Dr. 1948-8

DOE/MC/14771-1475
(DE83017983)

FEASIBILITY STUDY OF COAL FRACTURE
ENHANCEMENT USING AQUEOUS
SODIUM HYPOCHLORITE

Final Report

By
Arnold H. Pelofsky
Frank W. Dittman

Work Performed Under Contract No. AC21-80MC14771

For
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Rutgers, The State University of New Jersey
Piscataway, New Jersey

TECHNICAL INFORMATION CENTER
UNITED STATES DEPARTMENT OF ENERGY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from copy supplied by the originating organization. Although the copy supplied may not in part or whole meet the standards for acceptable reproducible copy, it has been used for reproduction to expedite distribution and availability of the information being reported.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A04
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

FEASIBILITY STUDY
OF
COAL FRACTURE ENHANCEMENT
USING
AQUEOUS SODIUM HYPOCHLORITE

Final Report

by

Arnold H. Pelofsky, Co-Principal Investigator
Frank W. Dittman, Co-Principal Investigator
Department of Chemical and Biochemical Engineering
College of Engineering
Rutgers, The State University of New Jersey
Piscataway, NJ 08854

Sponsored by

U.S. Department of Energy
Morgantown Energy Technology Center
P. O. Box 880
Morgantown, West Virginia 26505

Contract Identification Number
DE-AC21-80MC14771

TABLE OF CONTENTS

Abstract.	ii
Introduction.	1
Background.	1
Equipment Description	4
Coal-Bed Reactor	4
Reactor Supports	5
Reaction System.	5
Interconnections	5
Materials of Construction.	6
Experimental Procedure - Run No. 1.	6
Permeability Test - Run No. 1.	6
Sodium Hypochlorite Treatment - Run No. 1	6
Experimental Procedure - Run No. 2.	7
Preparation of Test.	7
Permeability Test, Run No. 2	8
Sodium Hypochlorite Treatment, Run No. 2	8
Experimental Procedure - Run No. 3.	9
Preparation Test	9
Sodium Hypochlorite Treatment of Coal	9
Permeability Test	10
Results - Run No. 1	10
Results - Run No. 2	12
Results - Run No. 3	14
Permeability Increase.	14
Temperature Increase	14
Composition.	14
Discussion of Results	19
Conclusions and Recommendations	21
Figures	22

ABSTRACT

This research project was a pilot-scale simulation in the laboratory of the treatment of underground coal deposits by solutions of sodium hypochlorite (NaOCl) in water. Sub-bituminous coal packed tightly in a steel reactor 23" long x 29" I.D. was exposed to the solution pumped through at a rate of 1 gallon per hour. Flow-pressure drop measurements were made before and after each run; from these data, permeability was calculated by means of Darcy's equation.

Three runs were made--12.3 wt% NaOCl for 16 hours; 10.9 wt% NaOCl for 17.5 hours; and in the last run, 6.5 wt% NaOCl for three 15-hour periods, followed by 11 wt% NaOCl for 15 hours. These were designated, respectively, as Runs No. 1, No. 2, and Nos. 3-1, 3-2, 3-3, and 3-4.

In Run No. 1, permeability of the coal bed was increased by 6% to 13%. In Run No. 2, however, the permeability increased by a factor of 5.4 to 8.85, i.e. 440 to 585%. The increase from Run No. 1 to Run No. 2 is believed to be due to a better location of the feed inlet, plus the installation of baffles to direct the solution toward the centerline of the coal bed.

Run 3-1, using relatively weak solution, showed a decrease of about 60% in permeability compared to that of the coal before treatment. Runs 3-2 and 3-3 brought the permeability back up to about 70% of the original value. Run 3-4, in which 11.0 wt% NaOCl solution was used, resulted in a 13 to 29% increase in permeability over the original value.

Twenty-four thermocouples were symmetrically distributed within the coal bed. The increases of temperature due to reaction, which were different for each thermocouple, permitted the tracing of the path of maximum reaction within the coal bed.

INTRODUCTION

Underground coal gasification (UCG) technology is currently being developed to make use of the United States' coal reserves without the need of mining. Like aboveground coal gasification, UCG converts solid coal into low or medium BTU synthesis gas which can be used directly as a fuel or as a petrochemical feedstock.

For the process to operate efficiently and to also achieve maximum coal utilization, reasonably high permeability channels are needed to link the injection wells with the production wells. The USSR and, in recent years, the United States have tried many different techniques to improve linkage. This proposal discusses one such technique. To our knowledge, it has never been described in the open literature.

This proposal describes a linkage enhancement technique that uses an oxidative reactant, NaOCl , to dissolve the organic carbon-containing molecules which are in the coal, thereby leaving behind a more porous structure.

BACKGROUND

The efficiency of UCG is seriously limited by two major problems. The first is the lack of directional control. The flame front and product gases could travel in many directions. The second problem is the lack of sufficient gas flow. Many coal seams are quite impermeable to flow and incapable of sustaining large gas flow rates at low velocity. According to Gregg and Olness, "The Soviets achieve directional control by using highly permeable linkage paths with predetermined spacing at the bottom of the coal seams. These paths render the gasification process insensitive to variations in the natural coal permeability."

