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PRELIMINARY RESULTS

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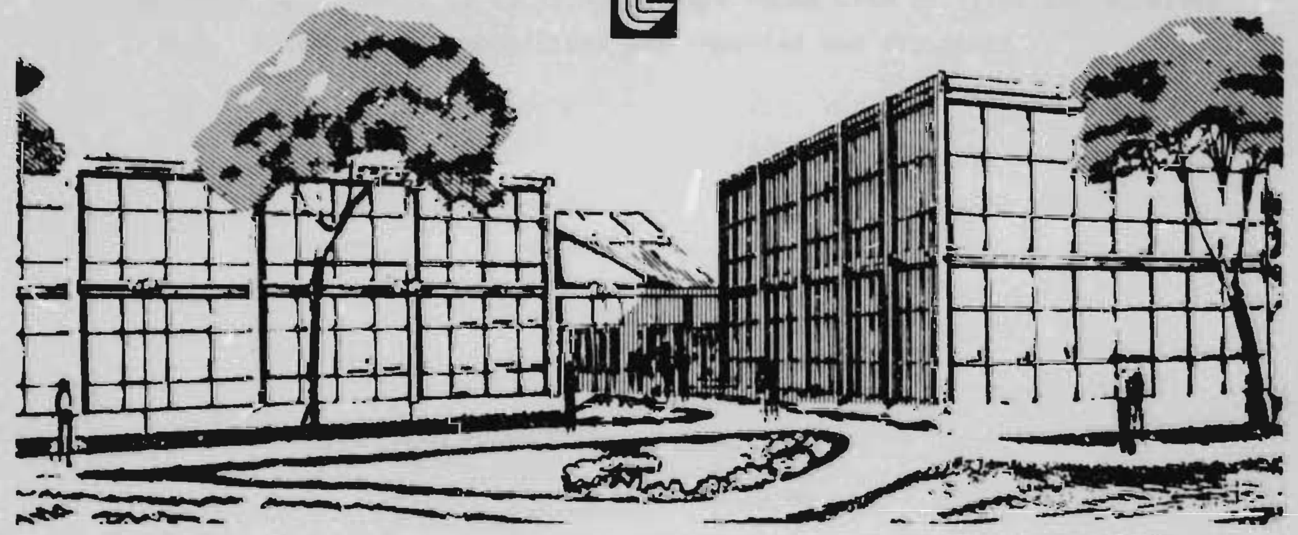

REVERSE COMBUSTION ALONG A BOREHOLE IN A SHRINKING COAL, PRELIMINARY RESULTS

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ABSTRACT

Reverse combustion along a bored hole (76 mm diameter) will be used during Lawrence Livermore Laboratory's next field experiment in underground coal gasification: Hoe Creek III. The enlarged channel produced by the reverse combustion will allow high gas velocities for the forward combustion phase of gasification.

In the present experiments, reverse combustion along smaller boreholes (6.35 and 12.7 mm diameter) was investigated in coal blocks which were 0.5 m in diameter and 0.9 m long. In these experiments reverse combustion did not propagate with air as the feed gas. Three air velocities (14, 27, and 32 m/s) were tried in the 6.35 mm borehole and two velocities (7.5 and 21 m/s) were tried in the 12.7 mm borehole. All experiments were conducted at atmospheric pressure.

Reverse combustion did propagate when the feed gas oxygen content was increased to 32%. Rates up to 14 m/day were found with an inlet gas velocity of 27 m/s. Product gas compositions are reported and discussed.

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The next field experiment on in situ coal gasification to be conducted by Lawrence Livermore Laboratory (Hoe Creek III) will use the linked vertical well method with the link provided by a horizontal drilled hole - 7.6 cm (3 in.) in diameter.[1] This hole has been drilled successfully. The drill rig was inclined to about 30° to the surface and the borehole was deviated (or bent) as it was drilled so that it became horizontal in the area of interest. The minimum radius which could be attained with this technique was 350 m (1150 ft). The small, relatively inexpensive drilled hole will be enlarged by use of a reverse combustion* process, so that a high gas flow can be used with a moderate pressure drop.

Use of a reverse combustion process along the hole has two other benefits. The hole is preheated so that when the gasification products flow through the hole, condensation and plugging of the hole with tars and water is less likely. If the coal being gasified were bituminous, a second advantage would be that the tendency for the hole to swell shut would be reduced. In a reverse combustion process, as the bituminous coal swells in the combustion zone, the coal is burned away. This reduces the tendency of the hole to swell shut compared to forward combustion.

One primary question required an answer in order to design the Hoe Creek III experiment: At what rate should we flow the air? Or to state the same question more elaborately: What is the effect of air flow on the progression rate of the burn front and on the final diameter of the hole? The present experiment was designed to answer these questions.

To a great extent the final diameter is inversely proportional to the progression rate. The burned gas has a relatively constant "carbon carrying capacity".

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*"Reverse" and "forward" combustion are the two possible processes that can occur when an oxidizer flows through a permeable solid fuel. "Reverse" combustion occurs when the combustion fronts move upstream against the flow of oxidizer.

This "capacity" depends primarily on the temperature of the burn zone because of the effect on the $CO-CO_2$ ratio. At higher temperatures, CO/CO_2 increases and more carbon can be carried per oxygen atom in the stream. Since the reverse burn temperature is relatively constant, a given amount of O_2 can remove a given amount of coal, and the faster the burn progresses at a given air flow rate, the narrower the burn will be. Such a relationship can be seen in Figure 1 which was derived from data reported by Capp, et al.(2) for reverse combustion through hydrofractured bituminous coal.

