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Hydrothermally Treated Coals for Pulverized Coal Injection

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ABSTRACT

HYDROTHERMALLY TREATED COALS FOR PULVERIZED COAL INJECTION

This project is investigating the suitability of hydrothermally dried low-rank coals for pulverized fuel injection into blast furnaces in order to reduce coke consumption. Coal samples from the Beluga coal field and the Usibelli Coal Mine, Alaska, are being used for the study. Crushed coal samples were hydrothermally treated at three temperatures, 275, 300 and 325°C, for residence times ranging from 10 to 120 minutes. Products have been characterized to determine their suitability for pulverized coal injection. Characterization includes proximate and ultimate analyses, vitrinite reflectance, TGA reactivity and thermochemical modeling. A literature survey has been conducted.

I. INTRODUCTION

Injection of pulverized coal into blast furnaces to reduce coke requirements has been investigated in the past and serious trials took place in the 1960s. However, the cost of fitting blast furnaces with pulverized fuel systems and the ready availability of low cost oil at that time, encouraged Japanese steel plants to substitute oil for coke. The shortage of oil during the 1979 oil crisis forced steel industries to take a serious look at replacing oil with pulverized coals. The steel industry soon discovered the advantages of pulverized coal injection (PCI). Large scale conversions to PCI were made both in Japan and Europe.^{1,2,3,4} By 1991, 26 of 33 operating blast furnaces in Japan were equipped with PCI systems, consuming 6 million tons of pulverized coal. Worldwide use of PCI was 13.2 million tons in 1990 and is expected to grow to 25 million tons by 1995. The current practice of pulverized coal injection at the Kakogawa No. 2 blast furnace, operated by Kobe Steel, uses coke (289 kg/t) along with pulverized coal (129 kg/t) and oil (65 kg/t).⁵

Coal injection rates are limited by:^{1,6}

1. Reactivity of injected coal
2. Chemical composition of injected coal
3. Particle size of injected coal
4. Gas distribution in the burden column
5. Furnace permeability

A proposed upper limit for pulverized coal injection, which would burn completely in the tuyere combustion zone, is estimated at 180 kg/t when the fuel rate is 500 kg/t. An upper limit for pulverized coal grain size is 0.7 mm.⁷

Calculations based on furnace trials have shown that pulverized coal can replace up to 30-50% of the coke previously used in blast furnaces employing oxygen enriched blast, without impairing productivity or hot metal quality. A pulverized coal injection rate of 150 to 200 kg/t hot metal, with a blast enrichment of 25-27% oxygen, is possible.⁸

The high price of coke has resulted in progressive substitution of coke by low cost pulverized coal. PCI combustion is differentiated from normal coal combustion by:⁹

1. High combustion zone temperatures; 1200 to 2000°C.

2. Short residence times in the presence of oxygen; less than 30 ms.
3. Gasification in the presence of CO₂.

Research conducted at the University of Alaska Fairbanks has shown that hydrothermal treatment of subbituminous 'C' coals can produce a high quality product suited for metallurgical use.¹⁰ The hydrothermally dried product has low moisture, very low sulfur, 0.2%, and is highly reactive. This project addresses the suitability of hydrothermally processed low-rank coals (LRCs) for metallurgical use as pulverized coal for injection into blast furnaces.

The fact that Alaska has over 5 trillion tons of low sulfur coal reserves and that each trillion tons has an energy equivalency of approximately 5,500 years of Alyeska pipeline production (1.5 MM barrels/day) demonstrates the enormous economic potential for Alaska's coal resources. This includes over 4 trillion tons of bituminous and subbituminous coal located in the Northern Alaska basin, north of the Brooks Range. The Usibelli Coal Mine, the only current operating coal mine in Alaska, has an annual production of about 1.5 million tons. Half of this is exported to Korea while the remainder supplies heat and power for interior Alaska. The Beluga coal field, adjacent to Cook Inlet, is readily accessible to ice-free tide water. The field has been extensively drilled and evaluated by Placer Dome Inc. and Diamond Alaska Coal Co.

Coals from Usibelli Coal Mine and the Beluga coal field are of subbituminous 'C' rank and typically have calorific values of 8,000 Btu/lb. The moisture of these coals is about 28%. The combination of high moisture and low heating value has restricted most low-rank coal usage worldwide to mine-mouth power generation, which in turn has limited export sales of Alaskan coal to only 0.75 MM tons per year from Usibelli Coal Mine. This comes at a time when Australian coal exports have topped 100 MM tons per year and the steam coal market is expected to more than double in this decade. Alaskan LRCs can participate in the Pacific Rim coal market by suitable upgrading to enhance quality.

