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ADVANCED IN-DUCT SORBENT INJECTION FOR SO_2 CONTROL

TOPICAL REPORT NO. 4
TASK 3: OPTIMIZED ADVANCED PROCESS EVALUATION

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TOPICAL REPORT NO. 4, TASK 3: OPTIMIZED ADVANCED PROCESS EVALUATION

ABSTRACT

The objective of this research project is to develop second-generation duct injection technology as a cost-effective compliance option for the 1990 Clean Air Act Amendments. Specific performance targets are 90% SO_2 removal and 60% sorbent utilization efficiency. Research focused on the Advanced Coolside process, which showed the potential for exceeding these targets. The objective of Subtask 3.1, Performance Testing, was to develop process performance and operability data for design and scale-up of the optimized Advanced Coolside process. Results of long-term pilot plant testing with 24 hour/day operation provided a positive indication of process operability. The objective of Subtask 3.2, Waste Characterization, was to determine the chemical and physical properties of the waste materials for designing the waste handling and disposal systems for the process. Test results show that the combined spent sorbent and fly ash waste is suitable for landfilling. Further, the waste management study indicated a potential for by-product utilization for synthetic aggregate production; a more thorough investigation of this potential is required.

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TOPICAL REPORT NO. 4, TASK 3: OPTIMIZED ADVANCED PROCESS EVALUATION

BACKGROUND AND INTRODUCTION

The objectives of the project entitled "Advanced In-Duct Sorbent Injection for SO_2 Control" (DOE Contract DE-AC22-91PC90360) are to improve the applicability of in-duct sorbent injection technology as a compliance option for the 1990 Clean Air Act Amendments and to reduce total SO_2 control costs. Specific desulfurization performance targets were to achieve 90% SO_2 removal and 60% sorbent utilization, while retaining the low capital cost and retrofit advantages inherent to in-duct technology. These targets represent a substantial improvement over existing sorbent injection technologies.

In Subtask 2.1 of this project, Evaluation of Advanced Concepts, pilot plant tests indicated that a process concept, referred to as the Advanced Coolside process, had the potential to achieve the process performance targets (Topical Report No. 1[1]). SO_2 removals over 90% and sorbent utilization efficiencies over 60% were achieved. Other concepts for advanced sorbent injection were evaluated in Subtask 2.1, but none showed the potential to meet the process performance objectives. As recommended in Topical Report No. 1, all further testing focused on optimizing the Advanced Coolside process.

The Advanced Coolside process involves flue gas humidification to near the adiabatic saturation point using a contacting device which simultaneously removes most of the fly ash from the flue gas. The sorbent (hydrated lime) is injected into the highly humid flue gas downstream of the contactor, where it captures SO_2 before being removed by the existing particulate collector. The very high humidity allows high SO_2 removal. High sorbent utilization is achieved by sorbent recycle. Greater recycle rates are possible than for existing duct sorbent injection processes because the fly ash is removed by the contactor prior to sorbent injection. Furthermore, previous testing[1] indicated that addition of some moisture to the recycle sorbent prior to reinjection can significantly improve process performance.

Subtask 2.1 of this project indicated several approaches for improving the Advanced Coolside process, including optimization of sorbent recycle, optimization of process equipment to reduce capital cost, and optimization of the sorbent.

Recycle optimization and process design optimization were evaluated through pilot plant tests in Subtask 2.2 and are reported in Topical Report No. 2.[2] By optimizing recycle, 90% SO_2 removal was achieved at sorbent utilizations of up to 75%, exceeding the original performance target of 60% sorbent utilization efficiency. Recycle tests showed that the Advanced Coolside process has the potential for very high SO_2 removal efficiency. With a baghouse, removals of >99% were achieved at sorbent utilization efficiencies exceeding 60%. In the design optimization portion of this program a second generation contactor and a third generation contactor were designed, tested and optimized through pilot plant testing. For both designs, tests were conducted to maximize humidification efficiency while reducing flue gas pressure drop and water flow. In addition to contactor optimization, the recycle wetting/mixing equipment was optimized. This involved testing a pugmill in place of the high intensity mixer used in initial recycle tests. Use of a pugmill results in significant capital and operating cost savings.

The Sorbent Optimization program (Subtask 2.3) explored means of improving performance and economics of the Advanced Coolside process through optimizing the sorbent system, as described in Topical Report No. 3.[3] Pilot plant tests of commercial and specially prepared hydrated limes showed that the process is relatively insensitive to sorbent source. This can be an important economic advantage, allowing the use of the lowest cost sorbent available at a site. A pilot plant hydration study conducted in cooperation with Dravo Lime Company further indicated the insensitivity to lime source and to lime physical properties. Pilot plant tests indicated that very small amounts of additives added within the Advanced Coolside process can marginally improve performance; however, additives are not necessary to exceed process performance targets.

The information generated in Subtasks 2.1, 2.2, and 2.3 was used to optimize the Advanced Coolside process. In Task 3, the optimized process was the subject of additional testing. The objective of Subtask 3.1, Performance Testing, was to generate performance and operability data for design and scale-up of the process. The Performance Testing involved long-term pilot plant testing with 24 hr/day operation; total on-stream time was ~300 hours. The objective of Subtask 3.2, Waste Characterization, was to determine the chemical and physical properties of the waste materials and to develop the data needed for designing the waste handling and disposal systems for the process. The Waste Characterization test program was expanded to include exploratory tests of by-product utilization options. This involved pelletization tests and preliminary evaluation for production of synthetic aggregate materials. The potential for by-product utilization is important, because the cost of waste disposal is a significant component of process cost. This report discusses the results of both the Performance Testing and the Waste Characterization Study.

CONCLUSIONS

PERFORMANCE TESTS

Following are the major conclusions of Subtask 3.1, Performance Testing.

1. Although the scale of the 1000 acfm pilot plant is not sufficient to fully resolve process operability issues, the performance test provided a positive indication of the operability of the Advanced Coolside process. The performance test included three separate weeks of 24 hr/day operation for a total of approximately 300 hours on stream. There were no major operation problems in the flue gas duct with sorbent injection at high humidity or in operating the recycle wetting, handling, and transport systems. These operability issues should be further addressed in larger scale, longer term tests.

2. The level of water addition to the recycle sorbent was limited to about 0.12 lb/lb recycle in the pilot plant. Too much water on the sorbent caused excessive particle agglomeration and operability problems with recycle feeding and transport. As observed previously, less water can be incorporated into highly utilized, lower porosity sorbents. The limitation on recycle water addition is not expected to be as significant a factor for larger scale operation, since less water addition is required to maintain a close approach in larger scale operation than in the pilot plant. In the pilot plant, excess water is needed to allow for evaporation into the transport air; for this small-scale system the transport air flow is an order of magnitude greater than typical for commercial scale pneumatic transport systems.

3. A system SO_2 removal of around 90% at 1.25-1.3 Ca/S was achieved during the performance test. In-duct SO_2 removals were lower (average, 78%) than previously observed at similar conditions (~85%). This was likely partially a result of a higher approach at the duct exit (ca. 5-7 °F) than in previous tests (~3-4 °F). The approach can normally be controlled by adjusting the amount of recycle water addition; however, the pilot plant was operated at the maximum operable water addition rate. The sorbent

agglomeration caused by operating at the maximum amount of moisture addition may have also contributed to the lower SO_2 removal in the duct.

4. A higher degree of sorbent carbonation was observed in the performance test than in most previous tests. The $CaCO_3$ content of recycle sorbent ranged from 20 to 30 wt %. The degree of carbonation may be high in the pilot plant because the sorbent in the baghouse is intimately contacted by flue gas with a low SO_2 content and high humidity. The extent of carbonation and its effect on performance should be further evaluated in larger scale testing with an ESP.

5. The performance testing indicated an apparent positive effect on performance when the baghouse solids were allowed to stand for extended periods before wetting and reinjection (e.g., during shutdown periods). This apparent effect should be further investigated. Since there were shutdown periods in the Performance Testing, process performance needs to be verified with continuous operation more closely simulating commercial operation.

WASTE CHARACTERIZATION STUDIES

Three Advanced Coolside waste samples were prepared for testing in Subtask 3.2, Waste Characterization. These samples represent simulated Advanced Coolside waste produced from a boiler using feed coals with 7.5% ash and 3.5%, 2.5%, and 1.5% sulfur. Following are the major conclusions of this study.

1. The maximum dry bulk density of Advanced Coolside waste increased from 75 to 80 lb/ft^3 with increasing fly ash component in the waste. The fly ash component in the waste increased with decreasing sulfur content of the coal from which the waste was generated.

2. Advanced Coolside waste compacted to 95% of Proctor density and optimum moisture has an unconfined compressive strength that is suitable for landfill disposal. The strength increases from 20 psi (uncured) to 100 psi or more after 28 days of curing.

