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Project Summary

Pilot-Scale Investigation of Closed-Loop Fly Ash Sluicing

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This project was a pilot-scale demonstration of the technical feasibility of closed-loop operation of fly ash sluicing systems. Chemical species leached from the ash increase the dissolved solids concentration of recycled sluice water to a point where scaling of equipment may occur. Tests were conducted at two power plants using a 50 gpm pilot unit to demonstrate the feasibility of closed-loop operation, both with and without sluice water treatment. An ash sluice computer process model was developed to predict chemistry and process conditions in full-scale systems.

Fly ash sluicing systems handling highly reactive alkaline ashes cannot be operated closed-loop without treating sluice water to control scale formation. Acid addition for pH adjustment was effective in controlling calcium carbonate scale formation in the sluice water return line; however, use of sulfuric acid increased the potential for gypsum scale formation. Gypsum was ultimately the limiting species which prevented reliable closed-loop operation at the plants tested. Increased ash/water contact time in a reaction tank was not adequate to control the potential for gypsum scale formation at the residence times tested.

The ash sluice computer process model proved to be accurate in predicting the chemical composition and potential for scale formation in the pilot unit. This model is an effective tool for the resolution of ash sluicing system operating problems or to support the design of systems in new plants.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in two separate volumes (see Project Report ordering information at back).

Introduction

The intimate mixing of coal-fired power plant ash and water during sluicing causes soluble species (e.g., calcium, chloride, sulfate, sodium, and trace elements) to be leached from the ash. An increase or decrease in the pH level can also result, depending on the characteristics of the coal ash. The effluent guidelines limitations for the steam electric power industry require zero discharge from new plants with fly ash sluicing systems. Restrictions for existing plants were not included in the final effluent limitations promulgated in November 1982. Operation of a zero discharge (closed-loop) fly ash sluicing system has not been common in the utility industry. To meet the zero discharge requirement for fly ash sluicing in new plants, designers have three options: 1) operate systems closed-loop, 2) dispose of the dry fly ash, and 3) blend the fly ash with sludge from a wet flue gas desulfurization (FGD) system at plants with wet FGD systems.

Recycling ash pond water to create a closed-loop ash sluicing system can cause many operating problems. Scale formation in the system is a major concern in closed-loop operations. Calcium, magnesium, sodium, sulfate, and silica are the major species leached from the fly ash and subsequently concentrated with recycle. Concentrating these soluble species in a closed-loop system can supersaturate the sluice water with calcium carbonate ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), magnesium hydroxide ($Mg(OH)_2$), or silica compounds, resulting in precipitation which, in turn, causes scale formation in parts of the system. Failure to control the buildup of scale-forming compounds in the ash sluicing system by appropriate treatment may result in plugging of piping, pumps, and other system equipment encountering elevated temperatures. This scaling can adversely affect the reliability of the ash sluice system, thus reducing the availability of the generating unit.

To address the potential impacts of closed-loop operation on power plant ash sluicing systems, EPA has conducted three projects to define potential chemistry-related operating problems, and to test several control approaches. The first project was to provide technical and economic evaluations of water recycle/reuse and treatment options to assist utilities operating or designing coal-fired power plants to reduce water consumption and treatment costs. Results of the first project indicated that closed-loop operation of fly ash sluicing systems would require treatment to control scale formation. Because of the variability and developmental nature of the computer model used in the evaluation, additional bench- and pilot-scale studies were recommended.

In response to the recommendations of the first project, the second and third projects were initiated. In the second project, funded by EPA's Effluent Guidelines Division in 1979, the ash sluice systems at three power plants were characterized. Ash collected in the field was used in a bench-scale simulation of a closed-loop ash sluice system to evaluate ash leaching and dissolved solids buildup. These data were used to refine the accuracy of the ash sluice system computer simulation model as well as to provide a design basis for a pilot-scale field testing system.

The third project, which is the subject of this report, involved the design, construction, and field testing of a pilot unit and use of the field data to evaluate the ash sluice process model.

Project Objective

The primary objective of this project was to investigate the technical feasibility of closed-loop operation of fly ash sluicing systems. To achieve this objective, three major tasks were completed:

- Development, design, and construction of a pilot system—The pilot system design was developed using both full- and bench-scale ash sluicing data. The system was designed and constructed with a high degree of flexibility to be able to 1) duplicate the wide range of flow and mixing conditions found in full-scale systems, and 2) provide three treatment approaches for reducing the potential for scaling. The system was also designed to be easily transportable and adaptable to several plant locations.
- Test plan development and field testing of the pilot system—Detailed test plans were prepared for operating the pilot unit at each participating plant. Test conditions were determined using bench-scale ash sluice system characterization data and ash leaching studies.
- Development/verification of the ash sluice computer process model using field data.