To date, seven methods have been tested to improve the permeability of coal beds. These are:

- (1) reverse combustion
- (2) pneumatic fracturing
- (3) hydraulic fracturing
- (4) directional drilling
- (5) electrolinking
- (6) explosive fracturing
- (7) shape-charge linking

In reverse combustion, high pressure air is injected into the production well. Combustion is started in the injection well, and the flame front proceeds toward the source of the air. After a link is formed, normal forward gasification can occur. Hill notes that "Reverse burn tends to follow a coal seam parting. The boundary between the parting layer and the coal tends to have a higher permeability than the rest of the coal because the natural fracturing occurs at discontinuities." Reverse combustion is not practical in seams with very low permeabilities because sufficient air flow is not attainable.

Pneumatic linking is necessary to carry out reverse combustion in coal seams with very low permeability. Very high pressure air is injected into the coal seam until the air pressure can overcome the strength of the seam and fracture it. Reverse combustion can then proceed. Problems with this method include possible increased product gas loss, directional control problems, and high costs involved in supplying high pressure air for long periods of time.

Hydraulic fracturing is produced by injecting water or hydraulic fluids, at high pressures, into coal seams. The fracture is then washed to enlarge it and make it capable of sustaining high gas flow rates. Problems with this method are basically the same as those mentioned for pneumatic linking.

Directional drilling is a method in which linking is produced by horizontally drilling it. Injection and production wells are drilled to connect with the horizontal hole. Although this method is attractive because it poses no directional

control problems, it is extremely expensive.

With electrolinking, a high voltage electric field is applied between the injection and production wells. Electric current chars the coal and forms a link between the electrodes. Directional control and high voltage requirements are the chief difficulties in this method.

Shape-charge linking is the term used to describe the process of generating a shock wave from an explosive charge which compresses a "coneshaped linear into a highspeed jet", according to Hill. This jet penetrates the coal, thereby increasing the permeability of the coal bed. Although a promising idea, the penetration of the charges must be greatly increased before the idea is applicable to commercial UCG.

Using NaOCl to improve linkage in the field has not been attempted. To our knowledge, this proposal is the first to suggest that NaOCl can, in fact, enhance permeability in situ.

S.K. Chakrabartty and H.O. Kretschmer first suggested the use of NaOCl to dissolve coal. They started their work in the early 70's. When the organic material in the coal has reacted, carboxylic acids and carbon dioxide are formed. The reaction is exothermic. The lower the coal rank, the more reactive is the coal to NaOCl. Total oxidation by NaOCl leaves a carboxylic acid solution, unreacted ash and the evolution of CO₂. The reaction is exothermic.

Briefly, crushed Gillette, Wyoming subbituminous coal was packed as tightly as possible into the vessel and aqueous solutions of NaOCl of various concentrations were made to flow through the packed bed of coal. Permeability measurements were taken before and after each run, as was the concentration of the spent NaOCl solution.

In each experiment, permeability was increased substantially. The results suggest that the flow rate and concentration of the NaOCl solution is critical. If the concentration is too low or if the flow rate is too low, the reacting coal

may swell, thereby blocking the channels that are being created by the NaOCl. If the flow rate and NaOCl concentrations are high enough, the solution will take the lowest pressure drop. This approach would probably be the most economical, since less NaOCl would have to be used.

In the laboratory, the NaOCl pathway was easy to track because of the exotherm of approximately 130 F degrees when 11% NaOCl was used at a flow rate of 1 gal/hour. The thermocouple readings indicated the pathway.

In the field, this would not be possible because of the high surrounding temperatures of the in-situ coal. As a result, there is the need to find another technique which could track permeability enhancement which is due to the NaOCl treatment.

If the channels of increased permeability could be mapped, then it would be possible to drill the production wells in line with those channels. The following scenario might be possible: drill an injection well to the bottom of the coal seam; flow the NaOCl solution and allow it to react with the coal; map the channels of increased permeability by means of small-diameter exploratory wells; locate and drill the production wells accordingly; start the burn.

EQUIPMENT DESCRIPTION

Coal-Bed Reactor

Coal in an underground deposit was simulated by tightly packing sub-bituminous coal from Gillette, Wyoming, into a cylindrical carbon steel reactor 23" long x 29" inside diameter x 1/2" shell thickness. The two ends of the cylinder were closed by welded flanges and bolted cover plates, each 38-3/4" O.D. x 2-1/4" thick. The flat cover plates determined the maximum allowable internal working pressure, which was 650 psig.

To protect against possible large-scale evolution of gas, the piping system at the inlet of the reactor, and the reactor itself, were provided with 600 psig

pressure-relief valves. The internal pressure during the experiments never approached the set value, since the evolution of gas was quite small.

The reactor was not thermally insulated. Even though some temperatures over 200F were recorded within the coal, the shell temperature was affected only slightly, and heat loss was unimportant.

Reactor Supports

Trunnions supported the reactor, so that it could be oriented with its axis vertical, horizontal, or any angle between. The trunnions, in turn, were part of a structural pipe framework on wheels, which permitted the entire reactor assembly to be moved around easily.

