**Oxidation Editorial Group**

Jolanta Kus1 and Magdalena Misz-Kennan2

1) Federal Institute for Geosciences and Natural Resources, Hannover, Stilleweg 2, D-30655 Hannover, Germany

2) University of Silesia, Faculty of Earth Sciences, ul. Będzińska 60, 41-200 Sosnowiec, Poland

**Notice:** Use only for internal review!

**Feedback:** please, supply your comments, remarks, suggestions, etc. to content of the text and the plates in form of annotations in the Word document, using Microsoft Word’s Track Changes feature. Grammar/English language and spelling is at moment corrected by a native speaker and does not need your attention. The deadline for receiving your suggestions is 18.01.2015.

Contact person for feedback: J.Kus@bgr.de

**Natural and laboratory (artificial) oxidation**

**I. Origin of term**

First studies of coal oxidation were carried out in the second half of the 18th century followed by intensive coal research in the twentieth century (Parr and Francis, 1908; Parr, 1925; Parr and Milner, 1925; Parr and Coons 1925; van Krevelen, 1982).

The process of aerial coal oxidation is introduced here to denote in situ complex reactions of coal with oxygen at ambient and at low temperatures (< 250°C), (Cox and Nelson, 1984) occurring at diverse conditions and time intervals and resulting in changes of coal’s optical, physical, chemical and technological properties as well as of its molecular structure, (Tab.1).

The process of aerial coal oxidation takes place in situ during weathering at ambient and at low temperature conditions and during laboratory experiments in which coals are artificially oxidized during drying at ambient conditions and at low temperatures up to approximately 250°C. The upper temperature limit of 250°C is marking beginning stage of coal pyrolysis.

Tab. 1. Conditions of natural and artificial (laboratory) oxidations.

|  |  |
| --- | --- |
| Natural (weathering) oxidation | Artificial (laboratory) oxidation |
| at ambient conditions atabout < 35-50°C | At low temperature conditions at about 35°C -250°C | Drying at about 25-30°C | At low temperature oxidation conditions at about 25°C -250°C |

In situ natural as well as artificial (laboratory) oxidation of coals can be defined as a series of physical, chemical or biological weathering processes (Marchioni, 1983). The process of weathering can take place in situ at outcrop, coal face (coal wall), waste piles, stockpiles, or during coal processing or transport and the resulting coal oxidation can cause alteration of coal properties (Chandra, 1962; Ingram and Rimstidt, 1984; Taylor et al., 1998). The process of artificial oxidation of coals takes place in laboratory experiments at various conditions.

Related terms:

Low temperature oxidation: Schmidt (1945), Berkowitz (1985), Larsen et al. (1986), Nelson (1989), van Krevelen (1993), Carras and Young (1994)

Natural oxidation: Bustin et al. (1985)

Mild oxidation: Sánchez and Rincón (1997)

Artificial weathering: Wachowska et al. (1974)

Air oxidation: Mastalerz et al. (2009)

Low temperature coal weathering: Wu et al. (1988)

Incipient coal oxidation: Kruszewska and du Cann, (1996)

**IIa. Definition, origin of in situ weathering**

In situ weathering of coal including oxidation at ambient and at low temperature conditions starts upon the exposure of coal to oxygen with oxygen acting as an oxidizing agent and continues to exert its influence prior to and/or during mining, coal extraction, washing, storage at stockpiles or waste damps, transport (Chandra 1962; Bustin et al., 1983; Ingram and Rimstidt, 1984; Klein and Welleck, 1989; Nelson, 1989).

The factors governing weathering of coal are divided into internal such as coal rank, composition, moisture content and external such as temperature, oxygen partial pressure, rate of coal oxidation, particle size, oxidation history/extent of previous oxidation, climate, ground water conditions, extent of fracturing of coal and adjacent rock, tectonic faults, and depth.

**Coal rank**

In general, the lower the rank of coal, the higher is its susceptibility to interact with oxygen (Stopes and Wheeler, 1923a, 1924; Wheeler and Woolhouse, 1932; Schmidt, 1945). Similar conclusion reached Fieldner et al. (1945) whereby oxygen absorption of coal generally decreases with increasing rank that is, being the lowest for anthracite and highest for subbituminous coal and lignite. La Grange (1950, 1951), Bustin et al. (1985), and Wu et al. (1988) confirmed that coal rank is generally regarded as a reliable indicator of coal’s relative propensity towards coal weathering. The lower the coal rank the more liable coal appears to be towards weathering. Moore (1931, 1932) studied rates of coal oxidation and suggested an approximate correlation of coal rank with oxidation rate.

**Coal composition**

Stopes and Wheeler (1923a,b,c) concluded that the four studied banded constituents of coal (vitrain, clarain, durain, and fusain) exhibited no significant difference in oxidation rates. Tideswell and Wheeler (1920) reached the same conclusion. According to Chandra (1962, 1982) and Leythaeuser (1973), varying oxidation temperatures as well as oxidizing conditions can exert an influence on petrographic features of weathered coals. In a given sample all macerals are prone to coal oxidation, although liptinite and vitrinite macerals display the greater proneness to in situ coal oxidation. On the contrary, fusinite macerals and especially pyrofusinite due to its molecular structure are extremely resistant to oxidative changes.

**Moisture content**

The oxidation rate is generally influenced by presence and removal of moisture content from coal of different rank and by presence of the relative air humidity. It has been found that coal reacts with oxygen more rapidly when wet than when dry under laboratory conditions (Graham 1914, 1915; Haldane and Makgill, 1934; Jones and Townend, 1949; Mukherjee and Lahiri, 1957; Lowry, 1963; Itay et al., 1989; Smith and Lazzara, 1987; Beier, 1962). Similarly, Cronauer et al. (1983b) suggested that rate of oxidation of subbituminous coal is influenced by the remaining moisture content of the coal. Further, there appears to be critical moisture content at which coals exhibit accelerated oxidation rate. Panaseiko (1974) found that there was a critical moisture level at which the adsorption of oxygen by surface of coal was the highest and the oxidation proceeded rapidly. This critical moisture level was found to decrease with increasing rank and was suggested to be 5-8 wt % for brown coal, 1.5-2.0 wt % for subbituminous coals and 0.5-0.7 wt % for low-volatile bituminous coals and anthracites. Chen and Stott (1993) observed that the maximum oxidation rate of sub-bituminous coals occurred at a “critical” moisture content of 7-17 % db (dry basis). Regarding removal of moisture, Walker (1967) and Banerjee et al. (1970) showed that stripping moisture from coal would expose more fresh active sites for oxygen contact and would therefore accelerate oxidation. In contrary, Huggins et al. (1983) reported that the depletion of moisture at low temperatures by storing of coal over a desiccant retarded the rate of oxidation. With respect to relative air humidity, Beier (1962) concluded based upon his comprehensive studies that in dry or very moist air conditions the oxidation rate was higher than at medium humidity levels. Berkowitz (1985) suggested that this can be linked to the change in the mechanism of coal oxidation at about 70°C. Below 70°C, acid functions and peroxides are forming during coal oxidations. Above 70°C peroxides forms only transiently or not at all. It is possible, that humidity promotes coal oxidation at lower temperatures and inhibits it at higher temperatures. The different oxidation conditions influence the development of different coal oxidation reactions and products Huggins et al. (1983) and Gethner (1986, 1987b) found that coal oxidation reactions and products were significantly different under moist conditions compared to conditions without moisture. Further, Huggins and Huffman (1989) suggested that hydrolysis reactions in which water is available to form hydrolyzed species such as hydroperoxides and hydrated ferrous sulfates are likely to be important in the weathering process.

