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A REVIEW OF SUPPORTING RESEARCH AT OAK RIDGE NATIONAL LABORATORY FOR UNDERGROUND COAL CONVERSION*

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DISCLAIMER

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ABSTRACT

Chemical and physical properties of lignite, subbituminous coal, bituminous coal, and overburden have been measured in research that began in 1974 at Oak Ridge National Laboratory. Generally, large, monolithic blocks of sample have been dried and pyrolyzed. Thermal data and product yields can be correlated to provide an extrapolation from powder pyrolysis to the pyrolysis steps in underground coal gasification.

Significant results of the past year include correlation of block pyrolysis data for low-rank coals, interpretation of mechanisms, and comparison between low-rank and bituminous coals; heating tests of overburden cores from the Hoe Creek field gasification site; and measurement of physical properties, particularly thermal diffusivity and thermal conductivity of low-rank coals. Correlations, mechanisms, and property measurements are reviewed, and applications to underground coal gasification are discussed.

Introduction

Process research in the laboratory can be classified as a scaled simulation of a process, a study of process steps, or a characterization of materials involved in the process. By the nature of underground coal gasification (UCG), laboratory simulation can only approximate the UCG field conditions.[1-3] As a result, field results dictate certain process steps and materials that can be productively analyzed in laboratory supporting research such as block pyrolysis, overburden testing, and measurement of physical properties.

Block pyrolysis of coal couples heat transfer, mass transfer, pyrolysis, and drying in the laboratory, much as these process steps are coupled in UCG. Heating tests on overburden samples outline the physical and chemical changes that contribute to subsidence and gas production. Finally, measuring physical properties of coal, char, and overburden provides data for better modeling, design, and interpretation of the UCG process.

Block pyrolysis experiments on Wyodak subbituminous coal and Pittsburgh bituminous coal have been reported in previous years.[4-6] During the past year, modeling and correlation of these data were expanded, and experiments were conducted on Wilcox lignite. Overburden tests and physical property measurements have also been conducted during the past year.

Pyrolysis and Drying in Low-Rank Coals

A brief series of block pyrolysis experiments was conducted with lignite from the Calvert Bluffs formation of the Wilcox group in Texas (Sandow Mine, ALCOA). As was seen in new correlations of data from Wyodak subbituminous coal, four mechanisms occurred in addition to pyrolysis:

1. A steam front or plateau forms, as is observed in UCG thermal data,
2. The flux of escaping steam, moving countercurrent to the heat flux, causes a self-gasification of the coal as it escapes through >670°C char,
3. Secondary cracking of pyrolysis products occurs as they slowly escape through hot char,
4. Escaping steam inhibits the penetration of reactive gases into the pyrolyzing coal.

Coal pyrolysis is usually characterized by pyrolyzing dry coal powders to minimize side effects such as those above. Ideally, powder data describe only the thermal decomposition of the coal structure. Thermal decomposition (pyrolysis) is coupled with these side effects during UCG, as well as with subsidence and partial combustion; therefore, block pyrolysis is a useful method for studying some of these couplings in a controlled environment.

The results of block pyrolysis also fit into different geometries and mechanisms of UCG. One mechanism of flame front movement is the growth of a cavity or porous channel, with heat moving into and products moving out of the coal.[5] Roof fall is another means of cavity growth, and the resulting

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chunks of coal are subjected to heating like that in block pyrolysis experiments. Fracturing would produce a similar situation. Even in the models that assume a broad, flat flame front, a "fingering" of the flame occurs through cracks, isolating sections of reacting coal.[7]

The block pyrolysis experiments have coupled the drying and pyrolysis steps by heating 6-in-diam (150-mm) cylinders of coal (Fig. 1). Temperature profiles and gas evolution are measured as block surface temperature is increased at a constant rate [0.3, 3, or 10°C/min (0.5, 5, or 18°F/min)] to some maximum temperature [500 to 1000°C (930-1830°F)], where temperature is permitted to equilibrate. After the experiment, char and condensibles (water and organic liquids) are weighed and sampled. Inert gas normally sweeps products from the reactor, but hydrogen, the most mobile of the UCG products, has also been used as a purge gas. Standard analyses of the Wilcox lignite and Wyodak subbituminous coal are presented in Table I.

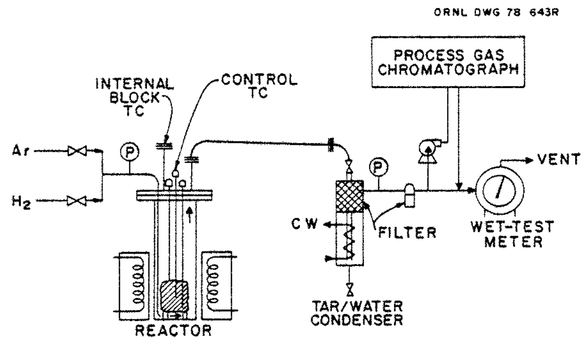

Figure 1. Schematic diagram of apparatus for block pyrolysis

Steam Front or Plateau--Thermal data from UCG field tests show that steam plateaus and drying fronts form as heat moves out into the virgin coal; steep temperature gradients exist in the dried coal.[8,9] Such conditions can be set up in the coal blocks by choosing the proper heating rate, which is about 3°C/min in this size block. Heating at 0.3°C/min gives a gentle gradient, and 10°C/min gives a steeper gradient.