Reverse combustion in bored holes (and cracks or crevices) has been investigated previously but these reports do not contain all of the information desired. A general idea of the effects of the parameters can be obtained from Russian experiments with "brown" coal and wood. The effects of O_2 concentration in the feed gas,(3) water content of the coal,(4) width of the channel,(5) and velocity of the feed gas in the channel,(5) are shown in Figures 2-5. These data indicate that higher O_2 concentration in the feed gas and lower H_2O concentration in the coal both will increase the rate of burn progression up the bore hole, while channel width above 10 mm and feed gas velocity above 3-5 m/s have little effect on the progression rate. There is considerable scatter in these data and caution should be used in interpretation.

Experimentation

Blocks of coal were collected at the Wyodak Mine near Gillette, Wyoming; trimmed to fit in 55 gallon drums; and shipped to the laboratory under water. Provisions were made to prevent freezing of the coal blocks. This Roland seam coal is 32.9% water and 6.2% ash with a pseudo-molecule of $CH_{0.95}O_{0.19}N_{0.014}S_{0.004} \cdot 0.489H_2O$ which has a dry, ash-free molecular weight of 16.3 (26.8 with the ash and water). The density is 1.35. These blocks were approximately 0.6 m in diameter and 0.9 m long.

The disposable reactors for this experiment were constructed starting with 55 gallon drums to which the various fittings were brazed (Figure 6). A set of sixteen thermocouples monitored the temperatures inside the barrel as shown. A special insulated lid was constructed which holds the ignitor coil and an O_2

lance. The O_2 lance is used to aid ignition. The coal blocks were potted into the reactor with a plaster mixture to provide a pneumatic seal. A borehole was drilled down the center of each block and an ignition cavity was counterbored into the coal block. The ignition coil, formed from a length of heater rod, fitted into the ignition cavity as shown in Figure 6. A later modification to this design, not shown in the figure, provided a fused silica window for observation of the combustion processes.

These reactors were cut apart with a circular saw after each experiment. After a preliminary examination, the coal blocks were cut into segments with a chainsaw.

The LLL Laboratory Coal Gasifier Facility metered the gas flows and recorded the temperatures as described in detail by Reference 6. In this Facility an HP 21 MX-E computer monitors the experiment. Data is processed in real time and results are displayed to aid in controlling the experiment.

RESULTS

Five runs were made atte..pting to attain steady progress of reverse combustion up the borehole toward the air inlet. This effort was not successful. Three air velocities (13, 27 and 32 m/s) were tried in the 6.35 mm (0.25 in.) borehole and two velocities (21 and 7.5 m/s) in the 12.7 mm (0.5 in.) borehole. In none of these runs was there a discernible progression up the non-pretreated borehole.

The ignition in each case was very powerful. Initial ignition was via a coil of heater rod, then O_2 was injected into the ignition cavity (not down the borehole). This O_2 burned with the coal around the ignition cavity. The resulting high-temperature combustion provided highly favorable conditions for the initiation of the reverse combustion. It was planned that the O_2 would be turned off after the reverse combustion front was well under way. However, the reverse combustion never propagated away from the ignition region.

Reverse combustion would propagate up the borehole when O_2 enriched air flowed down the borehole. In several runs O_2 was added to the inlet air after it had been established that air alone would not promote the reverse combustion. In each case, the reverse combustion would progress up the borehole with O_2

enriched air. In the last experiment which has been performed, the combustion limit was established. Reverse combustion did progress up the borehole when the oxygen concentration was 32% vol%, but not when it was 30 vol %. This experiment will be discussed below.

During the experiments, it was observed that the combustion did not tend to extinguish on air. Wherever the coal face had been ignited it continued to burn. It just did not propagate up the borehole. Combustion continued while the burned out cavity increased in size. In one experiment, O_2 was added to the air until the reverse combustion was observed propagating up the borehole. After the reverse combustion up the borehole was well established, the O_2 was shut off. Although the combustion continued to widen the burning cavity, progress up the borehole stopped.

Another observation was that reverse combustion would progress on air if the borehole had been pretreated. In the first experiment, the ignitor burned out early in the experiment. Since it appeared that the combustion was going out, O_2 was added to the inlet air. It was intended that the added O_2 would promote ignition and that we would shut it off when ignition had been achieved. Instead, a reverse combustion propagated up the borehole supported by the enriched air. After this combustion was detected, the air and O_2 were shut off and CO_2 was flowed down the borehole to put out the combustion in the borehole. Care was taken not to cool the ignition cavity excessively, and when air was reintroduced reignition was achieved. After reignition, the reverse burn proceeded up the borehole. This borehole had of course been preheated and charred slightly.

The last experiment which has been performed was a satisfactory determination of the oxygen concentration required to support reverse combustion in a borehole. The borehole was 6.4 mm (.25 in.) in diameter and 35 mmol/s of air-oxygen mixture flowed down the hole giving a velocity of 27 m/s and a Reynolds number of 11,000. The reactor was open to the atmosphere at the outlet. Ignition was via a coil of heater rod with no oxygen injection into the ignition cavity.

