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**DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT: EVALUATION
OF ENGINEERING DATA**

Topical Report No. 2

July 1990

Work Performed Under Contract No. AC22-88PC88852

**For
U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania**

**By
United Engineers & Constructors, Inc.
Denver, Colorado**

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PROTOTYPE DEVELOPMENT

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EVALUATION OF ENGINEERING DATA

TOPICAL REPORT NO. 2

July 1990

Prepared For

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SUMMARY

One of the primary work products to be developed under the Department of Energy's Duct Injection Technology Development Program is a design handbook that will provide the practical process, equipment, and economic information required for evaluating, designing, and retrofitting a full-scale duct injection system. As a first step in developing the design handbook, United Engineers & Constructors Inc. (UE&C) has performed evaluations of the existing data and test results relevant to duct injection technology. This report contains a summary of these evaluations.

The evaluations were divided into six major areas:

- ° Literature review/Status Reports
- ° Review of other contractors' test plans
- ° Development of a preliminary design handbook
- ° Review of results from the Utility Duct Survey
- ° Development of preliminary duct injection economics
- ° Examination of corrosion/erosion impacts on existing plant materials of construction

The information compiled from UE&C's literature review was classified into several major areas, e.g., sorbent characteristics and selection; sorbent storage and preparation; sorbent and water injection; corrosion of materials in the flue gas path; material deposition in ducts; controls; electrostatic precipitator (ESP) performance; waste handling; and others. A Status Report has been completed for each of these topics which summarizes the significant practical design and scale-up criteria available for each specific area.

From the information compiled in the Status Reports, the review of other contractors' test plans, the development of the preliminary design handbook, and the examination of corrosion impacts on existing plant equipment, several areas have been identified which could present obstacles to applying duct injection technology to potential retrofit candidates. The most significant of these include:

- ° The impact of duct injection on the existing ESP,
- ° The capability of the existing ash handling system to handle the increased solids volume,
- ° The potential for corrosion of the existing ESP outlet and stack or chimney liner due to the low temperature, humidified flue gas, and
- ° The potential for duct deposition.

Since much of the research effort has concentrated on proving and enhancing the SO₂ removal performance of duct injection, less emphasis has been placed on the impacts of the process on existing plant equipment.

ESP Impacts - While the impacts of duct injection on ESP performance and operation have been a point of concern, only recently have concentrated efforts been undertaken to quantify these impacts. The inlet grain loading to the ESP may increase by a factor of 3 to 12 as a result of a duct injection system retrofit, depending on SO₂ removal, recycle ratio, etc. Although partially offset by the positive effects of the low-temperature, humidified flue gas, re-entrainment due to low resistivity and inlet field space charge quenching could result in difficult-to-control particulate emissions. Tests to be conducted at the 1.7 and 12 MW pilot facilities as part of this DOE program will systematically address these issues. Even after these impacts are quantified, significant efforts are still likely to be required to develop cost-effective ESP upgrade strategies to overcome these impacts.

Ash Handling System Impacts - Little attention has been given to the ability of existing fly ash handling systems to handle the increased ash/sorbent solid waste from a duct injection retrofit. As noted above, duct injection is expected to significantly increase the solids loading to the ESP and ash handling system. This will probably require equipment and operational modifications, and possibly complete replacement of the existing ash removal system. Depending on the extent and difficulty of the modifications (space restrictions, required down-time, etc.), this may present a significant additional cost to the process. The waste solids will have a higher moisture content than before the retrofit which might lead to additional handling problems.

Corrosion Impacts - There is very little experience with duct injection or similar (e.g., spray drying) processes to predict their impact on existing ESPs, ductwork, and stacks or chimney liners designed for hot, dry flue gas. The impact of low-temperature, high humidity flue gas on these components must be determined. Most of the utility station candidates for duct injection retrofits are likely to have stacks or chimney liners with carbon steel or non-acid resistant brick liners. Replacing the stack, relining the chimney, or adding a reheat system will have significant cost impacts for the process.

Duct Deposition Impacts - In order for duct injection technology to be successful, continuous deposition of solids in the ductwork must be eliminated or a means of on-line removal of deposited solids must be developed. The duct injection system must be capable of operating continuously between regularly scheduled plant outages. Most testing to date has resulted in moderate to heavy deposition of material. Optimization of sorbent injection is required to minimize and limit buildup, and/or strategies to handle buildup on-line must be developed.

From our review of the Burns and Roe Utility Duct Survey, two items were identified which have a potentially significant impact on the retrofit of a duct injection system. First, when the longest straight run of ductwork between the existing air preheater(s) and ESP is considered, 57% of the units surveyed have less than 1 second residence time available for humidification and reagent/SO₂ reaction. This indicates that improvements in atomizer performance and other efforts to reduce drying time will be necessary. The alternative of installing additional ductwork or humidification/reaction chambers may add significantly to capital costs and may be impossible in many cases due to space constraints.

The second item of note from the Utility Duct Survey is that about 57% of the plants surveyed have sufficient space to increase their ESP size by 50%. Increasing the SCA may be desirable depending on the ability of the existing ESP to maintain compliance after a duct injection retrofit.

The final evaluation completed by UE&C was the development of preliminary economics for the duct injection processes. Preliminary economic analyses have been completed for both dry sorbent injection (DSI) and duct spray drying (DSD) processes. Additional refinements must be made to several areas (e.g., installation factors and contingency factors) of the economic portion of both programs. These final modifications are not expected to greatly impact the present levelized control costs. The current economic models do not include ESP upgrade costs or stack modifications since technical and economic data are still undefined for these areas. The program does include ash handling system modifications. Based on our preliminary economic models, the current cost estimates for duct injection technology exceed the DOE's stated goal of \$500/ton SO₂ removed. The 15 year levelized control cost for DSI with on-site hydration is about \$770/ton of SO₂ removed; for DSD, the control cost is about \$665/ton of SO₂ removed. If sorbent utilization can be improved as duct injection technology is developed, these costs should decrease.

During the course of the UE&C evaluations, several items were identified which will be required to complete the design handbook but which are not currently included in the work plans of the participating contractors. These items are summarized in Table SUM-1; UE&C has prioritized each item in this table and identified the most appropriate contractor to develop or obtain the necessary information.

In addition, the experience gained from the Coolside demonstration at Edgewater would be extremely useful to UE&C in the development of the handbook. UE&C recommends that the DOE obtain a detailed evaluation of the experiences from the Edgewater testing in the following areas:

- ° Effects of utilizing different sorbents
- ° Effects of sodium additives
- ° Evaluation of humidification nozzles and operating conditions
- ° Material deposition
- ° Corrosion including effects of additives
- ° Effects of duct injection on ESP performance
- ° Operating and maintenance procedures

TABLE SUM-1

DATA REQUIREMENTS OUTSIDE OF EXISTING PROGRAM SCOPE

<u>Item</u>	<u>UE&C Priority</u>	<u>Recommended Contractor To Obtain Information</u>
Verify the contribution of scavenging to overall SO ₂ removal	Low	Radian at Meredosia
Evaluate additives including ligno-sulfonates, sodium compounds, and chlorides	High	G/C at Beverly
Identify compounds which can be added to hydrated lime for wetting	Medium	Acurex
Expanded nozzle array testing	High	B&W at Alliance
Evaluate spacing including "zero spacing" between sorbent injectors and humidification nozzles	High	G/C at Beverly
Dry sorbent injector design modeling	Medium	EER
Extensive evaluation of on-line material deposition detection and disposal schemes	High	G/C at Beverly
Incorporate mechanical material removal devices into duct injection models	Medium	CHAM/B&W
Develop methodology for site specific evaluation of suitability of existing stack	High	UE&C
Develop technical and economic feasibility of adding a reheat system in conjunction with a duct injection retrofit	Medium	UE&C
Determine impacts of duct injection waste on wet ash sluicing system/ash ponds	Low	Contractor to be determined
Develop methodology for site specific evaluation of suitability of existing ash handling system	High	UE&C
Evaluate methods to activate recycle material including grinding	Medium	G/C at Beverly

TABLE SUM-1 (Cont)

DATA REQUIREMENTS OUTSIDE OF EXISTING PROGRAM SCOPE

<u>Item</u>	<u>UE&C Priority</u>	<u>Recommended Contractor To Obtain Information</u>
Incorporate recycle/additive effects into EER submodel	High	EER
Obtain three-dimensional data to support model development/ validation	High	B&W at Alliance

INTRODUCTION

The objective of the Duct Injection Technology Prototype Development Project is to develop a sound design basis for applying duct injection technology as a post-combustion SO₂ emissions control method to existing, pre-NSPS, coal-fired power plants. The project is being executed by United Engineers & Constructors Inc. (UE&C) for the U.S. Department of Energy - Pittsburgh Energy Technology Center (DOE-PETC). UE&C will develop the necessary engineering design and scale-up criteria for the commercialization of duct injection technology for the control of SO₂ emissions from coal-fired boilers in the utility industry.

Task 2 of the UE&C project is dedicated to the development of engineering design criteria. Under Task 2, Subtask 2.1 involves the collection and analysis of engineering data. This Topical Report No. 2 presents the results of UE&C's compilation and evaluation of engineering data relevant to duct injection technology.

The primary focus of the analyses summarized in this Topical Report is the review of the known technical and economic information associated with duct injection technology. Based on this review, missing or conflicting information are identified, and possible program changes which could generate or clarify these data are recommended. It is intended that any missing data or information required for the development of the final design handbook and/or predictive mathematical model be identified now such that they may be generated by the two pilot-plant programs and/or bench-scale efforts which are being accomplished by the other program participants.

In the UE&C Work Plan, Subtask 2.1 was broken into eight major areas, and this Topical Report No. 2 is similarly divided:

<u>Task</u>	<u>Topical Report No. 2 Section No.</u>
Literature Review/Status Reports	1.0
Review of Other Contractors' Test Plans	2.0
Preliminary Design Handbook	3.0
Results from Utility Duct Survey	4.0
Preliminary Duct Injection Economics	5.0
Corrosion/Erosion Impacts on Existing Plant	
Materials of Construction	6.0
Identification of Missing Data Requirements	7.0
Duct Injection Program Change Recommendations	8.0

The first six sections of this report present the results of UE&C's technical evaluations to date. From these analyses, several items were discovered which need to be addressed in order to complete the final design handbook in 1992. These are listed in Section 7.0. Comparing these items against the Work Plans of the participants revealed the information that is not projected to be developed or evaluated under the current DOE program. Possible changes in the program which are recommended in order to obtain this information are presented in Section 8.0.

1.0 LITERATURE REVIEW/STATUS REPORTS

A literature search was conducted to identify the reports, design studies, and articles relevant to duct injection technology. The final reports issued by Bechtel (9), General Electric Environmental Systems (19), and Dravo Lime Company (1) presenting the results of the Proof-of-Concept test programs were reviewed in detail as were the numerous papers and reports published by the Electric Power Research Institute (EPRI) and Consolidation Coal Company (Consol). The literature reviews generated by Energy and Environmental Research Corporation (11), Gilbert/Commonwealth (13), and Radian (17) under this DOE program were also reviewed.

UE&C personnel visited the Coolside demonstration at Edgewater and the Meredosia duct injection pilot plant to determine the design and arrangement of the duct sorbent injection equipment in operation at these sites. A site visit to the Beverly test facility has been delayed due to the delay in construction and start-up at this facility. Symposia and contractors conferences involved with duct injection were also attended by UE&C personnel.

Information from related SO₂ removal processes was reviewed as it applied to duct injection technology. Related processes evaluated were furnace sorbent injection, Tampella LIFAC, economizer sorbent injection, dry sodium injection, HYPAS, E-SO_x, and ADVACATE.

The information compiled from the sources listed above was classified into several major areas. A summary of UE&C's evaluation of pertinent information in each area was prepared and presented in a Status Report format. Status Reports are analyses which summarize the significant, practical (versus theoretical) design and performance information currently available for a specific topic relating to the duct injection process. Some of the reports contained information specific to dry sorbent injection (DSI) or to duct spray drying (DSD), and some were more generic and applied to duct injection in general. Seventeen such topics were identified early in the project and are listed in Table 1.0-1 along with the company designated to prepare the Status Report.

The first thirteen Status Reports shown in Table 1.0-1 have been completed and are attached to this report in Appendix A. The focus of the Status Reports was the state-of-the-art in duct injection equipment design. Nine of the fourteen reports were prepared by UE&C with the balance by one of our subcontractors on this project, Babcock & Wilcox (B&W). Our other subcontractor, the Energy & Environmental Research Center of the University of North Dakota (EERC), reviewed and provided input on several of the reports.

Three of the four Status Reports not attached; System Turndown, Start-up/Shutdown, and Maintenance, were not prepared due to lack of experience on commercial-scale installations. Experience at the Coolside demonstration and the 12 MW Beverly test facility will constitute the bulk of these evaluations. Instead of writing Status Reports for these three areas, however, the appropriate section in the design handbook will be developed based on the full-scale experience discussed above. This is further addressed in Section 3.0 and Appendix C of this report.

The final Status Report listed, Measurement/Sampling Methods for Site Specific Characterization, was not generated because, upon further analysis, this topic will actually constitute a portion of the second and third chapters of the design handbook. It will be a discussion of the site-specific information that plant personnel will need in order to determine if duct injection technology is feasible at their site. If it is feasible, this information will be required as inputs to the design for the retrofit. This is discussed further in the preliminary design handbook included as Appendix C of this report.

Feasibility will be determined by comparing the site-specific data to technical and economic criteria to be established and presented in the design handbook. If the retrofit of duct injection is determined to be feasible, the subsequent chapters of the handbook will assist plant personnel in determining the scope and design of the necessary equipment and modifications.

Each of the Status Reports contained in Appendix A consists of an introduction to the topic, conclusions and recommendations, a discussion section, and applicable references. In addition to presenting recommended designs and criteria, the conclusions and recommendations sections identify any "gaps" in the data base and recommend additional test work or evaluation based on a review of the topic. These items are included in the missing data requirements listing in Section 7.0 of this report. The discussion section reviews the data/designs from duct injection experience contained in the literature or from ongoing programs. A review of the data/designs as a result of experience on similar applications, such as furnace sorbent injection and lime spray drying, is also presented in the discussion section.

A comparison of the list of Status Reports with the Table of Contents from the preliminary design handbook in Section 3.0 indicates that the completed Status Reports will become the basis for many of the sections in the final handbook. This is discussed further in Section 3.0.

TABLE 1.0-1
PLANNED STATUS REPORTS

	<u>Preparer</u>
Sorbent Selection	UE&C
Sorbent Storage and Preparation (for both DSI and DSD)	UE&C
Humidification and Slurry Nozzle Specifications (for both DSI and DSD)	B&W
Dry Sorbent Injector Design (for DSI)	UE&C
Material Deposition on Duct Walls/Turning Vanes	B&W
Corrosion of Materials in Flue Gas Path	B&W
Temperature Instrumentation and Controls	UE&C
SO ₂ Measurement Instrumentation and Process Control	UE&C
Velocity and Temperature Profile	B&W
Electrostatic Precipitator	UE&C
Waste Handling System (On-Site Transfer, Storage, and Conditioning)	UE&C
Recycle System (for both DSI and DSD)	UE&C
Waste Disposal (Transport and Disposal)	UE&C
System Turndown Considerations	UE&C
Start-up/Shutdown Considerations	UE&C
Maintenance Considerations	UE&C
Measurement/Sampling Methods for Site Specific Characterization	UE&C

2.0 REVIEW OF OTHER CONTRACTORS' TEST PLANS

Test plans submitted by Acurex, Gilbert/Commonwealth, and Radian have been reviewed by UE&C and our subcontractors. Detailed questions and comments were generated and subsequently submitted to DOE, and they are attached to this report as Appendix B.

2.1 Acurex

UE&C's comments on Acurex's revised overall test plan, dated May 31, 1990, were transmitted to DOE in Letter No. S-R/DOE-62, dated July 6, 1989. UE&C was later requested to review just Task 4 of Acurex's test plan, dated January 22, 1990. These comments were submitted in Letter No. S-R/DOE-128, dated February 13, 1990. These letters are included in Appendix B of this report.

2.2 Gilbert/Commonwealth

Gilbert/Commonwealth (G/C) and their subcontractor, Southern Research Institute, have not submitted an official test plan for the 12 MW pilot-plant project at Beverly to UE&C. Section 5 of their December 1988 draft work plan, however, presents a fairly comprehensive description of their anticipated activities along with detailed preliminary test matrices. This document was submitted in 1988, and it does not reflect any recent developments in this project or duct injection processes in general. Keeping the preliminary nature of this work plan in mind, UE&C has made several comments which are listed in Appendix B. The primary areas of concern are summarized below.

It is important that there is consistency and continuity between the 1.7 MW and 12 MW efforts. Some test conditions and parameters should be duplicated as well as possible to identify any differences in performance. These differences must then be attributed to scale or problems in operations or testing. When possible, experimental techniques should be consistent for both projects. Currently, there are different techniques indicated for resistivity measurement and for determining the effects of residence time on SO₂ removal.

The tests to evaluate on-line deposition removal are important. Expanding the efforts to develop these techniques may be beneficial, since deposition control is so important to the success of duct injection.

Recycle should be tested at conditions representative of realistic full-scale plant operations. The more fundamental investigations should be conducted at the 1.7 MW scale.

There has been increasing evidence that low-resistivity re-entrainment may be a significant limiting factor in ESP performance. More emphasis on tests to evaluate solutions to this problem is recommended.

In addition to these comments, B&W has recently identified the potential for significant wall deposition in the 12 MW test facility. This was documented in Letter No. S-R/DOE-147, dated March 28, 1990, which is also included in Appendix B. G/C has responded to this concern by modifying their atomizer lance assembly by tilting the nozzles inward to direct the spray away from the walls and towards the center of the duct.

2.3 Radian

The test plan for the 1.7 MW duct injection pilot-plant project at Meredosia, dated May 31, 1989, was reviewed. UE&C's comments, along with those of its subcontractors, B&W and EERC, are listed in Appendix B. Some of the more significant comments are summarized below.

Many of the comments concerned the proposed number of tests to be conducted each week. There is concern over the required test length due to recycle. More test conditions can be investigated with lime only since steady state is reached much more quickly. The general concern is that this approach is not the most efficient use of test time.

ESP's require considerable time to reach steady state operating conditions (both electrically and thermally). Useful ESP data may not be obtainable during the short run sorbent SO₂ removal tests. Long duration operation (12 to 24 hours) at a given operating condition is desirable to ensure a stabilized ESP; however, maintaining the pilot plant at close approach temperatures with high solids loading may not be possible due to duct pluggage.

Another question regarding recycle tests is the proposed recycle ratio of 5:1. This may be too high to be practical from an operational standpoint, and may not be measurably more effective than lower ratios of 2:1 to 3:1 in terms of increasing overall sorbent utilization.

Very few repeat tests were listed in the test plan. More repeats are considered necessary to verify data quality.

One of the primary objectives of the 1.7 MW testing was to validate the predictive models being developed by Energy and Environmental Research Corporation and Radian. Very little emphasis is placed on this task in the preliminary test plan. A matrix of tests specifically designed for model validation should be included.

The small duct dimensions (18" diameter) of this pilot plant may prevent operating at the 20°F approach to saturation proposed as a baseline condition by Radian. Severe wall wetting and deposition has been experienced at other pilot facilities of similar size. Operating at the closest approach to saturation achievable with minimum wall wetting and deposition may be a better baseline condition. Closer approaches to saturation may be better evaluated at the 12 MW Beverly facility.

If operational problems such as wall wetting solids deposition are insurmountable with single stage-single nozzle humidification, provisions should be made to operate and test multiple nozzle humidification configurations (parallel and/or series arrangement).

There is concern about conducting baseline fly ash only ESP characterization after the dry injection and slurry baseline tests. If, after these tests, the ESP is found to be operating in a non-representative fashion (not representative of a typical duct injection candidate), or if there are any effects of residual dry sorbent or slurry materials that may interfere with the fly ash only tests, it could potentially cast suspicion on the ESP data from the baseline DSI and DSD tests.

3.0 PRELIMINARY DESIGN HANDBOOK

The Table of Contents (TOC) for the preliminary issue of the design handbook is shown in Table 3.0-1. The format of the preliminary handbook has been revised extensively from the proposed format contained in the UE&C proposal for this project. The preliminary design handbook has been organized to present a logical sequence of steps which the user will need to take in order to 1) gain a basic understanding of duct injection technology, 2) decide whether a duct injection process is feasible for a specific plant, and 3) implement the retrofit of this technology.

A preliminary issue of the design handbook has been prepared and is attached as Appendix C. The text under each section heading gives a detailed description of what that section will contain in the final issue and what sources of data will be required in order to complete it. All of the Status Reports and several UE&C Topical Reports to be submitted later will supply the bases for several of the sections in the handbook. This is detailed in Appendix C.

During the preparation of this preliminary edition, a number of questions and unknowns were uncovered that need to be addressed before the final handbook may be written. These items are included in the missing data requirements listing in Section 7.0 of this report. Addressing these requirements will provide significant focus and direction for the remainder of the project.

As mentioned above, the design handbook is organized to serve three primary functions:

- ° Section 1.0 gives a general background and basic understanding of duct injection technology including dry sorbent injection (DSI) and duct spray drying (DSD).
- ° Sections 2.0 and 3.0 provide enough criteria and information to allow utility personnel to make decisions regarding the technical and economic feasibility of retrofitting duct injection technology to a specific plant.
- ° Sections 5.0 - 10.0 provide detailed design and specification information for actually retrofitting the equipment and modifying the existing plant.

A section (Section 4.0) is also included which describes the use of the mathematical model to complement the decision making and design processes outlined in the handbook. Due to the potential hardware requirements required to run the model, it is likely that the typical user will not be able to use the model. Therefore, the design handbook is being written as a "stand alone" document which can be used by itself or interfaced with the model if the user has the capability to exercise it.

Section 11.0 of the handbook will present general operation and maintenance guidelines. Only equipment which is unique to the duct injection process, e.g., slurry or water atomizers, slurry pumping, etc., will be covered. Standard-type plant equipment such as new water pumps and blowers will not be addressed in this section. Modifications to the operation and maintenance of existing plant equipment, such as the ash handling system and ESP, required after the retrofit is completed will also be discussed.

After the design of the duct injection retrofit is fairly well established, a detailed capital and operating cost estimate may be prepared. The economic guidelines and methodology presented in Section 12.0 will facilitate the preparation of these estimates.

Finally, a complete sample case study will be presented for both DSI and DSD in Sections 13.0 and 14.0, respectively, to act as examples for determining the feasibility and actual design of these processes.

It is anticipated that five appendices will be attached to the handbook:

- ° Process chemistry for DSI and DSD
- ° Decision Making Criteria Resources (the work sheets, nomographs, and data tables required to establish the feasibility of a duct injection retrofit)
- ° Sorbent selection guidelines
- ° By-product (waste) utilization
- ° Bid specifications

All of the major sections, as well as subsections and appendices, are discussed in detail in the preliminary design handbook in Appendix C of this report.

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Appendix D	By-Product Utilization
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4.0 RESULTS FROM UTILITY DUCT SURVEY

A survey was conducted by Burns and Roe Services Corporation to provide a general design basis for existing duct configurations at plants considered as potential candidates for duct injection system retrofits (14). The objectives of the study were to determine ranges of various flue gas ductwork parameters and operating conditions that need to be included in the design handbook and predictive mathematical model.

To ensure that the survey included those units judged to be potential candidates for this low to moderate SO₂ removal retrofit technology, some general criteria were used. Coal-fired utility boilers without FGD scrubbers which were built before, or grandfathered under, the Clean Air Act and whose 1986 emissions of SO₂ were calculated to be 1.8 lbs of SO₂/MMBtu or higher. Further restrictions were that these units should be currently in operation with an aggregate coal-fired generating capacity of greater than 50 megawatts and should be no more than 35 years old. Of the 484 boilers identified as candidates, 340 responded to the survey representing over 87,000 MW of net generating capacity.

4.1 Information Requested

Plant and duct information requested in the survey included:

<u>Description</u>	<u>Units</u>
1. Generating Capacity	MW
2. Duct Geometry	N/A
3. Duct Dimensions	W x H
4. Number of Ducts	
5. Total Duct Length from APH Outlet to Inlet of Particulate Control Device	Ft.
6. Longest Straight Run (LSR)	Ft.
7. Duct Orientation of LSR	Vertical/Horizontal
8. Distance from End of LSR to Particulate Control Device	Ft.
9. Constant Dimensions of LSR	Y/N
10. Transition Dimensions	W x H
11. Flue Gas Temperature at APH Outlet	
A) 100% Load	°F
B) 50% Load	°F
12. Superficial Velocity	Ft/S

<u>Description</u>	<u>Units</u>
13. Available Space to Increase Size of ESP	Y/N
14. Unusual Factors at Plant Site	N/A

4.2 Discussion of Results

The results of the survey were presented in terms of both number of units and megawatt percentages; the percentages given below are for number of units.

The vast majority of ducts (86%) from the units surveyed were rectangular in shape. Although the predictive models being developed for this project will be capable of modeling round ducts as well as rectangular, most efforts in process development should be tailored to flow characteristics of rectangular ducts.

Over 90% of the surveyed units have either one or two outlet flue gas ducts, with two ducts being more typical (58%). DSI and DSD systems will be necessary on each duct in most cases for adequate SO₂ removal.

Of the utility boilers surveyed, there was no clear majority regarding duct cross-sectional area. About 32% of the units have duct cross-sectional areas of less than 100 sq. ft., 45% have 100-300 sq. ft., and 17% have 300-500 sq. ft. Although each application will be site specific, these data suggest 100-300 sq. ft. is a reference range for scale-up projections.

Figure 4.2-1 gives a breakdown of the 100% load flue gas temperature as it exits the air preheater for the units surveyed. Nearly 80% of the units had full-load gas temperatures between 275°F and 350°F. Flue gas temperature is important in determining humidification and cooling requirements which impact nozzle or atomizer selection and placement.

Flue gas velocity is important in estimating residence time for droplet evaporation and SO₂ removal. In addition, there are minimum velocities required to carry variously sized ash and sorbent particles without fallout. Figure 4.2-2 presents the distribution of superficial velocity over the population of surveyed units. Almost 70% of the units reported superficial velocities between 30 and 70 feet per second at full load.

One of the most important items to be obtained from the survey was the existing residence time available for droplet drying and SO₂ removal. Duct length and flue gas velocity from the survey were used to determine the total residence time from the air preheater outlet to the inlet of the particulate control device. In most cases, however, the longest straight run of duct is more important in determining drying time because of the potential for wall wetting and solids deposition at duct turns and bends. Figure 4.2-3 presents the distribution of total residence time through the entire duct for the 340 units surveyed. If this entire flue gas path was available for drying, nearly 80% of the units would possess at least 1 second residence time. However, when the longest straight run is considered (Figure 4.2-4), 57% of the units have

less than 1 second residence time. This indicates that improvements in atomizer performance and other efforts to reduce drying time requirements will be necessary to increase the application potential for duct injection processes. The alternative of installing additional ductwork or humidification/reaction vessels may add significantly to capital costs and may be impossible in many cases due to space constraints.

Two-thirds of the longest straight run sections were reported to be horizontal (30° angle maximum). The remaining vertical ducts may offer advantages in solids removal capability. Nearly two-thirds of the units reported constant duct dimensions throughout the longest straight run. Changes in duct dimensions could potentially result in wall wetting and solids deposition in some cases due to turbulence.

Although the retrofit of a duct injection process will likely cause little additional flue gas pressure drop, the potential addition of flow straightening devices and/or a reheat system and potential solids deposition may require additional induced draft fan head. The survey indicated that nearly 75% of those responding would require at least some modification to provide an additional head of 5 inches of water.

Some form of electrostatic precipitator (ESP) upgrade may be necessary to accommodate increased solids loading from the duct injection process. About 57% of the plants surveyed were judged to have sufficient space to increase their particulate collector size by 50%. Other ESP upgrade options may need to be investigated and developed for the large percentage of plants without the space availability for ESP expansion.

FIGURE 4.2-1

FLUE GAS TEMPERATURE, DEG. F

NO. OF UNITS

MEGAWATTS

NOTE: @ 100% LOAD

FIGURE 4.2-2

SUPERFICIAL VELOCITY, FPS

MEGAWATTS

FIGURE 4.2-3

RESIDENCE (DRYING) TIME, SECONDS TOTAL DUCT LENGTH

NO. OF UNITS

MEGAWATTS

FIGURE 4.2-4

RESIDENCE (DRYING) TIME, SECONDS LONGEST STRAIGHT RUN

ABOVE 2.0 (15.8%)

NO. OF UNITS

1.5-2.0
(11.9%)

1.0-1.5
(15.2%)

0.75-1.0 (13.1%)

BELOW 0.5 (22.6%)

0.5-0.75 (21.4%)

ABOVE 2.0 (17.1%)

MEGAWATTS

1.5-2.0
(11.0%)

1.0-1.5
(14.2%)

0.75-1.0 (14.9%)

BELOW 0.5 (20.7%)

0.5-0.75 (22.2%)

5.0 PRELIMINARY DUCT INJECTION ECONOMICS

UE&C has developed computer programs to perform economic evaluations of both the DSI and DSD duct injection processes. These economic programs are in a spreadsheet format using Lotus 1-2-3 software, Release 2.01.

5.1 Design Bases

The economic programs are flexible enough to allow a range of plant sizes, fuels, reagents, economic factors, etc. to be used as inputs. The preliminary duct injection economics presented in this Topical Report No. 2 are based on a typical utility retrofit application for a single 250 MW power plant burning a medium sulfur coal. Specific plant and duct injection process parameters for this base case study are presented in Table 5.1-1. The economic criteria and assumptions used for this study are listed in Section 5.3.

The SO₂ removal performance for each process is based on results from previous pilot-plant work. For DSI, the SO₂ removal relationship (Figure 5.1-1) was developed from a composite of data collected during testing at the EPRI Arapahoe duct injection pilot plant (2), the Dravo HALT pilot plant (1), and the Coolside demonstration at Edgewater (15). The SO₂ removal vs. reagent stoichiometry relationship for DSD (Figure 5.1-2) was developed from the calcitic hydrated lime portion of Bechtei's proof-of-concept testing at the Campbell Station (9).

5.2 Process Description

The economic programs represent the most current technology. Ongoing pilot-plant work will determine any process changes or refinements which need to be made to the programs. Both the DSI and DSD processes are divided into four major areas - the sorbent handling system, the sorbent injection system, particulate control modifications, and waste handling system modifications.

The sorbent handling system includes hydrated lime or quicklime receiving, unloading, storage, preparation, and handling equipment. The base case for the DSI process is based upon the receipt of pebble quicklime at the plant and on-site hydration using an atmospheric hydrator. Off-site hydration can be input as an option. For the DSD system, a ball mill slaker is assumed. Both processes use a new rail spur for sorbent delivery and a ten day bulk lime storage capacity.

The sorbent injection system consists of all sorbent injection equipment as well as any duct or stack changes. Until more conclusive information becomes available, the only duct changes included in the economic programs are removal of internal braces and addition of external stiffeners. No duct linings or modifications to the existing stack are currently included.

The particulate control area consists of modifications required to bring the ESP back to pre-duct injection emissions. Since technical and economic criteria have not been defined for many of the potential ESP upgrade strategies, the current programs assume flue gas humidification will be sufficient to maintain ESP compliance.

The waste handling system modifications include demolition of the existing ash piping and removal of associated equipment (excluding the existing ash silo); a new ash conveying system is then added. Other modifications include the addition of waste storage silo and pug mill capacity based on the incremental increase in waste solids compared to fly ash alone. Solid waste is disposed of using pug mills for conditioning and end-dump trucks for hauling to a landfill. The waste is then spread and compacted with earth moving equipment.

5.3 Base Case Economic Criteria and Assumptions

Equipment and installation costs vs. plant capacity equations were developed from vendor quotes for various equipment sizes. An overall retrofit factor of 1.2 was used for both DSI and DSD.

5.3.1 General Economic Criteria

1) Minimum Acceptable Return (MAR)	11.53%
2) Allowance for Funds Used During Construction (AFUDC)	0.00%*
3) First Year Fixed Charge Rate	24.50%
4) Levelized Fixed Charge Rate	19.70%
5) Remaining Plant Life	15 years
6) Inflation Rate	5.00%
7) Escalation Rates:	
Consumables (O&M)	5.00%
Power	5.32%
Fuel	5.32%
Capital Cost (prior to start up)	5.00%

*8) Construction Period = 1 year (no allowance for funds used during construction)

5.3.2 Operating and Maintenance Cost Criteria

1) Operating Labor Cost	\$20.00/hr
2) Reagent Cost FOB (Wheeling, WV):	
- Mississippi Pebble Quicklime	\$55.85/ton
- Mississippi Hydrated Lime	\$57.95/ton
3) Railroad Reagent Transportation Cost	\$ 0.07/ton-mile
4) Power Cost	\$ 0.050/kWh
5) Waste Disposal Costs, Sorbent/Fly Ash	\$ 8.00/ton
6) Bituminous Coal Cost (Delivered)	\$ 2.00/MMBtu

5.4 Results of Base Case Economic Analyses

All capital and operating costs are presented in January 1990 dollars.

5.4.1 Dry Sorbent Injection - With On-Site Hydration

	<u>1990 \$</u>	<u>\$/kW</u>	
Total Process Capital	8,510,000	34.1	
Total Capital Required	14,092,000	56.5	
	<u>First Year</u>	<u>First Year</u>	<u>15 Year</u>
	<u>1990 \$</u>	<u>\$/ton SO₂</u>	<u>Levelized</u>
		<u>Removed</u>	<u>\$/ton SO₂</u>
Major Costs:			<u>Removed</u>
Fixed Operating & Maintenance	1,053,000	77.76	106.59
Variable Operating	4,497,000	332.11	456.09
Fixed Charges	3,453,000	254.96	205.01
Total	9,003,000	664.83	767.69

5.4.2 Dry Sorbent Injection - With Off-Site Hydration

	<u>1990 \$</u>	<u>\$/kW</u>	
Total Process Capital	7,930,000	31.8	
Total Capital Required	13,453,000	54.0	
	<u>First Year</u>	<u>First Year</u>	<u>15 Year</u>
	<u>1990 \$</u>	<u>\$/ton SO₂</u>	<u>Levelized</u>
		<u>Removed</u>	<u>\$/ton SO₂</u>
Major Costs:			<u>Removed</u>
Fixed Operating & Maintenance	1,021,000	75.36	103.30
Variable Operating	5,569,000	411.29	564.62
Fixed Charges	3,296,000	243.40	195.71
Total	9,886,000	730.05	863.63

5.4.3 Duct Spray Drying

	<u>1990 \$</u>	<u>\$/kW</u>	
Total Process Capital	8,251,000	33.1	
Total Capital Required	13,356,000	53.6	
	<u>First Year</u>	<u>First Year</u>	<u>15 Year</u>
	<u>1990 \$</u>	<u>\$/ton SO₂</u>	<u>Levelized</u>
		<u>Removed</u>	<u>\$/ton SO₂</u>
Major Costs:			<u>Removed</u>
Fixed Operating & Maintenance	1,041,000	76.87	105.37
Variable Operating	3,597,000	265.65	365.34
Fixed Charges	3,272,000	241.65	194.30
Total	7,910,000	584.17	665.01

5.5 Sensitivity Analyses

Tables 5.5-1 and 5.5-2 list sensitivity factors for thirteen important process variables for each process. The definition of sensitivity factor is the percent change in levelized control cost (+ or - indicating a higher or lower cost, respectively) divided by the percent change in the process variable. The sensitivity factors are intended to rank the process variables in their order of importance to the economic evaluation. For these analyses, the sensitivity factors reflect the change in control cost as the process variable is increased by 10% over the base case design parameters defined in Sections 5.1 and 5.3. In Table 5.5-1 for example, when SO₂ removal increases by 10% in the DSI process (at a constant Ca/S molar ratio), the levelized control cost decreases by 8.9% (for on-site hydration).

Accompanying each sensitivity factor is a figure. These sensitivity curves (Figures 5.5-1 through 5.5-13 for DSI and 5.5-14 through 5.5-26 for DSD) show the resulting levelized control costs (in \$/ton SO₂ removed) as the process variables are varied over a range representative of the diverse population of existing power plants which are candidates for duct injection retrofit. These sensitivity analyses have resulted in the conclusions given below.

5.5.1 SO₂ Removal at a Constant Ca/S

This variable demonstrated the greatest effect on control cost. It is apparent from Figure 5.5-1 for DSI and 5.5-14 for DSD that the levelized cost decreases significantly as percent SO₂ removal increases at a constant reagent stoichiometry reflecting an increase in reagent utilization. Reagent utilization is limited by reaction kinetics and reaction time.

5.5.2 SO₂ Removal with Variable Ca/S

Figures 5.1-1 and 5.1-2 give the relationships between Ca/S stoichiometry and SO₂ removal for each process. The sensitivity of levelized cost as SO₂ removal and reagent stoichiometry increase is shown in Figure 5.5-2 for DSI and 5.5-15 for DSD. For DSI, the economic optimum SO₂ removal appears to be about 40-50% removal when the control cost for on-site hydration is about \$760/ton SO₂ removed. Above 50% removal, the cost per ton of SO₂ removed begins to increase (positive sensitivity factor). The sensitivity factor for DSD is negative because 50% SO₂ removal is not the optimum. The optimum occurs at about 65% SO₂ removal when the levelized control cost is \$615/ton SO₂ removed. Therefore, the cost per ton of SO₂ removed will decrease until 65% removal. Above 65% SO₂ removal, the curve would be theoretically expected to increase in a pattern similar to DSI; however, there is very little available technical data to determine the SO₂ removal above 65%.

5.5.3 Coal Sulfur Content

As coal sulfur increases, the control cost decreases for both DSI (Figure 5.5-3) and DSD (Figure 5.5-16). This is typical of most other FGD systems as well due to economy of scale. Application to high sulfur coal may be limited by the impracticality of high particulate loadings required to achieve the required SO₂ removal.

5.5.4 Reagent Feed Ratio at a Constant SO₂ Removal

This analysis indirectly shows how calcium utilization affects control cost. As Ca/S increases at a constant SO₂ removal, the utilization must decrease. The decrease in reagent utilization increases levelized control cost. This is shown clearly in the sensitivity curve for DSI (Figure 5.5-4) and DSD (Figure 5.5-17).

5.5.5 Plant Capacity Factor

For both processes, the control cost decreases by 3 to 4% as the plant capacity factor increases by 10% over the base case plant capacity of 65% (reference Figure 5.5-5 and 5.5-18 for DSI and DSD, respectively). This is typical for other SO₂ reductions methods as well. However, the use of duct injection on a high capacity plant might be less favorable when compared to alternative FGD processes.

5.5.6 Unit Size

Control cost decreases significantly as plant size increases from 50 to 200 MW. This is apparent in Figure 5.5-6 for DSI and Figure 5.5-19 for DSD. For plant sizes greater than 200 MW, there is little additional economy of scale.

5.5.7 Reagent Cost

The sensitivity analysis on reagent cost shows a 3 to 4% increase in control cost as the price of reagent increases by 10% over the base case values. DSI has the greater sensitivity factor; this is expected because DSI has lower calcium utilization. The sensitivity curves for both processes are given in Figures 5.5-7 and 5.5-20.

5.5.8 Inflation Rate

The sensitivity factor for both processes is +2.6% (reference Figures 5.5-8 and 5.5-21). This indicates that inflation rate has a moderate effect on levelized control cost.

5.5.9 Waste Disposal Cost

From Figures 5.5-9 for DSI and 5.5-22 for DSD, it is apparent that an increase in waste disposal cost increases the control cost slightly. The sensitivity factor is small with only a 1.2 - 1.3% increase in control cost when disposal cost increases by 10%. Even though duct injection produces large amounts of solid waste, the disposal cost still remains a relatively small part of the control cost.

5.5.10 Power Cost

As the cost of auxiliary power increases, control cost increases by a small amount. The sensitivity curves for power cost are shown in Figure 5.5-10 for DSI and 5.5-23 for DSD. The additional power required due to retrofit of a duct injection system is estimated to be approximately 0.6% and 0.8% of the plant net generating capacity for DSI and DSD, respectively. The major power consumer is the atomizing air compressor. The sensitivity factor for DSD is slightly greater because the air compressor required in the DSD system is substantially larger than that required in the DSI process. This is true because, for the same air-to-liquid mass ratio, slurry atomization requires more air than humidification water atomization only.

5.5.11 Remaining Plant Life

Both processes show an optimum service life of ten years (see Figures 5.5-11 and 5.5-24). For a service life of less than ten years, the capital costs have to be paid out over too short of a time. For a remaining plant life of more than ten years, the effect of inflation on the variable costs causes the control cost to increase slightly. This is typical for any process with low capital but high operating costs.

5.5.12 Reagent Transportation Distance

Transportation distance can affect the choice of reagent. Transportation costs can vary widely depending on the geographic availability of the required reagent. With a \$0.07/ton-mile rail transportation cost, the sensitivity factor is 0.4-0.5% (reference Figures 5.5-12 and 5.5-25).

5.5.13 Nozzle Air to Liquid Ratio

Based on pounds of atomizing air per pound of liquid (water for DSI or slurry for DSD), the sensitivity factors show that the increase in capital and operating cost of the atomizing compressor produces only a small increase in levelized control cost. This is apparent from the small slope of the lines in Figures 5.5-13 and 5.5-26.

TABLE 5.1-1

BASE CASE DESIGN PARAMETERS

Plant Net Generating Capacity	250 MW
Plant Location	Rural Ohio
Coal:	
Type	Bituminous
Sulfur Content	2.6%
Heating Value	13,084 Btu/lb
Plant Capacity Factor	65%
Particulate Control	Existing ESP
Reagent:	
For DSI with off-site hydration	Mississippi Hydrated Lime
For DSD and DSI with on-site hydration	Mississippi Pebble Quicklime
Transportation Distance	100 miles
Required SO ₂ Removal	50%
Ca/S Molar Ratio to Achieve Required SO ₂ Removal:	
DSI	2.0
DSD	1.4
Nozzle Air/Liquid Ratio	
DSI	0.365
DSD	0.365

TABLE 5.5-1
SENSITIVITY ANALYSIS-DRY SORBENT INJECTION

% Change in Levelized Control
Cost (\$/ton SO₂ Removed) With
a 10% Increase in Process
Variable:

Process Variable:

SO ₂ Removal @ Ca/S = 2.0	-8.9%
SO ₂ Removal With Variable Ca/S	+4.7%
Coal Sulfur Content	-3.9%
Reagent Feed Ratio @ 50% SO ₂ Removal	+5.5%
Plant Capacity Factor	-3.7%
Unit Size	-2.8%
Reagent Cost FOB	+3.8%
Inflation Rate	+2.6%
Waste Disposal Cost	+1.3%
Power Cost	+0.6%
Remaining Plant Life	+0.9%
Reagent Transportation Distance	+0.5%
Nozzle Air/Water Ratio	+0.9%

TABLE 5.5-2
SENSITIVITY ANALYSIS-DUCT SPRAY DRYING

% Change in Levelized Control Cost
(\$/ton SO₂ Removed) With a 10%
Increase in Process Variable:

Process Variable:

SO ₂ Removal @ Ca/S = 1.4	-8.9%
SO ₂ Removal With Variable Ca/S	-6.0%
Coal Sulfur Content	-4.9%
Reagent Feed Ratio @ 50% SO ₂ Removal	+4.4%
Plant Capacity Factor	-4.1%
Unit Size	-3.3%
Reagent Cost FOB	+3.1%
Inflation Rate	+2.6%
Waste Disposal Cost	+1.2%
Power Cost	+0.9%
Remaining Plant Life	+0.8%
Reagent Transportation Distance	+0.4%
Nozzle Air/Slurry Ratio	+0.2%

FIGURE 5.1-1

SO2 REMOVAL VS. STOICHIOMETRY

Dry Sorbent Injection

FIGURE 5.1-2

SO₂ REMOVAL VS. STOICHIOMETRY

Duct Spray Drying

FIGURE 5.5-1

CONTROL COST VS. SO2 REMOVAL

Dry Sorbent Injection

FIGURE 5.5-2

CONTROL COST VS. SO2 REMOVAL

Dry Sorbent Injection

FIGURE 5.5-3

CONTROL COST VS. COAL SULFUR CONTENT

Dry Sorbent Injection

FIGURE 5.5-4

CONTROL COST VS. REAGENT FEED RATIO

FIGURE 5.5-5

CONTROL COST VS. PLANT CAPACITY FACTOR

FIGURE 5.5-6

CONTROL COST VS. UNIT SIZE

Dry Sorbent Injection

FIGURE 5.5-7

CONTROL COST VS. REAGENT COST

Dry Sorbent Injection

FIGURE 5.5-8

CONTROL COST VS. INFLATION RATE

Dry Sorbent Injection

FIGURE 5.5-9

CONTROL COST VS. WASTE DISPOSAL COST

Dry Sorbent Injection

FIGURE 5.5-10

CONTROL COST VS. POWER COST

Dry Sorbent Injection

FIGURE 5.5-11

CONTROL COST VS. REMAINING PLANT LIFE

Dry Sorbent Injection

FIGURE 5.5-12

CONTROL COST VS. TRANSPORT DISTANCE

Dry Sorbent Injection

FIGURE 5.5-13

FIGURE 5.5-14

CONTROL COST VS. SO2 REMOVAL

Duct Spray Drying

FIGURE 5.5-15

CONTROL COST VS. SO2 REMOVAL

Duct Spray Drying

Levelized Control Cost, (\$/ton SO2)
(Thousands)

SO2 Removal, (%)

FIGURE 5.5-16

CONTROL COST VS. COAL SULFUR CONTENT

Duct Spray Drying

FIGURE 5.5-17

CONTROL COST VS. REAGENT FEED RATIO

Duct Spray Drying

FIGURE 5.5-18

CONTROL COST vs. PLANT CAPACITY FACTOR

Duct Spray Drying

FIGURE 5.5-19

CONTROL COST VS. UNIT SIZE

Duct Spray Drying

FIGURE 5.5-20

CONTROL COST VS. REAGENT COST

Duct Spray Drying

FIGURE 5.5-21

CONTROL COST VS. INFLATION RATE

Duct Spray Drying

FIGURE 5.5-22

CONTROL COST VS. WASTE DISPOSAL COST

Duct Spray Drying

FIGURE 5.5-23

CONTROL COST VS. POWER COST

Duct Spray Drying

FIGURE 5.5-24

CONTROL COST VS. REMAINING PLANT LIFE

Duct Spray Drying

FIGURE 5.5-25

CONTROL COST VS. TRANSPORT DISTANCE

Duct Spray Drying

FIGURE 5.5-26

CONTROL COST VS NOZZLE AIR/SLURRY RATIO

Duct Spray Drying

6.0 CORROSION/EROSION IMPACTS ON EXISTING PLANT MATERIALS OF CONSTRUCTION

The relative short-term nature of pilot-plant test programs has made it difficult to assess the long-term effects of duct injection processes on existing plant equipment. The results of an ongoing corrosion study (UE&C Subtask 4.3) and the 12 MW pilot-plant testing at Beverly will provide data concerning corrosion/erosion impacts from duct injection. Commercial lime spray drying installations have provided the closest relevant experience. Materials for new duct injection process components such as mix tanks, pumps, conveying lines, nozzles and atomizers should be carefully selected in the original design, and these will be addressed in the design handbook. The emphasis of this discussion is to identify potential impacts on the materials of construction of the existing plant components due to the retrofit of a duct injection process.

