

**MIRL REPORT NO. 92**

**REPORT TO  
ALASKA SCIENCE AND TECHNOLOGY FOUNDATION**

***CHARACTERIZATION OF COAL PRODUCTS FROM HIGH  
TEMPERATURE PROCESSING OF USIBELLI LOW-RANK COAL***

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## EXECUTIVE SUMMARY

This research project was conducted in association with Gilbert/Commonwealth Inc. as part of an overall techno-economic assessment of high temperature drying of low-rank coals. This report discusses the characteristics of the dried/pyrolyzed products of two high temperature, evaporative processes and the dried product from a hydrothermal process.

The long term goal of this and other coal drying studies conducted at MIRL, was to define drying technologies that have significant and real potential to competitively move Alaska's, low-rank coals (LRCs) into the export, steam coal market of the Pacific Rim. In 1990, Japan imported 33 million metric tons (mt) of steam coal with an additional 39 million mt imported by other Far East nations(2). Australia dominates the export steam coal market to these Pacific Rim countries and exported 48 million mt in 1990 and an additional 61 million mt of metallurgical coal(2).

The worldwide steam coal export market has been expanding rapidly, from 20 million mt in 1973 to 150 million mt in 1989, and is expected to double to nearly 300 million mt by the end of the century(3). Could Alaska capture only 3% of the projected new world steam coal market, which is not an unreasonable expectation, the value of the state's coal exports would soar from nominally \$28 million per year to over \$100 million per year. However, without development of economical methods for drying/stabilizing Alaskan LRCs, the only increase in export of Alaskan coals may be from the few "higher rank" coals within a "reasonable" transport range of the existing Alaska rail system or tidewater. Presently the coal from the Usibelli Coal Mine is the only low-rank coal exported internationally as a steam coal; primarily for its blending properties with other coal to improve combustion. But for Alaskan low-rank coals to truly stand on their own merits, economical drying processes must be developed that produce a physically and chemically stable dried product.

The technologies that have the most potential for increasing the use of Alaskan coals are those that can reduce the moisture content of these coals economically, and produce a fuel that is accepted in the international market place. Drying technologies will no doubt differ, depending on the end use of the fuel; be it dried lump coal, briquettes or pellets for pulverized coal or stoker applications, or concentrated coal-water fuels made from hot-water dried LRCs. There are a number of developing processes that may work with Alaskan coals. Some drying processes, however, have been plagued by the production of excessive amounts of coal fines. Since the demand for Alaskan coal is currently limited to lump size coal, large quantities of fines are a definite liability.

In this study, two high temperature drying/pyrolysis processes and one hydrothermal process were investigated. The high temperature drying/pyrolysis processes were conducted at (1) the Western Research Institute, (WRI) an affiliate of the University of Wyoming Research Corporation, Laramie, WY, and (2) Coal Technology Corporation (CTC) of Bristol, VA. Hydrothermal processing was conducted at MIRL, University of Alaska Fairbanks. A summary of these processes and the products they produced follows. In all cases, Usibelli coal was processed.

### The CTC Process

The CTC pyrolysis process utilized 6 inch pipe reactors to treat minus 2 inch coal with a flow of high temperature nitrogen gas. Residence times of 400-420 minutes were required to achieve the process temperatures of 900-1300°F. The product chars were 2-3 times more friable than the raw coal and were very susceptible to spontaneous heating. Char equilibrium moisture levels were 9-11% compared to 25-30% for the raw coal. Post process moisture levels of the char ranged from 0.2-2.8%. Despite the high fuel ratio (fixed carbon: volatile matter) of the char products, they seem highly reactive with respect to self heating. The CTC process produced calorific value increases in the 26-35% range, with products ranging from 9870 - 10610 Btu/lb from a parent coal of 7830 Btu/lb. However, these energy density increases were accompanied by significant mass and energy losses during devolatilization of the raw coal. Briquetted char from CTC showed poor physical stability and had no advantages over the lump char with respect to equilibrium moisture.

### The WRI Process

The WRI dual, inclined fluidized bed (IFB) drying process uses minimum fluidization velocities, allowing the dried coal to move in plug flow gently through the slightly sloping reactor. By avoiding the turbulence and intense back-mixing found in most fluid bed applications, the WRI process may yield a high proportion of lump coal to fines. In the first IFB, heated CO<sub>2</sub> supplies the heat required to dry/pyrolyze the coal, while ambient temperature CO<sub>2</sub> supplied to the second IFB quenches the dried/pyrolyzed product before it exits the process. For the samples of dried product, which MIRL received from the WRI process, temperatures ranged from 632-700°F. Charring process temperatures were in the 1090-1230°F range. Due to the small size of the WRI continuous IFB system, the size of the feed coal was restricted to minus 1.2 mm.

The two dried coals, which MIRL characterized, had raw coal moisture levels of 24.5% and 20.6%, post process moisture levels of 0.6% and 0.9% and equilibrium

moisture levels of 17.3% and 14.8% respectively. Energy densities for the dried products increased from 8000 and 8400 Btu/lb to 8700 and 9050 Btu/lb on an equilibrium moisture basis, with fuel ratios of 0.9 to 1.3 respectively, from a raw coal fuel ratio of 0.9. The dried WRI coal tested for self heating characteristics, showed very similar reactivity to the raw coal.

WRI char products characterized by MIRL had 0% post process moisture, but equilibrium moisture levels from 10.7-13.3%. Like CTC chars, these products were highly reactive on a self heating basis, showed high fuel ratios, 3.0-4.2, and energy density increases from 16%-26% on an equilibrium moisture basis for calorific values ranging from 9250-10100 Btu/lb. Because of the size of the coal processed by the WRI system (-1.2mm), friability tests could not be performed by MIRL. However, due to the similarity between CTC and WRI char products, it is doubtful that WRI lump char would be significantly more physically stable than the CTC chars tested. In general, low-rank coals that are treated by high temperature evaporative processes tend to develop cracks along their bedding planes which results in severe particle degradation during handling.

#### The Hydrothermal Process

This process, also known as hot-water drying (HWD), is a high temperature, high pressure, non-evaporative drying technology. Hot-water drying induces coalification and alters the hydrophilic nature of LRC into a hydrophobic material that has equilibrium moisture levels similar to those of bituminous coal. Water is removed via expansion and expulsion of CO<sub>2</sub> given up by the coal. Devolatilized tars and oils, being hydrophobic, are retained on the coal surface in the pressurized, aqueous environment and seal the micropores, reducing water reabsorption. For hydrothermal treatment of Usibelli coal at MIRL, approximately 1400 grams of 1.5 x 1 inch coal were treated at slightly above saturated steam pressures in a 2 gallon autoclave at 527, 572, and 617°F.

Equilibrium moisture levels for the products ranged from 6.1% for the highest temperature to 11.6% at the lowest treatment temperature. From the raw coal calorific value of 8150 Btu/lb, energy density increases ranging from 31% - 46% were achieved from HWD, with products ranging from 10,700-11,900 Btu/lb on an equilibrium moisture basis. Fuel ratios remained at low levels of 1.2 - 1.4 versus 0.9 for the raw coal. Physical stability was poor and comparable to that of the CTC product. Self heating propensity has not been determined. The Hardgrove grindability of the hot-water dried coal improved dramatically, from 34 for the raw coal to 78-115 for the products. Increases in Hardgrove grindability were less significant for WRI and CTC products.

None of the three high temperature processes had significant effect on ash composition or ash fusibility. In general, the low sodium content of Usibelli coals indicates low boiler fouling propensity. The relatively high calcium content would likely fix some sulfur in the ash and further reduce already low sulfur emissions and reduce the boiler fouling propensity of the ash due to the coal's sulfur content.

Petrographic studies of products from the three drying processes showed variable structural changes versus thermal treatment. The mean, maximum reflectance of ulminite, as measured in oil, proved to be sensitive to treatment temperature and heating rate. Hydrothermal processing increased reflectance from 0.30 in raw coal to a maximum of 0.79. CTC products showed increased reflectance to a maximum 3.66 at 1300°F, and WRI products increased up to 2.4 for sample treated at 1230°F. The higher reflectance of CTC products is due to a very low heating rate compared to WRI.

The method of thermal treatment is also reflected in the microstructure of the products. In hydrothermally treated coals, pore structure developed in ulminite bands due to development of thermoplasticity. Ulminite did not show any cracks that did not heal towards the particle surface. The highly volatile exinites, particularly suberinite and sporinite, volatilized leaving cavities. Resinite partially volatilized at higher temperatures.

The CTC products showed total loss of exinites resulting in cavities. Ulminite was quite intact. Some ulminites developed plasticity and cell structure due to slow evolution of gases. This again was the result of slow heating rate. In contrast WRI products developed significant cracks both in ulminite layers as well as desmocollinite due to rapid evolution of gases. Particles of ulminite that have gone through a plastic stage can also be found. The density of particles decreased with increased severity of hydrothermal treatment and was also a function of the presence of pure ulminite layers. These enhanced development of cell structure due to fluidity. The presence of trimacerite and mineral matter tended to inhibit particle swelling.

CTC samples developed the lowest porosities ranging from 1 to 2.1 percent. WRI products had intermediate porosities ranging from 2.8 to 6.3 percent. Hydrothermally treated coals developed highest porosity ranging from 14.5 to 31%. Again the slow heating rates used for CTC samples promoted devolatilization without undue cracking and resulted in the lowest porosities. WRI samples, with rapid heating rates and fast devolatilization, developed cracks. Hydrothermally treated coal developed a more plastic property and the gases, such as CO<sub>2</sub>, expelled during treatment, altered the pore structure, since the system was operating under pressure. The apparent particle densities of products hydrothermally treated at or above 572°F were decreased to near unity. Porosities of these particles exceeded 30%.

A transportation study conducted for the WRI process showed it to be very sensitive to transportation costs, which comprise approximately 50% of the product's present value in Korea. In year 2000 dollars, the breakeven economics would demand a coal sale price from Usibelli Coal Mine of less than \$0/tonne for WRI process. Though proprietary, the production cost of coal from Usibelli Coal Mine at present is estimated at between \$8-\$18 per tonne. Modifications to the present Alaska Railroad System could yield cost savings to rail transportation of Usibelli coal at higher tonnage rates of 1.5MM tons per year and 2.5MM tons per year. Given markets for increased tonnage of the dried lump coal or briquettes, reduced transport costs coupled with improved economics of scale for both mining and production could shift the WRI process economics to a more favorable position. However, at the present production and export rates, and with the present transportation structure, economics are unfavorable.

If Alaska is to become a serious competitor in the rapidly expanding steam coal market, it must begin immediately to develop an aggressive coal technology development program and spearhead a drive to educate users that coal should not be viewed as a commodity sold on a dollar per ton basis but that it should be sold on a dollar per million Btu basis. Users should also be educated to forget about the outdated concept of LRCs being equated to low-quality fuels. They need to be shown that LRCs possess superior combustion properties and that utility boilers designed for LRCs can utilize the lower cost LRCs for efficient power generation and pass the rate savings on to their customers. Users also need to be shown that hundreds of thousands of megawatts are being generated efficiently in this country every day from LRCs. As evidenced by the tremendous surge in sales of LRCs from the Powder River Basin, fuel switching from bituminous coal to LRCs in order to meet air quality standards is occurring almost daily in boilers designed for bituminous coals.

Technology development needs for Alaska that can have the largest impact on increasing coal exports are, 1) Coal drying process development, 2) Coal-water fuel production/combustion demonstration, and 3) the demonstration of the environmentally superior and cost effective power generation from raw, Alaskan LRCs. Coal use within the state could be increased by the development of small reliable coal-fired generating plants to replace diesel-fired generators in remote villages.



## INTRODUCTION

### Background

The Mineral Industry Research Laboratory's (MIRL) near term goals for this project, which has now been completed, were: 1) develop data on the responses of Alaskan coals to advanced drying/pyrolysis processes; 2) assess the stability of the dried/pyrolyzed products towards moisture readsorption, fines production and oxidation (an estimation of reactivity and tendency for spontaneous combustion) as a function of the process and operating parameters; and 3) reassess transportation requirements and costs based on altered coal properties. The candidate coal for this test work was subbituminous "C" coal from the Usibelli Coal Mine, Healy, Alaska; chosen due to existing domestic and export markets, its environmental quality, and its association with Alaska's developed transportation infrastructure.

Like other Alaskan low-rank coals (LRCs), Usibelli coal has extremely low sulfur content and is already a compliance coal (0.4 lb SO<sub>2</sub>/MM Btu). A recent, three year average, sulfur content for Usibelli coal was 0.17%. The Nenana Basin, which hosts the Usibelli Coal Mine, Alaska's only operating coal mine, has approximately 10 billion tons of reserves(1). Ten billion tons of subbituminous "C" coal contains the energy equivalent of nearly 55 years of Alyeska Pipeline production at 1.5 million barrels per day.

Despite this enormous energy reserve, the Nenana Basin is a small component of Alaska's total wealth of coal. Alaska's 5.5 trillion tons of estimated coal resources comprise about half the United States' coal resources(1), with each trillion ton containing the energy equivalent of approximately 5,500 years of Alyeska Pipeline production (1.5 MM Barrels/day). The locations of the major coal regions in Alaska are shown in Figure 1. The largest of Alaska's coal basins, estimated to be over 4 trillion tons, is the Northern Alaska Basin. It consists of a tremendous subbituminous coal deposit, which in areas overlies a rich bituminous deposit(1). The Cook Inlet-Susitna Basin, which is composed mainly of low-rank coals, may contain over a trillion tons. The remainder of the coal basins are small by Alaskan standards but still contain billions of tons of reserves.

In addition to their low sulfur levels, many of the LRCs have moderate ash levels and reactivities typically an order of magnitude higher than their bituminous counterparts. They are prime candidates for use in advanced applications such as gasifiers and fluid-bed combustors. Some Alaskan LRCs are recoverable by strip mining and near tidewater, making them amenable to low-cost ocean transport.

Major reasons for the limited use of Alaskan coals include low population density, distance from high energy use areas, abundant more convenient energy forms (gas and oil)

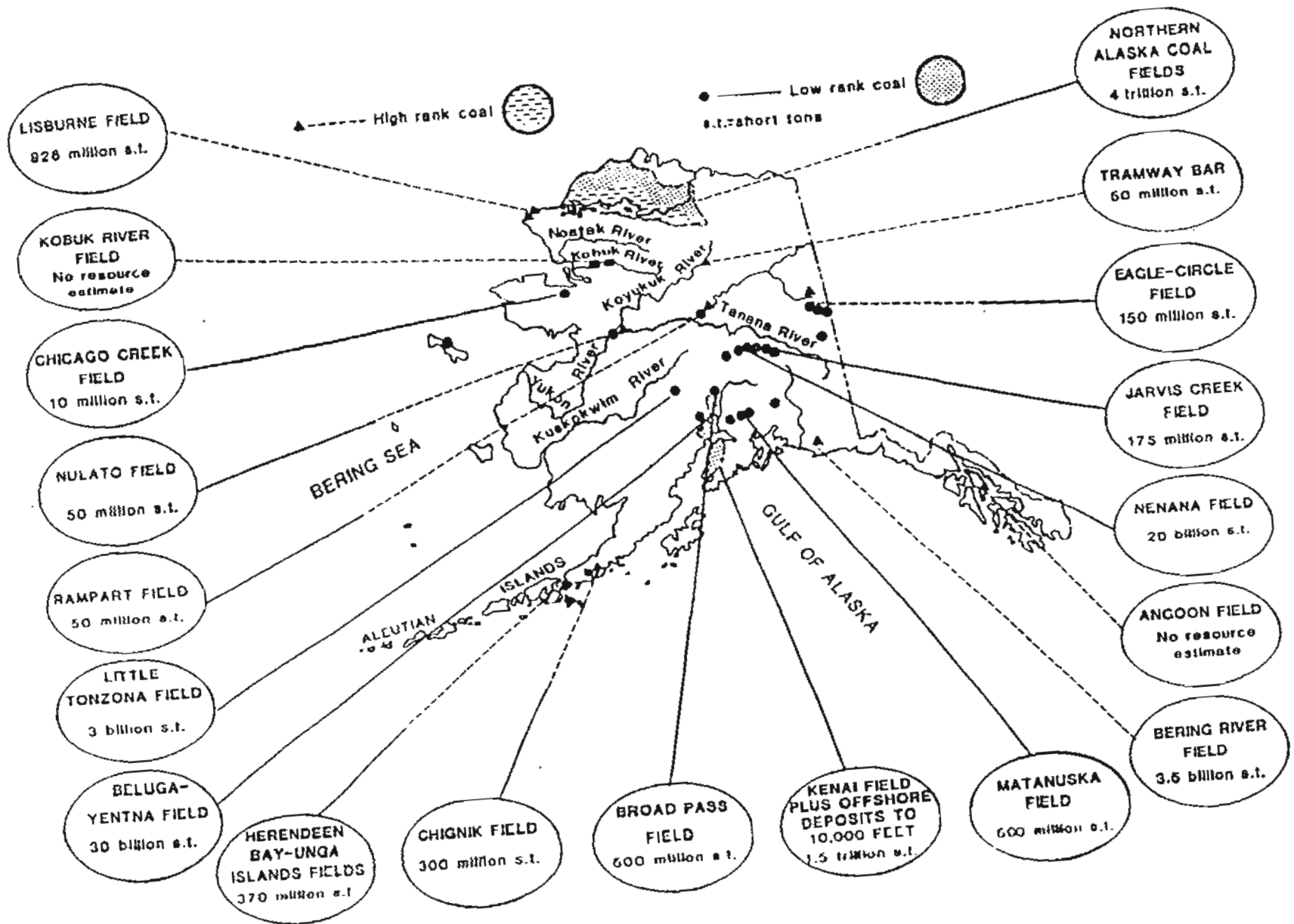


Figure 1. Coal Resources of Alaska.

and mining and transportation costs. In addition, the low-sulfur, highly reactive LRCs are plagued with the high moisture inherent to their rank. This has restricted the worldwide usage of most LRCs to mine mouth power generation.

The initial focus of this project was to evaluate the impact of two high temperature drying/pyrolysis processes on the product coals' properties and transportation costs. During the course of the study, it was also decided to evaluate a third drying process, hydrothermal treatment of lump coal. Of course, the long term goal of this and other coal drying studies conducted at MIRC, was to define drying technologies that have significant and real potential to competitively move Alaska's, low-rank coals into the export, steam coal market of the Pacific Rim.

In 1990, Japan imported 33 million metric tons (mt) of steam coal with an additional 39 million mt imported by other Far East nations(2). Australia dominates the export steam coal market to these Pacific Rim countries and exported 48 million mt in 1990 and an additional 61 million mt of metallurgical coal(2).

The steam coal export market has been expanding rapidly, from 20 million mt in 1973 to 150 million mt in 1989, and is expected to double to nearly 300 million mt by the end of the century(3). Much of this new demand will be by Western Europe, where coal production is experiencing rapid decline due to exhaustion of reserves. At the same time, there will be increased demand for coal for the social and economic development of eastern European nations emerging from oppressive communist regimes. It is worth noting that Western European countries imported 90 millions mt of steam coal in 1990, compared to 80 million mt in 1989 and 74 million mt in 1988(2). Increased demand by Europe should keep the price of steam coal on a stable to positive slope worldwide. For example, in Japan the contract price for steam coals rose by 4.3% in 1990 to \$41/mt (fob Australia and Canada)(2).

There is also potential for Alaska's low sulfur coal to enter the European markets as air quality issues assume a more prominent status there. Recently, Spain purchased a bulk tonnage sample of Powder River Basin (low sulfur) coal from Wyoming for combustion tests. This coal requires rail, barge and ocean transport to reach Spain.

Could Alaska capture only 3% of the projected new, steam coal market, which is not an unreasonable expectation, the value of the state's coal exports would soar from nominally \$28 million per year to over \$100 million per year. However, without development of economical methods for drying/stabilizing Alaskan LRCs, the only increase in export of Alaskan coals may be from the few "higher rank" coals within a "reasonable" transport range of the existing Alaska rail system or tidewater. The only high-rank

candidate yet identified is the Wishbone Hill property being developed by Idemitsu Kosan, near Palmer, Alaska.

For Alaska to truly participate in the expansion of the Pacific Rim steam coal market, existing drying technologies must be modified and/or new technologies developed for application to Alaskan coals that will yield a product which will be competitive in the open market. In addition to the State's need to develop environmentally sound industries that offer generations of employment opportunities, any increase in the export of Alaskan coal will be welcome to the U.S. economy in its struggle to reduce the trade deficit.

As discussed above, the overall aim of this project was to evaluate three coal drying technologies that showed promise for enhancing the quality of Alaskan low-rank coals and improve its marketability as a steam coal. Presently the coal from the Usibelli Coal Mine is the only low-rank coal exported internationally as a steam coal; primarily for its blending properties with other coal to improve combustion. But for Alaskan low-rank coals to truly stand on their own merits, economical drying processes must be developed that produce a physically and chemically stable dried product.

### Coal Drying Technologies

Drying processes are generally categorized by operating temperature, drying environment and the type of feed; either sized or ground coal. Within these broad categories, processes differ according to the type of drier and methods of quenching and stabilizing the dried product.

o Conventional Evaporative Drying - There are numerous low temperature drying technologies available, each with its pros and cons. Most processes use hot flue gases to evaporate the coal moisture. The final product moisture is dependent on feed size and residence time at temperature. For entrained reactors like a Parry drier, moisture can be reduced to a few per cent(4). For larger sized feed such as those used in rotary kiln driers, a nominal moisture level of 15% is typical(4).

Due to the low temperatures used, these processes are the least expensive and are preferred if the dried product is to be used immediately. However, since the drying temperatures are too low to cause permanent changes in the coal structure, the dried coals behave like sponges, and, when re-exposed to humidity or water, reabsorb the lost moisture unless steps are taken to minimize the exposed dried surface area(4). The untreated dried product is also susceptible to spontaneous heating and fines production.

Methods for minimizing these problems include: coating the coal with residual tar or oil; drying only larger lump coal; or producing briquettes or pellets from dried pulverized

coal. All of these additional processing steps increase the cost of the final product and must be evaluated on a coal and site specific basis. For oil treatment, the key economic factor will be how much oil is required to stabilize the product. For large sized coal drying, the key will be the amount of fines produced and their use. For briquettes or pellets, an important economic factor will be binder requirements and processing costs.

The largest commercial drying venture in the U.S. has entered its initial operating phase at AMAX's drying plant near Gillette, Wyoming. Drying of the subbituminous coal to a "stable," 10 - 15 % moisture product in a fluid-bed drier is the main objective. The gravel sized dried product is stabilized by a coating of residual oil and fines are returned to the process combustor(5). Technically the project has met with little success due to the extreme friability of dry LRCs and the problems associated with reactive coal fines. To date the owners are constrained to ship a product with a slight moisture reduction and an increase in the heating value of less than 10% to 8,900 Btu/lb(6,7).

o High Temperature Drying - If LRCs are dried at temperatures above about 465°F (240°C) the basic chemical and physical coal characteristics begin to change. Decarboxylation occurs and CO<sub>2</sub> is evolved(8). Decarboxylation helps reduce the coal's capacity to bind water by ridding the surface of hydrophilic functionalities(8). Much of the coal's additional volatile matter, tars and oils, are also liberated and migrate to the coal's surface(8). If the tars are not stripped during drying, they remain on the coal, effectively sealing the micropores and reducing the coal's ability to hold water.