Field Testing Approach

The approach used involved operating the ash sluice pilot system with ash and makeup water from a host power plant. Figure 1 is a flow diagram of the ash sluice pilot system. The system contains a makeup tank for blending recycled ash sluice water with makeup water. The mixture flows to a mixing tank where fly ash is added to produce a slurry. The mixing tank is large enough to provide a slurry residence time comparable to that required to transport ash from the plant to a settling pond. Additional mixing time can be obtained by using a reaction tank. A filter press is used to remove ash solids from the system. The filtered water is collected in a recirculation tank and pumped to the makeup tank for reuse. The pilot system includes three treatment options to control scaling in the system:

- Adjusting the pH of the recycle stream,
- Softening the sidestream of the recycle stream, and
- Mixing the ash slurry longer to allow chemical precipitation in the reaction tank.

The system is designed so that one or a combination of these treatment options can be evaluated in a single test run.

Pilot testing was completed at Plants 9677 and 9991 during the program. Both plants produce highly reactive fly ash that results in an alkaline ash sluicing water. The fly ash from Plant 9991 is more reactive than that from Plant 9677. Plant 9991 burns a western subbituminous coal, and Plant 9677 burns a bituminous coal mined in western Kentucky. The fly ash from Plant 9991 contains about twice as much leachable calcium as does that from Plant 9677.

A complete series of tests with and without treatment were initially planned at each site. However, due to project budget limitations, only the following tests were conducted:

- Plant 9677
  - no treatment
  - using the reaction tank to increase contact time; and
- Plant 9991
  - no treatment
  - pH adjustment using sulfuric and hydrochloric acids.

Sidestream softening was not used a either plant.

Both plants also sluice ash to settling ponds and reuse pond water for ash sluicing. A portion of the sluice water is discharged from the ash settling pond at Plant 9677. Nevertheless, some scaling has been observed at this plant. However, since the installation of a pH control system, no scaling has been experienced in any part of the ash sluicing system at this plant. Plant 9991 operates its ash sluicing system closed-loop and has experienced some scaling in recirculation pump screens. This scaling has not been severe enough to cause a major plant operating problem. The plant is relatively new, and the ash sluice water had not concentrated significantly at the time of the field test with the pilot system. Because scaling had been noticed at various points in the system, plant personnel were concerned about scale buildup and control

Results

Program results can be divided into three major areas: (1) ash leaching characteristics, (2) feasibility of closed-loop operation, and (3) verification of the ash sluice computer process model. Each area is summarized below.

Ash Leaching Characteristics

During the project the weight fractions of key chemical species leached from fly ash were evaluated based on three sources of test data: laboratory leaching tests, pilot unit tests, and full-scale system characterization tests.

Table 1 summarizes the Plant 967 ash leaching data from the laborator batch tests, the full-scale system, and the pilot unit. Both the average and the range of calculated values are reported. Also shown in Table 1 are the calcium carbonate and gypsum relative saturation values calculated by the equilib