Figure 2 dramatically shows the steam front movement through Wilcox lignite in a time sequence of radial temperature profiles. The profile for time t_3 is particularly interesting. Heat conducts rapidly into a shrinking core of wet coal (T<100°C). A 100°C zone forms between the wet and dry regions, and above 100°C, heat moves through poorly conductive dry coal and against the steam convection, causing the steep temperature gradient.

TABLE I

Standard Analyses of Lignite and Subbituminous Coal

	Wilcox lignite	Wyodak subbituminous
Moisture, wt %	37.5	33.6
Proximate analysis, dry wt %		
Ash	14.0	5.3
Volatile matter	54.7	47.0
Fixed carbon	31.3	47.7
Parr mineral matter	16.0	6.1
Ultimate analysis, maf wt %		
Carbon	73.4	73.3
Hydrogen	6.1	5.2
Nitrogen	1.38	1.12
Sulfur	1.9	0.59
Oxygen (by difference)	17.2	19 8
Heating value, MJ/kg (Btu/lb)		
Moisture- and ash-free, maf	29.8 (12820)	29.2 (12700)
Moist, mineral-matter-free	19.08 (8210)	19.9 (8560)

Observe that the 100°C steam plateau must be a two-phase drying zone in the porous medium of coal. If heat transfer were the only limiting step, a sharp steam front would form (as seems to be the case at t_1 and t_2). However, Lyczkowski's modeling[10] has shown that momentum transfer can cause a discrete drying region containing both steam and water phases. Note also that as steam and other reaction products escape through hot coal and char, they can react with each other and with the solid in a self-gasification reaction.

Coal Self-Gasification--If steam contacts char that is ≥670°C it can gasify carbon by the reaction:

$$C + H_2O = H_2 + CO.$$

(The equilibrium constant K_p is 1 at 670°C and increases with temperature.)

This reaction is observed experimentally by comparing gas yields of powders,[11,12] predried blocks, and slowly heated blocks (little or no self-gasification) to yields from wet blocks heated at 3°C/min or more (significant self-gasification), as shown for lignite in Fig. 3 and for subbituminous coal in Fig. 4. This deviation from powder pyrolysis data, which intensifies at about 650 to 700°C, is largely H_2 and CO. (Leveling of the deviation above 900°C in the subbituminous coal occurs because the wet core dries out at about 900°C surface temperature for this size block and heating rate.) In Table II, increasing yields of H_2 and CO are linked to

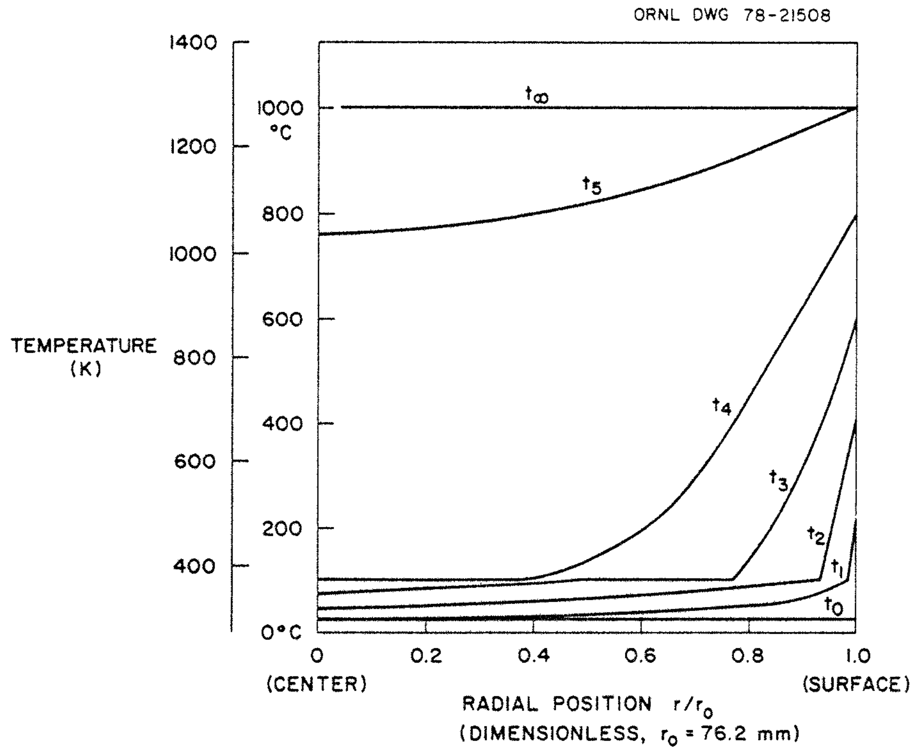

Figure 2. Internal temperature profiles as time progresses (t_0, t_1, ...) during block pyrolysis of lignite in inert gas at 3°C/min; based on data from experiments BP2-48 and BP2-55

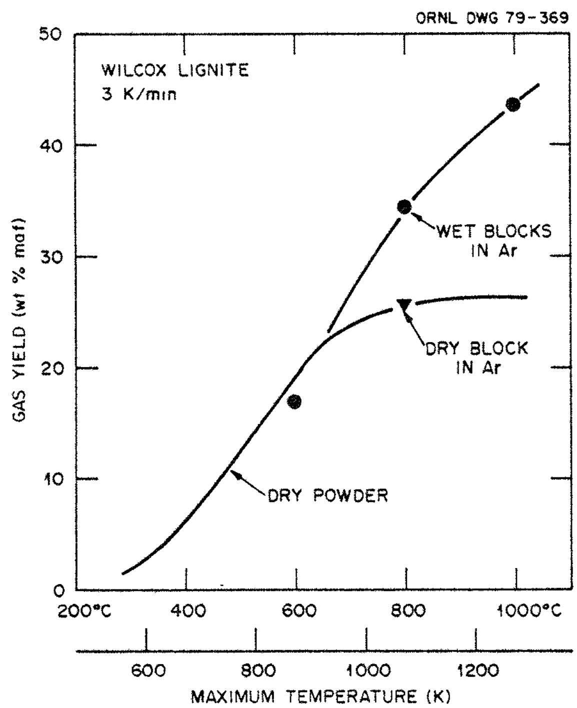

Figure 3. Gas yield from pyrolysis of Wilcox lignite (powder data from ref. 11; all data at 3°C/min)