Product stability, especially towards fines production and spontaneous combustion, is a major concern for most high temperature processes that yield a dry product. The same stabilization methods described previously for low temperature drying processes are proposed to enhance product stability, but to date we are unaware of any high temperature drying process, which produces a dried LRC product that can withstand the rigors of shipping.

o Hot-Water Drying (HWD) - This process, also referred to as hydrothermal processing, is an advanced technology featuring high temperature/pressure, non-evaporative drying. In this process LRC is treated at coal specific temperatures beginning as low as 465°F (240°C) at the corresponding saturated steam pressure. Water is removed via expansion and expulsion of CO<sub>2</sub>. Devolatilized tars and or oils, being hydrophobic, are retained on the coal surface in the pressurized aqueous environment, Figure 2. This uniquely uniform tar distribution seals most of the micropores, reducing water reabsorption. The overall process, induced coalification, removes the inherent moisture and for some high moisture

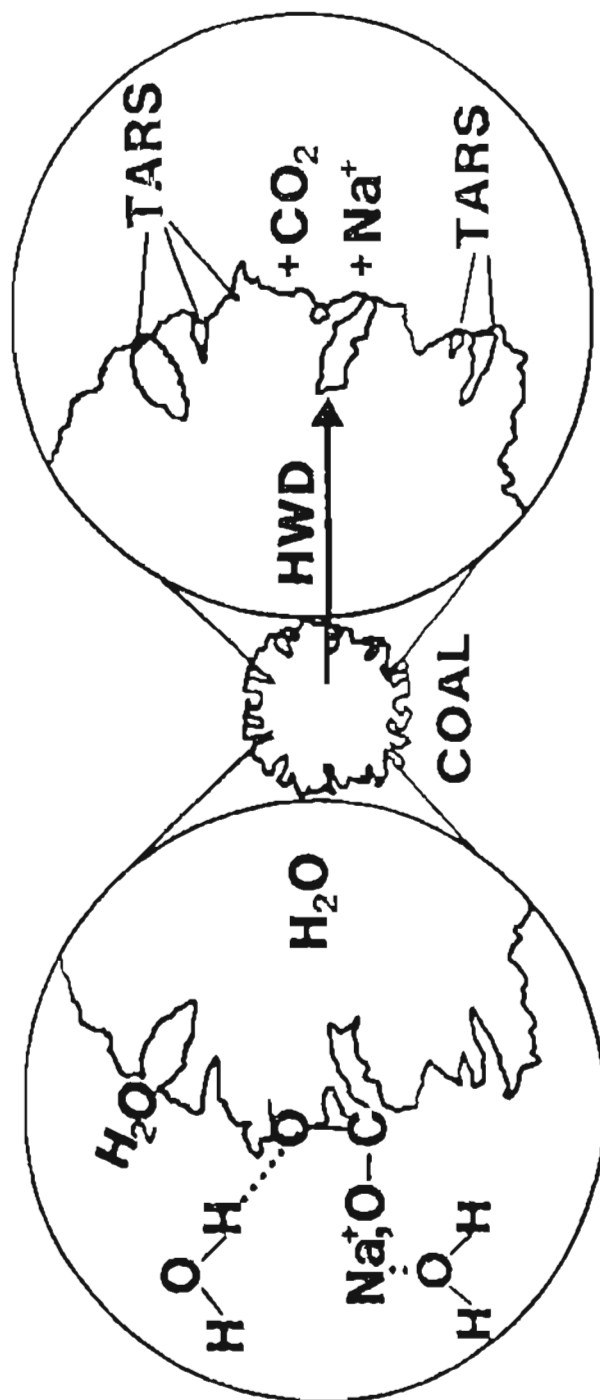


Figure 2. Decarboxylation, Tar Sealing and Alkali Cation Release; Benefits of the Hot Water Drying Process.

coals the process even become a net producer of water. In some coals, alkali cations associated with the carboxyl groups are released into the aqueous phase and can be removed by washing the product during the final mechanical dewatering step. This gives a product with a much lower propensity for boiler tube fouling(9).

Hot-water drying induces coalification and alters the hydrophilic nature of LRC into a hydrophobic material that has equilibrium moisture levels similar to those of bituminous coals. This process also enables the production of coal-water fuel (CWF) from finely ground LRCs with solids loadings comparable to those obtained with high-rank coals. CWF is a concentrated mixture of finely ground coal and water, 55-70% solids by weight. CWF should not be confused with coal-water slurry, CWS, which is a dilute, unstable mixture of coarsely ground coal and water used for pipeline transportation of coal.

The ability to produce CWFs from LRCs takes on added significance when considering Pacific Rim countries. Japan already produces 75 megawatts from CWFs, coal-water mixtures, Japan's name for CWFs produced from bituminous coals, which require costly chemical additives to maintain high solids loading. Lead by Japan, Pacific Rim countries are moving rapidly to achieve a diversified energy mix from stable suppliers(10). No longer will the users be restricted to the purchase of CWFs made from expensive high-rank coals. With HWD, the cheaper, more reactive LRCs of Alaska become attractive.

## DESCRIPTION OF DRYING PROCESSES

The technologies that have the most potential for increasing the use of Alaskan coals are those that can reduce the moisture content of these coals economically, and produce a fuel that is accepted in the international market place. Drying technologies will no doubt differ, depending on the end use of the fuel; be it dried lump coal, briquettes or pellets for pulverized coal or stoker applications, or concentrated coal-water fuels made from hot-water dried LRCs. There are a number of developing processes that may work with Alaskan coals. Some driers, however, have been plagued by the production of excessive amounts of coal fines. Since the demand for Alaskan coal is currently limited to lump size coal, large quantities of fines are a definite liability.

In this study, two high temperature drying/pyrolysis processes and one hydrothermal process were investigated. The high temperature drying/pyrolysis processes were conducted at (1) the Western Research Institute, (WRI) an affiliate of the University of Wyoming Research Corporation, Laramie, WY, and (2) Coal Technology Corporation

(CTC) of Brisol, VA. Hydrothermal processing was conducted at MIRL, University of Alaska Fairbanks.

### The WRI Process

The Western Research Institute, offers new inclined-fluid-bed (IFB) technology to produce dried lump coal. The WRI IFB drier uses minimum fluidization velocities, allowing the dried coal to move in plug flow gently through the slightly sloping reactor. By avoiding the turbulence and intense back-mixing found in most fluid bed applications, the WRI process may yield a high proportion of lump coal to fines.

In order to block the coals micropores, and cap hydrophylic functionalities on the dried coal's surface towards moisture readsorption and oxidation, the coal tars produced in-situ must remain with the coal. To date, no process which seeks to add stability by "recoating" with coal tars or "inexpensive" stabilizing agents has been successful. WRI uses a second IFB fluidized with cool, process generated CO<sub>2</sub> in an attempt to quench the tars on the coal surface. The experimental bench-scale IFB coal processing equipment, used at WRI is shown in Figure 3.

"It consists of two 5-ft-long IFB reactors in series separated by lockhopper valves that pneumatically isolate the two reactors while allowing for solids transfer from the first reactor to the second. The reactor provides for particle disengaging space above the bed. Effluent gas is withdrawn from multiple openings to avoid imparting significant horizontal velocity to gas in the disengaging space. Effluent gas piping is arranged such that gas from all outlets flows the same distance and through the same number of turns to balance flow from each withdrawal point. Heaters are placed to give four zones of independent temperature control. Bed thermocouples, gas sample points, and solid sample points are located such that complete sets of samples at known temperatures can be taken from the bed.

Controlled amounts of CO<sub>2</sub> fluidizing gas are introduced into each of the IFB reactors. In the first reactor (IFB coal dryer) the CO<sub>2</sub> is heated prior to introduction into the dryer. This hot CO<sub>2</sub> supplies the process heat required for drying the coal. The coal is fed to the dryer from a sealed hopper using a variable-speed screw conveyor. Fine coal particles entrained in the fluidizing gas are collected in a cyclone separator and in a settling chamber (secondary fines collector). The exit gas from the settling chamber flows into a series of three air-cooled and two water-cooled condensers to remove water from the gas. A small amount of the dry solids-free gas is



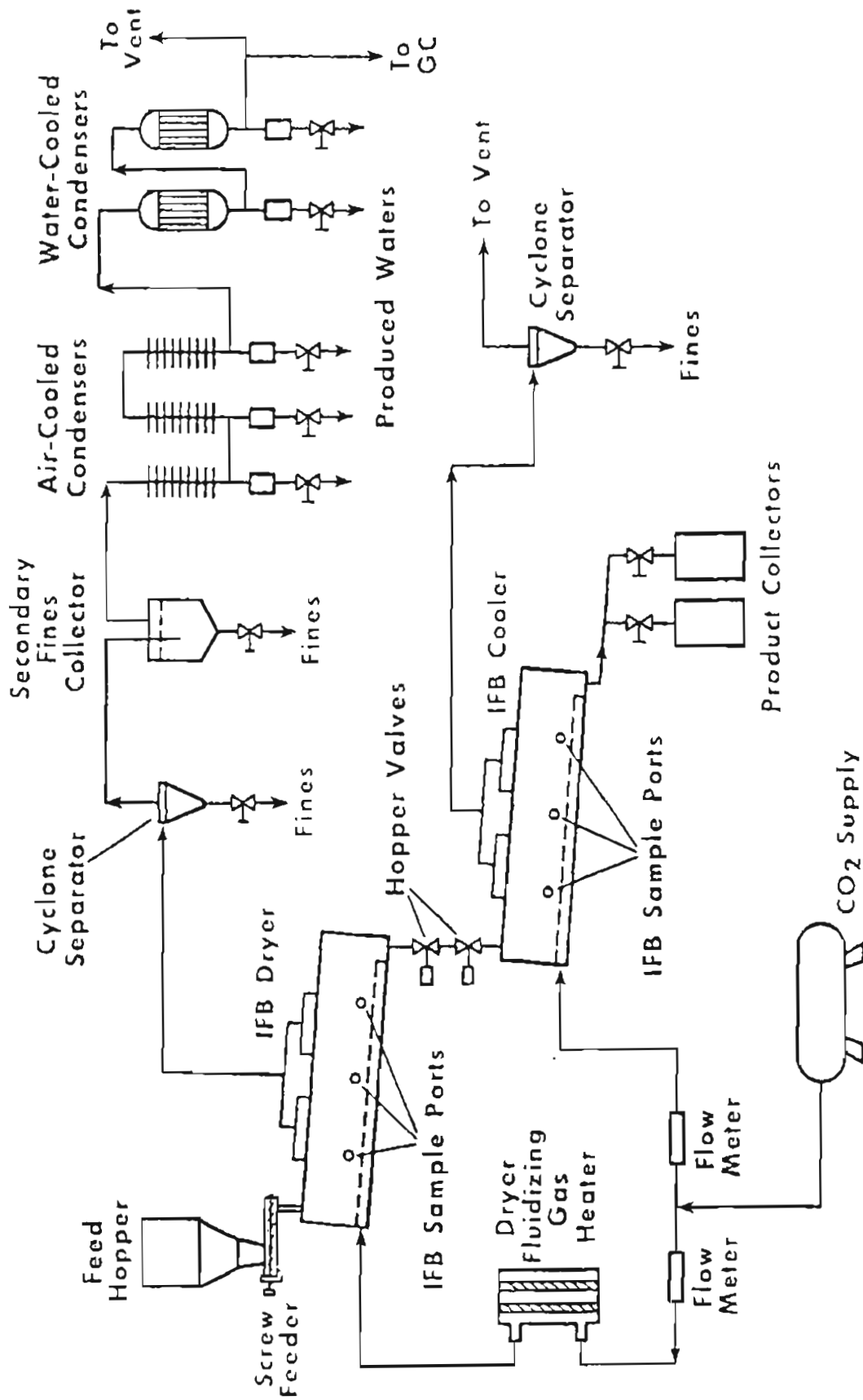


Figure 3. WRI's Bench-Scale Coal Drying Unit (II).

sampled and analyzed using a gas chromatograph (GC). The remainder of this gas is vented to atmosphere.

The fluidizing gas (CO<sub>2</sub>) introduced into the second reactor (IFB cooler) is at ambient temperature. It is used to cool the dried coal that exits the IFB dryer. Entrained solids in the exit gas are collected in a cyclone separator prior to venting the gas to atmosphere. The cooled dry coal is collected as product after it exits the IFB cooler." (11)

During the tests, gas-to-solids weight ratios varied from approximately 0.7 to 4.0 for Usibelli coal. Similarly, average IFB reactor temperatures varied from approximately 632 to 1230°F. Residence times varied from 1 to 12 minutes. Depending upon the temperature and residence time employed, the WRI IFB reactor could produce a range of coal products from a dried coal to a pyrolyzed char.

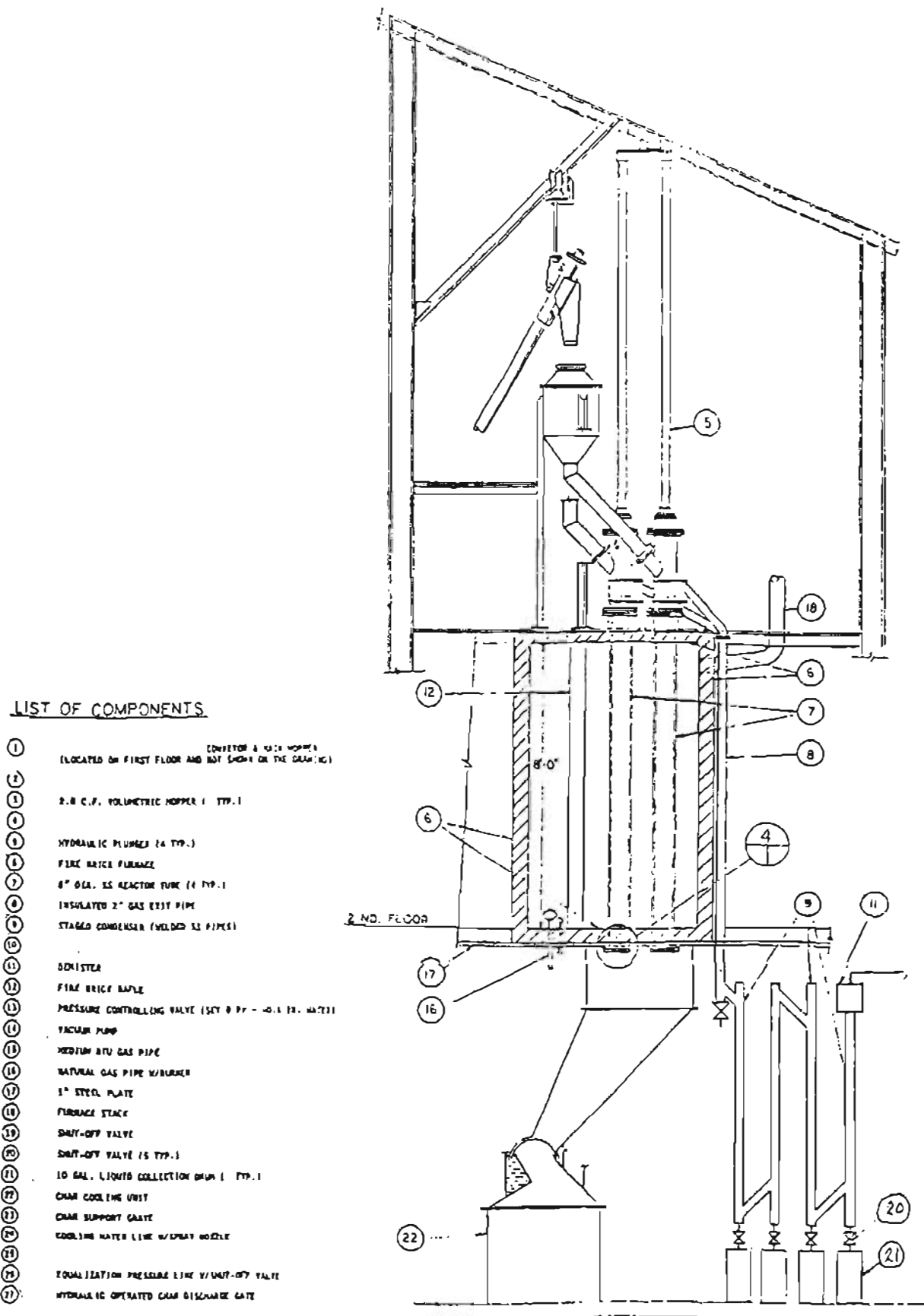
#### The CTC Process

Coal Technology Corporation processed samples of Usibelli coal in the bench scale pyrolysis unit shown in Figure 4. There are two reactor tubes 6 inches in diameter x 8 feet long with a coal capacity of approximately 70 pounds of coal in each tube, or 140 lbs/batch. Coal is placed in the reactor tubes, preheated inert gas is used to assure that air is excluded at all times during the process, the temperature in the tubes is gradually raised at a planned rate over a 4-6 hour period to a maximum of 1300°F. Gases from the reactor are piped to a condensing system to collect coal liquids. The non-condensable gases go to a flare after samples have been obtained. At the end of the heating period, the char is discharged to a cooling bin by opening gates at the bottom of the reactor tubes and by pushing from the top of the tubes by a hydraulic plunger.

For a given coal the customary variables in the pyrolysis process are: heating rate (usually about 0.5 degree Fahrenheit/minute); final char temperature and coal particle size. The heating rate and the final char temperature determines the residence time. Also diminished gas flow to flare indicates completion of devolatilization of the char at the specific operating temperature. Normally CTC's objective has been to select operating conditions that will maximize the quality and quantity of the coal liquids, as well as making a char that can be used in a specific market application.

#### The Hydrothermal Drying Process

Fischer and Schrader first studied hydrothermal treatment of coals in 1921. Their process involved subjecting coals to a temperature of 610° to 750°F in the presence of



LIST OF COMPONENTS.

- ① CONCRETE & RUBBER HOOPER (LOCATED ON FIRST FLOOR AND NOT SHOWN ON THE DRAWING)
- ② 2.0 C.F. VOLUMETRIC HOOPER ( TYP. 1)
- ③ HYDRAULIC PLUNGER (4 TYP.)
- ④ FIRE BRICK FURNACE
- ⑤ 8" DIA. SS REACTOR TUBE (4 TYP. 1)
- ⑥ INSULATED 2" GAS TEST PIPE
- ⑦ STAGED CONDENSER (WELDED SS PIPES)
- ⑧ DENISTER
- ⑨ FINE BRICK Baffle
- ⑩ PRESSURE CONTROLLING VALVE (SEE 8 Pp - 40.1 IN. WATER)
- ⑪ VACUUM PUMP
- ⑫ MEDIUM BTU GAS PIPE
- ⑬ NATURAL GAS PIPE W/BURNER
- ⑭ 1" STEEL PLATE
- ⑮ FURNACE STACK
- ⑯ SHUT-OFF VALVE
- ⑰ SHUT-OFF VALVE (5 TYP.)
- ⑱ 10 GAL. LIQUID COLLECTION DRUM ( TYP. 1)
- ⑲ CHAR COOLING UNIT
- ⑳ CHAR SUPPORT GATE
- ㉑ COOLING WATER LINE W/Spray NOZZLE
- ㉒ EQUALIZATION PRESSURE LINE W/SHUT-OFF VALVE
- ㉓ HYDRAULIC OPERATED CHAR DISCHARGE GATE

Figure 4. CTC's Pyrolysis Unit.

water in an autoclave. In 1927, Fleissner patented a pressurized, saturated steam drying process that is still being used today to hydrothermally dry lignite in what was East Germany as well as in Yugoslavia and Turkey. Koppleman's process, used in the K-fuels system, treats LRCs at temperatures of 930° to 1110°F and high pressure. The process liberates moisture as well as light hydrocarbon gases and liquids. The process developed by University of North Dakota and Bechtel uses temperatures less than 750°F. The gases liberated principally consist of CO<sub>2</sub>(12).

In cooperation with Dr. Warrack Willson (Director, Fuel and Process Chemistry Research Institute, EERC, University of North Dakota), the University of Alaska acquired a hydrothermal treatment system consisting of a 2 gallon autoclave and a 1 gallon quench autoclave (Figure 5).

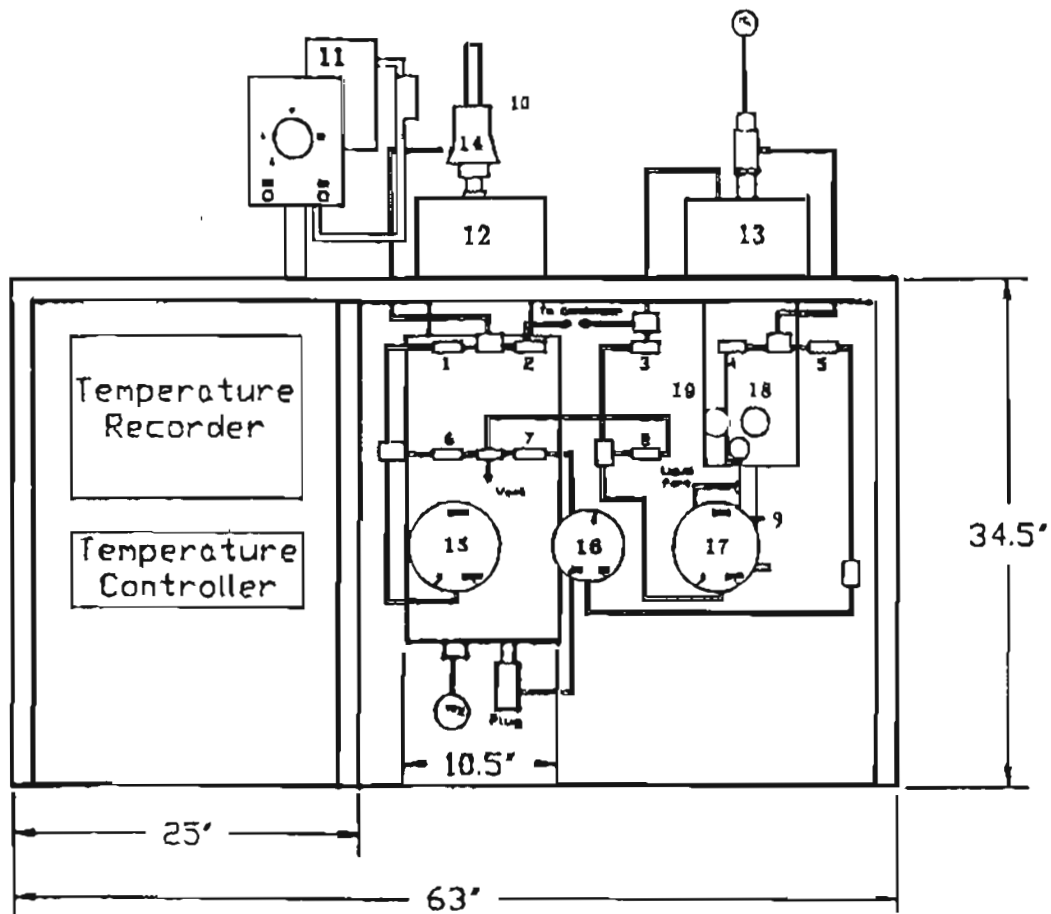
Sized 1 x 1-1/2 inch Usibelli coal samples were subjected to hydrothermal treatment while (a) immersed in hot water, and (b) subjected to steam pressure. These resulting hydrothermally treated coals were used for chemical and physical characterization as well as petrological study.

Approximately 1400 gm of coal and 2800 gm of water were loaded into the 2 gallon autoclave. For hot water treatment, coal pieces were submerged in water in a specially built stainless steel basket. For steam treatment, coal pieces were held in a stainless steel basket and suspended above water level. The autoclave was heated to the desired temperature, then turned off when the desired temperature was reached for tests 1, 3 and 5, while the desired temperature was maintained for 60 min. for tests 2, 4, and 6 to evaluate residence time effects. Three different temperatures, 527°F, 572°F and 617°F were tested at 0 and 60 min. residence times.