Reaction System (see Fig. 1)

The reaction system consisted of the following equipment:

- 1 Reactor, as described above
- 1 Sodium hypochlorite solution feed tank
- 1 Metering pump, 0-1 gallon per hour
- 2 Pressure and 2 temperature indicators
- 1 24-point temperature recorder with copper-constantan thermocouples
- 1 Spent solution collecting tank
- 1 Liquid-gas separator
- 1 Volumetric gas meter
- 2 pressure relief valves
- 1 Set process tubing and manual shutoff valves

Interconnections

The above-listed equipment was interconnected as shown on the attached flow diagram, (Fig. 1) so that sodium hypochlorite solution could be pumped continuously at a set constant rate from the feed tank through the pump and reactor to the collecting tank, separator and gas meter.

Connections were also provided for collecting samples of the spent solution, and for running air or water through the bed at known rates before and after sodium hypochlorite treatment of the coal, so that the change in the pressure drop-flow relationship as a result of the treatment could be observed.

Materials of Construction

Carbon steel construction of the reactor proved to be satisfactory because little of the sodium hypochlorite solution came into contact with the reactor shell; practically all of it reacted with the coal.

However, for the pump, lines, and valves subjected to 11% or 5.5% sodium hypochlorite solution, neither carbon steel nor stainless steel were satisfactory in corrosion resistance. The pump, a Jaeco Pak I Simplex metering pump, 0-1 GPH, therefore had wetted parts of Hastelloy C and Teflon; the piping and valves were of polypropylene.

EXPERIMENTAL PROCEDURE - RUN NO. 1

Permeability Test - Run No. 1

During Run No. 1, permeability of the coal bed was measured before and after sodium hypochlorite treatment by passing compressed air through the bed at different pressures and flow rates. The pressure drop across the bed at various constant air flow rates was measured by installing two pressure gauges, one at the inlet and the other at the outlet of the bed. The air flow rates were measured by a wet test meter and timer. From the observed data on flow rates, pressure drops, and temperatures, the permeability of the bed was calculated using Darcy's equation

$$K = 2.2458 \times 10^{-6} \frac{Q \mu}{F \Delta P}, \quad K \text{ in Darcy's } \quad \begin{array}{l} \ell \text{ in ft} \\ Q \text{ in scfm} \quad F \text{ in ft}^2 \\ \mu \text{ in } \mu\text{P} \quad \Delta P \text{ in psi} \\ \text{(micropoise)} \end{array}$$

Sodium Hypochlorite Treatment - Run No. 1

The experiment was carried out continuously for 16 hours at a feed rate of about 1.0 gal/hr of 12.3 wt% sodium hypochlorite solution in water. The feed was introduced at the top of the bed. Figs. 1 and 2 show the feed location.

After 4-1/2 hours of operation, product liquid and gas appeared through the outlet. Samples of product liquid were taken at different times and were titrated to determine the concentration of unreacted sodium hypochlorite. Temperatures at all the thermocouple points were measured by a manually operated potentiometer at regular time intervals. After hypochlorite treatment, the coal bed was cooled down by pumping water through the reactor for about five hours. Temperatures were noted during the cooling period.

EXPERIMENTAL PROCEDURE - RUN NO. 2

Preparation of Test

Some modifications were made for the second test run:

(i) To reduce flow along the wall, two baffles were installed touching the inside wall of the reactor. Further reduction of wall flow was made by inserting the feed line 14.5 inches to the center of the bed. This also helped in obtaining uniform initial distribution of the feed.

(ii) A vacuum pump was connected with the outlet to give a higher driving force for liquid flow and to reduce flow along the wall.

(iii) A 24-point temperature recorder (Honeywell cl.15) was attached to the thermocouples. This made it possible to read the bed temperatures continuously.

(iv) Radial positions of the thermocouples were changed to cover maximum area of the bed so that the reaction front could be better observed from the temperature readings.

(v) Thermocouple wells which were previously fabricated from copper were replaced by thin stainless steel wells.

(vi) A high capacity gas flow meter was used for permeability tests. Permeability was measured both by air and water tests.

In the second run, the same operating conditions as in the first run were used, i.e., 1.0 gal/hr of 11-12% sodium hypochlorite solution for 16 hours.

Coal was packed in the reactor with its original size particles (powder to three inches); every effort was made to make the coal bed as compact as possible. Coal was loaded on the bed little by little and hit by hammer. After a thin layer had been loaded, water was poured on the bed and drained from the bottom

The two baffles previously mentioned (with depth 1-3/4 inches) were installed along the inner wall of the reactor. Each baffle was set midway between two sets of thermocouples (see Figure 2).

24 copper-constantan thermocouples in stainless steel protective tubes were used with the recorder to measure temperature. They were divided into three sets: No. 1 to No. 8 is the first set, No. 9 to No. 16 is the second set, No. 17 to No. 24 is the third set. Table 1 shows the depth of each thermocouple in the coal bed.

The flow scheme is the same as Run 1; the pump, pressure gauges, and feed tube were installed in the same places as before.