Carbon steel and Corten A are alloys that are presently used as the ductwork material for most boiler plants. These alloys will be present where duct injection spray assemblies will be installed. The majority of installations will be retrofits to existing ductwork. Therefore, the corrosion behavior of carbon steel and Corten A will be evaluated in Subtask 4.3 in a range of spray chemistries that could deposit on the duct walls. Stainless steel (300 series) is a bolt and hanger material in existing duct structures and also a possible duct material. Hastelloy C-276 was also chosen for this evaluation because it is a highly corrosion-resistant alloy in back-end environments. Alloy C-276 can be applied as a clad over carbon steel construction materials.

The plant components downstream of the duct injection process most likely to be affected by the low-temperature, high humidity environment include:

- 1) Ductwork downstream of sorbent or slurry injection
- 2) Particulate collection device
 - A) Electrostatic precipitator
 - B) Fabric filter
- 3) Ductwork downstream of particulate collection device
- 4) I.D. Fans
- 5) Stack/Chimney liner

6.1 Ductwork Downstream of Sorbent or Slurry Injection

The alkaline nature of the sorbent or slurry should protect duct surfaces from corrosive attack. There is some concern about under deposit corrosion due to moisture trapped between the duct surface and the reacted sorbent which may build up on duct walls. Special protective coatings will be evaluated on test sections of the duct wall upstream of the ESP at Beverly.

When sorbent is present, the potential for acid corrosion is relatively low. An exception to this is the configuration in which the humidification water is sprayed in upstream of sorbent injection. There is potential for severe corrosion of the ductwork between the humidification spray and the sorbent injection locations, especially when SO_3 concentration is high. EPRI encountered extensive corrosion

of ductwork when evaluating the HYPAS process at their high sulfur test center pilot plant (12). If this or similar process configurations are to be considered, materials upgrades or protective coatings may be necessary for the ductwork between the humidification stage and sorbent injection locations.

Operational safeguards should be designed to prevent operating the humidification system in the absence of sorbent injection.

6.2 Particulate Collection Device

6.2.1 Electrostatic Precipitator (ESP)

The prevention of condensation is very important in protecting ESP components from corrosion. Increased insulation on ESP inlet and outlet nozzles and ESP sidewalls may be necessary to accommodate low-temperature operation. Special attention must be paid to minimize in-leakage through access doors and hoppers. Two areas that may require additional modification are the high voltage insulator compartments and hoppers. Most insulator compartments and some hoppers are equipped with heaters to prevent condensation and corrosion. Additional insulation and/or heating capacity may be required to overcome the low-temperature, high humidity environment. At a spray dryer retrofit to Pacific Power and Lights' Wyodak Station, condensation and corrosion problems were encountered in ESP outlet ductwork, the final ESP field, and some of the high voltage insulators (10). The installation of additional insulation to these areas and increased insulator heating capacity solved these problems. Similar corrosion problems with high voltage insulators were reported for the spray dryer/ESP system at a Grand River Dam Authority plant (17). The most likely candidate for materials upgrade or protective coating is the outlet nozzle or duct of the precipitator. Very little sorbent is available to protect these surfaces. Insulation alone may not be sufficient in all cases.

6.2.2 Fabric Filter

Due to the high collection efficiency of fabric filters, very little sorbent penetrates to the "clean side." Early experience in pilot- and full-scale spray dryer facilities revealed severe corrosion tendencies on fabric filter walls due to in-leakage and insufficient insulation (3, 4). Most of these problems can be prevented by proper insulation and good seals on compartment doors and dampers. Special protective coatings on fabric filter walls have been investigated and used in high sulfur applications (5, 7). Epoxy and vinyl ester resins have both shown effectiveness in preventing exfoliation of wall surfaces. Bag caps composed of mild steel have exhibited pitting and premature failure in some installations (3). Bag caps composed of stainless steel or epoxy coated mild steel, although more expensive, have been demonstrated to withstand the low-temperature environment downstream of spray dryers.

If high concentrations of chlorides are present (from coal or CaCl_2 additive use), series 300 stainless steel components may pitting and become brittle. Stainless steel band clamps on bag thimbles were observed to fail due to chloride induced stress attack at the Arapahoe pilot spray dryer/fabric filter (3). Cadmium plated stainless steel band clamps were evaluated at Arapahoe, but failed even more rapidly than the stainless steel clamps. High nickel alloys are typically used in high chloride concentration environments, but no source of band clamps of such alloys has been identified.

6.3 Ductwork Downstream of Particulate Collection Device

Because little or no reactive sorbent will escape the ESP or fabric filter, any condensation can lead to corrosion. As with the ESP outlet nozzle section, supplemental insulation may be required.

Corrosion has been an ongoing problem in the duct downstream of the ESP at Wyodak (10). A test program to evaluate the effectiveness of protective coatings on this ductwork is currently underway. Additional data from Edgewater and Beverly will help to determine if more resistant ductwork materials or protective coatings are necessary. Steel expansion joints common on many older plants may have to be replaced or protected. Severe corrosion led to a Viton joint being installed on the inside of an existing steel expansion joint at Wyodak. EPRI has sponsored research to evaluate the use of chemical additive corrosion inhibitors for wet scrubber outlet ducts (18). Application to duct injection or spray dryers is unknown.

6.4 I.D. Fans

Induced draft fans may be adversely affected by the retrofit of duct injection. Corrosion potential may be increased due to the low-temperature, high humidity flue gas. I.D. fans have high tendencies for in-leakage which can exacerbate the condensation corrosion potential. Minimizing in-leakage is important. A second consideration for I.D. fans might be increased fan blade wear due to additional ash/sorbent waste exiting the ESP. If the proper ESP upgrades and operational modifications are successfully implemented, this should not be an issue.

6.5 Stack/Chimney Liner

Because of wet stack problems encountered during the development of wet FGD technology, there is concern about the possible negative impacts of duct injection retrofits on existing power plant stacks or chimney liners. Stacks and chimney liners in these applications have exhibited problems including corrosion, cracking, pitting, and buckling which threaten the structural integrity of the stack and which have caused leaking and, in some cases, leaning chimney liners (8,16).

Plants considered to be candidates for duct injection retrofit will most likely have stacks or chimney liners composed of steel, reinforced concrete, or non-acid resistant brick which were designed to handle hot, dry flue gas. New installations with wet FGD or lime spray dryers have typically incorporated acid-resistant brick or fiber reinforced plastic (FRP) liners to protect the chimney from the corrosive nature of flue

gases exiting desulfurization processes. Operating practices such as pressurizing the annulus between the chimney shell and liner have been developed to prevent flue gas from permeating the liner (6).

There is little experience from which to predict the effects of retrofitting duct injection on an existing stack or chimney liner. Replacing or relining the stack, or adding a reheat system, will have significant cost impacts for the duct injection process. Conventional lime spray drying creates a similar effluent gas, but most spray dryers have been new plant installations and have typically included modern chimney design with acid-resistant brick or FRP liners. One exception is the spray dryer retrofit at Pacific Power and Light's Wyodak Unit 1. The chimney at Wyodak, however, has an acid-resistant brick liner. No significant problems with it have been reported in over three years of spray dryer operations.

It may also be necessary to upgrade the chimney breeching and expansion joints. In-leakage is not uncommon in these components. Coatings or liners may be effective in protecting these surfaces.

7.0 IDENTIFICATION OF MISSING DATA REQUIREMENTS

As the evaluations presented in the previous six sections were being performed, a substantial number of questions and unknowns were generated. These represent "gaps" in our knowledge which need to be addressed before the final design handbook can be completed. These missing data are summarized below in the same order as the evaluations in which they were identified. If these data are currently scheduled to be obtained as part of the current scope of work for this DOE program, the participating contractor is listed.

7.1 Literature Review/Status Reports

7.1.1 Sorbent Selection

- 1) Verify the contribution of scavenging to overall SO₂ removal.
- 2) Resolve discrepancies regarding the effects of additives, especially sodium compounds, which some researchers (Consol) have found more effective than others (EPRI). G/C has indicated they may investigate these additives at Beverly.
- 3) The addition of chlorides has been demonstrated to improve both SO₂ removal and ESP efficiency in spray dryer pilot-plant tests. Tests will be conducted at Meredosia and possibly Beverly to assess the effectiveness of chloride addition in duct injection.
- 4) The effectiveness of lignosulfonate additives on lime utilization and sorbent handling remains unclear for DSI applications. Further evaluation is recommended. G/C has indicated they may investigate these additives at Beverly.
- 5) Determine the effect of hydrated lime particle size and possible agglomeration on SO₂ removal and lime utilization. Radian has indicated they will evaluate this at Meredosia.
- 6) Review results from the Coolside demonstration at Edgewater to help determine the impact of different hydrated limes.

7.1.2 Sorbent Storage and Preparation

- 1) Determine technical and economic criteria to choose off-site vs. on-site hydration for DSI. This will be accomplished by UE&C using the economic programs as discussed in Section 5.0.

7.1.3 Humidification and Slurry Nozzle Specifications

- 1) Determine the minimum compressed air requirement for adequate nozzle performance. Continued work by B&W and G/C should provide this information for a variety of nozzles. A review of the Edgewater operating data will also provide input.
- 2) Determine feasibility of multistage humidification if duct constraints prohibit adequate humidification in a single stage. Radian will evaluate this at Meredosia in an effort to improve humidification and minimize solids deposition in the test duct. These tests with multistage nozzles may not be

representative of full-scale ducts. Multistage humidification may be evaluated by exercising the Second Generation Model.

- 3) For large flue gas flow rates, it might be desirable to use atomizers with significantly larger capacities than are currently being tested so that a large number of atomizers is not required. At least one large atomizer should be tested to decide if data obtained from smaller atomizers can be scaled up. Characteristics of interest include drop size, momentum and the interaction between adjacent atomizers.
- 4) The interaction between flue gas velocity and flow pattern and nozzle characteristics (flow, velocity, spray angle, number of nozzles, etc.) should be studied. Past projects have largely used trial and error to establish nozzle array geometry. G/C has indicated they will not have time to optimize nozzle configuration. This effort will be performed by B&W in their nozzle array testing subtask. The Second Generation Model may also be capable of evaluating various array configurations.
- 5) Determine maximum acceptable hydraulic sensitivity, i.e., variation in flow rate with pressure of nozzles manifolded together. This will be determined as part of B&W's nozzle development task.
- 6) Develop relationships among gas residence time, approach to saturation temperature, and required mean and largest droplet sizes. This information will likely be obtainable by exercising the Second Generation Model using several ranges of input. G/C's test results at Beverly should provide several points to verify the model results.
- 7) Determine acceptable materials of construction for wear parts in slurry nozzles. This will be determined as part of B&W's nozzle development task.

7.1.4 Dry Sorbent Injector Design

- 1) Develop dimensional spacing criteria between sorbent injectors and humidification water spray.
- 2) Evaluate different types of injector designs (cross duct lances, wall injectors, parallel flow injectors, etc.) to determine which design is optimum for different duct configurations.
- 3) The interaction between flue gas velocity and flow pattern and sorbent injector characteristics (flow, velocity, jet size, number of jets, etc.) should be studied. Past projects have largely used trial and error to establish injector array geometry.

7.1.5 Material Deposition on Duct Walls/Turning Vanes

- 1) Automatic, mechanical removal of deposited material using such devices as rappers, sonic horns, droplet impingement devices (DIDS), soot blowers, air lances, coatings and hoppers may be necessary if deposition cannot be entirely prevented.

Research has shown that material deposition is usually confined to a small area within the duct. Future research could take advantage of this fact by installing appropriate solids handling equipment in areas where deposition is expected. The DIDS concept, for example, was effective in E-SO_x research. This shall be investigated by G/C at Beverly.

- 2) Determine minimum acceptable inlet flue gas velocity and temperature profiles to minimize deposition. G/C is in the process of investigating this at Beverly.
- 3) Determine minimum practical approach to saturation temperatures and residence times to minimize deposition for both DSI and DSD. G/C will be investigating this fairly extensively at Beverly.
- 4) Shielding devices to prevent deposits on the atomizer tip should be developed. Deposition on the atomizer tip has been identified as a cause for reduced atomizer performance that can lead to material deposition within the duct. More research is needed to develop methods to prevent atomizer tip deposition or automatically removing the deposits that form. This will be addressed as part of B&W's nozzle development task.
- 5) The effect of potential sorbent additives on deposition tendencies should be determined. Deliquescent salts, for example, could potentially delay sorbent drying, and aggravate deposition. G/C will be investigating this when they perform their additive evaluations at Beverly.
- 6) Determine optimal method to detect deposition in full-scale installations, e.g., duct skin thermocouples, weigh cells, etc. G/C has indicated that they will be evaluating these options at Beverly.

7.1.6 Corrosion of Materials in Flue Gas Path

- 1) Determine minimum insulation thicknesses for ESP outlet nozzle and ductwork between ESP and stack after retrofit of duct injection technology. UE&C will determine this parameter based on a review of experience at spray dryer installations.
- 2) Chlorides, either as sorbent additives or in coal, may condense to form HCl. Corrosion attributed to chlorides has been a problem for some spray dryer installations. The role of chlorides in DSI or DSD equipment corrosion should be determined. Determine how chloride corrosion can be predicted in a feasibility evaluation. This will be addressed as part of B&W's corrosion study.
- 3) The effect, if any, of additives such as NaOH on corrosion potential and characteristics should be evaluated. Review results from the Coolside demonstration at Edgewater to help determine this.

- 4) The necessity and effectiveness of protective coatings on duct surfaces upstream and downstream of the ESP should be evaluated for retrofit applications. Preliminary information indicates that there is a potential for acidic corrosion underneath wall deposits despite the alkaline nature of the deposit. G/C will be investigating test patches of coatings on duct walls at Beverly.

7.1.7 Temperature Instrumentation and Controls

- 1) Establish minimum practical operating approach to saturation temperatures at the ESP outlet for minimizing corrosion. This will follow based on determination of minimum practical approach to saturation temperatures in the duct.
- 2) The application of a wet bulb temperature monitor to duct injection systems would enable highest reagent utilization with minimal wall wetting. UE&C will follow the progress of vendors who are developing these continuous wet bulb monitors.

7.1.8 SO₂ Measurement Instrumentation and Process Control

No missing data requirements identified.

7.1.9 Velocity and Temperature Profile

- 1) Once minimum acceptable inlet flue gas velocity and temperature profiles have been developed, determine what internal corrective devices in the duct are required to provide the required profiles. G/C will be evaluating this at Beverly.

7.1.10 Electrostatic Precipitator

- 1) Investigate methods to overcome low-resistivity re-entrainment problems:
 - a) Flue gas conditioning with NH₃ or other conditioning agents. Determine the interaction or side effects of NH₃ with sorbent injection. This will be evaluated by Radian and G/C.
 - b) Chloride additives. This will be evaluated at Meredosia and possibly Beverly.
 - c) Power-off rapping. This will be evaluated by G/C.
 - d) Special discharge electrodes. This will be evaluated by Radian and G/C at the pilot plants.
 - e) Collection plate modifications (shields or baffles) for older units. UE&C will contact ESP vendors to determine equipment availability and cost data.
- 2) Define minimum SCA requirements for DSI and DSD applications below which ESP upgrade will be required. Determine economics of practical ESP upgrade options. UE&C will determine economics of ESP upgrades; Radian and G/C will provide input for minimum SCA as a function of operating conditions based on pilot-plant data and the modified ESP model being developed by ADA.

- 3) Generate an accurate temperature vs. resistivity curve for DSI and DSD ash/sorbent waste. ADA will be making these measurements at Meredosia, and they have already taken measurements at Edgewater.
- 4) Develop guidelines for rapper intensity and sequencing changes to adjust an existing ESP for low-resistivity operation. Experiences at Edgewater, Meredosia, Beverly, and other programs (TVA spray dryer, E-SO_x, etc.) will be evaluated by UE&C to develop these guidelines for the design handbook.
- 5) Determine practical limitations to recycle including collection efficiency, hopper capacity, existing ash removal capacity, etc. These limitations will be evaluated at Meredosia and Beverly.
- 6) Determine if sorbent additives affect collectibility in the ESP or the cohesive properties of ash/sorbent waste. Determine if removal of wire deposits from duct injection is a function of ESP design type (rigid frame vs. weighted wire). This will be determined by comparing ESP operation at Meredosia, Beverly, and Edgewater.
- 7) Determine the technical and economic feasibility of a precollector upstream of the ESP. Technical feasibility will be conceptually evaluated by G/C at Beverly. UE&C will investigate economic viability.

7.1.11 Waste Handling System

- 1) Some plants considering DSI or DSD retrofits may have wet ash removal systems. Research is needed to determine the impacts of a DSI or DSD waste product on these ash sluicing systems. Physical characterizations being conducted by EERC should contribute information to this issue.
- 2) Develop criteria to determine if a new ash handling system needs to replace or supplement the existing one.

7.1.12 Recycle System

- 1) Determine the technical and economic optimum recycle ratios for both DSI and DSD considering existing ESP and ash handling capacity limitations. Radian and G/C will evaluate these aspects at Meredosia and Beverly.
- 2) Define factors which limit reactivity of recycled material, and determine strategy to improve reactivity. Acurex is investigating such strategies, and G/C will also evaluate recycle reactivity.

7.1.13 Waste Disposal

- 1) The impact(s) of potential additives (NaOH, NaCl, deliquescent salts, etc.) should be considered when characterizing a DSI/DSD waste. Since there is potential for incorporating

additives in the process, it should be determined if the additives in their given concentration constitute an environmental risk. Sodium compounds, due to their solubility, are of concern. There may be other effects to consider with respect to disposal requirements and by-product utilization options. The EERC will likely perform a detailed characterization of one sample with a sodium additive from Edgewater. Final selection of solid waste samples for detailed characterization will be made in August 1990.

- 2) There may be potential for utilization of the ash/sorbent wastes from DSI/DSD processes. Some possibilities include: structural fill, pozzolanic base for pavement, additive to concrete, soil stabilization, and waste fixation. Minimum physical and chemical property requirements should be determined for these and other end-use markets, to properly assess this potential. The EERC will develop a complete by-product utilization study.
- 3) Some plants considering DSI or DSD retrofits may use ash ponds as part of their ash disposal process. Research is needed to determine the impacts of a DSI or DSD waste produced where ash ponds are used.

7.2 Review of Other Contractors' Test Plans

7.2.1 Acurex

- 1) Determine if there are any compounds or additives which can be added to dry $\text{Ca}(\text{OH})_2$ sorbent to allow it to be wetted to 10-20% or more free moisture and still be free flowing.
- 2) For model validation, determine contribution of scavenging vs. condensation to $\text{Ca}(\text{OH})_2$ wetting and subsequent SO_2 removal.
- 3) Determine upper practical limit on percent solids in the feed slurry in the DSD process. This will be determined as part of B&W's nozzle development task, partly from their dry scrubber experience.

7.2.2 Gilbert/Commonwealth

- 1) Determine the minimum practical approach to saturation temperature for both DSI and DSD. As mentioned in Section 7.1.5, G/C will be investigating this fairly extensively at Beverly.
- 2) Determine the usefulness of additives such as NH_3 and proprietary compounds to enhance ash cohesiveness thereby reducing rapping and velocity re-entrainment from the ESP. This will be evaluated by both Radian and G/C.
- 3) Evaluate the effect of modified discharge electrodes and collecting plates on ESP performance. This will be evaluated by both Radian and G/C.

7.2.3 Radian

- 1) Validate the Energy and Environmental Research Corporation submodel.
- 2) Test different hydrated and pebble limes to evaluate changes in SO₂ removal performance, if any.

7.3 Preliminary Design Handbook

1. Develop realistic relationship among SO₂ removal, approach to saturation temperature, Ca/S ratio, and recycle ratio. This information will likely be obtainable by exercising the Second Generation Model using several ranges of input. G/C's test results at Beverly should provide several points to verify the model results.
2. Determine technical limit of percent SO₂ removal and the relationship between percent SO₂ removal and levelized cost. SO₂ removal limits will be determined from the Beverly and Edgewater experiences. UE&C will develop relationships between SO₂ removal and cost.
3. Determine methodology to predict ESP emissions after the duct injection retrofit as a function of existing SCA and added ESP upgrade options. Radian and G/C will provide input for minimum SCA as a function of operating conditions. The modified ESP model being developed by ADA can be used to predict parametric conditions outside the operational range of the pilot plants.
4. Determine feasibility of modifying existing ash handling systems to accommodate the increased loadings, and determine economic impacts of replacing the existing ash handling system.
5. Determine feasibility of duct injection in sloped ducts or in ductwork with elbows, and determine any special design considerations for these arrangements. This information may be obtainable by exercising the Second Generation Model. Experience at Virginia Power's Yorktown furnace sorbent injection project should also provide useful information since the test unit has sloped ESP inlet ducts.
6. Develop specific control philosophy and safety and interlock approaches for controlling a duct injection system. Control and monitoring instrumentation requirements also need to be determined. G/C will provide substantial input in this area as they will be evaluating process control response to normal variations as well as upset conditions. UE&C will also provide input based on a review of experience at spray dryer installations.

7. Develop specific operation and maintenance requirements for a duct injection system. Specific areas of interest are nozzle wear, nozzle turndown, hydrated lime handling problems, and dry sorbent injector turndown. Identify what operational and preventative procedures are necessary to reduce low-temperature corrosion conditions during start-up and shutdown. G/C will provide information on nozzle wear and turndown as part of their work scope. The Coolside experience will also be very useful in this area.

7.4 Results from Utility Duct Survey

1. Determine the minimum practical residence time for duct injection technology. This will be evaluated by G/C. In addition, this information will likely be obtainable by exercising the Second Generation Model.
2. Evaluate duct injection in vertical ducts. This will be evaluated by G/C. In addition, this information will likely be obtainable by exercising the Second Generation Model.
3. Evaluate duct injection in ducts with variable duct dimensions. This information will likely be obtainable by exercising the Second Generation Model.
4. Determine the minimum practical flue gas velocity applicable for duct injection technology. UE&C/B&W will determine this based on past spray dryer experience and results developed by G/C at Beverly. The Second Generation Model should also provide useful information.

7.5 Preliminary Duct Injection Economics

1. Develop capital cost and lost generation information for replacing an existing plant ash handling system or stack. UE&C will develop this information to be included as an optional economic assessment in Subtask 2.4.
2. Develop capital and operating cost information for the most promising ESP upgrade strategies. UE&C will develop this economic information based upon the technical assessments conducted at Meredosia and Beverly by Radian and G/C, respectively.

7.6 Corrosion/Erosion Impacts on Existing Plant Materials of Construction

1. Determine coatings or other corrosion resistant measures that need to be implemented for the ductwork, ESP, and stack or chimney liner.

7.7 Model Development

In addition to the data required to complete the design handbook, there are several items for which additional information would be helpful for the development of the Second Generation Model.

1. It is not clear how the EER submodel accounts for the effects of recycle and additives on SO₂ capture. Recycle has been found to increase significantly calcium utilization for dry scrubbing applications, and it is expected to be important for duct injection as well. It appears that the effect of recycle and additives is not treated in a fundamental sense by the EER model. Additional model development would be useful.

Although the effect of recycle and additives will be measured during the Beverly tests, fundamental data needed for model development and verification do not appear to be in the work scope of this DOE program. Acurex's testing may provide information in this area.

2. The momentum added by the atomizers controls the flue gas flow pattern within the humidification duct, influencing mixing, droplet evaporation, deposition and SO₂ capture. Atomizer momentum cannot be predicted and must be measured. However, atomizer momentum is only being measured within B&W's work scope. Atomizer momentum should be measured for each atomizer tested in the pilot facilities.
3. It does not appear that scavenging efficiency is being directly measured in any of the test programs. Instead it will be inferred from test results that are influenced by many other factors. Tests to directly measure scavenging at controlled conditions are necessary. This could be accomplished at Beverly by using the Insitec probe or Video Droplet Analyzer.

8.0 DUCT INJECTION PROGRAM CHANGE RECOMMENDATIONS

Section 7.0 presented a list of information which UE&C considers, at this time, necessary in order to develop a useful and complete duct injection design handbook. Much of the information listed will be obtained as part of the current work scope for the DOE Duct Injection Technology Development Program. Some of the items identified in Section 7.0, however, are currently not addressed in the work plans of the participating contractors. These items are listed below with UE&C's recommendations as to the priority of obtaining the information and the most appropriate strategy to develop it.

8.1 Contribution of Scavenging to Overall SO₂ Removal

There appears to be some question as to the role scavenging of dry hydrated lime particles by water droplets plays in duct SO₂ removal. The EER one-dimensional model uses scavenging as a primary mechanism. In order to verify the contribution of scavenging, one possibility would be to lower the flue gas temperature by heat extraction instead of humidification to achieve the desired approach temperatures. Heat extraction "tubes" are available for this type of testing. Comparing the results of SO₂ removal by heat extraction to those by humidification would give an indication of the role of scavenging in the SO₂ removal kinetics.

These tests could be run at the Meredosia facility by Radian. Because this testing would primarily be accomplished to validate model mechanisms and would likely require considerable capital investment, it is considered a low priority.

8.2 Effects of Sorbents and Additives

The values of lime utilization (18-23%) and SO₂ removal (18-49%) from test results to date in this DOE program are fairly low. Various additives including lignosulfonates, sodium compounds, and chlorides may be required to improve performance. These tests with additives are considered a high priority, and testing by G/C at Beverly is recommended.

A detailed evaluation of different sorbents and additives used during the Coolside testing at Edgewater should be obtained by the DOE for use in this Duct Injection Technology Development Program. This information will aid in the development of the appendix on sorbent selection. This is considered a medium priority.

Identifying any compounds or additives which can be added to dry Ca(OH)₂ sorbent to allow it to be wetted to 10-20% or more free moisture and still be free flowing would be advantageous. This would reduce humidification requirements. Acurex would be a likely candidate to perform this search and perform bench-scale tests on any identified compounds. It is considered a low to medium priority.

8.3 Nozzle Array Testing

Due to the wall deposition observed from test results to date in this and other programs, nozzle array testing for scale-up to full-scale applications is considered very important. B&W's funding for this effort limits detailed measurements to one or two array configurations. More testing will likely be required to develop nozzle momentum, velocity, and pressure data to define the jet expansion region near the nozzles. Since B&W may also need to develop data for model validation using their 6 ft by 6 ft test duct, additional testing is recommended including large capacity atomizers to determine scale-up potential. This is considered a high priority.

8.4 Dry Sorbent Injector Design

The optimal configuration of dry sorbent injectors/humidification nozzles at Edgewater was for both to inject in the same plane; i.e., no axial spacing between the two. UE&C recommends that the spacing (including "zero spacing") between dry sorbent injection and humidification water injection be tested at Beverly. This is considered to be a high priority.

Although considerable work has been, or is planned to be, performed on humidification water spray analyses, little attention has been given to dry injector design and placement. As an example, nine injectors were originally installed at Edgewater, but operation with only five was subsequently found to provide good distribution with minimum floor buildups. UE&C recommends that computer modeling be performed as a first step in characterizing and optimizing injector configuration (including different types of injectors). This work should be done with existing models (such as EER's existing computer programs) and with the Second Generation Model. Based on these results, field tests would be recommended. This is considered a medium priority.

8.5 Material Deposition

It is UE&C's opinion that a certain degree of material deposition will be unavoidable. Therefore, it is extremely important that technical designs to detect and dispose of this buildup on-line be developed. This is in G/C's existing scope, and we consider that it is a high priority item.

A detailed description of the causes and remedies of deposition problems during the Coolside testing at Edgewater should be obtained by the DOE for use in this Duct Injection Technology Development Program. The information from Edgewater will be valuable in predicting problems and avoiding redundant experiences. This is considered a high priority.

If mechanical material removal devices such as DIDS (from E-SO_x) and duct hoppers are considered integral components of the duct injection process, they should be incorporated into the mathematical models being developed. This is considered a medium priority.

8.6 Corrosion

Based on experience from spray dryer retrofits to existing plants, corrosion of the existing particulate collection device and outlet ductwork will be a potential problem for duct injection technology. Corrosion or leaning in the stack or chimney liner could also be a problem. A site specific evaluation will have to be performed on a case-by-case basis regarding the suitability of an existing stack or chimney liner. UE&C could develop a methodology and criteria for performing this evaluation. The impacts of a long plant outage for a chimney liner replacement would have to be considered. This is considered a high priority.

A detailed description of the effects, if any, of sodium additives on ductwork and ESP corrosion during the Coolside testing at Edgewater should be obtained by the DOE for use in this Duct Injection Technology Development Program. This is considered a low priority.

The technical and economic feasibility of a reheat system retrofit either upstream or downstream of the ESP needs to be investigated. UE&C could accomplish this; it is considered a medium priority.

8.7 Electrostatic Precipitator

The ability of an existing ESP to maintain compliance after substantially increasing the inlet grain loading and altering the particulate resistivity is a major unknown of this technology. Considerable work will be performed by Radian and G/C to define ESP operation in conjunction with duct injection technology. However, a detailed description of ESP performance during the Coolside testing at Edgewater should be obtained by the DOE for use in this Duct Injection Technology Development Program. This is considered a high priority.

8.8 Waste Handling System

Research is required to determine the impacts of duct injection waste on a wet sluicing ash handling system. There are a number of plants that wet sluice their fly ash to an ash pond. If duct injection waste material cannot be accommodated in a wet sluicing system, conversion to a dry removal system (with its corresponding economic penalty) should be evaluated. Since some information will be provided during the EERC physical characterizations, this is considered a low priority.

A site specific evaluation will have to be performed on a case-by-case basis regarding the suitability of an existing waste handling system. The amount of waste collected in the ESP will increase substantially after retrofit of a duct injection system. UE&C could develop a methodology and criteria for performing this evaluation. The impacts of a long plant outage for replacement of the waste handling system would have to be considered. This is considered a high priority.

8.9 Recycle System

Preliminary results from testing with recycle are not conclusive as to its effect. If recycle solids are partially unreactive due to CaSO_3 blinding, methods to activate the material should be investigated. Possible methods include grinding and chemical activation. Encouraging

results obtained by EPRI during their HYPAS testing suggest that grinding of the recycle material should be evaluated. The Beverly test facility is probably the most suitable for these tests. This is considered to be a medium priority.

8.10 Operation and Maintenance Considerations

A detailed description of operating procedures and experience during the Coolside testing at Edgewater should be obtained by the DOE for use in this Duct Injection Technology Development Program. This is considered a medium priority.

8.11 Model Development

Although the predictive computer model is a separate deliverable from the design handbook, it is important to provide the status of UE&C/B&W's efforts. The validation of EER's submodel is not clearly in the work scope of any contractor. In addition, the effect of recycle and/or additives on SO₂ capture is not included in the present submodel. It would likely be necessary for EER to make these modifications to their model. Since recycle may be an integral part of the duct injection process, the modeling of recycle is considered a high priority. The benefits of additives remain unclear at this time; therefore, these modifications are considered low to medium priority.

It appears that neither Radian nor G/C will be able to provide three-dimensional data for model evaluation in time to support model development by B&W. These tasks could be added to the UE&C/B&W scope. This would require a significant effort; the B&W 6 ft by 6 ft test duct could be used to obtain these data for model evaluation. In view of the lack of data from other sources, increased funding would undoubtedly be desirable. This is considered a high priority.

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APPENDIX A
STATUS REPORTS
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

Sorbent Selection

Sorbent Storage and Preparation (for both DSI and DSD)

Humidification and Slurry Nozzle Specifications
(for both DSI and DSD)

Dry Sorbent Injector Design (for DSI)

Material Deposition on Duct Walls/Turning Vanes

Corrosion of Materials in Flue Gas Path

Temperature Instrumentation and Controls

SO₂ Measurement Instrumentation and Process Control

Velocity and Temperature Profile

Electrostatic Precipitator

Waste Handling System (On-Site Transfer, Storage,
and Conditioning)

Recycle System (for both DSI and DSD)

Waste Disposal (Transport and Disposal)

STATUS REPORT
SORBENT SELECTION
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

The process economics of duct injection are significantly impacted by sorbent cost, while its technical feasibility is largely dependent upon sorbent reactivity. These two facts demonstrate the importance of sorbent selection in bringing duct injection technology to the point of commercial readiness. A considerable amount of work has gone into both bench- and pilot-scale testing of sorbents with varying physical characteristics. This Status Report reviews the results of the evaluations performed to date on duct injection sorbents.

2.0 CONCLUSIONS

1. For SO_2 removal by $\text{Ca}(\text{OH})_2$, the rate limiting step appears to be bulk SO_2 diffusion to the droplet surface.
2. The major wetting mechanism for Dry Sorbent Injection (DSI) with downstream humidification is scavenging. The major wetting mechanism for DSI with upstream humidification is condensation and absorption.
3. Results from pilot-scale tests indicate that little improvement in SO_2 removal is achievable with high surface area lime in the DSI with downstream humidification process. This is true because SO_2 diffusion to the droplet surface is rate limiting - not the dissolution of calcium from the lime particles within the droplet.
4. The physical characteristics of hydrated lime in the DSI with upstream humidification process may have a greater effect on SO_2 removal compared to DSI with downstream humidification.
5. The effect of hydrated lime particle size on SO_2 removal and sorbent utilization in DSI processes is not clear because of the tendency for hydrated lime to agglomerate.
6. Calcitic lime is more reactive than pressure hydrated dolomitic lime on a mass basis.
7. A variety of chemical additives intended to enhance sorbent utilization have shown promise in the laboratory; however, their

benefits have not been clearly demonstrated in pilot- or full-scale evaluations. Based on limited testing, sodium based compounds and surfactants appear to be the most promising additives for duct injection technology.

8. Calcium silicate sorbents show considerable promise in removing SO_2 , but they are outside the scope of this project.

3.0 RECOMMENDATIONS

1. Because SO_2 diffusion to the droplet surface is the rate limiting step, small droplets with high surface area, dispersed across the entire flue gas path, are necessary.
2. For DSI with downstream humidification, use the most economical high calcium hydrated lime available. For DSI with upstream humidification, high surface area hydrated limes should be further evaluated.
3. For DSD, slake the most economical high calcium pebble lime available.
4. Monitor the results from the particle size testing at the Meredosia and Beverly pilot plants to determine the effect of hydrated lime particle size on SO_2 removal and lime utilization.
5. Monitor the results from Consolidation Coal Company's Coolside Demonstration at Edgewater to collect more information on the effect of hydrated lime type and sodium addition.
6. Pilot-plant testing of sodium and calcium lignosulfonate addition should be performed at the Beverly pilot plant to determine if a significant increase in SO_2 removal is possible.

4.0 DISCUSSION

4.1 Reaction Rate

In the duct injection process, calcium hydroxide ($\text{Ca}(\text{OH})_2$) is injected into the ductwork upstream of an existing precipitator. The $\text{Ca}(\text{OH})_2$ is in the dry form in the Dry Sorbent Injection (DSI) process and in the slurry form in the Duct Spray Drying (DSD) process.

Chemical kinetics, thermodynamics, and mass transfer all influence the removal of SO_2 by $\text{Ca}(\text{OH})_2$. The sequence of reaction steps is (14):

I. Sulfur dioxide diffusion to the droplet surface

II. Dissolution of sulfur dioxide at the surface

III. Lime dissolution

IV. Chemical reaction

V. Product oxidation

Since residence times for duct injection are short, the only way to increase the efficiency of a duct injection system is to increase the overall rate of reaction. The overall rate is largely determined by the slowest step in the reaction sequence. For the case of SO_2

removal by Ca(OH)_2 , the rate limiting step is Step I, bulk SO_2 diffusion (9). Therefore, the easiest way to increase the rate of SO_2 removal is to increase the area of the gas-sorbent interface. By increasing the interface area, the diffusion of SO_2 to the surface will have less influence on the overall rate. This is best achieved by generating droplets which are small enough to have the needed high surface area and by distributing these droplets across the entire flue gas path. The droplets cannot be too small, however, or else they will evaporate before scavenging and subsequent reaction can occur in DSI or before reaction is complete in DSD.

4.2 Physical and Chemical Sorbent Properties

Research on sorbent reactivity has been motivated by laboratory evidence that a more reactive calcium sorbent is an effective method to improve the SO_2 removal efficiency of a duct injection system. Tests have concentrated on studying the effect of the following parameters on sorbent reactivity:

1. Surface area
2. Porosity
3. Particle size
4. Lime type
5. Chemical additives
6. Calcium silicates

Surface Area and Porosity

Surface area of hydrated lime is determined by the conditions during hydration. Most limes have a specific hydration temperature which optimizes the hydration process. Typical commercial hydrates have surface areas around 15-20 m^2/g while high surface area hydrates range from 25 to 40 m^2/g - some as high as 75 m^2/g . Some high surface area hydrates are produced under high pressure; however, with the addition of alcohol or sugar to the hydration water, they can be produced at atmospheric conditions (12). With alcohol addition (methanol or ethanol), the hydration temperature is controlled at the boiling point of the evaporating alcohol. Sugar, on the other hand,

is incorporated with the sorbent and actually increases the solubility of the lime in water.

Sorbent surface area testing at the bench scale indicates that the following are related linearly to the sorbent surface area: percent SO_2 removed (3), calcium utilization (16), and initial reaction rate (11). However, these results have never been confirmed at the pilot scale. Pilot-scale testing indicates little improvement of SO_2 removal with increasing sorbent surface area. This has been shown in multiple tests. Blythe showed little difference between SO_2 removal with alcohol hydrate (25-36 m^2/g) and commercial hydrate (18 m^2/g) with either a baghouse or ESP (3). In separate tests, both Giovanni and Babu found no increase or effect on SO_2 removal with a high surface area hydrated lime (6,1).

The discrepancy between pilot- and bench-scale tests is believed to be due to the mechanism of sorbent wetting. Bench-scale tests showed success using a high surface area particle because the sorbent was never present in a slurry. Conditions were such that the moisture in the solids approached equilibrium with the water vapor. The moisture required for reaction generally resulted from condensation and absorption. This magnified the importance of surface area because high surface area particles had more surface moisture. Since this reaction is highly moisture dependent, the increase in water allowed for a greater extent of reaction.

During pilot-scale testing, however, the sorbent was either injected in the slurry form, or, even if it was injected dry, most of the sorbent was scavenged by humidification water droplets. Once scavenging occurs, the hydrated lime within the droplet behaves essentially like a lime slurry droplet: the surface area of the droplet controls the rate of SO_2 diffusion which controls the overall rate. In a slurry droplet, the surface area of the lime particles controls the dissolution rate of calcium, but this is not a rate limiting step. "The surface area of lime is not very important when excess lime is present in the slurry droplet because the overall rate is limited by bulk mass transfer of SO_2 to the

droplet surface and not by the dissolution rate of lime" (9). The surface area of lime becomes more important as calcium utilization increases.

Since the DSI with downstream humidification duct injection method results in the formation of slurry droplets, the initial surface area, porosity and, to some extent, particle size of the hydrated lime particles will have little or no influence while present in an aqueous droplet. Once drying is complete, these initial parameters will have been altered due to physical property changes of dissolving, reaction, and recrystallization. Only in the case of DSI with upstream humidification (where the wetting mechanism is primarily condensation) should these sorbent physical characteristics be critical.

Additional information on the effect of scavenging should be provided by both the 12 MW pilot plant operated by Gilbert/Commonwealth and the Consolidation Coal Company's Coolside Demonstration at the 104 MW Edgewater Station.

Particle porosity is closely related to surface area. Laboratory tests have shown improved SO_2 capture with increasing porosity (15), but as with surface area, the effect appears to be minimal or non-existent at the pilot scale.

Particle Size

The importance of lime hydrate particle size on sorbent utilization in low temperature duct injection processes is not well defined. A great deal of this uncertainty is due to the propensity of hydrated lime particles to agglomerate. Individual particles of typical atmospheric hydrates range from 2 to 10 microns mass mean diameter (MMD), but tend to form agglomerates as large as 30 to 60 microns MMD. The effective size of lime particles (or agglomerates) in the process stream has been difficult to determine.

A promising electronic analyzer has recently been developed which may be capable of accurately measuring in-situ sorbent particle size within the

duct injection process stream. Like similar optical devices, this instrument is based on laser light scattering techniques; unlike the other devices, it is apparently not limited by high grain loading environments like those found in DSI process streams. This device will be used at Meredosia and Beverly to measure in-situ sorbent particle (or agglomerate) size.

Sorbent particle size reduction by grinding and/or the use of surfactants or parting agent additives have been effective in increasing lime reactivity in both furnace and economizer lime injection technologies (4)(7). Similar testing on low temperature duct injection at the pilot scale has been inconclusive (3). The scavenging mechanism is again believed to be responsible for obscuring any potential beneficial effects of decreased sorbent particle size.

Lime Type

Some early programs included testing of pressure hydrated dolomitic limes (PHDL). The presence of $Mg(OH)_2$ improved the physical properties of the slurry in DSD testing making it more stable with a lower viscosity. This resulted in smaller droplets than produced by most calcitic limes (12). At the bench scale, PHDL performed well, demonstrating either equal or greater SO_2 removal than with calcitic sorbents. With its high concentration of inert $Mg(OH)_2$, its higher utilization of calcium looked promising. But, when compared on a mass basis during pilot-scale tests, PHDL performance dropped (3). Lower SO_2 removals and increased abrasive properties have resulted in PHDL being eliminated from most future test programs.

The full-scale tests at Edgewater will provide additional information on the effect of lime type. The test program will compare Mississippi hydrate with the locally most economical lime, Black River hydrate.

Chemical Additives

Chemical additives can be added either to the humidification water or to the hydration water during preparation of the hydrated lime, and they typically fall into four categories.

1. Deliquescent salts - Cause sorbent to retain moisture allowing more time for reaction.
2. Sodium based compounds - React directly with SO_2 and may promote calcium-sulfur reactions.
3. Organic Acids - Increase SO_2 absorption by buffering the pH at the gas-liquid interface.
4. Surfactants - Lignosulfonate compounds reduce lime particle agglomeration.

Deliquescent Salts - Studies have indicated that the addition of deliquescent salts, particularly calcium chloride (CaCl_2) and sodium chloride (NaCl) can substantially improve reactivity of hydrated lime in bench-scale reactors and pilot-scale spray dryers (8, 13). Pilot-scale tests of these additives in conjunction with DSI processes, however, have been far less encouraging. Deliquescent salts have been evaluated as a dry admixture, an aqueous solution sprayed on the dry hydrate, and dissolved in the water used to hydrate the lime. The results of these various tests indicate little or no enhancement in sorbent utilization (3). Spray dryer literature suggests that the enhancement mechanism of such additives is through promoting increased humidity at the particle surface in the final stages of slurry droplet drying, thereby sustaining the liquid phase necessary for SO_2 adsorption. This has potential advantages for long residence time applications (spray dryer vessels, fabric filters), but may aggravate solids buildup on duct walls in DSI or DSD. If scavenging is the dominant wetting mechanism in DSI, then the use of deliquescent salts is questionable.

Sodium Based Compounds - Investigators at Consol have extensively evaluated the potential of additives. Apart from laboratory studies, their practical applications have concentrated mainly on NaOH added to the spray water used for duct humidification. The Coolside process adds NaOH at a 0.1 Na/Ca weight ratio. Tests show greater SO_2 removal than can be stoichiometrically accounted for by the sodium (16). It is not clear how the calcium enhancement actually occurs, but the results were

reproducible. Pilot- and bench-scale tests have demonstrated up to 80% SO₂ removal. Similar testing at Arapahoe, in which NaOH was added to the humidification water, however, showed no excess SO₂ removal beyond that which directly reacted with the sodium. The full-scale tests at Edgewater will provide additional information on the effect of sodium addition. The test program will compare lime hydrate injection both with and without NaOH addition.

Organic Acids - Organic acids have never received serious attention in duct injection applications because the low SO₂ uptake and high calcium dissolution along with the short residence time produce conditions such that the pH at the interface does not significantly change (12).

Surfactants - Organic surfactants have been used to enhance sorbent reactivity in furnace and economizer hydrate injection studies (4)(10). Calcium lignosulfonate, when added in small amounts to the water of hydration, can produce hydrates with reduced particle size by reducing the agglomeration tendency. EPRI evaluated several lignosulfonate additives in the duct injection pilot plant at Arapahoe and, although successful in reducing the lime particle size, very little effect on sorbent utilization was measured (3). The effects of scavenging and wall wetting at the small scale Arapahoe facility may have obscured any potential benefits of particle size reduction. Evaluation on a larger scale, such as at the 12 MW pilot plant, may be more informative.

In slurry injection cases, surfactants decrease the surface tension and/or the viscosity of the slurry which may decrease the size of the droplets produced by the atomizer. This could potentially allow increased slurry flows (higher Ca/S ratios or closer approach temperatures) or higher recycle solids concentrations. There is little data available on the effectiveness of surfactants on slurry injection. One pilot-scale in-duct slurry project reported slight improvements in duct wall deposition (perhaps due to improved atomization) when a surfactant was added to the slurry (14).

The addition of sugar to the hydration water may have a similar net effect on slurry properties. Sugar has been used in certain analytical techniques to complex with calcium hydroxide and dissolved solids present in the lime slurry (12). Since SO_2 reacts primarily with the dissolved calcium hydroxide, using sugar as a dissolution enhancer should improve SO_2 removal and lime utilization. No experimental evidence has been reported as to the effectiveness of sugar addition.

Calcium Silicates

These new sorbents are produced by reacting fly ash and lime in water at high temperature and pressure. The resulting calcium silicates, when injected into the duct, show very promising SO_2 removals: 80% at a Ca/S molar ratio of 1.8 (13). Currently, however, the high cost of producing this sorbent raises economic questions. Calcium silicates are outside the scope of this project and will not be discussed further.

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STATUS REPORT
SORBENT STORAGE AND PREPARATION
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

Sorbents such as hydrated lime and pebble lime have been used for several years in various utility flue gas desulfurization applications as well as in chemical and metallurgical processes. The methods of storing and handling these materials have been developed and somewhat standardized through the years. This Status Report summarizes the options and equipment design for the storage and preparation of sorbent for duct injection processes.

2.0 CONCLUSIONS

1. Commercially available lime unloading and storage systems using mechanical or pneumatic conveying equipment should be used for sorbent storage in duct injection systems. Rail car or truck unloading should be utilized depending on plant size and available plant real estate. Storage silos can be steel or concrete with a steel cone bottom.
2. For Dry Sorbent Injection (DSI), the decision to utilize off-site vs. on-site hydration depends on the plant size (and corresponding sorbent rate), the proximity of the plant to sources of hydrated and pebble lime, and the availability of plant real estate.
3. For DSI processes, the most likely method of transporting the hydrated lime to the duct injection point is by a dilute phase pressure system similar to those used at full-scale furnace sorbent injection demonstrations.

4. For Duct Spray Drying (DSD) processes, the slaking and slurry feed systems will be essentially the same as those used in existing utility spray dryer installations.
5. Auxiliary items which are not related directly to the process but must be considered are weather protection of the sorbent storage and preparation equipment and dust control and collection.

3.0 RECOMMENDATIONS

1. For either a DSI or DSD duct injection system, the size, sulfur loading, available real estate, and distance from lime supplies of the existing plant need to be studied before a final decision can be made on the method used to store, prepare, and transport the sorbent.
2. In general, it is recommended that pneumatic conveying be used wherever possible in order to minimize the dusting problems associated with lime handling.
3. Sorbent preparation systems are relatively maintenance intensive and should be weather protected if possible.