## PRODUCT CHARACTERIZATION

After representative samples of Usibelli Coal had been subjected to the various drying/pyrolysis processes (WRI, CTC and HWD), the products were subjected to a suite of coal characterization tests. These tests were chosen to describe the physical and chemical stability of the dried coal, as well as its composition, grindability, and ash fusibility. Not all tests were run on all dried products due to constraints imposed by product size, time and funding. However, enough data has been generated to describe the dried products and allow general conclusions about their desirability as end use materials.

Where ASTM procedures existed for a particular test and/or analysis these were followed. The general format of this section of the report is to present the data and a



- |  |  |
|--|--|
| 1— Two-gallon reactor pressure gauge isolation valve (V1)                        | 10— Wet oxidation valve (V10)                          |
| 2— Condenser/product receiver isolation valve (V2)                               | 11— Drive motor of Magnedrive assembly                 |
| 3— Liquid/gas product receiver and condenser pressure gauge isolation valve (V3) | 12— Two-gallon autoclave with safety head assembly     |
| 4— Product gas regulation isolation valve (V4)                                   | 13— One-gallon autoclave with safety head assembly     |
| 5— Vacuum isolation valve (V5)   | 14— Magnedrive assembly                                |
| 6— Two-gallon reactor pressure gauge vent valve (V6)                             | 15— Two-gallon reactor pressure gauge (P1)             |
| 7— Two-gallon reactor vent valve (V7)  | 16— Vacuum gauge (P3)                                  |
| 8— Liquid/gas product receiver pressure gauge vent valve (V8)                    | 17— One-gallon product receiver pressure gauge (P2)    |
| 9— Flush bottom valve for liquid sampling valve (V9)                             | 18, 19— product gas regulator pressure gauges (P4, P5) |

Figure 5. MIRL's Hydrothermal Autoclave System.

discussion thereof by characterization test category, i.e., grindability, oxidative stability, ash composition, ... Discussion emphasizes the dried products' characteristics with respect to handling, transportation, and combustibility.

### Proximate and Ultimate Analyses

The most notable characteristic of both WRI pyrolyzed coal (Table 1) and CTC pyrolyzed coal (Table 3) is devolatilization. This is not surprising nor unexpected given the mild gasification/pyrolysis nature of the processes. Devolatilization increases with higher temperatures and longer residence times, and is demonstrated by the increasing percentage of fixed carbon (Figure 6) and decreasing fractions of volatile matter, hydrogen, and oxygen. The most serious consequence of this devolatilization is the loss of considerable mass, which has valuable calorific value, and increasing the coal's fuel ratio, fixed carbon: volatile matter.

The fuel ratio is an empirical ratio. Many coal users consult it when buying coal to assure high enough reactivity to achieve nearly complete carbon burnout. The higher the fuel ratio, the lower the volatile content, which is indicative of a material that is difficult to ignite and requires longer residence times for complete carbon burnout. (1.6 is suggested as a cut off point for many combustion applications). It is important to note that the fuel ratio for WRI and CTC chars increased dramatically with process temperature (Figure 7).

In the case of WRI chars, the raw coal's fuel ratio of 0.9 was altered to fuel ratios from 3.0 to 4.2 for process temperatures above 1000°F. CTC chars showed the same trend, with fuel ratios increasing within the 1.8 to 5.5 range for temperatures ranging from 900°F to 1300°F respectively. Despite the drastic alteration in fuel ratios these chars appear highly reactive with respect to spontaneous heating. Thus, without true combustion tests, it is difficult to predict how the chars would combust in a power plant setting, i.e., fuel ratios indicate poor ignition and combustibility but they are highly reactive. It is possible that the spontaneous heating which the chars demonstrate, is initiated by the heat of wetting from moisture reabsorption and that the chars may be otherwise refractory, but this dichotomy was not resolved in this study. The bottom line here is that if the market for a coal product is power generation (combustion), then it behooves the process not to strip the calorifically valuable volatile matter from the parent coal. These volatiles aid ignition and combustion of coal particles.

Tables 4 and 5 shows proximate and ultimate analyses for hydrothermally dried lump coal. Even at the highest temperature and longest residence time tested, the fuel ratio remained below the 1.6 suggested as a cut off point for many combustion applications (Figure 7). The fuel ratio of 0.9 for the parent Usibelli coal, was altered upwards to 1.2 to

Table 1.

Proximate and Ultimate Analyses of Raw Coal, Dried Coal and Char Products from Mild Gasification Treatment in WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size Mesh	Treatment Temp., °F (°C)	Retention Time Min.	Basis	Moisture,%	Ash,%	Volatile Matter,%	Fixed Carbon,%	Fuel Ratio, (FC/VM)	Heating Value, Btu/lb	Total Sulfur,%	C,%	H,%	N,%	O,%
Raw Coal	N/A	N/A	N/A	2	24.47	8.61	34.99	31.93		7999	0.27	45.58	6.87	0.55	38.13
				3		11.39	46.33	42.27	0.9	10591	0.35	60.34	5.47	0.73	21.72
				4			52.29	47.71		11952	0.40	68.10	6.17	0.82	24.50
101/102	16x0	700 (371)	3	1	0.61	13.55	44.43	41.41		10460	0.40	59.35	5.20	0.77	20.73
				2	17.30	11.27	36.97	34.46	0.9	8704	0.33	49.38	6.21	0.64	32.16
				3		13.63	44.70	41.66		10524	0.40	59.71	5.16	0.77	20.31
				4			51.76	48.24		12185	0.47	69.14	5.98	0.90	23.51
59	16x100	1090 (588)	1	1	0.0	17.39	20.74	61.87		10870	0.25	65.74	3.05	0.99	12.58
				2	12.54	15.21	18.14	54.11	3.0	9507	0.22	57.50	4.07	0.87	22.14
				3		17.39	20.74	61.87		10870	0.25	65.74	3.05	0.99	12.58
				4			25.11	74.89		13158	0.30	79.58	3.69	1.20	15.23
63	16x100	1120 (604)	4	1	0.0	19.08	20.30	60.62		10660	0.25	64.68	2.76	1.02	12.21
				2	13.27	16.55	17.61	52.58	3.0	9245	0.22	56.10	3.88	0.88	22.37
				3		19.08	20.30	60.62		10660	0.25	64.68	2.76	1.02	12.21
				4			25.09	74.91		13174	0.31	79.93	3.41	1.26	15.09
64	16x100	1180 (638)	7	1	0.0	19.76	17.88	62.36		10640	0.25	66.00	2.52	1.03	10.44
				2	12.01	17.39	15.73	54.87	3.5	9362	0.22	58.07	3.56	0.91	19.85
				3		19.76	17.88	62.36		10640	0.25	66.00	2.52	1.03	10.44
				4			22.28	77.72		13260	0.31	82.25	3.14	1.28	13.01
62	16x100	1230 (666)	12	1	0.0	17.44	15.97	66.59		11290	0.36	69.27	2.35	1.12	9.46
				2	10.73	15.57	14.26	59.44	4.2	10079	0.32	61.84	3.30	1.00	17.97
				3		17.44	15.97	66.59		11290	0.36	69.27	2.35	1.12	9.46
				4			19.34	80.66		13675	0.44	83.90	2.85	1.36	11.45

- 1 As Received Basis
- 2 Equilibrium Moisture Basis (ASTM D-1412)
- 3 Moisture Free Basis
- 4 Dry, Ash Free Basis

Table 2.  
Proximate and Ultimate Analyses of Raw Coal and Dried Coal Product from WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size Mesh	Treatment Temp., °F (°C)	Retention Time Min.	Basis	Moisture, %	Ash, %	Volatile Matter, %	Fixed Carbon, %	Fuel Ratio, (FC/VM)	Heating Value, Btu/lb	Total Sulfur, %	C, %	H, %	N, %	O, %
Raw Coal	N/A	N/A	N/A	2	20.58	8.56	36.75	34.11		8383	0.19	47.95	6.59	0.54	36.19
				3		10.78	46.27	42.94	0.9	10555	0.20	60.38	5.40	0.69	22.56
				4			51.87	48.13		11831	0.23	67.67	6.05	0.77	25.28
D-39	16x0	632 (333)	-	1	0.90	13.60	36.78	48.72		10530	0.15	61.28	4.60	0.76	19.61
				2	14.78	11.70	31.63	41.90	1.3	9055	0.12	52.70	5.52	0.65	29.31
				3		13.72	37.11	49.16		10626	0.15	61.84	4.54	0.77	18.98
				4			43.02	56.98		12316	0.17	71.67	5.26	0.89	22.01

- 1 As Received Basis
- 2 Equilibrium Moisture Basis (ASTM D-1412)
- 3 Moisture Free Basis
- 4 Dry, Ash Free Basis



Table 3.

Proximate and Ultimate Analyses of Raw Coal and Char Products from Mild Gasification Treatment in CTC's Vertical Column Reactor

Test Number	Feed Size Inches	Treatment Temp., °F (°C)	Retention Time, Min.	Basis	Moisture, %	Ash, %	Volatile Matter, %	Fixed Carbon, %	Fuel Ratio, (FC/VM)	Heating Value, Btu/lb	Total Sulfur, %	C, %	H, %	N, %	O, %
Raw Coal	N/A	N/A	N/A	2	25.24	7.66	35.03	32.06		7831	0.21	44.96	6.63	0.49	40.05
				3		10.25	46.86	42.89	0.9	10475	0.29	60.14	5.08	0.66	23.57
				4			52.22	47.78		11671	0.32	67.01	5.66	0.74	26.27
11	2x1/4	900 (482)	420	1	2.79	14.69	29.89	52.63		10780	0.32	62.91	4.48	0.85	16.75
				2	10.75	13.49	27.44	48.32	1.8	9897	0.29	57.76	5.03	0.78	22.65
				3		15.11	30.75	54.14		11089	0.33	64.72	4.29	0.87	14.68
				4			36.22	63.78		13063	0.39	76.24	5.05	1.03	17.29
7/10	2x0	1000 (538)	420	1	2.49	16.85	23.67	56.99		10750	0.34	63.91	3.79	0.88	14.23
				2	10.45	15.47	21.74	52.34	2.4	9872	0.31	58.69	4.39	0.81	20.32
				3		17.28	24.27	58.45		11025	0.35	65.54	3.60	0.90	12.33
				4			29.35	70.65		13328	0.42	79.23	4.35	1.09	14.90
12	2x1/4	1100 (593)	400	1	1.83	18.44	20.55	59.18		10990	0.34	65.56	3.39	0.91	11.36
				2	9.38	17.02	18.97	54.63	2.9	10145	0.31	60.52	3.99	0.84	17.32
				3		18.78	20.93	60.28		11195	0.35	66.78	3.24	0.93	9.92
				4			25.77	74.23		13784	0.43	82.23	4.00	1.14	12.21
13	2x1/4	1300 (704)	400	1	0.19	17.46	12.72	69.63		11610	0.33	71.70	2.35	1.01	7.15
				2	8.78	15.96	11.63	63.64	5.5	10611	0.30	65.53	3.11	0.92	14.18
				3		17.49	12.74	69.76		11632	0.33	71.84	2.33	1.01	6.99
				4			15.45	84.55		14098	0.40	87.07	2.83	1.23	8.48

1 As Received Basis

2 Equilibrium Moisture Basis (ASTM D-1412)

3 Moisture Free Basis

4 Dry, Ash Free Basis

Table 4.  
Proximate and Ultimate Analyses of Raw and Hydrothermally Treated 1" x 1-1/2" Coal in Hot Water.  
No. 4 Seam, Usibelli Coal Mine

Test No.	Max Temp/ Res. Time at Max Temp.	Basis	Moisture, %	Ash,%	Volatile Matter,%	Fixed Carbon,%	Fuel Ratio, (FC/VM)	Heating Value, Btu/lb	Total Sulfur, %	C,%	H,%	N,%	O,%
Raw Coal		1	27.27	4.04	35.87	32.82		8155	0.13	47.17	7.10	0.51	41.05
		2		5.56	49.32	45.12	0.9	11213	0.18	64.86	5.57	0.70	23.14
		3			52.22	47.78		11873	0.19	68.67	5.90	0.74	24.50
UHW 1 527°F/0 min. (275°C)		1	9.46	4.78	39.47	46.29		11059	0.16	62.61	5.95	0.75	25.76
		2		5.28	43.60	51.12	1.2	12215	0.17	69.15	5.40	0.83	19.17
		3			46.03	53.97		12896	0.18	73.00	5.70	0.87	20.24
UHW2 527°F/60 min. (275°C)		1	11.27	4.92	38.26	45.55		10710	0.15	61.47	6.11	0.71	26.63
		2		5.55	43.12	51.33	1.2	12070	0.17	69.27	5.47	0.80	18.73
		3			45.65	54.35		12779	0.18	73.34	5.79	0.85	19.83
UHW3 572°F/0 min. (300°C)		1	8.29	5.04	39.64	47.03		11283	0.15	63.92	5.94	0.76	24.20
		2		5.49	43.23	51.28	1.2	12303	0.16	69.70	5.47	0.82	18.36
		3			45.74	54.26		13019	0.17	73.75	5.78	0.87	19.43
UHW4 572°F/60 min. (300°C)		1	7.78	5.17	38.00	49.05		11535	0.15	65.09	5.87	0.76	22.96
		2		5.60	41.21	53.19	1.3	12509	0.16	70.59	5.43	0.82	17.40
		3			43.65	56.35		13251	0.17	74.78	5.75	0.87	18.43
UHW5 617°F/0 min. (325°C)		1	6.97	5.43	38.47	49.12		11785	0.14	66.51	5.84	0.77	21.30
		2		5.84	41.35	52.80	1.3	12668	0.15	71.50	5.43	0.83	16.25
		3			43.92	56.08		13454	0.16	75.93	5.77	0.88	17.25
UHW6 617°F/60 min. (325°C)		1	6.83	6.24	35.76	51.17		11901	0.15	67.08	5.78	0.76	19.98
		2		6.70	38.38	54.92	1.4	12773	0.16	72.00	5.39	0.82	14.93
		3			41.14	58.86		13691	0.17	77.17	5.77	0.88	16.00

1 - ASTM equilibrium moisture basis

2 - Moisture free basis

3 - Dry, ash free basis

Table 5.  
Proximate and Ultimate Analyses of Hydrothermally Treated 1" x 1 1/2" Coal in Steam.  
No. 4 Seam, Usibelli Coal Mine

Test No. Max Temp/ Res. Time at Max Temp.	Basis	Moisture, %	Ash,%	Volatile Matter,%	Fixed Carbon,%	Fuel Ratio, (FC/VM)	Heating Value, Btu/lb	Total Sulfur, %	C,%	H,%	N,%	O,%
US-1 527°F/0 min. (275°C)	1	11.62	7.67	39.54	41.16		10102	0.19	57.02	6.16	0.67	28.30
	2		8.68	44.74	46.58	1.0	11430	0.21	64.52	5.50	0.75	20.34
	3			49.00	51.00		12517	0.23	70.65	6.02	0.83	22.27
US-2 527°F/60 min. (275°C)	1	10.51	6.90	39.24	43.35		10479	0.19	59.08	6.06	0.69	27.08
	2		7.71	43.85	48.44	1.1	11710	0.22	66.02	5.45	0.77	19.83
	3			47.51	52.49		12689	0.24	71.54	5.91	0.83	21.48
US-3 572°F/0 min. (300°C)	1	10.50	8.79	36.43	44.28		10507	0.19	58.62	6.02	0.77	25.62
	2		9.82	40.70	49.47	1.2	11740	0.21	65.49	5.41	0.86	18.20
	3			45.14	54.86		13019	0.24	72.63	6.00	0.95	20.18
US-4 572°F/60 min. (300°C)	1	9.08	7.33	35.39	48.20		11029	0.19	61.80	5.77	0.75	24.15
	2		8.07	38.92	53.01	1.4	12130	0.21	67.97	5.22	0.83	17.70
	3			42.34	57.66		13194	0.23	73.94	5.68	0.90	19.25
US-5 617°F/0 min. (325°C)	1	7.61	6.34	38.03	48.01		11558	0.20	64.73	5.89	0.74	22.10
	2		6.87	41.17	51.97	1.3	12510	0.21	70.06	5.46	0.81	16.60
	3			44.20	55.80		13432	0.23	75.22	5.86	0.87	17.82
US-6 617°F/60 min. (325°C)	1	6.13	9.66	37.05	47.16		11856	0.19	65.26	5.83	0.84	18.22
	2		10.29	39.47	50.24	1.3	12630	0.20	69.52	5.48	0.89	13.62
	3			44.00	56.00		14078	0.23	77.49	6.11	0.99	15.17

1 - ASTM equilibrium moisture basis

2 - Moisture free basis

3 - Dry, ash free basis

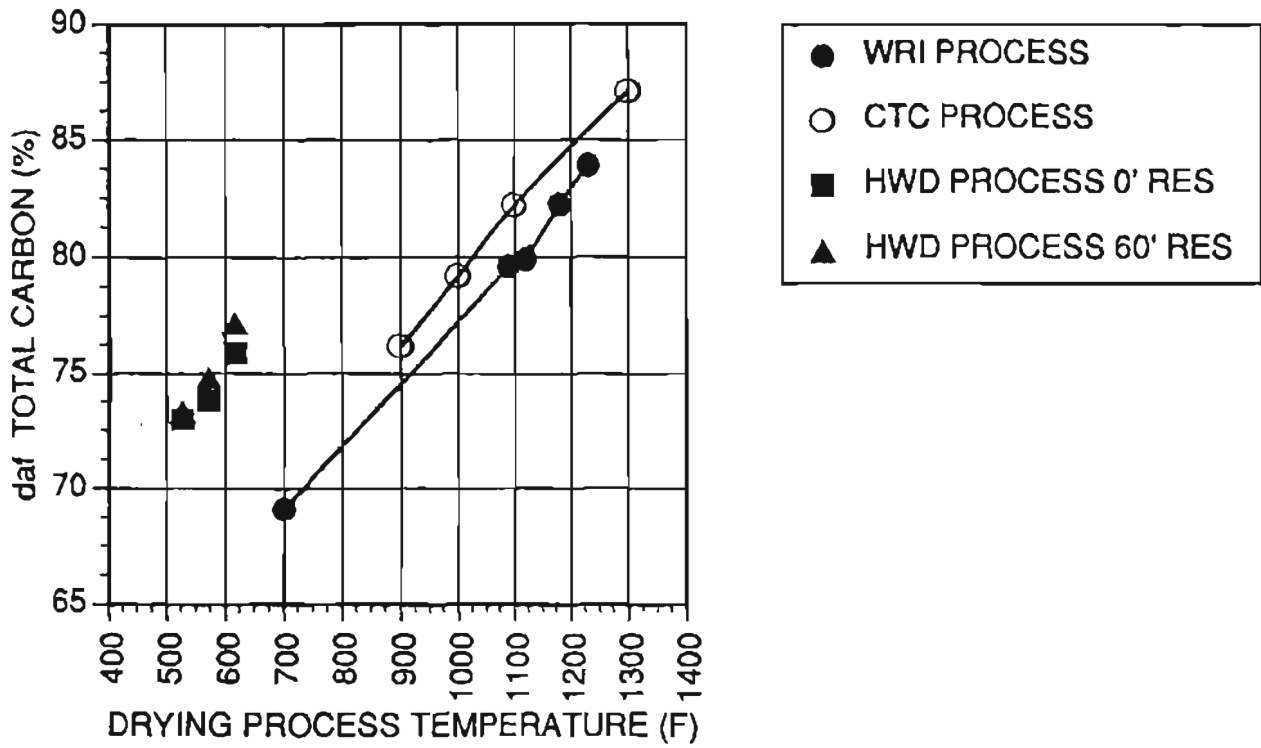


Figure 6. Products' Total Carbon (%) as a function of Drying Process and Temperature.

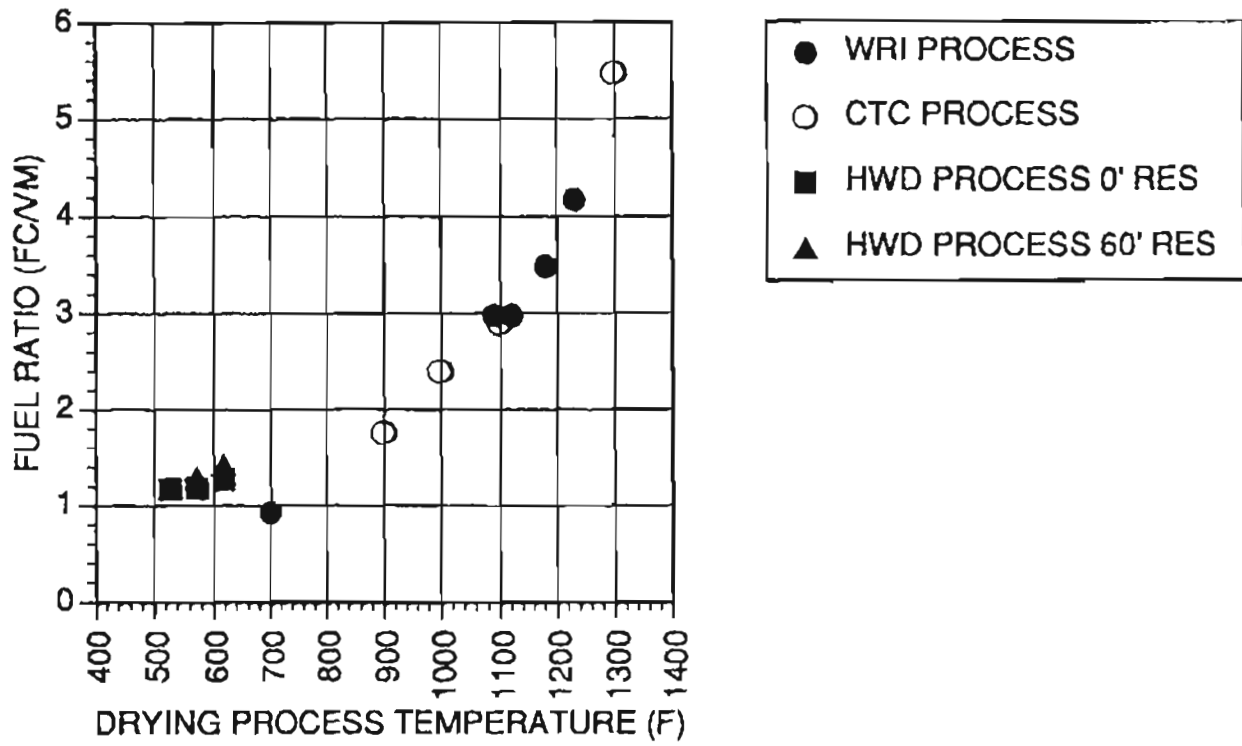


Figure 7. Products' Fuel Ratio as a function of Drying Process and Temperature.

1.4 for HWD temperatures from 527°F to 617°F respectively. The proximate analyses show there is still a decrease in volatile matter and an increase in fixed carbon associated with HWD (Figure 6), but nowhere nearly as severe as in the evaporative processes of WRI and CTC. In addition, the volatile matter removed during HWD is primarily CO<sub>2</sub>, which has no calorific value. Previous work conducted at MIRL in preparing coal-water fuel from finely ground Usibelli coal has shown that while there may be 88-92% mass recovery from HWD, the energy recovery is 95-97% that of the parent coal on a dry basis. This difference can be explained by CO<sub>2</sub> evolved during the drying process. Like hydrothermally treated coal, the WRI products produced at temperatures below 700°F, maintained a low fuel ratio, 0.9-1.3. (Tables 1 and 2, samples 101/102 and D-39).

In discussing proximate analyses, there must be some mention of the calorific value changes observed for the various drying processes (Figure 8). However, these values must be considered in the light of mass recovery and energy recovery to be truly meaningful. While reference to mass and energy recoveries have already been made for hydrothermal processing, these values are unavailable to MIRL for the WRI and CTC process samples characterized.