3. The leachate toxicity of Advanced Coolside waste was determined. The leachates were prepared according to both the TCLP and ASTM leaching procedures. In all cases, the trace element concentrations were well below (1/50th or less) RCRA allowable limits. The waste can be classified as non-hazardous for landfill disposal.

4. The Advanced Coolside wastes were pelletized on a disc pelletizer. Pellets are lightweight and have a low bulk specific gravity. The pellets also have a desirably low LA abrasion index, low water absorption, and a coarse size distribution; however, they also have a high soundness index (low durability). These pellets appear to have the potential for use as lightweight aggregates in concrete masonry units. This potential needs to be more fully evaluated.

DESCRIPTION OF ADVANCED COOLSIDE PROCESS

Figure 1 shows a schematic of the Advanced Coolside process. The process achieves greater SO_2 removal and sorbent utilization than previous duct sorbent injection processes by operating at a higher flue gas humidity and by more fully exploiting the potential of sorbent recycle. A key to the process is a gas/liquid contacting device downstream of the air preheater. The contactor serves two purposes: to nearly saturate the flue gas with water and to remove most of the coal fly ash from the flue gas. The sorbent is injected downstream of the contactor into the highly humid flue gas. Hydrated lime is very active for SO_2 capture near the saturation point, even in the absence of liquid water droplets. Because the flue gas is humidified prior to sorbent injection, there is no residence time requirement for droplet evaporation. SO_2 is removed in the duct and by the sorbent collected in the existing electrostatic precipitator (ESP) or baghouse. The heat of reaction between SO_2 and hydrated lime raises the temperature of the flue gas by roughly 8-10 °F for each 1000 ppm of SO_2 removed. Therefore, the particulate collector can be operated at an elevated approach to saturation without flue gas reheat. However, because hydrated lime activity is highly sensitive to the approach to saturation, this reaction heat effect also acts as a limiting mechanism for SO_2 capture.

The spent sorbent is captured in the existing particulate collector as a dry powder. Sorbent recycle is an integral component of the Advanced Coolside process. Laboratory and pilot plant tests have shown that recycle sorbent is quite active for SO_2 capture at high humidity. The recycle capacity is increased because fly ash is removed separately before sorbent injection. Furthermore, process performance can be improved by adding small amounts of moisture to the recycle sorbent (or to the combined recycle and fresh sorbents) prior to re-injection. The water, by evaporating and counteracting the heat of reaction, acts to maintain a close approach to saturation.

In Subtask 2.2 (Design Optimization), a third-generation flue gas/water contactor (Venturi contactor) was developed, as reported in Topical Report 2.[2] Pilot plant tests confirmed the feasibility of the design, consisting of a low-pressure-drop venturi and a cyclonic separator. The particulate collection efficiency and operability were good. Humidification was typically to within about 1 to 4 °F approach to saturation. Injection of small amounts of steam at the cyclonic separator exit was found to give a closer approach to saturation (0 to 1 °F).

The Advanced Coolside process generates two waste streams: the dry spent sorbent from the particulate collector and the fly ash/water slurry collected in the contactor and subsequently concentrated by hydrocyclones. The proposed concept for disposal or utilization is to mix the two streams, producing a material with near the optimum moisture content.

EXPERIMENTAL

ADVANCED COOLSIDE PILOT PLANT DESCRIPTION

Figure 2 is a schematic of the Advanced Coolside desulfurization pilot plant. It is designed to simulate integrated Advanced Coolside operation with combined flue gas saturation and fly ash removal using a contactor, and sorbent injection downstream of the contactor into the saturated flue gas. The pilot plant consists of a flue gas generation system, a flue gas/water contactor, a spent slurry handling system, a sorbent injection system, a recycle sorbent moisture addition system, the test duct section/reactor, a baghouse, and a flue gas analysis system.

Flue Gas Generation System

A simulated flue gas stream is produced by mixing the combustion products of a natural gas combustor, bottled gases (SO_2 and CO_2), steam, plant N_2, and fly ash with a recycle gas stream from the process. Gas flow rates of 150 to 350 scfm are generated in this manner. The gas combustor serves to generate make-up flue gas and to raise the flue gas temperature to the desired level. The inlet SO_2 content can be varied from 500 to 2500 ppm by SO_2 injection. The fly ash loading can be varied from 0 to 5 gr/scf. The flue gas adiabatic saturation temperature at the baghouse exit is controlled by the rate of steam injection upstream of the contactor.

Gas recycle provides over 80% of the simulated flue gas flow. After particulate removal, the flue gas is cooled by a heat exchanger, and condensed water is removed by an impaction separator. The gas then is recycled by a blower.

Contactor

Testing was conducted using the third generation (Venturi) contactor, which consists of a low pressure drop venturi and a centrifugal separator (Figure 3). It is designed to remove fly ash and humidify the flue gas to near saturation. The contactor design and performance is detailed in Topical Report No. 2.[2]

To increase contactor gas throughput, a contactor recycle fan provides the ability to recirculate flue gas from the contactor exit directly back to the contactor inlet; this was provided because the contactor was designed for

1000 acfm, which is higher than the maximum output of the flue gas generation system. During operation of this contactor recycle fan, coal-fired post-air-preheater flue gas conditions are simulated by mixing high-temperature (~450 °F) flue gas from the flue gas generation system with the low-temperature flue gas recycled from the contactor exit.

Spent Slurry Handling

Fly ash is removed as a slurry from the contactor. The spent slurry is pumped to a gravity separator. Solids are removed as a sludge (approximately 50/50 fly ash/water by weight). The clarified liquor is recycled to the contactor. Make-up fresh water is added as needed.

Flue Gas Ductwork

The saturated flue gas exiting the contactor passes through 53 ft of 5-inch pipe, then 24 ft of 8-inch pipe, and then 7 ft of 4-inch pipe before entering the baghouse. This simulates the ductwork in the Advanced Coolside process, providing contact between sorbent particles and the humid flue gas. Sorbent is injected at the contactor exit into the 5-inch pipe.

Recycle Sorbent Moisture Addition

A batch mixer manufactured by Littleford Bros., Inc. (Model FM-130) is used for tests with water addition to recycle sorbent. The mixer is equipped with low-speed, plow mixers and a high-speed chopper. Water is added to recycle sorbent using a hydraulic nozzle while the mixer is operating. The water addition/mixing procedure takes about 3-4 min for each 60-70 lb batch of recycle sorbent.

Baghouse

A baghouse is used to remove particulates from the duct effluent flue gas. It is a pulse-jet type baghouse with 9 bags, giving a total cloth area of 144 ft^2. Solids are collected in a 55-gal drum under the baghouse hopper. The hopper is sealed by a butterfly valve. The baghouse is heat traced to maintain adiabatic operation.

The flue gas can be reheated before the baghouse to control the approach to saturation at the baghouse exit. Reheat is accomplished by injecting hot air between the duct exit and the baghouse. The approach to saturation at the baghouse exit can be varied from 10 to 25 °F. As mentioned previously, a 10 °F approach can be maintained without reheat, due to the reaction heat effect.

Flue Gas Analysis

The flue gas composition is measured continuously by on-line analyzers at four locations: the contactor inlet, the contactor exit (duct inlet), the duct outlet, and the baghouse exit. This allows calculation of SO_2 removals in the contactor, in the ductwork, and in the baghouse. SO_2 and O_2 contents are measured at all locations. The O_2 content is used to correct for air in-leakage. Gas sampling systems are designed to prevent further reaction of SO_2 with the sorbent particles.

TEST SORBENT

Commercial hydrated lime from Mississippi Lime Co., Ste. Genevieve, Mo. was used in this study. Typical analysis of this sorbent is given in Table 1.

PILOT PLANT TEST PROCEDURES

Sorbent Injection

The sorbent was injected into the humidified flue gas at the contactor exit duct. Between the sorbent injection point and the baghouse there was 84 ft of ductwork, providing an in-duct gas residence time for each test of 2.5 to 2.7 sec.

Moisture Addition

Moisture was added to a blend of the recycle and fresh sorbents in the mixer using the following procedure. The fresh and recycle sorbents were blended for one minute. A set amount of water was added to the blend over a two- to three-min period, followed by one additional minute of blending. The blend of fresh and recycle sorbents was injected into the duct using a single feeder.

Steady-State Recycle

Spent sorbent from the baghouse is removed periodically during operation. A portion is blended with fresh sorbent and moisture and returned to the recycle feeder hopper while the remainder is discarded. The recycle blend is fed continuously back into the flue gas. A test is initiated using baghouse solids from previous once-through or recycle tests as the initial recycle sorbent.

Baghouse Operation

In the recycle tests reported here, two modes of baghouse operation were employed. In some tests, the baghouse was operated at a relatively high approach to adiabatic saturation (~20 °F) by reheating the flue gas with hot air at the baghouse inlet. In other tests, no reheat was used and the baghouse exit was operated at a lower approach (<10 °F).