The initial oxygen concentration in the inlet gas was 30 vol %. The ignition was slow but satisfactory and a dull glow could be observed on the surface of coal in the ignition cavity. The experiment was continued in this mode for 2.2 hr. No significant progress of the burn up the borehole was noted and the exhaust oxygen concentration was about 26 vol %. The oxygen concentration in the inlet gas was then increased to 32 vol % at the same total molar flow rate. The burn zone became brighter, the temperature in the ignition cavity gradually increased, and the exhaust oxygen concentration gradually approached zero (Figure 7).

At this slightly higher oxygen concentration, the reverse combustion was successful. The burn progressed up the borehole as can be seen in Figure 8. The rate of progression of this reverse combustion was not yet steady at the end of the experiment. Between the successive thermocouples shown in Figure 8 the rate was 2.8, 2.1, 5.6, and 14.3 m/day. These rates are considerably below those reported by Kreinin and Reva[7] of 40 m/day for air supported reverse combustion in a borehole underground. The current results may not represent steady state rates and there are a number of differences in the gasification conditions: lower pressure (1 atm vs 3 atm), higher water content of the coal, and a much smaller borehole (6.4 mm vs 152 mm). Each of these differences seem likely to result in a less vigorous reverse combustion in the present case, but the scaling laws remain to be determined.

DISCUSSION

Although reverse combustion could not be attained with air, only moderate amounts of O_2 enrichment were able to promote reverse combustion. Thus air must be rather close to being able to support reverse combustion under the conditions of the experiments. It is known that in situ reverse combustion proceeds more rapidly at higher pressures. Since the Hoe Creek III experiment will be conducted with the pressure approximately 350 kPa (50 psia), combustion may progress very well on air. A new reactor is being prepared to explore this possibility.

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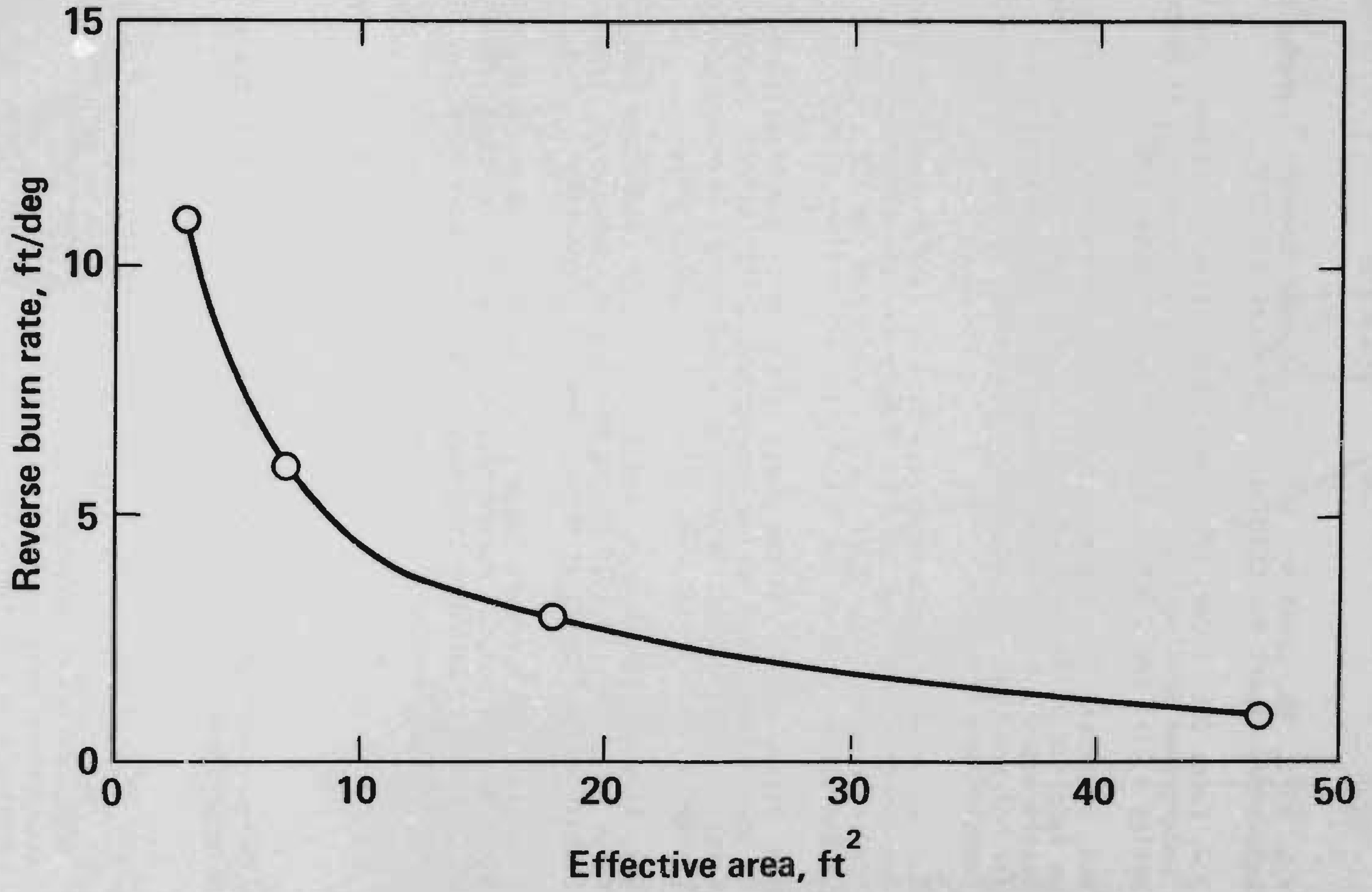


Figure 1. The relationship between the reverse burn rate and the resulting effective area for flow in hydrofractured coal seams.