While the objective of this project is applied research directed at Alaskan low-rank coal, the larger goal is to increase the available market for our state's and nation's coal resources. The relevance of such research is highlighted by the recent difficulty Usibelli Coal Mine, Inc.

experienced in renegotiating its 1993 coal export contract with KEPCO, a Korean electric utility. Technology and sound engineering management must be applied to enhance the marketability of Alaska's low-rank coals. One potential market for hydrothermally dried, Alaskan, low-rank coals is pulverized coal injection.

II. MIRL'S HYDROTHERMAL DRYING RESEARCH BACKGROUND

Fischer and Schrader first studied hydrothermal treatment of coals in 1921.¹¹ The process involves heating coals to a temperature of 320° to 400°C in the presence of water in an autoclave. Koppleman's process, used in the K-fuels system, treats LRC's at temperatures of 500° to 600°C 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 400°C.¹¹ The gases liberated principally consist of CO₂. Some tars are mobilized and these tend to condense on the surfaces of coal particles and in pores.¹⁰

Beginning in 1989, the Mineral Industry Research Laboratory (MIRL), University of Alaska Fairbanks, undertook a preliminary investigation of hydrothermal treatment of Alaskan low-rank coals to 1) determine the quality of the product that can be prepared, and 2) study petrologic changes that accompany hydrothermal treatment that will eventually influence the mechanical properties, surface area and product reactivity. The products obtained during these tests were surprisingly different from conventional, evaporatively dried LRCs. Expected, as well as surprising characteristics are summarized below:¹⁰⁻¹³

1. As expected, the products had low equilibrium moistures and enhanced heating value.
2. Although rank enhancement was expected, vitrinite reflectance increased from 0.25% to over 0.7%, placing the product in a high volatile bituminous range.
3. Improvement in grindability was expected, but surprisingly the HGI increased from 34 for the raw coal up to 115 for the products.
4. Most surprising was the physical property of the product. The coals went through a plastic stage and the resulting products resembled coke produced from coking coal. Beluga coal showed the most thermoplastic behavior upon hydrothermal treatment.

Sectioning of the dried particles showed that the particles were devoid of cracks. The size distribution of cells in the product varied and could be related to petrology. Most significant of all, was that the surface of each particle so fused, that the presence of the inner cell structure is only revealed upon sectioning.¹⁰ The density of the particles varied with the severity of hydrothermal treatment. Some particles have densities as low as 0.75 compared to 1.49 for the raw coal.¹⁰ Of special significance is the fact that although the processed particles are very porous, the fused skin strength of the particle is high and may allow handling without significant degradation.

The high reactivity and porosity of the LRC products, coupled with low ash and sulfur, may make them unique raw materials for numerous metallurgical applications. It is therefore important to characterize the hydrothermally dried low-rank coal products for possible applications, which until now have not been considered for Alaskan coals. Among these alternative applications, pulverized coal injection appears to offer promise, and is the focus of this project.

III. PROJECT PROGRESS: APRIL THROUGH JUNE 1995

Project progress for the fourth quarter of the project includes a continuing literature search and review emphasizing coal characteristics required for pulverized coal injection into blast furnaces (bibliography included in the appendix), and characterization of hydrothermally dried Beluga and Usibelli coals.

Previously, 4 X 8 mesh, crushed coal samples from the Beluga coal field and the Usibelli Coal Mine, Alaska, were hydrothermally treated at three temperatures, 275, 300 and 325°C and three residence times, 10, 60 and 120 minutes. Hydrothermal treatment was conducted using a reactor system similar to the one designed by Youtcheff.¹⁴ The system provides excellent isothermality and accurate residence time measurements. Hydrothermally dried products were filtered and air dried.

