Management of Dry Flue Gas Desulfurization By-Products in Underground Mines

**Quarterly Report
October 1 - December 31, 1995**

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CHAPTER I

INTRODUCTION AND SUMMARY

Introduction and Summary

On September 30, 1993, the U.S. Department of Energy - Morgantown Energy Technology Center (DOE-METC) and Southern Illinois University at Carbondale (SIUC) entered into a cooperative research agreement entitled "Management of Dry Flue Gas Desulfurization By-Products in Underground Mines" (DE-FC21-93MC-30252). Under the agreement SIUC will develop and demonstrate two technologies for the placement of coal combustion by-products in abandoned underground coal mine workings, and assess the environmental impact of such underground placements.

Previously Technical Progress Reports have set forth the specific objectives of the program, and a discussion of these is not repeated here. This report discusses the technical progress achieved during the period October 1 - December 31, 1995.

Rapid Aging Test columns were placed in operation during the second quarter of 1995, and some preliminary data were acquired during this quarter. These data indicate that the highly caustic pH is initially generated in the pneumatic mix, but that such pH is short lived. The initial pH rapidly declines to the range of 8 to 9. Leachates in this pH range will have little or no effect on environmental concerns.

Dedicated sampling equipment was installed in the groundwater monitoring wells at the proposed placement site at the Peabody Number 10 mine. Also, the groundwater monitoring wells were "developed" during the quarter to remove the fines trapped in the sand pack and screen. A new procedure was used in this process, and proved successful.

A series of tests concerning the geotechnical characteristics of the pneumatic mixes were conducted. Results show that both moisture content and curing time have a direct effect on the strength of the mixes. These are, of course, the expected general results.

The Christmas holidays and the closing of the University during an extended period affected the progress of the program during the quarter. However, the program is essentially on schedule, both technically and fiscally, and any delays will be overcome during the first quarter of 1996.

CHAPTER 2

ENVIRONMENTAL CHARACTERIZATION

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Introduction

The environmental safety of underground disposal of coal combustion by-products can be evaluated from two major standpoints. One standpoint is the site specific question of whether contaminated leachates from the fill could have environmental consequences at the actual demonstration site. Each site is unique and while techniques to evaluate site specific impacts may be broadly applied, the actual results and monitoring apply only to the site considered. This section of the project, Environmental Characterization of Materials focuses on the second question, which is whether the materials to be placed are capable of generating leachates that could act as a contaminated input to a hydrogeologic domain.

Data generated in the last quarter has focused on the "Rapid Age" testing covered in protocols attached to previous reports. Unlike the shake tests done for permitting purposes, which involve only contact of fresh solutions with fresh coal combustion byproducts, the Rapid Age test focuses on behavior of the material over time. The experimental design is similar to the ASTM column except that leachate volumes from 1 to 10 times the pore volume per day are allowed and attempts are made to force several pore volumes through each day. The Rapid Age tests were also designed to run for a period of 1 year in order to detect long term trends that might not be available with ASTM columns that typically run for a month or less. As the name indicates the procedure attempts to produce aging and break-down effects in the material that would take many years to occur in nature. Like the ASTM column, pressurized nitrogen is used to force solution through the test material. This permits estimates to be made on the permeability of the material, which is expected to vary over time. Unlike the ASTM column, the Rapid Age procedure uses synthetic leaching mediums designed to simulate either the brines in the rock layers around the disposal site or worse case acid mine drainage.

Technical Discussion

Previous reports have shown that there is little risk of leachates produced by the proposed mixes carrying harmful levels of trace elements, although high dissolved solids and sulfate were identified as potential problems. Also, calcium oxide and hydroxide compounds found in the pneumatic mixes seemed capable of producing leachate with a very caustic pH.

In order to cause damage to the environment a mix of combustion residues placed underground must be capable of producing a significant volume of leachate relative to the groundwater already flowing through the system. If the leachate volume is small by comparison, the potential for dilution of trace elements to within usable water limitations is high. Similarly the output of hazardous leachate must continue over a significant period of time. The process of dispersion tends to mix water that has contacted the fill during different periods of time. This is the process that reduces the sharpness of front of groundwater contamination plumes. If a material produces hazardous leachate concentrations only for a short period of time, the chances for a clear and dangerous contamination front in the groundwater is small.

During this quarter the Rapid Age test results on the pneumatic mix are to be evaluated with respect to two key criteria, namely, 1- is the permeability high enough over time to produce large volumes of leachate, and 2- Do high pH concentrations persist over a long enough period of time to impact groundwater systems. The groundwater surrounding the mine site is a brine with a high concentration of dissolved solids. Thus, the site will be in a class 4 regulatory scheme with respect to dissolved solids. From the shake tests it is already known that leachate concentrations for dissolved solids will probably be lower than concentrations already in the groundwater. No class 4 violations are expected for dissolved solids. In the experiments reviewed this quarter, synthetic brine solutions made to resemble the deep Pennsylvanian strata regional brines near the site, are used for leaching mediums. The Rapid Age test was run in triplicate to check for reproducibility of the results.

Although not a strict permeability unit measurement, Figure 2.1 plots the milliliters of leachate per day produced by each column for each PSI of pressure applied. A material with high permeability will allow the flow of a large volume of liquid for each PSI of pressure. The results and trends for the triplicate experiment are similar. Initially the Rapid Age columns produce around 550 ml/day of leachate for every PSI across the assembly. After about 3 months, the flow is typically around 70 ml/day of leachate for every PSI across the assembly. There is some variation since replicate #2 appears close to only 40 ml/day/psi, while replicate #3 seems closer to 120 ml/day/psi. As in a real field situation, solution channels block and shift with time, causing variations in leachate volume, pH or trace element concentrations. Thus, while the down-trend is unmistakable, not all data points fall on a single line. Since the relationship between pressure drop and leachate volume is linear for calculation of permeability, this indicates over an 87 percent reduction in permeability in the first 3 months, most of it occurring during initial hydration.