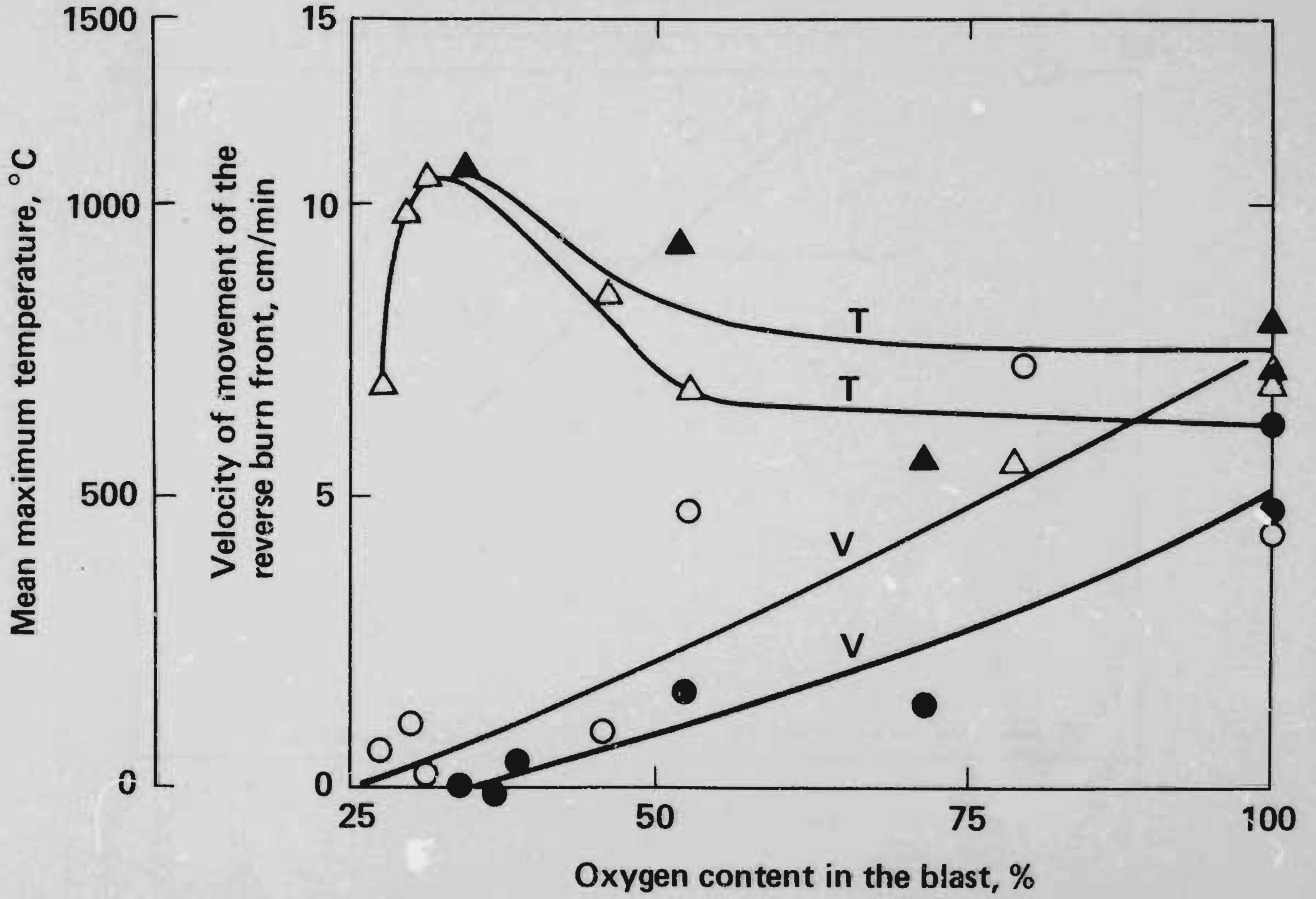


Figure 2. Reverse burn velocity vs the oxygen content of the feed gases.