The hydrothermally dried products have been characterized using proximate and ultimate analyses, vitrinite reflectance and TGA reactivity. This characterization data is presently being used to model hydrothermally treated low-rank coals' suitability for PCI using a thermochemical model. Mr. Tom Oshnock of US Steel is assisting the project with this part of the characterization. Tables 1 and 2 (appendix) show the proximate and ultimate analyses data. Sulfur values of the hydrothermally dried products were unchanged from those of the raw coals, remaining at 0.2%. Tables 3 and 4 (appendix) present TGA reactivity and vitrinite reflectance values. These data confirm earlier hydrothermal drying studies of Alaskan low-rank coals conducted by MIRL¹³:

1. The degree of upgrading is affected by both process temperature and residence time, but process temperature has a greater influence than residence time on low-rank coal upgrading.
2. The upgrading takes place rapidly. Most occurs in the first 10-20 minutes of residence time and the rate of upgrading decreases thereafter. Significant upgrading can still take place given long enough residence time.
3. Beyond 40-60 minutes, the upgrading response versus residence time tends to level off.
4. Upgrading response increases linearly with increases in process temperature within the temperature range of 275-325°C.
5. Vitrinite reflectance increases significantly from the raw coal to the hydrothermally dried products, indicating significant structural changes, i.e. induced coalification has occurred during the hydrothermal drying process.
6. Small, laboratory scale, tubing reactor hydrothermal drying studies predict pilot plant performance well.

TGA reactivity studies were conducted using a Perkin-Elmer TGA, Series VII. Char from the raw coals and their hydrothermally dried products were obtained by heating 10 mg of coal in the TGA under a nitrogen atmosphere from room temperature to 1000°C at a scan rate of 20°C/min. Isothermal reactivity of the char was then determined at 1000°C in a gas mixture consisting of 10.09% CO₂, 2.06% O₂ and 87.85% N₂, which simulates conditions in the raceway of a typical blast furnace during combustion of pulverized coal. Examination of the data reveals an increase in TGA reactivity for the coal after hydrothermal treatment, which is attributed to the

increased porosity and permeability of the char, due to hydrothermal treatment. For comparison, two Western British Columbian bituminous coals, which are presently used for PCI, have reactivities of 0.88 - 0.90 wt. % loss per minute, and metallurgical coke, produced from a Western British Columbian bituminous coal has a reactivity of 0.73 wt. % loss per minute.

Vitrinite material (ulminite, telecollinite, desmocollinite) in low-rank coals is present in several forms as precursors to vitrinite in high-rank coals. Although vitrinite reflectance is not the best indicator of rank for low-rank coals, it is a very good indicator of structural changes accompanying thermal treatment of coals. In this study, ulminite and telecollinite were chosen as indicators. Mean, maximum reflectance was measured in oil. Ulminite reflectance is found to be very sensitive to process conditions. Ulminite reflectance for Usibelli coal increased from 0.30% in the raw coal to 0.86% for coal treated at 325°C for 120 minutes. These changes in ulminite reflectance are indicative of induced coalification, i.e. rank progression, by the hydrothermal drying process. The data show that reflectances for Usibelli coal of 0.60% can be achieved by a treatment time of 120 minutes at 275°C or 10 minutes at 325°C. Treatment times can therefore be dramatically reduced by increasing the temperature of treatment. Beluga coal showed similar reflectance changes.

Table 5 (appendix) compares raw Usibelli coal to its hot water dried products produced at the various process temperatures at a 10 minute residence time. After only a 10 minute residence time, a very significant improvement in coal quality was achieved. Ash levels remain essentially unchanged; the apparent increase in ash content above that of the raw coal being due to the dramatic decrease in equilibrium moisture (37% - 51%). Calorific values increased from 14% to 26% on an equilibrium moisture basis. After an initial increase above the raw coal level, volatile matter changed little, while there was a steady increase in fixed carbon levels.

In contemplating the industrial scale production of hydrothermally treated lump coal from raw low-rank coal, a cost-benefit analysis of operating parameters versus product marketability would be helpful. While lower process temperatures would allow lower process pressures and enable lower capital costs to be realized, higher temperatures obviously produce a higher quality

product. Process residence time and reactor volume would also need to be considered. Induced coalification is seen even at the lowest temperature (275°C) and a short residence time (10 minutes), yielding a hydrothermally dried Usibelli coal product with 37% lower equilibrium moisture and 14% higher calorific value. Detailed studies will be required to demonstrate that hydrothermally treated lump coal has the physical and oxidative stability to withstand the rigors of transportation.

Though final review and analysis of the characterization data is still pending, hydrothermally dried, Alaskan low-rank coals have many characteristics, which are comparable to those of coals presently being utilized for PCI. Tables 6 and 7 (appendix) show data for coals used for PCI at Tata Steel in India and Hoogovens in France, respectively. Table 8 presents ash analyses for Usibelli and Beluga coals from previous MIRC characterization research.¹⁵ The elevated phosphorous levels of Beluga coal may prove problematic for PCI applications.