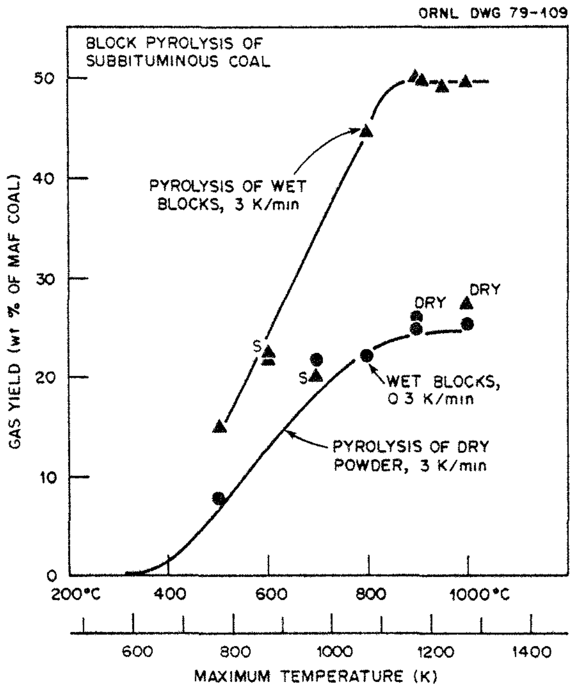

Figure 4. Gas yield from pyrolysis of Wyodak subbituminous coal (powder data from ref. 12; S designates small, 60-mm-diam blocks)

TABLE II

Influence of Water in the Wet Core on Gas Yields; Argon-Purged Experiments with 800°C max temp

Conditions of Pyrolysis	Percent of Block Still Wet at 650°C[a]	Gas Yields (mol/kg maf lignite) H_2	CO	Overall
"Wet" block,[b] 0.3°C/min	0	5.97	3.59	13.93
Predried block, 3°C/min	0	8.51	3.41	17.27
Wet block, 3°C/min	~25	10.85	4.38	21.05
Wet block 10°C/min	~50	13.10	4.82	24.90

[a]Surface temperature.

[b]Because of slow heating, block was completely dried by the time the surface temperature reached 410°C.

the size of the wet core (amount of steam yet to be generated) at the time that surface char temperature reached 650°C in lignite. As further verification of this reaction in lignite, char,[13] and water[14] consumption data were also measured.

To understand the application of this result to UCG, note that it is the contact of steam with hot char that causes gasification, not a particular coal type or heating rate. No self-gasification would occur in small particles of wet coal heated at 10°C/min. By contrast, self-gasification of a 12-in block would occur even if the surface were heated at only 0.3°C/min. Likewise, in the coal seam where 3°C/min may be a typical point heating rate, steam will continue to be generated and forced to escape through dry coal regardless of the heating rate. Clearly, if no steam is injected during UCG, water intrusion and this mechanism must account for steam gasification in UCG.

Secondary Cracking of Pyrolysis Products--Just as steam is forced to escape through hot char, so do oil and tar vapors that are generated by pyrolysis. These vapors can be cracked (pyrolyzed) as they escape, producing lighter hydrocarbons and char.

Evidence of secondary cracking was observed in block pyrolysis experiments on lignite and subbituminous coal. Most noticeably, oil yield from lignite blocks was reduced (Fig. 5), but char yield was slightly higher (Fig. 6) than from pyrolysis of powders. Such cracking also occurs in bituminous coal, where it becomes the dominant side reaction because coal moisture content is low.[6] To observe secondary cracking more clearly in low-rank coals, yields from dry powders are compared to the yield from predried blocks in Table III; all yield changes are consistent with this mechanism.

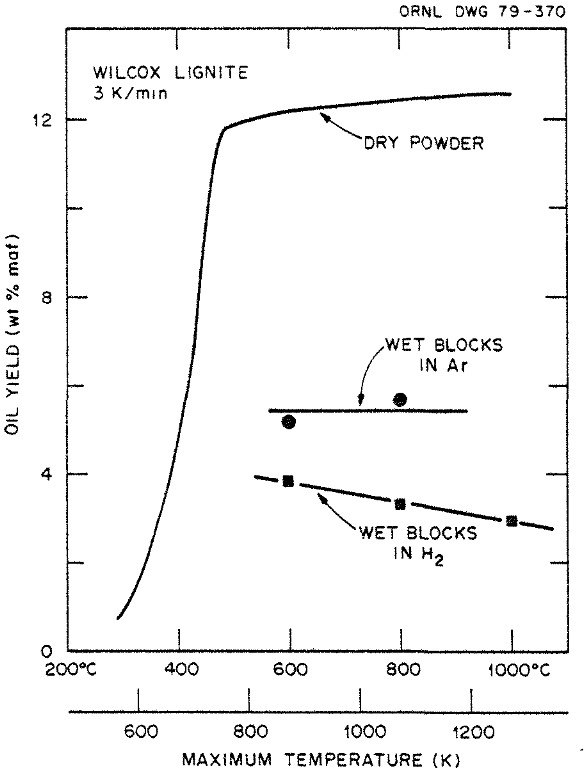

Figure 5. Yield of organic liquids from pyrolysis of Wilcox formation (Texas) lignite. (Powder data from ref. 11.)