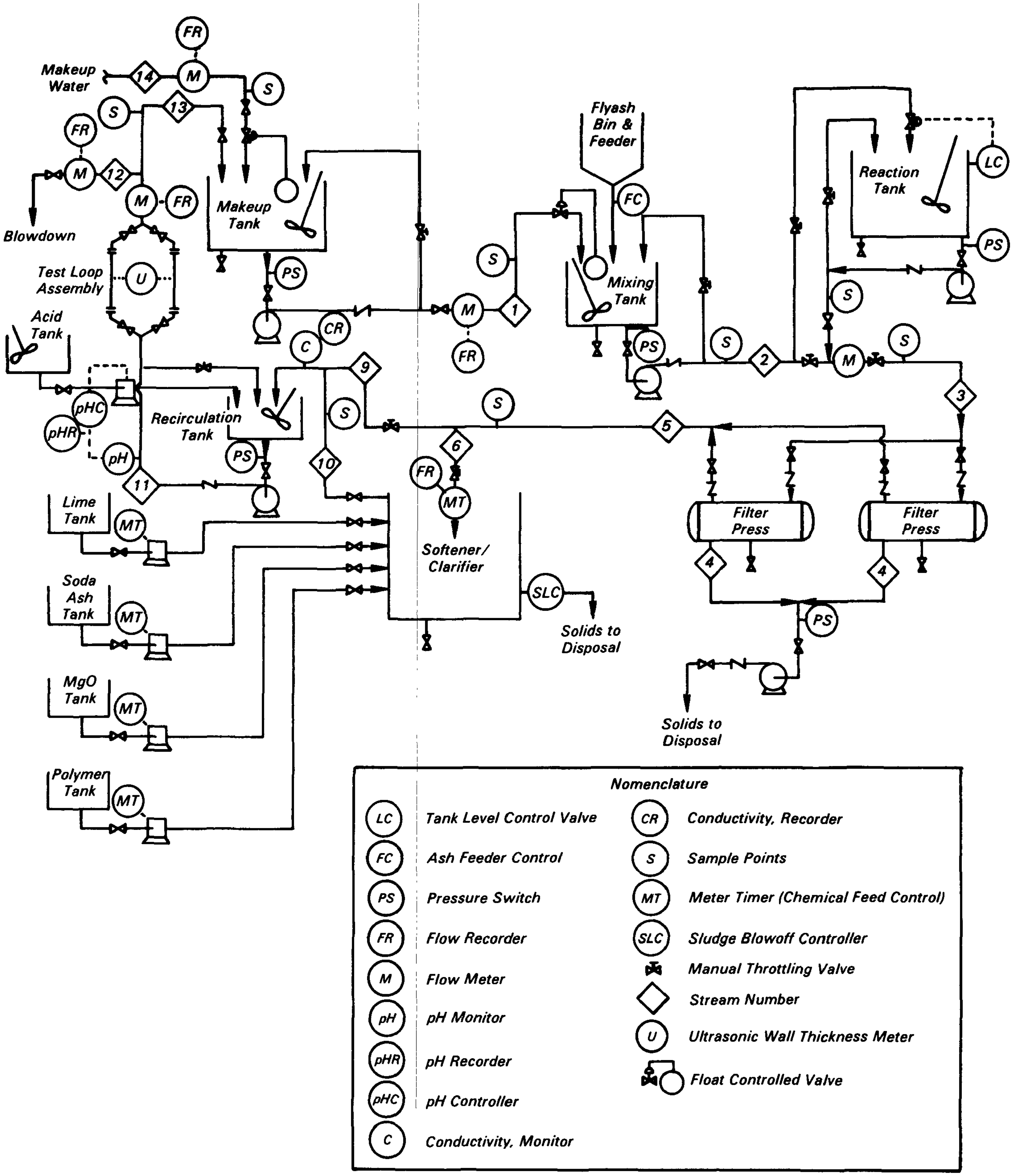

Figure 1. *Ash sluice pilot system flow.*

rium model for the leachate composition. The relative saturation values were used to determine if a potential for precipitation existed, since precipitation must be accounted for during the leachability calculations. The relative saturation values indicated that, for each data set, the potential for precipitation of calcium carbonate existed in the leachate. A potential for gypsum precipitation existed only for the pilot unit tests.

Based on the average values, the calculated quantities of species leached for the laboratory and full-scale data agree extremely well. The differences in the relative saturation values in Table 1 are due primarily to differences in the water (recycled plus makeup) composition prior to being mixed with the ash. The relative saturation values were used to determine if reprecipitation of calcium, sulfate, or carbonate would be expected. The average calculated quantity of calcium leached during pilot testing was about 20 percent lower than that for the laboratory or full-scale data. This does not necessarily indicate a decrease in the quantity of calcium leached, but may reflect additional precipitation of calcium that was not accounted for during the calculation. The transfer of CO_3 from the atmosphere was suspected during the pilot unit test, which could have precipitated with the calcium as calcium carbonate resulting in a lower calculated leach quantity. The quantity of sulfate leaching during the pilot unit tests could not be calculated because of the precipitation of gypsum. For this reason, the laboratory sulfate leach data were used for pilot unit calculations.

The ranges of values in Table 1 indicate considerable variation in calculated leaching quantities. These variations can be attributed to two factors: 1) there is some analytical error (±5 percent) associated with the measured values used in the calculation, and 2) fluctuations in the coal composition would affect the fly ash composition and the leachability of the species from the fly ash. The comparison of Plant 9677 leaching data indicates that (although there is a fairly wide range in the values calculated from the three sources) the average values compare well. In addition, the results suggest that (for similar ashes) the quantities of species leached during pilot- and full-scale sluicing can be adequately estimated from laboratory batch leaching tests. Also, these results suggest that the quantity of a species leached from the ash is not a function of the initial water composition; however, reprecipitation of supersaturated species may occur at high concentrations.