Since the Rapid Age column is a constant head permeameter the units of ml/psi can be converted to hydraulic conductivity according to Darcy's Law.

$$K = Q \cdot L / h \cdot A \quad (K = \text{hydraulic conductivity cm/sec})$$

Where Q = Quantity of Leachate/Unit Time (cm³/sec)

L = Length of Sample Chamber (61 cm)

A = Cross Sectional Area of Sample (81 cm²)

h = Pressure Drop Across Sample (cm of water)

Using this conversion the hydraulic conductivity of the pneumatic mix is approximately 3.63×10^{-3} cm/sec. initially, dropping to 4.62×10^{-4} cm/sec within 3 months. These hydraulic conductivity's are not high enough to constitute an aquifer, but will readily allow movement of groundwater. It should be understood that the pneumatic mix was placed into the Rapid Age column by pouring, with packing applied only around the edges to control channeling along the interface. When the Rapid Age Columns were packed, it was only a few days before it was no longer possible to detect water movement through the column. For the Rapid Age assembly as

FIGURE 2.1

Rapid Age Pneumatic Mix

Permeability with Brine Solution

designed, permeability's down to 4.62×10^{-6} can be measured. With changes in the pressure gages, detection down to close to 10^{-7} cm/sec could be measured. Thus, it is known that the degree of packing in the column will alter hydraulic conductivity by two to three orders of magnitude at least.

Surrounding rock layers at the site have hydraulic conductivity's at or below 10^{-8} cm/sec. Again the material in the field had permeability less than the detection limit of the instrumentation used. One result of these relative hydraulic conductivity's is that if the pneumatic mix is placed without packing energy, the mine will be the most permeable geologic unit at depth at the site. It will function as a preferred conduit for water flow and leachate volumes from the fill will be large compared to water moving in the surrounding layers. (A mine opening has essentially infinite hydraulic conductivity). Of course with the low permeability in the surrounding rock layers, any leachate front will advance extremely slowly so that off-site groundwater contamination (if a 5% solids brine can be "contaminated") may take centuries.

How well the pneumatic mix is compacted during placement may become an issue in determining whether an underground fill will or will not be a major source of leachate. A 10^{-4} cm/sec material will conduct significant water flows, while a 10^{-7} cm/sec material will not. At the demonstration site, the depth and quality of the groundwater surrounding the mine may be such that "contamination" may not have an environmental impact regardless of the what type of material is buried there. If the technology developed as part of this project is to become a standard industry practice, it is necessary to consider that future sites may have a higher quality groundwater and rock formations that allow the advancement of leachate fronts over periods of months, rather than centuries. For more general application a closer resolution on the permeability of the pneumatic mix is required. To this end, the materials placement team on this project has been contacted to see if and when they can supply reliable data on the actual packing density of the pneumatic mix. It is possible that this data will have to come from the surface demonstration of Phase II this summer.

Another issue that may become key to the permeability of the fill is whether the FBC fly ash is "preconditioned". In this context "preconditioning" means that the ash has been exposed to water in order to convert free CaO to calcium hydroxide. Originally the placement team indicated that FBC fly ash would not be preconditioned for disposal because of the cost of adding an extra step. Several factors have called the placement teams original decision into question. If the FBC fly ash is not preconditioned there will be a tremendous heat release when the material contacts water. In order to set the pneumatic mix, water additions will be necessary as the mix is injected underground. Heat release could add wear and stress to the injection equipment, create new safety hazards, or perhaps even cause flash setting of the ash in the equipment. When one injects large volumes of air into an underground mine with an atmosphere with probably more than a 50% methane content, the combination of heat and friction as the atmosphere goes through an explosive methane to oxygen ratio should be considered. Finally, the heat release in the mix will promote micro-cracking, which reduces setting strength. In part because of the placement teams other research, it now appears possible to incorporate preconditioning into the injection equipment cycle.

Preconditioning would have implications for the permeability of the mix. The rapid fall in permeability when the mix first contacts water is caused in part by swelling of the hydrating material. Preconditioning would eliminate much of the swelling and initial mineral reformation and might effect the steep initial loss of permeability. For packed FBC ash mixtures this initial loss of permeability is sharp enough that the Rapid Age columns cease to function within about 3 days, meaning that permeability has fallen below the detection limit of the assembly. (Of course the elimination of micro-cracking may have implications on the long term permeability of the fill). Again, input from the placement team has been sought on whether the mixes will be preconditioned. The Rapid Age Experiment has been suspended pending reliable data on initial packing density and whether the ash will be preconditioned. This data is crucial to the question of whether a pneumatic fill could be a large volume source of leachate.

One of the specific concerns about leachate from an underground fill is the initially caustic pH. Most geochemical models indicate that eventually the calcium oxide and hydroxide responsible for the caustic pH values will be converted to carbonates and gypsum with pH values around 8 to 9. Work done on other research projects has repeatedly shown that FBC fly ash caustic pH values are only short term. The Rapid Age Test examines the specific mix to be placed at the site. Examination of Figure 2.2 shows that the pH values are falling exactly as expected from geochemical modeling and previous research experiments. High pH values will be only a short term problem. This will greatly reduce any potential for significant off-site caustic contamination of groundwater. Again, at the demonstration site for this project the site conditions are such that it is almost impossible to contaminate anything that will have an environmental impact. For more general applications where the site hydrogeologic conditions are not "perfect" for containment of environmental contamination, it is important to know that caustic conditions are short term only.