**Temperature**

Temperature is one of the major factors exhibiting an influence on the rate of oxidation as concluded by Wu et al. (1988), Carras and Young (1994) and Wang et al. (2003). In the studies, rate of oxidation increases exponentially with temperature. Similar conclusion reached Zelkowski (2004) who reported that the higher the temperature during coal oxidation the more insensitive development of coal oxidation is to be expected. The velocity of coal oxidation is exponentially dependent on temperature. The temperature dependency of oxidation reactions was further confirmed by Gethner (1987a, b), where each oxidation reaction displayed a different temperature dependency at a temperature range from 25 to 100°C

**Other factors**

Coal weathering appears to be promoted by tectonic shearing, fracturing leading to generation of fines and rubble resulting from brittle behavior of coal. In sheared coals or coals acting as aquifers, coal oxidation is observed at depths up to 100 meters and is expected to decrease with depth (Bustin et al., 1985). Also the extent of fracturing of coal and adjacent rock has a notable effect on degree of oxidation with fractures promoting oxidation. While Nötzold (1940b) observed coal weathering occurred in situ at a planar fracture surface of fault surface of coal face, he could not detect weathering further along the same fault plane. According to Bustin et al. (1985) coal weathering was observed up to 10 m below the surface in an audit (No. 6 coal seam) from Tent Mountain in the SE Canadian Cordillera. This was further confirmed by Mathews and Bustin (1984) who reported weathered vitrinite occurring in the near-surface coals. Also Fredericks at el. (1983) and Nelson (1989) conclude that coal weathering occurs in the first few to several meters below the outcrop surface.

**IIb. Definition, origin of laboratory (artificial) oxidation**

Laboratory (artificial) oxidation includes laboratory drying and low temperature oxidation (Pisupati et al., 1993; Mastalerz et al., 2009) and begins upon the exposure of coal to oxygen with oxygen acting as an oxidizing agent during laboratory experiments at diverse conditions (Chandra, 1962; Bustin et al., 1983; Klein and Welleck, 1989; Nelson, 1989; Ingram and Rimstidt, 1984). The exposure conditions range from ambient conditions up to approximately 250°C covering a different range of heating rates. Laboratory artificial oxidation is applied to dry, fresh wet coals and carried out in laboratory ovens with forced air convection or non-specified air circulation in wet or dry conditions.

 **III. Reaction mechanisms**

The reaction mechanism of in situ weathering was studied in a number of laboratory coal oxidation studies (Wachowska et al., 1974; Painter et al., 1980; Cronauer et al., 1983a,b; Liotta et al., 1983; Larsen, 1986; Gethner, 1987a,b; Khan et al., 1988; Clemens et al., 1991; Butakova et al., 2013). Laboratory oxidation of bituminous coals up to around 150°C is a complex process involving the following phenomena (Kochi, 1973; Cronauer et al., 1983a,b; Liotta et al., 1983; Calemma et al., 1988; Khan et al., 1988; Clemens et al., 1991; Azik et al., 1993; Lopez et al., 1998; Wang et al., 2003; Zhang et al., 2013):

* Oxygen transport to the coal surface and within coal pores
* Chemical interaction between coal (certain aliphatic species, generally methylene groups α to aromatic rings or to –OR groups; R denotes an attached hydrogen, or a hydrocarbon side chain of any length, but may sometimes refer to any group of atoms) and molecular oxygen producing peroxides and hydroperoxides
* Subsequent thermal decomposition of activated oxygenated complexes
* Release of heat

**IV. Oxidation effects in naturally oxidised coals**

**Macerals**

Jüttner (1956) found that coal lithotypes follow their proneness of oxidation in the following order: vitrain, clarain, durain, and fusain. Ferrari (1938), Kukharenko and Ryzhova (1956), Bustin (1982), Bustin et al. (1985), Wagner (2007) supported this finding and concluded that under natural conditions vitrain and or vitrinite were more easily oxidized than fusain displaying most of the weathering characteristics. Similarly, Yohe (1958) reported that fusain was the most resistant to weathering.

**Colour**

Mathews and Bustin (1984) observed a darkish cast of naturally oxidized vitrinite with oxidation progressed throughout the grains. Marchioni (1983) examined weathered inertinite and observed their lighter colour as a result of coal weathering.

**Oxidation rims, oxyrims, reaction rims**

The presence or absence of oxidation rims has been reported in weathered bituminous coals, occurring generally in vitrinite macerals. In addition, oxidation rims were also observed in resinite and in inertinite and semi-inertinite macerals.

Chandra (1962) did not report any oxidation rims in the studied weathered coal samples. The author suggests that when the temperature of oxidation is low, oxidation rims do not appear in the studied coal samples. Similarly, Marchioni (1983) observed no oxidation rims in weathered subbituminous coals. This is in agreement with Alpern and Maume (1969) who suggested that low rank coals were unlikely to form oxidation rims.

The presence of oxidation rims at grain boundaries of vitrinite macerals as a result of in situ weathering is petrographically well documented (Ferrari, 1938; Teichmüller and Teichmülle,r 1950; Nakayanagi, 1956; Chandra, 1962; Stach et al., 1975; Gray et al., 1976; Crelling et al., 1979; Lowenhaupt and Gray, 1980; Bustin, 1982; Gray, 1982; Marchioni, 1983; Ingram and Rimstidt, 1984; Mathews and Bustin, 1984; Kruszewska et al., 1992; Bend and Kossloski, 1993; Pisupati and Scaroni, 1993; Lo and Cardott, 1995; Kruszewska and du Cann, 1996;Korte, 2001; Valentim et al., 2006; Wagner, 2007). Oxidation rims have been observed at fissured and non-fissured grain boundaries and along fractures and fissures. Numerous authors observed oxidation rims occurring at the periphery of vitrinite particles and throughout the grains. In the more weathered coals, oxidation zones have progressed throughout the coal grains.

Van Krevelen and Schuyer (1957) stated that the width of oxidation rims formed in a given length of time and at a given temperature is a simple measure of reactivity of coals. Sommers and Peters (1954), Edwards et al. (1964), Dawson (1967), Alpern and Maume (1969) and Prado (1972) agree that penetration of oxygen into the coal particles is a process that depends on the exposed surface area, and that the width of the oxidation rims depends on coal rank, and temperature and time of weathering. Also van Krevelen and Schuyer (1957) stated that the width of oxidation rims in a given length of time and at a given temperature might give a simple measure of reactivity of coal.

Oxidation rims have been noted in samples where the temperature of oxidation was low (e.g., during coal fires at 150°C; Nötzold, 1940a). The oxidation rims of in situ weathered coals at the oxidation temperature of < 150°C are often described as dark in colour. The development of darker oxidation rims has been associated with formation of humic acids due to weathering (Teichmüller and Teichmüller, 1950; Nakayanagi, 1956; Gray et al., 1976; Crelling et al., 1979; Marchioni, 1983; Wagner, 2007) or due to low temperature oxidation in a wet atmosphere, (Chandra, 1982). Alpern and Maume (1969), Gray and Krupinski (1976), Crelling et al. (1979), Bustin (1982), Bustin et al. (1983, 1985), and others attribute the origin of the observed darker rims of lower reflectance in weathered coals to air oxidation under subaerial or subaqueous conditions at ambient temperatures or to circulation of oxygenated waters. Dark oxidation rims are believed to represent removal of material without chemical restructuring.