IV. FUTURE PROJECT RESEARCH GOALS

Thermochemical modeling will continue, and a summary of the test data will be forwarded to PCI users in Japan and Korea to obtain their input relating to the most suitable hydrothermally treated coal for PCI applications. Letters soliciting participation in this project continue to be sent to Japan and Korea, after consultation with persons knowledgeable concerning appropriate contacts there. A final project report will be submitted by September 30, 1995.

V. SUMMARY

In summary, progress on the project to date is on schedule as defined by the original proposal. The special attributes of Alaska's low-rank coals, i.e., extremely low sulfur content, low ash and a possibility of preparing coal suitable for PCI by varying hydrothermal treatment temperatures and residence times, may offer an exciting new product for iron ore reduction, both in blast furnaces and for the direct reduction of beach sands in rotary kilns.

VI. REFERENCES

1. Oshnock, T.W., 1988, "Pulverized Coal Injection for Blast Furnace Operation," Industrial Practice of Fine Coal Processing, Klimpel, R.R. and Luckie, P.T., Editors, SME of AIME Publication, pp. 339-345.
2. Ma, J., et al., 1992, "The Balanced Oxygen Blast Furnace Iron Making Process," *Scandinavian Journal of Metallurgy*, Vol. 21, No. 3, June, pp. 104-111.
3. Brouwer, R.C., et al., 1991, "Massive Coal Injection at Hoogovens Ijmuiden Blast Furnace," *La Revue de Metallurgie*, Vol. 88, No. 4, April, p. 323.
4. Poos, A., et al., 1991, "Possibilities and Problems of Injection of High Pulverized Coal Rates in the Blast Furnace," *Stahl and Eisen*, Vol 111, No. 8, August 15, pp. 69-75.
5. Ono, R., et al., 1992, "Low-Coke-Rate Operation at Kobe Steel, Kakogawa No. 2 Blast Furnace," *Kobelco Technology Review*, No. 15, October, pp. 7-11.
6. Yamagata, C., et al., 1992, "Fundamental Study on Combustion of Pulverized Coal Injected into Coke Bed at High Rate", *ISIJ International*, Vol. 32, No. 6, pp. 725-732.
7. Tamura, K., 1991, "Upper Limits to Combustibility of Pulverized Coal in Blast Furnace Raceway and Desirable Injection Position," *Journal of the Iron and Steel Institute of Japan*, Vol. 77, No. 6, June, pp. 775-782.
8. Yaroshevskii, S.L., et al., 1989, "Investigating Pulverized Coal Combustion in Blast Furnace Hearth with Oxygen Enriched Blast," *Steel in the U.S.S.R.*, Vol. 19, No. 12, December, pp. 513-515.
9. Prado, G., 1988, "Physico-chemistry of Coal Combustion Under Blast Furnace Tuyere Conditions," *Revue de Metallurgie*, Vol. 85, No. 10, October, pp. 749-756.
10. Rao, P.D., et al. 1992, "Dehydration of Alaska's Low-Rank Coals by Hydrothermal Treatment," *Minerals and Metallurgical Processing*, Vol. 9, No. 1, February, pp. 41-47.
11. Li, Y., 1990, "Hot Water Drying of Two Alaskan Low-Rank Coals," M.S. Thesis, University of Alaska Fairbanks, Fairbanks, Alaska.

12. Walsh, D.E., et al., 1993, "A Study of Non-Evaporative, Hot Water Drying of an Alaskan Low-Rank Coal," *Coal Preparation*, Vol. 13, pp. 115-130.
13. Walsh, D.E., et al., 1993, "A Study of Non-Evaporative, Hot Water Drying of Three Alaskan Low-Rank Coals," *Proceedings of the Focus on Alaska's Coal 1993 Conference*, Anchorage, Alaska, May, 1993, (Rao, P.D. and Walsh, D.E., editors), MIRL Report No. 94, University of Alaska Fairbanks, Fairbanks, Alaska.
14. Youtcheff, J.S., 1983, "Contributions to the Understanding of the Phenomenology of Coal Liquefaction," Ph.D. Thesis, Pennsylvania State University, State College, PA
15. Rao, P.D., 1986, "Characterization and Evaluation of Washability of Alaskan Coals," MIRL Report No. 75, University of Alaska Fairbanks, Fairbanks, Alaska.