Performance Measurement

The SO_2 removals reported here were based on the readings of the continuous gas analyzers located at the contactor exit (prior to sorbent injection), the duct exit and the baghouse exit. The removals reported were averaged after steady-state recycle conditions had been closely approached.

Contactor Operation

Performance testing was conducted with the third generation contactor (venturi contactor) with a small amount of steam injection at the contactor exit. The contactor was operated to achieve near-saturation conditions. Operating conditions for achieving saturation are given later in this report.

TEST PROGRAM: PERFORMANCE TEST

The performance test consisted of about one week of operation with two shifts per day followed by three separate weeks of 24 hour/day operation. The three weeks of 24 hr/day testing were conducted July 25-29, August 22-26, and September 26-30, 1994. The total on-stream time was 295 hours. The purpose of the initial week of testing was to establish near steady-state operating conditions and sorbent composition. The purpose of the around-the-clock operation was to evaluate performance and operability issues in longer term periods of continuous operation. Although the three periods of 24 hour/day operation were separated, the same sorbent material was used. That is, the baghouse material collected at the end of one period was used as the recycle material at the beginning of the subsequent test period.

The test conditions for the performance test were selected based on the results of the previous process optimization tests.[2] The Ca/S ratio was in the range of 1.2 to 1.3 for the test. The recycle ratio was 6.5 lb/lb fresh lime and the recycle water addition level was 0.12 lb/lb recycle. The third generation contactor (venturi + centrifugal separator) was employed for all the testing; it was operated to achieve near saturation (0 to 2 °F approach) conditions. For most of the testing the flue gas was reheated to give a baghouse approach of ~20 °F and the baghouse was pulse cleaned continuously; this approximately simulated the SO_2 removal expected with an ESP. For part of the last test period, no reheat was employed; this maximized SO_2 removal in the baghouse.

WASTE CHARACTERIZATION TEST FACILITIES

The moisture-density relationships and unconfined compressive strengths of Advanced Coolside wastes were determined with laboratory equipment complying with ASTM Standards. The equipment includes a laboratory mixer, a mechanical soil compactor and a unconfined compression tester. TCLP and ASTM leaching tests were conducted with laboratory equipment as specified in the Standards. The major equipment used in waste pelletization include a Littleford Brothers LM-130 batch mixer, a 36" I. D. rotary disc pelletizer and a 55-gal curing drum. The laboratory equipment used to determine properties of pelletized wastes as synthetic aggregates includes a sieve shaker and a LA abrasion machine. All equipment complies with the respective ASTM Standards.

WASTE CHARACTERIZATION TEST PROCEDURES

Sample Preparation

Three Advanced Coolside waste samples were used in this study. They were prepared by blending a composite baghouse solids sample from the Advanced Coolside pilot plant with different amounts of fly ash to simulate the combined waste streams (spent sorbent plus fly ash) produced from feed coals with 7.5% ash and 1.5%, 2.5% and 3.5% sulfur. The composite baghouse ash sample, which was prepared by blending baghouse ash samples from several previous pilot plant runs, had a sorbent utilization of 62.5%. The Coolside waste samples were prepared as follows:

1. Mixed 185 lb of the composite baghouse solids with either 54.4 lb, 76.6 lb, or 126.5 lb of fly ash (from the Ohio Edison Bruce Mansfield Station) in a 55-gal drum to simulate Advanced Coolside waste from coal with 7.5% ash and 3.5%, 2.5%, and 1.5% sulfur.

2. Tumbled each drum, end over end, for at least four hours for homogenization.

3. Transferred each waste sample to a drum equipped with a plastic liner for the waste characterization study.

Pelletization Procedure

Advanced Coolside waste was pelletized with a three-step process involving densification, disc pelletization and curing. The dry waste was first mixed with an appropriate amount of water in a Littleford LM-130 batch mixer for densification. The wetted material was pelletized with an additional amount of added water in a rotary disc pelletizer (36-inch diameter) for enlargement of particle size. The pelletized products then were cured in a 55 gal curing vessel under high humidity (~90%) at a temperature of 180 °F for curing times up to 24 hr for pellet strength development. The curing vessel is equipped with steam injection for heating and humidity control. About 70 lb of pellets was produced in each batch test for evaluation of pellet properties.

DISCUSSION OF PERFORMANCE TEST RESULTS

PROCESS OPERABILITY

Although the scale of the 1000 acfm pilot plant is not sufficient to fully address process operability issues, the performance test provided a generally positive indication of the operability of the Advanced Coolside process. In the scale up of the conventional Coolside process, the pilot plant proved to be a useful tool for identifying and preliminarily evaluating operating concerns.[2] Key operability issues addressed in the performance test included operability of the flue gas duct with sorbent injection at high humidity, operability of the recycle wetting, handling and transport systems, and operability of the baghouse. The performance test included three separate weeks of 24 hr/day operation for a total of 295 hours on stream. In all previous testing, the plant was operated for two shifts per day. Operability issues are discussed below. These issues should be further addressed in larger scale and longer term tests.

Duct Sorbent Injection at High Humidity

No major problems were encountered with deposition of solids on the duct walls. Overall, the operating results show that sorbent can be injected into very humid flue gas without significant operability problems. The results also show that it is possible to operate with changes in flue gas direction and with a short straight-run residence time (~0.5 sec) after sorbent injection. This flexibility is an advantage for retrofit of the process. Further, the results indicate that, if necessary, soot blowing can be effective in controlling solids accumulation.

In the performance test, the flue gas at the contactor exit was at or near the saturation point (0 to 2 °F approach to saturation), and as SO_2 capture proceeded, the gas temperature and the approach to saturation increased along the duct length. As described in Topical Report No. 2,[2] the ductwork between the sorbent injection point and the baghouse was comprised of 53 ft of 5-inch pipe, 24 ft of 8-inch pipe, and 7 ft of 4-inch pipe. The gas velocity ranged from 18 to 58 ft/sec. There were seven locations where the flue gas changed direction, including one 180° bend and one 130° bend. The residence time between the sorbent injection point and the first 90° bend was less than 0.5 sec.

Because soot blowers are included in the conceptual process design developed in Task 5 of this project, the duct was periodically air lanced to simulate soot blowing. This was done manually using a 1/2" diameter tube and 50-80 psig air. The soot blowing was effective in preventing accumulation of solids in the pilot plant duct. The material which adhered to the duct walls was generally soft and easily removed and carried to the baghouse by the soot blowing. The soot blowing was used primarily at elbows and near the sorbent injection point. As observed previously,[2] the amount of accumulation in straight duct runs was small and tended to level off with time even without soot blowing.

In one instance a larger, more compacted deposit formed, forcing shutdown of the unit. This occurred in a reducing section immediately downstream of a 130° change in direction; this section was not easily accessible to air lancing. This shutdown is not of much concern because this duct configuration is not typical of a utility duct.

In earlier pilot tests,[1] it was observed that solids deposition could become an operating problem if sorbent is allowed to impact a duct wall very soon after injection. Although this was not a significant problem in the performance test, these results indicate that sorbent injection design and flue gas flow conditions are important considerations for process design.

Recycle Sorbent Moisture Addition

For this program, few operating problems were encountered in preparing the wetted recycle sorbent. The preparation of wetted recycle in a mixer was straightforward, as described previously. For much of the testing, the wetted material generally looked and behaved as a powder, although it tended to compact more than hydrated lime under compressive loads. However, after extended hours on-stream the wetted recycle material appeared to be more agglomerated than earlier in the testing. This was similar to observations in previous recycle optimization tests.[2] In these tests it was concluded that highly utilized sorbent has less pore volume and less capacity for water addition, which can lead to the presence of moisture on the surface of the sorbent and to agglomeration. It was further concluded[2] that this phenomenon would be more pronounced in the small-scale equipment of the pilot plant.

As discussed in detail in Reference 2, the above observations are consistent with findings of Rochelle and Kind[4] in work with wetted ADVACATE sorbents. In their work, it was found that there is a critical pore volume and moisture content for the production of these sorbents. If there is sufficient pore volume, a powder-like material is formed; if there is insufficient pore volume and excess water, a paste-like or agglomerated material can be formed. It was reported that exceeding the critical moisture content for a given pore volume can adversely affect sorbent reactivity. This is because the sorbent agglomerates and mass transfer is adversely affected. These observations also are consistent with previous in-house data generated by CONSOL.[2] These data indicated that increasing moisture addition level above a critical value resulted in a decrease in performance, because of sorbent agglomeration.