Ferrari (1938), Nötzold (1940a,b), Szadeczky-Kardoss (1944), Wagner (2007), Kus et al. (2010), Misz et al. (2007), Misz-Kennan and Fabiańska (2010) suggest that the development of bright oxidation rims is a result of high temperature oxidative alteration, often observed in situ at surface of coal face, tectonic fractures, stock piles, and waste piles subjected to self-heating and subsequent coal fires processes.

Mathews and Bustin (1984) observed oxidized inertinite and semi-inertinite in the near-surface coals characterized by distinct oxidation rims.

**Relief and grain outline**

A relatively higher polishing relief of coal particles is a result of in situ coal weathering as reported by Teichmüller and Teichmüller (1950) and Chandra (1962). Also Marchioni (1983) suggested an overall marked relief in weathered coals. Similarly, Nötzold (1940a,b), Bustin (1982) and Mathews and Bustin (1984) observed high relief in weathered vitrinite. In addition, Kruszewska et al. (1992) reported edges of weathered vitrinite particles to be rounded.

**Micropores**

In situ weathering results in formation of micropores of few µm in diameter observed under optical microscope (Chandra, 1962; Leythaeuser, 1973). Bustin (1982) and Mathews and Bustin (1984) observed micropores forming at an advanced stage of coal oxidation.

**Microcracks, microfissures**

With the progress of oxidation processes, i.e., at an advanced stage of coal oxidation, vitrinite among other maceral types display most extensive development of microcracks and microfissures (Teichmüller and Teichmüller, 1948, 1950; Nakayanagi, 1956; Noel, 1958; Podgajni, 1961; Chandra, 1962; Jacob, 1964; Bustin, 1982; Mathews and Bustin, 1984; Wagner, 2007; Mangena and du Cann, 2007). The size of microfissures is defined by Wagner (2007) to have a width < 1 μm and that of microcracks of > 1 μm width. Apart from macerals types, oxidation related microfissures and microcracks are also reported to occur in microlithotypes (Wagner 2007). These microcracks and microfissures are usually not related to cleat direction or pseudovitrinite (Kruszewska et al., 1992; Wagner, 2007). In weathered coal samples, formation of microfissures is predominantly observed at grain margins of vitrinite giving rise to the so called corroded margins. At stages of intensive coal oxidation, occurrence of microfissures is also reported to occur throughout the vitrinite grain. The form of developed microcracks and microfissures differs widely in weathered coals. Alpern and Maume (1969) and Lowenhaupt and Gray (1980) suggest that microfissured occurring in weathered coals are usually conchoidal or bifurcating. Nelson (1989) and Korte (2001) observed characteristic irregular microfissures in weathered vitrinite. Ghosh (1997) on the other hand observed irregular or radial fracture pattern in vitrinite and Wagner (2007) documented curved or sinuous microfissures and short tapered microcracks. The propagation direction of microfissures varies between oblique or perpendicular propagation respective to microlamination, (Wagner, 2007). A relation between size, penetration and directions of microcracks and microfissures and the respective coal rank was not precisely researched.

**Reflectance and bireflectance**

In sub-bituminous coals weathering caused an increase in vitrinite reflectance by 0.05% to 0.10% (Marchioni, 1983). Similarly Pawlewicz and Barker (1989) also reported a rise in reflectance values for low rank coals by 0.2 to 0.3% attributed to weathering of exposed coals and differential erosion.

In general, a decrease in vitrinite reflectance in high to low volatile bituminous weathered coals was observed (Teichmüller and Teichmüller, 1950; van Krevelen, 1961; Alpern and Maume, 1969; Kojima and Ogoshi, 1973; Crelling et al., 1979; Pearson and Kwong, 1979; Bustin, 1980, 1982). This is in accordance with Marchioni (1983) who reports a marked decrease in mean maximum vitrinite reflectance by 0.15 % at 10 m depth in coals collected at outcrop. Also, Correa Da Silva and Pereira Neto (1993) observed a decrease of vitrinite reflectance in artificially weathered coals stocked in piles open to the atmosphere for 10 months. Mathews and Bustin (1984) reported slightly lower vitrinite reflectance in the near surface samples. Chandra (1962) also reported minor changes to vitrinite reflectance in coals affected by coal weathering. These results supported the observation of Seyler (1938), Ammosov and Musyal (1952) and Josten (1956). In contrast, Pisupati and Scaroni (1993) observed no significant changes in vitrinite reflectance of weathered high to medium volatile bituminous coals. Similarly Kruszewska and du Cann (1996) also did not report any changes in the mean maximum reflectance of weathered high volatile bituminous coals.

In weathered high to medium volatile bituminous coals at outcrop or at stock or waste piles subjected to coal oxidative and self-heating conditions, an increase in random vitrinite reflectance at elevated temperatures of about >150°C is reported byMisz et al. (2007), Misz-Kennan and Fabiańska (2010) and Kus et al. (2010). Also Mangena and du Cann (2007) reported slightly higher vitrinite reflectance of 0.82% compared to the average vitrinite reflectance for the unweathered Witbank coals of about 0.7% observed in coal sample subjected to heat alteration. Chandra and Srivastava (1978) reported a diversified vitrinite reflectance values for high to low volatile bituminous coals subjected to coal oxidation accompanied by temperature rise.

Benedict and Berry (1964) indicated a minor increase in bireflectance with increased oxidation. Also Marchioni (1983) reported a marked to slight increase of bireflectance of up to 0.21 % for weathered high volatile A to medium bituminous coals and no change in bireflectance for sub-bituminous A coals.

**Fluorescence**

The utilization of fluorescence in blue or UV light and in particular monochromatic fluorescence intensity measurements on huminite and vitrinite is one of the most sensitive methods in detection and quantification of weathered coals. Davis et al. (2007) suggested that subtle oxidation associated with weathering is best recognized performing comparative studies on fresh and oxidized coals under blue light.

The decline in the fluorescence intensity caused by in situ coal weathering occurs in both the subbituminous and bituminous coals (Stach et al., 1982; Diessel, 1985; Bend et al., 1989; Quick et al., 1988; McHugh et al., 1991; Bend and Kosloski, 1993). However, in accordance to McHugh et al. (1991) and McHugh (1992), the loss of fluorescence as a result of weathering appears to be more prominent in low rank coals.

Another parameter applied in assessment of coal weathering is the empirically derived oxidation quotient of mean maximum fluorescence intensity at 550 nm and vitrinite/huminite reflectance. Quick et al. (1988) and Bend and Koslowski (1993) applied the quotient of fluorescence intensity and reflectance to weathered coals and concluded that with increasing degree of coal oxidation a decrease of the above quotient followed.

