash	7.5
Sulfur	2.5
Heating Value, Btu/lb	13,200
<u>Ultimate Analysis, wt % dry</u>	
Hydrogen	5.2
Carbon	77.5
Nitrogen	1.4
Oxygen	5.2
Sulfur	2.7
Ash	7.9
Chlorine	0.1
Heating Value, Btu/lb	13,968

TABLE 3

SUMMARY OF COST

Coal Sulfur	Plant Size	Pebble & Hydrate	Capital Cost		Levelized Cost	
			Advanced Coolside w/o Hydrator	Advanced Coolside w/Hydrator	Advanced Coolside w/o Hydrator	Advanced Coolside w/Hydrator
% AR	MW	$/ton	$/Net KW	$/Net KW	$/ton SO_2	$/ton SO_2
River Site						
2.5	262	54/60	82	94	315	303
Inland Site						
2.5	262	57/65	82	94	323	306

TABLE 4

DETAILED COSTS OF 262 MW, 2.5% SULFUR COAL CASE
FOR RIVER DELIVERY

Process	Advanced Coolside	
Hydration	Off-site, $	On-Site, %
Capital Section		
Reagent Preparation	2.103	3.552
Sorbent Injection	0.807	1.102
Venturi Train	1.554	1.554
Flue Gas Handling	4.265	4.265
Reaction Duct/Absorber	0.166	0.166
Recycle System	0.897	0.897
Particulate Collection	0.215	0.215
Reheat	0.248	0.248
Waste Handling	1.665	1.665
Chimney	0.000	0.000
Miscellaneous	0.715	0.820
Total Direct	12.635	14.484
Field	1.744	1.999
Home Office	2.831	3.244
Bond, ARI, Tax	0.126	0.145
Contingency	3.121	3.577
TPI	20.457	23.449
$/net KW	82	94
Levelized Cost Section		
<u>Capital</u>		
Levelized TPI	2.117	2.427
Preproduction	0.195	0.205
Working Capital	0.136	0.138
Total Capital	2.448	2.770
<u>Variable O&M</u>		
Reagent	2.235	1.547
Water	0.054	0.054
Waste Disposal	0.543	0.543
Power	0.537	0.552
Total Variable O&M	3.369	2.696
<u>Fixed O&M</u>		
Operating Labor	0.626	0.626
Maintenance	0.522	0.590
Administration	0.250	0.259
Total Fixed	1.398	1.475
Total O&M	4.766	4.171
Total Levelized Cost	7.214	6.941
$/ton SO_2 Removed	315	303

*Note: Costs are expressed in $MM unless stated otherwise.

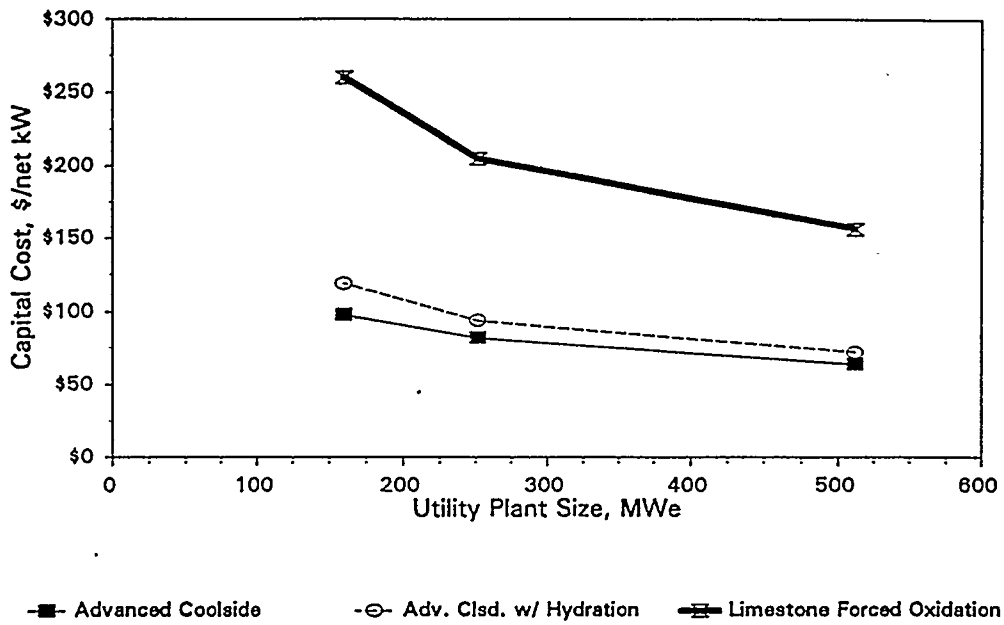

Figure 1. FGD Capital Costs (2.5% Sulfur Coal).

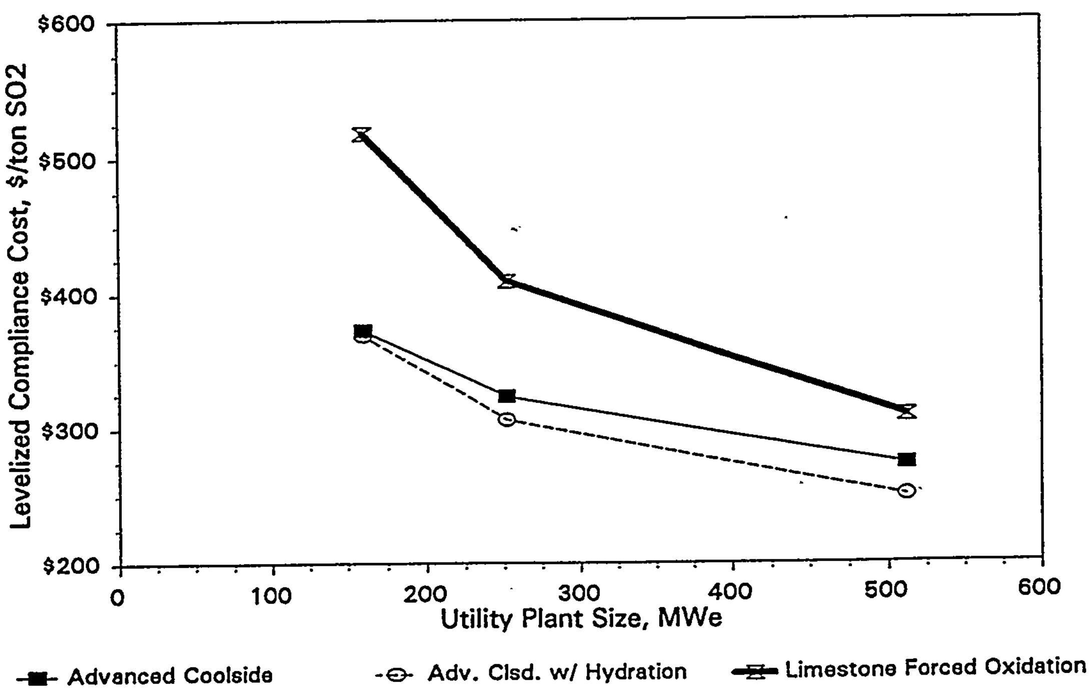

Figure 2. Levelized Compliance Cost for FGD
(2.5% Sulfur Coal, Inland Plant Site).