Permeability Test, Run No. 2

Permeability of the coal bed in this run was measured before and after sodium hypochlorite treatment by passing water through the bed at different flow rates. The pressure drop across the bed at each water flow rate was measured. The permeability of the bed was calculated by Darcy's equation:

Sodium Hypochlorite Treatment, Run No. 2

The experiment was carried out continuously for 17.5 hours at a feed rate of 1 gal/hr of 10.9 wt% sodium hypochlorite solution. Samples of product liquid were taken and were titrated to determine the concentration of unreacted sodium hypochlorite. The reaction was stopped when the temperature of No. 1 thermocouple (which showed the highest temperature during the reaction) began

decreasing continuously. After hypochlorite treatment, the coal bed was cooled down by pumping water through the reactor for 3.5 hours.

Temperatures of the coal bed during the reaction and cooling period were recorded continuously

EXPERIMENTAL PROCEDURE - RUN NO. 3

Preparation Test

The equipment and preparations for this experiment were essentially the same as those for the second run.

Sub-bituminous coal from Gillette, Wyoming, was packed into the high-pressure steel reactor as tightly as possible, using water and a hammer. Twenty-four copper-constantan thermocouples in stainless steel wells, distributed as shown in the original reactor drawing, Fig. 2, were connected to the Honeywell 24-point temperature recorder. The lengths of the thermocouples were reduced somewhat, however, as shown in the attached revision of the original drawing (Fig. 3).

However, the arrangement of the solution inlet and outlet, pump, tank, and connections were slightly different than before; the object was to have the solution traverse a longer path through the coal bed. The flow diagram is as shown in Fig. 1.

Sodium Hypochlorite Treatment of Coal

The experiment was divided into four periods of 15 hours each, designated as 3-1, 3-2, 3-3, and 3-4.

During the first three periods, 6.5% NaOCl in water was pumped through the reactor at a constant rate of 1 gal/hr. The thermocouple temperatures were recorded by the 24-point recorder. Samples of spent NaOCl solution were taken at the outlet every 2 hours and titrated for the OCl⁻ ion. Pressures were read from the indicating gauges and recorded on the data sheet.

During the fourth period, the procedure was the same, except that 11% NaOCl solution was used.

Permeability Test

Before the first period and after each period, the permeability of the coal was determined by water-flow and pressure-drop measurements. The permeability of the bed was calculated from the Darcy equation, as before.

RESULTS - RUN NO. 1

Temperature measured by each thermocouple was plotted against reaction time (Figs. 10 to 15). The initial bed temperature was 18°C (64.4°F). Thermocouple No. 2 showed the highest temperature of 96.5°C (205.7°F). In the first set of thermocouples, 3 and 7 showed a rapid rise of temperature initially. No. 3 stopped increasing after six hours and remained almost constant for three hours and then again started increasing continuously. Though 6 and 8 increased initially, the temperatures were not significant compared to 1, 2 and 3. Near the end of the experiment, the temperature of No. 2 started dropping at a low rate but 1 and 3 were still rising. Nos. 4 and 5 were rising at a high rate during the end of the test. From this observation of temperature profiles of the first set of thermocouples, it can be noted that sodium hypochlorite was trickling down through the coal bed and initially was distributed on both left and right sides of the feed point, but after several hours, sodium hypochlorite had created a pathway towards the right of the feed inlet. This is evident from the similarity of the temperature profiles of 7 and 8 and temperature rise of 1, 2 and 3.

Study of the temperature profiles shown by the second set of thermocouples (9 to 16) leads to a similar conclusion. Thermocouple 15 (same radial position as 7) showed a fast increase of temperature initially, but decreased continuously after about 4-1/2 hours. This temperature profile is similar to that of 7. Again, the very slow temperature increase of 16, and the similarity of temperature profiles between 6 and 14 indicated an insignificant flow of

sodium hypochlorite towards the left side of the feed position after a few hours of operation. The significant rise of temperature at locations 9, 10 and 12 confirm that the sodium hypochlorite pathway was opened up along the right side of the feed inlet towards the outlet. The temperature at location 12 was rising continuously, like that at 4. Again, there is a similarity of temperature profiles between 5 and 13; both of them were increasing continuously.

Thermocouples 17, 18, 19 and 20 (third set, right of feed point) showed very similar temperature profiles. Near the end of the experiment, the rate of temperature rise slowed down (note that 9 and 10 reached constant temperatures of approximately 83 and 88°C, respectively). This observation, and differences in the maximum temperatures attained by the three sets of thermocouples indicated that sodium hypochlorite solution was reacting near the outlet but that the rate of reaction was relatively low compared to upstream positions because of the decrease of concentration of the solution as it flowed through the bed. The temperature profiles of thermocouples 4, 5, 12, 13, 20 and 21 and their increasing rate of change of temperature suggested that the sodium hypochlorite solution was entering another pathway by trickling down towards the bottom wall and moving axially towards the outlet.

Visual observation of the coal after opening the reactor also indicated that the sodium hypochlorite had a pathway going along the right side of the feed point, and that there was considerable wall flow in that side. This pathway was observed by the oxidized coal layer which was yellow in color. Some of the particles from the layer were very fragile.

Seven samples of liquid were taken from the outlet stream. No unreacted sodium hypochlorite was found in any of the samples.