Summary and Conclusions

The Rapid Age tests on the pneumatic mixes appear to be repeatable, as indicated by triplicate readings that follow similar trends. The permeability of the pneumatic mix will have a major influence on whether the underground fill will produce significant volumes of leachate. The experiment has shown that permeability varies sharply with how tightly the material is packed during placement. Loosely packed material will be a major source of leachate into the hydrogeologic system, while more tightly packed material will not. Swelling and reformation of minerals during initial hydration are probably responsible for sharp drops in permeability as the material first contacts water. If the FBC fly ash is preconditioned with water, this sharp permeability drop may be lost. It is impossible for experiments at this point to answer the question of whether the fill will produce significant volumes of leachate. For this reason the Rapid Age Experiments have been suspended until the placement team can give solid answers on whether the ash will be preconditioned and what the packing density will be. This information should be available from the Phase II surface demonstration this summer.

The Rapid Age experiments are confirming the expected result that highly caustic initial pH values will only exist over the short term and are therefore unlikely in most settings to impact groundwater pH outside the immediate area of a fill of this type.

FIGURE 2.2

Rapid Age Pneumatic Mix pH with Brine Solution

+ Replicate 1 ■ Replicate 2 ▲ Replicate 3

CHAPTER 3

**MIX DEVELOPMENT AND
GEOTECHNICAL CHARACTERIZATION**

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DR. X. YUAN
CO-PRINCIPAL INVESTIGATORS**

Introduction

During the time period from October 1, 1995 to December 31, 1995, additional tests were conducted for geotechnical characterization of pneumatic and hydraulic mixes. For the purpose of investigating the long term (more than 180 days) strength of hydraulic mixes, several groups of samples were prepared. To further study the geotechnical characters of pneumatic mixes a number of samples were prepared and some tests were conducted.

Hydraulic Mix

In previous studies and tests on the strength of hydraulic mixes involving different curing times, the maximum curing time was about 50 days (see previous technical progress reports). To further investigate the strength of the hydraulic mix over a long period, several groups of samples were prepared:

- A. Sample Group A (5 samples): 40% F.A., 55% S.S., 5% L.W., mixed with 29% water;
- B. Sample Group B (5 samples): 40% F.A., 55% S.S., 5% L.W. mixed with 28% water;
- C. Sample Group C (5 samples): 40% F.A., 55% S.S., 5% L.W. mixed with 30% water.

These samples will be tested after appropriate curing.

Pneumatic Mix

In this quarter, characterization of pneumatic mixes was continued to study the effects of preconditioning of FBC fly ash and moisture content in the mixes. Several groups of cubical samples with different moisture contents were made and tested. The mixes were composed of 80% FBC fly ash and 20% FBC bottom ash, and mixed with varying water content. These samples were cured for 7 days in a 70° F, 60% RH chamber. Figure 3.1 shows the strength of these cubic samples.

Figure 3.1 Curve of Strength of Cubical Samples vs. Moisture
(7 Days' Aerial Curing)

As can be seen from Figure 3.1, within the limits of the test, an increase in moisture content of the mixes results in an increase in compressive strength. It should be noted that this test holds only within the relatively narrow limits of the test, and should not be used as general rule.

The influence of moisture, curing time, and mixing proportions of materials on the strength of pneumatic mixes were studied by testing a series of cylindrical samples. These samples were 3 inches in diameter and 6 inches high.

Table 3.1 lists the groups of samples investigated in the quarter.

Table 3.1

Sample groups	No. of samples	FBC fly ash %	FBC bottom ash %	Moisture %	Curing time
1	3	100	0	30	7
2	3	100	0	30	28
3	3	100	0	30	60
4	3	100	0	30	90
5	3	80	20	30	7
6	3	80	20	30	28
7	3	80	20	30	90
8	3	80	20	28	7

All samples, both cubical ones and cylindrical ones, were made according to the following procedure:

A. Pre-Condition:

- (1). Mix materials uniformly; add 9% water, then mix 5 minutes;
- (2). Add an additional 5% water, then mix another 5 minutes;
- (3). Allow the mix to cool.

B. Sample Preparation:

- (1) After the temperature of mix falls below 30° C., place the mix into appropriate molds and then place in a curing chamber;
- (2) Remove the samples from the molds after 2 days;
- (3) Maintain the samples in a curing chamber for the appropriate curing period.

Some of the sample groups have been tested, and test results are given below.

Sample group 1 consists of samples which were made of 100% FBC fly ash, 0% FBC bottom ash, and 30% moisture. The curing time period for this group is 7 days. The average axial compressive strength is 58 psi, with an average Young's modulus of 2200 psi (see Figure 3.2).

Figure 3.2 Curve of Stress vs. Strain (Sample Group 1)

Figure 3.3 shows the test results of sample group 5. The samples in this group were made of 80% FBC fly ash, 20% FBC bottom ash, and 30% moisture, with 7-day curing time. The average axial compressive strength of this group is 59 psi, and the average Young's modulus is 3,900 psi.

The test results of sample group 8 are shown in Figure 3.4. The samples in this group were made of 80% FBC fly ash, 20% FBC bottom ash, and 28% moisture. The curing time for this group is also 7 days. Compared with sample group 5, the average axial compressive strength of sample group 8 is about 10 psi lower. However, the average Young's modulus for this group is much higher, about 11,000 psi.