4.0 DISCUSSION

The sorbent storage and preparation equipment arrangement and design which would be most appropriate for duct injection technology, particularly in a retrofit situation, depend on several factors:

- 1) Size of the plant and corresponding quantity of sorbent required
- 2) Real estate available for new equipment
- 3) Duct injection process selected
 - a) Dry Sorbent Injection (DSI)
 - b) Duct Spray Drying (DSD)

For the purpose of this Status Report, it is assumed that hydrated lime with a particle size of 200 mesh and a bulk density of 25-35 pcf will be used for injection in the DSI system, and 3/4" minus pebble lime with a bulk density of 55-60 pcf will be the source material for the lime slurry used in the DSD system (reference Table 1). If recycle material is used in the DSI process, it will be injected separately from the fresh hydrated lime. If recycle is used in the DSD system, the recycle material would be slurried separately and then added to the lime slurry before it is pumped to the atomizers. Recycle is covered in the Recycle System Status Report.

4.1 DSI System

For smaller plants, it would be most economical and practical to have the hydrated lime delivered by pneumatic truck and fed directly into a storage silo for subsequent injection into the duct.

For larger plants, it becomes more practical and economical, due to the relative cost of material and transportation of hydrated lime vs. quicklime, to have quicklime (pebble lime) delivered to the plant storage silos and hydrated on-site using a hydrator (9). If space is at a premium and rail unloading is not available, the quicklime could be trucked in using pneumatic or end dump trucks.

The break point between delivery of hydrated lime vs. on-site hydration of quicklime is essentially an economic determination and will depend upon the proximity of the plant to sources of the material. This break point, although site specific, is expected to be around 100 MW (9). Adequate plant real estate for the hydrator is also a consideration.

4.1.1 Equipment Description

Small Plants - For small plants, the most common method of delivery of hydrated lime is by pneumatic truck. The storage silo should be located as close to the injection points as is

practical. This will allow for one pneumatic conveying system to be used to transport the sorbent from the silo and inject it into the duct.

The pneumatic lime truck is usually a pressure-differential tank trailer (Figure 3a). It is available with capacities of about 20 tons of hydrated lime for one trailer or up to 27 tons with a "pup". The trailer is built as a tank with hopper bottoms. The hoppers connect through valves to a short manifold. The trailer is virtually self-unloading, requiring only that the receiving silo be equipped to accept the transport air and have a bin vent filter for dust control. The lime is unloaded from the truck by a self-contained truck blower into the silo. Normally a truck can be unloaded in about 60 minutes.

The silo should be large enough to contain 7 to 10 days of storage at the maximum usage rate. The silos can be either steel or concrete side walls with a steel bottom cone. The cone angle for hydrated lime should be 60-70 degrees from the horizontal. Hydrated lime tends to form rat holes, craters, or chimneys which can cause arching or bridging in storage. A bin activator or vibrator is not recommended on silos for hydrated lime storage as they have the tendency to pack the material rather than enhance flow (2). Air pads or other fluidizing system have been used successfully to enhance flow (3). On smaller bins, an offset cone design can be used with success (7).

The lime is discharged from the silo through a variable speed screw feeder or rotary valve and into a pneumatic conveying system through a constant speed airlock valve. The screw or rotary valve speed is controlled to maintain a specified SO_2 emission based on SO_2 monitor signal or coal sulfur and boiler load. Controls are discussed in the SO_2 Measurement Instrumentation and Process Control Status Report.

The conveying system should be a dilute phase pressure system to provide a constant flow at the required pressure to the injection nozzles. A single pipe conveys the lime to a distribution bottle near the flue duct where it is split into smaller balanced loss pipes to each injection nozzle. This transport system has been used successfully at full-scale furnace sorbent injection demonstrations (2,3) and at the Edgewater full-scale duct injection demonstration.

The conveyor piping should be routed either vertically or horizontally with no more than a 15 degree deviation from vertical or horizontal to minimize particle drop out in the pipe. Schedule 40 carbon steel pipe can be used for the piping with all elbows being minimum 4 foot radius sweeps. The sweeps should be designed to be replaceable as they are potential wear points.

The blower for the system would be an oil free, lobe type, positive displacement blower that delivers clean, dry air to the airlock valve. If the plant is located in a high humidity area, consideration must be given to heating the air before it enters the airlock valve.

Larger Plants - At larger plants, it will likely be more economical to have the lime delivered in a pebble lime form. This is usually a 3/4" minus material that can be hydrated without being crushed. The lime is delivered in rail cars with hopper bottoms (Figure 3b) or pneumatic or end dump trucks. With rail cars, use of a multiple unloading system connected directly to the rail cars allows capacities of 100 TPH of 60 pcf pebble lime to be reached without using a dump hopper and pit. Figures 1, 2, and 4 show typical rail car unloading alternatives.

If rail unloading is not available, the use of end dump or pneumatic trucks are required. End dump trucks are more feasible as they decrease the unloading time over pneumatic trucks. The lime is dumped into an underground hopper inside

of a weather shelter. From the hopper the lime can be conveyed mechanically by drag or screw conveyor and bucket elevators or it can be conveyed pneumatically. Mechanical conveying will involve a rather large and extensive dust collection system. Pneumatic conveying would be the system of choice. See Tables 2, 3, and 4 for comparison of conveying alternates. However, the capital cost for an underground hopper and associated conveying system is very high. Pneumatic truck unloading will take longer, but is much less expensive.

Pneumatic conveying from either the rail car or truck dump hopper would be similar. The conveying system would move the material to a series of silos depending on the plant capacity. The silos should contain at least 7 to 10 days of storage at full operating capacity to allow for delays in receiving material or maintenance time on the unloading system.

The bottom cone angle for silos handling quicklime can be 60 degrees. Bin activators have been used successfully on quicklime. When more than one silo is necessary for the required storage capacity, a metered flow device, either a rotary vane feeder or a sealed variable pitch screw feeder, is attached to the silo cone. The discharges of the silos are tied to a common screw conveyor. The flow from each silo is controlled either by blending the flows together or by total flow from each silo in sequence. The common screw conveyor feeds a hydrator sized to handle the full requirements of the injection system. A full size spare hydrator unit should be considered to maintain reliability of the system. The screw conveyor discharges into a feed hopper ahead of the hydrator (reference Figure 5). The feed hopper discharges to a weighing device, usually a totally enclosed weigh-belt feeder. The weigh-belt feeder is a short belt conveyor equipped with a weigh-deck which measures the weight

of lime carried on a section of the belt. Instrumentation adjusts a vertical gate so that only a set weight of material is allowed out of the feed bin and into the premixer of the hydrator.

The hydrator consists of a premixer, coupled with a water preheater, followed by a trough mixer (5). The premixer introduces just enough heated water into the pebble lime to cause the formation of a dry hydrate. The hydrate material overflows a weir at the discharge of the mixer. No further grinding would be required for this process. The commercial hydrators available today range in size from 2 to 30 TPH of hydrated product at 30 pcf. Figure 6 is a typical equipment arrangement for a 15 TPH lime hydrator.

The hydrator would discharge into a surge chamber feeding a pneumatic conveyor that would transport the hydrate to a day bin located near the injection points. This conveyor could be a dilute phase or dense phase pressure system.

The day bin would discharge into a variable speed screw feeder or rotary valve through an airlock valve to a dilute phase pressure conveying system. The injector nozzles would be fed through a distribution bottle or bottles similar to that described for smaller plants.

4.2 DSD System

The DSD system requires the same type of pebble lime unloading and storage equipment as required for the DSI systems at larger plants described in Section 4.1. From the silos, the lime is fed to a slaking system which converts the pebble lime to a lime slurry which is then pumped to dual-fluid or rotary atomizers in the flue duct. The equipment required is essentially the same as that used in existing utility spray dryer installations.

The size of the equipment would be based on the plant size and required sorbent rate. A larger plant would have larger or more equipment, but the equipment would be the same type regardless of size.

4.2.1 Equipment Description

Unloading Systems - The unloading method would be the same as for the DSI system. A small plant would use pneumatic truck delivery direct to the storage silo, except that the material would be pebble lime. The larger plants would use either end dump trucks or rail cars to deliver the pebble lime to a pneumatic conveying system feeding the silos.

Slaking Systems - The slaking system consists of a weigh-belt feeder to control the flow of lime, a mixer to thoroughly mix the lime and water and form a lime slurry that is 20 to 35% solids by weight, and a method of eliminating the grit and undissolved solids from the slurry (7).

There are three basic slaking methods that are currently being used (7): the detention slaker (Figure 7), the ball mill slaker (Figure 8), and the paste slaker (Figure 9).

The detention slaker is probably the simplest of the three slakers. It consists of a slaking unit and a classifier compartment. The slaking section is comprised of a steel cylindrical tank and an impeller type mixer supported by tank spanning beams. It is designed to promote rapid, intimate contact. The flared tank classifier compartment is connected to the slaker by submerged slurry passage ports. It consists of heavy duty reciprocating rakes, or a classifying screw, and a washed grit discharge section. Lime and slaking liquid are fed into the slaker through openings in the cover. Generally, for optimum results, a 3:1 water to lime ratio is used. After slaking, the slurry passes into the classifier where it is diluted and grit is settled. The classifier

moves the grit up an inclined deck for a final water spray and then to the discharge container. The degritted milk of lime flows into a launder, which spans the classifier, then to a pumping tank.

The ball mill slaker consists of a ball mill, an agitated slurry sump, slurry pumps, and a recycle cyclone or screen. The lime and water are fed into the ball mill where they are mixed. Iron balls in the mill pulverize the larger particles and produce a finer particle size slurry. The slurry overflows the ball mill discharge into a sump tank that is agitated to keep the slurry in suspension. The slurry is pumped to either a cyclone separator or a vibrating screen where the larger particles are removed and recycled to the ball mill for further grinding. The undersize portion flows to an agitated holding tank and then to the process. Any core or grit which may be in this lime is effectively ground up and its lime value recovered. A separate grit removal system is not required. Ball mills can slake low quality as well as high quality pebble lime; in addition, they can utilize poor quality slaking water because of the grinding action of the mill (1).

The paste slaker consists of a slaking compartment with two sets of counter-rotating paddles acting as a pug mill for mixing. Water and quicklime, usually at a low ratio of 2:1, are fed continuously and automatically by a torque-actuated water-inlet valve. Increasing torque indicates that the lime paste is too thick so additional water is added to reduce the viscosity of the paste to the desired level. As the paste is discharged over a weir into a dilution compartment, a continuous water spray dilutes the paste to a slurry. The grit settles and moving rakes on the same shaft as the mixing paddles maintain proper agitation of the lime suspension to remove the grit to a classifier for discharge into an external enclosed elevator. The slurry then flows over a weir and out the discharge port. The grit is washed free of

lime in the elevator, and the recovered lime water is returned to the dilution chamber.

Slurry Injection - Regardless of which slaking method is employed, the lime slurry is stored in an agitated lime slurry storage tank. A slurry pump feeds the lime slurry from the holding tank to the atomizers at the required pressure. The slurry pump is sized to handle the maximum flow required by coal sulfur content. The piping is designed as a loop system with recirculation back to the holding tank so that feed to the atomizers can vary from minimum to maximum flow and still maintain enough velocity in the piping to minimize lime build-up inside the pipes. The piping would be periodically flushed with water to remove any build-up that occurred. This would normally be done during a maintenance shut down.

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PHYSICAL AND CHEMICAL DATA PERTAINING TO LIME PRODUCTS (7)

LIMESTONES

	High Calcium	Dolomite
Primary Constituents	CaCO ₃	CaCO ₃ and MgCO ₃
Specific Gravity	2.65 - 2.75	2.75 - 2.90
Bulk Density (3/4" in. Stone), lb./cu.ft.	87 - 95	87 - 95
Specific Heat at 100°F., Btu/lb.	0.21	0.21
Angle of Repose (approx. average)	45 - 50*	45 - 50*

QUICKLIMES

	High Calcium	Dolomite
Primary Constituents	CaO	CaO and MgO
Specific Gravity	3.2 - 3.4	3.25 - 3.45
Bulk Density (Pebble Lime), lb./cu.ft.	55 - 60	55 - 60
Specific Heat at 100°F., Btu/lb.	0.19	0.21
Angle of Repose (approx. average for pebble)	50 - 55*	50 - 55*

HYDRATES

	High Calcium	Normal Dolomite	Pressure Dolomite
Primary Constituents	Ca(OH) ₂	Ca(OH) ₂ + MgO	Ca(OH) ₂ + Mg(OH) ₂
Specific Gravity	2.3 - 2.4	2.7 - 2.9	2.4 - 2.6
Bulk Density, lb./cu.ft.	25 - 35	30 - 40	30 - 40
Specific Heat at 100°F., Btu/lb.	0.29	0.29	0.29
Angle of Repose (most common)	70*	70*	70*

* Approximate average values since considerable variance may occur.

LIMITATIONS OF CONVEYING ALTERNATIVES (4)

PNEUMATIC CONVEYORS					MECHANICAL CONVEYORS				
	Dilute Phase Systems			Dense Phase Systems	Air-Activated Gravity Conveyors	Belt Conveyors	Screw Conveyors	Chain Conveyors	Bucket Elevators
	Vacuum	Positive Pressure	Vacuum/Pressure						
GENERAL MATERIAL PROPERTIES	Dry, granular or powdered materials; Max. particle size of 1"	Dry, granular or powdered materials; Max. particle size of 1"	Dry, granular or powdered materials; Max. particle size of 1"	Dry mat'l that can be aerated and fluidized	Dry mat'l that can be fluidized; Max particle size of 0.84 mm; 20-60% finer than No. 200 sieve	V Fine to 12" size depending on moisture content and bulk density; Limited to temps. under 300°F	V Fine to coarse free-flowing materials; Max. particle size 4"; Temps. to 900°F	V Fine to coarse free-flowing materials; Max. particle size 4"; Temps. to 900°F	V Fine to coarse materials. Suitable for broad range flowabilities; Max. particle size 6"; Temps to >900°F
CAPACITY (TPH)	0.35 - <60 *	10 - 200	0.35 - 200	<200	<1300 *	4 - 5,000 *	<375 *	<160 *	<100 *
DISTANCE	<1,000 ft	<7,500 ft	<7,500 ft	<8,000 ft	<1 mile	6 ft - 7 mi.	Horiz: <100 ft Vert: <80 ft (Min of five screw dia.)	Horiz: <250 ft Vert: <30 ft (drag) & >80 ft (enmasse)	Vert: 125 Ft
RELATIVE COSTS	Economical first cost; High operating costs	High initial cost; High operating costs	High initial cost; High operating costs	High initial cost; Low operating costs	Low operating costs; High maintenance costs	High initial cost; Low operating costs			

* For normal size buckets; super-capacity buckets can handle particle sizes >12".

^b Where dry collection of flyash is required, the size of available collectors limits vacuum system handling rates to a maximum of 60 tph.

^c For materials having a bulk density of approximately 50 lb/ft³.

COMPARISON OF PNEUMATIC CONVEYING ALTERNATIVES (4)

CLASSIFICATION AND TYPE OF SYSTEM	ADVANTAGES	DISADVANTAGES
DILUTE PHASE SYSTEMS		
Negative Pressure	<ol style="list-style-type: none"> 1. Simplified design. 2. Economic first cost. 3. Material can enter pipeline from several sources of supply. 4. Reduced fugitive emissions. 	<ol style="list-style-type: none"> 1. Limited conveying distance. 2. Special piping required. 3. Moisture and outside air can be drawn into system. 4. Erosion of blowers (if mechanical blower used). 5. Use of water jet eductor requires water disposal. 6. Efficiency affected by altitude and material temperature.
Positive Pressure	<ol style="list-style-type: none"> 1. Capable of transporting long distances. 2. Blower is not eroded by conveyed material. 3. Uses smaller pipelines than comparable vacuum systems. 4. Moisture and outside air cannot be drawn into system. 	<ol style="list-style-type: none"> 1. Higher initial cost. 2. Special piping required. 3. Airlock required at each entry point. 4. System leakage will result in fugitive emissions. 5. Throughput of airlock is less than comparable vacuum intake valve.
Vacuum/Pressure	<ol style="list-style-type: none"> 1. Permits pickup from several locations and transport to one or several discharge points. 2. Dust from vacuum-side receiver is delivered into conveyor line. 3. Same as for individual systems. 	<ol style="list-style-type: none"> 1. Same as for individual systems.
DENSE PHASE SYSTEMS		
	<ol style="list-style-type: none"> 1. Continuous removal from hopper. 2. Smaller pipe sizes. 3. Less pipe erosion. 4. Smaller Blowers. 5. Reduced operating cost. 6. Capable of transporting long distances. 	<ol style="list-style-type: none"> 1. Pulsed discharge. 2. Additional height required under the bin cone.
AIR-ACTIVATED GRAVITY CONVEYORS	<ol style="list-style-type: none"> 1. Continuous removal from hopper. 2. Capable of transporting long distances. 3. Low power requirement. 	<ol style="list-style-type: none"> 1. Few utility installations. 2. Other industries claim higher maintenance costs. 3. Limited to fluidizable material.

Table 3

COMPARISON OF MECHANICAL CONVEYING ALTERNATIVES (4)

TYPE OF CONVEYOR	ADVANTAGES	DISADVANTAGES
Belt Conveyors	<ol style="list-style-type: none"> 1. Low operating costs. 2. Safe to operate. 3. Nearly unlimited range of capacities. 4. Resistant to corrosion and abrasion. 5. Provides a continuous flow of materials. 6. Capable of receiving and discharging material from one or more locations. 7. Capable of transporting long distances. 8. Can handle a wide variety of materials including sticky or compressible substances. 9. Can deliver large tonnages economically. 	<ol style="list-style-type: none"> 1. High initial cost. 2. Allowable belt speeds are significantly influenced by properties of the conveyed material. 3. Enclosures required when transferring fine materials or material that aerate easily.
Screw Conveyors	<ol style="list-style-type: none"> 1. Numerous feed and discharge openings are possible. 2. Enclosing trough controls fugitive emissions. 3. Easy to maintain. 4. Inexpensive to replace. 5. Provides a continuous flow of materials. 6. Can be adapted to a wide variety of processing operations. 7. Can be designed to enable easy cleaning. 	<ol style="list-style-type: none"> 1. Typically limited to free-flowing materials. 2. Sensitive to the abrasiveness and corrosiveness of the conveyed material. 3. Limited horizontal conveying distance. 4. Not feasible for large capacities. 5. Cannot be operated at high speeds without creating serious abrasion problems.
Chain Conveyors	<ol style="list-style-type: none"> 1. Multiple feed and discharge points possible. 2. Occupies less space. 3. Can handle materials with elevated temperatures. 4. Uncontrolled feed possible. 	<ol style="list-style-type: none"> 1. Sensitive to the abrasiveness and corrosiveness of the conveyed material. 2. Limited to free-flowing materials. 3. Limited conveying distances.
Bucket Elevators	<ol style="list-style-type: none"> 1. Simplest and most dependable units for vertical lifting. 2. Some designs can accommodate materials that are somewhat sticky or compressible. 3. Suitable for abrasive materials. 4. Requires very little floor space. 5. Relatively low initial cost. 	<ol style="list-style-type: none"> 1. Not recommended for very sticky materials. 2. Limited to vertical lifting. 3. Maintenance costs tend to be high.

Table 4

FIGURE 1. LOW CAPACITY VACUUM UNLOADING SYSTEM WITH PRESSURE TRANSFER SYSTEM

Vacuum Unloading System

(8)

The vacuum unloading system is a reliable low cost system for unloading lump, granular, and powdered materials where high unloading rates are not required and the silo can be located near the unloading area.

Material can be unloaded at several points by using a suction header with multiple inlets so that the unloading hose can be moved along the header, or sections can be added or removed from the unloading hose so that it reaches the desired point. The material can only be transferred to the filter receiver which is mounted on the silo.

The rail car unloading adapters are clamped to the hoppers on the car and the hose assembly is then connected to the unloading adapter.

This system does not require a pit, but is limited in capacity by the size of unloading hose that can be handled by the unloading crew, and the space restrictions between the hopper outlet and top of rail.

The system shown above uses a single positive displacement blower package with valving which permits it to

be used as a vacuum source to transfer material from rail cars to the silo, or a pressure source to transfer material from the silo to point of use, when cars are not being unloaded. This system is often designed with a separate lower capacity pressure blower since the required transfer rate is usually lower than the unloading rate.

If multiple positive displacement blower packages are used to provide back up, the piping and valving can be arranged to permit unloading of material and transfer to points of use simultaneously.

When more than one product is to be unloaded and stored in several silos, or where high unloading rates are required, the vacuum pressure system shown in Fig. 2 or the pressure system shown in Fig. 4 will provide a more economical solution to your requirements.

Many design variations are possible on these three basic systems.

FIGURE 2. VACUUM PRESSURE SYSTEM

Vacuum Pressure System (8)

The vacuum pressure system provides a reliable low cost method of unloading and transferring lump, granular, and powdered material to multiple storage silos or points of use.

It usually is applied to low and medium capacity applications, but can be designed for high capacity. The pit required for this system is very shallow. The bottom of the pit normally will be less than 3 feet below the top of rail.

The system shown in Figure 2 is a medium capacity system with fixed unloading adapters located below the rail. These adapters are equipped with air cylinder operated boot lifts to make up the connection between the adapter and the car hopper. This eliminates the need for the unloading crew to crawl under the car to attach rail car unloading adapters.

Since the adapters are located below the rail, the restrictions on conveying line size imposed by above rail adapters and hoses are removed, permitting the system to be designed for low, medium, or high unloading rates.

The fixed pick-up points require the rail car to be accurately positioned, by a car puller or rail car positioner if

locomotives are not available for positioning cars.

When high unloading rates are required, an adapter is provided below each hopper on the car. Medium and low capacity systems require only a single adapter.

When unloading rates are low, considerable savings in first cost result from the use of the above rail unloading adapters shown in Figure 1.

Since the vacuum portion of the system requires high power consumption per ton moved, the filter receiver is located as close as possible to the unloading point.

Material is transferred from the filter receiver to the pressure system by a rotary airlock feeder. Diverter valves are used to direct the material to the desired silo or point of use.

The vacuum pressure system uses more energy than the pressure unloading system shown in Figure 4. However, it may have a significant first cost advantage because it requires only small below track pits. An economic evaluation is required to select the best system.

Figure 3a - Pressure-Differential Tank Trailer

Figure 3b - Covered Rail Car with Hopper Bottoms

FIGURE 4
High Capacity Rail Car Unloading and Material Transfer Systems for Flue Gas Desulfurization and Chemical Process Systems Requiring Fine Grinding of Bulk Materials Prior To Use

UNLOADING — TRANSFER — STORAGE

High capacity rail car unloading systems normally use a dilute phase pressure system, employing from one to three rotary airlock feeders to meter materials from the hopper car into the conveying line. Vacuum pressure systems are available for use where pits below the rail cannot be used.

A rail car pusher is used to position the hopper car over the unloading system.

Air cylinder operated boot type connectors make up the connection between the car and unloading system, eliminating the need to crawl under the car. Accessories such as portable power gate operators, vibrators, or car shakers and hoists can be supplied to assist in efficient operation of the system.

The feeders can be arranged for removal from above permitting a narrow below track pit with the skidways supporting the rails. The pit depth required is significantly less than with other types of unloading systems.

The packaged positive displacement blower assembly(s) are located near the unloading area and only a foundation and electric power supply are required. The blower assemblies are designed to meet system requirements.

Storage silos of welded steel, bolted steel, concrete stave, or reinforced concrete are provided, as required. The silos are equipped with all necessary accessories, including flow inducing devices, required to assure proper discharge of material from the silos.

Divert valves are used to direct material to the selected storage silo.

The use of reliable, compact airlock feeders which have low first cost and permit significant reductions in pit costs will help keep project costs low without sacrificing reliability.

GRINDING — STORAGE — TRANSFER

The material is transferred from the storage silo(s) to a surge bin(s) in the line grinding building by a dilute phase pneumatic conveying system which can use the same positive displacement blower packages that are used for rail car unloading. When more than one line grinding mill is used, diverter valves are used to direct the material to the selected surge bin.

The surge bin(s) are provided with all necessary accessories including flow inducers. Material is fed from the surge bin(s) to the line grinding mill(s) by variable speed airlock feeder(s).

The line grinding mill(s) will normally be roller mill(s) equipped with classifier(s) that can be adjusted with the mill in operation.

Adjusting the fineness of the product can compensate for variations in the reactivity of the line.

Other types of mills can be supplied, if suited to system requirements.

The mill(s) operates under negative pressure which reduces housekeeping problems and eliminates the need for seal air systems. Heaters can be provided in the air inlet duct, to reduce moisture pick up.

The ground product is collected in a bag house(s) and discharged into ground product storage bin(s) by a 40 airlock feeder(s). The ground product is transferred from the storage bin(s) to the process area by either a dilute phase or dense phase pneumatic conveying system, depending on the conveying distance and the abrasiveness of the product.

Dry grinding systems are

easier to keep clean than

wet grinding systems. This is

especially true when the dry grinding system is operated under negative pressure and a central vacuum system is installed.

STORAGE — TRANSFER — SLAKING

Fine ground product transferred from the line grinding building is stored in one or more storage silos depending on process requirements. When more than one silo is used, diverter valves are used to direct the material to the proper silo. The silos are equipped with vent filter, pressure vacuum relief devices, level switches, and, if required, continuous weight or level monitoring systems. Since the ground material is stored dry, there is no need for freeze protection or continuous agitation, which is required when slurries are stored in large open tanks. Flow inducing devices are used to assure uniform discharge of material from the silos. The material is metered from the silos into the slurry tank(s) or slaking tank(s) or directly into the reactor by airlock feeders.

Fine grinding of pebble line product as a unit free product that slakes rapidly permitting the use of a small slaker and elimination of the grit removal system. In some applications it may be possible to eliminate the slaker.

When adjustable classifiers are used on the mill(s), the fineness of grind can be varied to compensate for changes in pebble line reactivity.

Using airlock feeders with variable speed drive permits the material to be metered in proportion to any process variable that is selected. This could be plant load, fuel flow, or system pH. Water flow also can be varied in proportion to line feed to provide optimum slaking temperature or optimum slurry concentration.

Operating and maintenance costs for a system employing dry grinding are pneumatic conveying should be lower than for a system using wet grinding equipment. There is less equipment and it is smaller and is not subjected to as much abrasive wear.

Figure 5 (5)

Typical Flowsheet of a Lime Hydrating Plant

Figure 6

DORR-OLIVER

slaker SIZE RANGE ...

SIZE NUMBER*	TONS CaO PER DAY**	SLAKER MOTOR HP	CLASSIFIER MOTOR HP
5	35	2	1
6	65	3	1
7	95	5	1½
8	120	5	1½
10	200	7½	2
12	290	15	2
15	450	20	2
16	510	25	2
17	580	30	2
18	650	30	2
20	800	40	2

*Size numbers shown correspond to normal diameter of the slaking section.

**If the lime is highly reactive according to ASTM specifications, then the capacity of the slaker can be increased by 25% or more. Capacities are based on water temperatures of not lower than 60°C.

Typical Detention Type Slaker (7)

Figure 7

TYPICAL FLOW DIAGRAM FOR
BALL MILL SLAKING SYSTEM
(6)

Figure 8

FIGURE 9
TYPICAL PASTE SLAKER (10)

HUMIDIFICATION AND SLURRY NOZZLE SPECIFICATIONS
for
DUCT SORBENT INJECTION AND DUCT SPRAY DRYING

STATUS REPORT

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STATUS REPORT
HUMIDIFICATION AND SLURRY NOZZLE SPECIFICATIONS
FOR DUCT SORBENT INJECTION AND DUCT SPRAY DRYING

With Duct Sorbent Injection, a dry sorbent material is injected into a flue gas stream and water is injected in a separate process to humidify the flue gas. In the Duct Spray Drying process the sorbent material (usually lime) is mixed with water and injected into the gas stream.

Nozzles or atomizers used for humidification or spray drying are among the critical components for successful duct injection. Poor performance of the atomizers will lead to wall wetting, deposition and frequent and costly equipment maintenance. Additionally, the compressed air requirements to achieve the necessary small droplets represent the single most costly operating expense associated with in-duct injection.

All of the design specifications that apply to Humidification atomizers will likewise apply to atomizers used for Duct Spray Drying of slurries. For Duct Spray Drying the atomizers will have additional specifications that address the particular problems of slurry atomization. These problems are atomizer wear, and atomizer pluggage by dried slurry or agglomerates in the slurry. Both wear and pluggage have been cited as a cause of material deposition in the duct.

The most successful pilot scale duct injection projects have utilized arrays of small capacity atomizers (9 to 100) to achieve atomization with acceptable amounts of deposition. With arrays of atomizers, control of individual atomizers is no longer feasible. Atomizers manifolded into a parallel array will require good part to part consistency in hydraulic characteristics and atomization performance. The failure of only one atomizer in an array of 10 to 100 can lead to severe wetting and deposition in a very short time.

In most retrofit applications, the available length of duct suitable for humidification and dry sorbent injection corresponds to gas residence times of about 1 to 2 seconds. The corresponding droplet sizes that provide complete evaporation at approach temperatures of 30 F can be provided only at high consumptions of compressed air.

CONCLUSIONS

- Commercially available atomizers are capable of providing a drop size distribution acceptable for DSI or DSD in which the gas residence time is on the order of 1 to 2 seconds and the A.S. temperature is 20 to 30 F.
- The liquid capacities of atomizers providing acceptable atomization are usually small, on the order of .08 to 2 GPM.
- Acceptable atomization is achieved only at high consumption of

compressed air. Reported air-to-liquid flow ratios range from about 0.3 to 0.8

- the geometry of atomizer arrays that provide good performance without deposition has been determined through trial and error.
- full scale installations using dual fluid atomization will require arrays of atomizers with common sources of air and water. This arrangement will require good part-to-part consistency in hydraulic and droplet size characteristics so that the performance of each atomizer in the array is the same.
- the abrasiveness of slurries will require that these atomizers be designed with wear resistant materials (ceramics for example) to insure an acceptable lifetime.

RECOMMENDATIONS

- Although commercially available atomizers can provide a sufficiently small droplet size distribution for DSI and DSD the compressed air requirements are high. Reported air to water flow ratios range from about 0.3 to 0.8. This represents an extremely high operating cost associated with these technologies. Efforts should be directed toward improving the efficiency of atomization. Likewise, techniques that would relax the need for the small droplet sizes currently required should be pursued.
- The interaction between the flue gas velocity, atomizer capacity, spray angle, and the arrangement of atomizers in an array is not well understood. All past and on-going DSI and DSD projects have used a trial and error approach to optimizing these parameters. The use of many small capacity atomizers are understood to be an advantage because they provide less disturbance to the gas flow. Research should be directed toward quantifying the interaction of these parameters. It is probable that the math models under development may be able to characterize these interactions. However, these models will need to be validated and currently this data is not available.

DISCUSSION

Information regarding atomizer specifications has generally been obtained on an empirical basis. Based on a review of the available literature on the experiences of in-duct injection, several of the aspects of atomizers that tended to recur in all of the test programs were identified. The following text provides a description of atomizer characteristics that are important based on available information.

1) Atomizer Droplet Size

For successful duct injection of water or slurry, the atomizers must be capable of providing a spray in which the largest droplets formed in the atomization process are sufficiently small to completely evaporate in the available residence time. In every pilot scale duct injection program to date, the droplet size of the atomized sprays was recognized as a key parameter for achieving success. Yet it is only the most recent pilot scale programs [1,2,3,4] that have provided quantitative data on the size distribution provided by atomizers. In many programs, [5,6] the atomizers or atomizer positioning was selected based on trial and error. The deposition associated with a given atomizer or geometry was monitored over a short period of time in order to determine the best design. Bechtel (CZD) and B&W (LIMB and E-SOX) test programs included atomizer testing for droplet size as part of the overall program.

Prior to installation of the atomizers at the Seward Station, Bechtel had the candidate atomizer tested for droplet size and determined that the droplet sizes were too large to provide evaporation in the 35 foot, 1/2 second residence time available. Bechtel subsequently modified the atomizer to increase air flow and limited the liquid throughput to insure an acceptable degree of atomization. With these precautions, Bechtel operated the Seward station continuously for 1 month with little deposition attributed to "normal" atomization.

B&W tested a variety of dual fluid atomizers of different design and from different vendors to determine the atomizer that provided the smallest droplet size distribution at a specified air-to-water flow ratio. The B&W I-Jet atomizer was selected as the atomizer for LIMB Humidification. The LIMB Humidifier (operated at 100 MW) has operated at a 20 F approach temperature without significant deposition.

Bechtel (CZD) and B&W (LIMB) both indicate that for successful in-duct atomization of liquids or slurries spray Sauter Mean Diameters of 20 to 30 micrometers are required. Additionally, the amount of spray mass above 100 microns must be small so that complete dryout of is attained. In all cases, the required Sauter Mean Diameter and largest acceptable drop size can be estimated based on the gas residence time and the Approach to Saturation temperature.

Commercially available atomizers are capable of providing the required droplet sizes, but the liquid capacities of the atomizers are small (.07 to 2 GPM) and the air-to-water ratios are high (0.3 to 0.8)

2) Atomizer Liquid Capacity

The liquid capacity required for any specific duct-injection application is easily determined based on the flue gas flow rate and temperature and the desired approach to saturation temperature. However, the optimum number of atomizers to provide the total liquid flow rate is not well understood at this time.

The number of atomizers employed in humidification and spray

drying has ranged from 1 to over 100. The GE IDS [7] process used a single mechanical rotary atomizer in ducts with a cross section of about 4ft X 4ft. Bechtel's CZD process at the Campbell station (operated at about 3 MW) used a single dual fluid atomizer in a 3 foot diameter duct. At the larger Seward installation (operated at about 35 MW), Bechtel utilized a 9 atomizer array.

Dravo Lime Companies HALT demonstration used arrays of 5 and 8 dual fluid atomizers. Additional Multi-Nozzle Humidification Tests conducted at the same facility by Consolidated Coal Company used atomizer array of from 9 to 46 atomizers, each with a capacity of 0.067 GPM. B&W's LIMB program utilizes 100 dual fluid atomizers with a capacity of 0.8 GPM

The results of past and on-going projects indicates that multiple small atomizers perform better than a single larger atomizer even when the droplet size distribution is the same for both cases. However, all of the programs have used a trial and error approach. At this time there is no methodology for specifying either the atomizer capacity or the geometry of an atomizer array.

3) Droplet Trajectory or Spray Angle

Atomizers of different designs or of different types (mechanical vs dual fluid) provide sprays with widely varying droplet trajectory. Droplet trajectory influences atomizer performance because the initial direction of the high velocity spray can result in direct impingement of liquid on internal surfaces. In contrast, it is imperative that the spray adequately mix with the surrounding flue gas so that complete drying of the droplets can occur in the limited time available.

The extreme of spray trajectory is represented by the General Electric IDS process. This test program used a rotary mechanical atomizer in which the initial trajectory is a disk with an included angle of 180 F. Using this approach and with the addition of airfoils to direct the gas flow, GE was able to reach a liquid flow about 1/2 of the design flow before deposition and wall wetting became a severe problem. GE attributed this problem to the small duct size associated with the scale they were testing. However, better performance has been achieved in tests of a similar scale but with atomizers that provide a spray trajectory with a smaller included angle.

The test programs utilizing atomizers with a single discharge hole or with multiple holes oriented with a small included angle have achieved the highest success in operating pilot plants. Bechtel's nozzle testing at the Seward station eliminated several nozzle designs from consideration because of "wide spray angles".

A lower limit in spray angle is probably about 12 to 14 degrees which represents the expansion of a free jet. The upper limit on spray angle has not been defined, but correlations exist in the open literature for relating droplet momentum and angle to droplet trajectory when injected into co-flowing gas of a known velocity.

As with liquid capacity, there is not a technique for specifying the spray angle of atomizers.

4) Atomizer hydraulic characteristics

For successful DSI and DSD, uniform profiles of temperature and velocity across the duct cross-section have been shown to be important. Likewise, the mass flux of injected water or slurry must be uniform across the duct cross-section. A poor distribution of temperature, gas velocity, liquid mass flux (as droplets) will result in localized regions of saturated gas that can lead to wetting and deposition. Additionally, the droplet size performance of each of the atomizers on an array should be identical.

In small scale tests which involve 1 to 10 atomizers it is feasible to monitor the flows of air and liquid to each individual atomizer. However, with larger arrays of atomizers this approach is no longer reasonable. Rather, multiple atomizers are manifolded and controlled by a single source of air and liquid. With this geometry it is imperative that each of the atomizers in a group perform identically. Otherwise, with each atomizer supplied with a common liquid pressure, the liquid flow to each atomizer could be substantially different.

Before Bechtel installed the 9 atomizer array at the Seward station the atomizers were tested for droplet size and for the pressure flow characteristics. After installation, each of the nine atomizers were controlled individually. At B&W's LIMB Humidification test, five atomizers are grouped and can be controlled as a unit. However during normal operation, all 100 of the atomizers are controlled as a single unit.

Arrays of atomizers for DSI or DSD will require very good part-to-part repeatability and consistency. Also the sensitivity of the atomizers (i.e. variation in flow rate with pressure) must be sufficiently low so that normal process variation does not result in liquid flow mal-distribution across the duct.

5) Atomizer Wear And Pluggage

There are several concerns associated with, but not limited to, the atomization of slurries. Most of the concerns were identified in Bechtel's report on CZD. During the nozzle testing at the Campbell Station, atomizer pluggage was a common cause for failure of an atomizer to perform properly. Additionally, after only relatively short duration testing atomizer wear was likewise cited as a problem.

For these tests the atomizers used were fabricated of steel and did not have wear resistant ceramic components that would increase the wear life of the atomizers. It is possible that an increased ruggedness of design would also enhance the lifetime of the atomizer. B&W is currently investigating the use of wear resistant materials for duct injection and dry scrubber atomizers.

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STATUS REPORT
DRY SORBENT INJECTOR DESIGN
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

In the Dry Sorbent Injection (DSI) flue gas desulfurization process, the main components of the system are humidification of the flue gas and injection of dry sorbent. The humidification system is discussed in the Status Report on Humidification and Slurry Nozzle Specifications. This report covers the design of the dry lime injection system.

2.0 CONCLUSIONS

1. The aim of DSI is to disperse the dry sorbent, usually hydrated lime, in such a manner as to obtain rapid mixing, uniform distribution, and maximum utilization of the sorbent. Injector design for the DSI system is dependent on the nature of the sorbent, duct size, coal sulfur, type of sorbent injector utilized, and location of the humidification injection system in relation to the sorbent injection system.
2. The injection location should be in a straight duct section and as far upstream from the transition into the ESP as possible.
3. When sorbents are injected downstream of humidification water, acid (SO_3) induced corrosion of ductwork between the humidification water injection point and sorbent injection point is possible. Wet fly ash buildups are also possible on the upstream edge of the sorbent injectors and on the ductwork between humidification and sorbent injection.
4. From a process performance standpoint, sorbent injection upstream of, or in the same plane as, the humidification water nozzles is more beneficial than downstream sorbent injection.

5. In recycle applications, a combined fresh sorbent and recycled solids configuration may offer the most uniform dispersion, but would not offer as much flexibility and reliability as separate injection systems.

3.0 RECOMMENDATIONS

1. Further studies into the relationship between the location of the sorbent injectors and the humidification system need to be conducted on a large enough scale so as to be able to determine a reasonable design for a commercial scale installation.
2. Since very little emphasis has been placed on sorbent injector design in previous research efforts, it is recommended that a proven three-dimensional, two-phase modeling program be used to evaluate injector designs. EER used this type of model to predict the performance of various sorbent injection schemes for the Brayton Point study.
3. Since sorbent mixing and distribution across the duct cross section will vary with the injected solids loading and with boiler load (due to gas velocity), the turndown capability of injector systems should be evaluated during the course of the DOE program.
4. The fresh sorbent feed system should be separate from the recycle injection system to preserve flexibility and reliability.
5. Unless evidence is presented to the contrary, sorbent injection upstream of, or in the same plane as, the humidification water nozzles should be the first choice.

4.0 DISCUSSION

The aim of Dry Sorbent Injection (DSI) is to disperse the dry sorbent, usually hydrated lime, in such a manner as to obtain rapid mixing, uniform distribution, and maximum utilization of the sorbent. Sorbents can be injected either upstream or downstream of the humidification nozzle array. This configuration is site specific and is dependent on a variety of plant and process parameters including the type of sorbent used, duct dimensions, coal sulfur, and type of sorbent injector utilized.

The location of the sorbent injectors within the existing ductwork is critical for two major reasons. First, adequate retention time is required for SO_2 removal by the hydrate before the gas enters the ESP. Second, proper mixing and distribution of the sorbent across the duct cross section is required to promote optimum SO_2 removal and minimize wall deposition. The sorbent injection point should be in a straight duct section for proper mixing and distribution, and it should be upstream of the ESP as far as possible to maximize retention time.

Of critical importance is the turndown capability of the sorbent injection systems. As flue gas volume fluctuates, the sorbent injection distribution will change, and it must be capable of "following" flue gas variations, or material buildups and/or reduction in SO_2 removal will likely result. Very little testing or modeling has been done in this area. Possible turndown strategies are keeping conveying air pressure and volume constant and simply varying the sorbent feed into it, using variable conveying air volumes, and/or removing sorbent injectors from service.

In some early pilot-scale projects, sorbents were typically injected downstream of humidification. Attempts to inject sorbent upstream of the humidification water resulted in rapid and severe plugging of the duct with wet solids (2). Wall wetting due to the small (17-inch diameter) test duct was thought to be responsible. Operation with downstream

sorbent injection, however, resulted in significant buildups of fly ash on duct walls just downstream of the humidifiers and on the upstream edge of the sorbent injectors.

When EPRI tested the HYPAS system at its High Sulfur Test Center (HSTC), the humidification nozzles were again placed upstream of the sorbent injection point (4). The flue gas at the HSTC contained high levels of SO_3 , which caused severe corrosion to the sorbent injection nozzles and ductwork immediately downstream of the humidifiers. The corrosion in the HYPAS process may be more severe than a normal DSI application because, in HYPAS, the fly ash is removed prior to humidification. The alkaline components of fly ash may neutralize some of the flue gas SO_3 in a typical DSI retrofit.

Research suggests that, if sorbent particles come in direct contact with, and are encapsulated by, water droplets sprayed into the duct downstream of the sorbent injection point (scavenging), the sorbent utilization is significantly higher (6). It is believed that wall wetting deposition problems, like those encountered in small pilot-scale ducts, will not be as severe in the full-scale duct since the humidification nozzles can be adequately spaced. In addition, corrosion potential is reduced because, with upstream sorbent injection, the alkaline sorbent will remove most of the SO_3 before it contacts the humidification section.

Therefore, in more recent DSI projects, including Dravo's HALT process pilot plant and the full-scale Coolside duct injection demonstration at Ohio Edison's Edgewater Station, sorbents were injected upstream of, or in the same plane as, the humidification water (1,8). As expected, duct corrosion problems in these installations were minimal. There were some problems with material buildup of the humidification water airfoils at Edgewater. This was minimized by moving the sorbent injection location to the same plane as the water sprays. As expected, from a process performance standpoint, upstream hydrate injection was decidedly more beneficial than downstream injection (1).

The dry sorbent injector designs considered to date fall in three basic categories:

- 1) Cross Duct Lances
- 2) Cross Flow (Wall) Injectors
- 3) Parallel Flow Injectors

4.1 Cross Duct Lances

The cross duct lances consist of several tubes that extend the full width (or height) of the flue duct. There are holes in the tubes that disperse the sorbent parallel to the gas stream (reference Figure 1).

This system was used in a full-scale demonstration program at the City of Colorado Springs, R.D. Nixon Plant for EPRI in 1985-1986, using dry sodium as a reagent (3). The lances were installed in a duct that handled the flue gas from half of the 223 MW Unit 1. The application would be similar for dry hydrated lime except that there was no accompanying humidification in the sodium tests.

The system consisted of three vertical 6-inch pipes connected to a 12-inch header above the roof of the horizontal duct. Each vertical pipe had seven 3-inch diameter injection nozzles (holes) spaced along the vertical axis through the duct. The nozzles were pointed downstream, concurrent with the direction of flue gas flow.

Due to the geometry of the injection system, the vertical pipes tended to fill from the bottom with settled reagent. As the level increased, the lower injection nozzles along the pipe were obscured and rendered inoperative. This in turn meant that reagent was only being injected near the top of the duct.

While regularly scheduled cleaning of the vertical pipes is one way of dealing with the problem, redesign of the pipes for permanent installation would be required. A solution might be to have the

injector pipes in a horizontal rather than vertical configuration. Another option to be considered would be to taper the pipe in order to maintain a more uniform velocity as the sorbent is injected through the nozzles.

Cross duct lances would give good dispersion with low conveying pressure. The main concerns with this type injector are that the lances cause a significant obstruction to the gas flow and that frequent pluggage of the pipes is possible.

4.2 Cross Flow (Wall) Injectors

A study was conducted in 1987 to determine the feasibility of injecting dry sorbent into 1/2 (125 MW) of the New England Power Service Company's Brayton Point Unit 1 (7). The approach considered was the utilization of duct side wall injection jets. The duct was nominally 11 ft. high by 12 ft. wide. The sorbent injection was computer modeled, but actual sorbent injection tests were never performed.

Three possible configurations of the wall injection system were modeled: single wall (or roof), opposed wall, and staggered opposed wall (reference Figure 2). In both the single wall and staggered opposed configurations, the design approach was for individual jets to inject sorbent such that it would penetrate the full distance across the duct. In the opposed wall configuration, individual jets were required to treat only half the duct width. For each configuration, there were a large number of possible combinations of jet number, jet diameter, and jet velocity that could be applied. Systems comprising from 2 to 30 jets were modeled for both fresh sorbent and recycle streams by computation of the jet penetration characteristics and an evaluation of the overall mixing patterns.

For cross flow (wall) injection of sorbent, the major difficulty is generally one of achieving adequate penetration of sorbent into the flue gas stream. For example, a system with a sorbent flow of 2.5 tons/hr and a 0.72-inch diameter sorbent jet with a velocity of 420 ft./sec would penetrate approximately 5.5 ft across the duct. Increased penetration could be achieved by either using a larger jet diameter at the same velocity or by increasing velocity. For a fixed air flow through the jet system, both approaches lead to a reduced number of jets and a corresponding increase in jet spacing and reduced coverage of the flow in the lateral direction. The design trade-offs are between penetration and lateral distribution of the jet. The design problem is, however, limited by the available transport air capacity and by the supply pressure of the blowers. In order to identify the maximum tolerable velocities at the injection point, pressure drop calculations should be made for the fresh sorbent and recycle streams based upon estimates for the transport pipe configuration and splitter designs.

The computer modeling suggested that a combined fresh sorbent/recycle feed resulted in the best distribution within the duct. However, combining the recycle in with the fresh sorbent would normally not be done so as to preserve operation if the recycle system failed. If, for some reason, the recycle system is not available, the fresh lime injection system must still be operational.