On an equilibrium moisture basis, WRI char products increased in calorific value from 8000 Btu/lb for the raw coal to 9500-10080 Btu/lb for process temperatures of 1090°F - 1230°F respectively. This represents an increase in energy density of between 19 - 26%. The CTC process produced calorific value increases in the 26 - 35% range, with products ranging from 9870 - 10610 Btu/lb from a parent coal of 7830 Btu/lb. Note that none of these value ranges for WRI or CTC products contain any information about energy recovery, though for the cases of the chars, this must be considerably less than that observed for HWD due to the greater devolatilization and higher fuel ratios observed for the WRI and CTC processes. HWD produced calorific value increases of 31-46%, with products ranging from 10,700 - 11,900 Btu/lb from a raw coal of 8150 Btu/lb. WRI products produced at temperatures below 700°F increased from 8000 and 8400 Btu/lb to 8700 and 9050 Btu/lb on an equilibrium moisture basis; gains of 9% and 8% respectively.

#### Moisture Removal / Reabsorption

Contained in the same respective tables, just noted in the previous section, are moisture data for WRI, CTC, and hydrothermally dried coal products. The WRI process removes 99-100% of the as received moisture in Usibelli coal, though equilibrium moisture levels recover to approximately half the original moisture levels of the parent coal. This fractional moisture reabsorption probably has an effect on the increased spontaneous heating tendencies demonstrated by the WRI products. This will be discussed later.

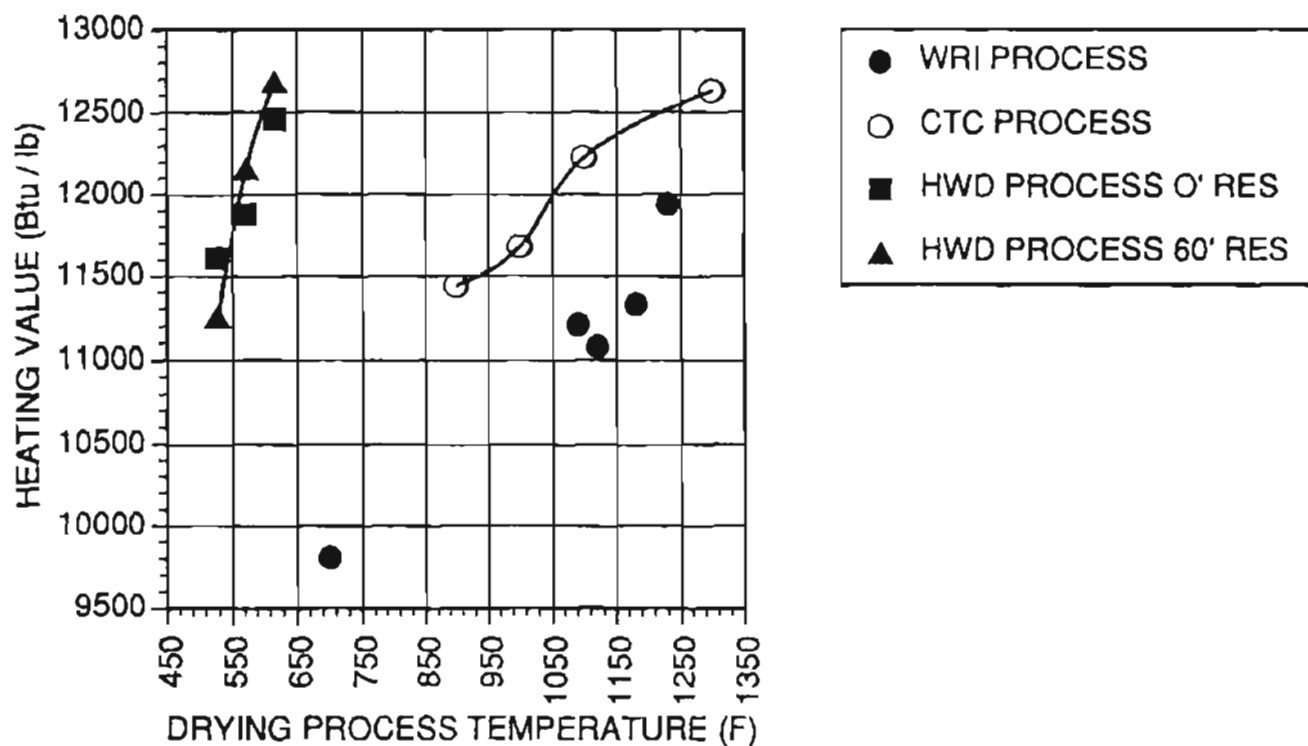


Figure 8. Products' Heating Values as a function of Drying Process and Temperature. Heating Values are given on an ash free, equilibrium moisture basis.

CTC products show the same basic moisture removal / reabsorption properties as the WRI process, though CTC products do not reach quite as low post process moisture levels. The CTC products also demonstrate slightly lower equilibrium moisture levels than WRI products. For both processes, the trend observed is that higher process temperatures and longer residence times yield products with lower equilibrium moisture levels (Figure 9). Again, this observation is not unexpected. It is well known that if LRCs are dried at temperatures above 465°F (240°C) the basic chemical and physical coal characteristics begin to change. Decarboxylation occurs and CO<sub>2</sub> is evolved(8). Decarboxylation helps reduce the coal's capacity to reabsorb water by ridding the surface of hydrophilic functionalities(8). Much of the coal's additional volatile matter, tars and oils, are also liberated and migrate to the coal's surface(8). If the tars are not stripped during drying, they remain on the coal, effectively sealing the micropores and reducing the coal's ability to hold water.

It would appear that only the first of these two criteria are met by the WRI and CTC pyrolysis processes. That is, they effectively destroy functional groups, but devolatilize the coal to such an extent that the tars and oils are stripped and unavailable to seal the coal surface against moisture reabsorption. WRI dried products demonstrate higher equilibrium moisture levels than the WRI char products. This brings into question the effectiveness of the tar/oil sealing of micropores, which is supposed to occur during the second IFB quench step of the WRI process. Perhaps this sealing quality could be enhanced through residence time and temperature control.

A serious drawback with both WRI and CTC processes is that in order to achieve lower equilibrium moisture levels in the dried/pyrolyzed products, they are required to reduce the product moisture level far below equilibrium moisture content. Hence, there is the propensity towards spontaneous heating as moisture is reabsorbed. In contrast to this, hydrothermal treatment of lump coal produces a product with equilibrium moisture levels lower than that of the product's initial, post process, moisture content. That is, the lump coal is discharged from an aqueous drying environment and contains considerable pore and surface moisture. If the moisture is then removed by mechanical / thermal processes to levels very near equilibrium moisture levels, the tendency towards moisture reabsorption is greatly reduced. It is proposed that the spontaneous heating, attendant to moisture reabsorption, should also be reduced, though to date MIRC has no data to support this supposition.

HWD produces lump coal with equilibrium moisture levels at least equal to and probably superior to those of the WRI and CTC processes. Despite the lower treatment temperatures of HWD, equilibrium moisture levels rival those of higher temperature drying



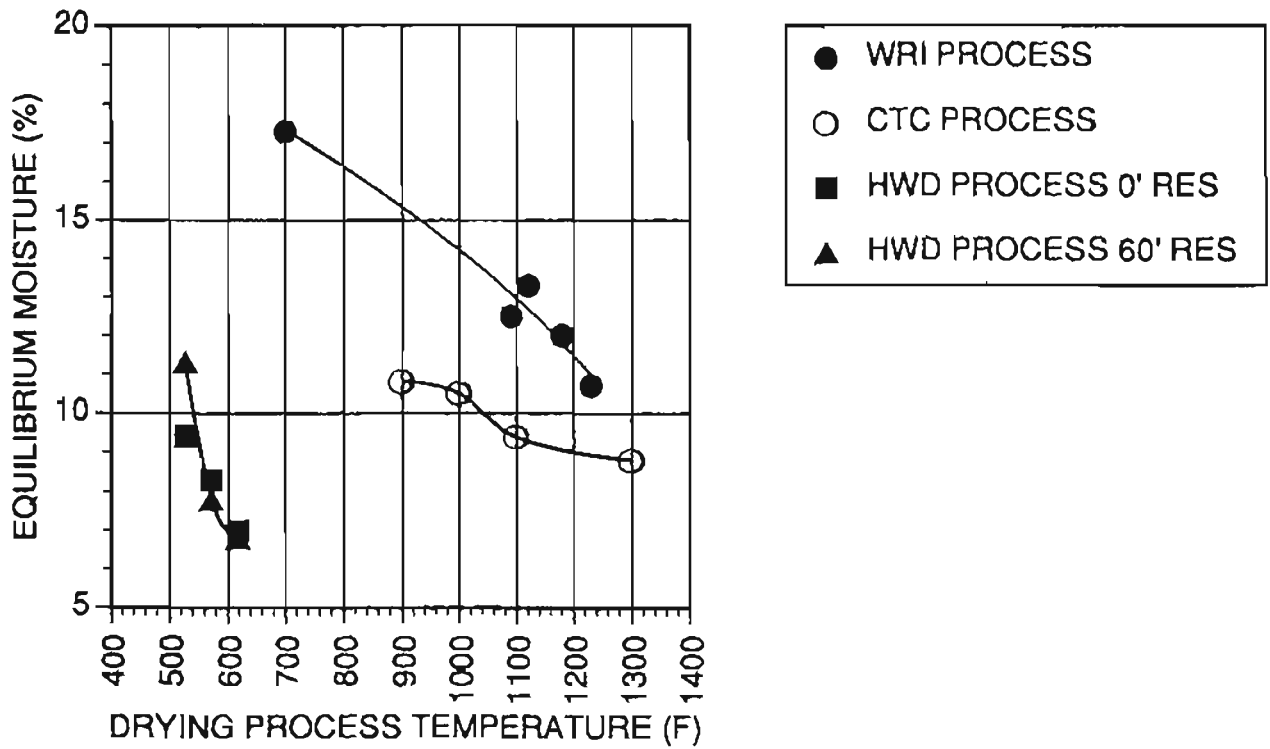


Figure 9. Products' Equilibrium Moisture as a function of Drying Process and Temperature.

processes. This is probably due in part to the surrounding high pressure aqueous phase, which promotes retention of tars/oils with the coal product, resulting in more effective coal particle surface sealing against moisture reabsorption. The fact that HWD does not devolatilize the coal to the extent of the atmospheric pyrolysis processes also supports this proposition.

Tables 6-9 and Figures A1-A11 (Appendix) show a more detailed description of moisture reabsorption characteristics for CTC and WRI products. In general, the products reach moisture levels within 0.5 - 1% of their equilibrium moisture levels within 3-5 days of exposure to 97% relative humidity at 30°C. This emphasizes the fact that moisture reabsorption and the attendant spontaneous heating is rapid and falls within the present transportation/storage scenarios experienced by Usibelli coals enroute to markets.

The argument could be made that briquetting the WRI processed fine coal would decrease moisture reabsorption tendencies. The effectiveness of briquetting would no doubt be dependent on binder consumption and binder type and the resulting integrity, porosity, and permeability of the briquetted products. MIRL received inadequate briquetted coal product from WRI with which to test moisture reabsorption or physical stability. MIRL did however receive a sample of briquetted char from CTC. This sample of briquetted char was pelletized from CTC test no. 13 char product. In this one case, for which binder consumption and type are not known, briquetting appears to have little impact on moisture reabsorption as compared between CTC sample 13 and CTC briquettes. (Tables 8 and 9 and Figures A10 and A11). As will be seen in a later section, briquettes of CTC sample 13 had no great physical stability advantage either.

### Oxidation Stability (13)

Nine samples of coal and/or char were sent to Australia for testing in the adiabatic calorimeter currently used in coal oxidation studies by BHP Research, Newcastle Laboratories. The oxidation propensity of the samples were determined using a modified version of the self-heating calorimeter described in the literature(14).

The calorimeter consists of an aluminum block with 18 cylindrical sample compartments which can hold up to 1 kg of coal. This sample block is separated from an outer aluminum shell by a 1 mm air gap. The outer shell is wound with a heater element which, in conjunction with a computer regulated proportional controller, raises the temperature of the outer shell to match the temperature rise being generated by the oxidation of the coal sample contained in the inner block. This adiabatic system controls the coal environment to 0.01°C. The temperature of the two calorimeter blocks are measured by highly sensitive and accurately calibrated thermistors. A second, larger heater, is also

Table 6  
Percent moisture reabsorption characteristics of raw coal, dried coal and char products from mild gasification treatment in WRI's Inclined Fluid Bed (IFB) reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	Residence time, days at 97% relative humidity										Equilibrium Moisture, Percent
				0	1	3	5	11	16	18	21	28	30	
Raw Coal	N/A	N/A	N/A	-	-	-	-	-	-	-	-	-	-	24.47
101/102	16x0	700	3	1.02	N.D.	15.76	16.08	16.45	16.52	16.61	16.42	-	-	17.30
59	16x100	1090	1	0.0	10.04	10.64	11.01	11.58	12.01	12.02	-	-	-	12.54
63	16x100	1120	4	0.0	11.32	11.81	12.29	12.79	13.10	13.17	13.42	13.42	-	13.27
64	16x100	1180	7	1.30	N.D.	10.39	10.36	10.47	10.57	10.57	-	-	-	12.01
62	16x100	1230	12	6.00	N.D.	8.92	9.07	9.25	9.22	9.42	9.50	9.58	-	10.73

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Table 7  
Percent moisture reabsorption characteristics of raw coal and dried coal product from WRI's Inclined Fluid Bed (IFB) reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	Residence time, days at 97% relative humidity							Equilibrium Moisture, Percent	
				0	3	5	11	16	18	30		
Raw Coal	N/A	N/A	N/A	-	-	-	-	-	-	-	-	20.58
D-39	16x0	632	-	0.25	13.36	13.46	13.89	14.10	14.13	14.37	-	14.78

Table 8  
Percent moisture reabsorption characteristics of raw coal and char products from mild gasification treatment in CTC's vertical column reactor

Test Number	Feed Size, Inches	Treatment Temp. of	Retention Time, Min.	Residence time, days at 97% relative humidity									Equilibrium Moisture Percent	
				0	1	3	5	11	16	18	21	28		
Raw Coal	N/A	N/A	N/A	-	-	-	-	-	-	-	-	-	-	25.24
11	2x1/4	900	420	1.11	N.D.	9.75	10.14	10.91	10.96	11.07	11.12	-	10.75	
7/10	2x0	1000	420	1.18	N.D.	8.85	9.15	9.41	9.58	9.74	9.71	-	10.45	
12	2x1/4	1100	400	0.83	N.D.	7.30	8.07	8.19	8.45	8.84	8.70	-	9.38	
13	2x1/4	1300	400	0.0	7.19	7.53	7.79	8.04	7.92	8.21	8.21	-	8.78	

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Table 9  
Percent moisture reabsorption characteristics of briquette made from char product of Test No. 13, in CTC's vertical column reactor

Briquette	Residence time, days at 97% relative humidity													
weight-gms	0	3	5	7	10	14	21	28	35	45	49	56	63	72
50	1.59	7.98	8.11	8.35	8.23	8.43	8.69	8.78	8.74	8.93	8.76	8.83	8.88	8.66

contained within the inner block to enable the sample temperature to be raised quickly to its initial temperature, typically 50°C.

The oxidizing gas is passed into the inner block via a manifold, passes down through the coal and out an exhaust manifold. The gas is heated to the temperature of the coal before entering the block to eliminate cooling affects. The flow rate of the oxidizing gas is monitored continually and the moisture content of the gas is adjusted to a predetermined level by passing it through a gas/water saturator consisting of two water filled Drexil bottles held at a constant temperature.

This system is used to monitor the temperature rise of a coal sample, under strictly controlled oxidizing conditions, over a 48 hour period or until a maximum temperature of 80°C is reached. The slope of the temperature/time plot is taken as a measure of the rate of oxidation of the coal sample. The reproducibility of this measurement, as determined by duplicate measurements on a number of coals under the same experimental conditions, is 0.01°C/hour.

In a typical calorimeter test the sample of coal was crushed to 1 mm, under conditions designed to minimize fines generation, and the minus 0.25 mm material removed. This sample size range was conducive to good permeability and significant oxidation rates. A representative 960 g sample was placed in the calorimeter for testing. Prior to the addition of oxygen, containing 4.2% moisture, the sample was further dried to a constant moisture content by passing nitrogen (500 cm<sup>3</sup>/min) through it at 50°C for 16 hours. Longer times were found to have a negligible effect on the resulting initial moisture content or observed oxidation rate. The sample was monitored as a function of time for approximately 48 hours or until a maximum temperature of 80°C was reached. The initial temperature of the system and the oxygen moisture content used in this procedure were chosen as a compromise between enhanced reaction rates and experimental convenience.

All samples were stored, "as received" in a freezer prior to testing to reduce oxidation. The results of the nine calorimeter tests are summarized in tables 10 and 11. All coals and chars tested in this series are regarded as having an extremely high propensity for spontaneous combustion. By comparison, the majority of black bituminous coals currently mined in Australia have heating rates of less than 0.2°C/hour. Australian lignites, from Victoria, typically have heating rates of between 0.4 - 0.6 °C/hr.

A number of observations were made during the test which are relevant to these results:

- Sample WRI Char IFB-59 ignited during sizing and could not be tested further. This was the first sample tested. Following this incident precautions were taken during the handling of all samples. In all

subsequent cases the samples were sized at reduced temperature under a steady stream of nitrogen. No further heating of the samples during preparation was observed.

- Samples CTC Char blend of #7 plus #10, CTC Char Test #11 and CTC Char Test #13 when opened gave off a burnt odor which was not present with the other char samples.

Tables 10 and 11 suggest that the heating rate decreases with increase in treatment temperature and retention time. CTC samples with seven hour retention time showed an

Table 10  
Oxidation Calorimeter Results for Raw Coal, Dried Coal and Char Products from Mild Gasification Treatment in WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	Oxidation Rate, °C/Hour	Observations
Raw Coal	N/A	N/A	N/A	1.2	Ignited after sizing
101/102	16 x 0	700	3	1.0	
59	16 x 100	1090	1	?	
64	16 x 100	1180	7	6.8	
62	16 x 100	1230	12	3.5	

Table 11  
Oxidation Calorimeter Results for Raw Coal and Char Products from Mild Gasification Treatment in CTC's Vertical Column Reactor

Test Number	Feed Size, Inches	Treatment Temp. °F	Retention Time, Min.	Oxidation Rate, °C/Hour	Observations
Raw Coal	N/A	N/A	N/A	0.4	} Slight burnt odor
11	2 x 1/4	900	420	1.2	
7/10	2 x 0	1000	420	0.6	
13	2 x 1/4	1300	400	0.4	

order of magnitude lower heating rate compared to WRI samples with maximum retention time of 12 minutes. Data on the spontaneous heating characteristics of hot water dried coal is unavailable at this time.

Thermogravimetric studies conducted by MIRL on samples of CTC and WRI chars, confirmed the same relative reactivities as demonstrated in the self heating calorimeter studies noted above. Thermogravimetric analysis (TGA) studies were conducted using a TGS-2, Perkin Elmer analog system and 0.15 x 0.21 mm size fractions of ground char samples using a 50% oxygen atmosphere. The TGA furnace was brought to 250°C rapidly (200°C/min), then increased in temperature to 450°C @ 20°C/min. Data are shown in Table 12.

Table 12.  
Thermogravimetric Data for Char Samples vs. Self Heating Value.

<u>Char Sample</u>	<u>Temperature of Maximum Rate of Mass Loss (°C)</u>	<u>Maximum Rate of Mass Loss (mg/min)</u>	<u>Self Heating Value* (°C/hr)</u>
CTC 11	350	2.45	1.2
WRI62	300	2.80	3.5
WRI64	309	3.50	6.8

\*Self heating value determined by BHP Research, Newcastle Laboratories, Australia.

#### Physical Stability and Grindability

Physical stability of CTC products was determined using a relative friability measure test as outlined by ASTM procedure D441-86. This test is useful in determining the relative resistance of coals to degradation during handling, but should not be construed as being servicable for determining friability within narrow limits. The size fraction of coal tested using this procedure is 1.5 x 1 inches. For this reason, WRI product could not be tested using ASTM-D441-86, because of the small particle size of the WRI products, -1.2 mm. However, due to the similarity between WRI and CTC char products analyses, it is the view of these authors that their friability and dust indices would also be similar.

The most striking feature of the effect of hydrothermal treatment is the development of thermoplasticity in a subbituminous 'C' coal; a characteristic generally attributed only to bituminous coals. This is particularly true for coal pieces that consist of large pure vitrinite

bands. Examination of sections of these coals showed evidence of the complete fluid character of vitrinite and the development of spherical cavities occupied by gases. The development of thermoplasticity is responsible for an eventual product with a very cohesive surface.

Petrographic examination of the hydrothermally treated products showed interesting textures. Increasing temperature promotes vesiculation of resinite and loss of subertinite. At 617°C ulminite showed development of slits and angular pits. The slit and pit development was restricted to pure ulminite, devoid of other associated macerals. This is followed by widespread vesiculation of ulminite. The shrinkage cracks that developed in coal pieces were elliptical in shape and were not connected. These cracks terminated before reaching the particle surface.

LRCs dried by evaporative processes characteristically develop cracks that run all along the bedding planes, resulting in particle degradation. Particle degradation was very apparent from friability tests run on CTC products. These data are shown in Table 13 and Figure 10, and demonstrate the friability range of 60-73 for the CTC products is considerably greater than the raw coal friability of 25. These numbers indicate the much higher propensity of the CTC products to degrade during handling. While their tendency to produce minus 0.3 mm fines (dust index) is not much greater than the raw coal (dust index of 7), the tumbled char does seriously degrade in size. The trend would indicate the increase in friability with higher drying temperatures, though this is not conclusive. Hydrothermally (steam) treated lump coal also degraded readily when tumbled. Two preliminary tests yielded friability values from 59-68 and dust indices of 20-25.

Tumbled, briquetted CTC product showed serious size degradation to produce 34% minus 0.3 mm particles after 1 hour of tumbling. This could pose a greater dusting problem during handling and transport of the briquettes. Again it should be emphasized that briquette stability will be significantly affected by binder type and dosage as will the economics of the briquetting process.

ASTM procedure D-409-90 was used to determine the Hardgrove grindability index (HGI) of the various dried/pyrolyzed products. This method produces data which may be used to evaluate the energy input required for grinding and/or pulverizing coal. A higher HGI is indicative of a material that is easier to pulverize.