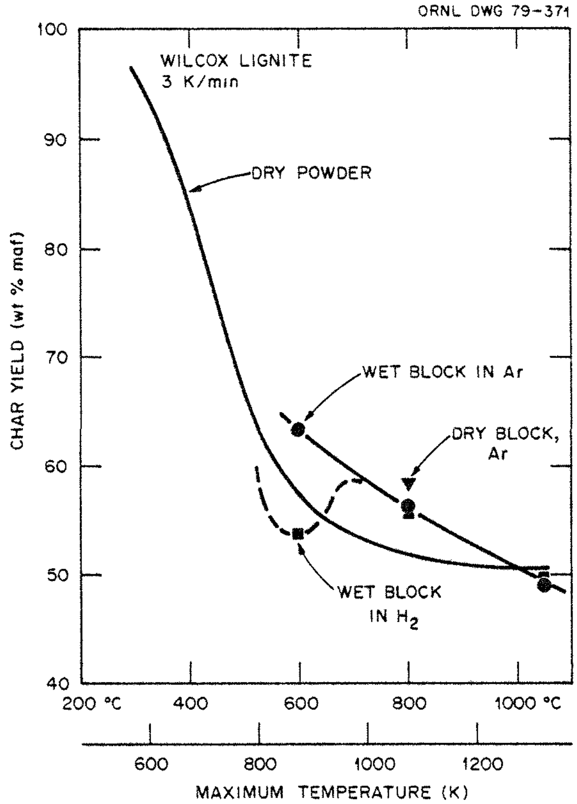

Figure 6. Char yields from pyrolysis of Wilcox formation (Texas) lignite. (Powder data from ref. 11.)

TABLE III

Evidence of Oil Cracking in Blocks of Low-Rank Coal (heating rates approximately 3°C/min)

Yield (wt % maf)	Oil and Tar	Gas	Char
Wilcox lignite, dried			
Powder to 800°C[a]	12.3	23.3	52.1
Block to 800°C	5.9	28.9	58.3
Wyodak subbituminous, dried			
Powder to 870°C[b]	11.7	24.5	54.4
Block to 1000°C	3.3	26.9	61.1
Cracking would make block yields:	Lower	Higher[c]	Higher

[a]Ref. 11.

[b]Ref. 12.

[c]Also may be higher because of self-gasification by pyrolysis-generated water.

Occurrence of this cracking is not surprising, but it is beneficial in UCG. Anthony and Howard[15] showed that these reactions can reduce the yield of organic liquids even from particles. In UCG, tars are undesirable because they can plug the porous flow path; cracking of tars not only reduces the plugging problem but also produces light hydrocarbons, which raise the heating value of the UCG product gas.

An interesting side effect of this cracking may be a reduced reactivity of the char. Chars of low-rank coals tend to be pyrophoric; that is, room-temperature char is so reactive that it begins to burn when exposed to air. As a measure of relative pyrophoricity, the associated rate of temperature rise was recorded and plotted against the experimental heating rate in Fig. 7. The decrease in char pyrophoricity with increasing heating rate (steeper temperature gradients) parallels the increases in cracking and carbon deposition. Kamashita and Walker[16] showed that such carbon deposits could block off the mouths of coal pores, reducing the amount of surface area for reaction and thus lowering the reactivity. In the field, this lowered reactivity may act to stabilize the UCG flame front.

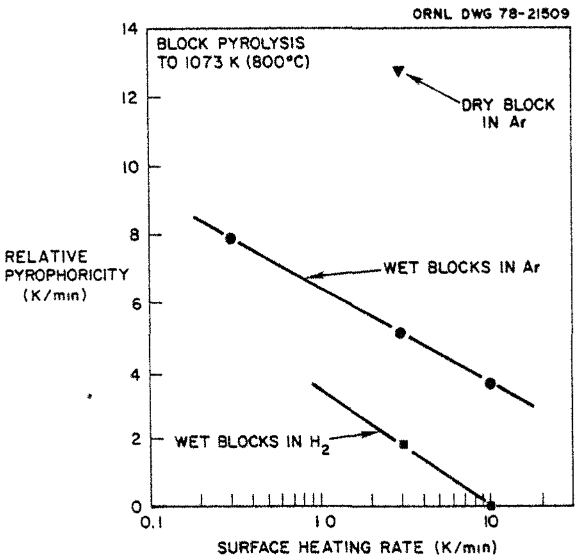

Figure 7. Pyrophoricity of blocks of lignite char as affected by pyrolysis conditions

Steam flux as inhibitor to mass transfer--Experiments using H_2 purge gas indicate that UCG product gases may have little effect on pyrolysis. Apparently, the outflow of steam inhibits mass transfer of other gases into the reacting coal.

For example, experiments in the absence of a steam flux such as with a predried block demonstrated that hydrogasification of char

$$C + 2H_2 \rightarrow CH_4$$

could occur at 500 to 600°C, as indicated by char (see Fig. 6), H_2, and CH_4 yields.[13] However, when steam flux was present there was little or no hydrogasification. Some H_2 seems to get into the coal, as evidenced by increased secondary cracking in H_2 compared to inert gas (see Figs. 5 and 7), but H_2 penetration probably occurs only in a narrow, surface region.