Table 2 gives the ash leaching data from laboratory, pilot-, and full-scale determinations from Plant 9991. The ranges of the quantities of species leached per gram of ash again show considerable overlap between the three data sources. In general, averages of the estimated quantities leached compare reasonably well for all of the species. The most important discrepancy is the estimated quantity of calcium leached from each source, although all of the calcium values are the same order of magnitude. Relative saturation values indicate that calcium carbonate was supersaturated in data obtained from all three data sources. The estimate of the quantity of calcium leached could have been affected if additional CO_3 were absorbed and unaccounted for, and leached calcium was precipitated as calcium carbonate during the tests. Since the laboratory apparatus was covered, the levels of carbonate were so low that the quantity of calcium carbonate that could have been precipitated would have been minimal. More opportunity for CO_3 transfer existed in the pilot unit, but the greatest opportunity for CO_3 transfer was in the ash ponds of the full-scale system. The greatest uncertainty in the ash leaching data is for the estimates prepared from full-scale data since the weight percent ash in the slurry was not determined. Also, in a full-scale system CO_3 could be introduced from the following sources:

- as a component of fluidizing air; and
- as a component of boiler flue gas contained in the fly ash interstitially or from leaking fly-ash hopper valves.

Feasibility of Closed-Loop Operation

Pilot unit test results indicated that closed-loop operation would not be possible at either plant tested without some form of treatment to control scale formation. Since funding limitations prevented test programs using all treatment options from being performed at each plant, the optimum treatment approach and control limits could not be determined. However, two of the three treatment capabilities of the pilot system were used during the two field tests.

Table 3 summarizes the test conditions and the scaling tendency (relative saturation) of the recycle water for tests at Plant 9677. All tests were conducted

Table 1. *Summary of Ash Leaching Data--Plant 9677*

Data Source	Quantity Leached, mg/g ash						Slurry pH	Relative Saturation	
	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate		Calcium Carbonate	Gypsum
Field Laboratory[a]									
– *average*	4.2	0.02	0.12	0.17	0.03	6.5		29	0.3
– *range*	3.6-5.3	0.01-0.04	0.10-0.16	0.13-0.20	0.00-0.08	4.0-10.1	10.0-11.0	19-45	0.1-0.5
Full-Scale System									
– *average*	4.1	0.05	0.11	0.25	0.02	6.6		[b]	0.2
– *range*	3.2-5.0	0.02-0.07	0.10-0.13	0.22-0.27	0.00-0.03	4.6-8.1	4.7-9.8	0.01-30.8	0.1-0.3
Pilot Unit									
– *average*	3.3	0.03	0.09	0.18	[c]	6.5[d]	10.2-10.5	>100	2.2
– *range*	2.9-3.8	0.01-0.05	0.02-0.20	0.06-0.35					1.9-2.5

[a]*Performed using deionized water.*
[b]*Average not reported due to variations in pH.*
[c]*No leaching was measured.*
[d]*Could not be measured due to precipitation of gypsum, assumed to be the same as the laboratory value.*

Table 2. Summary of Ash Leaching Data--Plant 9991

Data Source	Quantity Leached, mg/g ash						Slurry pH	Relative Saturation	
	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate		Calcium Carbonate	Gypsum
Field Laboratory[a]									
– average	8.1	–	0.37	0.03	0.03	3.7		7.9	0.2
– range	6.2-9.9	–	0.23-0.51	0.0-0.06	0.0-0.06	3.2-4.2	12.2-12.7	7.7-8.1	0.1-0.3
Full-Scale System									
– average	4.0	–	0.43	0.02	0.08	3.0		94	0.3
– range	1.8-7.8	–	0.23-0.78	0.01-0.02	0.08[b]	1.1-7.0	11.1-12.4	65-120	0.2-0.4
Pilot Unit									
– average	5.7	–	0.40	0.05	0.12	2.5		110	0.6
– range	3.5-8.1	–	0.24-0.73	0.04–0.08	0.12[c]	1.9-3.0	11.8-12.6	50-150	0.2-1.5[d]

[a]Performed using plant ash sluice system makeup water.
[b]Based on results from data collected on October 22, 1982.
[c]Based on Test 6 results only.
[d]Gypsum was not saturated except in Test 3.

with 100 percent recycle of sluice water with slurry concentrations in the 10-12 weight percent range. The only difference between the test runs was the incorporation of more ash mixing time in the reaction/hold tank in Tests 2 and 3. In all tests, the recycle water was supersaturated with respect to both calcium carbonate and gypsum. During the tests, a light coating of scale was noted in several parts of the pilot system. Unfortunately, the testing had to be completed before enough scale had accumulated for sampling and identification.