All three drying processes benefited the grindability of their products (Tables 13-17). HWD showed the greatest improvement, increasing the HGI from 34 for the raw coal to 78-115 for the hydrothermally treated products. Higher temperatures and longer residence times improved grindability. These values indicate a product which would



Table 13  
 Hardgrove Grindability Index, Friability and Density of raw coal and char products from mild gasification  
 treatment in CTC's vertical column reactor

Test Number	Feed Size, Inches	Treatment Temp., °F	Retention Time, Min.	HGI	Friability	Dust Index	Density, g/ml			Voids Vol. %
							14 mesh x 0	65 mesh x 0	Whole	
Raw Coal	N/A	N/A	N/A	33	25	7	-	1.35	-	-
11	2x1/4	900	420	48	60	10	1.42	1.42	-	-
7/10	2x0	1000	420	43	68	9	1.42	1.43	-	1.0
12	2x1/4	1100	400	43	73	9	1.41	1.44	-	2.1
13	2x1/4	1300	400	41	73	9	1.44	1.47	-	2.0
Briquettes	-	-	-	-	45	34	-	-	1.11	-

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Table 14.  
 Hardgrove Grindability Index and Density of raw coal, dried coal and char products from mild gasification  
 treatment in WRI's Inclined Fluid Bed (IFB) reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	HGI	Density, g/ml		Voids Vol. %
					14 mesh x 0	65 mesh x 0	
Raw Coal	N/A	N/A	N/A	33	-	1.37	-
101/102	16x0	700	3	43	1.39	1.39	-
59	16x100	1090	1	59	1.33	1.42	6.3
63	16x100	1120	4	60	1.32	1.39	5.0
64	16x100	1180	7	59	1.35	1.44	6.3
62	16x100	1230	12	60	1.39	1.43	2.8

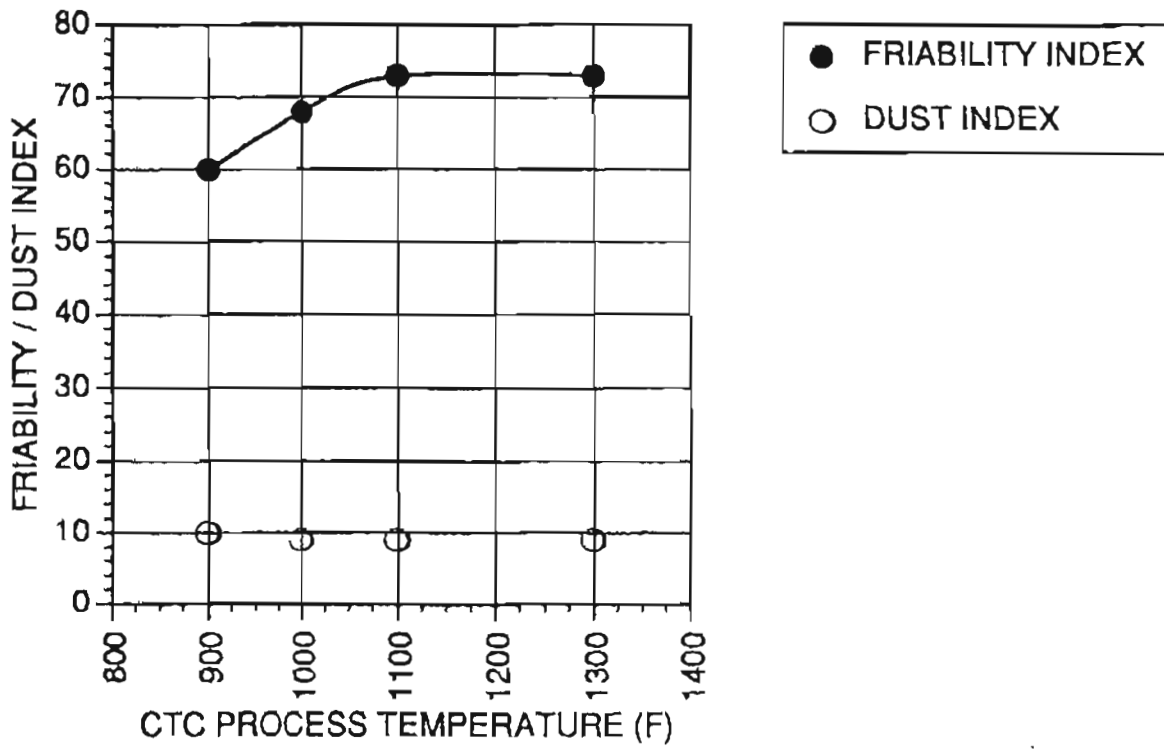


Figure 10. Product Friability and Dust Indices as a function of CTC Process Temperature.

Table 15.  
Hardgrove Grindability Index and Density of raw coal and dried product from WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	HGI	Density, g/ml		Voids Vol. %
					14 mesh x 0	65 mesh x 0	
Raw Coal	N/A	N/A	N/A	33	-	1.40	-
D-39	16x0	632	-	53	1.37	1.38	0.7

Table 16.  
Particle Density, Porosity and Hardgrove Grindability Index of 1" x 1-1/2" hydrothermally processed coal in hot water. No. 4 Seam, Usibelli Coal Mine

Test No. Max. Temp/Res. Time at Max. Temp.	Particle Density g/ml	Porosity, %	HGI
Raw Coal	1.32	-	34
UHW 1 527°F/0 min.	1.05	23.4	78
UHW2 527°F/60 min.	1.05	22.8	83
UHW3 572°F/0 min.	1.12	17.0	112
UHW4 572°F/60 min.	1.08	21.7	102
UHW5 617°F/0 min.	0.92	32.4	107
UHW6 617°F/60 min.	0.90	33.3	115

Table 17.  
Particle Density, Porosity and Hardgrove Grindability Index of 1" x 1-1/2" hydrothermally processed coal in steam. No. 4 Seam, Usibelli Coal Mine

Test No. Max. Temp/Res. Time at Max. Temp.	Particle Density g/ml	Porosity, %
US-1 527°F/0 min.	1.24	14.5
US-2 527°F/60 min.	1.17	14.6
US-3 572°F/0 min.	0.92	32.3
US-4 572°F/60 min.	1.03	23.1
US-5 617°F/0 min.	1.04	23.5
US-6 617°F/60 min.	0.95	31.0

require less than half the size reduction energy required for the raw coal, at significant cost savings to the power plant.

Improvements in HGI were less notable after WRI and CTC processing. Hardgrove grindability of WRI chars was improve from 33 for the raw coal to 59-60. CTC chars were only slightly improved to an HGI range of 41-48. For CTC chars, the benefit to HGI from pyrolysis seems to diminish with increasing temperature (Figure 11).

### Ash Composition

Tables 18-21 show the chemical composition of ash of the WRI, CTC and HWD products. Ash is the combustion product of the inorganic constituents in coal. For laboratory analysis, ash is prepared by heating coal to 750°C in a well ventilated furnace. The resulting residue is analyzed for eight major elements and three minor elements expressed as oxides. The major oxides are SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, and SO<sub>3</sub>. Minor oxides are TiO<sub>2</sub>, MnO, and P<sub>2</sub>O<sub>5</sub>.

The relationship of ash composition to its behavior during coal combustion operations has been correlated for many coals. The low sodium content of Usibelli coals indicates their low boiler fouling propensity. The high calcium content would likely fix some sulfur in the ash and further reduce already low sulfur emissions. High calcium levels would also reduce the boiler fowling propensity of the ash due to the coal's sulfur content. Calculations using emperical formulas show that the ash will have intermediate slagging characteristics. This can also be seen from the ash fusibility data (Tables 22-24).

### Ash Fusibility

Fusibility of ash was determined by subjecting cones prepared with coal ash to increasing temperatures. Temperatures at which transformations occur in the cones are recorded. The temperature at which rounding of cones occur is reported as initial deformation temperature. As the ash cone is heated to higher temperatures it softens further and the temperature at which the cone height is equal to the cone base length is termed softening temperature. When the ash cone completely melts and spreads over the base, the fluid temperature is recorded.

Coals with softening temperature below 2000°F are termed slagging coals. Coals with ash softening temperatures above 2600°F are termed non slagging. All of the Usibelli dried coal samples tested had ash softening temperatures between 2100 and 2300°F (Tables 22-24) and thus may or may not form slag depending on combustion process conditions.

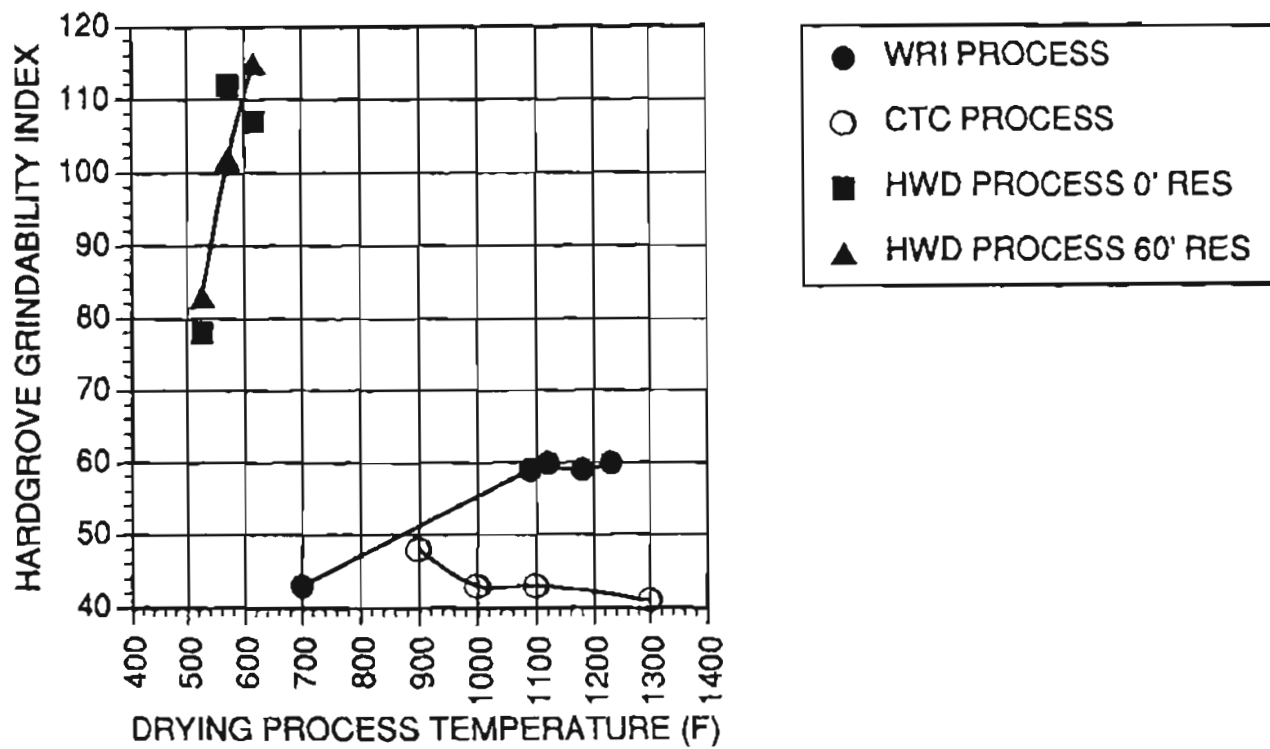


Figure 11. Products' Grindability as a function of Drying Process and Temperature.

Table 18.

Concentration of Major Elements as Percent of High Temperature Ash in Raw Coal, Dried Coal and Char Products from Mild Gasification Treatment in WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	BaO	SrO	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>
Raw Coal	N/A	N/A	N/A	45.6	18.9	5.45	3.29	19.4	0.35	1.17	1.01	0.11	0.53	0.20	0.51	5.05
101/102	16 x 0	700	3	45.4	19.3	5.98	2.92	16.5	0.19	1.32	0.97	0.11	0.47	0.18	0.45	2.78
59	16 x 100	1090	1	42.7	19.8	6.36	3.33	18.7	0.29	1.18	1.00	0.11	0.49	0.20	0.46	3.75
63	16 x 100	1120	4	44.1	19.6	6.73	3.96	18.9	0.26	1.28	1.00	0.13	0.51	0.19	0.55	2.75
64	16 x 100	1180	7	43.1	19.8	7.14	3.16	17.6	0.20	1.20	0.94	0.11	0.52	0.19	0.56	3.23
62	16 x 100	1230	12	41.3	20.0	6.72	3.74	19.4	0.36	1.12	1.00	0.10	0.55	0.22	0.63	3.78

Table 19.

Concentration of Major Elements as Percent of High Temperature Ash in Raw Coal and Dried Product from WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size, Mesh	Treatment Temp °F	Retention Time, Min.	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	BaO	SrO	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>
Raw Coal	N/A	N/A	N/A	42.4	20.2	6.37	3.78	20.2	0.38	1.14	1.02	0.11	0.66	0.26	0.76	3.28
D-39	16 x 0	632	-	43.2	19.0	5.54	3.25	20.2	0.40	1.20	1.02	0.12	0.67	0.26	0.73	2.95

Table 20.

Concentration of Major Elements as Percent of High Temperature Ash in Raw Coal and Char Products from Mild Gasification Treatment in CTC's Vertical Column Reactor

Test Number	Feed Size, inches	Treatment Temp., °F	Retention Time, Min.	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	BaO	SrO	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>
Raw Coal	N/A	N/A	N/A	39.1	18.7	6.74	3.32	20.7	0.21	1.02	0.88	0.12	0.51	0.21	0.26	4.90
11	2 x 1/4	900	420	43.1	19.9	6.80	3.18	18.8	0.22	1.88	1.00	0.11	0.50	0.18	0.40	5.18
7/10	2 x 0	1000	420	43.6	19.7	6.41	2.91	17.1	0.18	1.22	0.95	0.11	0.44	0.17	0.24	5.03
12	2 x 1/4	1100	400	42.2	18.6	6.62	2.77	18.7	0.19	1.19	0.87	0.11	0.40	0.15	0.21	5.45
13	2 x 1/4	1300	400	41.6	19.1	6.67	2.98	18.8	0.17	1.15	0.85	0.11	0.57	0.21	0.60	4.58
Briquettes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 21.

Concentration of Major Elements as Percent of High Temperature Ash in Raw Coal and Hydrothermally Treated 1" x 1-1/2" Coal In Hot Water. No. 4 Seam, Usibelli Coal Mine

Test Number	Treatment Temp., °F	Retention Time, Min.	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	BaO	SrO	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>
Raw Coal	N/A	N/A	9.60	12.7	12.2	7.09	50.3	0.32	0.16	0.53	0.24	0.84	0.63	0.02	6.14
UHW1	527	0	8.06	12.2	12.6	6.74	49.8	0.20	0.12	0.46	0.25	0.93	0.59	0.02	6.85
UHW2	527	60	7.96	12.2	12.7	7.91	50.7	0.18	0.12	0.44	0.29	0.89	0.58	0.02	5.77
UHW3	572	0	9.21	12.2	12.8	8.27	50.0	0.32	0.19	0.47	0.26	0.89	0.58	0.02	4.76
UHW4	572	60	9.56	12.0	12.4	7.17	50.5	0.23	0.12	0.58	0.25	0.91	0.58	0.02	5.01
UHW5	617	0	9.75	12.1	12.8	7.19	50.9	0.18	0.19	0.54	0.28	0.91	0.61	0.02	4.99
UHW6	617	60	9.60	12.4	13.0	7.09	50.7	0.18	0.16	0.52	0.27	0.85	0.61	0.02	5.44



Table 22.  
Fusibility of Coal Ash of Raw Coal, Dried Coal and Char Products from Mild Gasification Treatment in WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	OXIDIZING				REDUCING			
				Initial Deformation Temperature °F	Softening Temperature °F	Hemispherical Temperature °F	Fluid Temperature °F	Initial Deformation Temperature °F	Softening Temperature °F	Hemispherical Temperature °F	Fluid Temperature °F
Raw Coal	N/A	N/A	N/A	2185	2250	2260	2355	2095	2140	2150	2170
101/102	16 x 0	700	3	2210	2280	2305	2450	2100	2215	2235	2280
59	16 x 100	1090	1	2205	2240	2270	2460	2210	2255	2275	2400
63	16 x 100	1120	4	2215	2265	2285	2460	2095	2270	2280	2400
64	16 x 100	1180	7	2225	2270	2295	2370	2110	2185	2205	2250
62	16 x 100	1230	12	2185	2225	2235	2440	2135	2240	2260	2430

Table 23.  
Fusibility of Coal Ash of Raw Coal and Dried Product from WRI's Inclined Fluid Bed (IFB) Reactor

Test Number	Feed Size, Mesh	Treatment Temp., °F	Retention Time, Min.	OXIDIZING				REDUCING			
				Initial Deformation Temperature °F	Softening Temperature °F	Hemispherical Temperature °F	Fluid Temperature °F	Initial Deformation Temperature °F	Softening Temperature °F	Hemispherical Temperature °F	Fluid Temperature °F
Raw Coal	N/A	N/A	N/A	2145	2170	2200	2310	2060	2090	2110	2115
D-39	16 x 0	632	-	2115	2170	2180	2190	2080	2100	2110	2120

Table 24.  
Fusibility of Coal Ash of Raw Coal and Char Products from Mild Gasification Treatment in CTC's Vertical Column Reactor

Test Number	Feed Size, inches	Treatment Temp., °F	Retention Time, Min.	OXIDIZING				REDUCING			
				Initial Deformation Temperature °F	Softening Temperature °F	Hemispherical Temperature °F	Fluid Temperature °F	Initial Deformation Temperature °F	Softening Temperature °F	Hemispherical Temperature °F	Fluid Temperature °F
Raw Coal	N/A	N/A	N/A	2145	2163	2165	2175	2025	2060	2070	2100
11	2 x 1/4	900	420	2265	2300	2330	2485	2145	2220	2240	2295
7/10	2 x 0	1000	420	2225	2260	2305	2445	2070	2165	2185	2200
12	2 x 1/4	1100	400	2265	2300	2330	2485	2090	2150	2175	2200
13	2 x 1/4	1300	400	2205	2250	2260	2445	2100	2125	2130	2225
Briquettes	-	-	-	-	-	-	-	-	-	-	-

Combustion equipment could be designed to prevent ash from melting in cases where coal was burned in a stoker furnace. These low ash fusion coals can also be combusted easily in a fluidized bed unit, where bed temperatures are kept below 1800°F. Alternatively, provisions could be made to melt the ash and keep it flowing, removing it as slag from cyclone type furnaces.

### Vitrinite Reflectance and Microstructure

Vitrinite material (Ulminite, Telecollinite, Desmocollinite) in low rank coals is present in several forms as precursors to vitrinite in high rank coals. Ulminite is gelified plant tissue in which cell structure can be seen. Telecollinite is completely gelified structureless plant tissue. Both of these macerals can exist as thick bands. Desmocollinite is also a completely gelified structureless material but is found as a ground mass embedding other macerals such as exinites and inertinites. Desmocollinite is generally of lower reflectance than ulminite.

Although vitrinite reflectance is not a best indicator of rank for low rank coals, it is a very good indicator of structural changes accompanying thermal treatment of coals. For this purpose ulminite and telecollinite were chosen as indicators. Mean maximum reflectance was measured in oil. The data are included in Table 25 and shown in Figure 12. Hydrothermal processing increased reflectance from 0.30 in raw coal to a maximum of 0.79. CTC products showed increased reflectance to a maximum 3.66 at 1300°F, and WRI products increased up to 2.4 for the sample treated at 1230°F. The higher reflectance of CTC products is due to a very low heating rate compared to WRI. Reflectance in oil for ulminite proved to be very sensitive to treatment temperature and also to the heating rate to some extent. The separation of curves in Figure 12 for CTC and WRI is a reflection of heating rates used for the two systems.

The method of thermal treatment is also reflected in the microstructure of the products (Figures 13 to 20). In hydrothermally treated coals, pore structure developed in ulminite bands due to development of thermoplasticity (Figure 18). Ulminite did not show any cracks that did not heal towards the coal particle surface. The highly volatile exinites, particularly suberinite and sporinite, volatilized leaving cavities. Resinite partially volatilized at higher temperatures (Figure 19).

The CTC products showed total loss of exinites resulting in cavities. Ulminite was quite intact. Some ulminites developed plasticity followed by cell structure formation due to slow gas evolution (Figure 16). This again was the result of slow heating rate. In contrast, WRI products developed significant cracks both in ulminite layers as well as

Table 25.  
Ultimate Reflectance ( $\bar{R}_{max}$ , oil) of Products as a function of Drying Process and Temperature.

Drying Temperature (°F)	WRI	CTC	DRYING PROCESS			
			HW (0 min)		Hydrothermal Drying	
			HW (0 min)	HW(60 min)	STEAM(0 min)	STEAM (60 min)
Raw Coal	0.30	0.30	0.30	0.30	0.30	0.30
527	-	-	0.46	0.52	0.45	0.48
572	-	-	0.54	0.69	0.60	0.67
617	-	-	0.71	0.75	0.70	0.79
700	0.32	-	-	-	-	-
900	-	1.14	-	-	-	-
1000	-	1.67	-	-	-	-
1090	1.39	-	-	-	-	-
1100	-	2.23	-	-	-	-
1120	1.60	-	-	-	-	-
1180	1.84	-	-	-	-	-
1230	2.40	-	-	-	-	-
1300	-	3.66	-	-	-	-

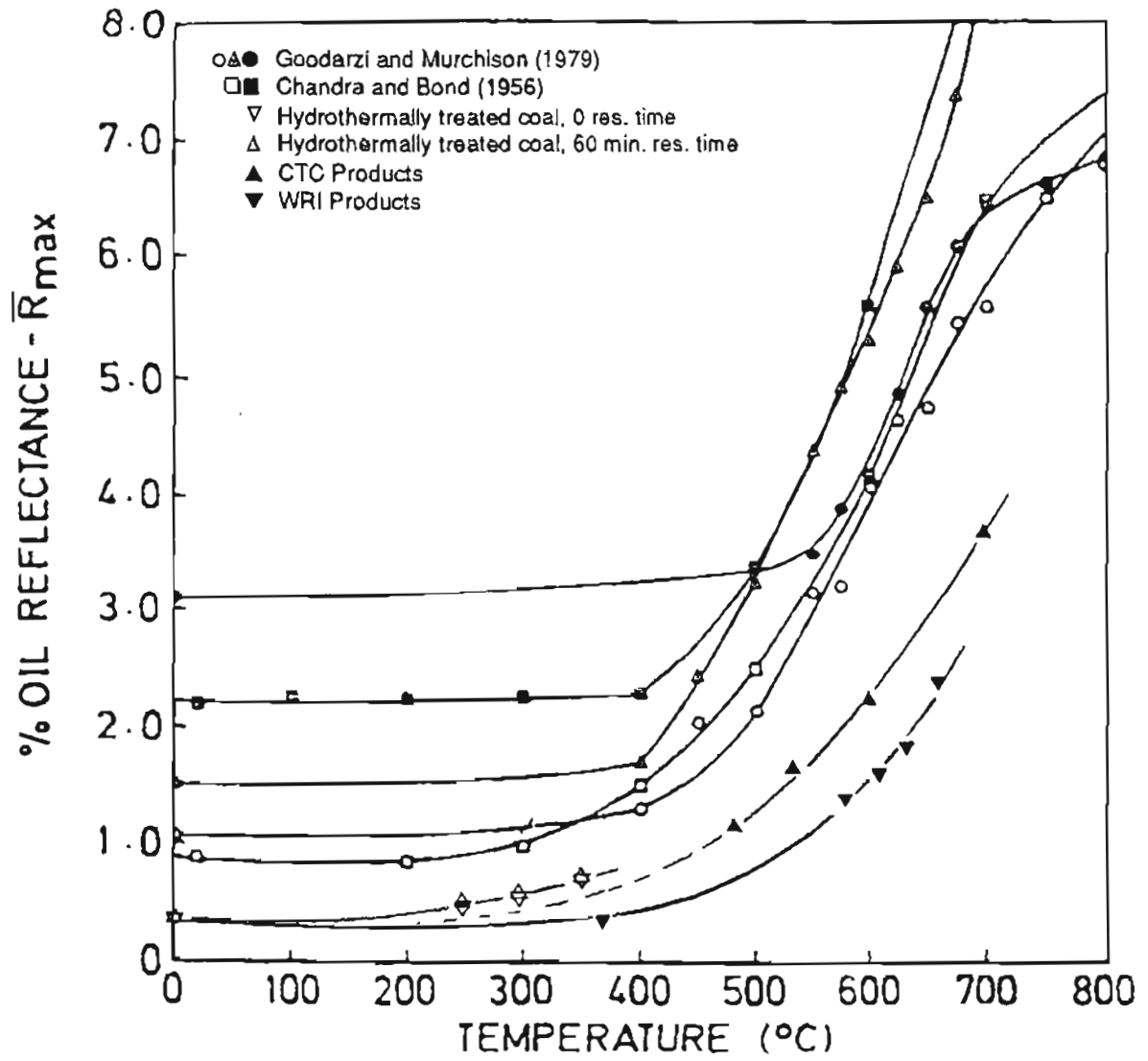


Figure 12. Variation of vitrinite and ulminite reflectance in oil with treatment temperatures.

desmocolinite due to rapid evolution of gases. Particles of ulminite that have gone through a plastic stage can also be found (Figure 13).