**V. Oxidation products in laboratory oxidised coals**

**Oxidation rims, oxyrims, reaction rims**

In laboratory experiments of coal oxidation, development of dark and pale oxidation rims in coals of different rank is largely observed in vitrinite macerals at low temperature oxidation. The development of dark in colour oxidation rims in huminite in laboratory oxidized lignite coal at low temperatures of 70°C for duration from 1 to 100 h is reported by Bend and Kosloski (1993). In contrast, generation of pale in colour oxidation rims has been generally observed in vitrinite and resinite macerals of laboratory oxidized bituminous coals at low temperature oxidation conditions. In laboratory oxidized bituminous coals, paler in colour oxidation rims are attributed to higher temperatures of up to 200°C and developed at grain boundaries and at fractures, fissures (Ferrari, 1938; Alpern and Maume, 1969; Goodarzi and Murchison, 1973, 1976; Gray and Krupinski, 1976; Gray et al., 1976; Nandi et al., 1977; Marchioni, 1983; Goodarzi, 1986; Bend and Kosloski, 1993). In contrary, Also Cronauer (1983a) did not observe oxidation rims in laboratory oxidized subbituminous coals at temperature of 150°C.

In addition to presence of oxidation rims in artificially oxidized vitrinite and huminite, reaction rims were also observed to occur in oxidised resinite. Murchison (1966) studied oxidized resinite concentrates derived from lignite to bituminous coals at 120°C and 140°C for periods of 3, 24, and 48 h and observed development of darker oxidation rims. Also, Goodarzi (1986) performed oxidation studies on resinite concentrates oxidized in air for 1 h intervals at fixed temperatures between 50°C and 400°C. Oxidised resinite macerals developed darker oxidation rims at 50°C and 100°C showing cellular morphology. Oxidized resinite at 200°C developed brighter oxidation rims and at 250°C both brighter outer and darker inner oxidation rims were documented. The higher reflectance of the outer rim indicates the formation of stable oxygen complex, “oxycoal” (Oreshko, 1949, 1950; van Krevelen, 1961) and the inner darker rim represents the reaction front characterized by the formation of chemisorbed components which subsequently decomposed to form stable oxygen complexes.

**Fractures**

Goodarzi and Murchison (1976) attribute substantial mechanical cracking present in carbonized preoxidised coals to coal oxidation. Correa Da Silva and Pereira Neto (1993) observed formation of fissures at grain boundaries and in the centre of vitrinite and inertinite macerals in artificially weathered coals stocked in piles open to the atmosphere for 10 months.

**Vitrinite reflectance**

Coals of different rank oxidized artificially in laboratory exhibit in general a marked increase in vitrinite reflectance resulting from low temperature oxidation carried out at different temperature and duration.

Valceva et al. (1976) examined oxidized lignite for 45 h at 150°C and reported a slight increase in reflectance by 0.048% Ro. Similarly, Bend and Koslowski (1993) reported an increase in huminite reflectance in lignite when oxidized at 70, 140, and 210°C for 24h.

In subbituminous coals, Markova and Valceva (1983) showed that low temperature oxidation of at temperatures of 150 and 200°C lead to increase of reflectance in the centre and at the peripheries of vitrinite macerals. The reflectance in the centre increased by 0.03% Ro and 0.01% Ro after oxidation at 150 and 200°C, respectively. The reflectance in the peripheries increased by 0.23% Ro and 0.41% Ro after oxidation at 150 and 200°C, respectively. Also Gentzis et al. (1992) report an increase in vitrinite reflectance in oxidized coals of sub-bituminous, rank coals at 100 and 200°C for 8h and 30 min. respectively.

Similarly, artificially thermally altered high volatile bituminous coals display increase in vitrinite reflectance when heated at 70°C for 1, 10, and 100 hours (Bend and Koslowski, 1993). Similarly, Nandi et al. (1977) observed an increase in vitrinite reflectance in oxidized high volatile bituminous coals for 72 h. At relatively higher temperatures approaching 100°C, Goodarzi and Murchison (1973) observed a general increase in the vitrinite reflectance in high-volatile rank coals oxidized different periods of time up to 128 days. Also Gentzis et al. (1992) report an increase in vitrinite reflectance in oxidized coals of high-volatile rank coals at 100 and 200°C for 8h and 30 min., respectively. In artificially oxidised high volatile bituminous coals in air at 300°C for 24h Prado (1977) reported a slight decrease of vitrinite reflectance occurring in the centre of vitrinite grains and a distinct increase of vitrinite reflectance at oxidation rims oxidized. Calemma et al. (1995) report similarly a rise in reflectance values as result of coal oxidation of high volatile bituminous coals at 200°C at up to 4h. In contrast, Kruszewska and du Cann (1996) observed no changes in vitrinite reflectance of high volatile bituminous coals subjected to artificial oxidation at ambient conditions and duration up to a period of 134 weeks.

Artificially oxidized low volatile bituminous coals up to 150°C and a maximum duration of 278 days displayed unchanged vitrinite reflectance values within the limits of measurement uncertainties (Copard et al., 2004). In contrast, artificially thermally altered low volatile bituminous coals display increase in vitrinite reflectance when heated at 70°C for 1, 10 and 100 hours (Bend and Koslowski, 1993), whereas Kojima and Ogoshi (1973) observed first a decrease of vitrinite reflectance followed by a rise in laboratory oxidized high, medium and low-volatile rank coals at 70°C for up to 3 months.

Chandra (1958, 1962, 1966) concluded that mean maximum reflectance of oxidized high and medium volatile bituminous coals did not reveal significant change at all or changes very little as a result of oxidation at ambient laboratory temperatures. He concluded that the observed variations were insignificant considering the accuracy of the measurement. Also Gentzis et al. (1992) report an increase in vitrinite reflectance in oxidized coals of medium-volatile rank coals at 100 and 200°C for 8h and 30 min., respectively.

**Resinite reflectance and bireflectance**

Murchison (1966) observed formation of lower reflectance of oxidation rims in oxidized resinites. Goodarzi (1986) performed oxidation studies on resinite concentrates oxidized in air for 1 h intervals at fixed temperatures between 50°C and 400°C. The reflectance of the central portion of resinite remained almost constant up to 250°C. The reflectance of the oxidation rims decreased initially to a minimum at 75°C and then increased continuously.

**Fluorescence**

Goodarzi (1986) performed oxidation studies on resinite concentrates and concluded that fluorescence of oxidized rims shifted from green towards the red spectral fluorescence region. Kruszewska and du Cann (1996) applied long-wave fluorescence and vitrinite elasticity methods to simulated weathered high and medium volatile bituminous coals. The results indicate a significant decline of fluorescence intensity and an increase in elasticity index with increasing oxidation time.

**Anisotropy of coke**

The cell walls of coke derived from oxidised coals develop a reduced anisotropy effects and smaller anisotropic units than produced from fresh coals (Goodarzi and Murchison, 1976; Yokono et al., 1981a,b; Grint et al., 1983; Qian and Marsh, 1984; Mochida et al., 1986; Casal et al., 2003). Oxidised coals favour the generation of isotropic and nonvesiculated precursor material with a microporous character and greater surface area (Ruiz et al. 2001, 2006). This is clearly related to an increased isotropy/anisotropy ratios of the chars obtained and is caused by prevention of any rearrangement of the turbostratic coal structure leading to densification of the carbonaceous material. Thomas et al. (1992), Menendez et al (1989), Patrick et al. (1989), Alvarez et a. (2003), Casal et al. (2003), Cimadevilla et al. (2003, 2005), and documented a decrease of the optical anisotropy index in cokes derived from oxidised coals.