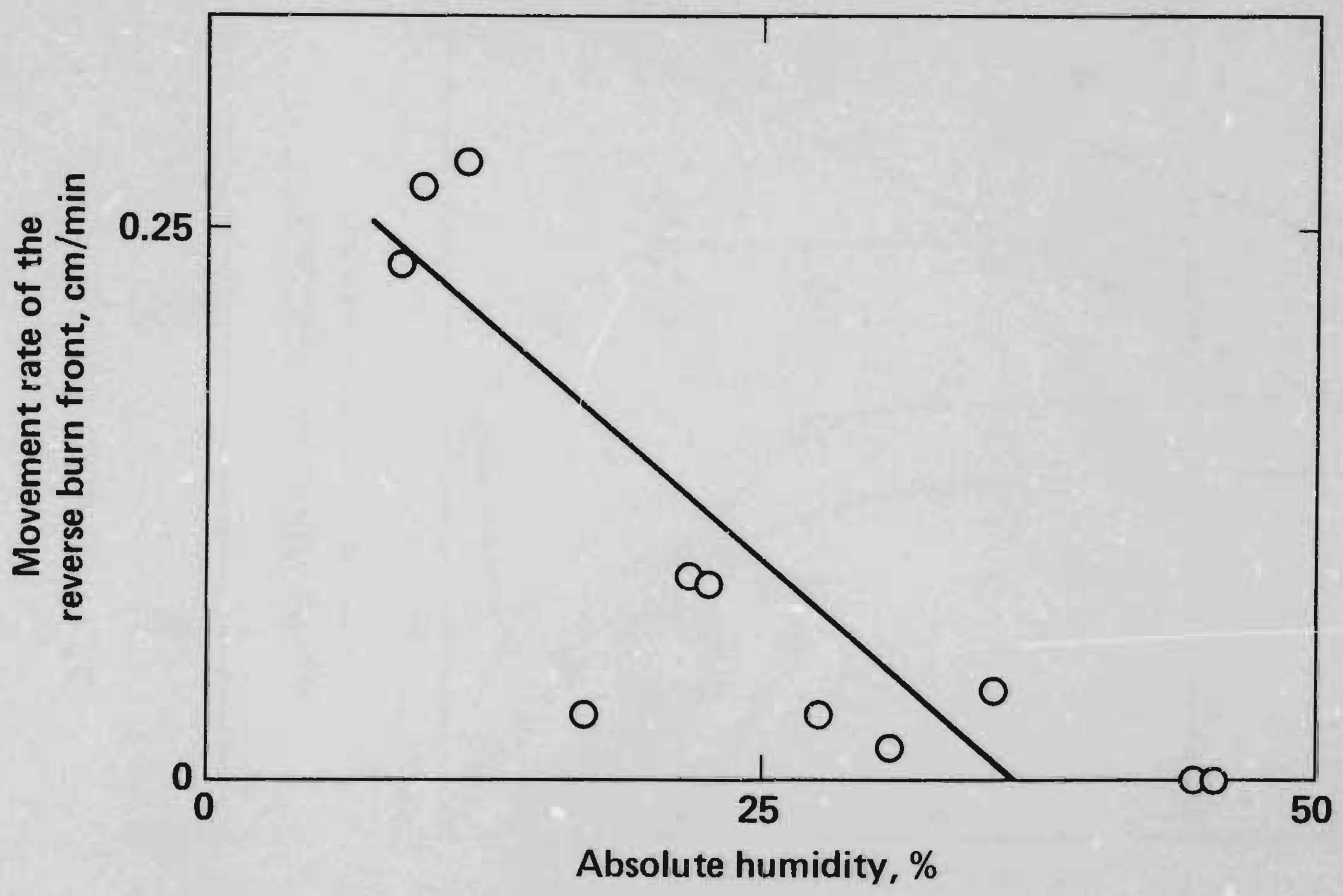


Figure 3. Reverse burn velocity vs the water content of the coal.

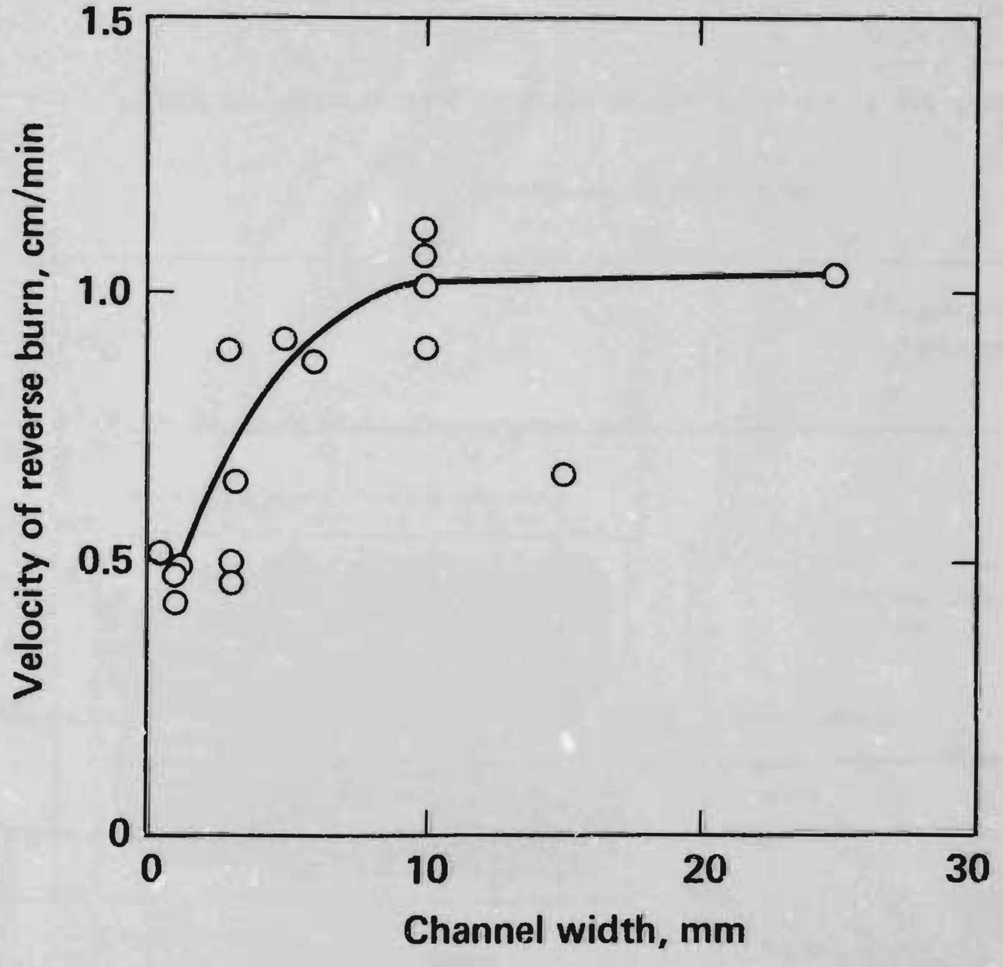


Figure 4. Reverse burn velocity vs the channel width.