Two implications for field operation of UCG are obvious. First, hydrogasification of char can occur at low pressure, boosting yields of CH_4. Secondly, for hydrogasification, CO_2 gasification, or other gas-char reactions to be important, steam flux must be low or at least not countercurrent to the influx of reactive gases. Since H_2 has the highest diffusivity, it would be more difficult for any other gases to reach the char against a flow of steam.

In summary, data from block pyrolysis of lignite, subbituminous coal, and bituminous coal indicate mechanisms in UCG that are not predicted by pyrolysis tests on dry powders. These mechanisms must be included when pyrolysis and drying steps are modeled for UCG.

Characterization of Overburden

Characteristics of overburden (the strata overlying a coal seam) are being measured using the block pyrolysis apparatus. Some of these characteristics are:

1. physical properties such as density, shrinkage, and thermal diffusivity;
2. chemical composition (moisture, carbon, hydrogen);
3. friability or collapse when dried or heated; and
4. products and yields from thermal decomposition.

Initial tests have used six cored samples from the Hoe Creek 2 site of Lawrence Livermore Laboratory.

The incentives for such testing are apparent in Fig. 8. To obtain samples of all strata, sampling well SS-2 was cored before the Hoe Creek 2 field test. Following the UCG test in the Felix No. 2 seam, coring revealed collapse of strata from as high as 15 m above the seam. Heating, weakening, and geological stresses had caused the overburden rock to fall into the hot gasification cavity, where any organic matter in the rock would be heated and pyrolyzed. Each of the tested cores came from strata that collapsed at the field site.

Cores were inspected at the drilling site and visually characterized by Livermore personnel. Several bands of unconsolidated sand were observed, but most of the strata of interest were siltstone and claystone (see Fig. 8). After descriptions were logged, the 60-mm-diam (2-3/8-in.) cores were cut in approximately 140-mm lengths (5-1/2-in.), wrapped in plastic and aluminum foil, and sealed in a layer of wax. At ORNL, the cores were drilled with 1-mm-diam (0.047-in.) thermocouple holes and x-rayed.

Before heating the core, a segment was sliced from the bottom for other tests. Analytical results (Table IV) showed that moisture content was fairly constant at 13 to 16%, but carbon and hydrogen content varied, reflecting apparent differences in amount of organic matter. Density of the wet solid was 2190 to 2200 kg/m^3 except for core 79, a more carbonaceous sample, which was 2000 kg/m^3. Shrinkage after drying varied from no shrinkage to 2.0%, so the calculated density of dry solids was 1800 to 2000 kg/m^3.

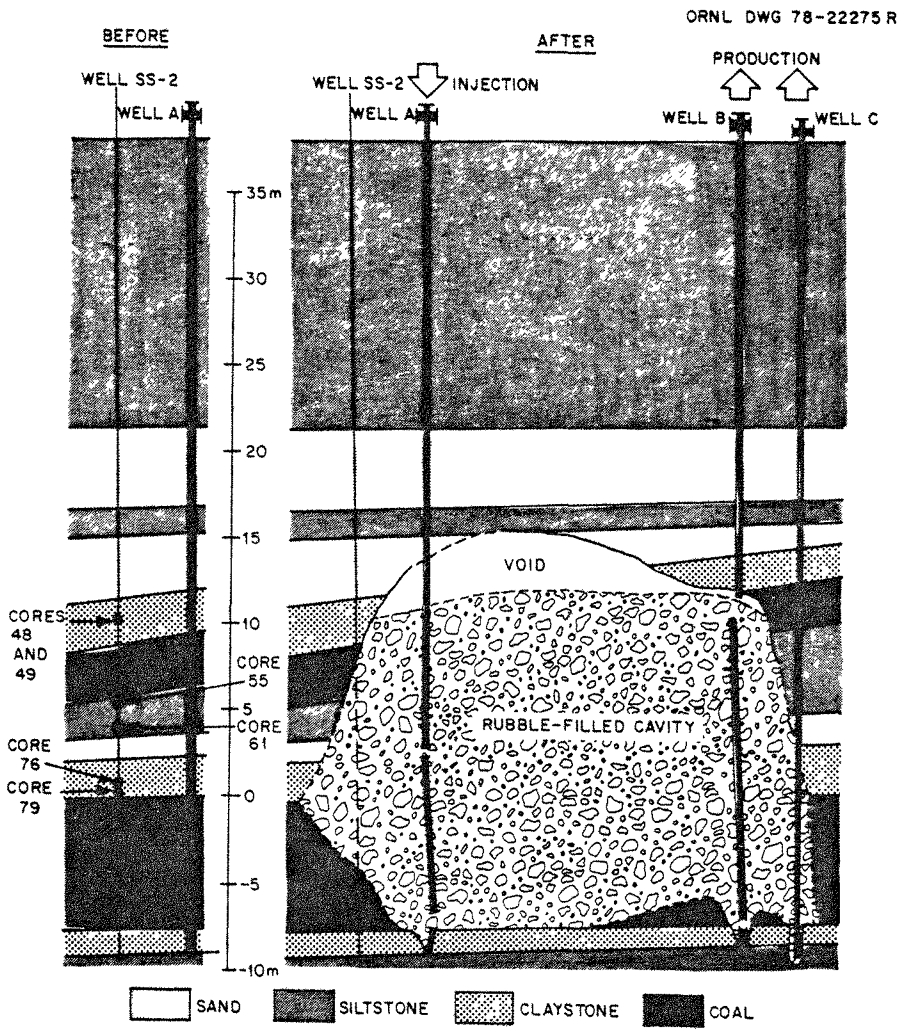

Figure 8. Location of overburden core samples from Hoe Creek 2 site, Gillette, Wyoming (left) before field test (at time of sampling), and (right) after field test.[17]