158.5 pounds of sodium hypochlorite solution was pumped into the reactor during 16 hours. During the reaction period, a total of 106.5 pounds of product liquid was collected. Another 19.5 pounds of liquid came out during air blowing through the reactor bed. Thus, by difference, 32.5 pounds of liquid

was adsorbed in the coal bed.

The gas flow meter recorded 14.6 actual cu. ft. of gas during the 16 hours of the experiment.

Fig. 7 shows the permeability of the coal bed before and after the sodium hypochlorite treatment. The pressure drop across the coal bed was plotted against permeability obtained from Darcy's equation. The dependence of pressure drop on air flow rate, and their non-linear relationship in a packed bed are shown in Fig. 4. Though the bed was not tight enough to see greater increase in permeability, the result obtained from this experiment was significant.

RESULTS - RUN NO. 2

Temperature measured by each thermocouple was plotted against reaction time (Figs. 16 to 23). The initial bed temperature was 74°F. Thermocouple No. 1 showed the highest temperature of 207.5°F.

Visual observation of the coal bed after opening the reactor showed that around the inlet there was a round reacted area where the color of coal changed to orange. This indicating the direction of flow of the NaOCl solution.

Thermocouples No. 1 and 3 (which were closest to the inlet) showed a rapid rise of temperature during the first eight hours and remained almost constant (in a 10 degree range) in the remaining period. The temperature profile of No. 6 was higher than No. 5. The temperature profile of No. 4 was similar to that of No. 5; they were about the same distance from the inlet. Thermocouples No. 1 and 8 had similar temperature profiles, also. Study of the temperature of the first set of thermocouples showed that the flow pathway passed axially along the center.

Study of the temperature shown by the second set of thermocouples (9 to 16) leads to the conclusion that the flow path move axially and slightly toward the bottom and slightly to the left. Thermocouple No. 13 (at bottom) showed the highest temperature profile of those far from the inlet. Thermocouple No. 16

which is at the upper position and far from the inlet, had the lowest temperature profile. Nos. 10 and 11 (at left) are higher than No. 15 and No. 16; no significant wall flow has been observed. The similar temperature profiles of Nos. 10 and 11 showed that flow had by-passed the upper left side.

The study of the third set of thermocouples (17 to 25) leads to the same conclusion as the study of the second set of thermocouples. The temperature of No. 21 (bottom) increased rapidly. The temperature of No. 20 is higher than that of 23. No. 19 (at middle-left) and No. 22 (at lower-right) had similar temperature profiles.

The temperature change can be divided into two different periods. In the first 10 hours, the temperatures of the first set and second set increased rapidly; the third set changed slightly. After that, the temperature increase rate of the first and second sets slowed down, and the third set showed increasing temperature. It is evident that after several hours of reaction, a steady flow pathway had been created.

Near the end of the experiment, the temperature of No. 1 decreased continuously. Examination of the coal sample around No. 1 showed that each particle was covered with an oxidized layer of about the same thickness, which implied that the coal was protected from further oxidation. This, in turn, indicated that some of the NaOCl_2 remained available to act farther along the path.

208 pounds of sodium hypochlorite solution was pumped into the reactor. After the run, 161 pounds of cooling water was pumped through the reactor. A total of 264 pounds of outlet liquid was collected - 138 pounds during NaOCl_2 feed, 126 pounds during H_2O feed.

The gas flow meter recorded 13.4 actual cu. ft. of gas during the 17.5 hours of experiment. Seven samples of outlet fluid during the reaction were titrated; no unreacted sodium hypochlorite was found.

The permeability before and after the treatment of sodium hypochlorite solution is shown in Fig. 8. The result obtained from this experiment is significant. Pressure loss vs. water flow rate is shown in Fig. 5.

RESULTS - RUN NO. 3

Permeability Increase

This third run was made primarily to determine the effectiveness of 6.5 wt%NaOC₂ in increasing the permeability of the coal.

Compared to 11 wt%NaOC₂, this lower concentration proved to be much less effective. Also, the initial permeability of the coal was actually reduced during the first 15 hours of treatment. The two subsequent periods of treatment with 6.5 wt%NaOC₂ increased the permeability somewhat, but the initial permeability was never regained using this dilute solution.

Only when we went back to an 11 wt%NaOC₂ solution during the fourth 15-hour treatment did we see an increase over the initial values.

All of these permeability tests are grouped together in Fig. 9. Pressure loss vs. water flow rate is shown in Fig. 6.

Temperature Increase

The temperature-time profiles obtained in the 24-point recorder, when using 6.5 wt%NaOC₂, were similar to those reported for Run No. 2. The maximum value attained, however, (near the inlet) was only 144°F, on thermocouples Nos. 1 or 3.

When using 11.0 wt%NaOC₂, the maximum temperature attained on thermocoupled No. 1 went up to 211°F.

Composition

When using 6.5 wt%NaOC₂, the titration of spent liquid, sampled at the outlet every two hours, showed consistently a zero concentration of OC₂⁻ion.

Samples taken during the 11.0 wt%NaOC₂ test (last 15 hours of Run No. 3) showed zero concentration of OC₂⁻ also.