VII. APPENDIX

LITERATURE SURVEY BIBLIOGRAPHY

- Bordemann, F., et al., 1988, "Design, Construction and Operation of No. 5 Blast Furnace at Dillingen," *Iron and Steel Engineer*, Vol. 65, No. 10, October, pp. 42-46.
- Brouwer, R.C., et al., 1991, "Massive Coal Injection at Hoogovens Ijmuiden Blast Furnace," *La Revue de Metallurgie*, Vol. 88, No. 4, April, p. 323.
- Cappel, J., et al., 1988, "Present State of Blast Furnace Coal Injection Technology in Voeh Ember Works," *Metallurgical Plant and Technology*, Vol. 11, No. 5, pp. 20-26.
- Deguchi, M., et al., 1990, "Effect of pulverized Coal Injection on the Distribution of Pressure, Temperature and Fine Particle Fraction around Blast Furnace Raceway," *Journal of the Iron and Steel Institute of Japan*, Vol. 76, No. 5, May, pp. 691-698.
- Dibert, W.A., et al., 1994, "The Push for Increased Coal Injection Rates - Blast Furnace Experience as AK Steel Corporation," *Proceedings of the 11th Annual International Pittsburgh Coal Conference* (Shiao-Hung Chiang, editor), The University of Pittsburgh, School of Engineering, Center of Energy Research, Volume 1, p.403.
- Gathergood, D.S., 1988, "Coal Injection into the Blast Furnace," *International Iron & Steel Institute on Technology*, April 26.
- Gudenau, H.W., et. al., 1994, "High Coal Injection Rates into the Blast Furnace - Improvement of Combustion Properties," *Proceedings of the 11th Annual International Pittsburgh Coal Conference* (Shiao-Hung Chiang, editor), The University of Pittsburgh, School of Engineering, Center of Energy Research, Volume 1, pp. 405-410.
- Gudenau, H.W., et al., 1990, "Pulverized Coal Injection in the Blast Furnace; Increase of the Injection Rate by Use of Coal Mixtures," *Stahl und Eisen*, Vol. 110, No. 11, November, pp. 35-40.
- Gudenau, H.W., et al., 1988, "Model Investigations of Gas Flow in the Blast Furnace at High Injection Rates of Pulverized Coal," *Stahl und Eisen*, Vol. 108, No. 19, September, pp. 35-43.
- Hamilius, A., et al., 1989, "Pulverized Coal Injection at the Sidmar Blast Furnaces," *La Revue de Metallurgie*, Vol. 86, No. 5, May, pp. 393-403.
- Han, B. and Patrick, J.W., 1994, "Influence of Coal/Oil Injection on Coke in the Blast Furnace," *Proceedings of the 11th Annual International Pittsburgh Coal Conference* (Shiao-Hung Chiang, editor), The University of Pittsburgh, School of Engineering, Center of Energy Research, Volume 2, pp. 1217-1222.
- Ma, J., et al., 1992, "The Balanced Oxygen Blast Furnace Iron Making Process," *Scandinavian Journal of Metallurgy*, Vol. 21, No. 3, June, pp. 104-111.