4.3 Parallel Flow Injectors

A modified version of the cross duct lances is used at the Coolside injection demonstration at Edgewater (5). The arrangement used there is a series of single point parallel injectors. Nine 2-inch pipes configured in a 3 x 3 matrix are installed across the duct cross section for fresh sorbent injection, and nine identical pipes are installed for recycle material injection. The pipes enter from the top of the duct and are of varying length. Each pipe ends in an elbow that turns the stream so that it is injected parallel to the gas flow

(Figure 3). Diffusers have been used at the outlet of the nozzle to disperse the sorbent. One potential problem with this design is that the threaded rod supporting the diffuser may become eroded and make future adjustments or replacement difficult. Recently the diffusers were removed to reduce maintenance problems.

Each recycle nozzle is located about 6 inches to 1 foot away from its corresponding fresh sorbent nozzle. The current sorbent injection velocity is 15-20 ft./sec. This is considered too low and plans are underway to increase the velocity to 40-80 ft./sec.

The present arrangement has the sorbent injection system in the same plane as the humidification system. The injector arrangement has resulted in continuous operation for 1-2 weeks at a time before material buildup necessitates shutdown and cleanout. The humidification nozzle headers are in the form of an airfoil to reduce build-up on the surfaces.

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System A

System B

Figure 1. Cross Duct Injection Lance Design (3)

a) Single wall

b) Opposed wall

c) Staggered Opposed

Figure 2. Possible Sorbent Injection Configurations for Wall Injectors (7)

Figure3. Edgewater Coolside Sorbent Injectors (5)

MATERIAL DEPOSITION ON DUCT WALLS/TURNING VANES

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MATERIAL DEPOSITION ON DUCT WALLS/TURNING VANES

I. INTRODUCTION/STATEMENT OF TOPIC

Every duct injection project to date has had to deal with the problem of material deposition on duct walls or duct internals. Deposition occurs by several mechanisms, depending on the specific technology being applied. The two main mechanisms are direct impingement of slurry or water sprays on duct surfaces, and incomplete evaporation of droplets that impact with duct walls or other internals. Deposition has ranged from a thin coating to thick layers that choke off almost the entire cross-section of the duct. Material deposition is also a major concern of utilities because it can lead to boiler down time and increased maintenance costs. Any successful commercial application of duct injection technology must eliminate material deposition or limit it to manageable levels.

Material deposition is a more challenging problem for duct injection than with conventional spray drying systems. Conventional systems use large reactor vessels with ample wall clearances and residence time, and elaborate flow straightening devices to assure symmetric gas flow. Duct injection, on the other hand, is confined to the existing duct work between the air heater and particulate collection device. Most power plant duct work is rectangular, contains several turns, and lacks flow straightening devices. Rarely does it contain the long, square, straight sections needed to eliminate material deposition. Therefore, the sorbent and water injection scheme will be heavily dependent on the particular duct work layout and geometry. Atomizer capacity, performance, and arrangement will be critical in eliminating material deposition while maximizing SO₂ capture.

II. CONCLUSIONS

A. Summary of Literature Review and Ongoing Programs

- Both material deposition and SO₂ removal increase with decreasing approach to saturation temperature (T_{AS}).
- Atomizer type, capacity, spray angle, wall clearance, wear characteristics, air-to-water ratio, and drop size distribution are critical.
- Deposition on the atomizer tip reduces spray quality and can cause dripping. It must be reduced, eliminated, or removed by periodic cleaning.
- Poor inlet gas velocity profiles lead to material deposition.
- Poor inlet gas temperature profiles lead to material deposition.
- High gas velocities (> 35 fps) are needed to prevent solids dropout. High gas velocities also reduce residence time.

- Duct internals (e.g., support bracing, turning vanes, thermocouples, etc.) are possible sites for material deposition. Droplets must be dry before collision.
- At least 1 second of residence time is important.
- Atomizer plume interactions do not increase drop size or decrease performance.
- Duct skin temperatures less than 6°F above T_{as} indicate that wall wetting is occurring. Skin thermocouples are an effective means of monitoring wall wetting.
- Vendor quality control for atomizers is not adequate. An independent verification of vendor claims is advisable.
- Sauter mean diameters in the 20 to 30 μ range are required, and droplets larger than 100 μ cannot be tolerated.
- Mechanical devices, such as the DIDS, can be effective in preventing material deposition caused by unevaporated droplets in short ducts.
- Wall deposits are usually confined to small areas within the duct.

B. Evaluation Summary of Existing Designs

In-duct SO₂ removal processes involve the introduction of a sorbent and water into the flue gas to achieve SO₂ capture. Several variations of this technology are possible based on how and where the sorbent is injected. All processes suffer material deposition of some kind. To date, most research has been directed toward eliminating material deposition by atomizer design and arrangement. When deposition could not be avoided at low approaches, flow rate was reduced or run time decreased. Very little research has focused on devices or methods of mechanically cleaning or reducing deposits or selectively capturing large, unevaporated droplets.

A general description of the most common in-duct technologies is given below, along with the material deposition problems encountered and the methods used to eliminate them.

- In-duct dry scrubbing - This method combines the water and sorbent as a slurry that can be introduced into the flue gas by rotary or dual-fluid atomizers. Slurry atomization increases atomizer erosion that can lead to poor atomization quality. To avoid erosion, atomizers can be made from wear-resistant ceramic materials. Material deposition resulting from the direct impingement of slurry droplets is more difficult to remove than that caused by water impingement. To avoid wall wetting, researchers have reduced flow rate and run time. Material deposition is usually cleaned by hand during outages.

- Sorbent injection followed by humidification - This method involves dry injection of sorbent in the boiler, economizer, or after the air heater followed by water humidification. Material deposits have been observed on tube surfaces, atomizer lances, duct walls, and duct internals. Cleaning has consisted mostly of soot blowing, air lancing, and manual cleaning. Researchers have also reduced water flow rate and test duration to control or avoid deposition.
- Humidification followed by sorbent injection - This method is similar to the one above except humidification occurs first. Material deposition directly downstream of the atomizers is reduced because of the reduced dust loading. However, material deposition on the lime injection nozzles increases. This method also suffers from duct corrosion caused by acid condensation in the absence of sorbent particles. Cleaning methods have involved air lancing and manual cleaning.

E-SO_x is the only project that has tested a method to eliminate material deposition problems by confining deposition to an area that can easily be cleaned. E-SO_x employs the droplet impingement device (DIDS) that consists of two staggered rows of heated pipe installed at the end of the reaction chamber. Slurry droplets that do not evaporate are forced to impact the DIDS. The deposits that form on the DIDS are removed by rapping and fall into the existing ESP hopper.

C. Identification of "Gaps" in the Data Base

Material deposition is recognized as a serious shortcoming in all duct injection technologies. There are two schools of thought in dealing with this problem. One is to eliminate the formation of material deposits by innovative designs of the atomizer and atomizer arrays. The second is to admit that some material deposition is inevitable and to design systems for dealing with it. To date, the first school of thought has dominated research, but has been largely unsuccessful. This has created a large gap in research to selectively control and handle material deposition. The following list contains methods that have been used in the spray drying and other industries to deal with material deposition.

1. Automatic mechanical removal such as rapping, sonic horns, DIDS, soot blowing, air lancing, coatings, and hoppers - Research has shown that material deposition is usually confined to a small area within the duct. Future research could take advantage of this fact by installing appropriate solids handling equipment only in the areas where deposition can be expected. The DIDS device is one example of how deposition can be controlled in short duct sections.
2. Shielding devices to prevent deposition on the atomizer tip - Deposition on the atomizer tip has been identified as a cause for reduced atomizer performance that can lead to material deposition within the duct. More research is needed to develop methods to prevent deposition from occurring or automatically removing the deposits that form.

3. **Atomizer Development** - Most research has used commercially available atomizers for slurry and water humidification. These atomizers are often not suited for the abrasive, harsh environments of in-duct scrubbing. Further research is needed in the area of wear-resistant materials, rugged designs, better atomization at lower air requirements, and methods to prevent deposition on the atomizer tip. B&W is the only company that has conducted research to design an atomizer specifically for duct injection processes.

III. RECOMMENDATIONS

The design of the atomizer and atomizer array is critical in preventing or reducing material deposition. The atomizer must produce a spray with a 20 to 30 μ Sauter mean diameter and have no droplets greater than 100 μ . Wall clearances of at least 24 inches are recommended for atomizers with capacities greater than 1 gpm.

Skin thermocouples should be used to monitor the temperature of inside walls of the duct. Alarms should be placed on any temperature that approaches the adiabatic saturation temperature by less than 10°F.

Automatic mechanical equipment for the removal and disposal of material deposition should be investigated. These include, but are not limited to rappers, sonic horns, DIDS-like devices, soot blowers, air lances, duct coatings, and hoppers.

Atomizer deposition has been identified as one cause for reduced atomization quality and wall wetting. Therefore, shielding devices to prevent deposition on the atomizer tip should be investigated. Commercial atomizers usually do not come equipped with a device to prevent deposition and buildup on the atomizer tip. These atomizers should not be considered for use unless they can be fit into a particulate shielding device.

More research is needed to develop an atomizer specifically for use in duct injection processes. The research should be focused on reducing air requirements, increasing capacity and durability, decreasing erosion, decreasing drop size, and eliminating solids deposition.

IV. DISCUSSION

A. Literature Review

1. General Electric In-Duct Scrubbing (IDS)^{1,2,3}

The General Electric IDS process involves the injection of slaked lime slurry into the duct work using a rotary atomizer. The IDS process was tested in the 12 MW (50,000 acfm) pilot plant at Ohio Edison's Muskingum Power Station in Beverly, Ohio. Slurry was injected into the gas at 330°F and cooled to 165 to 190°F (i.e., approach of 40 to 65°F). Two different duct configurations were tested, a 50-inch diameter vertical duct and a 40x50-inch horizontal duct. In-duct SO₂ removals of 50% were obtained at a Ca/S stoichiometric ratio of 1.5 and an approach temperature of 40 to 55°F.

The major limitation on the performance of the IDS process was material deposition on the duct walls. To avoid severe wall wetting, the slurry flow had to be maintained to 3.8 gpm or one-half of its design value. Test runs were limited to 2 or 3 hours. Poor gas flow distribution, small duct size, and high slurry velocities in the direction of the duct walls due to the nature of rotary atomization were cited as the major causes of material deposition. Wall wetting in the horizontal duct was observed as far as 30 feet from the atomizer.

2. Bechtel Confined Zone Dispersion (CZD)^{1,2,4,5}

The Bechtel CZD process involves the injection of slaked lime slurry into the duct work using dual-fluid atomizers. The CZD process was tested in the 7 MW (21,000 acfm) pilot plant at Consumer Power Company's J. H. Campbell Power Plant. Slurry was injected into the gas at 300°F and cooled to 160°F (i.e., approach of 35°F). The duct for this test measured 3 feet in diameter and 130 feet long. In-duct SO₂ removals of 50% were obtained at a Ca/S stoichiometric ratio of 1.1 and an approach temperature 35°F.

The major limitation on the performance of the CZD process at 7 MW was material deposition on the duct walls. To avoid severe wall wetting, slurry was injected at two locations 40 feet apart. Slurry flow was maintained at 1.5 gpm in the upstream atomizer and 1.2 gpm in the downstream atomizer. Test runs were limited to 3 or 4 hours, at which time the duct was inspected and cleaned. Material deposition was reported to be progressive. That is, wall deposits led to greater impingement and accelerated growth.

Bechtel studied different aspects of atomization in an effort to reduce material deposition. Parameters such as atomizer type and alignment, injection rate, and gas velocity were varied to discover their effect on wall wetting. The result was to lower gas velocity to increase residence time and to use an atomizer that produced very fine droplets. Atomizer erosion, low gas velocity, load swings, and duct geometry were cited as the major causes of material deposition during the pilot study.

Bechtel continued testing of the CZD process on a 70 MW scale (690,000 acfm) at Pennsylvania Electric's Seward Station. Slurry was injected into the gas at 290°F and cooled to 170°F (i.e., approach of 45°F) using an array of 9 dual-fluid atomizers. The duct for this test measured 8x11x35 feet. In-duct SO₂ removals of up to 30% were obtained at a Ca/S stoichiometric ratio of 1.34 using pressure-hydrated dolomitic lime and an approach temperature of 35°F.

The major limitation on the performance of the CZD process at 70 MW was material deposition on turning vanes located 35 feet from the atomization plane. To avoid severe deposition, slurry flows were reduced and the operating air-to-water ratio of the atomizer was increased until deposition was minimized. Two months of parametric testing and one month of continuous testing were conducted. Very little deposition was observed in the duct due to the low slurry feed rate. Atomizer erosion, load swings, and insufficient residence time were cited as the major causes of material deposition during the 70 MW tests.

3. Dravo Hydrate Addition at Low Temperature (HALT)^{1,2,6}

The Dravo Hydrate Addition at Low Temperature (HALT) process involves the dry injection of hydrated lime followed by flue gas humidification using dual-fluid atomizers. The IDS process was tested in the 5 MW (20,000 acfm) pilot plant at the Toronto Power Station. Hydrated lime was injected into the gas between 300 and 380°F. The gas was then cooled by water injection to a 20°F approach temperature. Several different atomizer designs and capacities were tested prior to hydrate injection. The lowest approach, without wall wetting, was achieved with an array of 25 or 46 Spraying Systems J12 atomizers rated at 0.067 gpm and operated at 0.7-0.8 lb_{air}/lb_{water}. The test duct measured 31"x31"x65'. In-duct SO₂ removals of 31% were obtained at a Ca/S stoichiometric ratio of 1.74 and an approach temperature of 20°F.

The major limitation on the performance of the HALT process was the small size of the test duct and high inlet temperatures. To correct the problem of high inlet temperatures, two-stage humidification was used. The first stage of atomizers was used to control the inlet temperature. This was followed by dry hydrate injection and a second stage of humidifiers to cool the flue gas to low approaches. To avoid severe wall wetting, an extensive humidification pretest was conducted. The pretest screened several different atomizers and arrays. Arrays containing 9, 13, 16, 25, and 46 atomizers were tested. The lowest approach, 20°F, was obtained with the 25 and 46 atomizer arrays. Testing with hydrate addition was then conducted around the clock for one month with only minimal material deposition on the duct walls.

4. B&W E-SO_x^{1,7}

The Babcock & Wilcox E-SO_x process involves hydrated lime slurry injection into the first field of a modified electrostatic precipitator using dual-fluid atomizers. The E-SO_x process was tested in the 5 MW (16,000 acfm) pilot plant at Ohio Edison's R. E. Burger Station. Slurry was injected into the flue gas at 275°F, which was cooled to a 40°F approach temperature. Atomizer arrays containing six B&W MK-12 (0.8 gpm) and two B&W MK-4 (1.8 gpm) I-Jet atomizers were tested. The best results were obtained with MK-4 atomizers operated at 0.4 lb_{air}/lb_{water}. The test duct measured 6x14x14.5 feet. SO₂ removals of 60% were obtained at a Ca/S stoichiometric ratio of 1.4 and an approach temperature of 40°F.

The major limitation on the performance of the E-SO_x process was the short residence time available in the 14.5 foot long test chamber. At the beginning of the test, this limited runs to 4-5 hours before the walls had to be cleaned of a 2-3 inch deposit. This was corrected by changing atomizer array and reducing slurry flow rate. This allowed 400 hours of operation at a 40°F approach with no significant material deposition.

The E-SO_x pilot also used a Droplet Impingement Device (DIDS) at the end of the test chamber. The function of the DIDS is to collect the large, unevaporated slurry droplets before they enter the first field of the ESP. The DIDS operated well in that no material deposition occurred on the downstream stream, and material deposition on the DIDS was easily cleaned by rapping.

5. Consol Coolside^{1,8}

The Consolidated Coal Company Coolside process involves the dry injection of hydrated lime followed by flue gas humidification using dual-fluid atomizers. It is unique in that a sodium-based additive is added to the humidification water to promote additional SO₂ removal. The Coolside process was tested in a 1 MW (3000 acfm) pilot plant at Martinsville, VA, and is currently being tested in a 105 MW demonstration at Ohio Edison's Edgewater Station.

In the pilot study, hydrated lime was injected into the gas at 300°F. The gas was then cooled by water injection to a 20-25°F approach temperature using a single dual-fluid atomizer. SO₂ removals of 80% and sorbent utilization near 40% were obtained for both in-duct hydrate injection and boiler limestone injection at a Ca/S stoichiometry of 2 and a NaOH/Ca(OH)₂ weight ratio of 0.1. Sodium hydroxide (NaOH) was the additive used in the pilot test.

Material deposition consisted only of loose, dry material deposited on the floor of the humidifier due to particulate dropout at the low duct velocity (5 fps). No wall wetting occurred in the humidifier because of the large cross-section (about 42-inch diameter). No significant material deposition was observed in the ESP.

In the 105 MW Coolside Demonstration, hydrated lime is injected into the gas at 300°F. The gas is cooled by water injection to a 20°F approach temperature using an array of 100 dual-fluid atomizers. SO₂ removal and sorbent utilization have been comparable to the pilot results. Sodium hydroxide (NaOH) is used as an additive to the humidification water. The humidifier has a 14'7"x14'7" cross-section and is 63 feet long. The atomizers are B&W MK-12 I-Jets rated at 0.8 gpm and operated at 0.3 lb_{air}/lb_{water}.

Material deposition is not significant above a 20°F approach temperature. Significant deposits of loose, dry material have also been observed on the floor of the humidifier due to particulate dropout at the low duct velocity (27 fps). Loose, dry deposits have also been observed on the leading edges and tops of the humidifier lances caused by the cohesive properties of the hydrated lime injected upstream. The deposits on the lances and floor of the duct have been controlled by air lancing. The deposits on the turning vanes require shutdown and manual cleaning.

B. Review of Similar Applications

1. Babcock & Wilcox Limestone Injection/Multistage Burners (LIMB)^{9,10,11}

The Babcock & Wilcox LIMB process involves boiler sorbent injection and the use of low-NO_x burners to simultaneously reduce NO_x and SO₂ emissions. LIMB is currently being demonstrated at Ohio Edison's 105 MW Edgewater Station in Lorain, Ohio. SO₂ removals greater than 50% have been obtained at Ca/S stoichiometries near 2 using hydrated lime as the sorbent.

The similarity between LIMB and duct injection processes is that LIMB utilizes flue gas humidification downstream of the air heater to improve ESP performance and to increase SO₂ removal. Humidification takes place in a new section of duct work installed to avoid unnecessary boiler down time due to

upsets during testing. The duct measures 14'7"x14'7" and is 63 feet long. It contains an array of 110 B&W MK-12 I-Jet dual-fluid atomizers rated at 0.8 gpm. Humidification to a 20°F approach temperature has been achieved with no significant wall wetting or material deposition because of sufficient wall-to-atomizer clearance (27 inches). Dry, loose material has been observed on the floor of the duct because of settling at low gas velocity.

The design of the LIMB humidifier was developed during two research projects at B&W's Alliance Research Center. A 3x3 Operability Test involved humidification in a 3x3x40 foot slip stream using full-scale atomizers. The results of this test indicated that full-scale atomizers require at least 24 inches of wall clearance to avoid material deposition. The best performance that could be achieved without deposition was a 68°F approach to saturation. The test also showed the importance of a good inlet gas flow distribution and identified that material deposition on the atomizer tip leads to poor atomization and must be avoided.

The 6x6 Humidification Validation Test involved humidifying heated air in a 6x6x80 foot duct using an array of full-scale atomizers. Two arrays were tested, a 3x3 array of 1.8 gpm atomizers and a 4x4 array of 0.8 gpm atomizers. The best results were obtained with the 4x4 that achieved a 20°F approach temperature with no wall wetting and greater than 99% evaporation at the exit of the duct. The test demonstrated the importance of wall clearance, atomization quality, and mixing. It also showed that commercial in-duct humidification to low approach temperatures is feasible.

2. Dry Scrubbing

Several companies offer utility-scale dry scrubbers. The two most common designs are the vertical down-flow scrubber that uses one large rotary atomizer, and the horizontal chamber that uses an array of dual-fluid atomizers. Dry scrubber vessels differ from in-duct processes in that they are large, separate units designed with large wall clearances, ample residence time, and provisions, such as hoppers, for the removal of solids deposits. However, most units still suffer from severe material deposition during upsets. Material deposition in these units results from the direct impingement of unevaporated slurry droplets. Deposits are often several feet thick and must be dried before manual removal. Dual-fluid atomizers also suffer from a gradual buildup of material on the atomizer surfaces that can lead to reduced atomization quality and dripping. Commercial dry scrubbers demonstrate the importance of wall clearance, flow distribution, and atomization quality and demonstrate the need for close control and provisions for solids handling after upsets.

3. EPRI Hybrid Pollution Abatement System (HYPAS)^{1,12,13}

The EPRI HYPAS process involves flue gas humidification downstream of the existing particulate collector, followed by hydrated lime injection, followed by a new baghouse. The process has been investigated in a 2000 acfm pilot at Public Service of Colorado's Arapahoe Station. Results have shown 50-70% SO₂ removal across the entire system at Ca/S stoichiometries of 2.0 and low approach temperatures. Further tests are planned at EPRI's high sulfur test center.

Material deposition is minimized because of the absence of fly ash, because the sorbent is injected downstream of humidification, and because humidification takes place in new duct work designed specifically for humidification. Although HYPAS is able to achieve good SO₂ removal without material deposition, it is not a retrofit technology in that it requires new duct work and a baghouse. HYPAS testing has also demonstrated that corrosion of the duct walls is a severe problem for processes that humidify before sorbent injection. Corrosion results when the flue gas is cooled below the acid dew point and acid condenses on the duct walls. It does not occur in processes that inject sorbent before humidification because the sorbent absorbs the acid.

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CORROSION OF MATERIALS IN FLUE GAS PATH

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CORROSION OF MATERIALS IN FLUE GAS PATH

INTRODUCTION

Introduction - Statement of Topic

This is a review of the operative back-end corrosion processes of a coal-fired steam generator. A brief review of operating experience and corrosion problems in dry scrubbers is also presented. A review of the corrosion problems expected in duct injection sites/dry scrubbers is presented.

Identification of Potential Corrosion Problems

Cold-end condensation is the major corrosion problem in the boiler back-end. Sulfur and chlorine constituents of the combustion gas condense and rapidly corrode exposed metal surfaces. There are many variables that affect the cold-end corrosion. A description of these corrosion processes is presented in subsequent sections of this paper.

Corrosion from Sulfur in Flue Gas[1]

In sulfur-containing fuels, the sulfur is oxidized to sulfur dioxide and then sulfur trioxide as shown below:

The factors that influence the sulfur trioxide content are:[2]

- o sulfur content of the fuel
- o excess air
- o presence of catalysts
- o presence of impurities

Sulfur trioxide (SO₃) readily reacts with water vapor present in a gas process stream to form sulfuric acid. Below the boiling point of sulfuric acid (620°F), most of the SO₃ will combine with the available water to form this acid.

When hot flue gas comes in contact with a metal surface, the liquid in the gas will condense as a film on the cooler metal surface. The temperature at which the sulfuric acid condenses is called the acid dew point which is primarily dependent on the partial pressure of water vapor and SO₃ gas. Thus the percent concentration of the sulfuric acid as a gas is a critical factor in determining the concentration of the sulfuric acid condensing on the metal surface.

Operation Variables Affecting Dew Point Corrosion

Variation in water content of the flue gas depends on several factors, such as air inleakage from the condenser side or leaks in upstream water washing equipment. Other factors that can contribute to an increase in flue gas moisture content are:

- o instrumentation leaks
- o boiler tube leaks
- o forced draft fan ingestion
- o steam coil air preheater leak
- o excessive boiler or air heater soot blowing

At the dew point, liquid condenses as individual drops or a continuous film, depending on the surface tension characteristics of the liquid.

The heat flux through the film is defined by factors such as flow configuration and tube dimensions. The heat flux along with the mass velocity of the gas defines the turbulence of the film. There are a multitude of factors affecting the film formation and localized cold-end corrosion behavior in each specific boiler location. The film formation is also important in maintaining an adequate heat transfer on the cooling surface, since a thick film will have a measurable temperature gradient across its depth.

Variables that Affect Amount of Film Condensation

The variables that effect film condensation are: temperature, velocity of the flue gas, water partial pressure, design factors, and inert substances in the flue gas. The water partial pressure affects the equilibrium concentration of the condensing acid. This equilibrium concentration of the sulfuric acid is directly related to the metal temperature and ranges from 50 to 70% at 82°C (180°F) to 80 to 90% at 149°C (300°F) (Figure 1).

Figure 1. Relationship of concentration of condensed sulfuric acid to temperature of condensing surface (100 ppm SO₃ and 8.3 percent H₂O) [2].

The presence of other ions also affects cold-end corrosion. Chlorides and fluorides from coal can cause severe corrosion to many materials. Chlorides can form hydrochloric acid. Fluorides can form hydrofluoric acid or react with siliceous material fillers and reinforcements used in linings.[3]

It is appropriate to mention secondary factors that modify the condensation-corrosion mechanisms. These factors are:

- o time of exposure
- o material composition
- o presence of corrosion products
- o fuel ash
- o temperature cycling
- o air-in-leakage
- o hydrogen chloride
- o effects of cleaning systems.

To illustrate the time of exposure effects, laboratory work [2] indicates that the initial corrosion rate for mild steel is much higher than long-term corrosion rates (Figure 2).

Figure 2. Cumulative weight loss over 300 hours in laboratory rig (SO_3 26 ppm, excess O_2 8%, coupon temperature 105°C (221°F)) [1].

Another factor is the type and amount of the corrosion product. Corrosion products are different for each alloy. Carbon steel gives a relatively dense thin layer of oxides and sulfides which is not protective; but its presence after a few hours of exposure appears to reduce the rate of corrosion (as illustrated in Figure 2).

The influence of the metal temperature on the rate of both acid deposition and corrosion is shown in Figures 3 and 4. The corrosion rate measured immediately below 150°C (302°F) corresponds to metal temperatures just below the dew point. Figure 5 shows another high corrosion rate which is at the water dew point (~40°C). The water dew point is the temperature below which water condenses; the corresponding acid which condenses is sulfurous acid.

The leakage of air into the back-end of the coal-fired unit significantly increases the corrosion. Air leakage:

- o chills the flue gas increasing the condensation of a more dilute acid
- o locally increases the moisture content which decreases the acid dew point
- o accelerates the metal loss because increased flue gas oxygen produces ferric ions [5].

The effect of increased oxygen is demonstrated by Figure 6 [5]. Even though the data are from an oil-burning unit, the same effect would occur in a coal-fired plant: i.e., increased oxygen increases the acid dew point.

Figure 3. Corrosion rate versus surface temperature and acid concentration.

Figure 4. Rate of deposition vs. surface temperature.

Figure 5.

Figure 6. Decrease in dew point with low excess air in an oil-fired furnace [5].

The role of fuel ash in the coal-fired cold-end corrosion is complex and depends on the type of ash, the ash deposition, and the cyclic load condition. For instance, an ash that is high in pyrite oxide may increase the formation of sulfur trioxide through catalytic effect of the uncombined iron oxide. Calcium and magnesium containing ashes may absorb some of the sulfur trioxide, thus reducing the acidity of the condensate. Too much fly ash causes the presence of warm, moist, ash-packed areas which readily causes under-deposit corrosion. These ash deposits are hygroscopic and, at lower temperature conditions, caused either by design or off-load conditions, will absorb

will absorb moisture. This deposit will greatly increase the rate of corrosion if the alkaline ash has absorbed enough sulfur trioxide for the adhering wet mass to deplete the alkalinity and become acidic.

As previously mentioned, the sulfuric acid dew point depends on the concentration of acid within the system. The concentration of the acid depends on the water vapor partial pressures and the amount of sulfur trioxide present. Therefore, the moisture variation within the flue gas influences the acid dew point. Figure 7 demonstrates that as moisture in the flue gas increases, the acid dew point decreases.[4]

Figure 7. Effect of percent water on acid dew point [8].

Corrosion from Condensation of Chlorine Compounds

Chlorine compounds in the flue gas are a major contributor to corrosion in the flue gas path. The chlorine content (in the form of chlorides) of U.S. coals ranges from 0.1% to 0.5% (1000-5000 ppm). Also the water used in boiler operations contributes to the chlorine compounds present in the flue gas.

At the sulfuric acid dew point, the presence of chloride in the flue gas translates to a 190 HCl concentration in the deposit.[7] But below the water dew point the situation changes. Hydrochloric (HCl) acid readily condenses such that the concentration of the HCl in the condensate is ~85% of that in the flue gas. This study also reported a 200% increased short-term corrosion loss for a flue gas with 100 ppm HCl at the water dew point.

Precipitating chlorides and low pH will promote crevice attack and pitting under scale deposits. Chlorides also cause stress corrosion cracking of austenitic stainless steels over a wide range of pH.

Areas of Boiler Affected by Cold-End Corrosion

Air-Heater Elements, Framework and Seals. Acid deposition causes adherent deposits and corrosion of the element packs. This impairs gas flow and often reduces the amount of combustion air available. Element failure can often lead to air-heater seal damage, giving rise to high levels of air-heater leakage, increasing flue gas losses.

Ductwork and Expansion Seals. Duct and seal penetration due to acid dew point corrosion will increase the induced draught fan requirements due to air inleakage, thereby reducing plant efficiency, and in some cases the maximum plant output. Complete seal or duct failure can lead to an expensive plant outage and repair.

Precipitators. Isolation dampers can corrode, rendering them inoperable and preventing on-line precipitator maintenance. Corrosion of precipitator structural concrete can lead to roof collapse, while corrosion of precipitator wires, frames and plates can lead to precipitator zones failing, increasing dust emissions. This in turn will require a reduction in load to comply with emission requirements.

Chimney Stacks. The concrete or limestone concrete aggregate flues are generally lined with a corrosion resistant brickwork, but often metallic components (e.g., flashing, chimney tops) are used. Failure of brickwork or metallic components may lead to attack of the flue, thereby threatening its structural integrity. Acid penetration of the flue can be monitored by conductivity probes embedded at various depths into the concrete. Significant increase in conductivity above the norm is an indication of acid penetration.

Duct Injection Technology [8, 9]

Duct injection technology encompasses a wide variety of processes for the removal of SO_2 from flue gas. The major difference between the flue gas desulfurization duct-injection processes is the type of sorbent/gas mixture design. Figure 8 demonstrates the two types of duct injection processes and variation on the humidification model. One process humidifies the gas by injecting a slurry of calcium-based sorbent. The moisture in the slurry evaporates and humidifies the flue gas. The other process injects dry particles into the flue gas either before or after the gas is humidified by spraying a fine mist of water into the ductwork. The variation concerns whether the sorbent (dry) is injected before or after the injection of water. The humid gas wets the particle surface producing the reaction between the sulfur dioxide and the sorbent. When the sorbent is injected the particles are wetted, which improves the SO_2 /sorbent reaction.

Figure 8. Humidification Locations for Various Duct Injection Processes[8]

The sorbents used are either calcium (CaCO_3 , Ca(OH)_2) or sodium (NaOH) although the calcium type is heavily favored. The calcium types are many, and continuing laboratory studies are investigating many other variations including: high surface area limes, pressure hydrated limes, and limes with a variety of chemical additions. One variation is using recycled fly ash which contains silicon dioxide. This silicon dioxide reacts with the calcium sorbent to yield a calcium silicate. Calcium silicate is even more reactive with the SO_2 in the flue gas. Sodium hydroxide is another experimental additive that increases the reactivity of the calcium based sorbent. The design differences in the variety of processes encompasses the number of nozzles, the nozzle design, and material. The atomizing pressure, size of the flue duct, and component flow rates are other process variables.

The most important variable affecting the SO_2 removal and sorbent utilization is the approach to saturation temperature i.e., the lower the approach temperature, the higher the of SO_2 removal. For the dry sorbent/humidified gas, the lower approach temperatures produces wetter particles which are more reactive towards SO_2 . A lower approach temperature with the slurry injection process means an increased drying time for the droplets and a longer reaction time with the sulfur dioxide which increases the amount of SO_2 removed. However, the lower the approach temperature, i.e., closer to the adiabatic saturation temperature the greater probability of wet solid deposition on the walls. This is because the drops do not dry completely before hitting the walls of the gas duct. The increased amount of wall deposits will increase the amount of SO_2 removed from the flue stream because of the longer time available to react with the SO_2 .

Duct Injection Process Corrosion

Ideally, duct injection technology promises very low corrosion rates compared to the wet scrubber technology. The mixture of lime with the flue gas in duct injection technology yields a basic pH. The wet scrubber environment is acidic and rapidly attacks carbon steel. The environment in the ductwork at the injection and mixing site will be less corrosive because temperature of the walls, the flow rate, and design factors. But, ideal conditions that prevent corrosion and erosion are difficult to achieve while trying to get a good SO_2 removal.

The most significant influence on the corrosion of carbon steel is the pH.[15] Figure 9 shows the corrosion rates versus pH of carbon. However, at higher temperatures (300°C) the corrosion rate increases at the higher pH.[15] Most duct injection prototype investigations have had problems with solid deposition on the walls of the ducts[8, 9] The regions where deposits wet the walls is where the temperature drops. Wall deposits threaten the ductwork materials corrosion integrity with both underdeposit localized corrosion and wastage mechanisms operable. In this cooler area the SO₂ combines with the condensing water to form sulfuric acid resulting in acidic conditions adjacent to the wall. Besides the corrosive conditions at the wall, the lime water deposit can, under some conditions, form a concrete-like deposit which can build until the duct plugs completely. Gas flow distribution is also a factor in the presence of wall deposition and erosion.

Not surprisingly, the factors that affect the SO₂ removal efficiency also affect the amount of wall wetting, deposition and abrasion damage. One factor is the residence time of the sorbent/gas components in the ductwork. The longer the dwell in the ductwork the higher the SO₂ removal efficiency. But, this also means an increased likelihood of wall wetting and deposition. Also the flow rate, i.e. dwell time influences the amount of abrasion or erosion damage in the ductwork and delivery nozzle.

CONCLUSIONS

1. Severe corrosion results from a close approach to saturation temperature. Even if lime is present, the continued condensation lowers the pH[2] under the deposit.
2. Hotter temperature (higher approach) would ensure low corrosion rates.
3. Avoid temperature cycling, i.e., oscillating process temperatures, below and above saturation temperature.
4. Stainless steels are not suitable for downstream of a spray drying application. Stainless steel is susceptible to cracking where chlorides can condense.

Figure 9. Composite damage at dry scrubbers.

5. Hastelloys and Inconels (Ni-Cr-Mo alloys) are most resistant to acid condensation corrosion.
6. Downstream of the spray dryer, coated carbon steel or corrosion-resistant alloy clad of carbon steel can be used as a protection against dewpoint corrosion.
7. Measure gas conditions (sulfur presence, temperature) downstream of the precipitator to determine if reheat is necessary.

RECOMMENDATIONS [1-14]

Based on the present experience in dry scrubber units and overall back-end experience, the following design recommendations are made:

- o Provide means for monitoring temperature and velocity to avoid corrosive condensation.
- o Measure corrosive components of the process streams to estimate process stream corrosiveness.
- o Insulate outlet ducts, avoid cold spots.
- o In the ESP or baghouse and downstream to the stack, avoid crevices, dead legs, or other stagnant areas. Insulate properly.
- o It is desirable to bypass the baghouse or preheat system during start-up (until the gas stream reaches operating temperature) to avoid excessive condensation and flyash plugging.
- o In joints, corners, and other areas where condensation is possible, avoid contact of galvanically dissimilar materials; uncoated carbon steel and stainless steel or carbon steel and graphite impregnated rubber.[6]

- o Keep flow velocities within specification and provide means for removing ash build-up and deposits such as sweeping or vacuuming. Sweeping or vacuuming is preferable to flushing or washing.
- o In the Spray Dryer Modules all parts exposed to slurry should be abrasion resistant i.e., bushings, wheel body, wear plates, etc. (SiC)
- o Brace components to avoid excessive vibration (fans).

DISCUSSION

Time spans for pilot plant operations are too short to make definitive predictions about corrosion. Pilot testing is not always a good measure of corrosiveness in a plant. The test spans are too short and the process variables change frequently depending on the process data required.

The corrosion and erosion damage at operating units using dry scrubber or duct injection technology is shown on Figure 9. [2, 10, 11, 12] In Region A where a slurry is sprayed all parts are exposed to severe abrasion. When the material wears appreciably this affects the pattern of the spray and upsets carefully calculated mixing variables. In Region B, the seals around the isolation dampers plug frequently with ash. This area has to be cleaned frequently. In Region C significant corrosion has necessitated replacement of the door seals of the baghouse compartment doors. Also the areas around the bag hangers and the walls between the bags have displayed corrosion. Region D is the reverse air fan and fan housing. Carbon steel and stainless steel in this assembly have exhibited severe corrosion, both pitting and chloride cracking. The most severe potential for corrosion is the region between the fan and out the stack. Currently, a fiber reinforced plastic (FRP) liner is used to protect the stack walls.

Additional recommendations can be made as the body of field experience, pilot testing, and laboratory test programs increases.

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STATUS REPORT
TEMPERATURE INSTRUMENTATION AND CONTROLS
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

Flue gas temperature in the Dry Sorbent Injection (DSI) and Duct Spray Drying (DSD) processes is controlled by evaporative cooling. In the case of DSI, water is used to humidify the flue gas to the desired approach to adiabatic saturation temperature. For DSD, slurry solids content and flow rate control the flue gas to the desired temperature.

Measurement and control of flue gas temperature is a very important factor in the performance and operability of DSI and DSD. Flue gas temperature in the duct reaction zone directly affects SO_2 capture and sorbent utilization as well as water evaporation rate. The process should be optimized to achieve the closest practical approach to saturation for maximum sorbent utilization and SO_2 removal while avoiding wet solids deposition and corrosion problems caused by insufficient evaporation of water or slurry droplets. This critical balance requires accurate measurement and precise control of the flue gas temperature. This Status Report discusses the temperature measurement techniques appropriate in duct injection applications and the methods and criteria for controlling gas temperature. This Status Report does not attempt to define optimum operating temperature for these processes.

2.0 CONCLUSIONS

1. Since approach to saturation temperature directly affects sorbent utilization and SO_2 removal, maintaining the desired approach temperature is extremely important. This is more critical in processes with inherently low utilizations like duct injection than with more efficient conventional spray dryers. In addition, the potential for severe operating problems due to wet solids deposition in the ductwork is much higher than with spray drying.

2. Changes in upstream boiler operating conditions can cause rapid and significant variations in flue gas temperature and/or humidity entering the duct injection process.
3. To achieve a constant approach to saturation temperature, accurate and reliable measurement of both dry bulb and wet bulb flue gas temperature is important. Dry bulb temperature can be measured by a combination of shielded and unshielded thermocouples. The water flow rate control and alarm thermocouples should be unshielded and should be located just upstream of the particulate collector. Wet bulb should be periodically measured by hand upstream of humidification water or slurry injection until a reliable continuous monitor is developed.
4. Feed-forward as well as feedback control is desirable for controlling temperature, and safety interlocks are important.
5. Control temperature setting is site specific, but should be established at a safe approach to saturation based on normal wet bulb temperatures at a given boiler load operating condition.
6. Maintaining adequate flue gas temperature at the outlet of the particular collector is very important because the corrosion potential in this region is high.

3.0 RECOMMENDATIONS

1. Boiler operating conditions must be considered when establishing temperature control methods and criteria.
2. Location and number of thermocouples (grid) in the duct must be carefully determined to ensure representative temperature measurement. Duct temperature traverses should be conducted to define the temperature profile.

3. Thermocouples in the humidification water or slurry injection zone should be shielded to prevent liquid droplets and wet solids deposition from affecting temperature measurement.
4. The development of an automatic continuous wet bulb monitor or flue gas humidity monitor capable of operating in particulate laden flue gas streams is important to improve control of flue gas temperature to an optimum level. A survey of vendors and research organizations (such as EPRI) as to the status of development of these devices should be conducted.
5. A PLC or similar automatic feedback/feed-forward controller should be used to control the humidification water or slurry injection system to control temperature to the desired setpoint.
6. The temperature controller should be programmed for the proper response time/rate to changes in measured duct temperature caused by system dynamics. This will help prevent overspraying episodes.
7. Monitor and maintain the temperature of the flue gas exiting the particulate collector above the dew point to minimize corrosion potential.
8. The practical effectiveness of duct skin temperature thermocouples to detect wall wetting and deposition should be determined.

4.0 DISCUSSION

The important factors to consider in controlling the flue gas temperature in DSI/DSD processes are:

1. Understanding the effects of upstream boiler conditions on flue gas temperature and humidity entering the DSI/DSD process.
2. Measurement of flue gas dry bulb temperature.

3. Measurement of flue gas wet bulb temperature.
4. Selection of automatic control method.
5. Temperature control criteria.

4.1 Understanding Effects of Upstream Boiler Conditions

Temperature and humidity of the flue gas entering the DSI/DSD process can be affected by a variety of boiler operating parameters:

- ° Boiler load
- ° Changes in heat exchange profile (slagging, etc.)
- ° Soot blowing cycle
- ° Auxiliary heat exchangers (steam coils, etc.)
- ° Tube leaks

Any changes in these parameters can cause rapid and significant changes in flue gas temperature and/or humidity and must be considered when selecting the method and criteria for temperature control. Alarms and/or interlocks should be built in to the control system when possible. When soot blowers are activated, for example, a signal could be sent which would put the temperature control in manual. The unit load signal could be utilized in a feed-forward loop.

4.2 Measurement of Dry Bulb Temperature

Flue gas dry bulb temperature is typically measured with a grid of thermocouple probes located in the duct in the critical region downstream of humidification but upstream of the particulate control device. It has been necessary at some installations to shield the humidification zone thermocouples from wet solids or liquid water droplets. This approach is used at the Coolside duct injection demonstration at Edgewater Station (4). Shielded thermocouples are used to measure flue gas temperature in the humidification zone where unevaporated droplets exist; unshielded thermocouples are located

downstream of the humidification zone for humidification water flow rate control and to function as indicators and alarms for wet conditions. Since flue gas temperature can be maldistributed in ductwork downstream of DSI and DSD processes, care should be taken in determining the number and location of thermocouple probes.

Complete temperature traverses should be conducted prior to and after humidification water or slurry atomizer installation to determine the duct cross-sectional temperature profile and to identify any cold spots. The temperature data acquisition device in the permanent installation should have the capability of indicating average temperature in the grid as well as individual thermocouple probes. Alarms can be attached to the thermocouple probe outputs to indicate water or slurry injection problems.

4.3 Measurement of Wet Bulb Temperature

Wet bulb temperature measurement is a critical indicator of adiabatic saturation of the flue gas. The wet bulb temperature should be measured upstream of humidification water or slurry injection. Currently, the most reliable method of wet bulb temperature determination is a manual measurement in which a thermocouple covered with a wetted cotton wick is inserted into the flue gas stream. Several commercial spray dryer installations and DSI/DSD development sites rely on such manual measurement. Other spray dryer systems use currently available wet bulb or humidity monitors to measure wet bulb temperature at the outlet of the fabric filter or at the stack, where the flue gas is clean (3). The sensitivity of these monitors to particulates may prohibit their use upstream of ESPs. Several continuous wet bulb monitors are being developed for dirty flue gas applications. None are currently considered field ready for commercial use.

4.4 Miscellaneous Temperature Measurements

Other temperature measurements which are important to the successful operation of duct injection include:

- 1) ESP or Fabric Filter Outlet Temperature - Concerns about corrosion require maintaining this temperature safely above the flue gas dew point. Since saturation temperature can be affected by inleakage it may also be advisable to monitor the wet bulb as well as dry bulb temperature at this location.
- 2) Duct Skin Temperature - Research and development projects have used thermocouples on duct surfaces downstream of sorbent or slurry injection to detect wall wetting and solids deposition. It is unclear if these devices can be practical on a full-scale, commercial duct injection installation because of reliability and maintenance requirements.

4.5 Control Method

The use of a Programmable Logic Controller (PLC) or similar automatic feedback control system is desirable. The temperature signal from the dry bulb thermocouple grid can be input to the controller to operate a control valve or variable speed pump in the humidification water- or slurry-temperature control system to achieve a temperature setpoint value or approach to saturation temperature. Since DSI/DSD systems have the potential for operational swings and upstream conditions can change rapidly, it is advisable to have feed-forward capability, as well as the capability to adjust response time on the controller.

An example of a temperature control method from a utility spray dryer installation is taken from Northern States Power Company's Riverside Station (3). The approach to saturation is automatically controlled by the process computer using a combination feed-forward, feedback loop. The major control inputs are spray dryer outlet temperature and fabric filter outlet wet bulb temperature. Based on the difference between these values, the computer adjusts the atomizer feed slurry rate to maintain a constant approach to adiabatic saturation at the spray dryer outlet. Flue gas flow and temperature at the spray dryer inlet provide feed-forward signals to the

controller to prevent sudden load swings from causing process upsets. A sudden drop in gas flow, for example, would be sensed by the controller and the slurry feed rate would be reduced accordingly, rather than waiting for the outlet temperature to drop before reducing slurry flow.

Several other safety interlocks are part of the approach temperature control system. Three wet bulb indicators provide signals to the computer. The average of these three values is used to determine the wet bulb supplied to the controller. If one of the wet bulb measurements is more than 4°F from the average, it is considered to be erroneous and is not included in the average calculation. If all three of the wet bulb measurements are more than 4°F apart, the computer simply controls the outlet temperature to a preset, safe level. Another interlock provided to prevent loss of control is activated if the approach temperature drops to less than 15°F. In this event, the system would automatically revert to a preset outlet temperature.

The Riverside wet bulb indicators were supplied by the spray dryer vendor and designed specifically for this application. Because the wet bulb probes are installed at the outlet of a very efficient fabric filter, they are much less susceptible to reliability problems created by the relatively higher solids loading typically present of the outlet of an existing ESP. Ideally, it is preferable to measure wet bulb upstream of the ESP to minimize the effects of inleakage and thermal inertia in the particulate collector which tend to dampen process changes.

4.6 Temperature Control Criteria

Determination of control temperature is somewhat site specific. Ideally, a DSI/DSD process should be operated at the closest approach to saturation possible without operational problems such as deposition of wet solids. Since upstream conditions of temperature and humidity tend to change with load, fuel quality, and operations, as discussed in Section 4.1, and, considering the dynamic nature of

DSI/DSD processes, this 'ideal' operating temperature is difficult to maintain. The development of a continuous wet bulb monitor or similar device will improve this capability, but until this technology is perfected, a more conservative approach is recommended. This approach is site specific and depends on such factors as SO₂ removal, duct configuration, drying time, etc.

Most DSI/DSD developmental projects have been pilot scale and/or experimental in nature; therefore, there has been little experience operating these technologies in a realistic commercial mode. Typical operating philosophy in conventional spray drying technology is to operate the unit to maintain a specified flue gas dry bulb temperature at the scrubber outlet which results in a range of approach temperatures as the flue gas saturation temperature fluctuates with load, fuel quality, etc. The temperature setpoint is chosen low enough to give acceptable SO₂ removal and reagent utilization but high enough to avoid operational problems. This somewhat conservative practice is typical in spray drying, where sorbent utilization is generally higher than expected with DSI/DSD. Due to the potential severity of deposition problems associated with DSI/DSD, a similar control philosophy is recommended.

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STATUS REPORT
SO₂ MEASUREMENT INSTRUMENTATION AND PROCESS CONTROL
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

An accurate, reliable SO₂ monitor is a vital component in a Dry Sorbent Injection (DSI) or Duct Spray Drying (DSD) facility. Pollutant gas concentrations are measured by a continuous emissions monitoring system (CEMS). In addition to reporting emissions to the regulatory agency, the CEMS is used to monitor and control DSI or DSD system performance. Although CEM systems may monitor a broad range of pollutants and combustion products including NO/NO_x, CO, CO₂, HCL, etc., this Status Report is limited to SO₂ and O₂.