**VI. Chemical Properties of weathered and laboratory oxidized coals**

The process of coal oxidation in weathered and artificially oxidised coals is related to prominent chemical structural changes and compositional modifications. After Radspinner and Howard (1943), Jones and Townend (1945, 1949), Brooks and Maher (1957), Chalishazar and Spooner (1957), Chakravaty (1960a,b), Ignasiak (1970), Swann and Evans (1979), Painter et al. (1980), Painter et al. (1981), Fredericks et al. (1983), Liotta et al. (1983), Rhoads et al. (1983), Lo and Cardott (1995), Gethner (1985, 1987a,b), Anderson and Johns (1986), (Monthioux 1988), Huggins and Huffman (1989), Nelson (1989), Lopez et al. (1998), Worasuwannarak (2002), MacPhee et al. (2004) and Mao et al. (2010), coal oxidation results in general in chemisorption of oxygen at coal surface and formation of acid functional groups such as hydroxyl, carbonyl, carboxyl and others and their subsequent thermal decomposition as well as a decrease in the aliphatic and alicyclic carbon and hydrogen content in coal.

In course of oxidation, aliphatic groups are further oxidised to aldehydes, followed by aldehydes being oxidised to carboxylic groups and esters. Anhydrides are also formed from the carboxylic groups and the aldehydes. According to Pandolfo et al. (1995), Chandra (1958, 1962, 1966), Fredericks et al. (1983), Estevez et al. (1990), Pietrzak and Wachowska (2003), Fujijoka et al. (2006), the contribution of methylene groups decreases while that of oxygen groups increases.

In terms of elemental composition, natural and laboratory coal oxidation reveals a number of characteristic effects. Francis (1961) showed that laboratory oxidation for four weeks at 150°C indicate a decrease in carbon and hydrogen content for sub-bituminous to medium volatile bituminous coals. Similar effect is also observed in weathered coals (Painter et al., 1980; Marchioni, 1983; Cagigas et al., 1987; Calemma et al., 1988; Landais and Rochdi, 1993; Martinez and Escobar, 1995). In addition to a decrease in carbon and hydrogen weathered coals exhibit a general decrease in H/C atomic ratio and an increase in oxygen % and O/C ratio (van Krevelen, 1961; Chandra, 1958, 1962; Benedict and Berry, 1964; Alpern and Maume, 1969; Kojima and Ogoshi, 1973; Gray et al., 1976; Bustin, 1980; Marchioni, 1983; Mathews and Bustin, 1984; Clemens et al., 1989; Nelson, 1989; Pisupati et al., 1993; Taylor et al., 1998). With respect to sulphur, Yohe (1958) and Dryden (1963) observed a decrease in total sulphur in weathered coals whereas sulphur contents in weathered high volatile C bituminous coals stored for 88 weeks in summer and winter time remained unaffected by weathering (Rees et al., 1961).

With respect to Rock Eval parameters, in situ natural and laboratory coal oxidation results in alteration of HI, OI and Tmax values.

Van Krevelen (1981), Fredericks et al. (1983), Nelson (1989), Copard et al. (2002, 2004) used Rock Eval parameters (Tmax, OI, HI) as indicators of low-temperature coal oxidation. The relative decrease in HI and increase in OI values may indicate oxidative alteration in artificially oxidised humic (Landais et al., 1984; Hao and Chen, 1992; Landais and Rochdi, 1993; Lo and Cardott, 1995; Copard et al., 2002, 2004). Copard et al. (2002) concluded an increase in Tmax value for weathered medium volatile bituminous coal accompanied by a concurrent decrease in HI. In contrary Lo and Cardott (1995) showed, that weathering of low maturity coal (0.72% Vr) exhibited no significant variation in Tmax parameter.

**VII. Fuel chemistry properties**

**Moisture**

Savage (1951), Mathews and Bustin (1984), Klika and Kraussova (1993), Dunlop and Johns (1999) and Crelling (2008) suggested relatively higher moisture content determined in oxidised coals compared to unoxidized coals. Meuzelaar et al. (1984) revealed that artificially oxidised coals display gradual changes of the air-dried moisture content which enabled a relatively straight forward detection of coal oxidation.

**Ash**

With respect to ash content, weathering and artificial oxidation display different influence on the coal technological parameter.

While Savage (1951) reported a slight reduction in the ash content due to a loss of iron and leaching out of alkaline earths as sulphate as a result of oxidation, Rees et al. (1961), Correa Da Silva and Pereira Neto (1993), Pisupati and Scaroni (1993) and Mastalerz at el. (2009) did not report any major changes in the ash content of weathered and laboratory oxidized coals. However Teo et al. (1982) and Mathews and Bustin (1984) revealed rise in coal ash contents of weathered coals.

**Volatile Matter**

The content of volatile matter of weathered artificially oxidised and varies widely. Fuel chemistry analysis of artificially oxidized coal results in an anomalous volatile matter content (Jones and Towned, 1945, 1949; Nelson, 1989).

Weathering causes an increase in volatile matter content (Alpern und Maume, 1969; Gray et al., 1976; Painter et al., 1980; Marchioni, 1983; Cagigas et al., 1987; Calemma et al., 1988; Landais and Rochdi, 1993; Martinez and Escobar, 1995; Pisupati and Scaroni, 1993; Pisupati et al., 1991; Pisupati et al., 1993; Fredericks et al., 1983; Kona et al., 1968; Freyer and Szladow, 1973; Mathews and Bustin, 1984; Crelling, 2008).

A decrease in the volatile matter content is reported in artificially oxidised coals due to thermal oxidative alteration (Savage, 1951; Benedict and Berry, 1964; Kojima and Ogoshi, 1973; Kalemma and Gavalas, 1987; Khan et al., 1988; Gerus-Piasecka and Jasieńko, 1989; Klika and Kraussova, 1993; Wang et al., 2007; and Mastalerz at el., 2009).

On the contrary, Correa Da Silva and Pereira Neto (1993) observed no variations of volatile contents in artificially weathered coals stocked in piles open to the atmosphere for 10 months. Similarly, Rees et al (1961) observed no significant changes in volatile matter content of weathered high volatile C bituminous coals stored for 88 weeks in the winter and summer time.

**Calorific value**

Fuel chemistry analysis of oxidized coal revealed a marked fall of gross calorific value pointing also to a greater aromaticity within oxidised coals (Jones and Towned, 1945, 1949; Benedict and Berry, 1964; Kona et al., 1968; Freyer and Szladow, 1973; Teo et al., 1982; Fredericks et al., 1983; Liotta et al., 1983; Marchioni, 1983; Isaacs and Liotta, 1987; Nelson, 1989; Yun and Meuzelaar, 1991; Pisupati et al., 1993; Iglesias et al., 1998). Weathering causes a decrease in carbon and calorific values (Painter et al., 1980; Marchioni, 1983; Cagigas et al., 1987; Calemma et al., 1988; Landais and Rochdi, 1993; Martinez and Escobar, 1995; Pisupati et al., 1993; Mastalerz et al., 2009). La Grange (1950) showed loss of 5% of the original calorific value after 25 years of storage. Rees et al. (1961) examined the effect of storage of high volatile C bituminous coals for 88 weeks resulting in decrease of calorific value by 2.1% in 52 weeks for the summer storage and 1.4% for the winter storage. Isaacks and Liotta (1987) showed that long term storage of subbituminous coals for up to 156 days results firstly in its marked decrease and subsequently in distinct increase caused by chemical decarboxylation during laboratory oxidation process. According to Nelson (1989) low rank coals will lose approximately 0.44 MJ/kg for each 1% increase in oxygen content and that higher rank coals will experience a decrease of about 0.56 MJ/kg. Correa Da Silva and Pereira Neto (1993) observed decrease of calorific value from 29.018 to 27.402 J/g by 5.6 % in artificially weathered coals stocked in piles open to the atmosphere for 10 months.