The agglomeration of highly utilized sorbents at higher water addition levels was probably more severe in the pilot plant tests than would be the case for larger scale operation. In the pilot plant the ratio of transport air to sorbent is much higher (~2 to 4 lb air/lb solid) than typical for a large-scale transport system (~0.2 lb/lb). Also, the air used in the pilot plant is dry plant air. Consequently, in the pilot plant more water is required on the sorbent to allow for the evaporation into the dry transport air. Based on heat balance calculations and on sampling of recycle sorbent just before injection, the moisture content of recycle is reduced to roughly one half the initial 0.12 lb/lb. In the conceptual process design developed for the process in Task 5, the recycle moisture addition level is about 0.05 lb/lb for a 250 MW plant burning a 2.5% sulfur coal and operating at a recycle ratio of 7 lb/lb. This addition level is based on heat and material balance calculations and depends on the coal sulfur content, the extent of reaction, the design approach to saturation at the duct exit and the design recycle ratio. At lower water addition levels anticipated in a commercial design, agglomeration of highly utilized sorbents may not be a concern for process operability and performance.

Recycle Sorbent Feeding and Handling

For most of the performance test, the recycle sorbent was effectively fed, transported and injected into the flue gas. Recycle handling did, however, require frequent operator attention, although much of this attention was due to the small-scale and the specific equipment employed in the pilot plant. The operability of the feed system was also adversely impacted by the agglomeration of highly utilized sorbents after water addition, which is described in detail above.

The recycle sorbent was fed by a gravimetric screw feeder and was pneumatically transferred from the feeder to the injection point using an eductor and flexible transport line. There were rather frequent instances of eductor plugging, a fairly common problem in small-scale systems, because the orifice in the eductor is quite small. This problem is also frequently encountered in feeding hydrated lime at the pilot plant. The problem was effectively managed by periodically cleaning the orifice of the eductor with a rod to remove deposits. This allowed recycle feeding with short and relatively few interruptions. It is anticipated that this would not be a significant problem with properly designed, commercial-scale pneumatic transport equipment.

As observed in previous operation,[2] feeding and transporting the wetted recycle feed became more difficult as the test progressed. Operating problems such as plugging of the eductor became more prevalent. Visual observation indicated that later in the test the sorbent agglomerated more and the tendency to compact was higher. As discussed above, the increased tendency to agglomerate was likely a result of adding more than the optimum amount of water to the sorbent. With high utilization and reduced porosity, the capability to hold water within the pore structure is reduced, which can result in surface moisture. Surface moisture and agglomeration increase the tendency for plugging in the transport system. Further, the Joule-Thomson expansion effect at the eductor may have aggravated the problem by cooling the gas and the sorbent.

The difficulty in feeding wetted recycle may have adversely affected performance in the pilot plant. As discussed above, an agglomerated sorbent is likely to reduce gas/solid contact and thus the rate of mass transfer. Further, the operability of the recycle transport system limited the amount of water that could be added to the sorbent. The water on the sorbent acts to counteract the heat of reaction and to maintain a close approach to saturation in the duct. As discussed below, the approach at the exit of the duct in the performance test was somewhat higher than desired based on previous testing.

Baghouse Operation

Baghouse operability was good at approach temperatures as low as 5 °F. There were no problems in removing the spent sorbent from bags or from the baghouse hopper. The material from tests at lower approach with wetted recycle did have a tendency to compact under compression. This would be an important consideration in designing the spent sorbent handling system for a commercial-scale system.

PROCESS DESULFURIZATION PERFORMANCE

Process conditions and performance averaged over the entire 295-hour Performance Testing program are given in Table 2. The test conditions and results listed as Test LT-1 represent the test period when the baghouse was operated at ~20 °F approach to saturation. This represents a simulation of the process performance with an ESP and accounted for most of the test duration, 255 on-stream hours. The test conditions and results listed as Test LT-1-A represent the final 40 hours of testing where no reheat was applied to the baghouse and it was operated at a close approach (~5 °F) for maximum SO_2 removal efficiency.

Testing With Baghouse Reheat

The results in Table 2 show that at average conditions of 1.27 fresh Ca/S mol ratio and 6.6 recycle ratio (dry basis) with baghouse reheat, the overall average in-duct and system SO_2 removals were 78 and 87%, respectively, which are lower than observed in previous recycle tests at similar conditions. In the Design Optimization Tests (Topical Report No. 2[2]), in-duct SO_2 removals were 84 to 87% and system SO_2 removal was over 90% at similar process conditions.

One factor contributing to the lower SO_2 removals observed is the higher approach to saturation in the duct. The duct exit approach in test period LT-1 averaged 6 °F, compared to 3-4 °F approach in many of the previous tests at similar conditions. Pilot plant tests have shown that a small difference in the approach has a significant effect on desulfurization performance. A means of achieving a closer approach would be to add more water to the recycle sorbent; however, as discussed in the Process Operability section above, the pilot plant system was operated at the maximum operable water addition rate. More flexibility would be available in a larger scale system, where less water would be required on the recycle sorbent to counteract the reaction heat effect.

The agglomeration of the sorbent, caused by operating at near the maximum water/sorbent ratio in the pilot plant, may have contributed to the lower SO_2 removals. As discussed above, agglomeration of the sorbent can adversely impact its desulfurization performance. The high concentration of carbonate observed in the baghouse solids during these tests is another possible explanation for the lower SO_2 removal. The CO_2 pick-up by the sorbent is discussed below.

Testing at Close Baghouse Approach

In test period LT-1-A (Table 2), conducted at a ~1.3 fresh Ca/S ratio and a low approach to saturation (~5 °F) in the baghouse, the average system SO_2 removal was 94%. This SO_2 removal efficiency is typical of that observed previously when the pilot plant was operated to simulate SO_2 removal in a plant with a baghouse with high desulfurization efficiency.[2]

CO_2 Pick-Up

The CO_2 pick-up by the sorbent was higher in the performance tests than in the previous recycle tests. The $CaCO_3$ content of the baghouse solids ranged from 20 to 30 wt % during the testing, compared to 15 to 20 wt % in most previous testing.[2] The reason for the higher extent of carbonation is not known. The formation of carbonate is enhanced by the baghouse used in the pilot plant, because it provides intimate and extended contact between solids and flue gas with a high CO_2 concentration and a low SO_2 concentration. The extent of carbonation and the effect on performance should be evaluated on a larger scale and with an ESP.

The impact of carbonate formation on sorbent activity and process desulfurization is not certain. Calcium carbonate (limestone) has been shown in pilot plant tests to have some desulfurization activity under Advanced Coolside conditions (Topical Report No. 3[3]). In these tests the activity of finely pulverized limestone was substantially less than that of hydrated lime; however, this likely was largely a result of the very low surface area of the limestone (1.6 m^2/g) relative to that of hydrated lime (~20 m^2/g). However, the activity of calcium carbonate formed on the surface of a more porous hydrated lime sorbent is unknown.

A high level of calcium carbonate formation could have a negative impact on sorbent performance because it can moderately decrease sorbent porosity. Calcium carbonate has a molar volume ca. 12% larger than that of $Ca(OH)_2$ (36.9 versus 33.1 cm^3/mol).[5] Reduced porosity could adversely affect sorbent reactivity and intraparticle mass transport. Further, with reduced porosity less water can be incorporated in the sorbent without causing agglomeration.

Apparent Effect of Recycle Sorbent Hold Time

In the performance tests there was some indication of a positive effect of allowing the baghouse solids to sit for a period of time before water addition and reinjection. Between the initial two-shift operation and the first period of 24 hr/day operation and between each of the three periods of 24 hr/day operation, the in-duct desulfurization performance increased by ~10% absolute during start up, then declined over the next 16 to 36 hours. To further investigate this effect, for a brief period during around-the-clock operation, recycle material was allowed to sit for ~24 hours before water addition and reinjection. In this case the in-duct SO_2 removal increased by about 8% absolute, but decreased when sorbent was again directly recycled from the baghouse. The cause of this effect is unknown. In each of the cases, there were no apparent changes in process variables or process operating procedures. There also were no detected changes in recycle sorbent properties with time.

Further testing is recommended to fully investigate this apparent effect. The effect raises questions concerning long-term process performance without shutdown periods and periods of increased hold time employed in the pilot plant Performance Testing. This further investigation should be addressed in longer term tests at a larger scale. This would allow for more continuous operation than is possible in the pilot plant. It also would allow for a smaller transport air/sorbent ratio and thus less required water addition to the recycle. As detailed above, the excess water addition to the recycle sorbent affected operability and performance in the pilot plant tests.

DISCUSSION OF WASTE CHARACTERIZATION STUDY

ADVANCED COOLSIDE WASTE CHARACTERIZATION

Advanced Coolside waste samples were characterized to ensure that adequate information is available on the physical and chemical nature of the waste for the design and construction of safe and stable landfills. The properties of the waste characterized include composition, moisture and density relationship, unconfined compressive strength and leaching characteristics.