Material Balance - Run No. 3

Weight of coal loss in reaction

Weight of coal packed in reactor 586 lbs.

Estimated coal loss by water spray during packing - 15 lbs.

Estimated coal loss during packing - 5 lbs.

Weight of coal packed in reactor 586 - 15 - 5 = 566 lbs.

Weight of coal after reaction

Weight of coal after reaction 493 lbs.

Estimated loss during permeability test
(Five permeability tests, 4 lbs. each, 5x4 = 2) + 20 lbs.

Estimated loss during open reactor + 5 lbs.

Weight of coal 493 + 20 + 5 = 518 lbs.

Weight of coal reacted in reaction 566 - 518 = 48 lbs.

$$\frac{48}{566} \times 100\% = 8.48\%$$

Run No. 3

Maximum Temperature During Reaction

	<u>Max. Temp.</u>	<u>Thermocouple No.</u>
1st test (3-1)	144°F	3
2nd test (3-2)	92°F	4,5
3rd test (3-3)	138°F	5
4th test (3-4)	211°F	1

The following figures are the curve of temperature of first layer thermocouples of those four tests.

Figures 24 and 25 belong to Run 3-1.

Figures 26 and 27 belong to Run 3-2.

Figure 28 belongs to Run 3-3.

Figures 29, 30 and 31 belong to Run 3-4.

Run No. 3

Outlet Liquid Temperature Variation

	Initial Temp.(°C)	Final Temp.(°C)	Increase (°C)
1st test	18	25	7
2nd test	20	24	4
3rd test	23	26	3
4th test	25.5	30	4.5

Average 4.875°C = 8.775°F

Gas Collected from Outlet

1st test	6.056 ft ³
2nd test	4.5 ft ³
3rd test	8.0 ft ³
4th test	30.4 ft ³

Run No. 3

Titration of Samples Taken from Outlet

Time of Sample Taken

First Test

6/2/81	20:00
6/2/81	21:45
6/2/81	23:45
6/3/81	2:00
6/3/81	4:00
6/3/81	6:00
6/3/81	7:00

Time of Sample Taken

Second Test

6/3/81	18:00
6/3/81	20:15
6/3/81	22:00
6/4/81	0:00
6/4/81	2:00
6/4/81	4:00
6/4/81	6:00

Time of Sample Taken

Third Test

6/4/81	23:30
6/5/81	1:30
6/5/81	3:30
6/5/81	5:30
6/5/81	7:30
6/5/81	9:30
6/5/81	11:30

Time of Sample Taken

Fourth Test

6/10/81	10:30
6/10/81	11:30
6/10/81	13:30
6/10/81	15:30
6/10/81	17:30
6/10/81	19:30
6/10/81	22:00
6/10/81	23:30

Result

No color change was observed when titrating these samples, even when using starch indicator. This shows that the concentration of $(OCl)^-$ ion in the outlet samples was consistently zero or negligible.

The reactions are:

DISCUSSION OF RESULTS

The work described in this report has demonstrated that sodium hypochlorite solutions can be used to increase the permeability of sub-bituminous coal beds. This, in turn, should make it possible to increase the initial air or oxygen flow rate and the initial rate of reaction in the partial combustion and gasification of underground coal deposits.

Overall permeability increases were obtained by pumping room-temperature sodium hypochlorite solution at 1 GPH through sub-bituminous coal packed into a cylindrical steel pressure vessel 23" long x 29" I.D. The results of the 3 runs made may be summarized as follows:

Run No.	NaOCl conc. in H ₂ O, wt%	Time of Treatment (hours)	% Increase in Permeability Compared to Original Value
1	12.3	16	+6% to +13%
2	10.9	17.5	+440% to +585%
3-1	6.5	15	-74 to -57%
3-2	6.5	15	-44%
3-3	6.5	15	-28 to -34%
3-4	11.0	15	+15 to +14%

The great difference in results between Runs No. 1 and No. 2 can be explained by the possibility that in Run No. 1 some of the solution bypassed the coal bed and flowed along the walls. In Run No. 2, baffles were installed to prevent this; also, the feed pipe was placed in a more central location.

The decrease in permeability in Runs No. 3-1, 3-3 and 3-3, as compared to the original value, was obviously due to the use of 6.5% NaOCl solution instead of 11 to 12%. This indicates that solutions even stronger than 11 to 12% ought to be used.

The observed decrease with weak solutions indicates that these solutions cause swelling, which plugs the coal bed.

The more concentrated solution tended to dissolve the coal rapidly enough to prevent the swelling process from occurring.

Visual observation of the coal suggests that the above premise is correct. The coal that has been partially oxidized seems to have vertical cracks in its structure. In future experiments, the NaOCl solution must be made stronger (at least 11%) or the flow rate must be made faster.

The varying time-temperature profiles of the 24 thermocouples have been discussed in detail in the section entitled "Results"; that discussion is lengthy, and will not be repeated here.

It is evident, however, that the maximum reaction path, i.e. the path of least resistance, is indicated by the maximum temperature rise.

CONCLUSIONS AND RECOMMENDATIONS

The work described in this report has shown that sodium hypochlorite is a feasible reagent for increasing the permeability of coal deposits, which in turn may make possible economical underground gasification of coal.