2.0 CONCLUSIONS

1. There are two broad categories of SO₂ CEM systems.
 - A. In-situ - main gas analyzer components are in the gas stream.
 - B. Extractive - a sample of flue gas is withdrawn from the gas stream and transported to remotely located analyzers.
2. The SO₂ emission monitoring system CEMS has two important functions.
 - A. Accurate determination of pollutant emissions for compliance and reporting to the regulatory agency.
 - B. Monitoring and control of DSI or DSD system performance.
3. There are inherent advantages and disadvantages of both in-situ and extractive CEMS. Selection of one over the other is site specific.

4. The number and location of CEMS sampling probes or systems is site specific. Options include:
 - A. Single CEM system at stack or outlet - 1 or more probes.
 - B. Sample probe(s) at process inlet and stack or outlet - 1 CEM time-shared.
 - C. Complete, separate CEM system at process inlet and at stack or outlet.
5. The signal from the SO_2 CEM system can be used to control sorbent injection rate for DSI systems. The control scheme is site specific. A feedback or feed-forward/feedback system can use the SO_2 signal to control sorbent feeder speed, slurry rate, slurry composition, etc. for DSD.
6. System control can be based on a desired SO_2 removal level, or a set SO_2 emission limit. This again is site specific based on system configuration, regulatory requirements, and economics.

3.0 RECOMMENDATIONS

1. Precautions to avoid sorbent/ SO_2 reactions on probe surfaces or in the sampling system should be incorporated into the design and operation of a CEMS to be installed on a DSI or DSD process.
2. Placing of probe(s) in the duct or stack is extremely important. Care must be taken in determining probe location in order to ensure a representative sample, especially in in-situ systems. In particulate control device outlet sampling locations, sorbent streamlining and uneven SO_2 removal across the particulate control device could result in erroneous data.
3. It is not practical to sample at the inlet of the particulate control device downstream of sorbent injection, due to potential scrubbing on or in the sampling system by unreacted sorbent.

4.0 DISCUSSION

There are two broad categories of SO_2 CEM systems: in-situ and extractive. In-situ systems measure pollutant (SO_2) and diluent (O_2) concentrations directly in the flue gas stream. In contrast, extractive systems extract and transport samples of flue gas to an analyzer located outside the gas stream.

Both in-situ and extractive systems for monitoring SO_2 and O_2 are available commercially. However, inherent limitations of these monitors restrict their application to the measurement of effluents with certain characteristics. The applicability of each class of instruments is discussed in the following sections. Table 1 compares the advantages and disadvantages of in-situ vs extractive CEMS as they apply to DSI and DSD.

4.1 In-Situ Systems

Most in-situ gas monitoring systems use light beams to detect and quantify pollutant and diluent gas concentrations. The wavelength of the light depends on which gas is being monitored. Most in-situ systems can be thought of as "in-stack" spectrophotometers whose measurement path is some segment of the stack or duct cross section.

In-situ systems may be classified as either path in-situ systems or point in-situ systems. Path systems have a measurement path length that can be as long as the inside diameter of the duct or stack. Point in-situ systems typically have a measurement path that is only a few centimeters in length. As with single-point extractive systems, point in-situ systems are more susceptible to questions of sample representativeness than are path systems. This is a particularly relevant concern for monitoring applications downstream of FGD systems, including DSI/DSD systems, where streamlines of sorbent and SO_2 removal may occur.

Path In-Situ Systems

All commercially available path in-situ systems use a single-pass measurement technique. In this configuration, the light source (infrared for CO_2 , and ultraviolet or infrared for SO_2 and NO_x) is mounted on one side of the stack or duct and the detector assembly on the opposite side. As with single-pass opacity transmissometers, precise alignment of the transmitter and detector assemblies is imperative to assure accurate data.

Simplistically stated, photometric in-situ gas monitors (both point and path) are based on the operational principle that the gas being monitored absorbs light of a given wavelength. The wavelength is carefully chosen to minimize interferences from other gases. Although sophisticated electronic techniques are used to monitor the desired pollutant in the presence of accompanying particulate matter, particulate interference constitutes a fundamental limitation of path in-situ systems. This limitation may prevent using a path in-situ device downstream of sorbent or slurry injection and upstream of the particulate control device.

Path in-situ systems cannot be calibrated in the same manner as point in-situ or extractive systems. Because of the measurement path length, which extends across the stack or duct, it is usually impossible to zero or calibrate path in-situ systems by introducing a known zero or calibration gas into the detector's complete measurement path. Therefore, path in-situ systems are usually calibrated indirectly, either by incremental addition or by using auxiliary light sources.

Point In-Situ Systems

The point in-situ SO_2 monitoring system is designed to minimize the particulate interference problem typical of path systems through the use of a porous ceramic filter which surrounds a short (several centimeter) measurement cell located at the end of the sampling probe. The purpose

of the probe is not to serve as a sample transport conduit, but rather to provide a sealed, clear path from the light source to the measurement cavity. The filter is used to prevent particulate matter and entrained moisture from entering the cell, while permitting an unobstructed flow of gas into the measurement cavity. Although most of these monitors are equipped with a high-pressure "blow-back" for dislodging particulate matter from the outside of the ceramic filters, gas streams with high particulate grain loadings and/or entrained moisture can clog the ceramic filters, or, more detrimentally, provide a reaction substrate for sorbent/SO₂ scrubbing to occur.

In a typical point in-situ configuration, the light source/detector assembly is located outside the stack or duct at one end of the probe and a mirror is located at the other end of the probe in the measurement chamber. An example of this assembly is illustrated in Figure 1. In the case of SO₂ monitoring, an ultraviolet light beam is projected down the probe, through the measurement chamber, to the mirror which reflects the light back to the detector assembly. The absorbance of ultraviolet light by the gas in the measurement chamber provides a measure of pollutant concentration.

A point in-situ system measures the pollutant concentrations at a single point. Obtaining a representative sample from a single point is not always possible, especially downstream of a DSI or DSD process. Most in-situ CEM manufacturers offer multipoint systems, but, since each probe requires an analyzer, multipoint in-situ systems may be cost prohibitive. In order for pollutant measurements to be expressed in units of most applicable emissions standards (i.e., lb/MMBtu), measurement of a stack gas diluent (O₂ or CO₂) usually is made concurrently and at the same location as the pollutant measurements. Although appropriate for many monitoring applications, a wet basis system may not be acceptable for applications downstream of a DSI/DSD system because a constant moisture content must be assumed. Calibration of point in-situ analyzers is performed by passing a sample of bottled calibration gas of known concentration through the detector cell. The

instrument is adjusted electronically to compensate for any drift which may have occurred.

4.2 Extractive Monitoring Systems

Extractive monitoring systems withdraw a sample from the flue gas for external analysis. All extractive systems have three common subsystems:

- 1) sample withdraw probes
- 2) sample transport and conditioning
- 3) gas analyzers

A generic extractive CEM system diagram is shown in Figure 2.

Sample Withdraw Probes

Most extractive monitor probes are equipped with a filter to remove coarse particulate matter prior to transport of the gas samples to the analyzer. Filters can be located in the flue gas stream, or in a heated sample junction box just outside the duct sample location. A variety of filters and filtering materials are used, including sintered stainless steel, ceramic, glass, and quartz fiber filters. As with the ceramic filters discussed in the previous section, most extractive system probes are equipped with high-pressure "blow-back" systems to remove particulate matter or sorbent that collects in the probe and on the exterior surfaces of the filter. Problems similar to those discussed in relation to in-situ system probes are common to these systems as well. In applications where reactive sorbent may deposit on the filter surface, it may be necessary to heat the filter above the reaction temperature of the sorbent. Typically, sample probes are constructed of one of a variety of stainless steels and, in special sampling applications, may be lined with quartz or glass. Since, the gas analyzers are separate, multipoint, time-sharing sampling is possible. Probes can be sampled individually, or as a composite depending on site specific needs.

Sample Transport and Conditioning

Sample handling systems customarily begin at the junction of the probe and the sample transport line, usually just outside the stack or duct. Sample handling systems usually consist of heated and insulated Teflon sample transport lines and may include gas conditioning equipment. The purpose of the sample conditioning system is to provide a clean, dry sample to the analyzer without altering the gas concentrations. Sample conditioning equipment may include a primary or secondary particulate filter and a water removal apparatus.

The two types of water removal apparatus most frequently used in sample conditioning systems are refrigerated condensers and permeation dryers. Refrigerated condensers rapidly cool the sample, causing the moisture in the gas to condense. The condensed moisture is trapped and periodically removed from the condenser assembly, typically a function of the CEMS computer control system. Precautions usually are taken in designing the condenser and trap to minimize contact between the condensate and the cooled sample to avoid absorption of the pollutant gas by the condensed liquid.

Permeation dryers are an alternative to refrigerated coolers and offer some potential advantages. This type of drying system uses membranes that are selectively permeable to water vapor. The water vapor in the flue gas diffuses through the membranes into a dry purge air stream. This process occurs continuously as wet stack gas flows in one direction through the dryer while dry purge air flows countercurrently.

In addition to the coarse particulate filter usually located in the stack or just external to the stack at the junction of the probe and sample line, many sample conditioning systems include a secondary filter for fine particulate removal. Secondary filters are usually located downstream of the moisture removal system. For DSI/DSD applications, these may be undesirable due to potential for scrubbing if unreacted sorbent particles are deposited on the filter.

Gas Analyzers

The pollutant detector, or analyzer, is usually the most trouble-free and reliable component of extractive monitoring systems. Most analyzers are industrial adaptations of proven, laboratory gas analysis techniques. As with in-situ systems, the operating principle of the analyzer in most extractive systems is the absorbance of light by the gas sample.

The most common type of SO_2 analyzer operates on an ultraviolet light absorption principle. The instrument components typically include optical filters, photo multiplier tubes and amplifiers. The concentration of SO_2 is based on the absorption of ultraviolet light of a specific wavelength.

Other types of SO_2 analyzers, based on nondispersive infrared light absorption, flame photometric, and fluorescence, are also available, but less common.

Most regulations require that the SO_2 concentration be reported in units of mass of SO_2 per energy produced (e.g., lbs/MMBtu). To accomplish this, the excess oxygen (or CO_2) must be monitored in order to "back out" the excess dilution air. The oxygen analyzer uses the same gas sample (arranged in parallel or in series) as the SO_2 analyzer. Most oxygen analyzers utilize an electrochemical cell (or fuel cell) to produce a linearized voltage signal that is proportional to the ratio of oxygen concentration of a reference gas (usually air) and the oxygen concentration of the sample. Most CO_2 analyzers operate on the absorption of infrared light.

CEMS are required to be calibrated periodically as required by the appropriate regulations. Sample flow is interrupted or diverted and the data acquisition system flagged while bottled pollutant reference gases of known concentration are introduced through the sampling system to each analyzer. The CEMS computer performs the necessary electronic adjustments to calibrate the instruments. Calibration and drift data are recorded by the data acquisition system to generate the proper reports. Alarms can be set if excessive drift or an invalid calibration has occurred. Calibration can also be conducted manually.

Dilution Systems

A recent trend in extractive CEMS is sample dilution. By using a critical orifice, the withdrawn sample is diluted to a known ratio using dry oxygen or CO₂. Therefore, the pollutant gases entering the analyzers are much lower in concentration. The advantage of a highly diluted sample is that the net dewpoint is extremely low. The need for heated sample lines and water removal is typically eliminated. Figure 3 shows an example of a critical orifice dilution probe. There is an upper limit of flue gas moisture range in which a dilution system can be applied. This may limit its application in some DSI/DSO cases.

Emerging Technologies

A promising new type of extractive flue gas analyzer is being developed by several manufacturers. Fourier Transform Infrared (FTIR) detection technology may soon enable a single analyzer to accurately and simultaneously measure a wide variety of gases. Many manufacturers hope to offer a field proven product by the early to mid 1990's.

4.3 System Controller and Data Acquisition

Most CEMS packages offered today include an onboard computer control and data acquisition system. These may be separate components. The control system (many newer systems are PLC based) is responsible for all of the ongoing operations of the sampling system and gas analyzers. These include purging and blow-back of probes, purging and draining of refrigerated condenser unit, calibration of analyzers, etc. In time-share or multipoint sampling, the control system automatically switches probes, or sample locations. The system is also responsible for setting status flags and alarms.

One of the most important functions of the CEMS is to record and document the pollutant emissions to the environmental regulatory agency. The data acquisition system of a CEMS typically records real time data from the analog or digital outputs of the analyzers, performs some time averaging and provides some limited data storage. Typically, regulatory agencies have specific requirements for data reporting and record keeping. The CEMS data acquisition system should be designed to comply with these requirements. This data can be accessed by a customer's plant computer or datalogger or a PC. Most CEMS vendors offer data reduction and reporting software packages, or the customer may choose to use his own.

In addition to the computer data logging system, most plants choose to record real time gas analyzer output on chart recorders.

4.4 Sampling Location

Gas sampling location(s) may depend upon how the DSI/DSD process is to be regulated and controlled. If it is necessary to maintain a specified percent SO₂ removal, CEM samples at the inlet and outlet of the DSI/DSD process may be required. Typically, this means one system at the stack or particulate control device outlet, and one system upstream of sorbent or slurry injection. In some cases, one set of analyzers can be time shared between the inlet and outlet sampling locations. If regulations require simply a specified outlet SO₂ emission limit, a single sample location at the stack or particulate control device outlet may be sufficient. Process efficiency can still be estimated by sulfur balance calculations. Care must be taken in selecting probe (or probe grid) location downstream of particulate control due to potential streamlines of SO₂ caused by uneven sorbent distribution or flow stratification in the particulate control device.

Sampling downstream of the sorbent or slurry injection, but upstream of the particulate control device is not practical. Unreacted wet or dry solids can deposit on or in the sampling system generating false SO₂ removal measurements. Several methods have been used in research and

development to measure SO_2 in this environment (inertial separation, dilution, etc.) but are not practical for commercial use.

4.5 Role of SO_2 Monitor in Process Control

In addition to emissions reporting, the function of the SO_2 monitoring system is to set control parameters in the SO_2 removal process. Automatic control is desired in the operation of the DSI or DSD system. The two primary control schemes involve either maintaining a prescribed SO_2 removal level, or maintaining a prescribed SO_2 emission limit (lbs/MMBtu, lbs SO_2 /hr, etc.). The signal from the CEMS can be used to control the sorbent injection rate in DSI applications or to control the slurry composition and/or flow rate to the atomizers in the case of DSD. These can be simple feedback loops or more sophisticated feed-forward/feedback systems involving other input parameters and interlocks. This again is site specific. There is little experience with commercial full-scale DSI systems. The pilot-scale experimental projects have little operational experience in a hands-off commercial mode. The full-scale Coolside DSI project at Ohio Edison's Edgewater Station does not use SO_2 concentration to control sorbent injection rate, even though reliable CEM systems are installed at the process inlet and stack. Instead, sorbent feedrate is controlled on the basis of coal sulfur (measured and tracked several times daily) and boiler load (4). Although accurate and reliable at Edgewater, this technique may not apply to many potential DSI installations. This technique was originally developed and refined for furnace sorbent injection in which process inlet SO_2 could not be measured. The Edgewater unit fires a very consistent fuel, so rapid changes in SO_2 concentration are infrequent. Conventional spray drying technology is similar to DSI/DSD, and process control is also expected to be similar. A DSI application may be less complicated.

An example of a moderately sophisticated control scheme at a utility spray dryer installation is the one used at Northern States Power Company's Riverside Station (1). In addition to controlling approach temperature, the process computer automatically controlled SO_2 removal

efficiency in the spray dryer/fabric filter system. This control system employed inlet and outlet SO_2 monitors to determine removal efficiency, and adjusted the composition of the atomizer feed stream to obtain the desired SO_2 removal. The controller logic included calculation of the current lime-to- SO_2 reagent ratio and an estimation of the change in reagent ratio required to achieve a desired level of SO_2 removal. This control loop was quite slow. It involved adjusting the slaked lime production rate and required changing the composition of the slurry in the mix and atomizer feed tanks. Because of the slurry residence times in these tanks, such changes often required several hours to be fully effected.

It should be noted that the approach temperature and SO_2 removal control loops could not function independently. The approach temperature loop adjusted the slurry feed rate to the atomizer to maintain a constant approach to adiabatic saturation. However, such an adjustment would also change the reagent ratio and consequently the SO_2 removal efficiency in the system. This would then require the SO_2 removal controller to respond accordingly.

The above example is expected to be similar to that of a duct spray drying (DSD) installation. For DSI, simply controlling the sorbent feedrate may be all that is required.

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TABLE 1

COMPARISON OF IN-SITU vs EXTRACTION

CONTINUOUS EMISSIONS MONITOR SYSTEMS

SYSTEM TYPE	ADVANTAGES	DISADVANTAGES
Path In-situ Systems	1) Fast response time. 2) No calibration gas needed. 3) No sample transport or conditioning. 4) Simple less expensive installation.	1) Potential interference by particulate or droplets. 2) Gas measured on wet basis, moisture content must be assumed - sometimes not possible downstream of DSI or DSD systems. 3) Vibration sensitive - potential difficulty in maintaining calibration.
Point in-situ Systems	1) Fast response time. 2) No sample transport or conditioning. 3) Simple less expensive installation.	1) Single point, representative sample difficult if SO ₂ is stratified. 2) Gas measured on wet basis. 3) Vibration sensitive. 4) Access for maintenance can be difficult.
Conventional Extractive Systems	1) Most proven technology. 2) Multiprobe capability for representative sample. 3) Analyzer time share capability. 4) Analyzers can be installed in an accessible clean environment. 5) Gas measured on a dry basis.	1) Sample transport and conditioning system. Expensive to install and operate - high power requirements. 2) Sample transport and conditioning system has potential for pluggage, leaks, and condensation problems (both water and acid).
Dilution Extractive Systems	1) Heated sample lines and moisture removal system not necessary. 2) Multiprobe capability for representative sample. 3) Analyzer time share capability. 4) Analyzers can be installed in an accessible clean environment.	1) Questions concerning measurement and data precision with a highly diluted sample. 2) Dilution system may not work on high moisture flue gas, such as that encountered downstream of DSI or DSD. 3) Gas measured on a wet basis, this may not be a problem if CO ₂ is used as the dilution gas.

FIGURE 3
PROBE FOR SAMPLE DILUTION SYSTEM

VELOCITY AND TEMPERATURE PROFILE

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VELOCITY AND TEMPERATURE PROFILE STATUS REPORT

In order to complete the duct injection project, many topics must be covered to determine the feasibility of applying duct injection to existing utility plants. Since this project involves scrubbing the flue gas by injecting sorbent into existing ducts, it becomes necessary to know the flue gas velocity and temperature profiles inside the duct upstream and downstream of the injection location. Knowledge of the velocity profiles is necessary because a proper profile can stop the sorbent from directly impacting the wall; maintain sorbent entrainment; ensure proper residence time for chemical reaction and drying; and maximize sorbent and flue gas mixing to promote maximum contact with fresh sulfur dioxide. The temperature profiles must be measured so that it can be determined whether the flue gas temperature will remain above the water dew point and the acid dew point to prevent condensation on, and corrosion of, the duct walls. Also, knowing the temperature profile facilitates control of the amount of humidification necessary to hold the desired approach temperature and enables the attainment of an optimum temperature for chemical reaction.

The velocity profile at the exit of the air heater heat transfer surface is generally considered to be uniform. There is usually sufficient pressure drop in the air heater heat transfer surface to damp out most flow nonuniformities that may have been present upstream of the air heater. However, at the air heater outlet, the temperature profile can be nonuniform and independent of the velocity profile. As the flue gas flows from the air heater outlet to the injection location, either profile can become more or less uniform depending upon the duct configuration. It is in this section of the flue that distribution devices may be necessary to correct either the velocity and/or temperature profiles to provide the required distribution prior to the injection location.

Turning vanes used to correct a velocity profile will not necessarily correct a temperature profile. When using turning vanes, if there is a maldistribution in temperature upstream of the vanes, the same temperature distribution will exist downstream because the vanes do not increase gas mixing. Only gas mixing can correct an uneven temperature distribution, which

would require additional pressure drop that may not be available in a retrofit application. Therefore, it is imperative that a criteria be established for acceptable velocity and temperature profiles at the injection location.

The Industrial Gas Cleaning Institute (IGCI) has set criteria for the velocity profile entering an electrostatic precipitator. The IGCI standards state that a fixed percentage of the velocity data points at a given location, cannot be greater than the average value, by a fixed amount. This type of criteria ensures that there are no local velocity high spots in the velocity profile. The Air Movement and Control Association (AMCA) has set up standards for the velocity profile entering a fan. Their criteria ensure that the velocity profile is uniform for both high and low values of local velocity by forcing the standard deviation of the velocity data to be within a specified limit. These conditions are slightly more strict than those of the IGCI, but either set of criteria can be used as a guideline for duct injection. One of the objectives of the Duct Injection Technology Prototype Development Program should be to define the criteria needed to ensure acceptable velocity and temperature distribution upstream of the injection location. This will be important for application of this technology to a retrofit system where space and pressure drop can impose major limitations.

Conclusions:

1. Pilot plant duct size was a major cause of wall wetting.
2. Average velocities in the pilot plant were in the range of average velocities found in full scale plants: 20 - 60 ft/s.
3. A well-developed flow pattern is needed to minimize wall wetting.
4. Wall wetting was independent of duct geometry.
5. Flow in most ducts was turbulent with poor radial mixing.
6. Both DSI and CZD processes show the presence of an inner core of cooler gas.

7. Wall wetting resulted from direct contact between the wet slurry and the duct wall rather than from condensation occurring from the flue gas cooling due to poor flow distribution.
8. For DSD the minimum approach to saturation temperature to avoid wall wetting and maximizing SO₂ removal is 30-35°F.
9. For DSI for maximum SO₂ removal, efficient lime utilization and minimum wall wetting, use approach to saturation temperatures of 20-30°F.
10. Even gas flow distribution prior to injection port is required.
11. Correct poor temperature profiles by increasing gas mixing.
12. To correct the velocity distribution, use turning vanes or perforated plates.

Recommendations:

1. During the current test programs, the effect of nonuniform velocity and temperature profiles on duct injection should be determined. This can be done by placing obstructions in the duct upstream of the injection planes and monitoring SO₂ removal, wall wetting, etc. The purpose of these tests would be to define the necessary criteria for uniformity of velocity and temperature profiles. In addition to the test work, the mathematical models should be evaluated to determine if these can be used to define the sensitivity of the velocity and/or temperature profiles on the injection process.
2. A later literature review on Ohio Edison's Edgewater duct humidification system for both LIMB and Coolside processes.
3. For retrofit applications, measure duct velocity and temperature profiles to determine if corrective devices are needed.

4. A scale flow model can be used to determine the internal corrective devices in the duct to provide the required velocity and temperature profiles upstream of the injection location before implementing this technology in the full size unit. The flow model can also be used to minimize the system pressure drop for the retrofit application.
5. The fly ash distribution can also affect the velocity and temperature profiles and this effect should be tested.

Discussion:

The Dravo Lime Company operated a 5-MW Toronto HALT plant. Hydrate addition at low temperature (HALT) uses duct sorbent injection (DSI) technology to inject dry calcium hydroxide duct. The Toronto plant began test operations in November 1986 where it was determined that the small (31") duct size and high inlet flue gas temperature exaggerated the humidification problem. DSI requires humidification of the flue gas in order to supply the water needed for the chemical reaction. In addition, humidification allows for direct control of the flue gas temperature. Two fluid atomizers were used for water atomization.

While operating the Toronto plant, it was determined that direct temperature control was more effective in lowering and holding the flue gas to near its saturation temperature than indirect cooling with a shell and tube heat exchanger. By measuring the temperature of the duct's outside wall, the operator knew wall wetting had occurred when the wall's temperature was near the flue gas wet bulb temperature. From the shielded gas temperature profiles Dravo Lime determined that at low approaches to gas saturation, wall wetting occurred because of poor radial mixing. This lack of radial mixing produces an inner core of flue gas which is cooler and wetter; wall wetting results when this inner core breaks through the warmer wall envelope and contacts the wall. In fact, the operators believe that mixing at the nozzle happens due to turbulence and jet expansion and downstream mixing results from a combination of advection (bulk fluid motion) and diffusion. This is supported by the temperature profiles at 30 to 50 feet downstream of the nozzles. From these profiles the difference between the extreme values increases as the gas

velocity increases and the profiles' small slopes indicate the absence of any significant radial mixing; see figures (Dravo, pg. I29, Proof of Concept).

Velocity profiles were measured using pitot tubes. However, they were never measured with the injection system operating, so there is no information on radial mixing from the velocity data. Measurements at the injection point showed that flue gas flow rates were acceptable, but turning vanes and a distribution plate were needed at an upstream elbow in order to get a reasonable flow pattern upon entering the duct.

General Electric Environmental Systems Inc. (GEESI) operated a 12-MW pilot plant at the Ohio Power Company's Muskingum River Plant. They tested in-duct scrubbing (IDS) using a rotary atomizer. GEESI injected into a rectangular duct with a cross section of 50 inches wide by 40 inches high. Velocity profiles were measured using a hot wire anemometer. Measurements, however, could not be taken downstream of the atomizer stations during atomizer operation because the collection and evaporation of water on the hot wire tended to decrease the wire's temperature, which resulted in an increase in measured velocity. Although the downstream gas velocities were not measured during the slurry injection, the presence of the atomizers created only minor variations in the flow profile upstream of the atomization planes. The standard deviations of the velocity profile data ranged from 10 to 15% of the mean velocity which is under GEESI's 15% guideline for well designed ducts. Airfoils and airflaps were installed upstream of the atomizers to enable on-line flow modifications. GEESI found that these devices were not effective at the high slurry feed rates required for effective SO₂ removal.

Temperature profiles 6 feet downstream of the atomizers showed significant variations. At 30 feet downstream of the atomizers the flue gas had a smooth temperature profile, indicating that good mixing, and nearly complete evaporation, occurred within the half second resident time.

Bechtel National Inc. studied confined zone dispersion (CZD), a process which uses an array of two fluid nozzles to atomize the lime slurry. The idea behind CZD is similar to the results obtained from the Toronto HALT plant. After injection, the slurry forms a moist, cooler core separated from the duct

walls by a hotter layer of flue gas. Before the inner core contacts the duct the chemical reaction is completed and most of the water has evaporated, leaving a dry product to be removed by a baghouse or electrostatic precipitator (ESP). The CZD process was first tested at the Campbell pilot plant in 3-foot diameter circular ducts. The second CZD pilot study operated at the Seward facility with ducts measuring 8 feet wide, 11 feet high.

Like the other two pilot plants, Bechtel did not measure velocity profiles during slurry injection. Test gas velocities ranged from 20 to 50 feet per second and the velocity profiles showed a 40% difference between the extremes. The horizontal profiles taken 25 feet downstream of the first injection station showed classical turbulent flow.

Since the success of CZD is highly dependent on understanding the inner core, Bechtel determined the extent of the confined zone at the Seward facility by plotting isotherms at several locations downstream of the injector. The isotherms showed a well-defined core of gas at low temperatures relative to the wall which lasted the entire length of the duct. From their experiments, Bechtel determined the conditions, based on flue gas temperature, under which flue gas would contact a duct surface. They found:

- 1) below 140°F - wet deposits form
- 2) between 140-155°F - damp deposits form
- 3) between 155-170°F - dry deposits form
- 4) above 170°F - no deposits form.

Seward operators found that the major problem with injecting at a rate that will not cool the gas to below 170°F close to any duct surface, is that the amount of sulfur dioxide removed is considerably limited because of the half second residence time. Bechtel recommends two possible solutions:

- 1) Use a large number of atomizers and provide each of them with multiple discharge orifices. This increases surface area of the slurry, thus increasing heat absorption rate and shortening its evaporation and drying time.

- 2) Increase slurry hold-up time in the duct by adding more atomizing stages upstream of the existing stage (Bechtel, H-22 Appendices).

Bechtel operators found varying deposits throughout the duct, but they were not severe enough to interfere with plant operations.

Operators found that considerable wall wetting occurred at the high slurry injection rates which were required to remove any significant amount of sulfur dioxide. In addition, wet deposits formed within several feet downstream of the atomizers and injection nozzles. This is more a result of the duct size and flue gas velocity than the method of injection.

A 1/4th scale flow model of the 12 MW pilot plant at the Ohio Power Company's Muskingum River Plant was designed and tested by the Babcock & Wilcox Company (B&W) to aid Gilbert/Commonwealth in their field tests. All existing turning vanes were installed in the model and were found to produce uniform velocity fields. Velocity profile measurements showed that the flow was very uniform upstream of both atomization stations. Data was taken approximately 1.5 ft (full scale) upstream of the atomization plane. The standard deviations of the velocity data were less than 15% of the mean velocity. The effect of a maldistributed temperature profile was not tested in this model.

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STATUS REPORT
ELECTROSTATIC PRECIPITATOR
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

One of the most important issues to be addressed in the Duct Injection Technology Development Program is the ability of an existing electrostatic precipitator (ESP) to maintain emission levels after a duct injection retrofit. Due to the age of the plants targeted as potential candidates for duct injection retrofit, some may already have a marginally sized ESP. Depending on the desired SO₂ removal and coal sulfur content, duct injection will increase the mass loading to an ESP by 5-15 gr/acf; this corresponds to an increase in loading to the ESP by a factor of 3-12 (9). An ESP basically operates on an efficiency basis which means that, at any set operating condition, an increase in inlet mass loading will result in an increase in outlet emissions. Therefore, in order to maintain particulate outlet loading and opacity levels while the inlet loading increases, ESP efficiency must increase. This Status Report discusses the effects of duct injection technology on ESP performance and evaluates the options for increasing the efficiency of an existing ESP to maintain performance after the retrofit.

2.0 CONCLUSIONS

1. The generally positive effects of duct injection humidification on ESP performance may or may not offset the increased particulate loading. The net change in performance for a particular ESP will be site specific.
2. The low-resistivity condition of the particulate downstream of duct injection processes can provide excellent particulate collection and precipitator operating voltages; however, increased scouring and rapping re-entrainment may result due to reduced electrical holding forces. This problem tends to be more severe on precipitators with lower specific collection areas (SCA).

3. In addition to re-entrainment, ESP performance can potentially be limited by space charge quenching in the inlet fields which is caused by the high dust loading associated with duct injection.
4. Many ESP upgrade technologies were designed to overcome high-resistivity conditions. There are limited practical ESP upgrade options for low-resistivity applications:
 - Increasing SCA is effective but would involve significant capital investment.
 - Power-off rapping can successfully restore ESP electrical conditions if long-term residual ash/sorbent waste deposits form on the collection plates.
 - Flue gas conditioning with ammonia or other additives which promote particle cohesion is promising because it minimizes re-entrainment.
 - Special discharge electrodes are effective at producing a higher current density at a given voltage. These electrodes would also minimize space charge quenching.
 - Modifying collection plates to reduce scouring re-entrainment may be effective by minimizing gas velocity at the dust layer surface.
 - Correcting gas velocity distribution within the ESP may be effective in reducing short circuiting, local high gas velocities, hopper sweepage, etc.
5. Optimizing rapping intensity and frequency can improve ESP performance by reducing opacity spikes, but it may provide only limited improvement in overall mass emissions.
6. Increased ash/sorbent waste loading can result in ash re-entrainment from ESP hoppers, and possible grounding of electrical sections due to high hopper levels.

3.0 RECOMMENDATIONS

1. Complete a review of the electrical and mechanical condition of the existing ESP being considered for operation in conjunction with a duct injection system.

2. Measure velocity distribution to determine if the ESP meets the Industrial Gas Cleaning Institute guidelines for gas distribution.
3. Investigate methods to reduce ash re-entrainment and space charge quenching in the inlet fields such as:
 - increasing SCA
 - power-off rapping
 - flue gas conditioning with ammonia
 - adding special discharge electrodes
 - modifying collection plates
4. Re-evaluate ESP rapping schedule to optimize both intensity and frequency for new flue gas/particulate characteristics.
5. Re-evaluate ash pulling schedule to minimize hopper re-entrainment and the potential grounding of ESP electrical fields.
6. Evaluate flue gas conditioning with ammonia and addition of special discharge electrodes under this DOE program.
7. Determine if removal of wire deposits from duct injection is a function of ESP design type (rigid frame vs. weighted wire).

4.0 DISCUSSION

4.1 Effects of Duct Injection on ESP Performance

Flue Gas Effects

The retrofit of a Dry Sorbent Injection (DSI) or Duct Spray Drying (DSD) process causes the following changes to the flue gas entering the ESP downstream of the injection point:

- Increase in particulate loading
- Decrease in temperature
- Increase in density
- Decrease in gas volume with corresponding decrease in velocity
- Increase in humidity
- Decrease in SO_2/SO_3 content

The decrease in flue gas volume flow rate results in a higher specific collection area (SCA) for a given ESP and a lower velocity. The increase

in gas density allows the ESP to operate at higher power levels without back corona. All of these effects will allow better ESP performance to offset the increase in particulate loading. There have been extensive pilot studies and many full-scale demonstrations which indicate that upstream duct humidification can benefit ESP performance (12,16,18).

Low-Resistivity Dust

Humidification also results in a decrease in particulate resistivity. Tests at spray dryer installations and DSI pilot plants indicate that, although calcium-based sorbents have very high (10^{13} to 10^{14} ohm-cm) resistivities at 300°F, the surface conditioning due to humidification and cooling reduces the resistivities of the ash/sorbent wastes from these processes to extremely low (10^7 to 10^8 ohm-cm) values (10,11). This is primarily due to the low temperature, high humidity conditions in ESPs downstream of these processes. Figure 1 shows a typical fly ash resistivity-temperature relationship.

Although reduced resistivity allows the particulate to be collected more easily, ESPs operating on low-resistivity dusts can experience rapping and scouring re-entrainment of the collected solids due to reduced holding forces. When re-entrainment is a problem, the emissions can increase by a factor of 10 or more (16). Scouring re-entrainment is strongly influenced by velocity; this may not be a significant problem if the gas velocity drops substantially after the duct injection system is retrofitted.

Non-Ideal Effects

Re-entrainment may also occur when low-resistivity particles acquire the charge of the ESP collecting plates at high potential gradients which are typical in an ESP. The particles then can be repelled from the plates. ESPs with large SCAs may have enough excess collecting area to compensate for re-entrainment problems. Re-entrainment, however, was the major cause of poor ESP performance in the TVA spray dryer tests (6) and the Bechtel Confined Zone Dispersion (CZD) tests (4).

Space Charge Quenching

Another potential effect of a duct injection retrofit upstream of an ESP is space charge quenching due to high dust concentrations in the ESP inlet field. In pilot tests of the Dravo Hydrate Addition at Low Temperature (HALT) process, the current density in the first ESP field was severely limited (3,11). This current density reduction was sufficient to reduce both the charge on the particles and the electrical holding force of the collected dust.

Electrode Design

One retrofit concern that has not been investigated is the cleanability of deposits from weighted wire type discharge electrodes when operating under duct injection conditions. Increased quantities, as well as physical properties of the ash/sorbent waste solids, may lead to increased wire deposits. Most pilot-scale ESPs used in duct injection research have been of the rigid frame discharge electrode design, as have the full-scale ESPs in retrofit spray dryer installations. Rigid discharge electrodes can be rapped with more intensity, which results in better cleaning, and are not as prone to rapper induced failure as weighted wires. Most potential duct injection retrofit candidates, however, will have ESPs with weighted wire discharge electrodes. If wire deposits increase with duct injection, they could lead to potential degradation of precipitator electrical conditions if the deposits cannot be easily removed by the existing rapper system. Increased rapping intensity can lead to more wire failures which result in reduced collection efficiency and higher maintenance cost. The capital cost of converting a weighted wire ESP to a rigid frame system would be substantial. There is no evidence to indicate that the deposits resulting from duct injection will be difficult to remove, but, until operating data are collected from a weighted wire ESP/duct injection application, the possibility cannot be eliminated. Data from the Beverly pilot plant, which uses a weighted wire ESP, will help determine if discharge electrode type could be a limiting factor for duct injection retrofits.

Data from Spray Dryer/ESP Applications

Similarities between spray dryer and duct injection retrofits allow information gathered on spray dryers to be applied to duct injection systems. During tests at the Tennessee Valley Authority's (TVA) 10 MW spray dryer retrofit, the particulate removal efficiency of 99.7% with a four field ESP did not change significantly after the spray dryer installation (14). The spray dryer increased the inlet loading to the ESP by a factor of ten and the outlet emission also increased by a factor of ten, but it was still below the 0.11 lb/MMBtu emission limit set by the State of Kentucky (See Table 1).

The changes in gas conditions allowed for improvement in the electrical operation of the ESP with the electric field strength increasing by nearly 30%. The ESP electrical operation was limited not by electrical breakdown in the gas space but by current output from the transformer-rectifiers. Two concerns with adding a spray dryer upstream of an ESP were not observed. The first concern was space charge quenching resulting from a high concentration of fine particulates. Secondly, an increase in ash resistivity was considered possible. In fact, particulate resistivity decreased as a result of adding moisture and reducing flue gas temperature.

ESP efficiency did not increase at spray dryer conditions although the particulate generated from the spray dryer was in the range of 5-20 microns in size which is easily removed by ESPs. Emitted particles ranged from 2-5 microns. From Table 1, comparing spray dryer Test No. 2 to Test No. 3 shows that, when the velocity and SCA increased, particulate removal efficiency actually decreased. This, along with the decrease in resistivity, indicates that scouring and rapping re-entrainment may have limited the performance of the ESP. Modifying the rapping schedule produced a 25% improvement in performance; however, this was still lower than values predicted. "Although it appears that re-entrainment is a significant factor for the spray dryer/ESP application, the most recent data indicate that it is possible to maintain an emission level below the NPS limit of 0.03 lb/MMBtu with an ESP of 400 ft²/kacfm" (14).

Most plants considered to be candidates for DSI or DSD retrofits, however, include ESPs with an SCA much lower than the TVA system. Consequently, re-entrainment caused by the low-resistivity conditions as discussed above may be the most adverse effect of the DSI or DSD process on ESP performance. Baffles or shields on collection plates are effective in reducing scouring re-entrainment. However, this type of modification can be costly, and may not be possible on many older ESPs.

4.2 Potential Options for Upgrading ESP Performance

As noted in Section 4.1, the retrofit of a duct injection system will cause both positive and negative effects on ESP performance. The net change in performance for a particular ESP is site specific and very difficult to determine in advance.

Several methods exist for increasing the efficiency of an existing ESP. Potential options for upgrading ESP performance include:

1. Flue gas conditioning with SO_3
2. Cooled electrode precharging
3. Wider plate spacing
4. Pulsed Energization
5. Intermittent energization
6. Increasing specific collection area (SCA)
7. Power-off rapping
8. Flue gas conditioning with ammonia
9. Reheating the flue gas
10. Increasing ESP operating voltage
11. Special discharge electrodes
12. Modified collection plates
13. Correcting gas velocity distribution

Unfortunately, not all of these methods are applicable after the retrofit of duct injection technology. Many of these techniques for improving precipitator performance were developed to overcome problems associated

with difficult to collect, high resistivity (10^{11} to 10^{13} ohm-cm) fly ash. As previously mentioned, the particulate resistivity will decrease with the application of a duct injection system. Each of these options is discussed below as is its applicability after a duct injection retrofit.

Flue Gas Conditioning with SO_3

Flue gas conditioning with SO_3 or SO_3 -evolving compounds reduces fly ash resistivity by increasing the flue gas acid dew point. SO_3 condenses on the ash particle and forms a conductive layer making the particle easy to collect. This is a successfully proven technique when applied to 300°F flue gas with high-resistivity ash (21). However, SO_3 conditioning would be of little value in low-resistivity DSI or DSD applications. In addition, the alkaline sorbent would remove the injected SO_3 .

Cooled Electrode Precharging

Cooled electrode precharging accomplishes the same goal as SO_3 conditioning by lowering the particle temperature and promoting acid condensation. As with SO_3 conditioning, however, its intended application is for a typical air preheater outlet flue gas temperature (around 300°F) with high resistivity ash (17). The particulate is already cooled at the ESP inlet with a duct injection process. Therefore, this option is not considered applicable to duct injection retrofits.

Wider Plate Spacing

Widening the plate spacing from 9-10 inches to 12-18 inches has resulted in some operating improvement. Advantages of wider plate spacing for a new or modified ESP are lower capital, operating and maintenance costs. Wider plate spacing results in an increased electrical field near the plate which increases the electrical force for particle collection. EPRI tests at Arapahoe showed that removal efficiencies did not change for plate spacings of 9, 12 and 18 inches even though SCA decreased as the

plate spacing increased (1,2). Tests by TVA on a 1 MW spray dryer/ESP pilot plant indicated that increasing plate spacings from 12 to 15 inches caused efficiencies to rise slightly from 98.0 to 98.5% (14). For borderline sized precipitators, however, a wider spacing is not likely to solve the potential ESP degradation problems associated with the retrofit of a duct injection system (12). In fact, it is not suggested for duct injection system retrofits, but should be considered as an option if it is necessary to enlarge the existing precipitator.

Pulsed Energization

Pulsed energization improves the current density of ESP fields by superimposing a very fast rising, short duration, high voltage pulse on top of the normal voltage wave form. This commercially available technique has shown improvements in collection efficiency when applied to high-resistivity particles, but showed little or no improvement when applied to moderate- to low-resistivity fly ash (8). Therefore, this option is not likely to be viable in conjunction with duct injection technology.

Intermittent Energization

Intermittent energization (IE) is an easily applied, commercially available modification to conventional ESP energization which has shown the ability to reduce ESP power costs. IE involves modifying the existing silicon controlled rectifiers (SCRs) (part of the T-R sets) to alternately block and pass integral numbers of half cycles. When the SCR blocks the half wave, the ESP voltage does not drop to zero, but stays near the corona quench voltage due to the capacitance of the ESP.

Although the primary benefit of IE is cost savings, a few studies have shown that some improvement in ESP performance can be obtained with intermittent energization. In an EPRI study at the Arapahoe Test Facility, it was shown that, in a case of an ESP operating with severe back corona on high-resistivity dust, IE was capable of producing a 40%

reduction in emissions while decreasing primary power by greater than 60% (15). It is suggested that the improvement in performance was due to elimination of back corona. Typically, back corona should not be a factor after duct injection retrofit. Therefore, IE would only be recommended if it is necessary to enlarge the existing ESP or if the T-R controllers require replacing.

Increasing Specific Collection Area (SCA)

Some ESPs may need to increase in size to meet the required emission levels. This is likely the most expensive upgrade option, but an increase in SCA of up to 20% is usually possible by only increasing ESP height. Larger SCA increases would require additional precipitator fields which adds to the space occupied by the ESP and would involve a significant capital cost. A survey of potential duct injection sites indicates that 57% of the plants have sufficient space to allow a 50% increase in precipitator SCA (13). Thus, increasing the SCA of an existing ESP, although expensive, is an option that needs to be evaluated if the duct injection process results in increased emissions.

The addition of a second ESP in parallel to increase SCA has some special advantages. Re-entrainment due to low resistivity is a strong function of velocity. In these cases, a small decrease in velocity can cause a large decrease in emissions. A second ESP in parallel will allow both ESPs to operate at lower gas velocities while providing an increase in SCA. An additional advantage of adding a parallel ESP is that the boiler does not have to be taken off-line during construction; only a short outage is necessary for tie-in.

Power-Off Rapping

Extended operation of lime slurry injection at a full-scale DSD test site resulted in a long-term residual buildup of particulate on the ESP collecting plates. This resulted in severe ESP power degradations and increased opacity (4). Intermittent power-off rapping was generally

successful in removing these long-term plate buildups and in restoring stack opacity to acceptable levels. This was typically accomplished by de-energizing the electrical field and manually initiating the rapping. However, this sometimes resulted in high opacity excursions. While this practice in its crude form may not be suitable for normal power plant operation, it may be possible to automate the procedure. Several manufacturers offer microprocessor based programmable rapper controllers and automatic precipitator power controllers. It may be possible to periodically implement a sophisticated field-by-field power-off rapping procedure utilizing this technology as part of normal operations. This option is considered feasible in conjunction with the retrofit of a duct injection system.

Flue Gas Conditioning with Ammonia

The injection of a small amount (10 to 30 ppm) of ammonia (NH_3) has been successfully demonstrated to reduce emissions due to re-entrainment by increasing the cohesiveness of precipitated fly ash (7). By forming agglomerates and/or sheets, the ash will fall into the collection hopper instead of being carried out of the ESP as fine particles. This results in reduced emissions due to particle re-entrainment caused by rapping, high gas velocities (scouring), or hopper sweepage.

NH_3 combines with SO_3 in the flue gas and forms ammonium bisulfate and ammonium sulfate which condense on the surface of the particle. Since the ammonia requires the presence of SO_3 to increase cohesion, it would have to be injected upstream of where the sorbent is added. Therefore, it would only be effective for increasing the cohesion of the fly ash particles. However, from analysis of the particle size data, it appears that fly ash particles might represent a significant portion of the outlet emissions (9). This indicates that ammonia addition might provide some improvement in ESP performance in conjunction with a duct injection system. However, the fate of the ammonium compounds in the presence of unreacted calcium hydroxide is unknown and should be evaluated.

Another additive that should be investigated is a proprietary magnesium based compound produced by Calgon (19). It has shown the ability to improve cohesion and reduce re-entrainment from an ESP operating on low-resistivity ash.

Reheating the Flue Gas

Modification of the resistivity of the ash/sorbent waste resulting from a DSI or DSD system could be effected by increasing the temperature in the ESP. Since low approach-to-saturation temperatures are necessary to obtain the required levels of SO_2 removal in the upstream ductwork, increasing the temperature might be unacceptable. However, some form of reheat system might be considered in which the gas is heated just upstream of the ESP. Although this would be detrimental to SO_2 removal in the ESP, it might improve the particulate removal efficiency of the ESP. This would result in a substantial capital and operating cost, however, and the space requirement for a reheat scheme also makes this option unattractive.

Increasing ESP Operating Voltage

An additional advantage of the cooler gas stream which results from duct injection is that the increased density at the lower temperature will allow for higher ESP operating voltages. The voltage at which an ESP will operate is nearly proportional to the gas density. This means that an ESP operating at 45 KV at 300°F should be able to operate at 57 KV at 145°F (16). Theoretically, the performance of an ESP should be proportional to the square of the operating voltage. Therefore, neglecting non-ideal effects, this 28% increase in voltage would result in a 64% improvement in performance.

However, non-ideal effects may cause unexpected results. Low-resistivity duct injection ash/sorbent waste may acquire an induced charge that is the same charge as the ESP plates under the potential gradient and current density conditions typical of an ESP. This could cause collected material to be repelled from the plates and re-entrained in the gas stream.

It is unlikely that an older ESP operating in conjunction with the retrofit of a duct injection system could achieve the full benefit from the increased gas density because the existing power supplies will probably not be rated to deliver the increased voltage. Therefore, increasing voltage would likely require replacement of the existing T-R sets with higher voltage units to operate at the higher levels that can be obtained at the reduced flue gas temperature. This would result in a significant capital expenditure.