TABLE IV

Description and Properties of Overburden Samples from the Hoe Creek 2 Site

Core No.	79	76	61	55	49	48
Experiment	OB-4	OB-5	OB-6	OB-7	OB-3	OB-1 & OB-2
Location in well SS-2, m [a]						
Depth	38.9	38.4	35.1	33.8	28.4	28.1
Height above Felix No. 2	0.2	0.7	4.0	5.3	10.7	11.0
Distance from Felix No. 1	5.7 beneath	5.3 beneath	2.0 beneath	0.6 beneath	1.7 above	2.0 above
Description:[a]	Dark black, carbonaceous, slightly silty claystone. Carbonaceous material increases with depth and color darkens.	Thinly bedded clayey siltstone and claystone; medium black with brownish cast; tends to disk with stress relief.	Very silty claystone or very clayey siltstone; medium brown; very thinly bedded; slightly calcareous.	Medium brown to buff with black carbonaceous speckles; thinly interbedded, very fine-grained silty sand and claystone; dries quickly with formation of shrinkage cracks;[a] broke into pieces, so placed in mesh basket for experiment.	Slightly silty claystone· light brown to light black, slightly carbonaceous, thin-bedded.	
Analyses						
Moisture, wt %	15.6	13.4	13.0	14.3	13.3	e
Carbon, % moisture-free [b]	5.02	2.04	1.26	1.75	3.63	e
Hydrogen, % moisture-free	1.03	0.42	0.42	0.65	0.58	e
Density, kg/m^3, and shrinkage						
Bulk density of wet solid	2000	2190	2200	2190	2200	e
Shrinkage from drying, %	1.5[c]	0.6	0.8-2.0		None	e
Bulk density of dry solid[d]	1800	1930	2000		1900	e

[a] From ref. 18.

[b] Includes carbon in carbonates.

[c] Average linear shrinkage, three dimensions; sample of core dried in vacuum at 107°C for 16 hr.

[d] Calculated from moisture content, wet-bulk density, and shrinkage.

[e] Should be same as for core 49.

As each core was heated to 1000°C in an inert purge gas, internal temperatures and gas evolution were measured. Although no organic liquids were detected as products, significant amounts of H_2, CO, and CO_2 were released along with small amounts of CH_4, C_2's, and C_3's (see Table V); overall gas yields (dry, wt % basis) were as high as one-third of those from Wyodak coal.

After heat treatment, the solid residue was photographed and described to compare decrepitation. The different strata were composed of different-sized particles in various states of consolidation; therefore, this decrepitation varied in amount and type, as Figs. 9-14 illustrate. Cores 55 and 79 flaked apart at closely spaced bedding planes, but large cracks formed in cores 48, 49, and 61. The material in cores 48, 49, and 76 hardened, forming a brick-like residue. Note that the vertical bands shown in Figs. 10 and 13 were drilling mud from the coring operation and were not part of the overburden.

Geological descriptions have been published for Department of Energy UCG sites at Hanna, Wyoming;[19] Pricetown, West Virginia;[20] Hoe Creek, Wyoming;[21] and North Knobs, Wyoming.[22] Each is bounded by shales containing varying amounts of organic matter, which presumably can be degraded as in the cores discussed here. If possible, characterization of overburden samples from DOE sites will continue in this manner.

Physical Properties of Coal and Char

Accurate values for physical properties (e.g., thermal diffusivity, thermal conductivity, density, shrinkage upon drying, porosity, specific heat, and enthalpy) are important in modeling UCG. The data are used principally for modeling UCG to correlate or predict field results. Gunn[23] has used sensitivity analysis on his global model to show how the predicted values of field conditions such as peak flame temperature or product heating value are affected by uncertainties in physical properties. These properties are also important in models that have been developed to monitor and map the UCG burn front from thermal data.[24,25]

Thermal Diffusivity and Thermal Conductivity--These thermal properties have been determined for Wilcox lignite by modeling heat transfer as conduction into an infinite cylinder. Convection is minimized by using temperature data from either an entirely

TABLE V

Results of Heating Tests for Overburden from Hoe Creek 2 Site

Core No.	9	76	61	55	49	48
Experiment	OB-4	OB-5	OB-6	OB-7	OB-3	OB-1 & OB-2[a] [b]
Yields, wt %, H_2O-free						
Solid residue	84.3	90.8	93.6	90.?	94.5	90.7
Oils and tars	0[c]	0[d]	0[c]	0[c]	0[c]	0[c]
H_2	0.357	0.219	0.143	0.243	0.205	0.105
CH_4	0.104	0.075	0.056	0.105	e	e
C_2's	0.052	0.045	0.030	0.094	0[c]	0.040
C_3's	0.040	0.035	0.024	0.013	0[c]	0[c]
CO	2.61	3.50	1.610	1.469	e	e
CO_2	2.61	4.44	2.63	3.?6	4.73	3.61
H_2S	0.018	0[c]	0.022	0.003	0[c]	0[c]
Total gases	5.79	8.31	4.52	5.19	5.7	10.1
Total balance	90.1	99.1	98.1	95.4	100.2	100.8
Characteristics of solid residue	Spalled at bedding planes 3.6% shrinkage in each dimension	Solid with no signs of flaking or shrinkage Hard breaking smoothly when struck by a hammer	Several large cracks, vertical and horizontal splitting the block into hard segments Complete break-off of top two-thirds Broke into powder when struck	Layered spalling along bedding planes, very easily crumbled into dust	Hardened into a strong brick-like material with no detectable shrinkage	