Figure 3.4 Curve of Stress vs. Strain (Sample Group 8)

Figure 3.5 shows the test results for sample group 6. Sample group 6 is identical in composition to sample group 5, i.e. 80% FBC fly ash, 20% bottom ash, and 30% moisture. However, the curing time was 28 days. The average axial compressive strength of sample group 6 is 69 psi and the Young's modulus average is 9,000 psi. Thus the longer curing time increased both the axial compressive strength and the Young's modulus.

Figure 3.5 Curve of Stress vs. Strain (Sample Group 6)

The same relationship is shown when comparing sample group 1 and 2. Again, the composition is identical in both groups (100% FBC fly ash, no bottom ash, and 30% moisture). However, sample group 2 has a longer curing time of 28 days, and shows a somewhat higher axial compressive strength and a higher Young's modulus. Figure 3.6 shows the results of the tests of sample group 2.

Conclusion

These tests show that, within the limits of the experiment, both an increase in the moisture content of the mixture and an increase in curing time leads to an increase in both axial compressive strength and Young's modulus. However, the limits of the tests were quite narrow, and conclusions resulting from these tests should not be generalized over other ranges of moisture and curing times.

CHAPTER 4

MATERIAL HANDLING AND SYSTEM ECONOMICS

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Objectives

The objectives of the materials handling research are: 1) To identify the systems that are technically, economically, and environmentally feasible in handling and transporting the coal combustion residues from the power plant to the injection site, 2) To demonstrate the operation of one or two of the identified systems.

The objectives of the system economics research are: 1) To conduct economic analyses of the selected materials handling and underground residue placement systems, and 2) To develop a generalized "Economic Evaluation" model that can be used in evaluating various types of materials handling and placement systems for different distances and tonnages.

The term "materials handling" in this research project includes loading, transporting, unloading, and temporary storage of the dry coal combustion residues for the purpose of disposing them into abandoned areas of the underground coal mines in Illinois. Materials handling systems have been analyzed in four consecutive modules: 1) storage, handling and loading of the residues at the plant site, 2) transportation from the plant to the mine site, 3) unloading, handling and storage at the mine site, and 4) transportation from the mine site to the injection site.

In the past, several transportation and handling (T&H) alternatives were evaluated, whereby, three alternatives were found to be environmentally friendly:

- 1) Pressure differential rail cars (PD-car)
- 2) Collapsible intermodal containers (CIC)
- 3) Pneumatic trucks (PT)

Detailed engineering analysis of these systems have been conducted and operating policies developed. The operating policies of these systems were described in previous reports, hence, they will not be repeated here. A generalized "Economic Evaluation" model was developed and coded using Microsoft EXCEL software and FORTRAN language. Different segments of this model were configured under one roof using rapid application development tool called Delphi which facilitated the development of an interactive Windows application with dialog boxes. Information on this software was given in the Annual Report submitted on October 1995 and in a technical paper entitled "Interactive Software for the Evaluation of Residue Transportation and Handling Alternatives" published in the Proceedings of the 1995 International Ash Utilization Symposium held in Lexington, Kentucky on October 23-25, 1995.

Summary Of Activities

During the last quarter the following activities were undertaken:

- 1) Development of simulation models for efficient designs of systems
- 2) Completion of a master's thesis. Mr. S. M. Gwamaka, a graduate student in the Department of Mining Engineering, has worked in this research project and completed a master's thesis entitled "Development of Simulation and Cost Models to Evaluate Coal Combustion Residue Transportation and Handling Systems."
- 3) Completion of a technical paper to be presented at the Annual Meeting of the Society for Mining, Metallurgy, and Exploration, Inc, to be held on March 10-14, in Phoenix, Arizona. This paper, co-authored by Dr. Sevim and his graduate students Mr. S. M. Gwamaka and D. D. Lei, summarizes the simulation and cost models developed for the project. The title of the paper is "Simulation and Economic Evaluation of Coal Combustion Residue Transportation and Handling Systems."

Development of Simulation Models for Efficient Designs of Systems

In earlier evaluations of the alternatives, system designs were done to simply match the annual tonnage, without considering the interrelationship among the system components. Design, in this context, means determination of the number of transport units, capacities of silos, loading rate, unloading or transloading rate, injection rate, and operating schedule which is composed of plant schedule, transportation schedule between the plant and the mine, and injection system operation schedule at the mine site. The objective in system design was redefined as: "Deliver the annual tonnage by using the least number of transportation units, the least number of personnel, and the smallest size silos, so that the unit cost can be minimized.

The implication of the above redefined objective is that, for underground injection systems to be competitive, they must be optimally designed. The optimal design, however, is not easy to reach, because for each parameter that controls the system performance, there are a number of options to choose from. If the values of these parameters are not selected properly, the system will fail to deliver the targeted tonnages, that is, the design will be technically infeasible. Considering the pressure-differential (PD)-car alternative for example, if there are not enough PD cars in the system, there will be excessive accumulation in the plant silo, the injection system and the trucks at the mine site will have idle capacities, and consequently, the targeted injection tonnages will not be achieved. Therefore, there was a need of finding a design evaluation method whereby different designs can be tested for their technical feasibilities. It was envisaged that simulation models would be most appropriate in these circumstances.