Figure 2 summarizes chemistry and flow for Test 2 at Plant 9677. The calcium carbonate relative saturation is over 400 at all points in the system indicating that precipitation was probably occurring.

The gypsum relative saturations also indicate a potential for precipitation. The potential for gypsum precipitation is high because the concentrations of both calcium and sulfate in the recycle water are very high. A significant deposition of gypsum scale may form very rapidly in ash sluice system equipment, especially where higher temperatures may be encountered.

The reaction/hold tank was used to provide an additional 5-10 minutes of ash mixing. Bench scale studies had indicated that this approach might be an effective mechanism for increasing precipitation on the ash particles to desupersaturate the sluice water. The results of the field tests at Plant 9677 indicated that only a slight reduction in gypsum relative saturation was obtained. The relative saturation of calcium carbonate increased. This suggests that longer retention times would be required to promote precipitation to achieve solid/liquid equilibrium for plants with sluice water compositions similar to Plant 9677 (e.g., plants burning bituminous coals producing alkaline ash sluice water).

Table 3. Summary of Pilot Test Runs at Plant 9677

Test No.	Slurry Concentration wt%	Treatment	Recycle Water[a] pH	Relative Saturation[b] Calcium Carbonate	Relative Saturation[b] Gypsum
1	10.0	-[c]	10.5	180	2.5
2	10.2	Reaction tank (5 minute retention)	10.2	590	1.9
3	12.8	Reaction tank (10 minute retention)	10.4	470	2.1

[a]100 percent sluice water recycled.
[b]Relative saturations >1 indicate a potential for precipitation/scale formation.
[c]No treatment.

Table 4 summarizes the field tests performed at Plant 9991. Six tests were performed with varying degrees of recycle and slurry concentrations in the 5.8 - 11.9 weight percent range. After baseline tests with no treatment of the ash sluice water, tests were conducted using both sulfuric and hydrochloric acids to control the pH of the recycled water. Due to the higher reactivity of the ash, the approach at Plant 9991 was slightly different from that at Plant 9677. At Plant 9991, laboratory ash leaching data were input to the ash sluice computer process model, and a blowdown rate was calculated that would maintain gypsum relative saturation at a value of 1.0. Tests 3 through 6 were run with blowdown and recirculation rates eliminated in this manner.

Figure 3 summarizes chemistry and flow conditions during Test 4 with hydrochloric acid used to adjust pH. The relative saturation of calcium carbonate dropped from 122 to 12 across the recycle tank where the acid is added. A relative saturation of 12 is comparable to that measured in the effluent of a softener and, therefore, should not be high enough to promote precipitation. Gypsum was unsaturated in this test. However, a further decrease in blowdown would increase the gypsum relative saturation to a critical point. The high calcium and sulfate concentrations in the recycle water indicate that a large quantity of scale may form in the ash sluice system if gypsum becomes supersaturated.

The test program at Plant 9991 focused on pH adjustment as a way to operate closed-loop without scale formation. Hydrochloric acid was effective in reducing calcium carbonate relative saturation to levels of low potential for precipitation. Sluice water recycle at