- Malgarini, G., et al., 1989, "Use of Coal in Blast Furnaces," *Termotecnica* (Milan), Vol. 43, No. 3, March, pp. 71-76.
- Ohno, Y., et al., 1989, "Development of Oxygen Blast Furnace Process with Preheating Gas Injection into Upper Shaft," *Journal of the Iron and Steel Institute of Japan*, Vol. 75, No. 8, August, pp. 1278-1285.
- Ono, R., et al., 1992, "Test Operation with Lower Coke Rate," *Kobe Steel Engineering Reports*, Vol. 41, No. 2, pp. 85-88.
- Ono, R., et al., 1992, "Low-Coke-Rate Operation at Kobe Steel, Kakogawa No. 2 Blast Furnace," *Kobelco Technology Review*, No. 15, October, pp. 7-11.
- Oshnock, T.W., 1988, "Pulverized Coal Injection for Blast Furnace Operation," *Industrial Practice of Fine Coal Processing*, Klimpel, R.R. and Luckie, P.T., Editors, SME of AIME Publication, pp.339-345.
- Oshnock, T.W., et al., 1983, "Utilization of a Daily Material and Energy Balance Program to Evaluate and Improve Blast Furnace Performance," *AIME Ironmaking Proceedings*, Vol. 42, pp. 427-435.
- Peters, K.H., et al., 1989, "Operation of a Large Size Blast Furnace with Various Coke Grades and High Coal Injection Rates," *Stahl und Eisen*, Vol. 109, No. 10, November, pp. 1065-1072.
- Poos, A. and Ponghis N., 1991, "Possibilities and Problems of Injection of High Pulverized Coal Rates in the Blast Furnace," *Stahl und Eisen*, Vol. 111, No. 8, August 15, pp. 69-75.
- Prado, G., 1988, "Physico-chemistry of Coal Combustion Under Blast Furnace Tuyere Conditions," *Revue de Metallurgie*, Vol. 85, No. 10, October, pp. 749-756.
- Prasad, H.N., et al., 1994, "Coals for Cokemaking and Blast Furnace Injection Under Indian Conditions," *Proceedings of the 11th Annual International Pittsburgh Coal Conference* (Shiao-Hung Chiang, editor), The University of Pittsburgh, School of Engineering, Center of Energy Research, Volume 2, pp. 1446-1453.
- Tamura, K., 1991, "Upper Limits to Combustibility of Pulverized Coal in Blast Furnace Raceway and Desirable Injection Position," *Journal of the Iron and Steel Institute of Japan*, Vol. 77, No. 6, June, pp. 775-782.
- Yagi, J., 1991, "Recent Progress in Fundamental and Applied Research In Blast Furnace Ironmaking in Japan," *ISIJ International*, Vol. 31, No. 5, pp. 387-394.
- Yamagata, C., et al., 1992, "Fundamental Study on Combustion of Pulverized Coal Injected into Coke Bed at High Rate", *ISIJ International*, Vol. 32, No. 6, pp. 725-732.
- Yamaoka, H. and Kamei, Y., 1991, "Theoretical Study on an Oxygen Blast Furnace Using Mathematical Simulation Model," *ISIJ International*, Vol. 32, No. 6, pp. 701-708.
- Yaroshevskii, S.L., et al., 1989, "Investigating Pulverized Coal Combustion in Blast Furnace Hearth with Oxygen Enriched Blast," *Steel in the U.S.S.R.*, Vol. 19, No. 12, December, pp. 513-515.

Table 1. Analyses of hot water dried 4 x 8 mesh coal, No. 4 Seam Usibelli Coal Mine (all data expressed on a dry, ash-free basis except for equilibrium moisture, which is expressed on a raw coal basis).

PROCESS TEMPERATURE=275°C								
Residence Time, minutes	Equilibrium Moisture %	Volatile Matter %	Fixed Carbon %	Calorific Value Btu/lb	C, %	H, %	N, %	O, %
Raw Coal	25.5	53.2	46.8	11980	67.9	4.9	1.2	25.8
10	15.8	50.1	49.9	12040	69.5	4.9	1.3	24.1
	16.2	52.2	47.8	12265	69.6	5.0	1.2	24.0
60	15.0	49.6	50.4	12485	71.1	5.0	1.3	22.4
	14.1	49.8	50.2	12605	71.5	5.0	1.3	22.0
120	12.4	48.9	51.1	12785	72.0	5.0	1.4	21.5
	14.0	49.1	50.9	12780	72.0	5.0	1.3	21.4
PROCESS TEMPERATURE=300°C								
Residence Time, minutes	Equilibrium Moisture %	Volatile Matter %	Fixed Carbon %	Calorific Value Btu/lb	C, %	H, %	N, %	O, %
10	14.3	50.0	50.0	12535	70.7	5.0	1.2	22.9
	14.0	49.8	50.2	12580	70.2	5.1	1.2	23.2
60	11.3	48.0	52.0	12975	73.4	5.1	1.3	19.9
	9.9	47.4	52.6	13065	73.5	5.0	1.3	19.9
120	9.1	45.4	54.6	13200	74.2	5.1	1.3	19.2
	9.8	46.6	53.4	13130	74.1	5.1	1.3	19.3
PROCESS TEMPERATURE=325°C								
Residence Time, minutes	Equilibrium Moisture %	Volatile Matter %	Fixed Carbon %	Calorific Value Btu/lb	C, %	H, %	N, %	O, %
10	11.6	48.5	51.5	12960	73.4	5.0	1.3	20.1
	13.4	48.2	51.8	12890	72.6	5.0	1.2	21.0
60	9.3	44.5	55.5	13285	75.3	5.0	1.4	18.2
	8.6	43.8	56.2	13290	75.0	5.0	1.4	18.4
120	7.6	42.3	57.7	13450	76.2	5.0	1.3	17.3
	9.0	43.9	56.1	13480	76.2	5.0	1.4	17.1

Table 2. Analyses of hot water dried 4 x 8 mesh Beluga Coal (all data expressed on a dry, ash-free basis except for equilibrium moisture, which is expressed on a raw coal basis).