Composition

Table 3 lists the compositions of the waste samples used in this study. Sample Nos. 1, 2, and 3 simulated Advanced Coolside waste compositions expected to be produced from feed coals with 7.5% ash and 3.5%, 2.5% and 1.5% sulfur. The analyses conducted include ultimate analysis, major element analysis and lime index. Fly ash components, represented by the summation of SiO_2, Al_2O_3, and Fe_2O_3 in the waste, were calculated and are included in the table for comparison. As shown in Table 3, sulfur contents (total sulfur, sulfate and sulfite) decrease and the fly ash components in the waste increase with decreasing sulfur content of the coal from which the waste was generated. The differences in amounts of the sulfur compounds and fly ash components can have a significant effect on the properties of the waste, that are relevant to both disposal and utilization.

Moisture-Density Relationship

For landfill disposal, a sufficient amount of water may be added to the waste at the plant to improve handling during transportation and to achieve the optimum physical stability of the waste at the disposal site. In the Advanced Coolside process, the water content of the waste is controlled by controlling the water content of the fly ash that is mixed with the spent sorbent. The total amount of water required to produce the maximum dry density (i. e., the optimum moisture) of the Advanced Coolside waste can be estimated using the standard Proctor test (ASTM Method D698). The dry bulk density of the waste is plotted as a function of the amount of added water on a dry ash weight basis for Sample Nos. 1, 2, and 3 in Figures 4, 5, and 6, respectively. Sample Nos. 1, 2, and 3 represent simulated Advanced Coolside waste produced from feed coals with 7.5% ash and 3.5%, 2.5%, and 1.5% sulfur, respectively. Sample No. 1 has an optimum moisture content of 32 wt % and a maximum dry bulk density of 75.1 lb/ft^3.

Sample No. 2 has an optimum moisture of 32 wt % and a maximum dry bulk density of 76.5 lb/ft^3. Sample No. 3 has an optimum moisture content of 30 wt % and a maximum dry bulk density of 80.2 lb/ft^3. The maximum dry bulk density of the wastes increase from Sample No. 1 to No. 2 and to No. 3 as the sulfur content of the feed coal deceases from 3.5%, to 2.5% and to 1.5%, respectively. The fly ash components in the waste simultaneously increase with decreasing coal sulfur content, as indicated in Table 3.

Unconfined Compressive Strength

Waste disposed of in a landfill may be subject to numerous passes of earth-moving equipment and trucks. Because of this, the structural integrity of the waste is very important for landfill disposal. Unconfined compressive strength (ASTM Method D-1633) was used to predict the structural integrity in the Advanced Coolside waste. Standard Proctor specimens of the waste samples were cured in a humidity chamber, according to ASTM method D-559. Table 4 lists the unconfined compressive strength of the Advanced Coolside waste samples compacted to 95% of maximum Proctor density and optimum moisture content and cured at various curing times (0, 7, 14, 28, and 56 days). As shown in Table 4, the compressive strength of the Advanced Coolside waste sample No. 1, which simulates the use of a feed coal of 3.5% sulfur and 7.5% ash, increased from 19 psi (uncured) to 98 psi at 28 days and decreased slightly to 88 psi at 56 days. The compressive strength of the Advanced Coolside waste sample No. 2, which simulates the use of a feed coal of 2.5% sulfur and 7.5% ash, increased from 21 psi (uncured) to 150 psi at 28 days and to 158 psi after 56 days curing. The compressive strength of the Advanced Coolside waste sample No. 3, which simulates the use of a feed coal of 3.5% sulfur and 7.5% ash, increased from 18 psi (uncured) to 167 psi at 28 days and remained at 163 psi after 56 days curing. Thus, there is substantial strength development during curing from zero to 28 days for all three Advanced Coolside waste. In contrast, there is no significant change in strength between 28 days and 56 days curing. In general, for the same duration of curing, the strength of the cured waste increases as the sulfur content of the feed coal from which the waste was generated decreases from 3.5% (waste sample No. 1) to 2.5% (waste sample No. 2) and to 1.5%. (waste sample No. 3), as indicated in Table 2. As a point of reference for unconfined compressive strength values, the following data are useful. A person walking exerts pressure of about 5 psi. Tracked bulldozers used in landfills typically exert pressures ranging from about 12 psi to about 19 psi. Therefore, the unconfined compressive strength of Advanced Coolside waste compacted to 95% of maximum Proctor density and optimum moisture content is suitable for landfill disposal.

Leaching Characteristics

The Toxicity Characteristics Leaching Procedure (TCLP) is a laboratory test designed by the U.S. EPA to determine if a solid waste that will be disposed of in a landfill should be considered hazardous or non-hazardous. The ASTM leaching procedure is similar to the TCLP procedure except that the extraction medium is deionized water rather than 0.1 N acetic acid solution, as used in the TCLP procedure. Regulatory agencies in most states require that the concentrations of eight trace elements (As, Ba, Cd, Cr, Pb, Hg, Se, and Ag) in the TCLP and/or ASTM leachates be below the Resource Conservation and Recovery Act (RCRA) allowable limits if the material is to be disposed of as a residual solid or special waste, rather than as a hazardous waste.

Advanced Coolside waste was leached according to TCLP and ASTM leaching procedures. Table 5 lists the leachate characteristics and the allowable RCRA limits for comparison. The waste used in the leaching study was Sample No. 1, which simulated waste produced from coal with 1.5% S. This sample was selected for leaching because it has the highest amount of fly ash component, as indicated in Table 3, and the fly ash component is the major contributor of trace elements in the waste.

As shown in Table 5, concentrations of these eight RCRA trace elements in the leachates of the Advanced Coolside waste are well below the RCRA allowable limits. In fact, the concentration of all eight elements in both leachates is 1/50th or less of the RCRA limits. The Advanced Coolside waste can be classified as non-hazardous.

In addition to eight RCRA trace elements, other trace and major elements (Ca, Na, Al, sulfate, Fe, K, Mn) and total dissolved solids (TDS) were also determined. The leachate concentrations of Fe and Mn are low. The concentrations of Ca, Na, Al, sulfate, K and TDS in the leachates are similar to those from other dry flue gas desulfurization (FGD) wastes.[6,7]

PELLETIZATION OF ADVANCED COOLSIDE WASTE

Pelletization takes advantage of the cementitious properties of the Advanced Coolside waste to make pelletized products that have potential for use as synthetic aggregates. Pelletization also can improve waste handleability and reduce waste leachability. Pelletization tests were conducted using three Advanced Coolside waste samples which simulate wastes produced from feed coals with 7.5% ash and 3.5%, 2.5% and 1.5% sulfur. The pellet properties characterized in this study include LA abrasion index, unit weight (moist and dry), soundness index, compressive strength, specific gravity and water absorption and particle size distribution.

Two pelletization tests were conducted with each of the three simulated Advanced Coolside waste samples, one at each of two levels of water addition. Results are listed in Table 6. Pelletization proceeded readily in all cases. The particle size distribution of pellets made from Advanced Coolside waste is sensitive to water addition. An increase of one to two percent water addition during densification increases the coarse portion of pellets significantly. Pellets produced from waste sample No. 1 with 28% added water have 30.5 wt % of pellets larger than 3/4", whereas pellets produced with 30 wt % added water have 75.1 wt % of pellets larger then 3/4". For waste sample No. 2, pellets produced with 25% added water have 0.3 wt % of pellets larger than 3/4", whereas pellets produced with 27% added water have 14.4 wt % of pellets larger than 3/4". For waste sample No. 3, pellets produced with 25% added water have 0.3% of pellets larger than 3/4", whereas pellets produced with 26% added water have 26.9 wt % of pellets larger than 3/4". As shown in Table 6, pellets with low LA abrasion index can be made from Advanced Coolside waste. The values determined meet the ASTM C33 LA abrasion index specification (50% weight loss, max) for use as concrete aggregates. The moist (as is) pellets have unit weights ranging from 67.6 lb/ft^3 to 71.9 lb/ft^3. The dry unit weights of pellets from all three Advanced Coolside wastes meet the minimum ASTM C330 unit weight specification (55 lb/ft^3, dry basis) for use as coarse lightweight aggregates in concrete masonry units and in structural concrete. Other test results show that pellets made from Advanced Coolside waste had low water absorption and low specific gravity, but also a high soundness index (low durability).

These data indicate that pellets made from Advanced Coolside wastes may have potential for use as lightweight coarse aggregates in concrete masonry units. For this use, there is no soundness index specification. A more thorough evaluation of other pellet characteristics for this application is recommended.