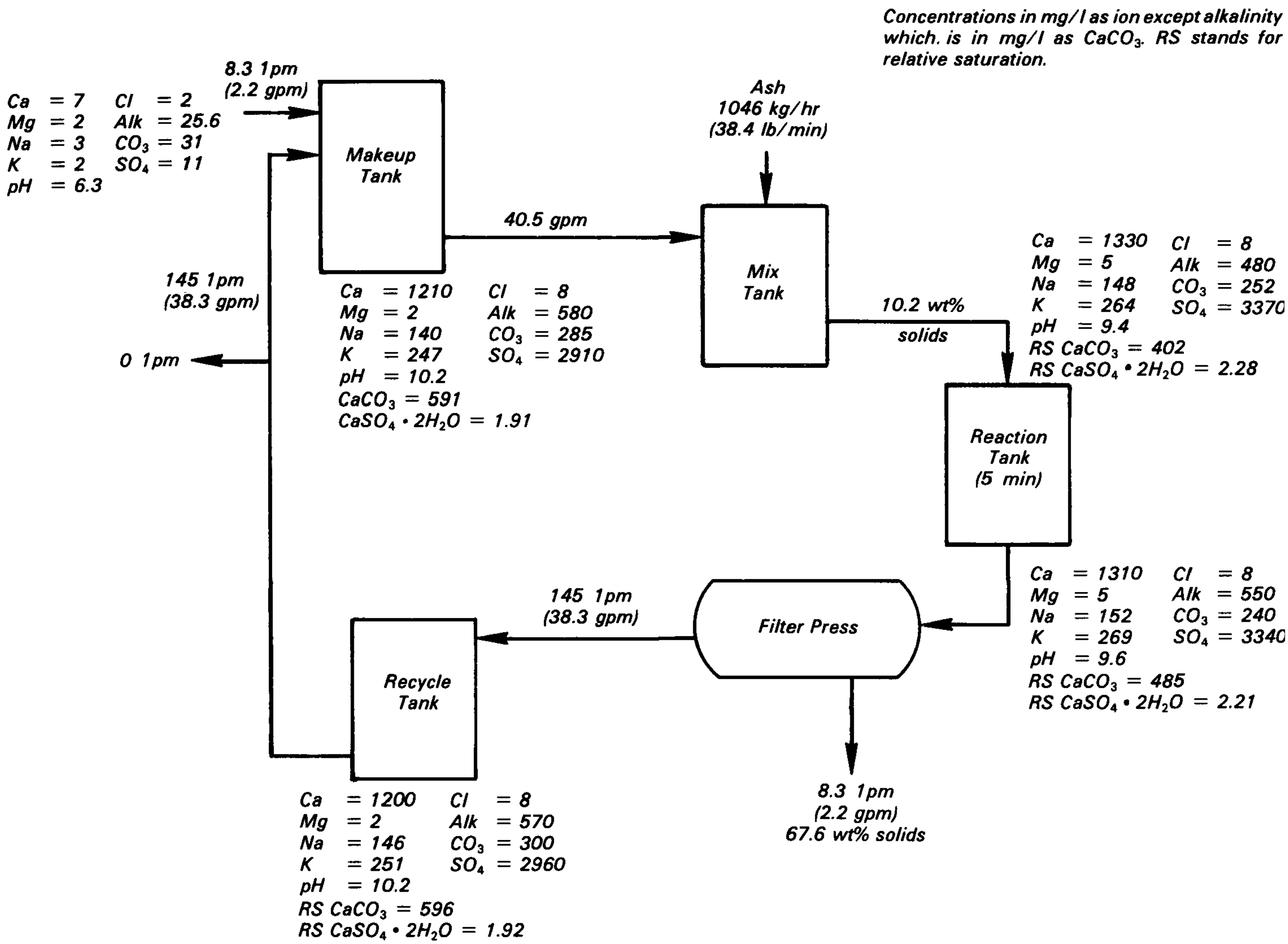

Figure 2. *Summary of pilot unit data from Test 2--Plant 9677.*

Table 4. *Summary of Pilot Test Runs at Plant 9991*

Test No.	Slurry Concentration wt%	Treatment	Percentage of Sluice Water Recycle	Recycle Water pH	Relative Saturation[a]: Calcium Carbonate	Relative Saturation[a]: Gypsum
1	6.3	-[b]	0	11.9	50	0.2
2	8.8	-[b]	0	12.4	100	0.3
3	5.8	Sulfuric acid[c]	68	9.3	46	1.8[d]
4	5.9	Hydrochloric acid[c]	78	8.4	12	0.6
5	11.9	Hydrochloric acid[c]	56	8.5	12	0.7
6	8.8	Sulfuric acid[c]	27	8.3	6	0.8

[a]Relative saturations >1 indicate a potential for precipitation/scale formation.
[b]No treatment.
[c]pH adjusted with indicated acid.
[d]During this test, makeup water sulfate concentration increased fivefold.

78 percent produced a gypsum relative saturation of 0.6 in the recycled sluice water. Sulfuric acid could not be used to control scale; the sulfate introduced increased the amount of blowdown that was required to avoid gypsum scale formation. At higher slurry concentrations (about 10 weight percent) and pH adjustment with hydrochloric acid, recycle rates were limited to about 56 percent. Adjusting pH with hydrochloric acid can control calcium carbonate scale in closed-loop operation; however, it may limit operation by gypsum scale.

Verification of Ash Sluice Computer Process Model

A secondary objective of the field testing was verification of the capability of the ash sluice computer process model to predict operation of pilot- and full-