Simulation technique can be used for both deterministic and stochastic scenarios. In deterministic scenarios, the occurrences and durations of the events are known with certainty, whereas in stochastic scenarios they vary randomly. Usually, a deterministic model is easily

transformed into a stochastic model by simply defining the events with probability distributions. It is noted that, when deterministic events occur in predictable cycles, i.e., cycles that occur at defined intervals, it is more convenient to use mathematical techniques which will bring faster and more precise solutions than those of simulation technique. In the evaluations of pneumatic truck alternative under deterministic scenarios, it was found that the cycles were indeed predictable. Therefore, a simple mathematical model was developed to find the optimal design in pneumatic truck alternative. This model was adapted into a spreadsheet format using the Microsoft Excel software. In addition to this mathematical model, however, a simulation model had also to be developed for stochastic scenarios.

In summary, the following models were developed for the T&H alternatives under study:

1. A deterministic and a stochastic simulation models for the PD-car alternative.
2. A deterministic and a stochastic simulation models for the CIC alternative.
3. A mathematical model and a stochastic simulation model for the PT alternative.

During this quarter, deterministic simulation models were tested more thoroughly than the stochastic models. Therefore, the outcomes of the runs corresponding to deterministic scenarios in each alternative will be summarized in this report. The PD-car alternative will be used to illustrate important points.

The general flow of the simulation logic for all systems are shown in Figure 4.1. As seen, for a given T&H alternative, the distance-tonnage combination must be stated first. The next item is the specification of control variables whose values affect the system behavior. In the case of the PD-car alternative, the control variables are: 1) transloading rate, 2) injection rate, 3) number of trucks, and 4) number of PD cars. Different combinations of control variable values are tested through the simulation model to find the best values. Whether proper combination has been selected or not can only be found by observing the behavior of response variables. In the PD-car system, response variables are; primarily, mine and plant silo capacities, number of train trips per week, and secondarily, waiting time of the trucks at the mine silo and at the injection system.

For each combination of control variable values, the system is simulated for one year. The residue accumulations in both silos were tracked for the entire year. Excessive accumulation in either silo, or both, long waiting times for trucks, and the necessity of making more than three trips per week are considered as indications of technically infeasible designs. Under these circumstances, the values of the control variables are re-adjusted and a new run is initiated.

After accumulating a number of technically feasible designs, a few designs with short waiting times are selected to be economically evaluated. Among the technically feasible designs, the one with the minimum unit cost is declared as the best design for the given distance-tonnage combination.

Figure 4.1. Block diagram for transportation-handling system simulation models

All simulation models were coded using GPSS/H (General Purpose Systems Simulation) language. The PD-car simulation model is composed of seven modules, all operating in parallel. The first module is the system input module that takes the values of all input parameters from either a keyboard or from a file. The second module simulates the pneumatic pipe operation that transports the ash from the boilers into the silo. Since ash flow is continuous and GPSS/H is a discrete simulation language, continuous events have been discretized to two-minute events. Thus, the pneumatic pipe brings ash to the silo every two minutes, at which time the silo capacity is updated.

The third module simulates the PD car loading at the plant. The silo plays the role of single-server which serves the cars only when there is more than 100 ton of ash in it. The loading time is assumed to be 20 minutes per car during which 100 tons of ash is extracted from the silo. The loading process stops when the counter for the loaded cars reaches the specified number. Then, the cars travel to the mine. Upon arrival to the mine site, two logic gates are checked before transloading operation starts; 1) gate indicating whether it is an active shift or not, and 2) gate indicating whether there are still cars from the previous set to be unloaded. As soon as the previous set of cars are pulled out from the rail siding the gate opens for the arriving set.

The fourth module simulates truck fleet operation. The silo and the injection system are single-servers to the trucks. A truck which arrives to the silo has to check two logic gates; 1) gate indicating whether there is another truck being served or not, and 2) gate indicating whether there is at least 50 tons of residue in the silo. If the message is negative, the arriving truck has to wait in line. Once it is served, the residue accumulation in the silo will be reduced by the capacity of a truck (20 tons). When the truck arrives at the injection system, it has to check in the line for service. The content of a truck will be transloaded at a rate equal to the injection rate.

The fifth module is a clock that keeps track of the simulation time minute by minute. This clock informs the gates for the end of shifts and for the day of the week. The sixth module is analogous to a "camera" that takes "snapshots" of the response variables. These snapshots can be used as input to an animation software to visualize the operation. In this study they are used for debugging the developed models. Finally, the seventh module is a clock that controls the beginning and ending of a simulation run according to the specified simulation time.

A spreadsheet model for the design of pneumatic truck alternatives under deterministic conditions

The steps of the model are shown in Figure 4.2. In addition to distance-tonnage combination and number of shifts per day, values of parameters such as average speed, truck loading time at the plant silo, and truck offloading time into the injection system hopper are input to the model. These last three parameters are used in the calculation of truck cycle time.

Figure 4.2. Selection of feasible designs in pneumatic truck alternative under deterministic conditions

The "maximum number of trucks without any queuing" at the injection system can be obtained by dividing the calculated cycle time to the offloading time. The assumption here is that the offloading time is longer than the loading time. The "required number of trucks" to deliver the annual tonnage, however, may be more, or less, than the "maximum number without queuing".

The "required number of trucks" can be calculated as a function of the annual tonnage, truck capacity, cycle time, number of shifts per day, and number of hours per shift. When the required number is greater than the maximum number without queuing, trucks will queue at the injection system. However, the objective here is not to allow any queuing. The only remedy in such situations is to decrease the offloading time, or equivalently increase the injection rate. As seen in Figure 4.2, when such condition is encountered, a new offloading time is set and the calculations restart from cycle time down. In this alternative, the plant silo capacity is determined by the accumulation of residue during non-working hours between two consecutive shifts. This duration may include one or two of the weekend days plus the remaining hours of a work day.