**VII. Physical properties**

Roy (1965) observed a weight loss in oxidised coals up to 168 hours of oxidation. The greatest weight loss is recorded in vitrinite macerals as opposed to fusinites. Also Sánchez and Rincón (1997) and Zelkowski (2004) reported a decreased weight of oxidized coals. With respect to adsorption capacity of artificially oxidised coals, Mastalerz et al. (2009) showed that methane adsorption capacity increased by 40%, whereas CO2 adsorption capacity increased by 18% in high volatile bituminous coals during a 13-month time period of laboratory exposure to oxidizing air at air temperature. These changes in adsorption are accompanied by changes in chemistry and surface area of the coal. The study demonstrates also that wet oxidation of high volatile bituminous coals stored in distilled water and bubbling air for 6 weeks caused significantly larger decreases of BET surface area and mesopore surface area than anoxic drying of freeze-dried coal samples placed in chamber with nitrogen gas for 4 days.

**VIII. Practical importance**

**Pyrolysis, coking**

Yohe (1958) provided detailed information of the first publication on the subject of the coal oxidation and its effects on coking. The process of oxidation in terms of weathered coals or coals oxidised in laboratory experiments is especially disadvantageous in case of coal technological coking properties such as volume contraction, expansion, devolatilisation, plastic range leading to:

* loss of coking ability at exposure to air at 60-80°C (Boyapati et al., 1984; Smith et al., 2001),
* reduction of coke strength and coke yield (Crelling et al., 1979; Boyapati et al., 1984),
* decrease of coke stability (Gray et al., 1976; Crelling et al., 1979),
* loss of plastic properties (Dryden, 1963; Wender et al., 1981; Seki et al., 1990),
* increase in coke reactivity (Korte, 2001),
* decrease in coke fluidity (Goodarzi and Murchison, 1973; Goodarzi and Murchison, 1976; Goodarzi et al., 1975; Neavel, 1982; Keogh et al., 1989); Davidson, 1990).
* decrease of dilatation as a function of storage timein oxidised coals (Boyapati et al., 1984),
* reduction of the decaking (heating large particles of caking coal through their plastic range in a free fall system to produce non-caking coal char), (Fuchs and Sandhoff, 1942; Orchin et al., 1951; Kam et al., 1976; Ota and Takarada, 2001),
* loss of caking properties (Seki et al., 1990; Sánchez and Rincón, 1997),
* decrease or loss of Gieseler fluidity (Jackman et al., 1957; Wen and Sun, 1976; Lowenhaupt and Gray, 1980; Senftle and Davis, 1984; Huffman et al., 1985; Huggins et al., 1985; Wu and Winschel, 1986; Cagigas et al., 1987; Huggins et al., 1987; Wu et al., 1987; Huggins and Huffman, 1989; Clemens and Matheson, 1992),
* decrease in swelling number (La Grange, 1950; Savage, 1951; Wen and Sun, 1976, Gray et al., 1976; Pearson and Kwong, 1979),
* decrease in free-swelling index (FSI) (Jackman et al., 1957; Pearson and Creaney, 1981; Mathews and Bustin, 1984; Huggins et al., 1985, 1987;Larsen et al., 1986; Wu and Winschel, 1986; Wu et al., 1987; Cagigas et al., 1987),
* loss of swelling and fluid properties of coals (Schmidt and Elder, 1940; Schmidt, 1945; Loison et al., 1963; Benedict and Berry, 1964; Kona et al., 1968; Freyer and Szladow, 1973; Kojima and Ogoshi, 1973; Guyot and Pollard, 1974; Ignasiak et al., 1974; Wachowska et al., 1974;Gray et al., 1976; Crelling et al., 1979; Mahajan et al., 1980; Anderson and Hamza, 1982; Malony, 1982; Malony et al., 1982; Lin et al., 1983; Liotta et al., 1983; Marchioni, 1983; Senftle and Davis, 1984; Huffmann et al., 1985; Pis et al., 1988; Wu et al., 1988; Clemens et al., 1989; Davidson, 1990; Valia, 1990; Worasuwannarak, 2002; Casal et al., 2003; Crelling, 2008; Suarez-Ruiz and Ward, 2008),
* decrease in conventional coking indices (Wu and Winschel, 1986; Wu et al., 1987; and Cagigas et al., 1987; McHugh et al., 1991;Kruszewska, du Cann, 1996),

Weathered coals also cause increase of oil uptake in coke ovens related to the increased fracturing in the coal disallowing for control of bulk density (Crelling et al., 1979).

Furimsky et al. (1983) found that a mild oxidation of high volatile bituminous coals of up to 105°C for 64 to 192h resulted in a decrease of liquid hydrocarbon yield and an increase in the proportions of aromatic carbon and oxygen content in liquid products during coal pyrolysis. Pisupati and Scaroni (1993) also suggest that coal oxidation causes a reduction in the yields of pyrolysis products.

**Combustion**

Numerous studies suggest that weathered coals are less reactive than fresh coals (Marchioni, 1983; Bend, 1989; Pisupati and Scaroni, 1993; Cloke and Lester, 1994; Lo and Cardott, 1995). On the contrary, Iglesias et al. (1998) reported that weathered coals could enhance the coal reactivity due to formation of molecular structures with associated oxygenated groups. Oxidised vitrinite can have a range of combustion behaviour, from good to poor in accordance to Kosina and Hrncir (1983).

**Liquefaction**

Weathering and low temperature oxidation may also drastically reduce the yield and quality of liquefied coal products or solvent extraction as free radicals resulting from thermal cleavage of ether or methylene bonds are stabilised by hydrogen transfer from the solvent (Liotta et al., 1983; Larsen et al., 1986; Lopez et al., 1998; Neavel, 1976; Whitehurst et al., 1980; Gransden et al., 1991; Khan et al., 1988; Cronauer and Ruberto, 1979; Cronauer et al., 1984).

Cox (1984), Cox and Nelson (1984) and Pisupati and Scaroni (1993) report that coal weathering decreases the liquefaction yield.

In turn, Senftle and Davis (1984) reported no changes to liquefaction yields upon coal oxidation.

**Gasification**

Mahajan et al. (1980) and Nelson (1989) reported that pre-oxidised coal may result in improved gasification reactivity and may improve the surface area of the char produced. Cox (1984) and Cox and Nelson (1984) reported that coal weathering may introduce changes in product composition and thus influence yields in gasification.

**Self-heating**

It is widely accepted, that exothermic reaction during low-temperature oxidation (< 100°C) is the primary source of the heat released in spontaneous combustion and self-heating processes (Huggins and Huffman, 1989; Schmal, 1989; van Krevelen, 1993; Lopez et al., 1998). Low-temperature oxidation is one of several processes involved in the self-heating and spontaneous combustion of coals, beginning with the evolution of oxides of carbon (up to 120°C), followed by rapid interaction with oxygen (up to 180°C), and ending with thermal decomposition (180-250°C) (Walker, 1999).