Oil well drilling technology, which at present is very highly developed, can be made available to the coal industry. By this means, the energy content, as well as the carbon and hydrogen content of the coal can be brought to the surface without the necessity of actually mining the coal.

Further pilot-scale work is needed to make possible the prediction of the path of underground gasification. The proposed method consists of drilling small-pilot wells from various points on the surface into the coal deposit and measuring the initial permeability of the deposit from each well to all other wells. The path of minimum resistance can then be computed by means of a program already developed.

A proposal has been submitted to do this type of work on the pilot-scale in the laboratory. Field trials should be made after the results of the computer study become available.

LIST OF FIGURES

Apparatus

- Fig. 1 - Flow Diagram of Apparatus
- Fig. 2 - Diagram of reactor, showing positions of thermocouples, and lengths of thermocouples for Run No. 1
- Fig. 3 - Lengths of thermocouples, Runs No. 2 and 3.

Pressure Loss vs. Flow Rate

- Fig. 4 - Pressure loss vs. air flow rate, before and after Run No. 1
- Fig. 5 - Pressure loss vs. water flow rate, before and after Run No. 2
- Fig. 6 - Pressure loss vs. water flow rate, before and after Run No. 3

Permeability

- Fig. 7 - Permeability vs. flow rate, before and after Run No. 1
- Fig. 8 - Permeability vs. flow rate, before and after Run No. 2
- Fig. 9 - Permeability vs. flow rate, before Run 3 and after Runs 3-1, 3-2, 3-3 and 3-4

Temperature vs. Time Graphs

- Fig. 10 - Run No. 1, Thermocouples 1, 2, 3 and 4
- Fig. 11 - Run No. 1, Thermocouples 5, 6, 7 and 8
- Fig. 12 - Run No. 1, Thermocouples 9, 10, 11 and 12
- Fig. 13 - Run No. 1, Thermocouples 13, 14, 15 and 16
- Fig. 14 - Run No. 1, Thermocouples 17, 18 and 19
- Fig. 15 - Run No. 1, Thermocouples 20, 21 and 23
- Fig. 16 - Run No. 2, Thermocouples 1, 2, 3 and 4
- Fig. 17 - Run No. 2, Thermocouples 5, 6, 7 and 8
- Fig. 18 - Run No. 2, Thermocouples 9, 10, 11 and 12
- Fig. 19 - Run No. 2, Thermocouples 13, 14, 15 and 16
- Fig. 20 - Run No. 2, Thermocouples 17 and 18

- Fig. 21 - Run No. 2, Thermocouples 19 and 20
- Fig. 22 - Run No. 2, Thermocouples 21 and 22
- Fig. 23 - Run No. 2, Thermocouples 23 and 24
- Fig. 24 - Run No. 3-1, Thermocouples 1, 2, 3 and 4
- Fig. 25 - Run No. 3-1, Thermocouples 5, 6, 7 and 8
- Fig. 26 - Run No. 3-2, Thermocouples 1, 2, 3 and 4
- Fig. 27 - Run No. 3-2, Thermocouples 5, 6, 7 and 8
- Fig. 28 - Run No. 3-3, Thermocouples 1, 2, 3 and 4
- Fig. 29 - Run No. 3-4, Thermocouples 1, 2, 3 and 4
- Fig. 30 - Run 3-4, Thermocouples 5, 6, 7 and 8
- Fig. 31 - Run 3-4, Thermocouples 9, 10, 11 and 12

FIG. 1

FIGURE 2

COAL FRACTURE ENHANCEMENT PROJECT
DIAGRAM SHOWS POSITION OF THERMOCOUPLES
IN COAL BED

ALL DIMENSIONS ARE IN INCHES

LENGTH OF THERMOCOUPLES
(FROM INSIDE WALL OF REACTOR TO TIP
OF THERMOCOUPLE)
FROM FIG. 1

THERMOCOUPLE NOS	LENGTH (INCHES)
1, 9, 17	14.00
2, 10, 18	11.75
3, 11, 19	9.75
4, 12, 20	7.75
5, 13, 21	6.75
6, 14, 22	5.75
7, 15, 23	4.88
8, 16, 24	3.66

Figure 3

Lengths of Thermocouples (Inches)

For Runs 2 and 3

No. Depth (inch)	Length
1	14 1/4
2	6 1/4
3	8 1/2
4	4
5	4 1/4
6	8 1/4
7	6 3/4
8	6 1/2
9	10 1/4
10	6 1/2
11	5 1/4
12	3 1/2
13	3 1/2
14	5
15	6 1/2
16	6 1/2
17	12 1/2
18	7 3/4
19	6 1/4
20	8 1/2
21	4 1/2
22	6 1/4
23	8 3/4
24	7 1/2

FIG. 4 Permeability Tests

FIG. 5

Permeability Tests

Second Run

Water Flow Rate vs. Pressure Drop

FIG. 6

Permeability Tests

Third Run

Water Flow Rate vs Pressure Drop

Straight line indicates laminar flow

PERMEABILITY RESULTS - RUN No. 1

COAL PROJECT

FIG 7.