Examples

The PD-car alternative was evaluated for annual tonnages of 100,000, 200,000, and 300,000 tons and for distances of 100, 200, and 500 miles, forming altogether nine tonnage-distance combinations. It is assumed that PD-car loading at the plant will be 3 shifts per day regardless of the annual production, whereas the transloading and injection at the mine will be 1 shift for 100,000 and 200,000 tons and 2 shifts for 300,000 tons. Several simulation runs were conducted for each combination. In these runs, the values of control variables were varied in the ranges given in Table 4.1. A reasonable increment was used in each range. For instance, PD cars were incremented by 5 units at a time. Also, in the exception of the "number of trucks", there was no need to test the entire range in all distance-tonnage combination.

Table 4.1. Ranges of Control variables

Control Variables	Range
Transloading rate (tons/min)	0.56 - 1.608
Injection rate (tons/min)	0.56 - 1.40
Number of trucks	2 - 4
Number of PD cars	20 - 110

It was assumed that for a given design to be declared feasible, two conditions must be satisfied: 1) Accumulation in either the plant or the mine silo must not exceed 1000 tons, and 2).The number of train trips per year must not exceed 156; that is, a maximum of three trips per week was allowable.

Table 4.2. Best technically feasible designs for the PD-car alternative

		<u>100,000 t/yr</u>			<u>200,000 t/yr</u>			<u>300,000 t/yr</u>		
		<u>Design 1</u>	<u>Design 2</u>	<u>Design 3</u>	<u>Design 1</u>	<u>Design 2</u>	<u>Design 3</u>	<u>Design 1</u>	<u>Design 2</u>	<u>Design 3</u>
100 miles	Transload. rate (t/m)	0.7	0.7	0.7	1.608	1.608	1.608	1.2	1.2	1.2
	Injection rate (t/m)	0.84	0.84	0.84	1.34	1.34	1.34	1	1	1
	Number of trucks	2	2	2	3	3	3	3	3	3
	Number of PDs	20	38	44	26	40	74	40	58	110
	Mine silo capacity	200	250	300	200	350	450	500	550	700
	Plant silo capacity	150	150	150	450	250	150	600	350	150
	Trips/year	99	52	45	153	99	53	149	103	54
	Cost (\$/ton)	7.82	10.03	10.79	6.30	7.10	9.05	6.54	7.18	9.15
200 miles	Transload. rate (t/m)	0.7	0.7	0.7	1.608	1.608	1.608	1.2	1.2	1.2
	Injection rate (t/m)	0.84	0.84	0.84	1.34	1.34	1.34	1	1	1
	Number of trucks	2	2	2	3	3	3	3	3	3
	Number of PDs	20	38	44	26	40	74	40	58	110
	Mine silo capacity	250	250	300	200	350	500	600	550	700
	Plant silo capacity	150	150	150	550	350	150	750	500	150
	Trips/year	99	52	45	153	99	53	149	103	54
	Cost (\$/ton)	8.15	10.28	11.05	6.61	7.42	9.34	6.89	7.49	9.41
500 miles	Transload. rate (t/m)	0.7	0.7	0.7	1.608	1.608	1.608	1.2	1.2	1.2
	Injection rate (t/m)	0.84	0.84	0.84	1.34	1.34	1.34	1	1	1
	Number of trucks	2	2	2	3	3	3	3	3	3
	Number of PDs	20	38	44	26	40	74	58	80	110
	Mine silo capacity	200	250	300	200	350	500	500	850	700
	Plant silo capacity	300	150	150	850	700	400	1000	750	250
	Trips/year	99	52	45	153	99	53	102	74	54
	Cost (\$/ton)	10.36	12.38	13.15	8.89	9.73	11.15	9.77	10.61	11.56

Figure 4.3. Cost-per-ton for the best designs of PD-car alternative

Table 4.3. Best technically feasible designs for the CIC alternative

		<u>100,000 t/yr</u>			<u>200,000 t/yr</u>			<u>300,000 t/yr</u>		
		<u>Design 1</u>	<u>Design 2</u>	<u>Design 3</u>	<u>Design 1</u>	<u>Design 2</u>	<u>Design 3</u>	<u>Design 1</u>	<u>Design 2</u>	<u>Design 3</u>
100 miles	Injection rate (t/m)	0.7	0.7	0.7	1.34	1.34	1.34	1.2	1.2	1.2
	Number of trailers	2	2	2	3	3	3	3	3	3
	Plant silo capacity (t)	800	450	100	750	550	450	900	650	450
	Total number of CICs	120	125	140	145	150	160	170	180	190
	Cost (\$/ton)	10.8	10.5	10.4	7.3	7.3	7.3	8.0	8.0	8.0
200 miles	Injection rate (t/m)	0.7	0.7	0.7	1.34	1.34	1.34	1.2	1.2	1.2
	Number of trailers	2	2	2	3	3	3	3	3	3
	Plant silo capacity (t)	750	350	100	850	450	150	600	300	100
	Total number of CICs	125	130	140	160	165	180	190	200	210
	Cost (\$/ton)	11.06	10.75	10.69	7.80	7.65	7.64	8.31	8.28	8.27
500 miles	Injection rate (t/m)	0.7	0.7	0.7	1.34	1.34	1.34	1.2	1.2	1.2
	Number of trailers	2	2	2	3	3	3	3	3	3
	Plant silo capacity (t)	300	200	100	1000	350	150	800	350	150
	Total number of CICs	140	145	150	190	200	210	240	250	260
	Cost (\$/ton)	12.10	12.10	12.10	9.36	9.14	9.13	9.88	9.80	9.80