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TABLE 1

TYPICAL ANALYSIS OF MISSISSIPPI HYDRATED LIME

BET Surface Area, m^2/g	24.4
Lime Index	93.9
As-Received Lime, wt %	
Moisture	0.5
Ash (925 °C)	75.1
Carbonate (CO_3)	2.2
$Ca(OH)_2$ (TGA)	90.9
Ash Elementals, As-Received Lime, wt %	
SiO_2	0.8
Al_2O_3	0.1
TiO_2	<0.1
Fe_2O_3	0.1
CaO	74.7
MgO	0.6
Na_2O	<0.1
K_2O	<0.1
P_2O_5	<0.1
SO_3	0.2
Malvern Particle Size, wt %	
+ 66.9 μm	0
66.9 x 42.9	1.1
42.9 20.5	6.3
20.5 x 11.4	9.3
11.4 x 5.4	31.3
5.4 x 1.9	40.9
-1.9	11.1
Mean Particle dia., μm	5.3

TABLE 2

TEST CONDITIONS AND RESULTS OF LONG-TERM PERFORMANCE TESTING, AVERAGES OVER ENTIRE TEST

Test	LT-1	LT-1A
Sorbent Data		
Fresh Ca/S Mole Ratio	1.27	1.31
Fresh Feedrate, lb/hr	6.60	6.85
Recycle Feedrate, lb/hr	53.5	53.8
Recycle Ratio, lb Recycle/lb Fresh Lime	8.11	7.86
Recycle Ratio, Dry Basis	6.64	6.44
Water Addition, lb/hr	5.96	6.00
lb Water/lb Recycle Sorbent	0.12	0.12
Flue Gas Conditions		
In-Duct Residence Time, s	2.7	2.7
Duct Inlet SO_2 Content, ppmv-dry	1501	1502
Approach to Saturation		
Contactor Exit	0-2	0-2
Duct Exit	6	5
Baghouse Exit	18	5
SO_2 Removal, %		
In-Duct	78	74
System (Duct + Baghouse)	87	94

TABLE 3

COMPOSITIONS OF SIMULATED ADVANCED COOLSIDE WASTES

	Sample No. 1(a)	Sample No. 2(b)	Sample No. 3(c)
Moisture, wt % as rec.	2.2	4.4	3.8
Ultimate Analysis, wt % dry			
Carbon	1.8	1.8	1.7
Hydrogen	0.54	0.17	0.06
Nitrogen	0.07	0.07	0.06
Sulfur (total)	13.1	12.3	10.2
Sulfate Sulfur	3.5	3.3	2.9
Sulfite Sulfur	9.2	8.9	7.4
Carbonate (CO_3^{2-})	8.3	9.9	6.7
Ash (950°C)	89.5	93.0	93.8
Elemental Analysis, wt % dry			
SiO_2	10.9	15.3	21.2
Al_2O_3	4.6	6.6	9.2
TiO_2	0.21	0.30	0.42
Fe_2O_3	4.5	6.4	8.9
CaO	36.4	34.4	29.1
MgO	0.48	0.54	0.61
Na_2O	0.16	0.21	0.28
K_2O	0.46	0.64	0.88
P_2O_5	0.07	0.10	0.17
SO_3	32.8	30.7	25.5
Unaccounted	9.4	4.8	3.8
Lime Index, as wt % of $Ca(OH)_2$	4.7	3.5	3.4
Fly Ash Components, wt % dry (d)	20.0	28.4	39.3

(a) Simulates waste produced from feed coal with 7.5% ash and 3.5% sulfur.
(b) Simulates waste produced from feed coal with 7.5% ash and 2.5% sulfur
(c) Simulates waste produced from feed coal with 7.5% ash and 1.5% sulfur.
(d) Represented by the total amount of SiO_2, Al_2O_3 and Fe_2O_3 in the waste

TABLE 4

UNCONFINED COMPRESSIVE STRENGTHS OF SIMULATED ADVANCED COOLSIDE WASTES AS A FUNCTION OF CURING TIME

Curing Time[b], Days	Unconfined Compressive Strength[a], psi		
	Sample No. 1[c]	Sample No. 2[d]	Sample No. 3[e]
0	19	21	18
7	39	71	61
14	65	97	116
28	98	150	167
56	88	158	163

(a) Compacted to 95% of maximum Standard Proctor density and optimum moisture content.
(b) Cured at ~100% humidity and ~70 °F.
(c) Simulates waste produced from feed coal with 7.5% ash and 3.5% sulfur.
(d) Simulates waste produced from feed coal with 7.5% ash and 2.5% sulfur.
(e) Simulates waste produced from feed coal with 7.5% ash and 1.5% sulfur.

TABLE 5

LEACHATE CHARACTERISTICS OF SIMULATED ADVANCED COOLSIDE WASTES

Parameter	Leachate Concentration, mg/L		
	Allowable Limit by RCRA	TCLP Leachate[a]	ASTM Leachate[a]
Total Dissolved Solids	---	---	3590
Calcium	---	2567	1340
Sodium	---	8.47	6.17
Aluminum	---	0.13	0.10
Arsenic	5	0.007	0.006
Barium	100	0.20	0.18
Cadmium	1	<0.001	<0.001
Chromium	5	0.007	0.046
Lead	5	0.002	0.004
Mercury	0.2	<0.001	<0.001
Silver	5	<0.001	<0.001
Selenium	1	0.02	<0.01
Sulfate	---	1186	1359
Iron	---	0.20	0.07
Potassium	---	6.48	5.01
Manganese	---	0.49	<0.05

(a) Leachates from Sample No. 1, which simulated Advanced Coolside waste produced from feed coal with 7.5% ash and 1.5% sulfur.

TABLE 6

PROPERTIES OF PELLETS MADE FROM SIMULATED ADVANCED COOLSIDE WASTES

	Sample No. 1 (1)		Sample No. 2 (2)		Sample No. 3 (3)	
Water Addition, % (4)	28%	30%	25%	27%	25%	26%
LA Abrasion Index, wt %	33.9	---	---	---	23.8	22.8
Unit Weight, lb/ft^3						
moist (as is)	70.8	68.9	67.6	71.0	65.6	71.9
dry	54.5	51.7	51.8	53.3	50.5	54.9
Soundness index, wt %	73.5	---	----	---	68.4	---
Compressive Strength, lb	75.2	57.6	26.0	43.0	21.4	56.4
Water Absorption, wt %	3.0	---	0	---	0.93	0
Specific Gravity	1.98	---	1.79	---	1.85	2.04
Size Distribution, wt %						
+1"	3.9	21.0	0.1	0.4	0	4.0
1" x 3/4"	26.6	54.1	0.2	14.0	0.3	22.9
3/4" x 1/2"	50.3	15.9	6.8	60.7	2.6	53.2
1/2" x 3/8"	11.4	3.8	51.0	15.5	8.8	12.3
3/8" x 1/4"	5.8	1.9	32.2	6.2	53.6	5.1
1/4" x 4 mesh	1.2	0.7	6.2	1.2	22.8	0.9
4 x 8 mesh	0.6	0.6	2.3	0.6	10.8	0.5
-8 mesh	0.2	2.0	1.2	1.4	1.1	1.1

(1) Simulates waste produced from feed coal with 7.5% ash and 3.5% sulfur
(2) Simulates waste produced from feed coal with 7.5% ash and 2.5% sulfur
(3) Simulates waste produced from feed coal with 7.5% ash and 1.5% sulfur
(4) The amount of water (dry basis) added during the densification step during pellet preparation.

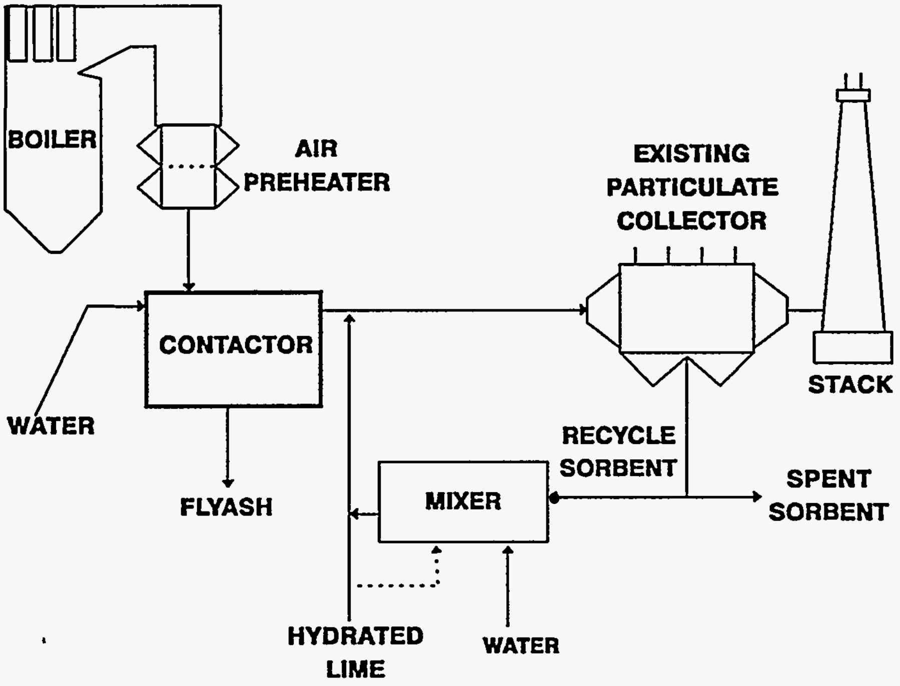

Figure 1. Schematic of Advanced Coolside Process.