INCREASING PERMEABILITY BY
SODIUM-HYPOCHLORITE SOLUTION

PERMEABILITY VS. ΔP

RUTGERS UNIVERSITY
The State University of New Jersey
Department of Chemical and
Biochemical Engineering
New Brunswick, New Jersey 08903

O: PERMEABILITY AFTER
SODIUM-HYPOCHLORITE TREATMENT

Δ : PERMEABILITY BEFORE
HYPOCHLORITE TREATMENT

DIA OF COAL BED: 29.25 INCHES

LENGTH OF BED: 20.25 INCHES

PERMEABILITY RESULTS - RUN NO. 2

FIG. 8

PERMEABILITY RESULTS-RUNS 3-1, 3-2, 3-3, 3-4

Figure 9

PERMEABILITY DETERMINATION

AFTER EACH TEST

RUTGERS UNIVERSITY
The State University of New Jersey
Department of Chemical and
Biochemical Engineering
P. O. Box 209
Piscataway, N.J. 08854

TEMPERATURE - TIME RESULTS - RUN No. 1

COAL TEMPERATURE

FIG. 10

THERMOCOUPLE NOS.

INCREASING PERMEABILITY BY SODIUM-HYPOCHLORITE SOLUTION
REACTION TIME VS TEMP. OF COAL BED

RUTGERS UNIVERSITY
The State University of New Jersey
Department of Chemical and
Biochemical Engineering
New Brunswick, New Jersey 08903

33

○
△
□
▽

1
2
3
4

RUN No. 1

TEMPERATURE - TIME RESULTS - RUN. No. 1

COAL PROJECT

FIG. 11

THERMOCOUPLE NOS.

INCREASING PERMEABILITY BY SODIUM-HYPOCHLORITE SOLUTION

REACTION TIME VS TEMP. OF COAL BED

△	5
○	6
▽	7
□	8

RUTGERS UNIVERSITY

The State University of New Jersey

Department of Chemical and

Biochemical Engineering

New Brunswick, New Jersey 08903

RUN No. 1

TEMPERATURE - TIME RESULTS — RUN No. 1

COAL PROJECT

FIG. 12

THERMOCOUPLE NOS

INCREASING PERMEABILITY BY SODIUM-HYPOCHLORITE SOLUTION
REACTION TIME VS. TEMP. OF COAL SED

△ 9
○ 10
▽ 11
□ 12

RUTGERS UNIVERSITY
The State University of New Jersey
Department of Chemical and
Biochemical Engineering
New Brunswick, New Jersey 08903

RUN No. 1

TEMPERATURE - TIME RESULTS - Run No. 1

COAL PROJECT

Fig 13

THERMOCOUPLE NOS

INCREASING PERMEABILITY BY SODIUM HYPOCHLORITE SOLUTION

REACTION TIME VS TEMP OF COAL BED

▲ 13
 ○ 14
 ▼ 15
 □ 16

RUTGERS UNIVERSITY

The State University of New Jersey

Department of Chemical and
Biochemical Engineering

New Brunswick, New Jersey 08902

Run No. 1

TEMPERATURE - TIME RESULTS - RUN No. 1

LOCAL PROJECT

Fig 14

THERMOCOUPLE NOS.

INCREASING PERMEABILITY BY SODIUM HYPOCHLORITE

Δ

17

REACTION TIME VS TEMP. OF COAL BED

○

18

□

19

RUTGERS UNIVERSITY
The State University of New Jersey
Department of Chemical and
Biochemical Engineering
New Brunswick, New Jersey 08903

RUN No. 1

TEMPERATURE - TIME RESULTS - RUN No.1

COAL PROJECT

FIG 15

THERMOCOUPLE NOS.

INCREASING PERMEABILITY BY SODIUM-HYPOCHLORITE SOLUTION

Δ

20

REACTION TIME VS TEMP OF COAL BED

○

21

□

25

RUTGERS UNIVERSITY

The State University of New Jersey

Department of Chemical and

Biochemical Engineering

New Brunswick, New Jersey 08903

RUN No.1

TEMPERATURE RESULTS - RUN No. 2

Figure 16

TEMPERATURE RESULTS, - RUN NO. 2

Figure 17

TEMPERATURE RESULTS - RUN No.2

Figure 18

TEMPERATURE RESULTS - RUN NO. 2

Figure 19

TEMPERATURE RESULTS - RUN NO. 2

Figure 20

TEMPERATURE RESULTS - RUN No. 2

Figure 21

TEMPERATURE RESULTS - RUN NO. 2

Figure 22

TEMPERATURE RESULTS - RUN NO. 2

Figure 23

TEMPERATURE RESULTS - RUN 3-1

Figure 24

RUN 3-1

TEMPERATURE RESULTS - RUN 3-1

Figure 25

TEMPERATURE RESULTS - RUN 3-2

Figure 26

RUN 3-2

TEMPERATURE RESULTS - RUN 3-2

Figure 27

TEMPERATURE RESULTS - RUN 3-3

Figure 28

TEMPERATURE RESULTS - RUN 3-4

Figure 29

TEMPERATURE RESULTS - RUN 3-4

Figure 30

TEMPERATURE RESULTS - RUN 3-4

Figure 81