### Density and Porosity

The apparent densities of various dried and char particles were measured: relatively coarse hydrothermally treated coal at 1 x 1-1/2 inch (larger after treatment); WRI products at 16 x 100 mesh with out any size reduction; CTC samples were crushed to 14 mesh for density determinations. Apparent densities of the hydrothermally treated 1 x 1-1/2 inch particles were measured by hanging individual particles in a fine nylon mesh, suitably weighted to keep the low density particles immersed. A top loading balance was used for these particle density determinations. Particle densities reported are mean values for 10 particles from each test. All other apparent density determinations are made using Hogarth bottles either with ethanol or kerosene as the displacement medium.

Raw coal and products were pulverized to 60 mesh for measurement of true density, using Hogarth bottles with kerosene as the displacement medium. Particle porosities which developed due to high temperature treatment were calculated from apparent and true density values (Tables 13-17). The density of particles decreased with increased severity of hydrothermal treatment (Figure 21) and was also a function of the presence of pure vitrinite layers. These enhanced development of cell structure due to fluidity. The presence of trimacerite and mineral matter tended to inhibit particle swelling.

CTC samples developed the lowest porosities ranging from 1 to 2.1 percent. WRI products had intermediate porosities ranging from 2.8 to 6.3 percent. Hydrothermally treated coals developed highest porosity ranging from 14.5 to 31%. Again the slow heating rates used for CTC samples promoted devolatilization without undue cracking and resulted in the lowest porosities. WRI samples, with rapid heating rates and fast devolatilization, developed cracks. Hydrothermally treated coal developed a more plastic property and the gases, such as CO<sub>2</sub>, evolved during treatment formed a coarse pore structure, since the system was operating under pressure. The apparent particle densities of products hydrothermally treated at or above 572°F were decreased to near unity. Porosities of these particles exceeded 30%.

## **TRANSPORTATION AND PRODUCTION COSTS CONSIDERATIONS**

The accompanying report by Dynortran(16) provides the details of the transportation system which connects the Usibelli Coal Mine to the export market and this information is not repeated here. Similarly the Dynortran report provides a detailed basis

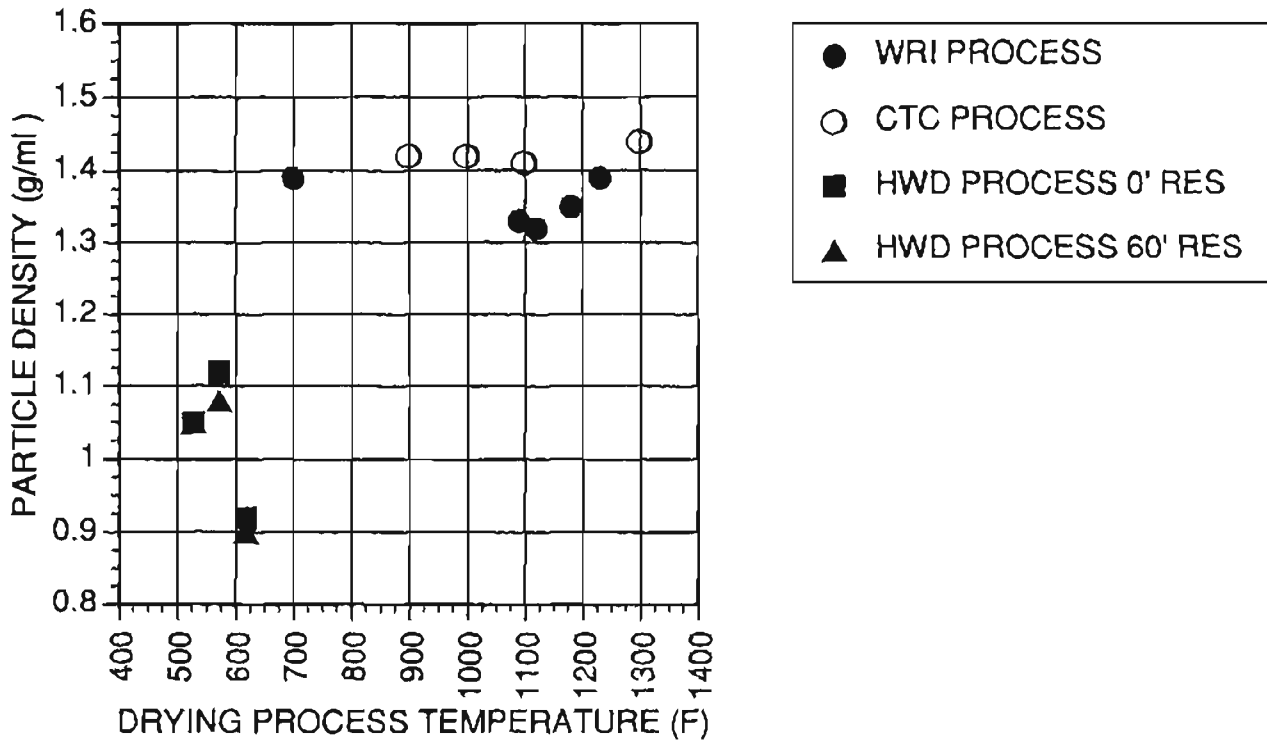


Figure 21. Products' Particle Density as a function of Drying Process and Temperature.

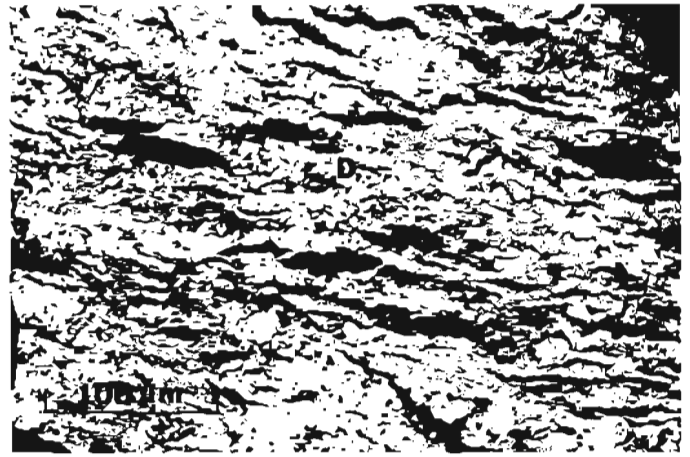


Figure 13. Brecciation of desmocollinite (D) and vesiculation (V) of ulminite (U). Test WRI 64. Reflected light.

Figure 14. Extensive fracturing of desmocollinite (D) parallel to bedding due to loss of exinite and shrinkage. Test WRI 64. Reflected light.

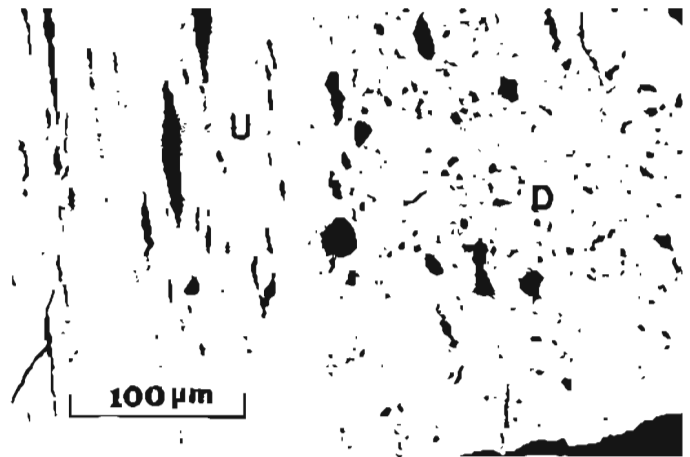
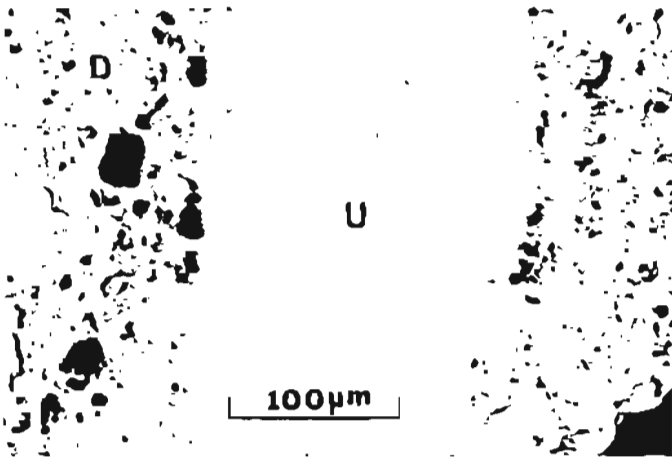


Figure 15. Desmocollinite (D) developed small vesicles while ulminite remained free of slits and vesicles. Test CTC 12. Reflected light, oil immersion

Figure 16. Ulminite (U) developed long slits parallel to bedding while desmocollinite (D) developed small vesicles. Test CTC 12. Reflected light, oil immersion.



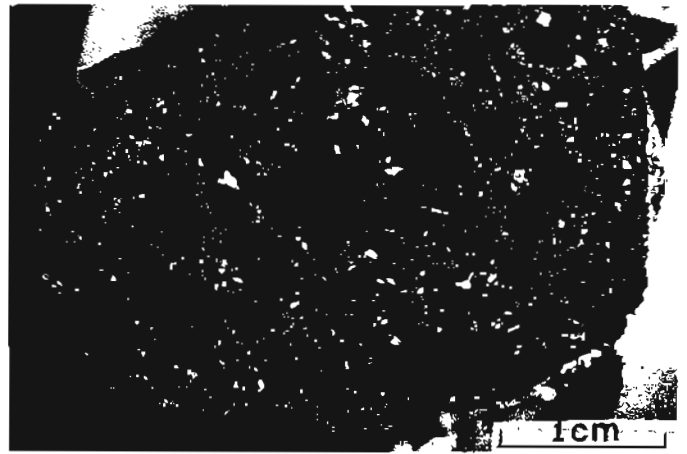
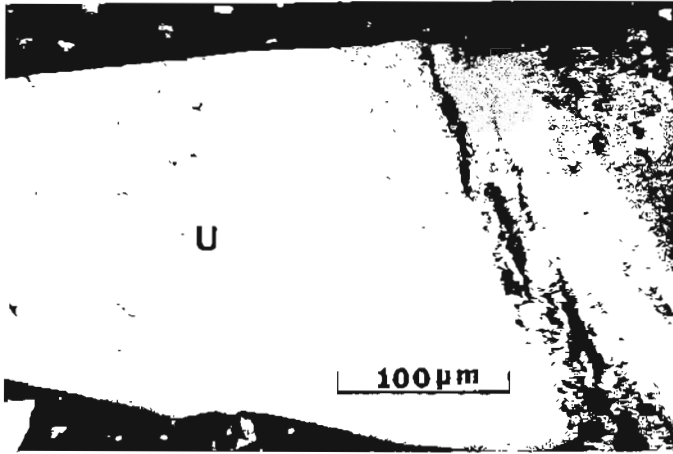


Figure 17. Development of microslits in ubminite (U). Note the slits are randomly oriented and very few are parallel to bedding. Test US 5. Reflected light, oil immersion.

Figure 18. Hydrothermally treated 1-1/2" subbituminous 'C' coal particle in section, showing evidence of the matrix undergoing a plastic stage and development of extensive vesiculation. Oblique illumination.

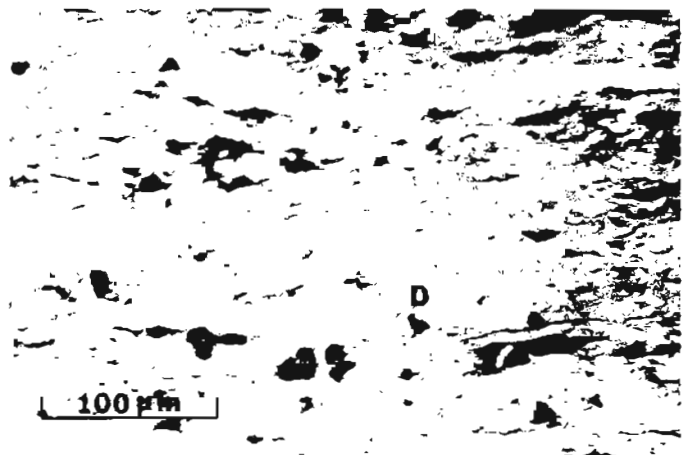
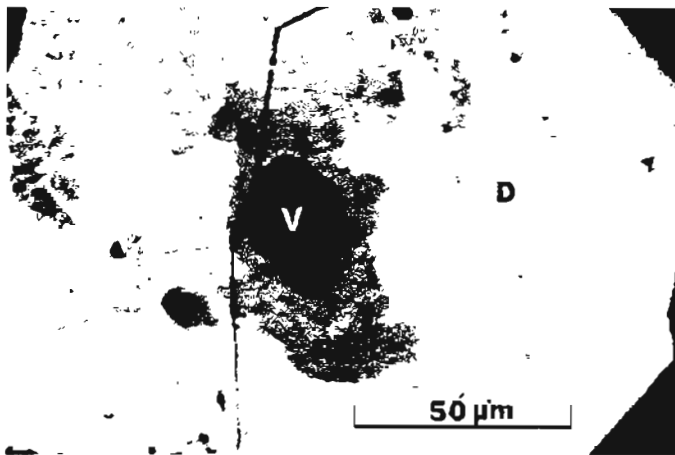


Figure 19. Vesiculation (V) of resinite (R) surrounded by desmocollinite (D) developing small vesicles. Test UHW-3. Reflected light, oil immersion.

Figure 20. Vesicles in desmocollinite (D) developed during volatilization of exinites. Test US-5. Reflected light, oil immersion.

for rail and ocean transport costs for the years 1989 and 2000. Though the derivation of these costs is not reproduced here, these values are utilized to summarize the effects of transportation costs on the marketability of briquetted coal produced by the WRI process.

Table 26 contains data for production costs, transportation costs and market value of the WRI briquettes delivered to Korea. For breakeven economics, the year 1991 and year 2000 coal sale prices from Usibelli Coal Mine would have to be less than \$0/tonne. Though proprietary, production cost of coal from Usibelli Coal Mine at present is estimated at between 8 and 18 dollars/tonne. The cost data from Table 26 indicates that transportation costs comprise approximately 50% of the total value of the delivered briquettes. Hence any efforts to improve the economics of producing briquettes at Usibelli Coal Mine and exporting them by rail/ocean transport must consider transportation cost reduction. Under the present circumstances and market value for Usibelli coal, the WRI process does not appear economically viable.

Dynortran has suggested the following changes in the Alaska Railroad transportation system in order to reduce the cost per ton of coal shipped:

- 1) The purchase of 100 ton aluminum hopper cars to replace the 80 ton steel cars presently in use.
- 2) The purchase of remote control systems to allow the use of mid-train locomotives in the 65 car unit trains.

These modifications would yield cost savings to rail transportation of Usibelli coal at higher tonnage rates of 1.5MM tons per year and 2.5MM tons per year (Table 27). Given markets for increased tonnage of the dried lump coal or briquettes, the reduced transport costs coupled with improved economics of scale for both mining and production could shift the WRI process economics to a more favorable position. However, at the present production and export rates, and with the present transportation structure, economics are unfavorable.

Table 26  
 Transportation and Production Costs and Market Value Associated with WRI Briquettes  
 and their Sale in Korea. For the Years 1991 and 2000.

	<u>Year 1991</u>	<u>Year 2000</u>
<b>Briquette Transportation Costs to Korea</b>		
(a) \$/tonne	\$ 27.89	37.56
(b) \$/MM Btu	1.28	1.73
<b>Briquette Production Costs:</b>		
(a) \$/tonne	24.97	35.54
(b) \$/MM Btu	1.15	1.64
<b>Market Value of Briquettes:</b>		
(a) \$/tonne	53.00	56.91
(b) \$/MM Btu	2.44	2.62
<b>Allowable Coal Cost for Breakeven:</b>		
(a) \$/tonne (C-A-B) / 1.74	<0	<0
(b) \$/MM Btu (C-A-B) / 1.74	<0	<0

- Assumptions:
- 1) WRI briquette heating value of 9,850 Btu/lb (equilibrium moisture basis);  $21.72 \frac{\text{MMBtu}}{\text{tonne}}$
  - 2) 4% cost escalation rate for briquette production and rail transport.  
2% cost escalation rate for ocean transport.
  - 3) 0.8% cost escalation rate for market value of briquettes, \$2.40/MM Btu in 1989 dollars.
  - 4) 1.74 tonnes as mined Usibelli coal required to produce 1.00 tonne WRI briquettes.
  - 5) WRI briquette production cost value derived using WRI production cost estimate of \$13.59/tonne of briquettes(11) and escalated to account for the difference in continental U.S. costs and Alaskan costs. Capital costs were escalated by a factor of 2.0 and operating costs by 1.52.(17)

Table 27  
 Rail Transportation Costs Associated with Variable Levels of WRI Briquette Production  
 and Modifications to the Alaska Railroad System. For the years 1991 and 2000.

<u>Assumed ARR System</u>	<u>Briquette Production (MM TPY)</u>					
	<u>0.75</u>		<u>1.5</u>		<u>2.5</u>	
	<u>1991</u>	<u>2000</u>	<u>1991</u>	<u>2000</u>	<u>1991</u>	<u>2000</u>
As it presently exists						
1) \$/tonne	\$27.89	37.56	27.89	37.56	--	--
2) \$/MM Btu	1.28	1.73	1.28	1.73	--	--
Upgraded with 100 ton aluminum cars and mid- train locomotives						
1) \$/tonne	28.02	37.73	25.58	34.26	25.38	33.98
2) \$/MM Btu	1.29	1.74	1.18	1.58	1.17	1.56

## SUMMARY AND CONCLUSIONS

The thrust of this study has been the characterization of dried and pyrolyzed products from Usibelli coal, with emphasis on how product characteristics will affect handling, transportation and utilization.

The CTC pyrolysis process chars were 2-3 times more friable than the raw coal and were very susceptible to spontaneous heating. Char equilibrium moisture levels were 9-11% compared to 25-30% for the raw coal. Post process moisture levels of the char ranged from 0.2-2.8%. Despite the high fuel ratio (fixed carbon: volatile matter) of the char products, they seem highly reactive with respect to self heating. The CTC process produced calorific value increases in the 26-35% range, with products ranging from 9870 - 10610 Btu/lb from a parent coal of 7830 Btu/lb. However, these energy density increases were accompanied by significant mass and energy losses during devolatilization of the raw coal. Briquetted char from CTC showed poor physical stability and had no advantages over the lump char with respect to equilibrium moisture.

WRI char products characterized by MIRL had 0% post process moisture, but equilibrium moisture levels from 10.7-13.3%. Like CTC chars, these products were highly reactive on a self heating basis, showed high fuel ratios, 3.0-4.2, and energy density increases from 16%-26% on an equilibrium moisture basis for calorific values ranging from 9250-10100 Btu/lb. Because of the size of the coal processed by the WRI system (-1.2mm), friability tests could not be performed by MIRL. However, due to the similarity between CTC and WRI char products, it is doubtful that WRI lump char would be significantly more physically stable than the CTC chars tested. In general, low-rank coals that are treated by high temperature evaporative processes tend to develop cracks along their bedding planes which results in particle degradation during handling.

The two WRI dried coals produced at temperatures below 700°F, which MIRL characterized, had raw coal moisture levels of 24.5% and 20.6%, post process moisture levels of 0.6% and 0.9% and equilibrium moisture levels of 17.3% and 14.8% respectively. Energy densities for the dried products increased from 8000 and 8400 Btu/lb to 8700 and 9050 Btu/lb on an equilibrium moisture basis, with fuel ratios of 0.9 to 1.3 respectively, from a raw coal fuel ratio of 0.9. The dried WRI coal tested for self heating characteristics, showed very similar reactivity as compared to the raw coal.

Hydrothermal drying produced equilibrium moisture levels for the products ranging from 6.1% to 11.6%. From the raw coal calorific value of 8150 Btu/lb, energy density increases ranging from 31% - 46% were achieved from HWD, with products ranging from 10,700-11,900 Btu/lb on an equilibrium moisture basis. Fuel ratios remained at low levels

of 1.2 - 1.4 versus 0.9 for the raw coal. Physical stability was poor and comparable to that of the CTC product. The Hardgrove grindability of the hot-water dried coal improved dramatically, from 34 for the raw coal to 78-115 for the products. Increases in Hardgrove grindability were less significant for WRI and CTC products.

The poor physical and oxidative stability of the lump char would preclude their export even if the processes were economical. In addition, there is the unanswered question of the chars' combustibility for pulverized fuel applications. This can only be resolved by combustion testing on a pilot scale. It is the view of these authors that if the end use of the fuel is combustion then there is no point in stripping the calorifically valuable volatiles from the coal; volatile matter aids ignition and combustion of coal.

It has been proposed by WRI, that IFB dried coal be briquetted to improve its physical and oxidative stability. Depending upon briquette binder type and consumption, this may be a valid approach, though limited work with CTC briquettes from chars has shown them to have poor physical stability and unimproved moisture reabsorption characteristics. Assuming favorable briquette stability, the economics of the process are not favorable given Usibelli coal costs, transportation costs, briquette production costs and their market value in 1991 dollars nor for projections to the year 2000. There is also the question of the impact of briquetting on coal pulverization, i.e. binder interaction ahead of combustion, since there may be an inadequate briquette market other than power generation.

Assuming export to Korea, transportation costs comprise approximately 50% of the total value of Usibelli dried coal products. Rail transportation costs account for at least two-thirds of the total transportation package. Hence, the WRI briquette process would be more economically attractive if applied to coals in close proximity to Alaskan coastal areas. A good example of this would be the Beluga coal field, located near tidewater on the Cook Inlet (Figure 1).

## RECOMMENDATIONS

If Alaska is to become a serious competitor in the rapidly expanding steam coal market, it must begin immediately to develop an aggressive coal technology development program and spearhead a drive to educate users that coal should not be viewed as a commodity sold on a dollar per ton basis but that it should be sold on a dollar per million Btus basis. Users should also be educated to forget about the outdated concept of low-rank coals (LRCs) being equated to low-quality fuels. They need to be shown that LRCs possess superior combustion properties and that utility boilers designed for LRCs possess superior combustion properties and that utility boilers designed for LRCs can utilize the lower cost LRCs for efficient power generation and pass the rate savings on to their customers.

The only thing standing in the way of an enormous export market for Alaskan coal to Japan and Korea is the perception that low-rank coal is an inferior fuel. Despite being the leader in many coal utilization processes, Japan seems unaware that the U.S. produces nearly 100,000 MW of some of the lowest-cost power in the world from LRCs. This includes over 15,000 MW from lignite alone, which is processed easily in boilers designed to fit its unique properties. All of this speaks to the need to educate potential users about the attributes of LRCs. Since seaborne shipping is relatively cheap and Cook Inlet coals are so close to tidewater, it's likely that Alaskan coals could be the lowest cost fuels on a Btu basis in Korea and Japan today. One good reason for optimism with respect to Alaskan coal exports is that fuel switching from bituminous coal to LRCs in order to meet air quality standards is occurring almost daily in boilers designed for bituminous coals.

A very interesting possibility is Alaskan coal to Europe, not by an exotic route through the Arctic with ice-breakers, but through the Panama Canal. An advantage of selling LRC in Europe is that LRC is used widely there and most countries are familiar with its use. Endesa, the Spanish national power company has just concluded very successful tests using Powder River Basin (PRB) coal in boilers designed for very poor quality Spanish lignite and is negotiating a long-term sales agreement that could reach 5-MM tpy. Even at the bargain basement prices for PRB coal, all the coal handling by different carriers in the Continental U.S. can't be cheap, and it seems that Alaskan, Cook Inlet, LRC might be competitive.