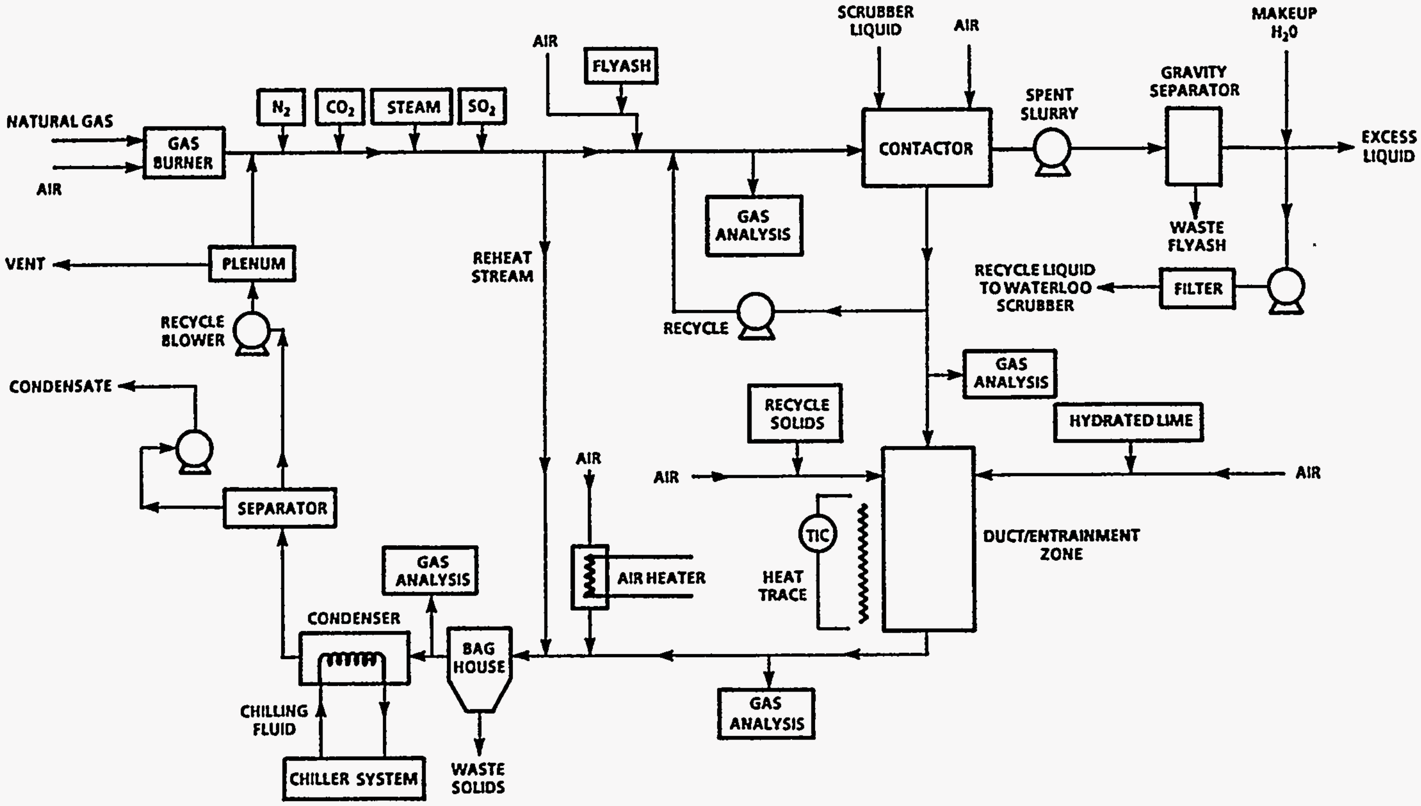

Figure 2. Schematic of Advanced Coolside Pilot Plant.

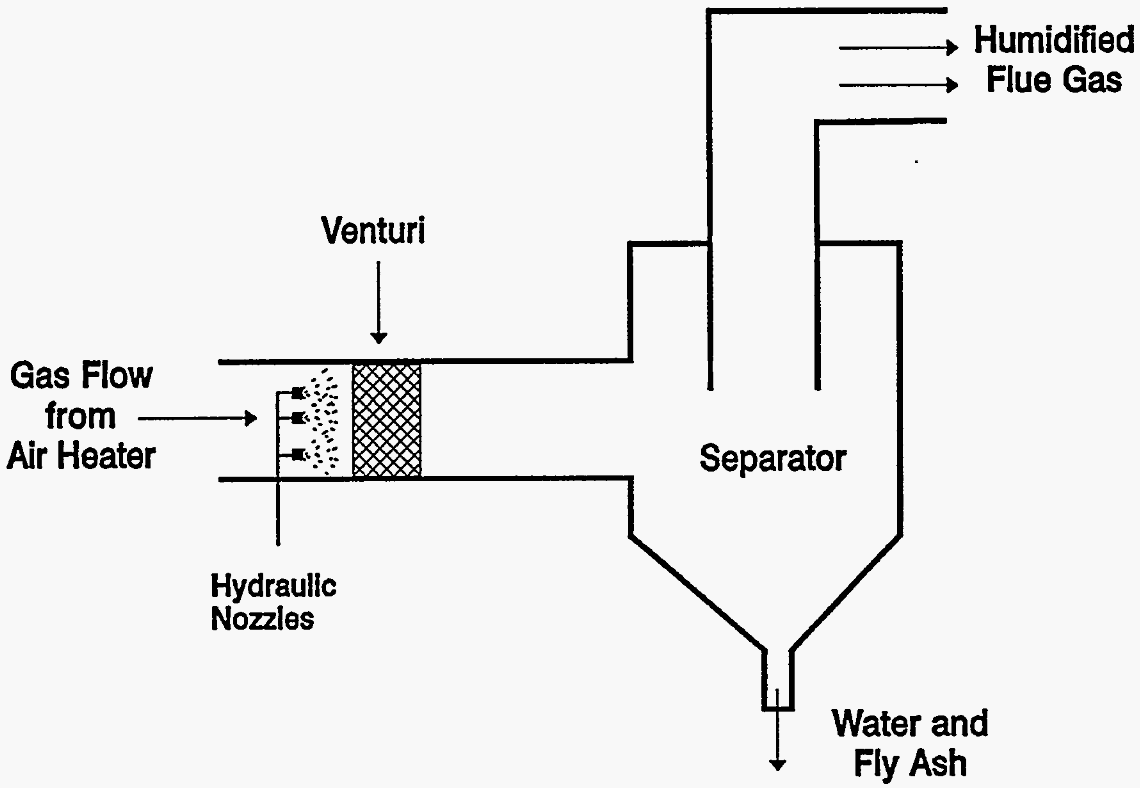

Figure 3. Schematic of Third Generation (Venturi) Contactor.