PROCESS TEMPERATURE=275°C								
Residence Time, minutes	Equilibrium Moisture %	Volatile Matter %	Fixed Carbon %	Calorific Value Btu/lb	C, %	H, %	N, %	O, %
Raw Coal	23.8	52.8	47.2	12075	68.7	5.1	1.4	24.6
10	12.0	48.1	51.9	12645	71.5	5.2	1.4	21.8
	13.2	49.9	50.1	12405	70.5	5.1	1.3	22.9
60	12.6	47.4	52.6	12555	71.4	5.1	1.4	21.9
	14.2	48.6	51.4	12315	69.8	5.1	1.3	23.7
120	10.9	48.7	51.3	12630	72.0	5.1	1.4	21.2
	12.0	46.9	53.1	12695	71.7	5.0	1.4	21.7
PROCESS TEMPERATURE=300°C								
Residence Time, minutes	Equilibrium Moisture %	Volatile Matter %	Fixed Carbon %	Calorific Value Btu/lb	C, %	H, %	N, %	O, %
10	11.0	49.2	50.8	12465	71.1	5.4	1.6	21.8
	13.3	48.1	51.9	12535	71.3	5.0	1.4	22.2
60	10.8	46.2	53.8	12810	72.9	5.0	1.4	20.5
	9.9	45.7	54.3	13045	73.8	5.2	1.4	19.5
120	9.8	46.1	53.9	13080	74.4	5.4	1.7	18.3
	10.5	44.7	55.3	13020	74.0	5.2	1.4	19.2
PROCESS TEMPERATURE=325°C								
Residence Time, minutes	Equilibrium Moisture %	Volatile Matter %	Fixed Carbon %	Calorific Value Btu/lb	C, %	H, %	N, %	O, %
10	10.4	47.2	52.8	12805	73.2	5.0	1.4	20.2
	11.8	47.2	52.8	12680	72.2	5.2	1.4	21.0
60	10.5	44.0	56.0	13155	74.7	5.0	1.5	18.6
	9.9	43.2	56.8	13305	75.0	5.2	1.5	18.0
120	8.0	43.4	56.6	13385	76.3	5.1	1.5	17.0
	8.1	43.3	56.7	13410	76.5	5.1	1.4	16.7

Table 3. Ulminite reflectance and TGA reactivity of raw and hot water dried Usibelli coal.

Process Temperature °C	Residence Time Minutes	Ulminite Reflectance $\bar{R}_{\max, \text{ oil}}$	Reactivity Wt.% loss/min
275	10	0.42	2.03
	60	0.54	2.09
	120	0.60	2.14
300	10	0.48	2.12
	60	0.60	2.21
	120	0.65	2.18
325	10	0.60	2.13
	60	0.77	2.25
	120	0.86	2.32
Raw Coal		0.30	1.96

Table 4. Ulminite reflectance and TGA reactivity of raw and hot water dried Beluga coal.

Process Temperature °C	Residence Time Minutes	Ulminite Reflectance $\bar{R}_{\max, \text{ oil}}$	Reactivity Wt.% loss/min
275	10	0.48	1.65
	60	0.64	1.66
	120	0.72	1.69
300	10	0.60	1.62
	60	0.84	1.66
	120	0.88	1.70
325	10	0.72	1.68
	60	0.94	1.71
	120	0.98	1.70
Raw Coal		0.32	1.53

Table 5. Improvement in Usibelli coal quality after hot water drying
(equilibrium moisture basis).

Property	Raw Coal	HWD PROCESS TEMPERATURE, °C (10 minute residence time)		
		275	300	325
Equilibrium moisture, %	25.5	16.0	14.1	12.5
Ash, %	4.6	5.5	5.8	6.2
Volatile matter, %	37.1	40.2	39.9	39.3
Fixed carbon, %	32.7	38.4	40.1	42.0
Fuel Ratio	0.9	1.0	1.0	1.1
Calorific Value, Btu/lb	8,365	9,545	10,050	10,505

TABLE 6. CHARACTERISTICS OF COALS USED FOR INJECTION AT TATA STEEL, INDIA.