To help enlist political support for an Alaskan coal development program, it will be necessary to develop a coherent coal technology development program with clear objectives. There are four similar technology development needs for Alaska that could have the largest impact on increasing coal export in the shortest time.

- 1) Continue to develop and evaluate economical processes to produce a dry bulk coal product with stability against moisture reabsorption, fines generation, and spontaneous combustion.
- 2) Demonstrate the efficient use of coal-water fuels (CWFs) made from hydrothermally processed Alaskan low-rank coals for power generation in coal-and-oil designed boilers, and later in coal-fired diesel and turbine engines.
- 3) Demonstrate environmentally superior and cost-effective power generation from raw Alaskan low-rank fuels. (The Healy Cogeneration Project should make an ideal showcase for this technology).
- 4) Probably the only other technology that could lead to a significant increase in coal exports would be mild gasification (carbonization or pyrolysis) to produce value-added products-char for activated carbon or coke substitutes, and coal liquids for fuels and chemicals.

Coal use within the state could be increased by the development of small reliable coal-fired generating plants to replace diesel-fired generators in remote villages. This type of development could ultimately lead to a reduction in the diesel fuel subsidy costs and add to local employment as small indigenous mines are developed to supply fuel.

The present project has focused on points 1 and 4 above. While meeting with success with respect to moisture reabsorption characteristics, none of the three processes produced a physically stable dried/pyrolyzed lump product. CTC and WRI products were shown to be more prone to spontaneous heating than the raw coal. HWD coals propensity towards spontaneous heating has yet to be tested.



## REFERENCES

- (1) R.D. Merritt and C.C. Hawley, "Map of Alaska's Coal Resources," Alaska DNR Special Report 37, 1986.
- (2) H.M. Lee, "Coal: Prices Steady Despite Oil Fears," Engineering and Mining Journal, Volume 193, No. 3, March, 1991.
- (3) W. Irwin, "Review of Coal-Water Fuel Technology," Report to the Alaska Science and Technology Foundation, February, 1991.
- (4) W.G. Willson, et al., "Low-Rank Coal-Water Slurries for Gasification - Phase 2 Analytic Studies," EPRI Final Report, AP - 4905, December 1986.
- (5) "SO<sub>2</sub> Talk Prompts \$20MM Dryer," Coal & Synfuels Tech. Vol. 10 (No. 1), pp. 3-4, Jan. 9, 1989.
- (6) WESTERN COAL REPT. #774, Aug. 21, 1990.
- (7) WESTERN COAL REPT. #777, Sept. 11, 1990
- (8) W.G. Willson, et al., "LRC Coal-Water Slurries for Gasification," Fuel Proc. Tech., 15, pp. 157-172, 1987.
- (9) W.G. Willson, et al., "Low-Rank Coal Water Slurries for Gasification," Final Report, EPRI Report No. AP-4262, Nov. 1985.
- (10) W. Irwin, "Future Prospects for Expanded Utilization of Steam Coal," Western Canada Geological Forum, April, 1989.
- (11) J.E. Boysen, et al., "Development of an Advanced Process for Drying Fine Coal in an Inclined Fluidized Bed," Report to U.S. Department of Energy, February, 1990.
- (12) Li, Yufu, 1990, Hot Water Drying of Two Alaskan Low-Rank Coals, M.S. Thesis, University of Alaska Fairbanks, Fairbanks, Alaska.
- (13) N. Moxon, Personal correspondence with MIRL, March, 1991.
- (14) N. Moxon and S. Richardson, "Development of a Calorimeter to Measure the Self-Heating Characteristics of Coal, Coal Preparation, 2, 1985.
- (15) D.G. Murchison, "Optical Properties of Vitrinites," Chapter 31, in Analytical Methods for Coal and Products, Edited by Clarence Karr Jr., 1978.
- (16) E. Rhoads and J. Crowley, "Economic Evaluation of the Transport of Dried Usibelli Coal," Report prepared for Mineral Industry Research Laboratory, University of Alaska Fairbanks, April 1991.
- (17) G.E. Sherman, et al., Analysis of Balboa Bay, Beluga, Point MacKenzie, and Lost River as Port Sites for Use by the Mineral Industry, U.S. Bureau of Mines OFR 36-90, 1990.

## APPENDIX

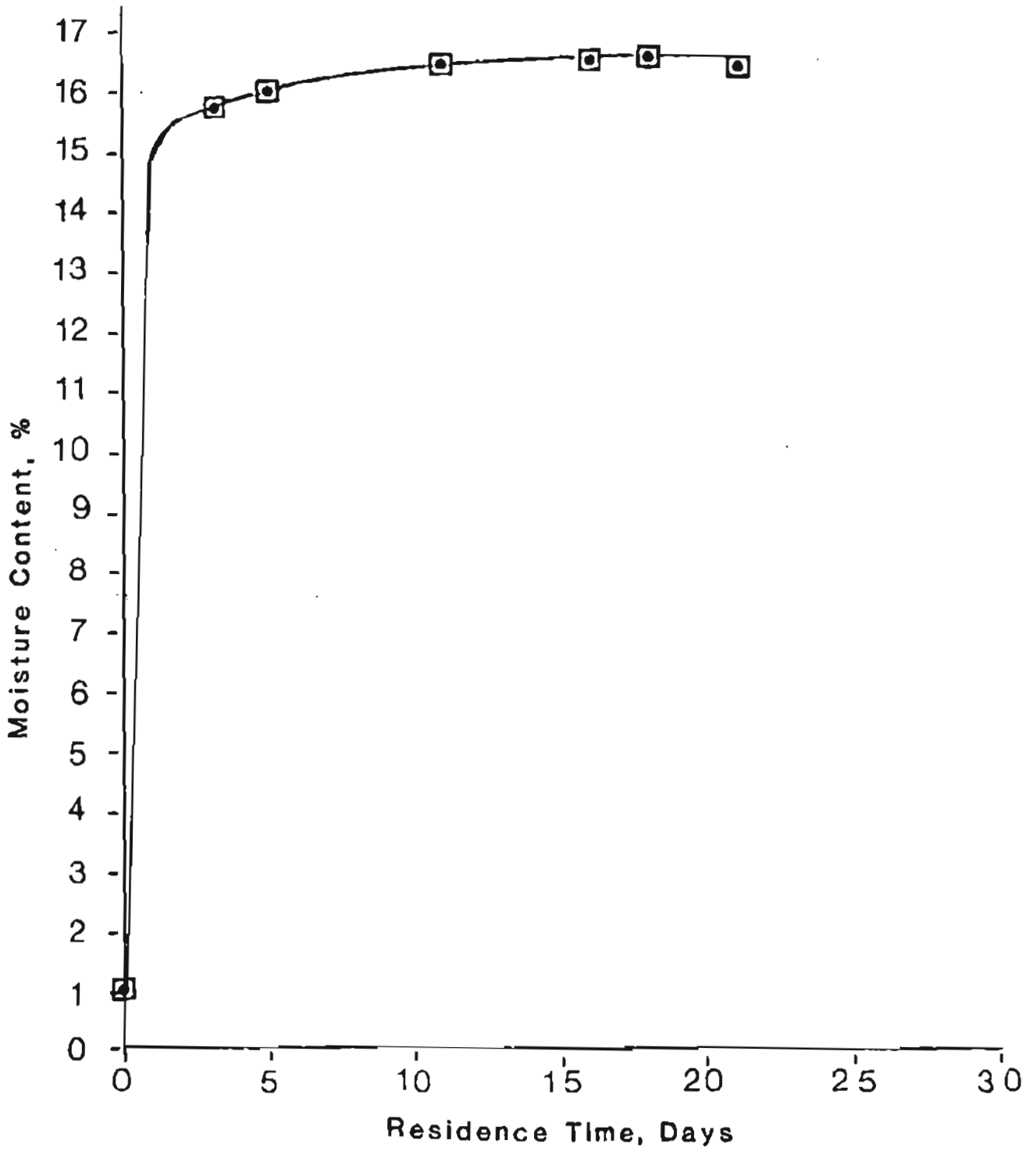


Figure A1. Moisture Reabsorption of Coal Dried in WRI's Inclined Fluid Bed Reactor at 700°F for 3 minutes. Test WRI 101/102.

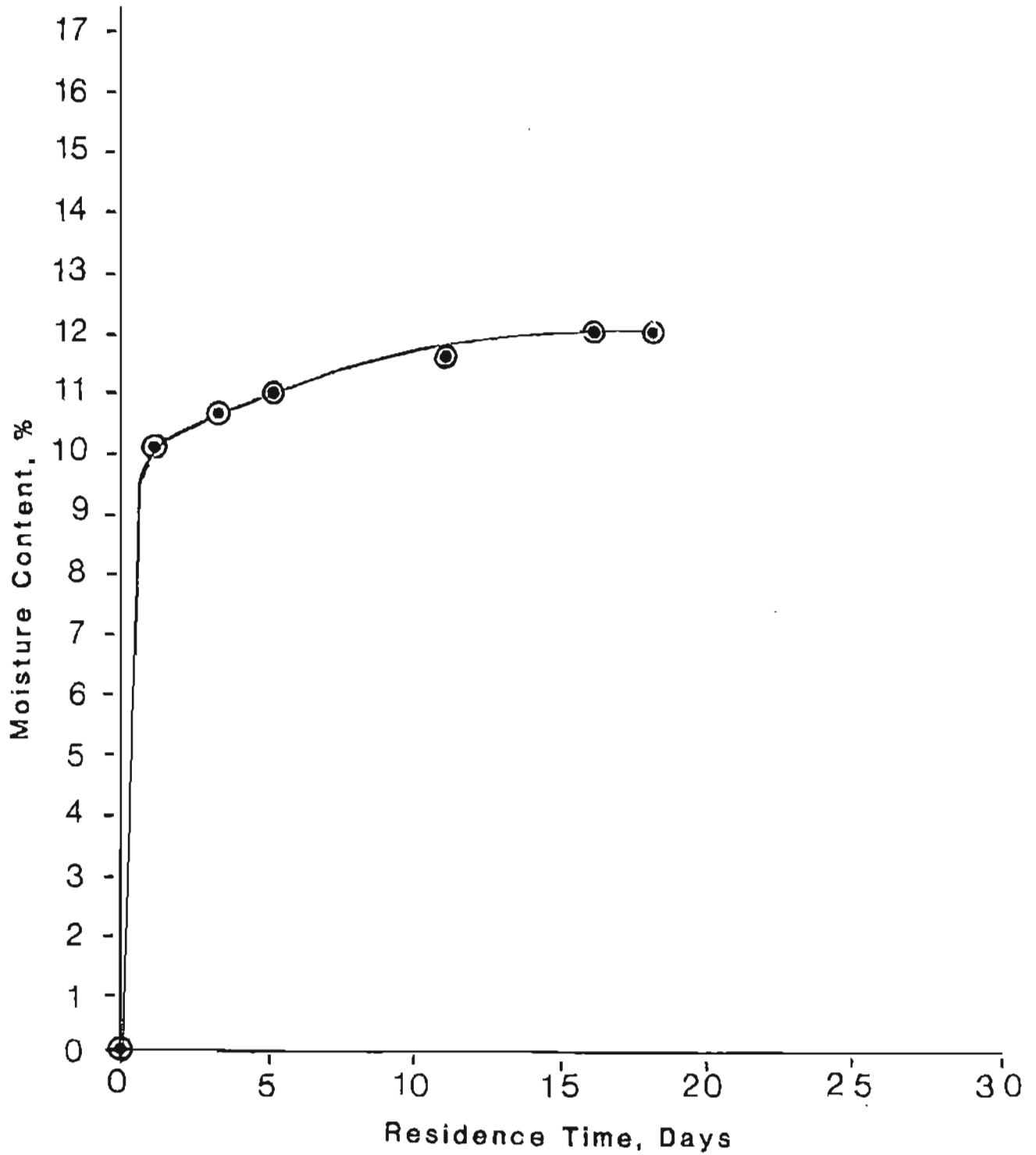


Figure A2. Moisture Reabsorption of Char from WRI's Inclined Fluid Bed Reactor at 1090° F for 1 minute. Test WRI 59.

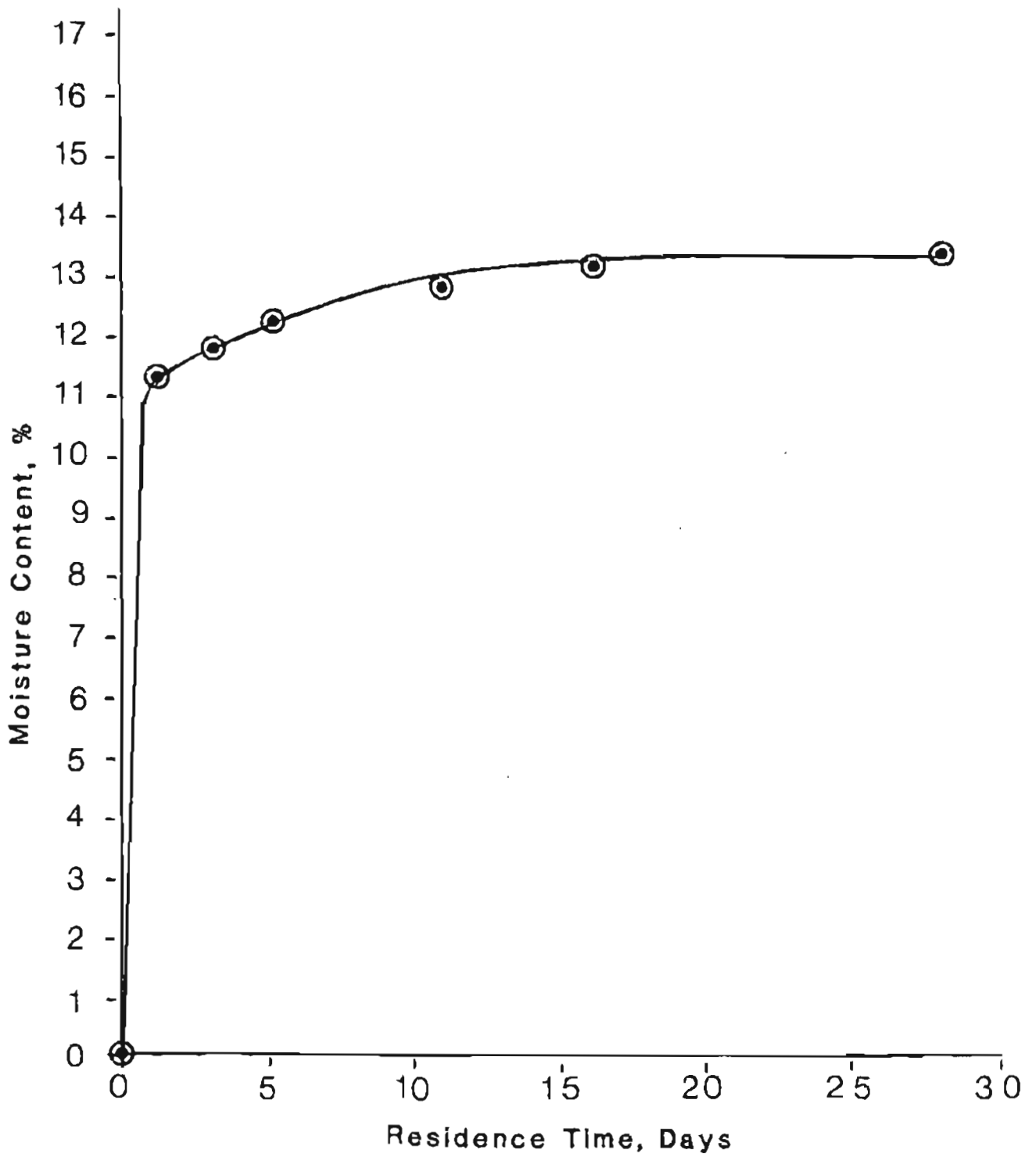


Figure A3. Moisture Reabsorption of Char from WRI's Inclined Fluid Bed Reactor at 1120°F for 4 minutes. Test WRI 63.

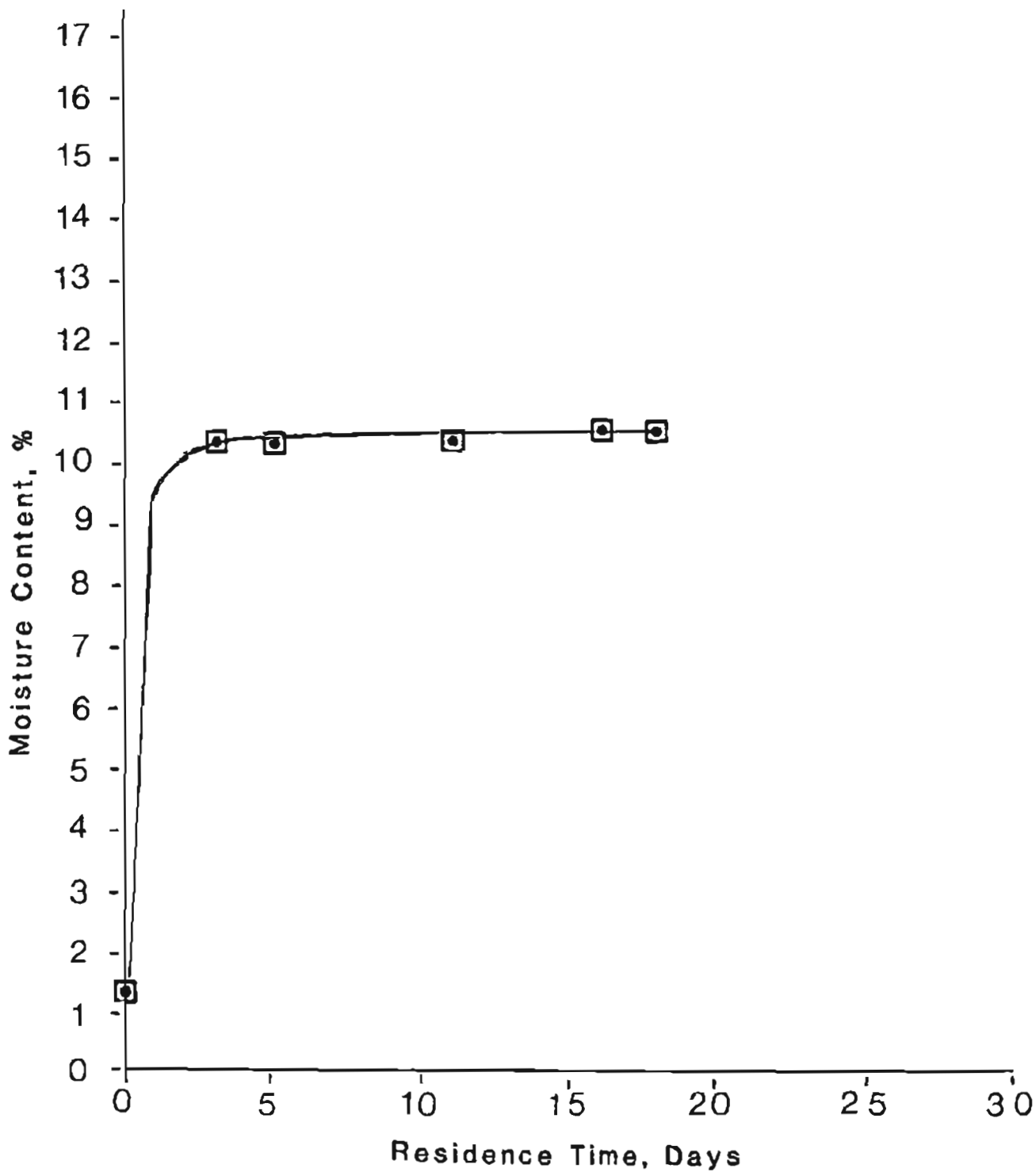


Figure A4. Moisture Reabsorption of Char from WRI's Inclined Fluid Bed Reactor at 1180°F for 7 minutes. Test WRI 64.

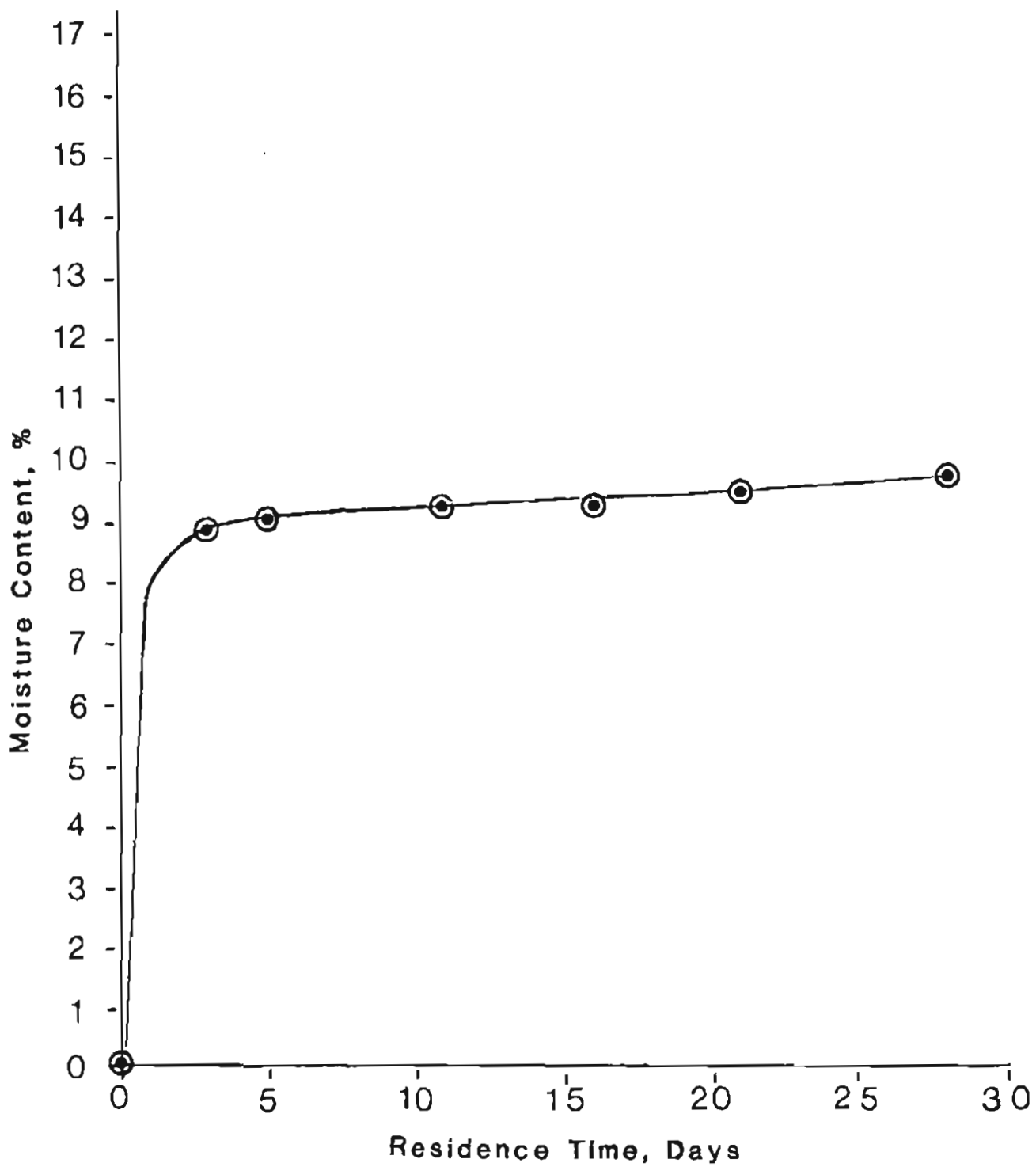


Figure A5. Moisture Reabsorption of Char from WRI's Inclined Fluid Bed Reactor at 1230°F for 12 minutes. Test WRI 62.