Table 4.4. Best technically feasible designs for the Pneumatic Truck alternative

1	Annual production (tons)	100000	100000	100000	200000	200000	200000	300000	300000	300000
2	Distance (miles)	30	100	200	30	100	200	30	100	200
3	Shifts per day	1	1	1	1	1	1	2	2	2
4	Loading time (min)	10	10	10	10	10	10	10	10	10
5	Average speed (mph)	50	50	50	50	50	50	50	50	50
6	Unloading time (min)	20	20	20	18	18	18	12	12	12
7	Duration of a shift (min)	600	600	600	600	600	600	480	480	480
8	Work days per year	312	312	312	312	312	312	312	312	312
9	Truck payload (tons)	20	20	20	20	20	20	20	20	20
10	Travel time loaded (min)	36	120	240	36	120	240	36	120	240
11	Travel time empty (min)	36	120	240	36	120	240	36	120	240
12	Cycle time (min)	102	270	510	100	268	508	94	262	502
13	Max. no. of trucks without queuing	5.10	13.50	25.50	5.56	14.89	28.22	7.83	21.83	41.83
14	Required no. of trips per year	5000	5000	5000	10000	10000	10000	15000	15000	15000
15	Required no of trips per day	16.03	16.03	16.03	32.05	32.05	32.05	48.08	48.08	48.08
16	Max. no. of trips per truck per shift	5.88	2.22	1.18	6.00	2.24	1.18	5.11	1.83	0.96
17	Required no. of trucks	2.72	7.21	13.62	5.34	14.32	27.14	4.71	13.12	25.14
18	Injection rate (tons / min)	1.00	1.00	1.00	1.11	1.11	1.11	1.67	1.67	1.67
19	Feasible scenario?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
20	Max. ash accumulation time (hrs)	38.00	38.00	38.00	38.00	38.00	38.00	32.00	32.00	32.00
21	Max. ash accumulation (tons)	433.79	433.79	433.79	867.58	867.58	867.58	1095.89	1095.89	1095.89
NUMBER OF TRUCKS										
		DISTANCE (miles)								
PRODUCTION (tons / yr)		30	100	200						
100000		3	8	14						
200000		6	15	28						
300000		5	14	26						

For each tonnage-distance combination, the best of the technically feasible designs were isolated using the above conditions together with waiting time minimizations at the silo and at the injection system. As indicated in the general flow of the simulation logic given in Figure 3, best technically feasible designs were economically evaluated to obtain the unit transportation cost. The designs that provided the minimum cost-per-ton were declared optimal. All designs were evaluated for a project life of 10 years, a minimum required rate of return of 12%, and an effective tax rate of 40%. Equipment were depreciated based on "Modified Accelerated Cost Recovery System, (MACRS)," and the expected salvage values were credited to the project at the end of the project life. It is noted that at the time this report was written, reliable cost data for the injection system could not be obtained. Therefore, the outcomes do not reflect the contribution of the injection operation into the overall cost.

The three best technically feasible designs for each distance-tonnage combination in PD-car alternative are shown in Table 4.2. In each combination, the values of the control variables are given in the first four rows, and those of the response variables in the next three rows. The unit cost (cost-per-ton) of each design is given in the last row.

The unit costs (cost-per-ton) for the best designs in all nine combinations of the PD-car alternative are shown in Figure 4.3. These unit costs correspond to Design 1 in all combinations due to the fact that they require the least number of PD cars. It is important to note that almost all of these designs require 3 trips per week, which may not be offered by the rail company. If so, Design 2 or Design 3 might be favored depending on the railroad schedule.

One would have expected to see the unit costs in 300,000-ton designs to be lower than the ones for 200,000 due to economies of scale. Figure 4.3, however, indicates that it is not so. This is because the 300,000-ton designs for 100 and 200 miles required 40 PD cars, whereas the 200,000-ton design for the same mileages required only 26 PD cars. The number of PD cars were almost the same (60 and 58) for 500-mile designs, but 102 trips were required to deliver 300,000 tons, while 66 trips were sufficient to deliver 200,000 tons.

The flatness of the cost lines in Figure 4.3 is an indication that the designed systems are not very sensitive to distance. On the other hand, the pronounced vertical separation between the lines is an indication that they are sensitive to tonnages transported.

The above described simulation runs and selection processes were also applied to CIC alternative. The three best technically feasible designs in each distance-tonnage combination are shown in Table 4.3. The unit cost of each design is given in the last row.

The PT designs were considered only up to 200-mile distance due to the fact that designs for longer distances would have been very costly. The design of PT system involves the sizing of a power plant silo, an injection system at the mine, and a fleet of pneumatic trucks.

The spreadsheet model described above was implemented for different tonnage-distance combinations and the outcomes are shown in Table 4.4. The first three rows in these tables

show the tonnage-distance-shift combinations. The next block, from row 4 to 9, exhibits the user-defined input data. The calculated values are given in rows 10 to 19. For example, for a tonnage-distance combination of 100,000 tons and 30 miles, it is found that the "maximum number of trucks without any queuing" was 5.10 (row 13). This number was found by dividing the cycle time (102 min) to truck unloading time (20 min). It is noted that the unloading time is greater than the loading time. Otherwise, loading time would have been used in the above calculation.