Parameter	South Black Water	West Bokaro
Proximate Analysis (db), %		
Ash	9-10	17-18
VM	24-26	26-28
Ultimate Analysis (Typical), %		
Ash	10.1	18.30
C	77.72	71.47
H	4.22	4.24
N	1.75	1.63
O	5.73	3.75
S	0.48	0.61
Alkalis (Na ₂ O + K ₂ O), %	0.25-0.27	0.25-0.35
Initial Ash Fusion Temp., °C	1170	1250
HGI	55-65	60-70
Calorific Value, kcal/kg	7250	6820
Tar Yield, kg/t	31.5	39.85

Table 7. Main characteristics of injected coals.
(Hoogovens, France)

Coal number	Volatile matter (d.b.)	Ash (d.b.)	S (d.b.)	HGI	Ultimate analysis				Replacement factor (%) Coke/Coal	Moisture			
					C (d.b.)	H (d.b.)	N (d.b.)	O (d.b.)		Total	Inherent	Evaporated	Pulverized coal
1	36.6	3.7	0.97	51	81.1	5.3	1.3	7.7	91.20	7.7	2.3	6.0	1.5
2	32.6	5.8	0.88	62	81.2	5.1	1.4	5.6	93.41	5.7	1.4	4.7	0.9
3	31.8	6.3	0.88	62	81.6	5.1	1.5	4.6	94.98	6.5	1.0	5.8	0.7
4	34.7	6.3	0.67	61	78.3	5.1	1.2	8.5	87.22	8.3	2.6	6.0	1.8
5	33.0	4.7	0.73	56	83.0	5.0	1.4	5.3	95.82	4.8	1.3	3.9	0.9
6	32.5	7.5	0.62	46	77.8	4.8	1.6	7.7	86.62	6.6	2.6	4.9	1.7
7	32.5	5.7	0.75	59	81.3	5.2	1.4	5.7	93.93	5.0	1.2	4.2	0.8
8	35.5	6.3	0.74	45	77.7	5.0	1.5	8.8	85.73	5.6	2.7	3.8	1.8
9	33.8	5.7	0.66	48	80.4	4.7	1.4	7.1	89.48	8.7	2.1	6.0	2.2
10	31.3	8.5	1.07	75	78.7	5.2	1.5	5.0	88.35	10.2	1.2	6.0	3.7
11	30.5	5.4	0.79	60	82.6	5.1	1.4	4.7	95.99	5.3	1.1	4.6	0.7
12	17.5	5.6	0.79	100	84.9	4.4	1.4	2.9	97.84	8.5	0.7	6.0	2.0
13	33.9	5.7	0.88	58	82.1	5.1	1.3	4.9	95.43	6.5	1.0	5.8	0.7
14	31.6	6.1	0.94	61	82.3	4.8	1.3	4.6	95.29	4.6	1.2	3.8	0.8
15	33.3	5.5	0.78	62	82.2	5.1	1.3	5.1	95.34	6.0	1.2	5.2	0.8
16	39.3	5.9	0.64	54	78.0	5.0	1.3	9.3	82.79	11.4	7.1	6.0	4.9
17	33.8	9.2	0.67	57	76.8	5.4	1.3	6.6	87.78	7.3	2.4	5.7	1.6
18	32.7	10.8	0.54	55	73.6	4.4	1.5	9.2	79.52	8.8	3.6	6.0	2.4
19	24.4	8.3	0.87	80	81.8	4.7	1.5	2.8	93.62	9.7	1.2	6.0	3.2
20	30.7	8.0	0.62	58	77.7	4.4	0.7	8.6	84.40	8.9	4.8	5.7	3.2
21	30.7	8.6	0.54	50	76.4	4.1	0.7	9.7	78.69	12.6	7.1	6.0	6.1

Evaporated moisture = total moisture - 2/3 inherent moisture (maximum = 6 %)

Pulverized coal moisture = total moisture - evaporated moisture.

Replacement factor coke/coal = 2 % C + 2.5 % H + 0.9 % ash

Pulverized coal moisture : 86 %

(d.b. = dry basis, sur sec).

Table 8. Concentration of Major Elements in Raw Coal Ash, percent¹⁵

Coal Field	Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	SO ₃	MnO	P ₂ O ₅
Poker Flat Pit No. 4 Seam	UA 119 (Usibelli)	43.4	22.7	6.7	2.7	16.6	1.08	2.2	1.1	6.5	0.21	0.09
Capps Bed	UA 127 (Beluga)	53.8	25.9	2.4	1.4	9.5	0.34	1.7	1.1	2.3	0.04	0.54