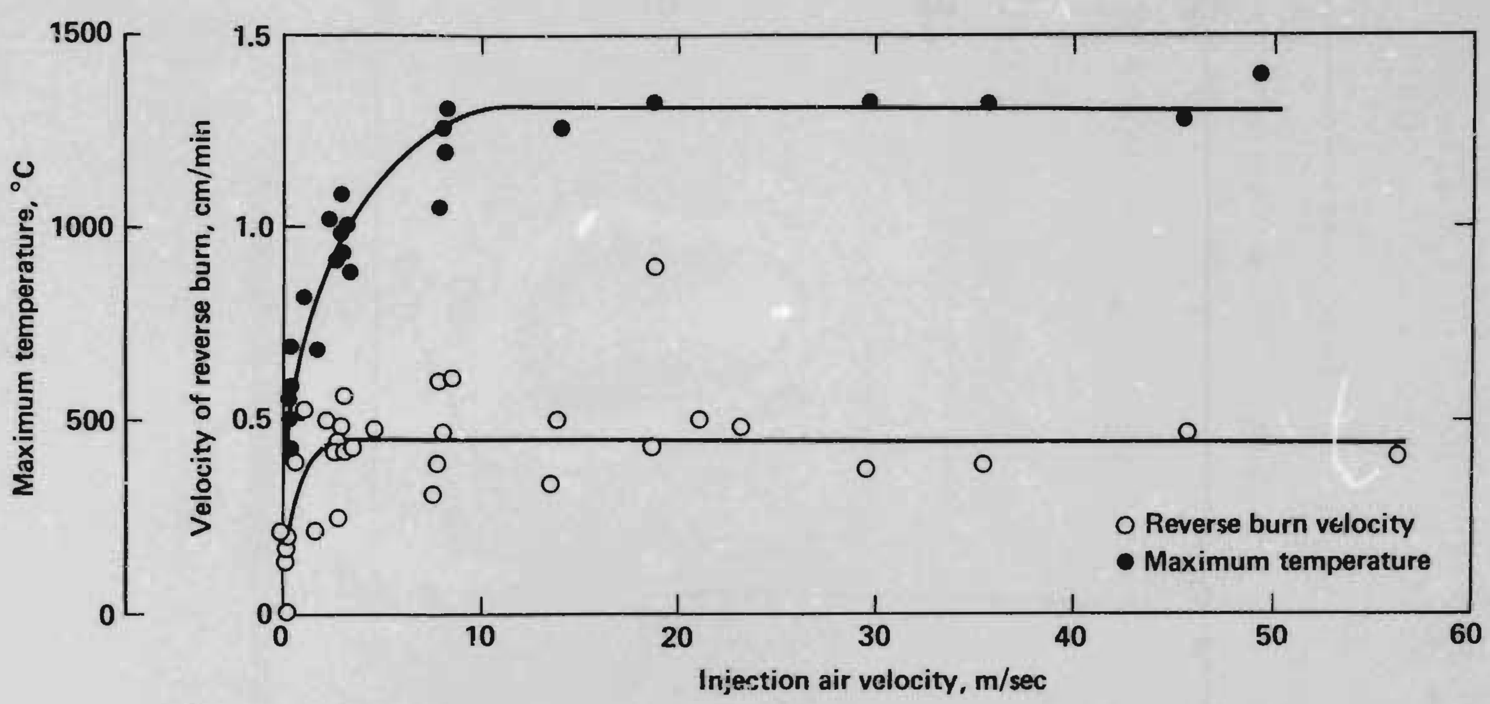
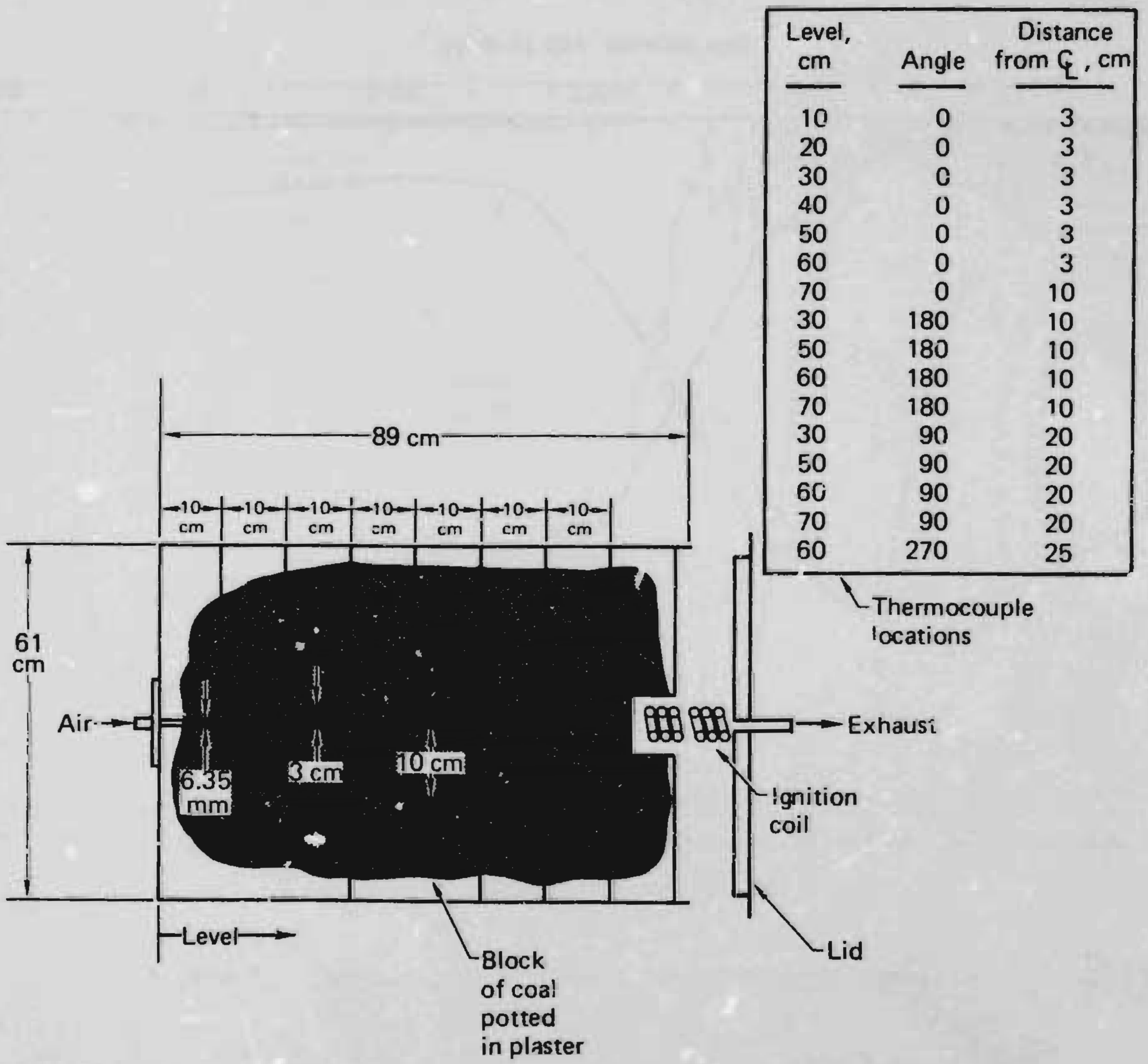