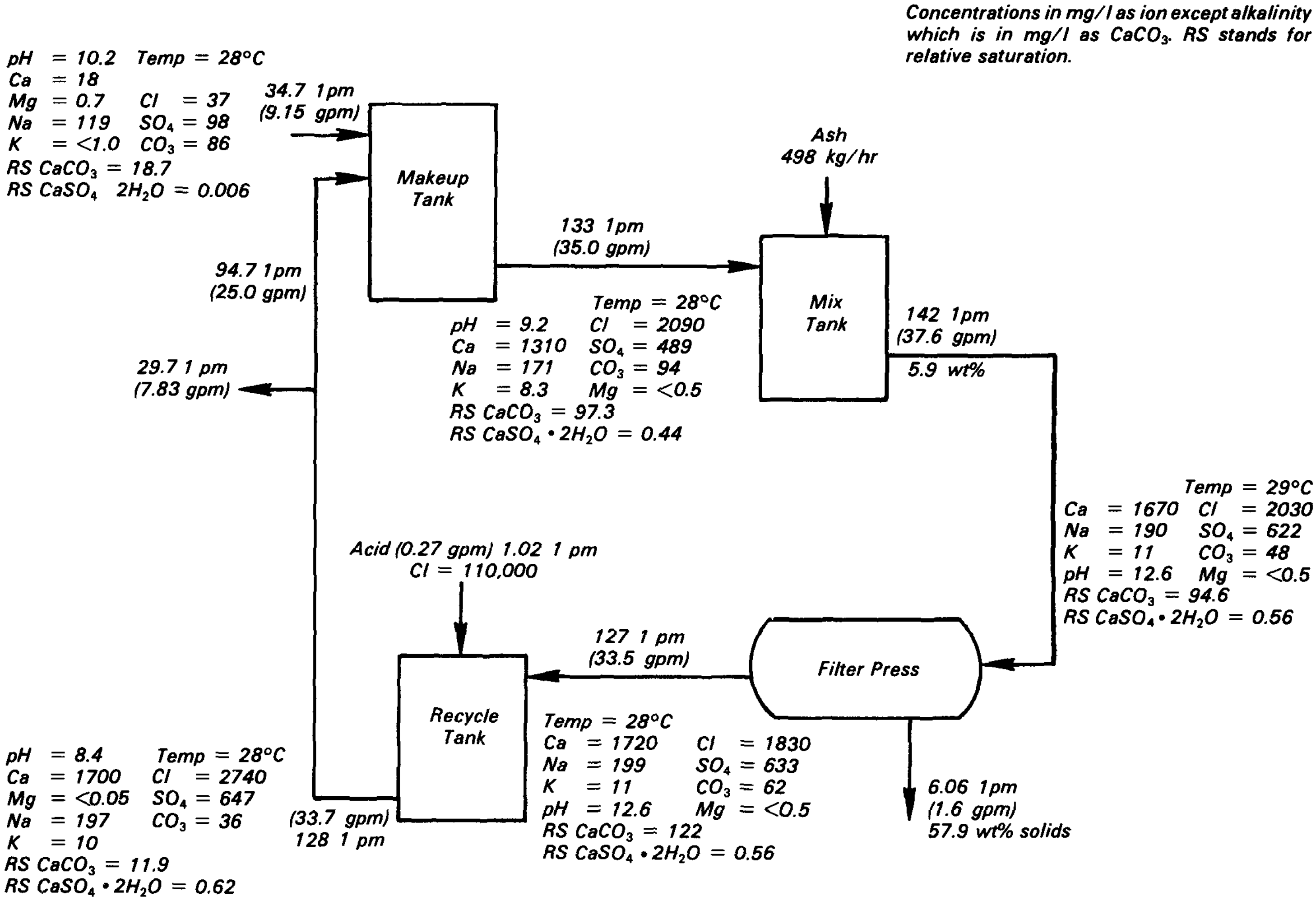

Figure 3. *Summary of pilot unit data from Test 4--Plant 9991.*

scale systems. The model consists of an internal chemical equilibrium model supported by a set of subroutines. The equilibrium model calculates ionic interactions and the potential for precipitation of solids in aqueous systems which contain calcium, magnesium, sodium, potassium, ammonia, silica, chloride, carbonate, nitrate, sulfate, and phosphate. The support subroutines simulate the various components of an ash sluicing system (pond, softener, reaction/hold tank, etc) and perform material balance calculations.

As discussed earlier under "Feasibility of Closed-loop Operation," the model was used to predict the blowdown flowrates that would result in a gypsum relative saturation value of 1.0 in the recycled sluice water for Plant 9991.

The output of the model can only be as accurate as the quality of the input data to the model. If the input data (e.g., ash leaching, makeup water chemistry) accurately reflect the characteristics of an ash sluice system, then the model should predict system chemistry and flows relatively accurately. Table 5 compares the chemistry, relative saturation, and system flowrates measured during Test 4 at Plant 9991 in the pilot system and predicted by the model. Ash leach rates, makeup water composition, and the approach to solid/liquid equilibrium measured in the pilot system were used as inputs to the model. The model accurately predicted all chemistry and flow rate data within the limits of analytical and flow measurement accuracy (±20 percent). The only significant deviation is in the prediction of alkalinity, which directly affects the relative saturation calculations. Although the relative error of the alkalinity is high, the actual concentrations involved are fairly low. Thus, even though the driving force for scaling (relative saturation) is high, the quantity of material that could potentially be deposited is relatively small.