Due to the non-ideal repelling potential and the capital cost involved, this upgrade option is not likely to be attractive after duct injection is applied.

Special Discharge Electrodes

Space charge quenching is often found in high dust-loading applications such as cement kilns or applications with large amounts of submicron particles such as smelters. For these applications, ESP vendors use corona electrodes designed with barbs to produce more current at a given voltage. If corona quenching in the first ESP section is found to be a limiting factor, a discharge electrode designed for increased current may be installed in the first section. This improvement would primarily be applicable to ESPs with a small SCA; therefore, testing of special discharge electrodes is recommended for an ESP in the lower SCA range downstream of a DSI and/or DSD process.

High-current discharge electrodes may have another advantage. As previously mentioned, low-resistivity material may be repelled from the ESP plates induced by the high potential gradient in the ESP. Increasing the voltage would aggravate this problem, but increasing the current density would help to hold particles to the plates.

Modified Collection Plates

Although many ESPs have some type of baffle arrangement on the collection plates to minimize gas velocity near the dust layer surface, this may be

inadequate for the low-resistivity conditions associated with duct injection systems. It may be possible, depending on existing wire-plate arrangement, to provide additional baffles or shields on the collection plates to minimize scouring and rapping re-entrainment. Examples of such baffles include: V-plate type shielding, zig-zag plates, and offset plates (20). Depending on the specific design of the existing ESP, such collection plate modifications may not be technically feasible or may require substantial capital expense.

Correcting Gas Velocity Distribution

Industrial Gas Cleaning Institute guidelines for ESP gas distribution recommend that 85% of velocity readings fall within 25% of the average velocity and no readings be more than 40% from the average value. On older ESPs which were in service before the establishment of these guidelines, it may be necessary to modify the inlet section by adding turning vanes or perforated plates to create an even gas flow and by adding baffles to prevent sneakage.

4.3 ESP Operating and Maintenance Considerations

As noted in Section 4.1, optimizing rapping intensity and frequency can improve ESP performance. A portion of the emissions from all ESPs is the result of rapping re-entrainment. The rapping frequency and intensity should be adjusted for the fly ash and flue gas conditions specific to each ESP application. When these conditions are altered, as in the case of a duct injection retrofit, the rappers must be readjusted. In many cases, optimizing rapping frequency and intensity can significantly improve the performance of an ESP.

For ESPs operating with low-resistivity ash, rapper adjustments can generally minimize opacity spiking, but they may not result in significant reductions in overall mass emissions. In these cases, mass emissions from velocity scouring far outweigh the contribution of rapper related re-entrainment (5,6). Since opacity is generally the day to day indicator

of ESP emissions compliance, however, rapper optimization is a very necessary task.

The increase in particulate loading to the ESP can result in generally higher ash levels in hoppers. This can result in increased ash re-entrainment from the hoppers, and ultimately cause grounding of electrical sections due to high ash levels. The design of the ash handling system and the frequency of pulling ash from the ESP should be re-evaluated after the retrofit of a duct injection system.

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TABLE 1. ESP PARTICULATE REMOVAL PERFORMANCE (14)

Condition	ESP Inlet Flow. acfm	ESP Inlet Temp. °F	Fields	SCA. sq ft/kacfm	Gas Velocity. ft/sec	Inlet Conc. gr/acf	Outlet Conc. gr/acf	Outlet Conc. gr/dscf	Outlet Conc. 1b/10 ⁶ Btu	Fly Ash Rem. %
SPRAY DRYER OFF										
1	34614	319	4	390	3.76	1.151	0.00198	0.00332	0.00705	99.832
2	34961	317	3	290	3.80	0.942	0.00240	0.00404	0.00877	99.732
3	43965	317	4	307	4.78	0.727	0.00221	0.00380	0.00870	99.690
4	26564	318	3	381	2.89	0.584	0.00220	0.00372	0.00778	99.601
5	35124	316	2	192	3.82	0.646	0.00942	0.01582	0.03385	98.485
SPRAY DRYER ON										
1	32832	142	4	412	3.57	9.223	0.0155	0.0219	0.0505	99.838
2	32623	144	3	311	3.55	8.987	0.0304	0.0433	0.0986	99.662
3	37752	145	4	358	4.10	10.286	0.0167	0.0893	0.1882	99.404
4	24242	144	3	419	2.64	9.167	0.0256	0.0355	0.0807	99.726
5	31856	147	2	212	3.46	8.582	0.2187	0.3134	0.6565	97.464

Spray Dryer Operating Conditions: Reagent Ratio - 1.3 moles fresh $\text{Ca}(\text{OH})_2$ /mole inlet SO_2

Approach to Adiabatic Saturation - 20°F

Inlet Temperature - 320°F

Lime Solids - 25 wt. %

Recycle Solids - 35 wt. %

Inlet SO_2 - approximately 2500 ppm

Figure 1
Typical resistivity versus temperature curves for fly ash at
three water vapor concentrations. (20)

STATUS REPORT
WASTE HANDLING SYSTEM
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

After the retrofit of a Dry Sorbent Injection (DSI) or Duct Spray Drying (DSD) system at an existing power plant, the quantity and physical and chemical properties of the waste collected in the existing electrostatic precipitator (ESP) will change significantly. These changes may necessitate modifications to the design and operation of the existing waste handling system such as increasing its capacity, altering its arrangement, and/or changing the frequency of pulling ash.

A waste management system consists of five principle subsystems: transfer, storage, conditioning, transport, and disposal. The transfer, storage, and conditioning operations are typically performed at the plant site, while transport and disposal are usually off-site operations. The transfer, storage, and conditioning of wastes produced by the DSI and DSD processes are addressed in this Waste Handling System Status Report. The transport and disposal of these wastes are covered separately in the Waste Disposal Status Report.

Recent experiences in handling dry calcium-based flue gas desulfurization (FGD) wastes have shown the need for a greater awareness of the uncertainties and potential problem areas with waste handling systems when adapted to DSI and DSD. This Status Report addresses these potential problems and the design and operation considerations that have evolved to overcome them. Design and operation considerations and alternatives will be presented for each subsystem based on experience from sorbent injection pilot plants/demonstrations and from related applications.

2.0 CONCLUSIONS

1. The properties and quantity of the waste are the two most important factors to consider when determining the adequacy of the existing

waste handling and storage systems after retrofit of a duct injection process. Proper testing and research must be done to determine what, if any, design and operation modifications must be made.

2. There are several types of waste transfer subsystems including pneumatic, mechanical, and wet sluice. Duct injection retrofits can affect each type of system differently. Existing pneumatic transfer systems may be usable with modifications after a duct injection retrofit. Existing mechanical systems likely will require modifications and still may be capacity limited. Very little is known about the effect of duct injection solids on the operability of a wet sluicing system.
3. The most economical and simple method to accommodate the increased waste solids volumes is to increase ash pulling frequency. This may not be sufficient or technically feasible in many cases.
4. Existing ash removal systems, which currently operate near capacity may require significant modification, and, in some cases, complete replacement to handle the substantial increase in solids.
5. Fluidizing pads may be required in ESP hoppers to get DSI or DSD ash/sorbent waste to flow into the transfer system.
6. Existing ash silos can likely be utilized after duct injection retrofit, but fluidization (if not already existing) will likely be required to effect material discharge. Vibrators should not be used. Because of the increase in mass loading, storage capacity (in terms of hours or days) will be sharply reduced. Additional storage capacity may be required. Expanding the ash hauling schedule over a longer period may also be necessary.
7. Conditioning of the ash/sorbent waste with water to 15-25% by weight water is effective. Ready access of conditioning equipment is important for daily wash-down.

3.0 RECOMMENDATIONS

1. To assess the adequacy of the existing waste handling system design after a duct injection retrofit, the following design information is required:
 - a. Characterize physical, chemical, and mineralogical waste properties specific to plant design and operating conditions.
 - b. Determine waste quantities.
 - c. Evaluate the size and arrangement of the plant for conveying distances vs. capacities.
2. Continue to monitor current practice in full-scale waste handling operations with related dry processes such as spray drying, furnace sorbent injection, etc.
3. Conduct research on the effects of duct injection wastes on wet sluice ash removal systems.

4.0 DISCUSSION

The physical, chemical, and mineralogical properties of the waste generated from a duct injection system will be different from fly ash. Several of these properties can affect the conveyance and storage of this material. A list of these properties is presented in Table 1.

To some extent, ash/sorbent waste from duct injection processes is similar to that from spray dryer scrubbers although there is considerably more unreacted Ca(OH)_2 in the duct injection waste because of its inherently lower sorbent utilization. A review of the waste handling systems at existing utility spray dryer scrubber installations, as well as those in use at other related applications and duct injection pilot plants, will provide design information for full-scale duct injection retrofits.

In addition to a change in waste properties, the quantity of waste generated is the other most important factor in evaluating the effects of a duct injection retrofit on an existing waste handling system. Depending on the desired SO₂ removal, coal ash and sulfur content, and recycle rate, duct injection will increase the particulate loading to the ESP by a factor of 3-12 (2).

4.1 Transfer

After the fly ash/sorbent waste is collected in the particulate collection device (usually an ESP), a waste transfer subsystem removes the waste from the collection hoppers and conveys it to a temporary storage area (bin or silo). The transfer equipment may consist of both feeders and conveyors.

There are several types of waste transfer subsystems:

- a. Vacuum Pneumatic
- b. Pressure Pneumatic
- c. Mechanical
- d. Wet Sluicing

The pneumatic and mechanical conveyor alternatives are presented in Table 2 along with their corresponding design considerations and limitations; Tables 3 and 4 summarize the advantages and disadvantages of these conveyors.

Vacuum Pneumatic Conveying

The dilute phase, vacuum pneumatic system is the most widely used in the utility industry. However, after retrofit of DSI or DSD, this conveying system can potentially experience one or more of the following problems:

- a. Plugging in ash intake valves.
- b. Build-up of material in conveyance lines.
- c. Insufficient conveying capacity.

Plugging in ash intake valves is the result of damp solids from the duct injection process and/or condensation caused by the reduced operating temperature in the ESP. Heat tracing and insulating these intake valves should solve this problem.

Air pads had to be installed in the ESP hoppers to aid solids flow out of the hoppers into the ash intake valves at the Dravo Lime Company DSI Pilot Plant (1). A fluidizing air system was also used on the ESP hoppers at the full-scale Coolside Demonstration at Edgewater Unit 4 (8). Two fluidizing stones per hopper were utilized.

Build-up and subsequent plugging in the system is a result of the relatively poor flowability and hygroscopic nature of these wastes. Compared to fly ash only, a significant amount of spray drying waste settled out of the air stream in vacuum conveying tests; most of these deposits consisted of calcium products (6). This is of special concern in areas of high ambient humidity. Such problems can be minimized by using dry, heated air for transporting the solids and/or heat tracing/insulating of conveying lines. Extending the air inlets into heated enclosures has been used successfully in spray dryer applications. Retrofitting wide-angle elbows can reduce the plugging problems at bends.

Insufficient conveying capacity is the result of increased solids loading to the ESP, especially in cases where recycle is used. A revision of the ash pulling schedule is the most straightforward and cost-effective solution. In cases when this is insufficient or impossible, increasing conveying air capacity and/or system component size may be necessary (conveying lines, bin receivers, etc.). If the existing system is currently at or near operational capacity, the best solution may be to replace the entire system with a new system designed to accommodate the full duct injection solids capacity. If adequate clearance exists, a pressure pneumatic ash handling system should be considered as the replacement if recycle of the collected waste will be utilized. This is discussed further in the pressure pneumatic subsection.

Three operating utility spray dryer scrubbers employ vacuum pneumatic conveying systems from their particulate collection device to the ash silo. Generally, these systems have worked fairly well although plugging of lines and elbows has occurred. No major modifications were required (6). Operators of stations experiencing these pluggage problems generally reported that they have established a regular maintenance program to keep the lines clear.

A vacuum-type transfer system was employed under the baghouse at the TVA 20-MW AFBC Pilot Plant (5). Problems of severe condensation in transfer lines, vacuum blowers, and disposal silo baghouse were initially reported. Several modifications had to be made to the system. The transfer lines were insulated and ash was allowed to remain in the hoppers during start-up to prevent excess low-temperature, moisture-laden flue gas from being entrained into the system. An additional air inlet valve was added prior to each hopper discharge point. These modifications significantly improved system operation. Although these modifications seemed to have improved the operations at the TVA Pilot Plant, it is not recommended that high moisture ash be allowed to remain in the hoppers for long periods. Other options considered if system performance during cold weather became unacceptable were routing the air intake line to a warmer area or to enclose the bottom portion of the baghouse.

Pressure Pneumatic Conveying

Pressure pneumatic conveying systems are subject to the same potential operating problems and limitations as vacuum pneumatic systems. The same solutions as discussed above apply to pressure pneumatic systems.

The majority of the operating utility spray dryer scrubbers utilize positive pressure pneumatic conveying systems. No major problems have been reported from these systems although line plugging is the most common nuisance.

Pressure pneumatic ash handling systems allow recycle solids to be diverted directly into a recycle bin for subsequent injection into

the duct. In vacuum systems, the waste must first be transferred to the ash silo, and then conveyed back to the duct or to a recycle bin. In some cases, it will not be possible to modify the existing ash silo to convey material back to the process.

Mechanical Conveying

When considering the retrofit of DSI or DSD to plants that use a mechanical conveying system, the primary concern is conveying capacity. Since many mechanical conveying systems are designed to operate continuously, increasing cycle frequency does not apply. It may be possible to increase this capacity by increasing feeder or conveyor speed, increasing motor size, gearing changes, increasing screw flight diameters, etc. If the existing system cannot be modified to meet the expected increase in solids from duct injection, it may be necessary to replace the entire system.

In addition to capacity limitations, the physical properties of the ash/sorbent waste material may cause operational problems. As previously mentioned, these wastes are hygroscopic and exhibit poor flowability characteristics. They tend to be sticky and bridge over easily. In addition, the material will likely be easily aerated (similar to spray dryer waste), and this limits the speed at which it can be conveyed using mechanical conveyors without being wetted or enclosed (3).

The following discussion, taken from Reference 6, describes potential modifications to mechanical conveying equipment after the retrofit of a duct injection system.

Belt Conveyors - The material to be transported may have to be wetted on the belt conveyor to minimize dusting problems. However, if the material is wetted it may become sticky and special belt cleaners or scrapers may have to be installed to prevent material from accumulating on the belt. Wetting duct injection wastes also increases their potential to cause corrosion; therefore, special corrosion resistant materials of construction should be used.

Screw Conveyors - The typical screw conveyor consists primarily of a standard pitch helix (pitch equal to its outside diameter) supported within a U-shaped trough. These standard components may be modified, however, to improve operations and thereby broaden the conveyor's range of useful applications.

The flight configuration (shape and/or pitch) can be varied to promote mixing, improve feed control or to improve the conveyability of sticky, lumpy or very free flowing materials. Almost any degree of mixing can be achieved with screw-conveyor flights which have been cut, cut and folded or replaced by a series of paddles. The use of ribbon flights allows sticky materials to be handled. Variable-pitch, tapered-flight, or stepped-flight units can provide precise control of the transport rate. Short-pitch screws retard flushing.

As stated previously, the conveyor screw is supported within a trough that typically is U-shaped. Alternate trough shapes also are available to improve conveyor operation. Rectangular troughs (with or without a detachable bottom) are frequently used for handling hot or abrasive materials. During transfer in this type of trough, the material forms a layer on the bottom and partially up the side forcing the material in transit to travel on itself. Thus, abrasion is reduced and internal insulation is provided by the material itself. Tubular troughs are used for outdoor applications and for loading full cross-sections.

Standard materials of construction for screw flighting, flight mounting, troughs, trough ends, covers, hanger straps, feed/discharge spouts, gates, and shafting are generally satisfactory for most screw conveyor applications. However, when any of the following conditions are encountered, special construction materials are required.

- a. Solids pack and build on the trough.
- b. Corrosive or abrasive materials are to be conveyed.
- c. The material to be conveyed is very wet.

For conveyor applications involving duct injection waste, abrasion and possibly corrosion of the conveyor components should be considered. Solids may tend to build up on the trough if moisture is encountered; consequently, the first item listed above also may require consideration. The last item is not expected to be a concern with duct injection wastes.

Stainless steel or mild steel coated with epoxy resin, plastic, rubber ceramic or galvanizing is recommended for trough construction if solids build-up is expected to occur. Constructing most remaining conveyor components with coated mild steel will minimize the effects of abrasive and slightly to mildly corrosive materials during transfer.

Chain Conveyors - The primary component of all chain conveyors is the chain. Selection of the appropriate construction material for a given application generally is dependent on the required strength, expected travel speed and needed attachments (if any). To minimize excessive wear, chain material hardness (based on the Brinell Scale) also must be compatible with the abrasive and corrosive properties of the material to be conveyed (based on the Mohs Index). When severely abrasive materials are handled, special localized hardening can be applied to the areas subjected to wear. The resulting Brinell hardness generally is 180 to 200. Tables and/or graphs presenting acceptable Mohs Index values for materials of specified hardnesses are available to provide guidance during chain material selection.

Drag chain conveyors frequently are equipped with a Type "H" or "C" chain. These chain types are relatively wide, have broad, flat sliding surfaces, and range in pitch (length of one complete unit of chain) from 5 to 8 inches. One of the primary differences between the two chains is working strength. Type "C" drag chains are available with working strengths of 7000 to 9300 pounds whereas Type "H" chains have lower strengths ranging from 3500 to 6500 pounds. Type "C" chains also have a greater wearing surface for sliding on both carrying and return runs. The welded steel chain is a relatively new development. This chain type is available as a drag

chain and has a working strength that generally ranges from 10,000 to 15,000 pounds. A fourth type of drag chain, the "SD" chain, is often used when abrasive materials such as cement clinkers, slag and ashes are handled. This type of chain is similar to the first two types ("H" and "C") except it is fabricated from heavy, heat-treated cast alloy steel and has wide, flat Z-section sidebars. "SD" chains are available with a 6- or 9-inch pitch and working strengths of 16,700 to 23,400 pounds.

A standard en-masse conveyor is provided with straight flights. When some materials are conveyed vertically or even up a steep incline with a chain having this configuration, particles may tend to fall through the chain rather than travel with it. Consequently, the straight flights are replaced with "U"- or "O"-shaped flights to increase the chain surface area in contact with the material and thereby enhance the ability of material particles to interlock with each other. These "U"- or "O"-shaped flights are covered with solid plates at calculated intervals when fine powdery materials are conveyed.

Bucket Conveyor - The primary components of a bucket elevator consist of:

- a. Buckets
- b. Carrying medium
- c. Terminals
- d. Casing

Presented below is a brief discussion of design considerations associated with each of these components.

Buckets - When relatively abrasive materials are handled and extra protection of the digging lip is required, style AA buckets are provided. Styles SC and C buckets are used to convey sticky materials that tend to pack in the bottom of the bucket. The style AC bucket, originally developed for cement plants, is primarily used for fine solids with fluid-like characteristics

where large capacities are required or for highly abrasive free-flowing materials. This type of bucket is provided with a high front lip to increase capacity.

Carrying Medium - Two types of conveying medium are available for bucket elevators -- chain and belt. Belts generally are limited to centrifugal discharge type elevators. Belt and bucket elevators are well adapted to handling abrasive materials that would produce excessive wear on chains. They also are more suitable for high speed applications. However, belt type elevators are sensitive to elevated temperatures. Consequently, when temperatures in excess of 300°F are anticipated, chain elevators are used. Chain and bucket elevators also are equipped frequently with perforated buckets when handling wet materials, to drain surplus water.

Terminals - Chain elevators operate over head sprockets or traction wheels. Using traction wheels at the head-end of an elevator greatly increases both chain and wheel life. The traction wheel can be used on all centrifugal elevators except when handling materials of a lubricating nature. To operate successfully, the traction wheel requires a high coefficient of friction between the chain bushing and wheel surface. Properly applied, a traction wheel operates without slip, thereby eliminating the relative angular movement or scrubbing action between the chain and wheel surface, which is typical of a sprocket and chain combination. The benefit derived from using a traction wheel in lieu of a head sprocket (increased chain and wheel life) is not as significant with continuous elevators because of the lower speeds. However, when used, care must be taken in the selection to eliminate the possibility of slip. Sprockets rather than traction wheels generally are used at the foot-end of an elevator. Engagement between the wheel and chain tends to be loose, resulting in poor guiding of the chain and buckets through the loading zone.

Pulleys are used with belts. Elevator pulleys are either cast iron or welded steel with a nominal crown face for tracking. Head pulleys sometimes are covered with rubber belting, vulcanized rubber or non-skid fabric to provide a higher coefficient of friction between the belt and pulley.

Casing - Elevator casing usually is sectional, dust-tight and is fabricated with structural steel, sheet steel or aluminum. The boot section typically is of heavier gauge. Doors are provided for accessing elevator machinery.

At the GEESI 12-MW DSD Pilot Plant, the waste product was conveyed from collection hoppers to storage by means of a drag chain conveyor (7). The drag chain motion was interlocked with motorized rotary valve feeders on all hoppers.

Wet Sluicing Conveying

Very little is known about the potential effects of DSI or DSD wastes on a wet sluicing ash removal system. There are concerns regarding the cementitious properties of calcium-based materials that can potentially lead to plugging and scaling of conveying lines. The calcium in DSI and DSD wastes, however, has been hydrated prior to entering the process; the potential for any additional hydration in the sluice line is minimal. It is possible that periodic pigging of these lines or cleaning with high pressure water lances may be required to remove scale and deposits. Water addition to the waste material may increase environmental concerns by requiring wet disposal (the unreacted lime in the waste will likely raise the pH of the sluice to as high as 12 (3)). More research is needed to understand fully the effects of DSI and DSD waste on wet sluice ash removal systems before retrofit feasibility can be determined.

Recommended Testing

The waste properties are expected to vary with different plant designs and operating conditions. Therefore, tests to assess accurate waste characteristics should be performed for each DSI or DSD installation as part of the selection and equipment design process. If testing is performed at laboratory-scale, field conditions must be duplicated to give as-conveyed conditions (e.g., ambient conditions at the plant must be considered).

4.2 Storage

An ash silo or bin is usually in place to provide surge capacity between ash production and transport to disposal. The increased volume of waste solids resulting from a duct injection retrofit will reduce the surge capacity. To compensate for this reduction:

- a. The frequency of discharging the waste solids for disposal must be increased. Expanding the ash hauling schedule over a longer period, or increasing the number of trips (or trucks) may be necessary.
- b. Additional storage capacity may be required. Additional waste solids silos may be added to maintain the number of hours or days storage.

Discharge of waste from the silo after DSI or DSD retrofit can be different from that with fly ash only. Due to the physical properties mentioned above, the potential for bridging and rat-holing is much greater.

Testing has indicated that calcium spray dryer wastes are generally free to average flowing (3). This may be attributable to their low moisture content. Higher levels of moisture will likely result in set up of material, reduction of its flowability, and serious storage problems. Flowability tests with waste from furnace sorbent injection indicate that either conical- or flat-bottom silos may be utilized (4).

Hopper modifications such as fluidizing pads, air cannons, poke holes, or strike plates may be required when using existing bins for storage.

At the GEESI 12-MW DSD Pilot Plant, the waste silo was cylindrical in shape with a diameter of 12 ft. and height of 55 ft. (7). This provided a 10-day storage capacity. The silo was fitted with two conical hoppers each of 6 ft. height, 4 ft. 7 in. base diameter, and included angle of 60 degrees. The hoppers were equipped with rotary valves to assist in discharge. In an effort to prevent ash bridging and to facilitate the flow of ash in the silo, the ash silo hopper was insulated and fitted with hopper heaters. The heaters prevented moisture condensation due to ambient temperature changes and, consequently, prevented ash agglomeration inside the silo (7).

In an EPRI survey of calcium spray dryer installations, fly ash bins from the majority of plants are steel and are equipped with fluidizing air pads to assist in discharge (6). At least three of these plants have conical hoppers on their fly ash silos whereas at least seven used flat-bottom silos. The flat-bottom design generally was selected because of the lower costs and its traditional acceptance for conventional fly ash applications. None of these stations reported the use of vibrators. Although EPRI tests show calcium/sulfur wastes are less responsive to fluidization than fly ash, no problems were reported with current storage systems. Two potential problems with fluidizing air are 1) localized pads or stones are less effective than uniform surface coverage, and 2) use of moist fluidizing air may cause wetting of reactive, self-hardening wastes.

Recommended Testing

To predict flow from storage vessels, flow properties should be determined by conducting special direct shear, controlled strain tests (4). The flow properties obtained from these tests are bulk density, effective internal angle of friction during flow, internal angle of friction in incipient flow, kinematic angle of wall

friction, and unconfined yield strength. To obtain an accurate assessment of these flow properties, test procedures must reflect the conditions expected to occur within a storage vessel such as compaction pressure and moisture content.

4.3 Conditioning

Conditioning can be used to make DSI or DSD wastes more amenable for transport and disposal. The alternatives are:

- a. Conditioning the waste with water.
- b. Blending the waste with sludge.
- c. Pelletizing or sintering the waste.

The technique of pelletizing or sintering the waste is used primarily for utilizing the waste product instead of disposing of it. But pelletizing or sintering also may be useful prior to disposal. This process reduces and controls the waste volume, prevents dusting problems, and reduces leaching potential in the landfill. However, the costs associated with these processes are typically very high.

Blending the dry waste with dewatered FGD sludge is another alternative for waste conditioning. The advantages of this method over separate disposal of these wastes are easier handling and stabilizing of the sludge. Calcium spray dryer wastes and wet FGD sludge are currently co-disposed at Basin Electric Power's Laramie River Station (6). The wastes are mixed in a pug mill and then transported to the landfill. No significant problems with the process have been reported.

The most common method of conditioning dry waste is the addition of water prior to disposal. The proper amount of water must be added to control dust generation during truck loading and transport without causing the waste to harden or set up. Generally this will require about 15-25% water, by weight, but this value should be verified by appropriate testing for specific applications. As with conveying and storage systems, additional equipment may be required to handle the

increased waste solids volume. As an alternative to water, specialty chemicals including surfactants and foam are commonly used to suppress dust from solids handling systems. The advantages of these specialty chemicals are that they reduce water requirements.

At the GEESI 12-MW DSD Pilot Plant, the dry waste produced was conditioned with water prior to disposal. Twenty-five percent water, by weight, was added and no problems were reported (7).

At the TVA 20-MW AFB/ Pilot Plant, conditioning with water was accomplished using a pug mill (5). Problems with the pug mill of material hardening on the mixing screws and paddles were resolved when a new mixer was installed that had an intersecting mixing blade (or paddle) design and hinged covers allowing quick and complete access for daily wash-down. This prevented buildup in the mixer that was causing wear and poor mixing. A problem still remained with erratic flow from the silo to the conditioner. This created a problem in regulating conditioning water addition. Rappers, vibrators, sonic horns, and types of aeration systems for the silo were considered for resolution of this problem.

At the calcium spray dryer applications surveyed by EPRI, there were few reported problems with conditioning of the ash using water (6).

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TABLE 1

Important chemical and physical properties of DSI and DSD wastes that can affect Waste Handling Equipment.

Abrasiveness
Tackiness
Corrosivity
Hygroscopicity
Aeration Tendency
Mean Particle Size
Particle Size Distribution
Fine Fraction
Bulk Density
Angle of Repose
Specific Gravity
Moisture Content
Temperature

Table 2

LIMITATIONS OF CONVEYING ALTERNATIVES (6)

PNEUMATIC CONVEYORS					MECHANICAL CONVEYORS				
	Dilute Phase Systems			Dense Phase Systems	Air-Activated Gravity Conveyors	Belt Conveyors	Screw Conveyors	Chain Conveyors	Bucket Elevators
	Vacuum	Positive Pressure	Vacuum/Pressure						
GENERAL MATERIAL PROPERTIES	Dry, granular or powdered materials; Max. particle size of 1"	Dry, granular or powdered materials; Max. particle size of 1"	Dry, granular or powdered materials; Max. particle size of 1"	Dry mat'l that can be aerated and fluidized	Dry mat'l that can be fluidized; Max particle size of 0.84 mm; 20-60% finer than No. 200 sieve	V Fine to 12" size depending on moisture content and bulk density; Limited to temps. under 300°F	V Fine to coarse free-flowing materials; Max. particle size 4"; Temps. to 900°F	V Fine to coarse free-flowing materials; Max. particle size 4"; Temps. to 900°F	V Fine to coarse materials. Suitable for broad range flowabilities; Max. particle size 6"; Temps to >900°F
CAPACITY (TPH)	0.35 - <60 *	10 - 200	0.35 - 200	<200	<1300 *	4 - 5,000 *	<375 *	<180 *	<100 *
DISTANCE	<1,000 ft	<7,500 ft	<7,500 ft	<8,000 ft	<1 mile	6 ft - 7 mi.	Horiz: <100 ft Vert: <80 ft (Min of five screw dia.)	Horiz: <250 ft Vert: <30 ft (drag) & >80 ft (enmasse)	Vert: 125 Ft
RELATIVE COSTS	Economical first cost; High operating costs	High initial cost; High operating costs	High initial cost; High operating costs	High initial cost; Low operating costs	Low operating costs; High maintenance costs	High initial cost; Low operating costs			

* For normal size buckets; super-capacity buckets can handle particle sizes >12".

° Where dry collection of flyash is required, the size of available collectors limits vacuum system handling rates to a maximum of 60 tph.

° For materials having a bulk density of approximately 50 lb/ft³.

Table 3

COMPARISON OF PNEUMATIC CONVEYING ALTERNATIVES (6)

CLASSIFICATION AND TYPE OF SYSTEM	ADVANTAGES	DISADVANTAGES
DILUTE PHASE SYSTEMS		
Negative Pressure	<ol style="list-style-type: none"> 1. Simplified design. 2. Economic first cost. 3. Material can enter pipeline from several sources of supply. 4. Reduced fugitive emissions. 	<ol style="list-style-type: none"> 1. Limited conveying distance. 2. Special piping required. 3. Moisture and outside air can be drawn into system. 4. Erosion of blowers (if mechanical blower used). 5. Use of water jet eductor requires water disposal. 6. Efficiency affected by altitude and material temperature.
Positive Pressure	<ol style="list-style-type: none"> 1. Capable of transporting long distances. 2. Blower is not eroded by conveyed material. 3. Uses smaller pipelines than comparable vacuum systems. 4. Moisture and outside air cannot be drawn into system. 	<ol style="list-style-type: none"> 1. Higher initial cost. 2. Special piping required. 3. Airtight required at each entry point. 4. System leakage will result in fugitive emissions. 5. Throughput of airtight is less than comparable vacuum intake valve.
Vacuum/Pressure	<ol style="list-style-type: none"> 1. Permits pickup from several locations and transport to one or several discharge points. 2. Dust from vacuum-side receiver is delivered into conveyor line. 3. Same as for individual systems. 	<ol style="list-style-type: none"> 1. Same as for individual systems.
DENSE PHASE SYSTEMS		
	<ol style="list-style-type: none"> 1. Continuous removal from hopper. 2. Smaller pipe sizes. 3. Less pipe erosion. 4. Smaller Blowers. 5. Reduced operating cost. 6. Capable of transporting long distances. 	<ol style="list-style-type: none"> 1. Pulsed discharge. 2. Additional height required under the bin cone.
AIR-ACTIVATED GRAVITY CONVEYORS	<ol style="list-style-type: none"> 1. Continuous removal from hopper. 2. Capable of transporting long distances. 3. Low power requirement. 	<ol style="list-style-type: none"> 1. Few utility installations. 2. Other industries claim higher maintenance costs. 3. Limited to fluidizable material.

Table 4

COMPARISON OF MECHANICAL CONVEYING ALTERNATIVES (6)

TYPE OF CONVEYOR	ADVANTAGES	DISADVANTAGES
Belt Conveyors	<ol style="list-style-type: none"> 1. Low operating costs. 2. Safe to operate. 3. Nearly unlimited range of capacities. 4. Resistant to corrosion and abrasion. 5. Provides a continuous flow of materials. 6. Capable of receiving and discharging material from one or more locations. 7. Capable of transporting long distances. 8. Can handle a wide variety of materials including sticky or compressible substances. 9. Can deliver large tonnages economically. 	<ol style="list-style-type: none"> 1. High initial cost. 2. Allowable belt speeds are significantly influenced by properties of the conveyed material. 3. Enclosures required when transferring fine materials or material that aerate easily.
Screw Conveyors	<ol style="list-style-type: none"> 1. Numerous feed and discharge openings are possible. 2. Enclosing trough controls fugitive emissions. 3. Easy to maintain. 4. Inexpensive to replace. 5. Provides a continuous flow of materials. 6. Can be adapted to a wide variety of processing operations. 7. Can be designed to enable easy cleaning. 	<ol style="list-style-type: none"> 1. Typically limited to free-flowing materials. 2. Sensitive to the abrasiveness and corrosiveness of the conveyed material. 3. Limited horizontal conveying distance. 4. Not feasible for large capacities. 5. Cannot be operated at high speeds without creating serious abrasion problems.
Chain Conveyors	<ol style="list-style-type: none"> 1. Multiple feed and discharge points possible. 2. Occupies less space. 3. Can handle materials with elevated temperatures. 4. Uncontrolled feed possible. 	<ol style="list-style-type: none"> 1. Sensitive to the abrasiveness and corrosiveness of the conveyed material. 2. Limited to free-flowing materials. 3. Limited conveying distances.
Bucket Elevators	<ol style="list-style-type: none"> 1. Simplest and most dependable units for vertical lifting. 2. Some designs can accommodate materials that are somewhat sticky or compressible. 3. Suitable for abrasive materials. 4. Requires very little floor space. 5. Relatively low initial cost. 	<ol style="list-style-type: none"> 1. Not recommended for very sticky materials. 2. Limited to vertical lifting. 3. Maintenance costs tend to be high.

STATUS REPORT
RECYCLE SYSTEM
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

Due to the low reagent utilization inherent in the Dry Sorbent Injection (DSI) and Duct Spray Drying (DSD) processes, high stoichiometric feed ratios are required to achieve the desired levels of SO_2 removal. This results in large quantities of unreacted reagent in the waste stream. Rather than discard the waste product and throw away this unreacted reagent, recycle can be used in an effort to increase the reagent utilization and improve the overall economics of these processes. This Status Report reviews the potential advantages and disadvantages of recycling the ash/sorbent waste collected in the electrostatic precipitator (ESP), and the design considerations for a DSI and DSD recycle system are discussed.

2.0 CONCLUSIONS

1. Recycle of ash/sorbent waste has the potential to improve overall sorbent utilization, thus reducing the fresh sorbent required and the total waste quantity produced, to achieve a given level of SO_2 removal.
2. Higher recycle ratios may result in higher utilizations, but there are practical limits to operating at high recycle rates. These limitations include existing ESP and ash handling capacity and are site specific.

3. In addition to existing ESP and ash handling capacity, there is a limit to the amount of solids in the slurry that can be pumped and atomized for any given approach to saturation in the DSD process.
4. Laboratory data indicate that recycle solids may become unreactive due to CaSO_3 crystal formation on the particle surface. There could be significant unreacted lime inside the particle, unavailable for SO_2 removal.
5. For DSI, the most straightforward recycle injection system would simply inject solids from the fly ash storage silo directly into the duct at a controlled rate. If this is not possible, the waste solids would be conveyed to a recycle storage bin first for subsequent injection into the ductwork.
6. For DSD, the recycle solids would be transported from the ash silo or ESP hoppers into a recycle storage bin. From the recycle bin, the solids would be slurried with water, and the resulting recycle slurry would then be mixed with the lime slurry to produce the desired feed slurry solids concentration.

3.0 RECOMMENDATIONS

1. Determine the factors limiting the reactivity of recycle waste, and the potential methods to increase recycle material reactivity:
 - Grinding
 - ADVACATE
2. The effects of recirculating large quantities of waste products on duct buildups, particulate collection, and ash handling equipment should be determined in addition to continued efforts to improve SO_2 removal and sorbent utilization.

3. Determine an optimum recycle ratio (considering technical and economic factors) for each duct injection process that provides 50% SO_2 removal for the least cost. Determine the operating conditions which result in increased SO_2 removal efficiencies.
4. Determine best dual-fluid atomizers for DSD from the nozzle characterization tests. This is important in determining maximum feed slurry solids limitations.

4.0 DISCUSSION

Recycle in a sorbent injection system consists of returning a portion of the waste solids (fly ash, calcium-sulfur salts, and unreacted lime) to the flue gas stream. By providing multiple exposures of sorbent to the flue gas, recycling increases the opportunity for a given sorbent particle to react with SO_2 . For a given level of SO_2 removal, increased utilization of the reagent will result in less unreacted sorbent in the waste product. Thus, recycle of ash/sorbent waste material will reduce the total quantity of waste which must be disposed.

There are several sorbent injection processes that produce a dry waste product. Basic schematics of these are shown in Figure 1. Recycle systems typically used in these processes can be grouped into two categories: 1) injecting the recycle stream separately from the fresh feed (Figures 1a, 1b, and 1c), and 2) injecting a combined fresh feed and recycle stream (Figures 1d and 1e). While each of these processes utilize sorbent injection, this Status Report will concentrate on DSI and DSD (Figures 1c and 1d, respectively).

4.1 DSI System

4.1.1 Process Considerations

Most DSI sorbent injection processes described in the literature currently use recycle as an option. Since these processes are relatively new, the initial investigations have concentrated on demonstrating the feasibility of the technology on a once-through basis. Once the systems have been proven, the benefits of recycling can then be examined and the process optimized.

Typical DSI reagent utilizations for a once-through (no recycle) process range from 18-25% at an approach to saturation of around 20°F; corresponding SO₂ removal efficiencies range from 40-55% (2). Because of its low capital cost, the economics of DSI are strongly dependent on reagent costs. Recycling has been suggested to reduce fresh lime requirements. Pilot-scale testing with a recycle ratio of 2:1 (lb. recycle/lb. fresh reagent) improved SO₂ removal approximately 5 percentage points, and a 5:1 recycle ratio increased SO₂ removal by 15 percentage points (3). Radian's preliminary test results at the Meredosia pilot plant indicate that an improvement in SO₂ removal of 5-10 percentage points was possible with a recycle ratio of about 2.0; lime utilization increased by about 10 percentage points as well (8).

It appears that recycle ratios as high as 5:1 are feasible from a solids injection standpoint, but the impact on ESP performance and solids handling equipment must be determined. At the Coolside Demonstration at Edgewater Unit 4, for example, the recycle ratio was limited by the capacity of the existing vacuum ash handling equipment under the ESP (9). The maximum capacity achieved during Coolside testing was less than half the rated design capacity.

Although the General Electric (GEESI) proof-of-concept duct injection testing performed at Beverly utilized a slurry sorbent atomized in a rotary atomizer (DSD), the recycle testing was performed with dry

recycled ash/sorbent waste injected upstream of the lime slurry atomization zone (7). Only a few dry recycle tests were run, but GEESI stated that the Ca/S ratio required to achieve 50% SO₂ removal could be reduced from 1.5 to 1.0 by injecting dry recycle material at a rate of 4 gr/acf (estimated to correspond to a recycle weight ratio of 1.9).

EPRI is sponsoring research that will examine the effects of a 5:1 recycle ratio in a 4 MW pilot plant using the HYPAS FGD process (4). In the HYPAS process, there are two particulate control devices in series (Figure 1e). The first collector (usually an ESP) removes most of the boiler fly ash. Sorbent is injected between the two particulate collection devices. Because most of the relatively inert fly ash is removed by the upstream particulate collector, higher ratios of uncontaminated spent sorbent can be recycled. Another advantage of upstream fly ash removal is that the ash does not contain calcium-salt contaminants improving its reuse potential.

Recent DSI pilot-plant tests (50 cfm) by Acurex Corporation indicate that recycle material may not be very effective at improving SO₂ removal and sorbent utilization even though it contains substantial unreacted lime (1). Injection of dry lime and recycle downstream of humidification resulted in only a 1-2% increase in SO₂ removal compared to lime-only tests when long-term steady state recycle operation was simulated. Acurex suggested that CaSO₃ crystals on the surface of the lime tend to blind the active surface and plug the pores.

4.1.2 System Design

It is expected that many candidate plants for DSI retrofit will employ an existing vacuum pneumatic system to convey ash from the ESP to an existing ash silo. Because of the nature of vacuum ash handling systems, the ash has to be conveyed to the ash silo first before it can be recycled. It may be possible to modify the discharge equipment underneath the existing ash silo to allow a portion of the ash to either be blown directly back into the duct or conveyed to a recycle storage bin for subsequent injection into the duct.

For smaller units, the ash may be metered and then dilute-phase conveyed using a rotary feeder and rotary air lock underneath the ash silo directly back to the duct distribution header. For this design, the need for a separate recycle storage bin is eliminated. This is what was done at the Coolside Demonstration at Edgewater Unit 4 (9). For larger units, especially units with more than one duct/ESP, ash will normally be dilute-phase or dense-phase conveyed to a recycle bin; from the recycle bin, it will be metered and dilute- or dense-phase conveyed using rotary feeders/rotary air locks to the various injection points - one dedicated set of rotary valves and blower per injection point.

If a positive pressure or mechanical ash handling system exists at the plant, a diverter gate may be installed in the ash line(s) to the existing ash silo to direct the ash/sorbent waste to a recycle bin for a portion of the time. This design eliminates the need to convey the recycled solids out to the ash silo and then back to the process. In addition, no modifications to the ash silo discharge equipment would be necessary. It may be possible to direct ash from only the hoppers nearest the ESP inlet. Inlet fields collect the majority of the solids, including most of the unreacted lime. From the recycle bin, the ash would be metered and dilute-phase conveyed as described above.

A simple system similar to that used for the fresh dry sorbent injection can be used to inject the recycle solids. From a flexibility and reliability standpoint, fresh sorbent and recycle material should be injected separately. This would allow the recycle system to be shut down without interrupting the fresh sorbent system.

4.2 DSD System

4.2.1 Process Considerations

Recycle of ash/sorbent waste in conventional lime spray dryers is the normal mode of operation. Recycle not only improves reagent utilization, but it also facilitates drying of the atomized slurry. Recycle ratios in these lime spray dryers range from 1:1 to 9:1 (5). In

these processes, the recycle ratio depends on the SO_2 removal requirement, the coal ash content, and the maximum allowable solids content of the feed slurry.

4.2.2 System Design

When applying recycle to the DSD process, the dry fly ash/sorbent waste would be conveyed to a recycle storage bin. As with the DSI system, this would be accomplished by dilute- or dense-phase conveying from the ash silo if a vacuum ash handling system exists, or diverted directly to the recycle bin if a positive pressure or mechanical system exists. Material from this bin would be slurried with water and the resulting recycle ash slurry would be subsequently mixed with the fresh lime slurry. Dilution water will control the solids concentration in the final atomizer feed slurry to maintain the highest practical solids content at a given approach to saturation temperature. The maximum practical concentration of solids in the feed slurry is dependent on feed equipment and atomizer design. If the recycle stream is shut down, the solids ratio in the slurry would be reduced but the same amount of water would be used. The humidity would be maintained, but a greater Ca/S ratio will likely be required to make up for the loss of alkalinity in the recycle material.

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Figure 1. Calcium-based dry Injection SO₂ control processes

STATUS REPORT
WASTE DISPOSAL
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

1.0 INTRODUCTION

After the retrofit of a Dry Sorbent Injection (DSI) or Duct Spray Drying (DSD) system at an existing power plant, the quantity and physical and chemical properties of the waste to be disposed of will change significantly. These changes may necessitate modifications to the design and operation of the existing waste disposal system such as increasing its capacity, altering its arrangement, and/or changing the frequency of hauling ash.

A waste management system consists of five principle subsystems: transfer, storage, conditioning, transport, and disposal. The transfer, storage, and conditioning operations are typically performed at the plant site, while transport and disposal are usually off-site operations. The transfer, storage, and conditioning of wastes produced by the DSI and DSD processes are covered in the Waste Handling System Status Report. The transport and disposal of these wastes are addressed in this Waste Disposal Status Report.

Recent experiences in handling dry calcium-based flue gas desulfurization (FGD) wastes have shown the need for a greater awareness of the uncertainties and potential problem areas with waste disposal systems when adapted to DSI and DSD. This Status Report addresses these potential problems and the design and operation considerations that have evolved to overcome them. Design and operation considerations and alternatives will be presented for each subsystem based on experience from sorbent injection pilot plants/demonstrations and from related applications.

2.0 CONCLUSIONS

1. Although typically more alkaline than plain fly ash, DSI and DSD wastes should be capable of being transported and disposed of using

techniques similar to current practices for coal fly ash without incurring significantly increased operating problems or costs. To some extent, DSI/DSD waste is similar to that from lime spray dryer scrubbers, and experience gained with spray dryer waste has not revealed any unusual difficulties compared to the disposal of plain fly ash. Generally, the same conclusion can be drawn from experience with calcium-based furnace sorbent injection demonstrations.

2. The one property of DSI/DSD waste with potential deleterious impacts is its high alkalinity. This could potentially result in corrosion of the transport equipment and high (in excess of 12) pH runoff from the disposal area. Transport equipment materials of construction may have to be upgraded because existing materials will likely wear out more quickly due to the corrosive nature of the ash/sorbent waste. Runoff pH in excess of that allowed by applicable regulations will require neutralization.
3. Depending on the desired SO₂ removal and coal ash and sulfur content, retrofit of DSI or DSD will increase disposal waste quantity by a factor of 1.8 to 5.0. If a truck, rail, or barge haul system is used, additional vehicles and hauling shifts will likely be required. If conveyors are used to transport waste, the capacity of the system will likely require upgrading. Increased maintenance will likely be required for transport conveyor systems. The life of the existing disposal site will be shortened. If expansion is not possible, a new disposal site will be necessary.
4. Water conditioning to control dusting during transport and to achieve the optimum moisture content for disposal is a critical factor in the handling characteristics of DSI and DSD waste material. Too much water causes the material to become sticky and hard to handle and to possibly set up in the transport equipment. Not enough water results in ineffective dust control. Optimum moisture appears to be 20-30% by weight. A properly mixed fly ash/sorbent waste product will, in most cases, enhance the landfill operation due to the pozzolanic action of the lime portion. This will tend to decrease the permeability of the waste and form a cementitious crust that will

deter erosion of the exposed surface. In addition, it can significantly reduce the leachability of potentially problematic elements (As, Ba, Cd, Pb, Se, etc.).

5. The unreacted sorbent in the waste will generally be in the Ca(OH)_2 form, and so steaming and significant exothermic reactions should not be a problem with DSI/DSD waste.
6. In general, the potential environmental risks posed by DSI/DSD wastes appear to be minimal. The moisture content, dry density, strength, and permeability of these wastes are such that landfill without a liner should be generally adequate. The leachability of the RCRA-regulated elements are below current RCRA standards. However, certain State and/or local regulations may pose restrictions on the disposal of the waste from these processes. These regulations need to be considered when applying this technology.
7. If additives are used in the duct injection process, testing will be required to determine their effect on disposal properties such as strength, permeability, and leachate properties.
8. Although not detailed in this report, there could be a significant utilization potential for these wastes.

3.0 RECOMMENDATIONS

1. An evaluation of the existing transport system is required to determine if present equipment capacity and materials of construction are adequate or if they must be modified or upgraded after the duct injection retrofit.