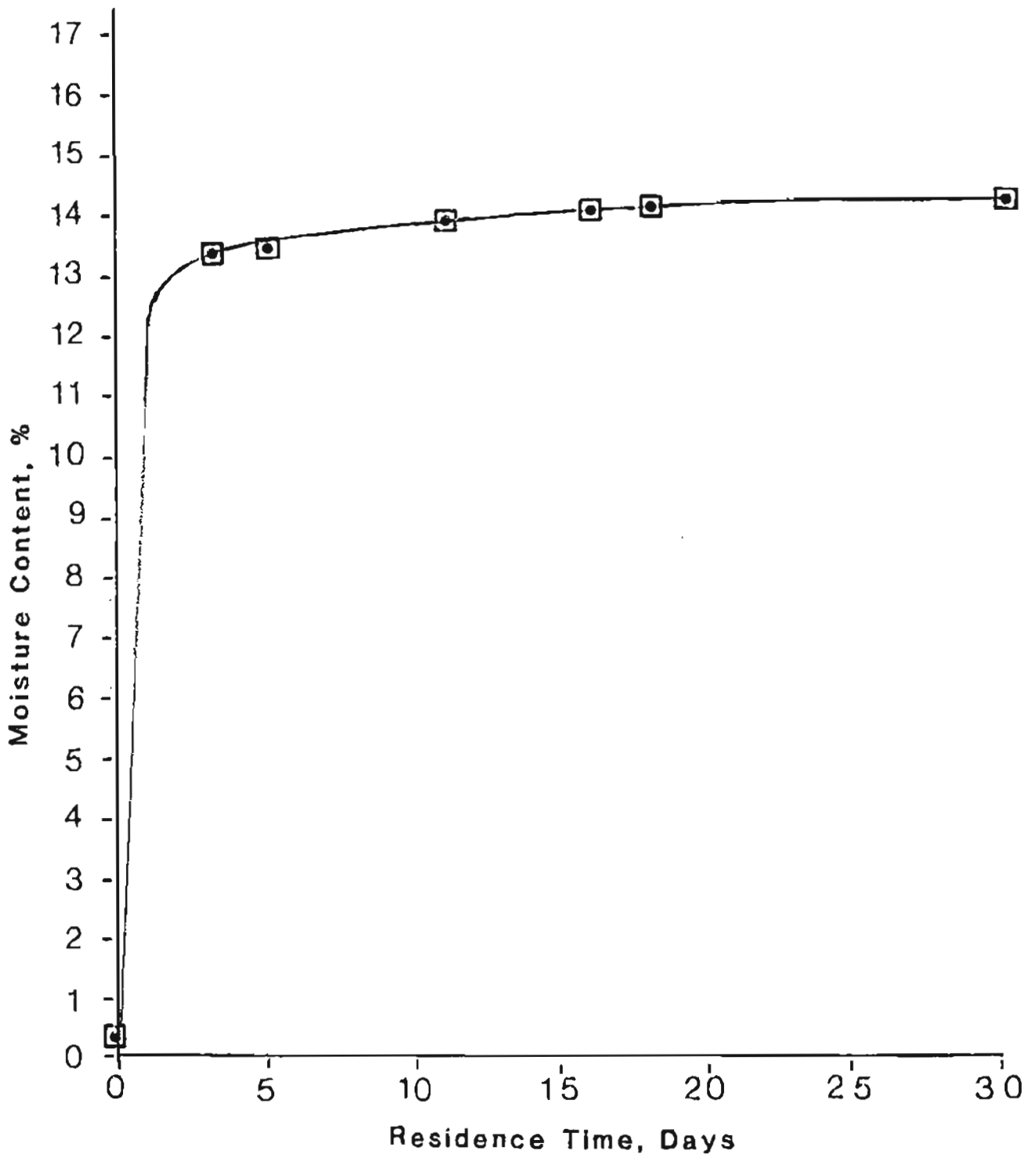


Figure A6. Moisture Reabsorption of Coal Dried in WRI's Inclined Fluid Bed Reactor at 700°F. Test WRI D-39.



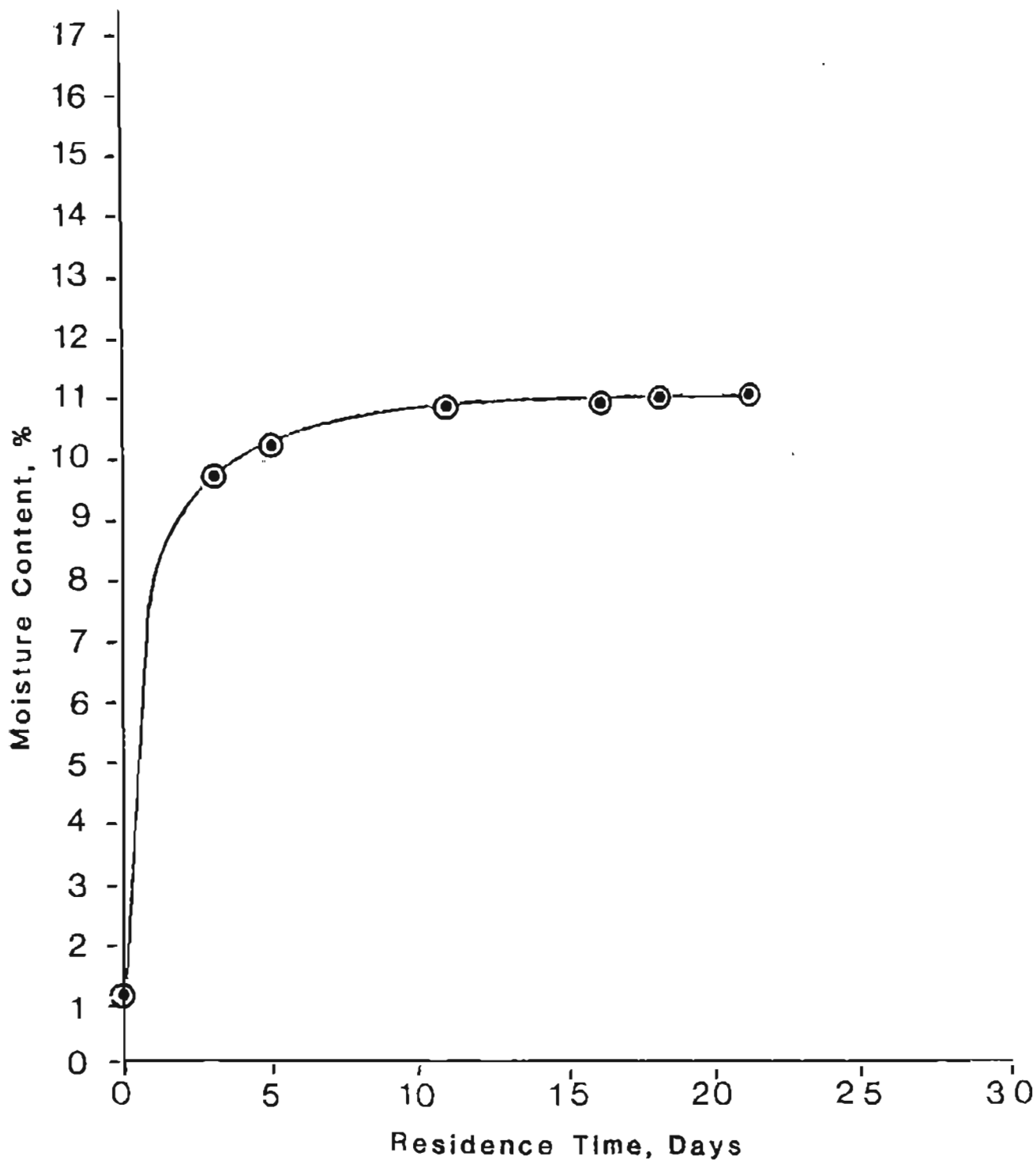


Figure A7. Moisture Reabsorption of Char from CTC's Vertical Column Reactor at 900° F for 420 minutes. Test CTC 11.

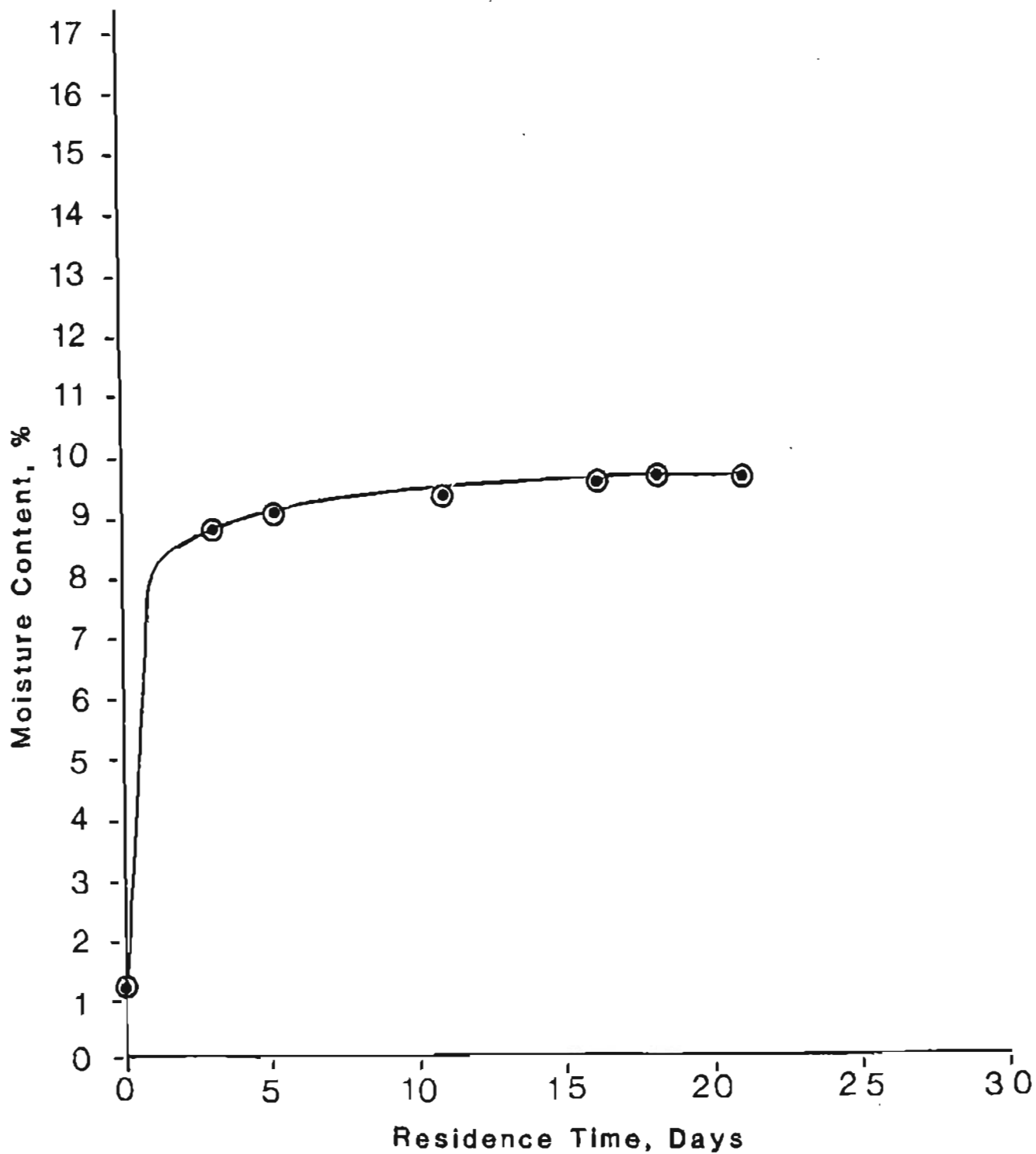


Figure A8. Moisture Reabsorption of Char from CTC's Vertical Column Reactor at 1000°F for 420 minutes. Test CTC 7/10.

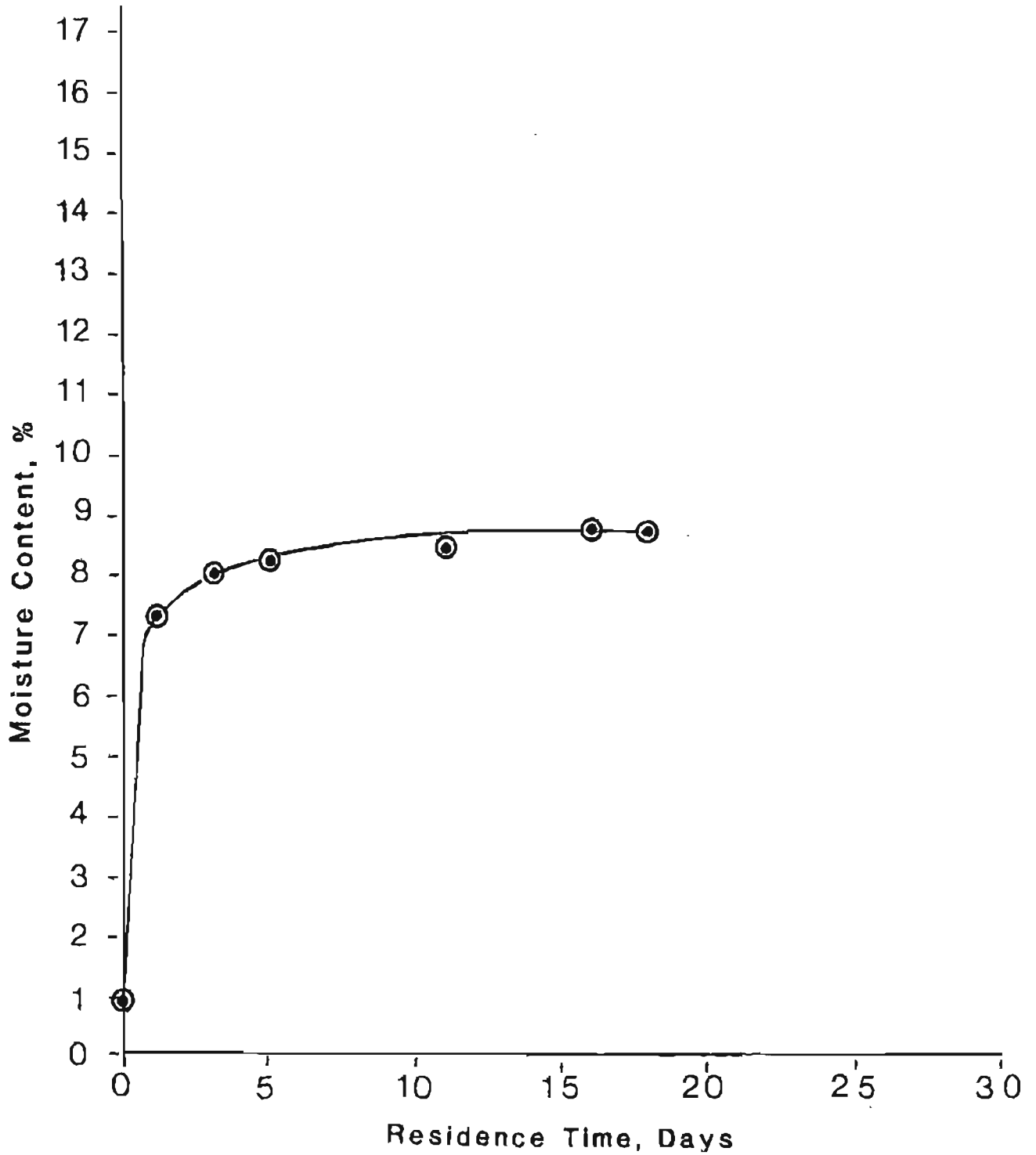


Figure A9. Moisture Reabsorption of Char from CTC's Vertical Column Reactor at 1100° F for 420 minutes. Test CTC 12.

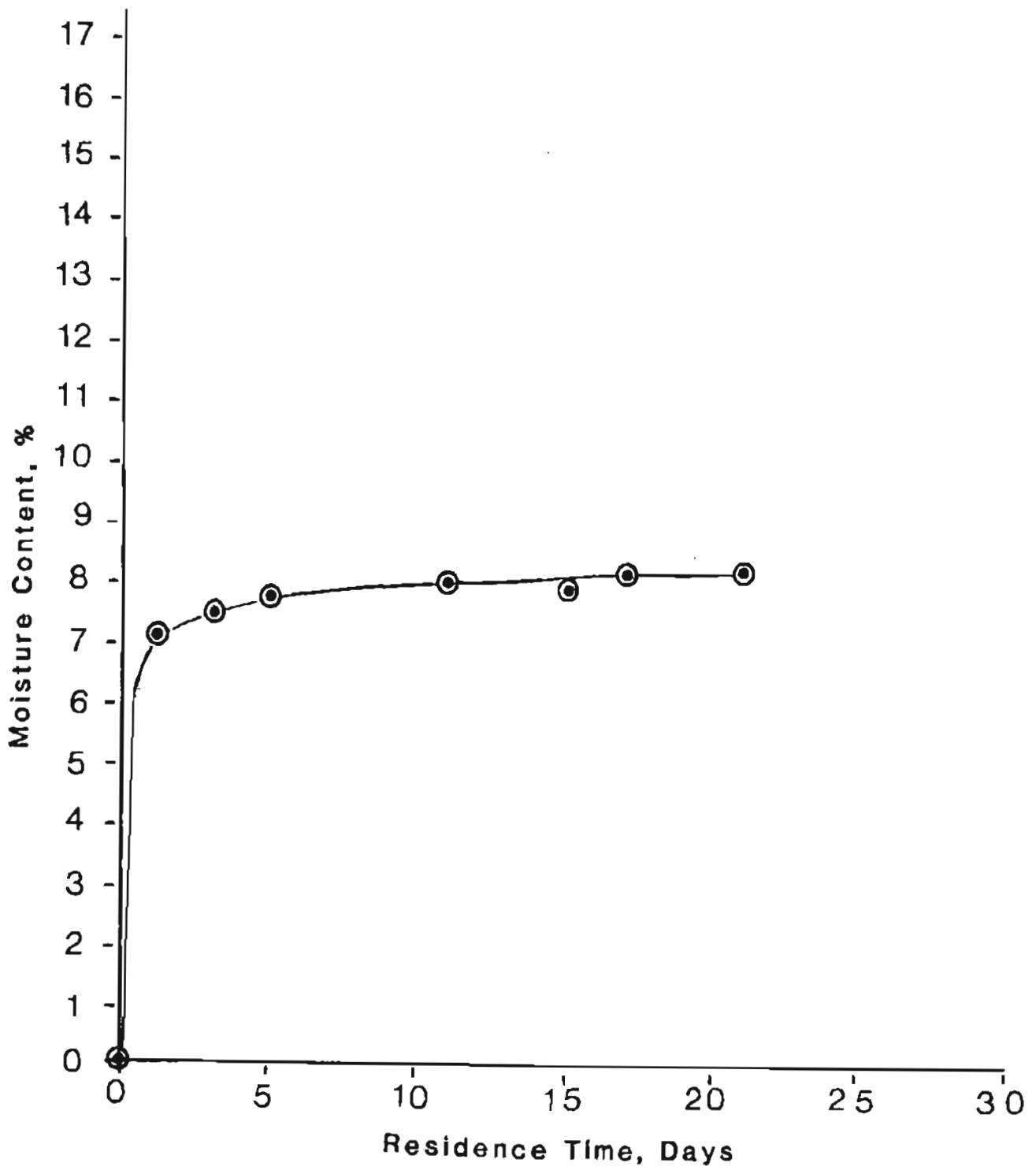


Figure A10. Moisture Reabsorption of Char from CTC's Vertical Column Reactor at 1300°F for 420 minutes. Test CTC 13.

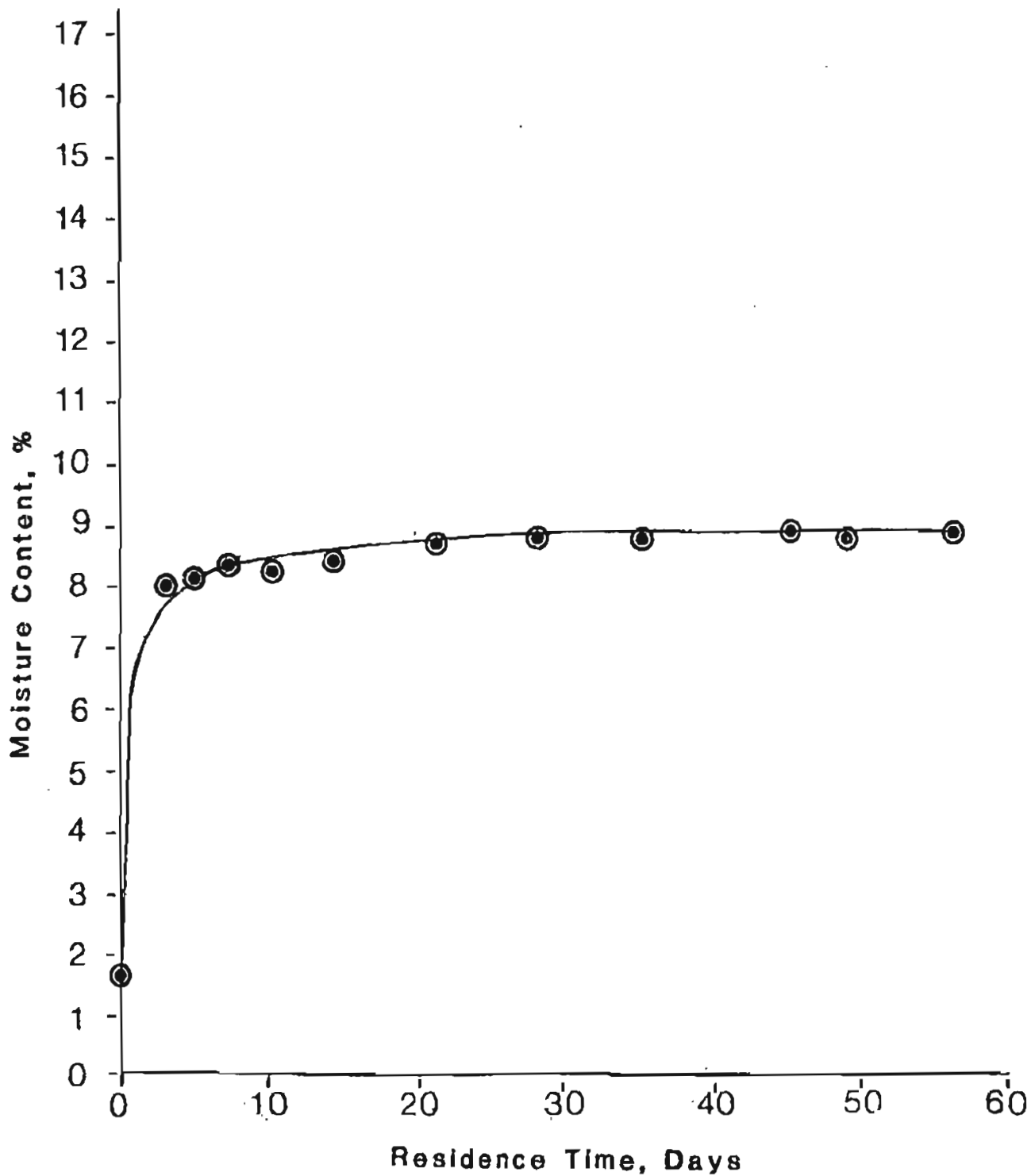


Figure All. Moisture Reabsorption of Briquetted Char from CTC's Vertical Column Reactor at 1300°F for 420 minutes. Test CTC 13.