**Flotation recovery**

Presence of newly formed functional groups such as humic acid complexes reduces the hydrophilicity among coal and mineral particles leading to increased difficulties in separation of mineral matter (Garcia et al., 1991; Gray et al., 1976) and decrease of the flotation recovery (Anderson and Hamza, 1982; Fuerstenau et al., 1983; Murata, 1981; Miller et al., 1983). This, in turn, results in reduction of efficiency in froth flotation and oil agglomeration (Zimmerman, 1968; Taylor et al., 1981). Further, weathering reduces particle size, causing dusting problems and altering coal surface properties and thus reducing flotation recovery (Gray et al., 1976; Crelling et al., 1979; Wu et al., 1988).

**Storage**

Hoover and Schweighardt (1989) give an overview on analytical techniques for monitoring coal sample storage. According to Mavor and Pratt (1993) oxidation can reduce sorption capacities of coals by as much as 11%. Mastalerz et al (2009) reported that air oxidation during laboratory storage result in increased adsorption capacities for methane and CO2, decrease of calorific values and moisture content.

**IX. Methods applied in identification of coal oxidation**

Instrumental techniques and methods applied to assess coal oxidation as well as its degree are reviewed extensively by Sen et al. (2009). Huffmann et al (1985) and Davidson (1991) give a general comparison of sensitivity of various analytical techniques applied to detect coal oxidation. Their comprehensive explanation is outside the scope of this report.

**Optical microscopy methods:**

**Incident white light microscopy**

For qualitative verification purposes petrographic analysis in incident light can be applied to identify effects of weathering and artificial oxidation in coals of various ranks upon coal maceral surface, its relief, colour and structure. Wagner (1998) developed Weathering Index Analysis (WIA) to quantify and qualify the degree of weathering in coals from discard stockpiles and dumps. The index is based on eight weathering features used as microscopic indicators of weathering. The analysis enables a qualitative and quantitative assessment of coal weathering features (Wagner, 2007).

**Incident fluorescence light microscopy**

Kruszewska et al. (1992), Kruszewska and du Cann 1996) found that oxidation of coal could be detected at the very early stages by the application of the so called long-wave fluorescence relative intensity measurements of vitrinite (FRI) and vitrinite elasticity index (EI). Coal oxidation results to a marked decrease in FRI and a substantial increase in EI. McHugh et al (1991) used fluorescence intensity to assess oxidation in low rank coals.

**Transmitted light microscopy**

Brenner (1981) studied effects of superficial coal oxidation at 365°C in thin sections and on coal pellets suggesting that many oxidation areas are not readily evident under reflected light. Thermally altered vitrinite particles studied under transmitted light display a usually uniform thin oxidation border of 4 μm around its periphery characterized by darker colour. The darkened oxidation regions are not a consequence of localized heating of the coal or pyrolysis but oxidation process. A similar darkening effect due to oxidation were observed in coal which was oxidizes at temperatures as low as 150°C. In heating experiments in the absence of oxygen to more than 20°C higher than the temperatures used in this experiment, no blackening effects such as those caused here by oxidation are observed. The internal region of the majority of vitrinite particles shows a number of cracks and holes with dominantly broad (thick) dark areas bordering these regions. The interior regions and at the border display large cracks and micro-fractures are present. The formation of vacuoles is observed only in a small fraction of coal samples studied at 365°C.

**Staining Tester**

Gray et al. (1976), Atkinson and Hyslop (1961), Lowenhaupt and Gray (1980), Marchioni (1983), Axelson et al. (1987), Osborne (1988) applied alkali etching of coal followed by cationing staining with red stain (safranin 0 in alcohols) as an extremely sensitive method of the detection of coal oxidation. The intensity and depth of staining may vary with the intensity of coal oxidation and is not applicable to sub-bituminous coals as they remain alkali-soluble. Further, Lowenhaupt and Gray (1980) suggested that the cutoff at 80 % should be used as a staining index for oxidized or weathered caking and coking coals. Osborne (1988) applied a safranin-O dye method to oxidized coal fragments in order to quantitatively asses the degree of coal oxidation.

**Optical anisotropy index (AI)**

The AI is an optical texture index based upon the Method of Moreland et al. (1988) by which a point counter analysis is applied to estimate the degree of anisotropy component developed on coke surface. The AI is thought to be reduced in oxidized coals.

**Non-optical methods:**

**FTIR spectroscopy**

FTIR-spectroscopy is commonly considered the most widely used technique applied in the study of coal oxidation/weathering since it provides information on structural changes of oxygenated functional groups (phenolic, carboxylic, hydroxyl, carbonyl, oxygenated groups), (Sen et al., 2009; Landai and Rochdi, 1993; Mastalerz and Bustin, 1993).

Calemma et al. (1988) performed research study on low temperature coal oxidation using FTIR method resulting in an increase in oxygenated functional groups (carboxyls, esters and anhydrides). Painter and Rhoads (1981) reported on FTIR study of laboratory oxidized caking coals in air at 150°C for 2 h. A comparison of the infrared spectrum of a sample of unoxidized coal to the spectrum of the same sample subsequent to heating showed structural changes resulting from an increase of carbonyl and carboxyl groups together with slight loss of phenolic OH. A similar effect was reported by Choudhury et al. (2009). FTIR spectra of 24 h, 50 h, and 216 h air oxidized coals were recorded and compared. It was found that there has been a gradual decrease in aliphatic- CH groups with increase in duration of aerial oxidation along with formation of COOH and > CO groups. Similarly, aliphatic bands are very prone to oxidation, (Kister et al., 1988).

**Gieseler Plastometer**

Huffmann et al. (1985) and Thompson (2000) described the utilisation of Gieseler Plastometer to study oxidised coals and concluded that Gieseler fluidity was by far the most sensitive to the early stages of oxidation. Davidson (1991) argues that the Gieseler test is generally recognized as the most sensitive to mild oxidation in these coals which, in the fresh state, exhibit Gieseler fluidity.

**Micro hardness tester**

Given (1976) and Nandi et al. (1977) reported that changes in microhardnes detected by the Vickers Hardness Test can be used to detect oxidation in coals. Similarly, Markova and Valceva (1983) showed that low temperature oxidation of subbituminous coals at temperatures of 150 and 200°C led to an increase of microhardness. Also, Korte (2001) showed the elasticity of the vitrinite particles measured with a micro hardness tester increase with increasing oxidation of the vitrinite particles. Equally, Kruszewska and du Cann (1996) reported on the increase in elasticity index in vitrinite in weathered coals, with EI increasing with weathering time. The resulting parabolic curves (max. vitrinite reflectance vs. EI) were distinct for low rank coals becoming less marked with increasing coal rank.

In contrast, Nandi et al. (1977) reported that artificially oxidised coals (drying at ambient laboratory conditions for 18 and 12 years and artificial oxidation at low temperature conditions at 105°C) exhibited no changes in microhardnes. Similarly, Alpern (1977) did not observe any change in the microhardness of coal sample of a French coal of the Stephanian age artificially oxidised (drying at ambient laboratory conditions) for 18 years.