[a]Core was heated in OB-1 at 0.3°C/min to 800°C, then cooled and reheated at 3°C/min to 1000°C in OB-2

[b]Assumes 13.3% moisture, same as for core 49

[c]Not detected

[d]Condensed water was dark and contained small black particles, possibly carbon from CO decomposition

[e]Errors in analysis by gas chromatograph

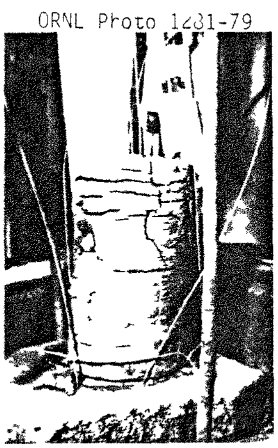

Figure 9. Core 79 after experiment OB-4

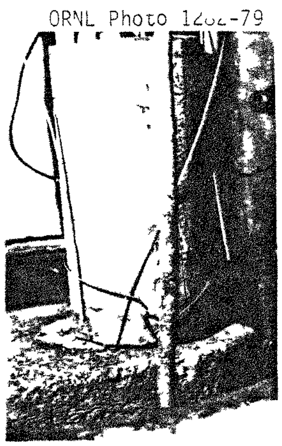

Figure 10. Core 76 after experiment OB-5

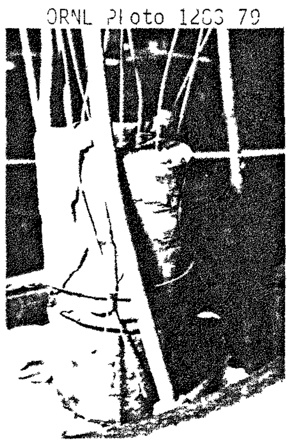

Figure 11. Core 61 after experiment OB-6

ORNL Photo 1234-79

Figure 12. Core 55 after experiment OB-7

ORNL Photo 1279-79

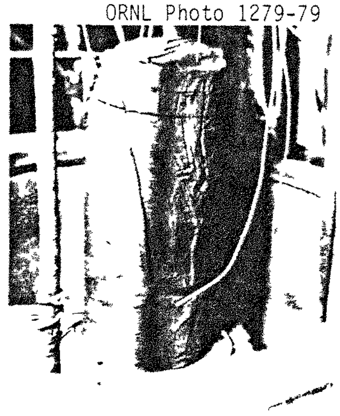

Figure 14. Core 48 after experiments OB-1 and OB-2

ORNL Photo 1280-79

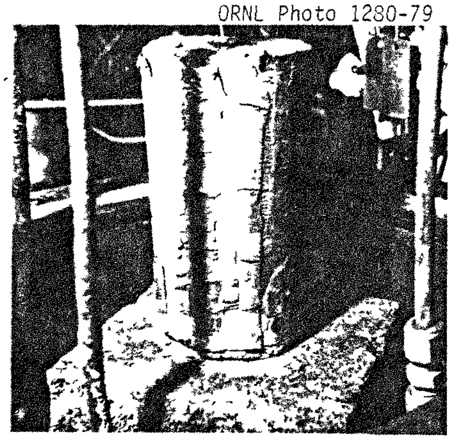

Figure 13. Core 49 after experiment OB-3

wet block or a predried block in which no steam front is present. Details of the methods are presented elsewhere, but the heat conduction equation is applied:

$$\rho \cdot C_p \cdot \frac{\partial T(r,t)}{\partial t} = k \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r}\right) \qquad (1)$$

or

$$\alpha \cdot \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r}\right) = \frac{\partial T}{\partial t} \qquad (2)$$

where

ρ = density, kg/m^3,

C_p = specific heat, J/kg·K,

T = temperature, K, a function of radius and temperature,

r = cylinder radial position, m,

t = time, sec,

k = thermal conductivity, W/m·K,

α = thermal diffusivity, m^2/sec = $k/\rho \cdot C_p$.

Either from an analytical solution or from substituting the measured derivatives, α is determined and k is calculated.

TABLE VI

Thermal Diffusivity and Thermal Conductivity of Coal

Coal Rank	Source (ref. no.)	Thermal Diffusivity, α (mm^2/sec)	Thermal Conductivity, k (W/m·K)	Comments
Lignite, dry	This work	0.26	0.15	410-570 K, 30% porosity
dry	26		0.151	303 K, 32% porosity
wet	This work	0.16	0.37	37% moisture
wet	27	0.142		Bed-moist
Subbituminous, dry	28		0.15-0.19	298-363 K
Bituminous, dry	29		0.17-0.22	298-673 K, 36 coals
Anthracite, dry	29		0.19-0.34	287-673 K, 17 coals

Table VI shows a comparison of these data to literature data for monolithic coal.[26-29] Agreement with the available literature values for lignite is satisfactory. Significantly, thermal properties of bituminous and anthracite coals have been studied extensively, but very few data are available for wet low-rank coal. As a result, previous UCG models have used thermal conductivities measured for dry bituminous coal. These new measurements indicate that dry low-rank coals have slightly lower thermal conductivity, and that wet low-rank coals may be higher by a factor of 2, depending on moisture content.