2. Thorough characterization of the waste material should be performed to define physical, chemical, and mineralogical properties to avoid potential disposal problems. Short- and long-term leachability as well as EP toxicity studies should be performed on specific wastes to verify that nonhazardous conditions apply. Other specific waste characterization tests may be required by State or local regulations. Determine if sorbent additives alter the waste properties or result in any environmental risks. Based on this information, appropriate consideration can be given to potential material reuse options and final disposal requirements.
3. Determine capacity of existing disposal area, and estimate remaining life span with the duct injection process retrofit. Determine State and local regulatory and permitting requirements for both existing and future long-term disposal sites. This should be considered early in a feasibility study for retrofitting a duct injection system. If an existing disposal area will be used for these wastes, evaluations of embankment stability and possible contamination of surface water and ground water should be conducted.
4. It is recommended that all waste material landfill operations incorporate a layered compaction procedure. If not already used, benches on embankments should be considered. Surface water entering the landfill should be minimized. Surface runoff from the active area of the disposal site should be collected and, as a minimum, passed through a sedimentation pond. Diversion channels at the landfill perimeter should be considered, as well as grading the waste material to minimize the water which soaks in and passes through it.
5. Conduct research on the effects of duct injection wastes on wet sluicing waste transport and wet pond disposal.
6. Monitor the results of the University of North Dakota Energy and Environmental Research Center's Waste Utilization Study. Potential waste utilization options should be investigated on a site by site basis.

4.0 DISCUSSION

The physical, chemical, and mineralogical properties of the waste generated from a duct injection system will be different from fly ash. Several of these properties can affect the transport and disposal of this material. A list of these properties is presented in Table 1.

To some extent, ash/sorbent waste from duct injection processes is similar to that from lime spray dryer scrubbers although there is considerably more unreacted Ca(OH)_2 in the duct injection waste because of its inherently lower sorbent utilization. DSI/DSD waste is also similar to waste material from furnace sorbent injection processes, although the excess calcium is generally in the CaO form in furnace sorbent injection waste compared to Ca(OH)_2 in duct injection waste. A review of the waste disposal systems at existing utility spray dryer scrubber installations, as well as those in use at furnace sorbent injection demonstrations and duct injection pilot plants, will provide design information for full-scale duct injection retrofits.

The most significant areas of potential concern for calcium-based furnace sorbent injection processes have been identified as (2):

- Possible human health and operating effects associated with handling very powdery, alkaline materials
- The heat generation caused by the reaction of unreacted lime with atmospheric moisture or process water
- The corrosive nature of very alkaline solutions
- The tendency of the waste to flash set or solidify when exposed to moisture
- The possibility of highly alkaline discharges (pH greater than 12) from storage areas

Processes such as furnace limestone injection produce waste streams which contain significant amounts of quicklime (CaO); these wastes can give off considerable heat and steam when wetted. Since hydrated lime (Ca(OH)_2) is used in both DSI (dry hydrated lime) and DSD (slaked lime) processes, there is less concern about safety or operational problems with the exothermic reaction when moisture contacts this waste. The wetting of Coolside DSI waste resulted in only a 10°F or less increase in temperature (8). The other four areas of concern, however, are applicable for DSI or DSD wastes and are discussed in detail below.

In addition to a change in waste properties, the quantity of waste generated is the other most important factor in evaluating the effects of a duct injection retrofit on an existing waste disposal system. Depending on the desired SO_2 removal and coal ash and sulfur content, duct injection will increase the disposal waste quantity by a factor of 1.8 to 5.0 (7).

4.1 Transport

After the fly ash/sorbent waste has been transferred from the ESP to the ash storage silo and conditioned, the transport subsystem transports the waste material from the plant area to the disposal site. Likely existing transport systems include:

- a. Trucks
- b. Belt Conveyors
- c. Pneumatic Conveyors
- d. Wet Sluicing
- e. Railroad Cars
- f. Barges

Trucks

The primary advantages of truck transport are flexibility and reliability. The capacity of the system can be increased by simply increasing the number of trucks and/or operating shifts. They are

typically the most flexible and practical alternative when considering the nature of landfill operations. Also, they often are the most practical alternative when considering surface mine disposal at mine mouth stations.

After new waste production rates have been determined the number of trucks and operating shifts which must be provided in order to transport the increased material quantity can be estimated. Different truck sizes and numbers of shifts should be investigated in order to satisfy the increased demand on the waste transport subsystem.

The potential corrosivity (high pH) and dust problems associated with duct injection wastes should be considered when an existing truck transport system is being utilized. Corrosion may cause deterioration of truck bodies faster than for plain fly ash. Special liners or materials of truck construction may be used and/or trucks can be cleaned regularly to minimize this problem. Dust problems can be minimized by either wetting the material, covering open trucks with tarps, or using enclosed truck trailers.

Trucks are by far the most common method used to transport calcium spray dryer wastes (6). No problems have been reported with trucking of these wastes.

Belt Conveyors

The speed of the existing belt conveyor(s) may have to be increased to accommodate the greater throughput after the duct injection retrofit. However, this may not be practical because, since DSI and DSD wastes are easily aerated, this limits the speed at which they can be conveyed using belt conveyors without being wetted or enclosed (3). The material to be transported may have to be wetted on the belt conveyor to minimize dusting problems. However, if the material is wetted, it may become sticky and special belt cleaners or scrapers may have to be installed to prevent material from accumulating on the

belt. Wetting duct injection wastes also increases their potential to cause corrosion; therefore, special corrosion resistant materials of construction may be required.

Belt conveyors are currently being used to transport calcium spray dryer wastes at Basin Electric Power's Antelope Valley and Laramie River stations. A single belt at the Antelope Valley Station transports wastes from spray dryers at both Units 1 and 2. A belt conveyor is also used to transport spray dryer waste from Unit 3 at Laramie River Station. The conveyors at both of these stations are approximately one mile long. No problems have been reported with these belt transport systems (6).

Pneumatic Conveyors

Pneumatic conveying has seen only limited applications in the transport of utility wastes. Pneumatic conveying systems are not economically efficient at distances greater than approximately 7,500 feet (6).

After retrofit of a DSI or DSD system, a pneumatic conveying system can potentially experience one or more of the following problems:

- a. Plugging in ash intake valves.
- b. Build-up of material in conveyance lines.
- c. Insufficient conveying capacity.

Plugging in ash intake valves is the result of damp solids from the duct injection process and/or conditioning. Heat tracing and insulating these intake valves should solve this problem.

Build-up and subsequent plugging in the system is a result of the relatively poor flowability and hygroscopic nature of these wastes. Compared to fly ash only, a significant amount of spray drying waste settled out of the air stream in vacuum conveying tests; most of these deposits consisted of calcium products (6). Buildup of

material in lines and elbows is a potential problem. A regular maintenance program would likely be required to keep these lines clear. This is of special concern in areas of high ambient humidity. Such problems can be minimized by using dry, heated air for transporting the solids and/or heat tracing/insulating of conveying lines. Extending the air inlets into heated enclosures has been used successfully in spray dryer applications. Retrofitting wide-angle elbows can reduce the plugging problems at bends.

Insufficient conveying capacity is the result of increased waste production rate. Increasing conveying air capacity and/or system component size may be necessary (conveying lines, bin receivers, etc.). If the existing system is currently at or near operational capacity, the best solution may be to replace the entire system with a new system designed to accommodate the full duct injection waste disposal rate.

There are no generating stations with calcium spray dryers using or planning to use pneumatic conveyors as a transport subsystem.

Wet Sluicing

Very little is known about the potential effects of DSI or DSD wastes on a wet sluicing transport system. There are concerns regarding the cementitious properties of calcium-based materials that can potentially lead to plugging and scaling of conveying lines. The calcium in DSI and DSD wastes, however, has been hydrated prior to entering the process; the potential for any additional hydration in the sluice line is minimal. It is possible that periodic pigging of these lines or cleaning with high pressure water lances may be required to remove scale and deposits.

Water addition to the waste material may increase environmental concerns by requiring wet disposal (the unreacted lime in the waste will likely raise the pH of the sluice to as high as 12 (3)). A liquid separation and reclaim water system or other special

modifications may be required at the disposal area similar to mineral tailings systems. More research is needed to understand fully the effects of DSI and DSD waste on wet sluice transport systems before retrofit feasibility can be determined.

Wet sluicing is used for transport of spray dryer wastes at Unit 10 of United Power Association's Stanton Station. No problems have been reported with this arrangement (6). However, at this station, the spray dryer wastes are diluted with the combustion wastes from other units. This minimizes problems associated with the cementitious and pozzolanic properties of the spray dryer wastes.

Railroad Cars

The same comments regarding increase in waste quantity, dustiness, and corrosivity apply to a railroad transport system as were discussed above for a truck system.

Barges

If analyses of the DSI or DSD waste indicate no major problems with corrosivity and dusting, standard barges can be used. More frequent hauling will be required due to the increase in waste to disposal.

4.2 Disposal

Waste disposal is the final placement of the waste in a permanent location. The three most common disposal methods in use for fly ash are landfill, mine disposal, and wet impoundment (pond).

Calcium spray dryer wastes from nine of the currently operating stations are disposed of in landfills. A pond is used for disposal of wastes at the Stanton Station. Wastes from two other dry scrubbers are disposed in an active surface mine. Six of the disposal sites, including the pond, are unlined. Of the other six sites, four are lined with clay and a fifth site, at Laramie River Unit 3, has a PVC liner. The liner type from the sixth lined site was not reported (6).

In addition to spray dryer wastes, other power plant wastes are placed in at least eleven of these disposal areas. Bottom ash, fly ash and scrubber sludge, in various combinations, are disposed of in the landfills in addition to the spray dryer wastes.

Experience gained with calcium spray dryer waste over the past several years has not revealed any unusual difficulties compared to the disposal of fly ash (5).

Evaluation of wastes from calcium furnace sorbent injection processes indicates that these potential environmental risks posed by these wastes appear minimal and that they may be disposed of in a conventional landfill (3,4).

4.2.1 Waste Properties Which Affect Disposal

For waste disposal design, the four parameters of primary interest are optimum moisture, maximum dry density, strength, and permeability and leachate properties (6).

Optimum Moisture - Maximum Dry Density

The optimum moisture is the amount of free moisture a material should contain for it to develop the maximum dry density possible under the applied compaction. These interrelated properties are important in landfill design for several reasons. Maximizing dry density will minimize required landfill volume. In addition, low void volume will generally result in higher unconfined strengths and lower permeabilities (6). Wetting is also required to minimize fugitive dust emissions during transport and disposal.

Water at 18-25% by weight is typically added to fly ash (5). The optimum moisture content for calcium spray dryer wastes was found to vary from 16-38% with an average of 28%; optimum maximum dry densities for these wastes varied from 71-104 lb/ft³ with an average of 86 lb/ft³ (6).

For calcium furnace sorbent injection wastes, the optimum moisture content varied from 28-52%, averaging 42%; maximum dry densities ranged from 68-80 lb/ft³, averaging 72 lb/ft³ (3,4). However, much of the moisture added is steamed during hydration of the calcium in the wastes.

The optimum moisture content of Coolside DSI waste was determined to be about 23%. At this moisture content, the dry bulk density was 67 lb/ft³ (8).

Strength

Unconfined compressive strength is a measure of the structural integrity of a disposal material. Unconfined compressive strengths (28-day cure time) for calcium spray dryer wastes ranged from 500-1450 psi (6). The most probable reason for the wide range of values reported is differences in chemical composition.

The unconfined compressive strength of Coolside DSI waste after 28-days curing at optimum moisture content was as high as 250 psi with NaOH addition (8). In the absence of the sodium additive, the compressive strength at the same conditions was 200 psi. These strengths appear adequate to permit landfill disposal. Bulldozers typically exert pressures ranging from 11-19 psi. The compressive strength of all samples increased with curing time indicating that pozzolanic reactions take place during curing.

Permeability and Leachate Properties

Permeability is a major parameter in landfill disposal design. The amount of rainwater that percolates through landfilled waste significantly affects the quantity of leachate. Permeability is a measure of the rate at which water passes through the material. Along with leachate data, permeability may be used to estimate possible impacts on ground water quality.

Waste materials should have a permeability of less than 10^{-5} cm/sec to be suitable for dry landfill disposal (5). Permeability of bituminous fly ash generally ranges from 10^{-7} to 10^{-4} cm/sec; values for subbituminous fly ash range from 10^{-5} to 10^{-6} . Compacted spray dryer wastes yield permeability coefficients of 10^{-9} to 10^{-6} cm/sec (5,6).

Permeability coefficients from calcium furnace sorbent injection wastes averaged 6×10^{-6} cm/sec in one study (4). For comparison purposes, the permeability designated by the EPA for impermeable liner materials for hazardous waste landfills is on the order of 1×10^{-7} cm/sec (typical of clay liners) (4). The low permeabilities of the calcium furnace sorbent injection waste indicate that liners will likely not be necessary for their disposal (3, 4).

The permeability coefficient of Coolside DSI waste containing the optimum moisture content ranged from 10^{-5} cm/sec (uncured) to 10^{-6} cm/sec after 7-days curing (8). Therefore, it is concluded that DSI and DSD wastes will generally have similar permeabilities to plain fly ash and that they are suitable for landfill disposal. Since DSI and DSD waste are similar to furnace sorbent injection waste, liners are not expected to be required after a duct injection retrofit.

Leachate properties of disposal wastes are important in determining adequacy of existing disposal areas. The presence of leachable elements in the waste largely depends on the type of fly ash with which the sorbent waste is codisposed; the chemical composition of the leachate is more a function of the fuel fired than the SO_2 control process (2, 5). Toxicity leaching tests provide data to evaluate the hazard potential of a solid waste. A typical leachate test is the U.S. EPA extractive procedure (EP) toxic leachate test. For DSI and DSD wastes, there are eight RCRA-regulated elements: arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver.

For eight calcium spray dryer waste samples tested, the EP test data show that none of these samples would be considered toxic under current RCRA regulations (6). Concentrations of the eight elements in the EP extracts from waste samples from calcium-based furnace sorbent injection processes were also well below levels at which the wastes would be classified as toxic (2, 4).

EPA leachate tests conducted on DSI waste met the RCRA requirements for nonhazardous solids waste disposal in all cases tested (1).

If additives are used, the leachate properties may change. Studies of leachate rates from the Coolside DSI process wastes were conducted on samples collected with and without NaOH addition (8). As expected, the leachates from the waste produced without the NaOH additive have reduced sodium, sulfate, and total dissolved solids (TDS) concentrations, but are otherwise similar to those from samples produced with the sodium additive. However, in all waste leachates, the trace element concentrations measured were below the allowable limits by RCRA, and the concentrations of trace elements, sulfate, and TDS were less than 30 times the EPA primary and secondary drinking water standards. There is little data regarding the effects that other potential additives will have on waste properties.

The pH of the leachates from spray dryer wastes, calcium-based furnace sorbent injection wastes, and Coolside DSI waste, have all been measured to be as high as 12 (2, 6, 8). These values are above the recommended drinking water limit. If the runoff from the disposal landfill is required to meet discharge water standards, it is possible that the runoff will need to be partially neutralized before discharge (5, 8). However, dilution effects or partial neutralization from other materials in the landfill may make this unnecessary (8).

4.2.2 Modification Of Existing Disposal Areas

If there is capacity remaining in the existing disposal area which is currently accepting coal combustion wastes, it should be considered for duct injection wastes. Because the site already is being used for waste disposal, information should be available for the site including geotechnical data and permitting information. This information will provide a basis upon which to begin analyses of any required disposal area modifications. Disposal modification also may require only modifying existing permits as opposed to repeating the entire permitting process.

Any modifications to existing disposal areas should consider embankment stability and possible contamination of surface water and ground water. The following discussion, taken from Reference 6, describes the evaluations required after the retrofit of a duct injection system.

Embankment Stability - Physical instability is a potential problem for all coal combustion by-product disposal areas. Stability is influenced by: physical waste properties such as waste density, strength, degree of saturation, effective cohesion, effective angle of shearing resistance, and behavior during shearing (dilatant versus densifying); site conditions including geotechnical characteristics of the in-place foundation material; and geometric factors such as the heights and outslopes (or slope angles) of embankments. In general, for a given material, the maximum safe embankment height decreases with increasing slope angle (6). The effective slope angle of the embankment may be flattened by either lowering the slope angle (outslope) itself or by constructing benches. Benches also aid in the control of surface runoff and in providing access to all areas of the landfill face. In fact, many State regulations require benches on embankments and dictate minimum spacing and sizes. Benches are usually placed every 20 to 50 feet in vertical height and typically vary in

width from 10 to 30 feet. However, flattening the outslope and/or constructing benches reduces the capacity of a landfill. Foundation material also should be analyzed; weak underlying material can lead to instability and slope failure. Design measures should be taken to minimize any potential problems with weak foundation material. Surface water and ground water controls influence the amount of moisture in the waste material and, therefore, effect the stability of embankments.

Surface Water - The potential for surface water contamination depends upon the amount of water that passes through or is in contact with the waste material. Therefore, in order to reduce contamination, the amount of surface water entering the landfill should be minimized. This is usually done by constructing diversion channels at the perimeter of the landfill to divert runoff from adjacent areas away from the site. Diversion of this water will reduce the amount of leachate generated, reduce erosion of the landfill, and decrease the amount of runoff from the site that must be controlled, collected or treated. All surface runoff from the active area of the site should be collected. As a minimum, this water should be passed through a sedimentation pond. In addition, it should be tested for possible contamination and treated if necessary. The site should be staged so that only runoff from the disturbed, uncovered area is collected. Limiting the drainage area to only the disturbed area reduces the amount of runoff entering the pond and reduces its size and associated cost. Therefore, landfill staging is important in sizing sedimentation ponds.

Ground Water - The potential for ground water contamination is related to the amount of water passing through the waste material, the quality of the leachate produced, and existing geologic and ground water conditions. Measures can be taken to reduce the potential for degradation of ground water aquifers.

These measures are instituted because of specific site conditions, waste material characteristics and regulatory requirements. The amount of water passing through the waste material and subsequent leachate generation can be reduced by constructing diversion channels at the perimeter of the landfill and grading the waste material to drain both during construction and after reclamation. The quality of leachate varies with different DSI or DSD wastes depending on many process factors. Whether or not the leachate is a potential problem is also a function of both site location and regulatory requirements (i.e., more control measures probably will be required if a landfill is located over an area with a shallow high quality aquifer than if it is located in an isolated area). If the leachate contains contaminants exceeding the EPA drinking water standards, hazardous waste criteria, or other appropriate limitations, measures may be required to reduce potential adverse ground water impacts. These measures could include: installing a liner under the disposal area to minimize leachate entering the ground water aquifer, constructing a leachate collection system to collect leachate, installing an under-drain for the landfill to collect springs and seeps thereby preventing this water from contacting the wastes, constructing diversion channels and grading the landfill to minimize surface water which can enter the landfill and generate leachate, and constructing a leachate treatment facility to treat this leachate before discharging it to the environment. Existing geologic conditions also can affect the ground water at the site. The site should ideally be located over an area with a deep, low quality, ground water aquifer containing low permeability soils. However, most sites do not involve ideal conditions and require at least some limited measures to minimize leachate.

Design conditions will vary depending on whether the existing disposal area is a landfill, surface mine, or wet impoundment.

Modifying Existing Landfill Disposal Areas

Conventional landfill disposal areas currently receiving other combustion wastes may be able to receive duct injection wastes without significant modifications to the landfill. Because of the additional waste quantities generated with duct injection, however, the storage capacity of the disposal area will be expended over a shorter time period, shortening the life of the disposal site in general. Expansion of the landfill may extend its life; expansion can be accomplished by either horizontally or vertically enlarging the landfill (6).

In designing modifications for an existing landfill disposal area, the first step is to compare properties of DSI or DSD wastes with the properties of those wastes currently placed in the disposal area. The new waste properties should be used to verify the original design and develop new designs if required.

As discussed in Section 4.2.1, DSI and DSD wastes should be placeable in landfills with few potential impacts due largely to their inherently cementitious properties which reduce permeabilities and leachate quantities as well as constituent leachability. These properties also increase the strength of the wastes generally as compared to conventional fly and bottom ash, thereby improving their engineering performance.

Waste disposal at a landfill site will be subjected to numerous passes of earth-moving equipment and trucks. Because of this, the structural integrity of the waste is very important. Permeability is greatly affected by the amount of landfill compaction. It is therefore recommended that all DSI and DSD waste material landfill operations incorporate a layered compaction procedure.

Modifying Existing Mine Disposal Areas

Existing mine disposal areas currently receiving other coal combustion wastes may be able to receive duct injection wastes without major modifications to disposal operations. However, the final grades of the reclaimed mine have to be raised to allow for increased waste quantities.

Leachate and strength properties of DSI or DSD wastes should be compared to like properties for wastes currently being placed in the mine. In many cases, the new wastes will have greater strength and, therefore, will not affect mine disposal adversely. If questionable, stability and leachate analyses for mine disposal of the wastes should be performed.

Modifying Existing Wet Disposal Areas

There are two basic approaches to utilizing existing wet impoundments for disposal of duct injection wastes. The first is to continue impoundment disposing of the wastes in slurry form. The second is to drain the impoundment, stabilize the existing wastes, and landfill dry DSI or DSD wastes upon the drained impoundment wastes.

If the impoundment will continue to be used for wet disposal, duct injection wastes can be pumped to the impoundment in slurry form. However, due to the increased quantities of wastes, the slurry line to the impoundment may have to be increased in size, and the remaining life of the impoundment will be shortened. Also, due to the high pH of the slurry and the tendency of these wastes to "set-up", steps must be taken to prevent associated problems with the waste transport system (e.g., sufficiently dilute slurry, line maintenance, etc.). More research is needed to understand the effects of DSI and DSD waste on wet disposal systems before retrofit feasibility can be determined.

4.2.3 New Disposal Areas

If it becomes necessary to build a new landfill, State and/or local permitting requirements may be much more stringent than Federal regulations. Site selection will be based upon transportation and economic considerations as well as technical and environmental criteria.

Because the landfill disposal option is so common, state-of-the-art environmental protection techniques have been developed and are becoming commonplace in the industry. Clay liners, impermeable synthetic liners, leachate collection/detection, ground water monitoring, and runoff/leachate collection, settling, and treatment systems are examples of this technology which are being used to meet today's stringent environmental protection requirements.

4.3 Utilization

Although not the focus of this Status Report, several potential uses for DSI/DSD waste have been identified including:

- additive to concrete
- roadbase material
- soil stabilization/structural fill
- agricultural applications
- sludge stabilization

The University of North Dakota Energy and Environmental Research Center is performing a detailed duct injection waste utilization evaluation as part of this DOE Program. The progress of this evaluation should be followed closely.

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TABLE 1

Important chemical and physical properties of DSI and DSD wastes that can affect Waste Handling Equipment.

**Abrasiveness
Tackiness
Corrosivity
Hygroscopicity
Aeration Tendency
Mean Particle Size
Particle Size Distribution
Fine Fraction
Bulk Density
Angle of Repose
Specific Gravity
Moisture Content
Temperature**

APPENDIX B
COMMENTS ON CONTRACTORS' TEST PLANS
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

**United Engineers
& Constructors**
A Raytheon Company

July 6, 1989

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S-R/DOE-62
Duct Injection Technology Prototype Development
DOE Contract Number DE-AC22-88PC88852
UE&C Project 9330.001
Review of Acurex Revised Test Plan Dated May 31, 1989

Dear Dr. Tischer:

At the Technology Working Group meeting on June 7, 1989, we were asked to comment on Acurex's revised Test Plan. In accordance with this request and our verbal comments offered at that meeting, our written comments to this Test Plan are attached.

Please call if you have any questions on our comments.

Very truly yours,

Ronald L. Claussen
Project Manager

RLC/gh/4794T

Attachment

COMMENTS TO ACUREX'S TEST PLAN - UNITED ENGINEERS

Section 2.1 Stirred Tank Reactor Experiments

NOT RECOMMENDED

The objective of this series of experiments is to characterize the system's gas and liquid phase mass transfer coefficients to "verify computer models." Our opinion is that either the Meredosia or Beverly pilot plant is the proper place to verify the computer models, not a small scale lab experiment. If the information were to be used as input to the computer model, this may be useful; however, EER has not indicated that their theoretical model is currently lacking this information. Thus, we cannot foresee how this information would be useful to the overall program and would not recommend it.

Section 2.2 Differential Reactor

NOT RECOMMENDED

It is not clear how the study of contact times of 10-600 seconds relates to this program, which is typically looking at residence times of 1-2 seconds. Thus, this series of experiments is not recommended.

Section 2.3 Short Time Differential Reactor

RECOMMENDED

This series of experiments seems to best simulate the conditions of duct sorbent injection. Based on the description of the test apparatus, it appears that these tests are fairly rapid and thus, inexpensive. In particular, the effect of solids moisture content and CO₂ are of interest. However, of the recommended tests, these are deemed least worthwhile and expendable if cost constraints prevail.

Section 3.1 Sorbent Selection for Slurry Injection

NOT RECOMMENDED

Although this information regarding relative reactivity of various commercial limes is important, it is felt that much of this information exists in the literature. A summary of the existing literature on this topic should be completed before deleting this item.

Section 3.2 Recycle Test for Dry Injection

RECOMMENDED

The recycle testing is one of the most useful items proposed. Although some information exists in the literature, it is not enough to be a predictive tool.

COMMENTS TO ACUREX'S TEST PLAN - UNITED ENGINEERS (Cont'd)

Section 3.2 Recycle Test for Dry Injection (Continued)

The major benefit seen to performing recycle tests at Acurex's 50 CFM pilot plant is the cost savings over the Radian pilot plant. Without recycle testing, many data points can be run in one day at the Radian pilot (perhaps 12 to 20). With recycle testing, however, only one data point can be run in one day at the Radian pilot since the system will take several hours to come to equilibrium. This becomes very expensive data. At the Acurex pilot, this data is cheaper to obtain.

A correlation should be made between the Radian and Acurex pilots both running recycle. Once it is verified that the Acurex pilot can predict performance at the Radian pilot, further recycle testing need only be performed at the Acurex pilot.

Section 4.1.1 Additive Evaluation (Slurry Injection Enhancement)

RECOMMENDED

Additive tests are deemed worthwhile at the Acurex test facility rather than at the Radian pilot plant. Of course, if any additives show promise, they should also be tested at the Radian pilot. If a choice must be made between additives, the literature we have reviewed to date indicates that the hygroscopic additives hold the most promise.

Section 4.1.2 Activated Recycle Tests (Slurry Injection Enhancement)

RECOMMENDED

Activation techniques should be examined only if recycle of dry material alone shows poor utilization. Activation techniques are not expected to provide significant increases in utilization over reslurrying alone, and therefore should be a relatively minor effort in the overall test plan.

Section 4.1.3 Slaking Modification (Slurry Injection Enhancement)

NOT RECOMMENDED

Before proceeding with this series of tests, it is recommended that a literature review be conducted, which would include contacting the National Lime Association. It is not anticipated that significant improvement in lime utilization can be achieved by producing finer particulate during slaking or reducing agglomeration tendencies.

Section 4.2 Enhancement of Dry Injection

RECOMMENDED

The various series of tests to be performed under 4.2 all appear worthwhile. Again, contact with National Lime Association is recommended for hydration modification tests since much of this test work may have already been completed.

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**United Engineers
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February 13, 1990

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S-R/DOE-128
Duct Injection Technology Prototype Development
DOE Contract Number DE-AC22-88PC88852
UE&C Project 9330.001
Review of Acurex's Test Plan Dated January 22, 1990

Dear Mr. Tischer:

In your letter dated February 1, 1990, we were asked to comment on Acurex's Task 4 Test Plan regarding its value to UE&C's efforts in developing the Design Handbook. In accordance with this request, our comments to this Test Plan are attached.

Please call if you have any questions on our comments.

Very truly yours,

Ronald L. Claussen
Project Manager

Attachment

RLC/gh/3983z

cc: P. A. Ireland
R. A. Goffredi
C. E. Martin

COMMENTS AND QUESTIONS REGARDING ACUREX'S TASK 4 TEST PLAN

UE&C PERSPECTIVE

1. Lower Lignosulfonate Concentrations. If 1% lignosulfonate addition is effective, run tests at lower rates: perhaps 0.5%, 0.1%. High lignosite addition rates may be cost prohibitive.
2. Pressure Hydration Testing. Pressure hydration systems add significantly to the capital costs of a commercial duct injection system. Previous research has indicated that increasing sorbent surface area has little effect on utilization, when scavenging is the primary wetting mechanism. UE&C recommends assigning low priority to this series.
3. Significant emphasis appears to be placed on activating the recycle material using an ADVACATE type approach. UE&C believes this process shows promise, but is uncertain as to how it fits into the original scope of the duct injection program. At the present time, we have no plans to incorporate ADVACATE into the Design Handbook, and it is our understanding that the ADVACATE process is not capable of being simulated in the First Generation Model.

In addition to requiring a chemical processing facility, the high solids loading characteristic of this process will likely require extensive upgrades to the particulate collector and ash handling system. The capital cost and space requirements may severely limit its retrofit potential.

If ADVACATE is to be included as a duct injection process option, perhaps some efforts should be made to incorporate it in some of the process and economic models.

4. Activating the recycle material by simple grinding should be tested at the 50 cfm pilot plant. Acurex's quarterly report presented recycle test results, which indicated calcium sulfate crystals on the surface of the spent sorbent may be limiting its reactivity.

5. The possibility of injecting magnesium sulfate or similar compounds, which carry their own water was suggested by Radian as a method to reduce humidification water requirements. Since this is very similar to the ADVACATE concept, Acurex should conduct some screening tests on their laboratory test apparatus before trying it at Meredosia.
6. UE&C recommends that Acurex conduct a literature search to determine what other compounds or additives may allow Ca(OH)_2 to be wetted to 10 - 20 % or more free moisture, and be free flowing. The materials handling industry may have parallel experience, which could be applied to hydrated lime.
7. Considering the operational problems at Meredosia, could some of the fundamental tests be conducted on Acurex's 50 cfm pilot plant? This may require some modification to the current system, such as spiking the air to more closely simulate flue gas constituents (SO_2 , NO_x , CO_2 , O_2).
8. More pilot plant tests are recommended. The test plan indicates testing only recycle and ADVACATE with the 50 cfm apparatus. Some valuable insight to the scavenging vs. condensation wetting mechanism could be gained with this device. The most promising conditions from each series of STDR screening tests (surface area, particule size, additives) should be evaluated at the 50 cfm plant. Both upstream and downstream sorbent injection should be evaluated for each case. Although residence time will be non-representative when injecting sorbent upstream of the spray dryer, it may still prove valuable, especially if Meredosia cannot be used effectively.
9. It should be fairly easy to close material balances on the 50 cfm pilot plant. This should provide additional information regarding carbonation, etc.
10. When evaluating surfactant additives in the slurry injection pilot plant tests, are there plans to determine if operation with higher solids contents is possible? Is the pilot scale system capable of determining this?
11. The literature indicates that sugar additives may enhance spray dryer performance. Is there any plan to evaluate this for DSD applications?

Comments by UE&C on Gilbert/Commonwealth & Southern Research Institute
Work Plan-Section 5

1. Some test parameter values for Ca/S and approach to saturation should be consistent for both the 1.7 MW (Meredosia) and 12 MW (Beverly) pilot-plant test programs in order to compare like data. Closer approaches (20-25°F) may be possible at 12 MW.
2. A consistent method for determining the effect of residence time on SO₂ removal should be used for both the 1.7 MW and 12 MW test programs. Radian proposed a fixed sample point and moving injection location, while Gilbert/Commonwealth proposes a fixed sorbent injection point, with a series of sample probes at points downstream. Caution is advised in dilution quench probe use. Small errors in diluent gas measurement can result in significant errors in corrected pollutant gas data.
3. Accurate wet bulb measurement and psychrometric data analyses should be conducted to ensure absolute and relative humidity conditions are known when using the dilution system described in the work plan for varying inlet SO₂ concentration. Care must be taken to provide conditions representative of real flue gas conditions.
4. When evaluating the humidification upstream of sorbent injection configuration, G/C and SRI should be prepared to respond to potential corrosion problems similar to those encountered at the EPRI high sulfur test center when HYPAS was evaluated. Duct surfaces and sorbent injectors may be exposed to attack by acid in those areas where sorbent is not present.
5. More detail is needed concerning on-line systems for removing deposits without process shutdown. It is unclear if this portion of testing is intended to develop a component of a typical DSI or DSD system, or simply a remedial tool for the pilot-plant effort. Scale-up and economic issues regarding soot blowers, sonic horns, hoppers, and other devices should be evaluated. The concept of controlled on-line collection and removal of deposits may be an area of growing interest if complete prevention of deposition proves to be impractical.
6. It is important to differentiate between SO₂ removal in suspension and SO₂ removal by wall deposits. The method described in the work plan involves analyzing the solids collected in the SRI dilution quench probe. Due to potential inconsistencies in laboratory analytical methods and results, several samples should be collected and analyzed for each test condition to ensure quality data.
7. Recent work by ADA indicate that the traditional SRI in-situ resistivity probe may not be accurate in low temperature, high velocity applications. ADA has developed an extractive resistivity measurement apparatus designed specifically for low-temperature ash/sorbent materials from spray dryer and duct injection processes. This device is being used at Meredosia, and it should be considered for use at Beverly.

8. Recent findings by Radian and ADA indicate scouring and rapping re-entrainment may be the most severe limiting factors in ESP performance associated with duct injection. The use of additives to improve ash cohesiveness may be an important test.
9. The possible use of special ESP collecting electrodes is mentioned. More detail is needed on the economic and practical aspects of implementing irrigated or moving electrodes on this pilot unit and on their feasibility for full-scale retrofits.
10. When evaluating recycle at the 12 MW scale, the most realistic approach representative of full-scale operation should be emphasized. More fundamental investigations should be conducted at the 1.7 MW pilot. This includes recycling from specific ESP collection zones. Full-scale plants normally do not have the capability of separating ash from individual ESP hoppers.
11. An after collector to reduce re-entrainment emissions is mentioned. Is this practical, or does this go beyond the scope of the simple retrofit control philosophy?
12. The use of louvre collectors upstream of the ESP is not well defined in this report. A precollector is of interest, however, and results with it would be very useful.
13. A specific test series to evaluate the effect of atomizer wear on deposition, atomization, and SO₂ removal should be conducted. This is mentioned in the failure mode test Table 5-7, Week 15, but does not seem complete. One objective here is to determine nozzle replacement schedule. Tests should be conducted on lime slurry only and with high recycle ratio.

United Engineers & Constructors

A Raytheon Company

March 28, 1990

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S-R/DOE-147
Duct Injection Technology Prototype Development
DOE Contract Number DE-AC22-88PC88852
UE&C Project 9330.001
Potential Wall Deposition at Beverly Test Facility

Dear Mr. Tischer:

As part of their model development effort, B&W has recently modeled the 12MW Duct Injection Test Facility at Beverly. The results of their analysis indicate that the potential for significant wall deposition exists. B&W's three-dimensional flow and droplet evaporation analysis is summarized in the attached memo prepared by Bill Oberjohn.

The dimensional inputs for B&W's analysis were those given to B&W by Gilbert/Commonwealth (G/C) during the cold flow physical modeling. If G/C's design has not changed, the atomizer-to-wall spacing will be 8.4 in. The wall deposition predicted by this preliminary computer modeling by B&W confirms what might be expected based on the Meredosia experience.

Considering the difficulties that duct deposition has caused at Meredosia and the significant changes Radian is having to implement, it may be prudent for G/C to re-evaluate its current atomizer array design.

We are not in a position to offer recommendations to G/C; however, B&W's experience in this area (from both model simulation and actual testwork) would indicate that a wall clearance of about 24 in. may be required to allow sufficient droplet evaporation to minimize deposition.

We would be happy to discuss this matter in more detail at your convenience. Please call if you have any questions or comments.

Very truly yours,

Ronald L. Claussen
Project Manager

RLC/gh/3983z

cc: P. V. Smith/B&W
P. A. Ireland
R. A. Goffredi

C. E. Martin

DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

**PREDICTED DEPOSITION POTENTIAL FOR
BEVERLY 12 MW TEST FACILITY**

PREPARED BY:

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PREDICTED DEPOSITION POTENTIAL
FOR
BEVERLY 12 MW TEST FACILITY

Introduction

This memo presents the results of a three-dimensional flow and droplet evaporation analysis of the 12 MW Duct Injection test facility at Beverly. The purpose of the analysis was to estimate the potential for wall wetting relative to the 18-inch Meridosia facility, B&W's 6' by 6' facility and the 14'7" Limb Humidification Duct at Edgewater. The predictions were made with B&W's DRYMO code.

Severe deposition is a problem for many reasons, one of which is that it prevents meaningful testing for code validation.

The following table summarizes the most important characteristics of the duct injection test facilities.

<u>Facility</u>	<u>Dimensions</u>	<u>Atomizers</u>	<u>Atomizer Flow nominal gpm</u>	<u>Area/Atomizer sqft</u>	<u>Wall Spacing</u>
Edgewater	14'7" square	110	0.8	2.13	27.5 in
6 by 6 (R0)	6' square	9	1.6	4.0	24.0 in
6 by 6 (R1)	" "	16	0.8	2.25	24.0 in
Meridosia	18 inch dia	1	1.5	3.71	9.0 in
12 MW	3'4" by 4'2"	6	2.0	2.31	8.4 in

Results

The results are presented as the distance downstream of the injection plane where wall temperature is first predicted to be influenced by the atomizer jet. Also listed is the location where wall wetting or deposition was first observed.

<u>Facility</u>	<u>Predicted</u>	<u>Observed</u>
Edgewater	17 ft	25 ft
6 by 6 (R0)	20 ft	22 ft
6 by 6 (R1)	-----	18 ft
Meridosia	10 ft	-10 ft
12 MW	1 ft	---

For both Edgewater and the 6 by 6 (R0) humidification ducts the effect of the atomizers is predicted to be initially felt at the duct wall 15 to 20 ft downstream of the injection point. The observed locations are in reasonable agreement with these estimates. Wall wetting and deposition were not severe enough anywhere in these ducts to impede operation at a 30-40°F approach to saturation temperature. At this distance downstream from the atomizers droplets approaching the wall have mostly evaporated.

At Meridosia, severe deposition was observed at about the location where the atomizer jet is predicted to reach the wall. Droplets approaching the wall 10 feet downstream of the atomizers have not been evaporated sufficiently to minimize deposition.

The relatively high capacity atomizers for the 12 MW facility are predicted to affect wall temperature almost immediately downstream of the atomizer plane. This prediction is consistent with the other results in that the 12 MW facility has the highest capacity atomizers and the smallest wall spacing of any of the facilities.

Conclusion

The DRYMO predictions and a comparison with observations at other facilities strongly indicate that significant deposition should be expected at the 12 MW facility. It seems unlikely that the test program can be carried out as planned.

Recommendations

The success of In-Duct Humidification at Edgewater demonstrates that severe deposition can be avoided at full scale. However, it is difficult to simulate a full-scale duct with pilot-scale facilities. Testing in B&W's 6 by 6 facility indicates that a wall clearance of about 24 inches is required to allow droplets to evaporate sufficiently before contacting the duct walls. Testing at Meridosia supports this conclusion.

Obtaining data to validate the three-dimensional duct injection model is vitally important. It is doubtful that the program at Meridosia can be carried out as planned, and the predictions for the 12 MW facility are equally discouraging. If severe deposition occurs at the 12 MW facility when it starts up in April, I suggest a two-pronged approach to obtain code validation data.

1) test at higher approach to saturation temperatures so that data can be obtained without deposition, and

2) obtain data at more severe conditions at other facilities that are known to function without deposition problems such as Edgewater, B&W's 6 by 6 and atomization facilities or Ohio Edison's E-SOx Pilot. ESP data could also be obtained at Edgewater and the E-SOx Pilot.

Although data at 20-30°F approach temperature is most important for code validation, data at higher approach temperatures is also beneficial since the prediction methods are the same. Operating the 12 MW facility with a single atomizer at lower flue gas velocity and a higher approach temperature might allow testing to take place without deposition problems.

W. J. Oberjohn

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July 18, 1989

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S-R/DOE-65
Duct Injection Technology Prototype Development
DOE Contract Number DE-AC22-88PC88852
UE&C Project 9330.001
Review of Radian's Test Plan Dated May 31, 1989

Dear Mr. Tischler:

At the Technology Working Group meeting on June 7, 1989, we were asked to comment on Radian's Test Plan. In accordance with this request, our comments to this Test Plan are attached.

Also attached are additional comments and questions which we solicited from our subcontractors. We have reviewed both B&W's and EMRC's comments and concur, therefore we are transmitting them in the form they were received.

A record of telephone conversation between Paul Ireland and Paul Nolan, B&W's Site Manager at Edgewater, which includes additional comments to Radian's Test Plan is attached for your information.

Please call if you have any questions on our comments.

Very truly yours,

Ronald L. Claussen
Project Manager

MJK/pat/4794T

Attachments

Comments on Radian Test Plan - United Engineers

1. Evaluate the possibility of using natural gas burner to achieve full gas flow rate (6300 ACFM @ 300°F) during outage for Validation Testing. (Could be a problem with particulate removal since Unit 5 ESP will be down.)
2. Three test points per week is very low. This may be reasonable during recycle tests since it takes so long to come to equilibrium with recycled material; but lime-only runs should achieve steady state very quickly. Try to increase the proposed number of test points/day or week.
3. We recommend more lime-only tests. Recycle is more difficult - and takes much longer because of time required to reach equilibrium as noted above. Radian's Work Plan indicated more lime-only runs at the beginning of the parametric testing.
4. Incorporate the results of validation tests of EER's model per validation methodology.
5. Is it possible to let gas pass through the system early (~ 2:00 a.m.) Monday morning so the system will be hot by 8:00 a.m. Monday morning? - (so Radian won't lose 1/2 day heating up the system).
6. Revise baseline conditions to those agreed upon in June 7, 1989 TWG meeting. New baseline values were agreed to for approach temperature and C_a/S ratio.
7. Evaluate the possibility of decreasing the air/water ratio for slurry/humidification water spraying. Compressed air is a relatively large expense.
8. Section 2.5. How does Radian plan on measuring moisture content of the solids from ESP?
9. Section 3.1. We suggest using a recycle ratio of 1:1 and 1:2 or 1:3; not 1:5.
10. Section 3.2.4. What are the units of "maximum achievable SO₂ removal"? %, lb/hr, or lb/10⁶ Btu?
11. Is NaOH additive testing planned with DSD? (It is in DSI.)
12. Overall, one test per day is predicated on using recycle for most all tests; this is very inefficient. Without recycle, Radian can do maybe 10 tests per day (i.e., equilibrium reached in a matter of minutes, if not seconds. Note: ESP tests may take 2-3 hours, therefore maybe two tests per day for ESP tests). Therefore, Radian should drop most recycle tests and use a correlation to extrapolate to recycle results with either Radian's own or Acurex's results.

13. Overall, the data used for the Design Manual is expected to come from the Gilbert/Commonwealth pilot. Therefore, We are not requesting much engineering data from Radian, but would like information on:
 - a) handleability of ash, and
 - b) Transport/storage properties of ash (bulk density, angle of repose, etc.
14. Radian needs to have some tests specifically set up to be identical to individual runs from the Edgewater Coolside demonstration and Gilbert/Commonwealth's 12 MW pilot.
15. Radian should test several hydrated limes to document changes in performance of the different candidates.
16. If one test/day is dictated by the time required by the system coming to steady state from cold start, then both DOE and Radian need to rethink the option to go to 24 hour operation.
17. A series of tests should be run towards the end of the parametric testing with optimized conditions to demonstrate "best" SO₂ removal, Ca/S ratio approach, etc.
18. Delete the slaker tests which vary temperature/type and the sugar additive tests addressed in Section 4.2.
19. The ESP tests as defined are adequate and well thought-out.

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June 29, 1989

Mr. R. L. Claussen
Project Manager
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Dear Mr. Claussen:

Bill Downs and I have reviewed the 1.7 MW Pilot Plant Test Plan prepared by Radian in accordance with your letter of June 12, 1989.

Our overall comment on the duct injection portion of the test program is that it is not too well thought out in that no problems are anticipated in operating the pilot plant at predetermined conditions. B&W believes this to be unrealistic in light of its and others experiences in injecting water and slurry into utility ducts. The test plan also seems totally divorced from any modeling work, and we believe that the test plan is supposed to provide data to validate and improve the ongoing project modeling efforts. The ESP portion was much better thought out, and the author appeared to have a good practical knowledge of ESP test problems and anticipated solutions, as well as a realistic knowledge of ESP pilot operation.

The actual comments are contained in Attachment 1 (W. Downs) and Attachment 2 (P. V. Smith).

Sincerely,

BABCOCK & WILCOX
Research and Development Division

Peter V. Smith
Chemical Engineering Section
Alliance Research Center

PVS/smb
Attachments

cc: W. Downs
C. H. Smith - CRD

ATTACHMENT 1

(W. Downs)

1. Page 2-4, second paragraph, concerning cold spots in the pilot ESP: When operating at low approach temperatures, air in-leakage can cause local gas phase condensation (rain) in the ESP. This would make the collected ash wet and difficult to remove from the ESP hoppers.
2. Page 2-5, paragraph 2: What criteria will be used to optimize the water-to-air pressure ratio?
3. Section 2.2 (Week 2): More attention must be paid to the injection system in the areas of:
 - A. The sorbent pulse frequency and amplitude must be determined. All solid injection systems pulse to some degree and the particular system at the pilot should be quantified, especially due to the lack of back-mixing in the in-duct process.
 - B. The axial dispersion rate of the sorbent should be determined.
 - C. The particle size distribution and spatial distribution should be determined at a point immediately upstream of spray nozzles.
 - D. The rate of sorbent dropout should be determined without the spray nozzles on.
4. Section 2.3 (Week 3): What will Radian do if a 20°F approach temperature cannot be achieved without serious wall wetting? (This is what I would predict.) Is the backup plan to operate at the minimum practical approach temperature? (This is what I would recommend.) What fixes to the test plan is Radian contemplating?
5. Section 2.4 (Week 4): Caution is in order when reducing the SO₂ concentration by air dilution, since the adiabatic saturation temperature will be strongly influenced by gas concentration. I would assume that the baseline inlet temperature and SO₂ concentration are the normal Meredosia flue gas conditions; this should be so stated in the test plan and an expected variation on conditions given.
6. Section 2.5 (Slurry System Start-up): The BET surface area of the slaked lime should be checked as a measure of quality.
7. The dry sorbent injection test plan has several problems, noted as follows:
 - A. In order not to have serious wall deposition problems, Radian will have to atomize to a very small drop size, probably to a Sauter mean of less than 20μ. Under this condition, particle-droplet impaction

- will be substantially diminished. Effort to operate with larger drop sizes will result in severe wall wetting.
- B. Water deposition on the sorbent injectors in the post-injection mode (AH) and sorbent deposition on the water injectors in the pre-injection mode (BH) are likely problems. Ash deposition will be a problem in both modes of operation.
 - C. The data is likely to be too scattered to have confidence in a partial factorial experimental design, especially with only one repeat.
 - D. No estimated tolerances are noted for the variables in Tables 3-1 and 3-2.
 - E. Humidifying the flue gas by the method described in Section 3.2.5 is meaningless and will have essentially no influence on the wet bulb temperature. Radian must inject either dry steam or water upstream of the flue gas heater. (Does the flue gas heater have sufficient thermal capacity for this?)
 - F. I believe that if this pilot has any useful function at all, it is as a tool to gather good data to substantiate math modeling. Given that premise, I would recommend that most of this data be collected in the vertical duct. Asymmetry is more realistically achievable and would therefore be more compatible with 1 - D modeling, i.e., EER's initial model. Flow skewing and solids dropout will be a problem in the horizontal duct.
 - G. I would recommend varying the residence time by moving the gas sampling locations, rather than the water injection point. I do not recommend in-duct filters for gas sampling.
 - H. Controlling the SO₂ content by dilution will alter the wet bulb temperature, O₂ concentration, and CO₂ concentration.
 - I. An additional parameter to study would be the effect of sorbent types on removal. It appears that only one sorbent will be used. What sorbent will be used and where will it be purchased?
8. Page 3-1, second paragraph: The use of random test sequences minimizes bias, but does not eliminate it.
 9. Page 3-1, third paragraph: Will the fresh sorbent and recycle sorbent be injected through separate nozzles?
 10. Page 3-2, Table 3-1 - Baseline Parametric Testing of Dry Solids Injection:
 - A. What are the acceptable tolerances on the control variables?
 - B. There is only one repeat in this entire table of 81 tests. I would recommend more.
 11. The slaked lime slurry injection tests (the concerns about these tests are the same as the dry injection tests, with addition of the following concerns and comments):
 - A. Does Radian have a realistic understanding of the atomizer wear which they are likely to experience on recycle tests? If they glibly

dismiss this as a vendor problem/solution, they will have serious problems, such as droplet size degradation during testing. It would be very difficult to design a Casterjet type nozzle to be wear resistant.