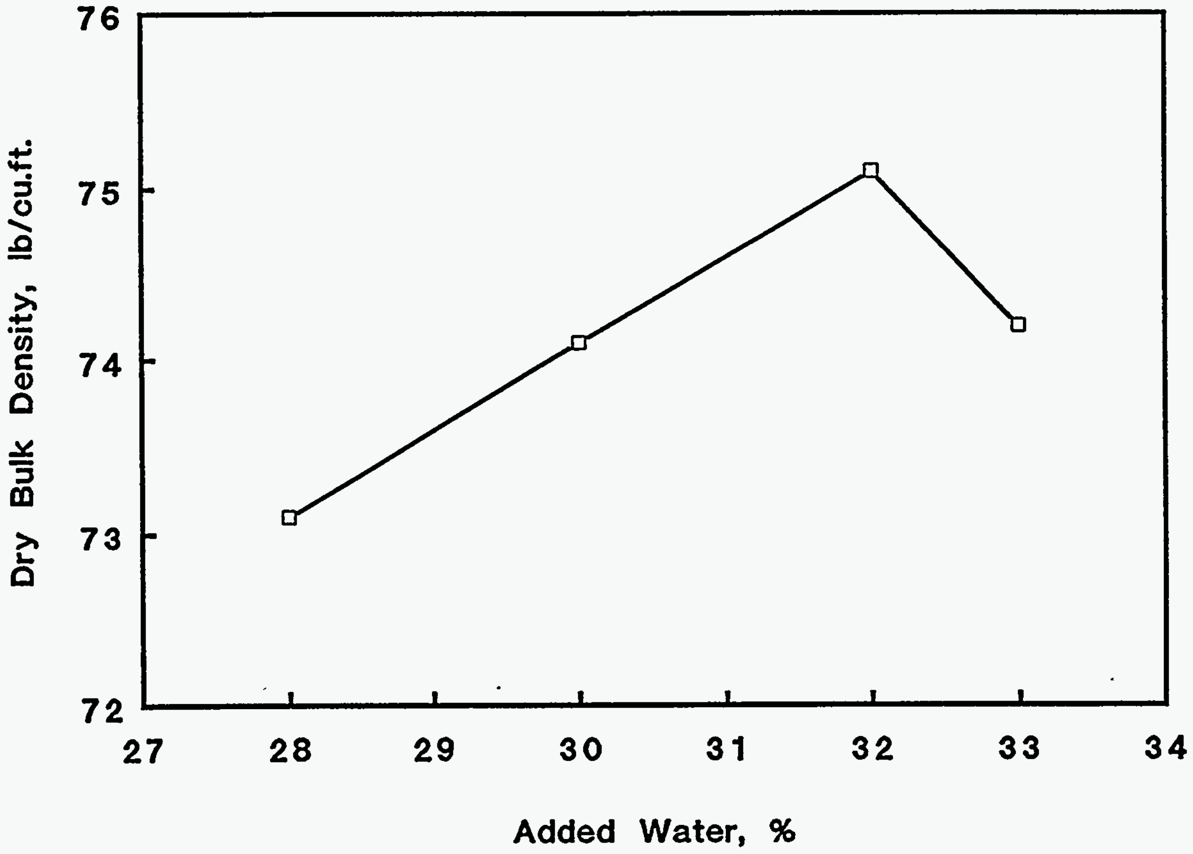

Figure 4. Moisture-Density Relation of Simulated Advanced Coolside Waste Sample No. 1.

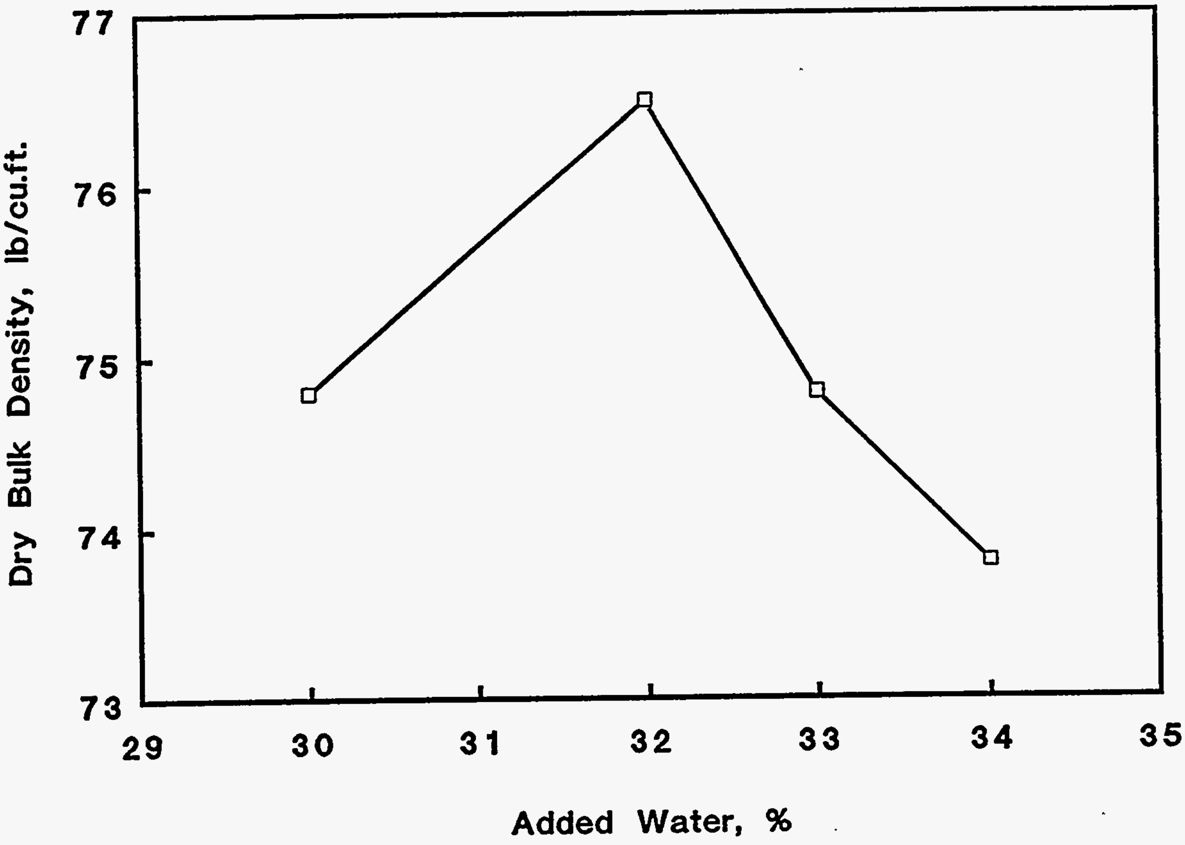

Figure 5. Moisture-Density Relation of Simulated Advanced Coolside Waste Sample No. 2.

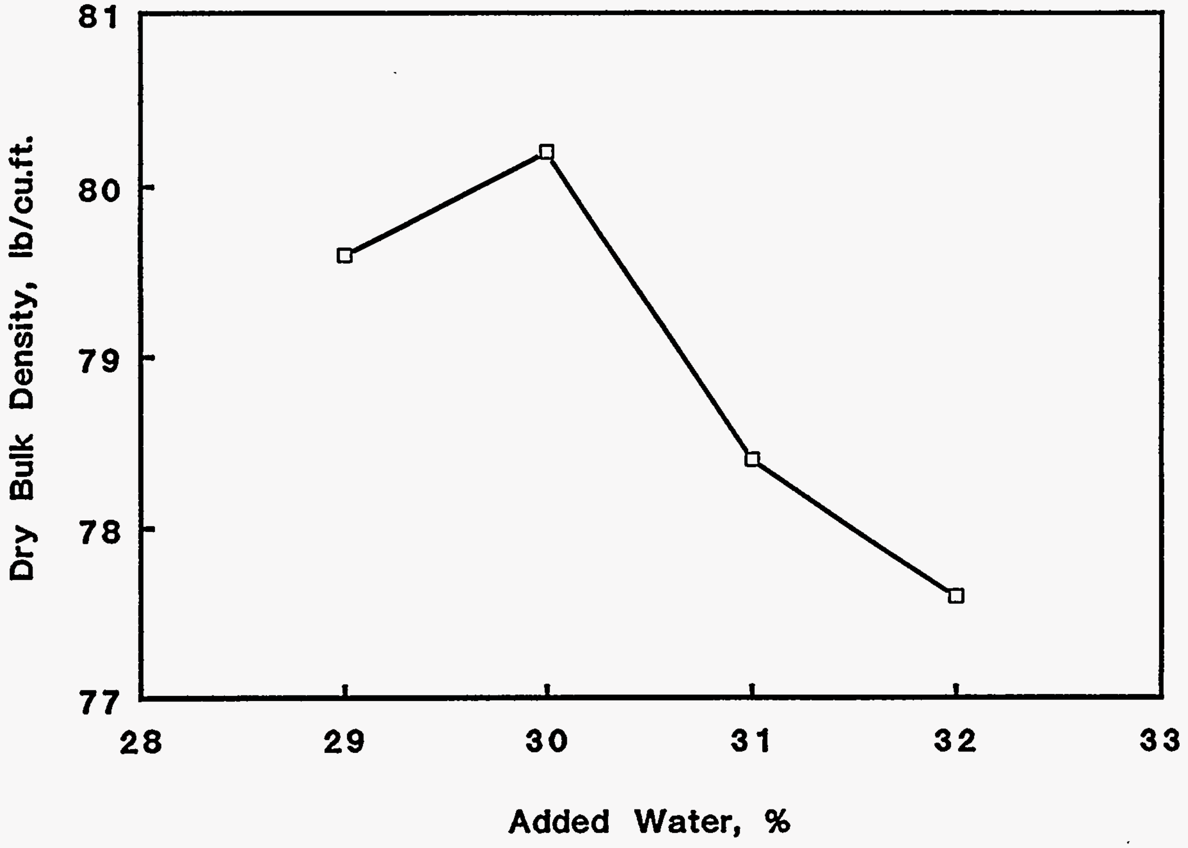

Figure 6. Moisture-Density Relation of Simulated Advanced Coolside Waste Sample No. 3.

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