Figure 5. Reverse burn velocity vs the velocity of the feed gases.



Level, cm	Angle	Distance from C_L, cm
10	0	3
20	0	3
30	0	3
40	0	3
50	0	3
60	0	3
70	0	10
30	180	10
50	180	10
60	180	10
70	180	10
30	90	20
50	90	20
60	90	20
70	90	20
60	270	25

Figure 6. Reactor for reverse combustion in a borehole.

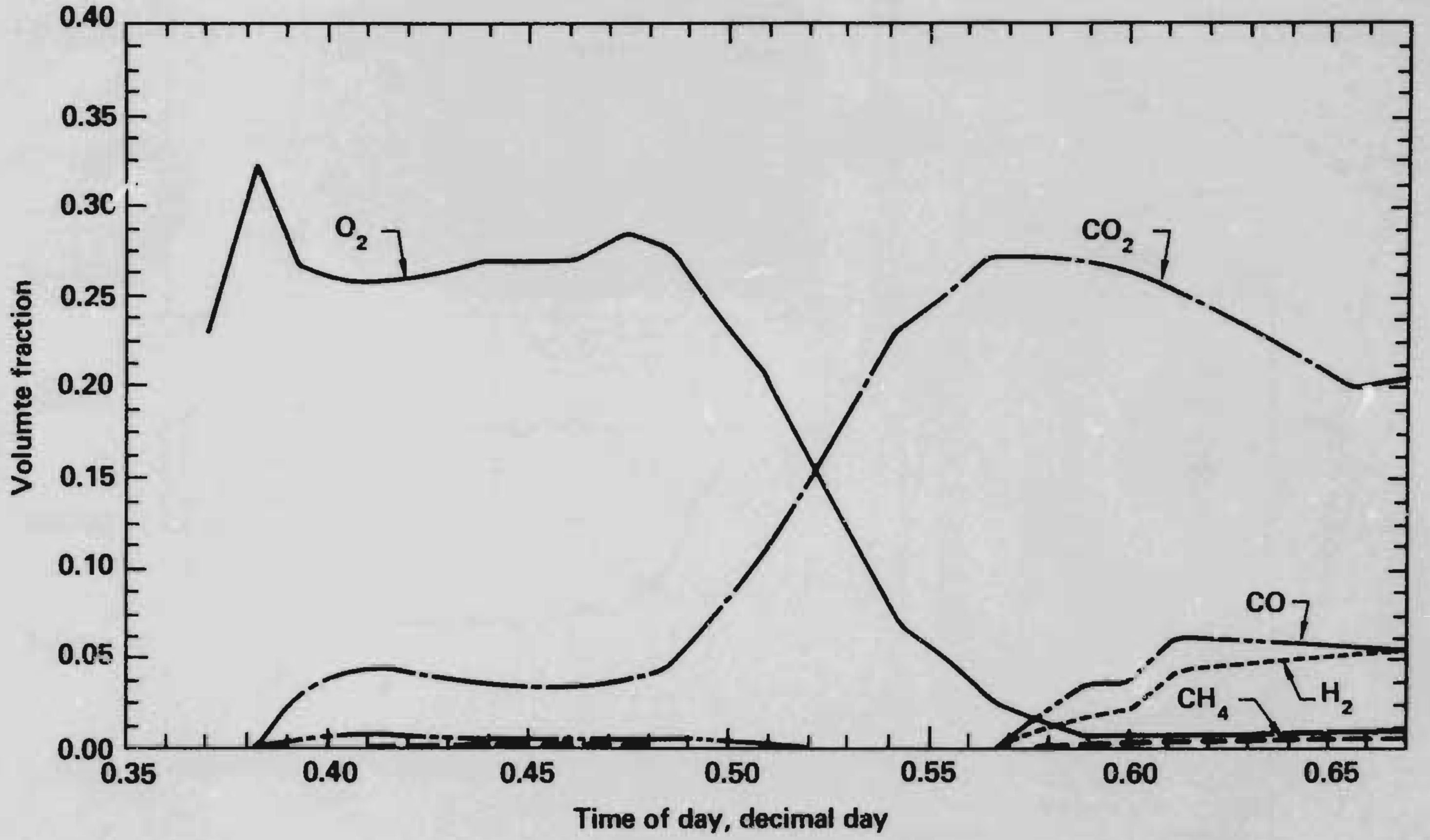


Figure 7. Composition of the dried product gases.

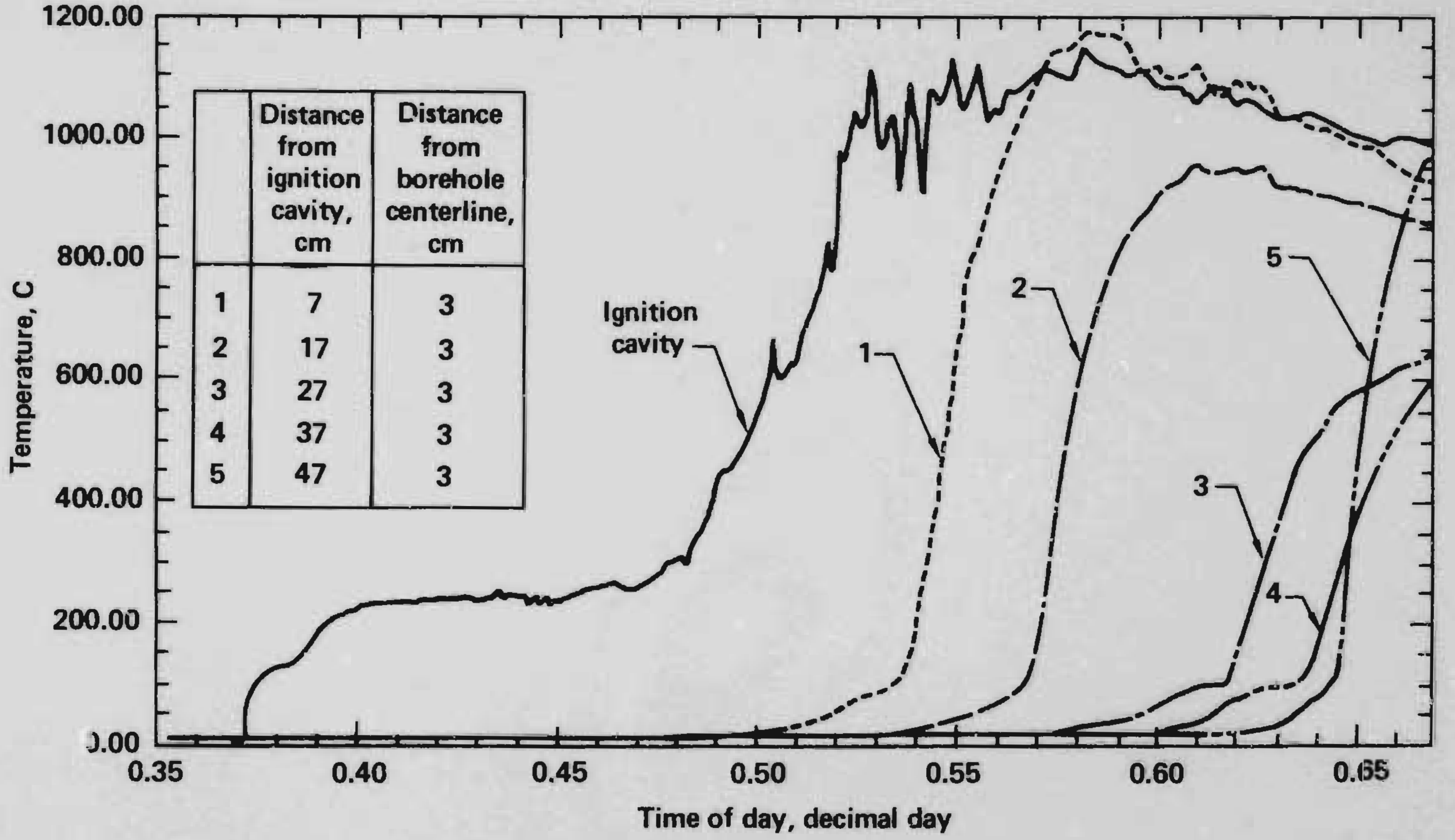


Figure 8. Thermocouple responses during reverse combustion.

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