To demonstrate the predictive capability of the model, data from Test 4 were used to project the minimum blowdown that could be achieved without gypsum supersaturation. Hydrochloric acid was used to adjust the pH of recycle water in this test. The blowdown composition for the minimum blowdown case is compared with the model prediction for Test 4 (78 percent recycle) in Table 6. At a 94 percent sluice water recycle rate, gypsum would become supersaturated, indicating that closed-loop operation may result in precipitation. This prediction could not be verified in the field; however, from the previous discussion showing the accurate duplication of field test results, this estimate should be reasonably accu-

Table 5. *Comparison of Ash Sluice Model Predictions with Pilot Unit Performance for Test 4*

	Predicted by Model	Measured in Pilot Unit	Difference percent
System Blowdown Composition			
Component, ppm as ion			
Ca	1650	1700	3
Mg	0.2	<0.5	N/A[a]
Na	186	197	6
K	9.6	10	4
Cl	2670	2740	3
Alkalinity (as $CaCO_3$)	14.8	30	50
SO_4	722	647	−12
pH	8.4	8.4	0
Relative Saturation			
$CaCO_3$	4.8	11.9	N/A
Gypsum	0.68	0.62	−9
System Flow Rates, lpm (gpm)			
Hydrochloric acid	0.80 (0.21)	1.0 (0.27)	22
Makeup	34 (8.9)	35 (9.2)	3
Sludge (water loss)	5.7 (1.5)	6.1 (1.6)	6

[a]*Not applicable.*

rate. Although gypsum scale formation had not been encountered at Plant 9991, the concentrations of species in the full-scale system were much lower than predicted by the model. This indicates that the plant had not yet reached steady state operation. Due to the large volumes of the ash ponds and the firing rate at the plant, several years could be required before gypsum scaling is observed.

Conclusions

Program results indicated the following conclusions.

- Fly ash sluicing systems handling highly reactive alkaline ashes (characteristic of low sulfur western coal ashes) cannot be operated closed-loop without encountering precipitation in the system unless water is treated to control scale formation. The results obtained from the full-scale plant characterization, the pilot unit, and the ash sluice computer model are consistent in indicating precipitation will occur.
- Adding acid to adjust pH should be effective in controlling calcium carbonate scale formation in the sluice water return line. Economic considerations will probably favor sulfuric acid over hydrochloric; however, use of sulfuric acid will increase the potential for gypsum scale formation. Other treatments, such as side-stream softening, will be necessary to prevent gypsum scale formation during closed-loop operation.

Table 6. *Comparison of Minimum Blowdown Simulation with Simulation of Test 4*

	Model Predicted Minimum Blowdown	Pilot Unit Test 4
System Blowdown Composition		
Component, ppm as ion		
Ca	3910	1650
Mg	0.1	0.2
Na	343	186
K	23.8	9.6
Cl	6695	2670
Alkalinity (as $CaCO_3$)	7.5	14.8
SO_4	1036	722
pH	8.4	8.4
Relative Saturation		
$CaCO_3$	3.1	4.8
Gypsum	1.1	0.68
System Flow Rates, lpm (gpm)		
Hydrochloric Acid	0.80 (0.21)	0.80 (0.21)
Makeup	12 (3.3)	34 (8.9)
Sludge (water loss)	5.7 (1.5)	5.7 (1.5)
Liquid Blowdown	7.6 (2.0)	29 (7.6)
Total Blowdown	13 (3.5)	34 (9.1)

- The ash sluice computer model was an effective tool for predicting the chemical composition and potential for scale formation in the pilot unit when accurate inputs to the model were specified. Critical inputs to the model that can significantly affect the accuracy of model predictions include 1) ash leaching data, 2) the quantity of CO_3 transfer in the ash ponds, and 3) estimates of the potential for precipitation in ash sluice equipment. Program results indicate that laboratory ash leaching data are adequate to use as inputs to the model.

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The complete report consists of two volumes:
"Pilot-Scale Investigation of Closed-Loop Fly Ash Sluicing: Volume 1. Final Report," (Order No. PB 85-204 378/AS; Cost: $16.00, subject to change).
"Pilot-Scale Investigation of Closed-Loop Fly Ash Sluicing: Volume 2. Appendices," (Order No. PB 85-204 386/AS; Cost: $32.50, subject to change).
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