The "required number of trucks" to deliver the targeted tonnage, on the other hand, is calculated by dividing the "required number of trips per day (row 15)" to "maximum number of trips/truck/shift (row 16)". If the "required number of trucks" is smaller than the "maximum number of trucks without any queuing" the scenario receives a "yes" for its feasibility. Otherwise, the unloading time is decreased (row 6), or equivalently, the injection rate is increased (row 18) and the new scenario is retested for feasibility. It is noted that the upper limit for increased injection rate is assumed to be 2 tons/minute. Any scenario that requires more than 2 tons/minute to become feasible is rejected.

The plant silo capacity is shown in rows 20 and 21. Assuming no work on Sunday and two idle shifts on Saturday, total fly ash accumulation hours at the plant adds up to 38 hours. This translates into an accumulation of 434 tons for an annual production of 100,000 tons. The selected truck fleets for each distance-tonnage combination are shown at the bottom of the table.

The unit costs of all three alternatives were summarized in Figure 4.4. As seen, at 100,000 tons, PD alternative gives lower costs than the CIC alternative. At 200,000 and 300,000 tons, however, it is not possible to favor one alternative over the other since the cost lines overlap. At tonnages of 200,000 to 300,000, the truck alternative clearly provides costs lower than the PD and CIC alternatives for distances less than 80 miles. At 100,000 tons, the truck alternative is better than the PD and CIC alternatives for distances less than 100, and 125 miles, respectively.

It is also observed that the cost lines for the truck alternative for all three annual tonnages overlap and they have steep slopes. This is an indication that the cost in truck alternative is not sensitive to tonnages but very sensitive to distances.

The costs given in Figure 4.4 are calculated based on the assumption that either the company operating the plant or the mine is undertaking the job. If, however, a contractor is hired to do the job, (a contractor under the same 40% tax bracket and 12% minimum required rate of return) the price that the contractor would charge is calculated by dividing the unit cost by (1-tax rate), that is, by 0.6.

Plans For The Next Quarter

1. Refine the simulation models
2. Test stochastic simulation models
3. Incorporate injection system cost into the economic evaluation model

Figure 4.4. Cost-per-ton for PT, CIC, and PD-car alternatives

CHAPTER 5

ENVIRONMENTAL ASSESSMENT AND GEOTECHNICAL STABILITY

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Accomplishments

Researchers from SIUC and Illinois Geological Survey ISGS completed two tasks during the last quarter: 1) development of the groundwater monitoring wells, and 2) installation of the dedicated sampling equipment. The purpose of well development is to remove fines from the well casing and screen in order to improve the hydraulic connection between the well and monitored geologic unit, so that water from the well shows little or no visible suspended solids. As described in the Quality Assurance/Quality Control document for the project, the wells were to be developed by circulating clean water down the casing and up the annulus prior to placement of the grout. Logistical problems, particularly the lack of a clean water supply at the mine, forced the alteration of these plans. Instead, the wells were developed after placement of the grout by circulating clean water from the base of the well to the top of the casing. This was accomplished by injecting water under pressure through a 1 inch plastic pipe with the pump built for the packer tests. Water was acquired at Pawnee from the city supply and hauled to the site. As water was circulated, the injection pipe was raised and lowered repeatedly to force fines out of the screen. This method of well development has two advantages over the original procedure; 1) it allows the sand pack to settle, and 2) it removes fines trapped in the sand pack as well as those in the screen. The procedure suffers from one drawback, however, as it allows clean water to remain in the casing after the pump is shut down. Some of this water will seep into the monitored interval and perhaps slightly alter groundwater chemistry. All wells at the site now yield relatively clear water.

Dedicated positive displacement sample pumps (QED type) were installed in the five monitoring sampling wells. Installation procedures followed the manufacturer's recommendations. A cap at the top of the PVC casing contains quick release fittings to two tubes connected to the pump at the base of the well, one for compressed gas (nitrogen) and the other for water. The cap also includes a port for monitoring hydraulic head with a tape.

Plans

Plans for the next quarter include; 1) monthly groundwater sampling; 2) a complete analysis of groundwater chemistry on the samples as described in the test plan; 3) installation of data logging equipment for monitoring hydraulic head; and 4) preliminary slug tests in selected wells. The wells will be purged until the pH, conductance, and temperature stabilize. It is likely, however, that the initial samples will reflect groundwater chemistry that may be somewhat altered by the well development procedure.

CHAPTER 6

NEXT QUARTER

The next quarter, January 1 - March 31, 1996, marks the end of Phase I of this program. Accordingly, most efforts will be directed at preparing for Phase II.

A comprehensive final report on Phase I will be prepared and furnished to appropriate DOE officials. The report will contain data and observations accumulated in the two and one-half year period of Phase I. Likewise, an application for continuation of the program into Phase II will be prepared.

Data accumulation will continue throughout the quarter, including the taking of groundwater samples, analyses of leachates, and other chemical and geotechnical data. Surface subsidence baseline data will also continue to be measured and recorded. In summary, the more or less routine data gathering tasks will continue throughout the quarter.

Specifications for the underground placement equipment, both pneumatic and hydraulic, will be developed, although procurement of specific components will not be undertaken until Phase II is in place. The services of Eric Powell and Associates and Mine Systems Design will be utilized in the design of pneumatic and hydraulic placement equipment respectively, and both will be greatly involved in the preparation of detailed equipment specifications and in the procurement process. The search for a suitable demonstration site for the Phase II surface demonstration will be accelerated, so that such site will be ready when the Phase II demonstration is undertaken. Also, the subject of permits for the Phase II demonstration will be explored with appropriate regulatory authorities.

In summary, the quarter will have two major areas of focus: (1), the "wrap-up" of Phase I of the program, and (2), the preparation for continuing the program into Phase II.