- B. The effectiveness of ash recycle has been shown to be time-dependent, i.e., several hours in a stirred tank to allow for the silicious reactions to take place. Is Radian aware of this?
 - C. Is Radian going to measure the BET surface or pore size of the lime?
 - D. Operation at 20°F with CaCl_2 is doomed. (Operating at 20°F is doomed for all cases.) Note the experience of MSW scrubbers which scrub HCl with lime at high approach temperatures to produce CaCl_2 .
 - E. A stoichiometry (reagent ratio) of 2.0 is excessive; a better series would be 0.5, 1.0, and 1.5. I believe the cost-effectiveness of going above 1.5 to be marginal.
 - F. I believe that additives to improve slaking will be more fertile ground for improved sorbent reactivity than additives to the spray slurry.
12. Page 5-1, 5th bullet: Where in the system will the in-situ particle resistivity be measured?
13. Page 5-1, 4th paragraph: Will the extractive in-situ resistivity measurements be made with a Denver Research type probe?
14. Page 5-2, first full paragraph: When is the boiler #5 outage going to end?
15. Page 5-9, 2nd paragraph: The ESP should not corrode with operation at a 20°F approach, since active lime in the solids will keep the liquid pH on the ESP surfaces high.
16. ESP Test Plan: In general, this was a good, well thought-out plan and the potential fixes were also well thought-out. The two aspects that I have difficulty with are:
- A. That reentrainment of ash will be a serious problem. The low resistivity may contribute to poor electrical clamping of the ash to the ESP plates, but the cohesiveness of the ash owing to moisture content should help compensate. If ADA Technology is right, B&W should have had problems at B&W's dry scrubber plus ESP (DSR-1), Edgewater LIMB, and Burger E-SO_x. Since B&W did not have any ash reentrainment problems at the above jobs, I would like to see some references to this problem.
 - B. The explanation of the failure of SoRI's resistivity probe to match laboratory measurements does not match with B&W's experience. SoRI frequently measures resistivity at duct velocity.

17. Page 6-2, Table 6-1: I would recommend that SO_2 be measured upstream of the ESP in addition to the other SO_2 measurements.
18. Page 6-7, first paragraph: I would recommend that the wet bulb temperature be taken at the outlet. The explanation on why Radian uses hot water to do their wet bulb measurements does not make much sense.
19. Page 6-8, Table 6-3: I would recommend that the spent sorbents be analyzed for sulfite, in addition to the other species. Sulfite is usually the dominant sulfur species in wet and dry scrubbing processes.
20. Page 7-1: The duct cleaning tests make no mention of duct orientation or geometry. Radian has also not mentioned any potential fixes or solutions to duct deposition. Who will determine these required fixes?

ATTACHMENT 2

(P. V. Smith)

1. A process flow diagram of the pilot should be included in the test plan. I had one from attending DOE-PETC meetings, but the test plan makes more sense with a process flow diagram.
2. A sample heat and material balance of the pilot plant at the expected Meredosia test conditions should be included. This should include a coal analysis of the Meredosia coal and the expected flue gas composition and temperature. It would then have been easy for the reviewer/operator to determine the maximum ESP dust loading and other process parameters for the various tests in the test program.
3. An equipment list should have been included in the test plan which would aid the operators in operation, as well as ensuring that the preset test conditions in the test plan can be met.
4. A daily test schedule for each day should have been written out to give the operators guidance in which order equipment would be brought on-line, as well as which equipment would remain on overnight. This daily schedule should also include some attempt to measure the amount of SO₂ removal from sorbent on the duct walls. A potential method is to measure the water only removal (for dry hydrate runs), i.e., measure the SO₂ removal with just the water spray on to the desired approach temperature. This will give Radian some indications of wall effects so that only the SO₂ removals of injected sorbent will be used for model validation work.
5. The test plan does not address model development or model validation, which is the primary purpose of this pilot work. How will the CHAM model development and the Radian pilot plant work be coordinated?
6. Page 3-1, Section 3.1: The recycle ratio should be expanded to more than two tests at the extremes, 1:1 and 1:5. The recycle ratio is an important variable for equipment sizing. The lime utilization versus removal may flatten out at 1:3, which would negate much recycle testing above 1:3. Another possibility might be that the ESP or ash recycling system cannot operate at such high recycle ratios.
7. Page 3-4, second paragraph: It should be clear whether the baseline tests are going to be run at unaltered Meredosia conditions or will be spiked/diluted to maintain an SO₂ concentration of 1800 ppm SO₂, and heated/cooled to maintain a pilot inlet temperature of 300°F. It will be difficult to maintain 60 ft/sec through the duct with all this dilution/heating.

8. Page 3-5, Figure 3-1: I would recommend the approach temperatures be changed to minimum, minimum + 20°F, and minimum + 40°F, and the stoichiometries changed to 0.5, 1.0, and 1.5. It is unlikely that good data can be taken at a 20°F approach temperature in such a small duct. Please see comment 11.F in the first attachment for further discussion.
9. Page 4-1, 3rd paragraph: Some reasoning should be given as to why testing will be done at the highest practical recycle. The maximum recycle ratio for each test case should be calculated in order to ensure that the recycle solids are not greater than 40 weight percent solids. It is imprudent to plan to do tests that the pilot equipment cannot handle.
10. Page 4-2, Table 4-1: Additional reagent ratio tests should be done to determine the baseline reagent ratio tests.
11. Page 5-1, 1st paragraph: There does not appear to be much coordination between the duct and ESP testing with regard to length of tests, since duct tests will be 8 hours in length and ESP 24 hours in length. Will the duct be run at test conditions for 24 hours so that the ESP tests can be done? There is no mention of this in the duct portion of the test plan.
12. Page 5-2, 1st full paragraph: I would suggest that the baseline ESP tests be done first, prior to any slurry injection. This is the best way to ensure that residual sorbent in the pilot plant does not interfere with the fly ash-only testing.
13. Page 5-7, 1st full paragraph: The effect of reagent and recycle ratio on the ESP will have to be 24-hour operation tests. The duct injection test plan should reflect this.
14. Page 5-11, 1st paragraph: Where are the additives for cohesion improvement added? Are there injection ports for them in the pilot plant?
15. Page 6-2, Table 6-1: The atomizing air rate should be measured. This is an important parameter in fixing droplet size and atomizing energy requirements.
16. Page 6-6, 4th paragraph: Sootblowing will also change the fly ash loading of the pilot inlet flue gas.

TELECON RECORD.

JUNE 30, 1989

FROM: PAUL NOLAN
COMPANY: BABCOCK AND WILCOX

TO: PAUL IRELAND
COMPANY: S R

SUBJECT: COMMENTS ON RADIAN TEST PLAN
DOE SORBENT INJECTION
SR PROJECT 9330001

Paul Nolan is the Site Manager for B & W at Edgewater responsible for EPA's field testing of furnace sorbent injection and duct sorbent injection. He is also a member of the Technology Working Group for the subject project and called with comments to the Radian Test Plan presented at the June 7, 1989 meeting of the TWG as well as general comments on the TWG.

GENERAL COMMENTS

1. Size of the TWG is OK.
2. The frequency and duration of the TWG meetings as proposed is OK.
3. He would like to see results of the pilot plants presented at future TWG meetings.

RADIAN TEST PLAN COMMENTS

4. It appears to Paul that a large portion of the Radian Test Plan has already been done by CONSOL in an 8" diameter duct several years ago. He suggested that Radian obtain a copy of the Consol Test Report and review their test plan for duplication.
5. Page 5 of Minutes, para 3.- He felt it was important to explore a wide range of approach to saturation temperatures and calcium/sulfur molar ratios in the pilot plant. He thought that a range of approach temperatures of 15 to 30 F and 30 to 50 F was too narrow and suggested that values outside this range be explored at least for some of these tests.
6. Page 5, para 5 - He pointed out that some degree of stratification can be accommodated in operation by adjusting the flow of water to the nozzles. This has been done at Edgewater.
7. There should be some effort to assure that the Beverly and Meridosia pilot plants run exactly the same conditions for some of the tests so that a correlation can be obtained between the two units. Of particular concern is the flue gas SO2 concentration which is nominally 3200 PPM at Beverly and 1800 PPM at Meridosia.
8. He thought it would be worthwhile to run the current version of the EER model to see whether it predicted droplet evaporation would occur in the residence time available at the Radian and Gilbert pilot plants.

**Energy &
Mineral
Research
Center**

Fuels & Process Chemistry Research Institute
ND Mining & Mineral Resources Research Institute
Combustion & Environmental Systems Research Institute

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June 30, 1989

Mr. Paul A. Ireland
Project Technical Director
Stearns-Roger Division
United Engineers & Constructors
P.O. Box 5888
Denver, CO 80217

Dear Paul:

In response to your letter of June 12, 1989, the Energy and Mineral Research Center (EMRC) has reviewed the Test Plan prepared by Radian Corporation for operation of the 1.7 MW pilot plant. I have reviewed the entire document and asked Mr. David Hassett and Dr. Charles Moretti for their comments concerning the solid waste sampling and characterization plans. Our specific comments and questions include the following:

1. During the first week of system checkout within the start-up plan, I suggest you consider using certified calibration gases (cal-gas) to verify the operation of the Continuous Emissions Monitor Systems (CEMS). If possible, draw cal-gas through each sample line from upstream of the filter element through the heat-trace line and the sample conditioner to the instrumentation. This should establish a baseline for the performance of the flue gas sampling system. Then periodically during the test program the verification can be repeated as a check on data quality. This technique very quickly identifies and quantifies leaks, moisture problems, or the presence of reactive solids in the flue gas sample system.
2. What are the proposed solid waste sampling locations other than the ESP hoppers? How many ESP hoppers are there? Differences may be noted in solids samples collected in a hopper servicing the front half of the ESP versus samples collected from a hopper servicing the back half of the ESP.
3. The discussion in the first paragraph on page 2-7 is not consistent with Figure 2-1. It is stated that the approach temperature will be reduced from 60°F to 30°F and then to 20°F. Figure 2-1, Week 3, indicates that the approach temperature will initially be 20°F, increased to 30°F, and then reduced to 20°F. As the approach temperature is decreased, sorbent utilization should increase resulting in a decrease in the amount of solids required to achieve a specific level of SO₂ control and the amount of unreacted calcium in the solid waste. Decreasing approach temperature will also increase the residual moisture in the waste solids which could lead to materials handling problems (wall deposition, hopper bridging, etc.)

4. In the last paragraph on page 3-1 it is stated that two recycle ratios will be tested, 1:1 and 5:1. In Table 3-1 both Run Nos. 1 and 2 are to be performed at a recycle ratio of 1:1. Increasing the recycle ratio should increase overall sorbent utilization resulting in a decrease in the total amount of solid waste requiring disposal. A recycle ratio of 5:1 seems high and may result in increased wall deposition and reduced ESP performance.
5. Table 3-1 on page 3-2 identifies Run Nos. 29 and 30 as dilution and spike tests, but the inlet SO_2 concentration is listed as 1800 ppm for both tests. From the discussion, it would appear that these numbers should be 750 and 3000 ppm. On page 3-4 the last paragraph discusses the dilution and spike tests that are to be performed at 750 ppm and 1800 ppm SO_2 . Should the 1800 value actually be 3000 ppm SO_2 ?
6. The second paragraph on page 3-7 discusses changing flue gas velocities and concerns with respect to solids stratification and drop out due to low gas velocities. Is there any concern that high flue gas velocities will result in particle deposition in the duct due to impaction as a result of directional changes in the flue gas duct? Also, how will changing flue gas velocities impact nozzle performance in terms of flue gas humidification (sufficient duct coverage without wall wetting) and slurry injection (sufficient duct coverage without wall deposition)? How will nozzle performance be evaluated and measured?
7. On page 3-8 the impact of inlet SO_2 concentration is discussed in terms of its impact on the maximum achievable SO_2 removal. An increase in solids loading to match the higher inlet SO_2 concentration would not only increase the amount of solid waste requiring disposal but would tend to increase the potential for wall deposition and impact the performance of the ESP.
8. Tests discussing the impact of inlet flue gas humidity are discussed in the last paragraph on page 3-8. If the approach temperature is maintained at 20°F for both tests, will it be possible to determine the effect of inlet flue gas humidity? Is flue gas humidity expected to effect system performance beyond the level of humidification required to achieve a 20°F approach temperature?
9. The last paragraph on page 3-9 discusses the use of NaOH as an additive in the humidification water. Work done by EPRI and EMRC has documented the oxidation of NO to NO_2 when a sodium-based absorbent is used in SO_2 control processes. Although the amount of NaOH will be small in comparison to the calcium-based solids, are there any plans to monitor for NO_2 emissions at the ESP outlet during this additive test? Since sodium-based materials can be very soluble, a thorough evaluation of solid wastes resulting from tests using sodium-based as well as other additives should be performed.
10. Table 4-1 on page 4-2 indicates that the recycle ratio tests (Run Nos. 31 and 32) will both be run at 1:1 rather than 1:1 and 5:1. Also the dilution and spiking tests (Run Nos. 54 and 55) both have specified inlet SO_2 concentrations of 1800 ppm rather than 750 ppm and 3000 ppm.

11. Table 4-2 on page 4-3 identifies CaCl_2 and sugar as additives which will be used during slurry injection tests. If a positive result is observed using NaOH as an additive in the dry solids injection tests, will NaOH also be used as an additive during the slurry injection tests?
12. Although its not listed on page 5-1, I expect that the flue gas flow rate will be measured at the inlet or outlet of the ESP and gas constituents will be measured at the inlet and outlet of the ESP during ESP tests.
13. On page 5-2 it says that the baseline tests (fly ash only) for evaluation of the ESP performance will be performed after the dry injection and slurry injection baseline tests are completed and the scheduled boiler #5 outage. If there happens to be an unexpected problem with the operation of the ESP will it be caught in time to ensure the quality of ESP performance data collected during the baseline tests using dry solids and slurry injection? Unless data already exists, it would be useful to characterize solid wastes resulting from ESP baseline tests (fly ash only) as a basis for comparison of solid wastes collected and evaluated during the duct injection tests.
14. The last paragraph on page 5-2 discusses specific ESP performance tests to be performed. The first sentence refers to ESP-B1 and ESP-B3 when I believe it intends to refer to tests ESP-B1 and ESP-B4. Also, the last two sentences in the paragraph refer to test ESP-B4 when I believe they intend to refer to test ESP-B5.
15. The first paragraph on page 5-4 refers to an SO_2 concentration of 1700 ppm when I believe the correct value is 1800 ppm. Also the reference to ESP-B5 should actually be ESP-B6 if Table 5-1 is correct.
16. Is the wording of the first sentence of the third paragraph on page 5-8 correct?
17. The first paragraph on page 5-11 discusses the use of ammonia as an additive to increase the cohesive character of the waste solids to potentially improve the performance of the ESP. My perception would be that the waste solids will be very cohesive due to their high calcium concentration and moisture content. If it is necessary to increase the cohesive character of the waste solids, the addition of ammonia alone would probably be ineffective due to the absence of SO_2 resulting from the highly alkaline nature of the solids entrained in the flue gas. The high alkalinity of the solids entrained in the flue gas would make it impractical to add SO_2 to the system.
18. In the second paragraph on page 5-13 the use of increased operating voltage is discussed as having the potential to improve ESP performance. In this particular discussion, how is ESP performance or an improvement in performance defined (mass emissions, power consumption, etc.)?
19. The reference to on-site wet chemical analysis (section 6.1.4) in the first sentence of this section is slightly misleading, especially the reference to this being a dry process. Wet chemical analysis generally refers to the method of chemical analysis, not the nature of the material being analyzed. Wet chemical analyses can be done on solid, liquid, and gaseous samples.

20. It may be desirable to quantify the trace elements in the waste solids to support material balance calculations that may be required if trace elements are identified/quantified in leachate samples. Also, determining the alkalinity of the waste solids will help in classifying the material.
21. Leaching potential, (section 6.2.3., paragraph 2) determined with a mixing time of only 30 minutes, may not provide adequate time for true equilibrium to be established. A time range from between 18 and 72 hours would provide greater assurance of establishment of equilibrium.
22. The statement "Leaching potential will come from any change in mass of solids from dissolution" (section 6.2.3., paragraph 2) is true in the broadest sense, leaching potential of most elements is determined by phase location which can only be determined by a thorough mineralogical characterization. A thorough mineralogical characterization of solids would benefit this program greatly.
23. Calcium stands alone as a parameter in leachate analysis (section 6.2.3., paragraph 3). There may be other elements to include, depending on the purity of raw material purchased and makeup of the boiler fly ash.
24. A rather extensive list of trace elements (section 6.3.2., paragraph 4), most likely the capability of a simultaneous ICAP, has been proposed for the analytical parameters for solids, digested for this purpose. A similar suite of elements should be proposed for the leachates. In addition, the use of a screening technique such as SIMS, PIXE, INAA, etc., would be well advised for use in the development of a list of potentially problematic elements to be included in the analysis scheme for testing solids and leachates.
25. The use of the TCLP for determination of hazardousness of materials by the EPA is not appropriate. The TCLP was developed for the determination of hazardousness of leachates generated in co-disposal from materials disposed in a sanitary landfill. If the solids from this process are to be disposed of in a monofill the leaching test best applied is the EPA acid rain leaching test. If material is to be disposed in a sanitary landfill then the TCLP is appropriate.

If you have any questions or require a clarification of one or more of our comments, please call me at (701) 777-5222.

Sincerely,

Greg F. Weber
Research Supervisor
Environmental Systems

GFW/flm

c: Frank Beaver
David Hassett
Charles Moretti

APPENDIX C
PRELIMINARY DESIGN HANDBOOK
DUCT INJECTION TECHNOLOGY PROTOTYPE DEVELOPMENT

PRELIMINARY DUCT INJECTION TECHNOLOGY DESIGN HANDBOOK

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1.0 INTRODUCTION

This section will present a brief abstract of the design handbook describing scope, objectives, etc. References will be made to acid rain legislation as the driving force behind the technology, along with references to the DOE goal to make this a viable and available technology.

1.1 Design Handbook Organization

A brief explanation of how the manual is organized will be given with a description of each section. This section will also explain how to use the design handbook.

1.2 Overview of Duct Injection Technology

This section will explain the concept of duct injection as a cost effective SO₂ control technology intended for retrofit to older plants with space constraints and/or other technical and economic restrictions that would prevent them from using conventional FGD. The two major duct injection options will be introduced: Dry Sorbent Injection (DSI) and Duct Spray Drying (DSD). The chemistry of these processes will be briefly described, and references will be made to Appendix A - Process Chemistry.

1.2.1 Dry Sorbent Injection

This section will describe the DSI process. A simple block diagram will be used to show the components and their position. Each process component will be briefly described to explain its function and operating principle. The major factors influencing performance (SO₂ removal and sorbent utilization) will be listed and briefly explained; approach to saturation temperature, calcium to sulfur molar ratio, residence time, recycle effectiveness, etc., will be explained in detail, accompanied by typical results plots (e.g., approach temperature vs. SO₂ removal or Ca/S vs. SO₂ removal). The major limitations and potential side effects will be mentioned, but no detail will be provided in this section.

1.2.2 Duct Spray Drying

This section on DSD will be very similar to the DSI overview (Section 1.2.1).

2.0 DECISION MAKING CRITERIA FOR SITE-SPECIFIC APPLICATIONS

This is an extremely critical section of the document. The objective is to enable the user to determine, on an initial pass basis, if duct injection technology is a feasible option for his plant. After completing the exercises described in this section, the user should be able to make a good determination as to whether duct injection is feasible. If the user's plant is determined to be a suitable candidate for duct injection technology, the user will be instructed to proceed to Section 3.0.

2.1 Plant Data Requirements

To make the feasibility determination, a significant amount of plant design and operating data must be available. This section will list all of the necessary (and some optional) data items along with explanation text. An example list is presented in Table C.2-1. Recommendations on how and where to obtain some of the less common information will be provided.

2.2 Decision Making Process

The information gathered in Section 2.1 will be used to systematically evaluate the user's plant based on a variety of feasibility criteria. There will be a central decision making flow diagram that will be referred to throughout the text. An example of what a section of this chart might look like is shown in Figure C.2-1. The text will aid the user to determine how to answer yes or no to each decision branch. In many instances, the user will have to refer to formulas, charts and nomographs to determine if and how his plant installation fits a particular criteria. These nomographs will be located in Appendix B - Decision Making Criteria Resources. An example of a nomograph might be minimum acceptable electrostatic precipitator SCA for a given plant and DSI or DSD operating conditions.

TABLE C.2-1

SAMPLE OF POSSIBLE PLANT DATA REQUIREMENTS

<u>Description</u>	<u>Units</u>
Unit Size	MW
Average Load	MW
Availability	%
Operating Characteristics	(Base Load, Peaking, Demand Following, etc.)
SO ₂ Emission Limit or % Removal	
Coal Heating Value	Btu/lb
Coal Sulfur (Avg & Max)	%
Coal Asn Content (Avg & Max)	%
Coal Burn Rate/MW	TPH/MW
Flue Gas SO ₂ Exiting APH	PPM or Lb/MMBtu
Flue Gas Temperature (Min & Max)	°F
Flue Gas Velocity (Min & Max)	Ft/S
Flue Gas Flow Rate (Min & Max)	ACFM or DSCFM
Total Duct Length from APH Outlet to ESP or FF Inlet	Ft
Duct and Gas Flow Configuration	N/A
Longest Straight Run of Duct	Ft
Cross Sectional Area of Duct	Ft ²
Turning Vanes, or other Duct Obstructions	N/A
Duct Insulation Thickness	In
ESP SCA	Ft ² /1000 ACFM
ESP Aspect Ratio	N/A
ESP Field Arrangement	N/A
ESP Design Efficiency	%
ESP Typical Opacity or Emissions	% or Lb/MMBtu

TABLE C.2-1 (Cont'd)
SAMPLE OF POSSIBLE PLANT DATA REQUIREMENTS

<u>Description</u>	<u>Units</u>
I.D. Fan Capacity	ACFM/In. Water
Stack or Chimney Liner Type	N/A
Type of Ash Removal System	Pneumatic, Mechanical, Sluice
Ash Removal System Design Capacity	TPH
Ash Storage Capacity	Ft ³
Ash Disposal Method	N/A
Special Local Waste Disposal or Landfill Regulations	N/A

FIGURE C.2-1
HYPOTHETICAL EXAMPLE OF DECISION CHART

3.0 DESIGN CRITERIA

The design criteria, as detailed below, will be prepared on a preliminary basis under Subtask 2.3 and contained in Topical Report No. 4.

3.1 Specific Plant Information

This section will instruct the user to obtain the design and operating data which will be required to begin the conceptual design of the duct injection system for his candidate unit. A list with necessary data items will be presented. More detailed information will be necessary to complete this list compared to that required in Section 2.1. As in Section 2.1, the accompanying text will aid the user in how and where to find the data items, and what units to present them in. The completed data sets from this section and Section 2.1 will be used for conceptual design, and they may also be used as input to the duct injection predictive model detailed in Section 4.0.

3.2 Process Design Criteria

This section will present design criteria which, when used in conjunction with data collected in Section 3.1, will determine the primary process design of the system. Formulas, worksheets and nomographs will be provided to enable the user to predict duct injection parameters including: required calcium to sulfur ratio, sorbent utilization, sorbent requirements, humidification water requirements, recycle requirements, duct residence time, necessary droplet size, mass of waste produced, approximate ESP emissions and plume buoyancy. These worksheets and nomographs will be located in Appendix B - Decision Making Criteria Resources.

3.3 Mechanical Design Criteria

The same methodology used in Section 3.2 will enable the user to determine most of the physical equipment design criteria. The user will be given the necessary methods to determine sorbent storage requirements, compressed air requirements, pump capacities, slurry mix tank capacities, etc.

3.4 Economic Evaluation Criteria

Data and references to aid the user in making rough estimates of capital and operating costs of the two duct injection technologies will be given in this section. Locations and names of reagent suppliers will be provided along with tables and nomographs to estimate transportation costs. Formulas and tables will also be provided which present capital cost estimates (\$/kW (1992 Dollars)). These economic criteria will be based on coal sulfur content, SO₂ removal requirements, plant size and other general parameters.

3.5 Final Process/Sorbent Selection

Based on the results of the exercises in Sections 3.1 through 3.4, the user will be able to make his final decision regarding the feasibility of duct injection for his candidate facility. He will also have the necessary information to select which of the two duct injection options (DSI or DSD) and which sorbent are best suited for his application.

4.0 DUCT INJECTION PREDICTIVE MODEL

A short section will inform the user that DOE has developed a sophisticated three-dimensional model of duct injection processes as a complement to the design handbook. The user will also be informed of the availability of the model software and a complete detailed users guide. The computer hardware requirement options will be explained. This section will be closed with a strong recommendation that the user run this model before proceeding any further in designing his system.

4.1 Model Description

This section will explain the basic concept and capabilities of the model along with a simplified explanation of how it works. Simple block flow diagrams of the program logic from the program documentation will be included. The limitations of the model will also be explained.

4.2 Model Input

The user will be informed about the necessary input data he must provide. A list of required inputs, in the proper engineering units, will be shown. The user will be reminded that this is simply the input data set required, and that this section of the design handbook is not intended to instruct him on how to use the model. He will again be referred to the users guide document. A sample input data set will be shown. There will be a brief discussion of this mock data and how it will be used by the model.

4.3 Model Output

Some introductory text will discuss the information that is contained in the model output. A sample of actual model output will be given based on the sample input data set presented in Section 4.2. Each output item will be referred to and briefly explained in text form.

4.4 Utilizing the Model Results

This section will instruct the user on how to apply the information provided by the model to aid in the design of his duct injection installation.

5.0 ENGINEERING DRAWINGS

The drawings, as detailed below, will be prepared under UE&C Subtask 2.3 and contained in Topical Report No. 4.

5.1 Process Flow Diagrams

Process Flow Diagrams (PFDs) will be developed for the DSI and DSD processes. These diagrams will show the major process streams for each system. Each PFD will contain a blank table including all of the streams and their characteristics (flow rate, temperature, pressure, etc.) which the user can fill out after he completes the conceptual design in Section 3.0 of the design handbook.

5.2 Material and Energy Balances

Material and energy balances will be developed for both the DSI and DSD processes in conjunction with the case studies in Sections 13.0 and 14.0 of the design handbook. These balances, which will be used in conjunction with the PFDs developed in Section 5.1, will be based on a single 250 MW unit. The material and energy balances will be given for different coal sulfur contents and recycle ratios.

5.3 Piping and Instrumentation Diagrams

Piping and Instrumentation Diagrams (P&IDs) will be developed for both the DSI and DSD processes. These P&IDs will give a reasonable level of detail, but detailed instrumentation drawings will not be provided. The P&IDs will be broken down into the following subsystems:

Sorbent Storage and Preparation

Sorbent Injection

Humidification System (DSI only)

Flue Gas System Controls and Modifications

Waste Handling System Modifications

Recycle System

Plant Utilities

6.0 EQUIPMENT SIZING AND DESIGN

This section will provide the design considerations for the equipment to be retrofitted in a duct injection application. It will take the user through a step-by-step method of designing and optimizing each subsystem of the process. The starting points for most of these sections will be the Status Reports included in Appendix A of this topical report. As the test work at the Edgewater and 1.7 and 12 MW pilot-plant facilities proceeds, the results from these installations will supplement the current information in the Status Reports. A preliminary write-up of the equipment sizing and design sections will be prepared under UE&C Subtask 2.3 and contained in Topical Report No. 4.

6.1 Sorbent Storage and Preparation

6.1.1 Dry Sorbent Injection

Based on the Status Report for DSI sorbent storage and preparation, this section will provide design considerations for receiving, unloading, and storage of either pebble lime or hydrated lime. If pebble lime is chosen (based on economics), on-site hydration will be subsequently discussed.

6.1.2 Duct Spray Drying

Using the Sorbent Storage and Preparation Status Report for DSD as a basis, this section will discuss the receiving, unloading, and storage of pebble lime. This portion of Section 6.1.2 will be identical to that for DSI sorbent storage in Section 6.1.1 which includes on-site hydration. Then, the slaking process and subsequent storage and pumping of lime slurry will be addressed.

6.2 Duct Sorbent Injection/Flue Gas Humidification

6.2.1 Dry Sorbent Injection

This section will discuss the design and placement of both the humidification and dry sorbent injector nozzles and atomizer lances. In addition to the Status Reports on these topics, the test work at Edgewater, the Beverly test facility, and the B&W testing at the Alliance Research Center (as part of Subtasks 4.1 and 4.3) will provide input to this section. The possibility of directing nozzle spray orientation to avoid wall wetting, currently under evaluation by G/C at Beverly, will also provide input. Topical Report Nos. 8 (Nozzle Development) and 10B (Nozzle Array Testing) to be prepared by B&W will summarize their efforts.

6.2.2 Duct Spray Drying

The design and placement of the slurry nozzles or rotary atomizers will be covered in this section. The same sources of information as cited above in Section 6.2.1 will be used for this topic except no DSD is being investigated at Edgewater.

6.3 Ductwork Modifications

6.3.1 Ductwork Internals

Based on the Material Deposition and flue gas Velocity and Temperature Profile Status Reports, this section will discuss the possibilities of providing a well mixed, uniform gas profile to the injection point. In addition, modifications to duct internals downstream of the injection point will be covered to minimize sites for material deposition.

6.3.2 Deposition Control Modifications

Based on preliminary results from Edgewater and the pilot-plant facilities, some level of material deposition is likely for these processes. This section will discuss the mechanical equipment which may be added to control deposition (rappers, sonic horns, soot blowers, floor puffers, etc.) as well as the use of hoppers. The Status Report on Material Deposition provides a summary of experience with mechanical deposition control equipment. Several deposition control systems and hopper configurations will be tested at the Beverly test facility, and the results from this work will be included. The results from Topical Report No. 10A, which presents the results of B&W's cold-flow model study of the Beverly test facility, will be included.

6.4 Particulate Collection Device Modifications

6.4.1 Electrostatic Precipitators

This section will reflect the conclusions of the Status Report on ESPs and the information gained through the Edgewater and pilot-plant efforts. Results from the recent fundamental research by ADA will also provide information. Equipment upgrades including flue gas conditioning, collecting plate modifications, special discharge electrodes and additional SCA will be discussed. A subsection on modifications to the operation of the ESP will also be included; rapping cycle modifications and power-off rapping will be highlighted.

6.4.2 Fabric Filters

This section is optional at this time.

6.5 Waste Handling System Modifications

6.5.1 Waste Handling System

The emphasis in this section is on conveying, storage, and conditioning of the fly ash/sorbent waste collected in the ESP. A waste handling system will already exist at each site; modifications to this system will be addressed. The Status Report on Waste Handling Systems will be the primary source of material for this section. In addition, the modifications implemented to the existing waste handling system at Edgewater will be discussed.

Four different types of material conveying will be addressed: vacuum pneumatic, pressure pneumatic, mechanical, and wet sluicing. EERC's Topical Report No. 9 on waste material characterization may also be used as input to this section.

6.5.2 Recycle System

This section will be broken down into DSI and DSD subsections since the recycle technique is unique to each process. In DSI, the recycle material is maintained dry, and the important design considerations are the same as for the waste material: dry conveying and storage. For the DSD process, the material is conveyed and stored dry but then slurried and combined with the fresh lime slurry before injection into the duct.

The Status Report on Recycle Systems, the Edgewater experience, and the pilot-plant experiences will be the major inputs to this section.

6.6 Waste Disposal

Based on the Waste Disposal Status Report, the transportation methods and final disposal methods (e.g., landfill, ponding, etc.) applicable after duct injection retrofit will be discussed. Additional input will be provided from EERC's Topical Report No. 9.

7.0 PLANT AND EQUIPMENT ARRANGEMENT CONSIDERATIONS

A preliminary write-up of possible equipment configurations and retrofit considerations will be prepared under UE&C Subtask 2.3 and contained in Topical Report No. 4.

7.1 Equipment Configurations

This section will give the user an idea of the real estate requirements of the components to be added and the various options for their configuration. It will enable the user to select a viable duct injection equipment configuration for his application and assist him in the proper equipment layout. Specific process configuration options considered will be recycle, on-site hydration, and upstream vs. downstream humidification in the DSI process.

Individual process component sizing and design information will have been developed in Section 6.1 and 6.2. This information will be used as inputs in the final process configuration and layout selection.

7.2 Retrofit Considerations

This section will present a general discussion of what to consider when retrofitting a duct injection process. Topics addressed will be general space constraints, conveying distance limitations, plant utility requirements, and multi-unit considerations. In addition, several special cases will be presented including:

- ° two ESPs in series
- ° an ash silo common to several units
- ° sloped ductwork or elbows in ductwork

Modifications to existing equipment will have been discussed in Sections 6.3 to 6.6. This information will be used as inputs in the general considerations for the retrofit.

8.0 PROCESS CONTROL

8.1 Process Control System Philosophy

This section will summarize the various options for controlling the overall duct injection process. Options will be based on typical regulatory reporting requirements (e.g., SO₂ percentage removal or outlet emission), process configuration, and site specific equipment. Each option will include a simple block diagram giving the overall logic. Safety and interlock approaches will also be described.

There are several process control subsystems including approach temperature control, sorbent injection feed rate, recycle rate, and slurry composition (for DSD). These subsystems are interrelated; the integration of these subsystems will be discussed.

Sources of information for this section will be the spray dryer scrubber industry, the Status Reports on Temperature and SO₂ Instrumentation and Controls, the Edgewater experience, and the pilot-plant work associated with this program. The G/C pilot program in particular will focus on process control.

8.2 Control Instrumentation Requirements

Process control instrumentation required to meet the objectives of the process control philosophy will be described in this section. After choosing the appropriate control scenario, the user can select the necessary instrumentation to implement it. Much of the information for this section will be based on the 12 MW pilot effort in which process control will be addressed in depth. Commercial spray drying experience will also provide important information.

8.3 Monitoring Instrumentation Requirements

This section will assist the user in selecting the type and proper application of process monitors to fit his duct injection requirements. The major processes to be monitored include flue gas temperature, pollutant gas concentration and slurry composition. The impact of a duct injection process on monitoring these parameters will be discussed. An overview of available instrumentation options will be provided which will include their applicability to duct injection processes. This section will use data and information from Status Reports on Temperature and SO₂ Instrumentation and Controls. Information obtained from the pilot-plant studies and related full-scale experience will augment the Status Reports.

8.4 Plant Monitoring and Control System Interfaces

It will likely be necessary to interface the duct injection process control system to the existing boiler and/or auxiliary process control systems. This will require both hardware and software modifications to transmit, interpret, and control the proper analog and digital signals. This section will provide general information to assist plant personnel in making control system interface decisions. Information will be

gathered from Edgewater, the spray dryer retrofit installations, and from manufactures to determine appropriate control systems, such as PLC's.

8.5 Existing Plant Control Modifications

Utility boiler operation can affect the operation and performance of duct injection technology and vice versa. Depending on the process control scenario, a variety of boiler operating parameters such as load, firing rate and soot blowing schedule may be necessary signal inputs for the new duct injection control sequence. The retrofit of a duct injection process can significantly increase solids loading to the particulate collector. An upgrade of rapper controls and/or ash pulling sequence control may be necessary. Some of these items will be covered in more detail in the ESP and ash handling sections of this document. Input for this section will come from the Edgewater experience and full-scale spray drying experience as well as from the pertinent Status Reports.

9.0 MATERIALS SELECTION AND LINING REQUIREMENTS

9.1 Humidification/Slurry Injection Ductwork

This section will review the effects of duct injection processes on steel plate ductwork and make any recommendations for replacement materials or liners. Experience from the spray dryer scrubber industry and from B&W's corrosion testing (Topical Report No. 10C) will be used as well as the Corrosion Status Report.

9.2 Particulate Collection Device

Corrosion in the ESP, particularly in the last fields, will be addressed with possible alternatives recommended to minimize it. The option of adding additional insulation will be included. The same sources of information as stated in Section 9.1 will be used.

9.3 Ductwork Between Particulate Collection Device and Stack

This section will include a similar discussion of added insulation and minimization of in-leakage to that in Section 9.1 including ductwork and I.D. fan casings with the added possibility of reheat for corrosion protection.

9.4 Stack/Chimney Liner

The typical stack and chimney liner materials will be discussed as to their suitability for withstanding low-temperature corrosion.

10.0 EQUIPMENT/SYSTEM BID SPECIFICATION GUIDELINES

There are two typical approaches to specifying the equipment required for retrofitting a duct injection system: 1) specify each component separately and procure them from individual vendors, or 2) specify the entire system as a package, make a single vendor the prime contractor, and make that vendor subcontract all of the components and services it cannot provide. These two approaches will be discussed in the subsections below.

The specifications required to procure the necessary equipment will be included in the design handbook. They will detail the performance and technical requirements for the equipment or system, and they will be generic enough to allow customizing to a specific plant site.

The basis for these specifications will be existing UE&C documents, the Status Report on Humidification and Slurry Nozzle Specifications, and existing dry scrubber package specifications. Experience gained at Edgewater and from the pilot plants will also be incorporated.

10.1 Equipment Specification Guidelines

This section will help the user to specify individual components using separate "furnish and deliver" specifications for each. The method of installing the equipment using one or more general contractors will be touched upon. The actual furnish and deliver specifications will be attached in Appendix E to the design handbook.

10.2 System Specification Guidelines

This section will give some guidance on procuring the entire system from a single vendor. Included in this section will be a write-up on guarantees. If a single vendor has responsibility for supplying the entire system, guarantees for SO₂ removal, particulate emissions, reagent consumption, pressure drop, etc. can be requested as part of the contract. The actual system specifications for both the DSI and DSD process will be attached as part of Appendix E to the design handbook.

11.0 OPERATION AND MAINTENANCE CONSIDERATIONS

A short section will introduce the subject of operation and maintenance. It will state that it is not the intent for this section to serve as an actual O&M manual, but rather to provide general guidelines which will enable the user to develop an O&M manual specific to his installation. Input from Edgewater, commercial spray drying installations, and the 12 MW pilot-scale studies will provide the majority of the data for all of Section 11.0.

11.1 General Operating Guidelines

11.1.1 Dry Sorbent Injection

This section will identify and explain the major operating guidelines common to all DSI systems, and it will also describe desirable operating procedures for the major process options (on-site hydration, recycle additive systems, etc.). Safety aspects, start-up/shutdown procedures, and turndown considerations will be covered for both the DSI process equipment and the affected plant equipment (particulate collector, ash removal system, etc.).

11.1.2 Duct Spray Drying

This section will be similar to Section 11.1.1, but will be specific to duct spray drying.

11.2 General Maintenance Requirements

11.2.1 Dry Sorbent Injection

On-line, scheduled, and forced maintenance guidelines will be discussed. Recommendations for inspection procedures and schedules will be provided for all components of the DSI process equipment. Schedules for typical replacement of various parts and components will also be presented.

11.2.2 Duct Spray Drying

This section will be similar to Section 11.2.1, but will be specific to duct spray drying.

11.2.3 Existing Plant Equipment

This section will address the potential changes required in the maintenance of existing equipment after the duct injection process is retrofitted. As in Sections 11.2.1 and 11.2.2, on-line, scheduled, and forced maintenance guidelines will be discussed. Subsystems addressed will include particulate collector, stack, ash removal and handling systems, and waste transport and disposal systems.

11.3 Ductwork Cleaning/Access Requirements

There may be some simple ductwork modifications required to enable removal of solids deposition. Access hatches, doors, strike plates and, in some cases, hoppers may be added to the existing ductwork. Recommendations on size, number and location of these modifications will be presented with proper guidelines to ensure that the modifications be utilized in a safe, effective manner.

11.4 Process Troubleshooting

This section will enable the user to use available operating data to troubleshoot operational and performance problems in a duct injection system. Examples include using flue gas thermocouple or duct skin thermocouple data to identify problem atomizers and duct deposition. General acceptable limits of various operating parameters will be summarized along with their potential impacts on system performance and operations. Troubleshooting procedures for the most common system problems (poor sorbent utilization, high ESP opacity, etc.) will also be presented.

12.0 ECONOMIC EVALUATION

Preliminary economics are included in Section 5.0 of this Topical Report No. 2 for capital, operating and maintenance, and levelized costs. More definitive economic evaluations will be included with the DSI and DSD case studies generated as part of UE&C's Topical Report No. 5.

12.1 Capital Cost

This section will provide guidance in estimating the capital cost associated with retrofitting either a DSI or DSD system. A typical design will be used to develop a base case cost with factors provided to adjust the base cost for difficulty of retrofitting, design coal sulfur content, size of the plant, etc. The source of data will be UE&C's in-house economic computer programs, EPRI TAG Guidelines, and any cost information available from Edgewater.

12.2 Operating and Maintenance Cost

This section will be similar to Section 12.1 but will allow estimation of O&M costs for a DSI or DSD system. A typical design will provide base case costs with factors provided for adjusting to a site-specific application.

12.3 Levelized Cost

This section will be similar to Section 12.2 but will allow estimation of levelized operating costs to determine the economic impact of adding a duct injection system on the cost of generating a kilowatt of power and in removing a ton of SO₂.

13.0 DRY SORBENT INJECTION CASE STUDY

This section will present the technical and economic results of the DSI process evaluation generated as part of UE&C's Topical Report No. 5. The design for the case study will be based on a 250 MW unit burning medium sulfur coal.

Material balances, component design selection and sizing, and drawings will be prepared for the process retrofit of this specific plant. With this information, vendor information will be solicited to develop actual cost and performance data. Based on the vendor information, sensitivity analyses will be performed to evaluate the impact of several parameters on cost. These parameters include the same process variables listed in Tables 5.5-1 and 5.5-2 in Section 5.0 of this report.

This case study will serve as an example of the step-by-step process for determining the feasibility and developing the DSI retrofit design and cost data starting with the necessary site-specific information.

14.0 DUCT SPRAY DRYING CASE STUDY

This section will present the technical and economic results of the DSD process evaluation generated as part of UE&C's Topical Report No. 5. It will be performed in an identical manner as discussed in Section 13.0 for the DSI process.

APPENDIX A - Process Chemistry

A fairly detailed discussion of duct sorbent injection chemistry will be presented in this appendix. All of the balanced chemical equations and kinetics will be presented and discussed. The various physical and chemical factors affecting the process will also be discussed. Experimental and theoretical research on the chemistry of duct injection processes performed by EER, FERCO and others will be used to provide the information in this appendix.

APPENDIX B - Decision Making Criteria Resources

This appendix will be made up of various formulas, tables, charts, worksheets, nomographs and test procedures to be used in the decision making and design criteria sections of the design handbook (Sections 2.0 and 3.0). These resources will enable the user to determine application feasibility and aid in determining optimum design and economic values. These figures will be generated by established calculation methods, data bases, and computer models and from operating results at various duct injection installations.

APPENDIX C - Sorbent Selection

This appendix will contain data and information to help the user determine the selection of the sorbent which is best suited to his specific plant. Performance data generated by pilot- and full-scale results will present SO₂ removal and utilization as a factor of Ca/S molar ratio, approach temperature, residence time, etc. There will also be discussions and data pertaining to the effects of various sorbent additives and recycle scenarios. DSI and DSD will be discussed separately. This information can be combined with the operating costs defined in the economic evaluation in Section 12.0 to enable final sorbent/additive selection. Information obtained from the pilot-plant studies will augment the Sorbent Selection Status Report.

APPENDIX D - By-Product Utilization

The research on characterization and utilization (including market analysis) of coal conversion residues has provided an indication of a variety of potential uses for the residues. Many of these utilization technologies can also be applied to emissions control process wastes. The characterization of wastes in this program by EERC will result in a better understanding of the material. This approach is valuable because it can provide the strategy for either disposal or utilization of the material. The EERC utilization study will focus on determining the most promising utilization alternatives for the materials characterized. The results of the utilization study will be reported in EERC's Topical Report No. 9, and it will be included as Appendix D of the design handbook.

The test data from the chemical, physical, and mineralogical characterization effort will be used to identify any significant or unusual problems with either the handling or disposal of the duct injection solid waste and to evaluate a broad range of different utilization options for this material. Potential uses for the duct injection solid waste will be identified by evaluating applications developed for similar materials, such as spray dryer solid waste.

APPENDIX E - Bid Specifications

This appendix will contain the actual equipment and system bid specifications referenced in Section 10.0 of the design handbook. A preliminary list of specifications is included as Table E.0-1. These specifications are in preparation on a preliminary basis under UE&C Subtask 2.3, and they will be contained in Topical Report No. 4.

TABLE E.0-1
EQUIPMENT AND SYSTEM BID SPECIFICATIONS

Spec. No. Title

Mechanical Equipment

M001	Blowers
M002	Humidification Water Nozzles
M003	Slurry Nozzles
M004	Dry Sorbent Injectors
M005	Flue Gas Reheater
M006	Rail Car Unloading
M007	Welded Steel Silos
M008	Pneumatic Transfer Conveyor/Injection Conveyor
M009	Welded Day Bins
M010	Gravimetric Feeders
M011	Rotary Air Locks and Feeders/Shutoff Gates/Diverter Valves
M012	Lime Hydrator
M013	Ball Mill Lime Slaker-Classified
M014	Detention-Type Lime Slaker-Classified
M015	Paste-Type Lime Slaker-Classified
M016	Water and Slurry Tanks
M017	Agitators
M018	Horizontal Centrifugal Water and Slurry Pumps
M019	Slurry Valves
M020	Air Compressors
M021	Bin Activators
M022	Screw Feeders
M023	Grit Screens
M024	Bin Vent Dust Collectors

Electrical Equipment

E001	NEMA Frame Induction Motors
E002	Electrical Requirements for Packaged Mechanical Equipment

Controls and Instrumentation Equipment

C001	Instrumentation and Controls for Packaged Mechanical Equipment
C002	Continuous Emissions Monitoring System

System Specifications

A001	Dry Sorbent Injection System
A002	Duct Spray Drying System

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