Density, Shrinkage, Porosity--Gan et al.[30] present an excellent analysis of porosity and density for coals of different rank, but they do not investigate density of wet coals, shrinkage from drying, or coal voids larger than macropores. Data for these properties are summarized in Table VII.

Of these properties, moisture content and shrinkage were measured by drying chunks of coal in a vacuum at 106°C for 16 hr. Linear shrinkage was determined in the dimensions normal to the three cleavage planes. Based on density of the wet coal (by water pycnometer), shrinkage, and moisture content, a density of bulk dry coal was calculated, which includes crack volume as well as pore volume. Particle density of dry lignite powder was measured by mercury porosimetry at 15 psi, and intrinsic density of the solid coal was determined from measurements or correlations of helium densitometer data.

TABLE VII

Shrinkage, density and porosity measurements

Coal type	Lignite A	Subbituminous C	High-volatile A bituminous
Seam	Wilcox, TX	Roland-Smith, WY	Pittsburgh, WV
Moisture content, wt %	37.48	33.42	1.77
Shrinkage from drying, %[a]	8.4 ± 3.0	9.3 ± 3.3	None
Density, kg/m^3			
Wet coal	1230	1270	1304
Bulk dry coal[b]	1000	1130	1280
Dry coal powder	1245		
Intrinsic density	1440	1372[c]	1315[c]
Porosity, vol %			
Powder particles	13.5		
Bulk dry coal	30	18	3.0

[a]Average linear shrinkage.

[b]Calculated by (wet density) × (1−moisture/100)/(1−shrinkage/100).

[c]From ref. 30, adjusted to mineral-matter-containing basis

Porosity or percent voidage is especially interesting. Porosity of bulk Pittsburgh coal is in line with the trend reported by Gan, but bulk Wilcox lignite is more porous (30%) than powder, as reported in the literature (12.7%)[30] or in this study (13.5%). This difference is probably caused by cracks that open up as the lignite dries, but which would be either eliminated by grinding or filled by mercury even at 15 psi (pores 3 μm or larger). It is also consistent with the tendency of pore distributions to shift toward larger pore size as rank decreases.[30]

Enthalpy and Specific Heat--Gomez et al.[31] reported enthalpy data and correlations for several coals, cokes, and shales. It was found that (1) a mass-weighted combination of coal (or char) enthalpy with ash enthalpy gave suitable correlations, (2) the correlation of ash enthalpy agreed for ash from all the materials studied, and (3) the ash-free coal enthalpy agreed for the lignite and subbituminous coal samples.

Using correlations of the Gomez data, enthalpy and specific heat functions were determined for Wilcox lignite, Wyodak subbituminous coal, and Hanna No. 1 coal (Table VIII). These properties had been measured for Wilcox lignite,[31] and agreement between correlation and data is satisfactory. A correlation is tabulated for a Wilcox lignite char prepared at 500°C, which was also tested.

TABLE VIII

Correlations of Enthalpy and Specific Heat for Coals and Chars as Functions of Temperature (K)

	Correlation
Enthalpy, kJ/kg	
Ash, 376-1031 K[a]	$-181.9 + 0.633 \times T + 2.967 \times 10^{-4} \times T^2$
Low-rank coal, maf, 305-450 K[a]	$-203.1 + 0.390 \times T + 1.212 \times 10^{-4} \times T^2$
Wilcox lignite, dry	$-200.1 + 0.424 \times T + 1.457 \times 10^{-4} \times T^2$
Wyodak subbituminous coal, dry	$-202.0 + 0.403 \times T + 1.306 \times 10^{-4} \times T^2$
Hanna No. 1 hvCb coal, dry	$-196.4 + 0.467 \times T + 1.767 \times 10^{-4} \times T^2$
Char from Wilcox lignite pyrolyzed at 500°C, dry, 368- 24 K[a]	$-169.8 + 0.190 \times T + 1.654 \times 10^{-4} \times T^2$
Specific heat, kJ/kg K	
Wilcox lignite, dry	$0.424 + 2.914 \times 10^{-4} \times T$
Wyodak subbituminous coal, dry	$0.403 + 2.612 \times 10^{-4} \times T$
Hanna No. 1 hvCb coal, dry	$0.467 + 3.535 \times 10^{-4} \times T$
500°C Wilcox char, dry	$0.190 + 3.318 \times 10^{-4} \times T$

[a]Data for correlation from Gomez et al.[31]

Summary and Plans

Research on pyrolysis of coal blocks has demonstrated that when pyrolysis of coal during UCG is modeled, other side effects that must be considered are drying, steam-flow patterns, possible self-gasification, and secondary cracking of pyrolysis products. Some experiments with Rosebud coal have been suggested[32] because that coal is more like Hanna coal in rank and moisture content than is Wyodak coal. Since improved modeling of UCG processes is the reason for block pyrolysis, increased effort will go toward incorporating these data into existing and new UCG models.

From tests on overburden samples, useful data on composition, physical properties, decrepitation, and pyrolysis behavior have been obtained. In addition, thermal diffusivity is also being determined. Future tests may also be conducted on cores from the Hanna and Hoe Creek 3 sites.

Finally, new data and correlations of literature data have been presented for the various physical properties of thermal diffusivity, thermal conductivity, density, shrinkage, porosity, enthalpy, and specific heat. This work continues with measurements of thermal diffusivity for Wyodak coal and char at different temperatures.

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