**Surface area, gas adsorption**

The effects of air oxidation on gas adsorption of coals during storage are important for accessing their gas saturation capacity. Weathering and laboratory oxidation of high and medium-volatile bituminous coals influences the surface area and pore-size distribution influencing methane and carbon dioxide gas sorption in coals (Mastalerz et al., 2009; Busch et al., 2004; Ludvig et al., 1983; Clarkson and Bustin, 1997). Ludvig et al. (1983) reported in high temperature oxidation experiments up to 400°C that an intermittent increase in surface areas after the experiments was followed by a reduction in surface areas after storage for up to 278 days in air at room temperature. He interpreted the observed reduction in surface area as a result of exposure to oxygen water vapor and other atmospheric gases suggesting that pore structure changes with storage time. Mastalerz et al. (2009) observed that oxidation and drying of coals increased their adsorption capacities. In contrary, Vessey and Bustin (1999) documented that coal oxidations resulted in decreased methane adsorption capacity.

**Miscellaneous techniques:**

**Mössbauer spectroscopy**

Mössbauer spectroscopy allows detection of transformation of pyrite to FeOOH correlating with parameters of oxidation (Huggins et al., 1980; Kolker and Huggins, 2007).

**Atomic force microscopy**

Bruening and Cohen (2005) applied atomic force microscopy (AFM) to assess the effects of weathering on coal macerals in terms of maceral topography or roughness. Surface roughness measurements can aid in assessment of surface changes in specific macerals before and after the oxidation by application of the cross-section analysis.

**Low temperature ash**

Pearson and Kwong (1979) have reported a method of direct correlation between the oxidation of a high-volatile coking coal and the presence of the mineral bassanite (calcium sulphate hemihydrate) in low temperature ash.

**NMR spectroscopy**

13C NMR spectroscopy was used by Havens et al. (1983) together with FTIR spectroscopy to show that coal oxidation took place predominantly at aliphatic carbons bonds. MacPhee and Nandi (1981) and Yokono et al. (1981b) derived oxidation sensitive parameters such as various relaxation times from 1H NMR and the aromatic/aliphatic ration for 13C NMR that changed with the length of time of oxidation at about 373 K. Mao et al (2010) demonstrated that solid-state NMR technique can be applied to chemically characterise coal oxidized at low temperatures by detecting obvious structural changes such as generation of COO groups.

**Bibliography**

Alpern, B. 1977. Minutes of the 30th Meeting of Commission for Coal Petrology. International Committee for Coal Petrology, Wegimont-Liége, Belgium, 26-28 April 1977.

Alpern, B., Maume, F., 1969. Etude petrographique de l'oxydation naturelle et artificielle des houilles. Revue Industrie Minérale, 51 (11), 974-997.

Alvarez, R., Cimadevilla, J.L.G., Barriocanal, C., Casal., M.D., Diez, M.A., Pis, J.J., 2003. [Influence of coal weathering on coke quality](http://www.ingentaconnect.com/content/maney/ias/2003/00000030/00000004/art00009).Ironmaking and Steelmaking Journal 30(4), 307-312.

Ammosov, I.I., Musyal, S.A., 1952. Otrazatelnaya spospbnost kak odna iz glawnych osobennostey izkopaemych ugley. Doklady Akademii Nauk SSSR 84(6), 1223-1226, (in Russian).

Anderson, N.E., Hamza, H.A., 1982. The characterization of oxidized coal - A review. Coal: Phoenix of the 80´. In: Taweel, A.M. (Ed.) Proceedings of the 64th CIC Coal Symposium, Ottawa, Canada, p.117.

Anderson, K.B., R.B. Johns, 1986. Oxidation studies of Australian coals—I. Aliphatic and aromatic hydrocarbon centres of oxidative attack. Organic Geochemistry 9(5), 219-224.

Atkinson, H.B., Hyslop, W., 1961. The assessment of incipient oxidation in Durham coking coals. Coke Gas 23, 102-106.

Axelson, D.E., Mikula, R.J., Munoz, V.A., 1987. Characterisation of coal oxidation in-situ and on a stockpile. In Moulijn, J.A., Nater, K.A., Chermin, H.A.G., (Eds). International Conference on coal science. Maastricht, Netherlands, October 26-30, 1987. Coal Science and Technology 11, 419-422.

Azik, M., Yurum, Y., Gaines, A., 1993. [Air oxidation of Turkish Beypazari lignite. 1. Change of structural characteristics in oxidation reactions of 150°C](http://pubs.acs.org/doi/abs/10.1021/ef00039a006?prevSearch=%255Bauthor%253A%2BAzik%255D%2BNOT%2B%255Batype%253A%2Bad%255D%2BNOT%2B%255Batype%253A%2Bacs-toc%255D&searchHistoryKey=). Energy Fuels 7(3), 367-372.

Banerjee, S.C., Banerjee, B.D., Chakrovorty, R.N., 1970. [Rate studies of aerial oxidation of coal at low temperatures (30–170 °C)](http://www.sciencedirect.com/science/article/pii/0016236170900244?_rdoc=9&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231970%23999509996%23447159%23FLP%23display%23Volume)&_docanchor=&_ct=15&_refLink=Y&_zone=rslt_list_item&md5=6e71789118d311a8f741755ef663ce18). Fuel 49(3), 324-331.

Beier, E., 1962. Die Oxidation von Steinkohle an Luft. PhD Thesis D82. Mitteilungen der Westfälischen Berggewerkschaftskasse 22, pp. 105.

Bend, S.L., Edwards, I.A.S., March, H., 1989. The effects of oxidation and weathering on coal combustion. American chemical society, division of fuel chemistry 34(3), 923-930.

Bend, S.L., 1989. Coal characterization and combustion. PhD Thesis, University of Newcastle upon Tyne, Department of Chemistry, p. 179.

Bend, S.L., Kosloski, D.M., 1993. A petrographic examination of coal oxidation.

International Journal of Coal Geology 24(1-4), 233-243.

Benedict, L.G., Berry, W.F., 1964. Recognition and measurement of coal oxidation. Monroeville, PA, Coal Research, 41 p.

Berkowitz, N., 1985. The Chemistry of Coal. Amsterdam, the Netherlands, Elsevier, p. 513.

Boyapati, E., Oates, W., Moxon, N., Day, J.C., Baker, C.K., 1984. The weathering characteristics of coking coals: Use of a gas flow test in assessing weathering propensity. Fuel 63(4), 551-556.

Brenner, D., 1981. Thin section microscopic studies of the diffusion of oxygen into coal at elevated temperatures. In Proceedings of the Conference of the American Chemical Society, Division of Fuel Chemistry, Symposium on the Chemistry of Engine Combustion Deposits, Atlanta, GA, USA, 29 Mar 26(1), 42-49.

Brooks, J.D., Maher, T.P., 1957. Acidic oxygen-containing groups in coal. Fuel 36, 51-62.

Bruening, F.A., Cohen, A.D., 2005. Measuring surface properties and oxidation of coal macerals using the atomic force microscope. International Journal of Coal Geology 63(3-4), 195-204.

Busch, A., Gensterblum, Y., Krooss, B.M., Littke, R., 2004. Methane and carbon dioxide adsorption–diffusion experiments on coal: upscaling and modeling. International Journal of Coal Geology 60(2-4), 151-168.

Bustin, R.M., 1980, Oxidation characteristics of some sheared coal seams of the Mist Mountain Formation, southeastern Canadian Cordillera: Geological Survey of Canada, Paper 80-1B, p. 249-254.

Bustin, R.M., 1982. The effect of shearing on the quality of some coals in the southeastern Canadian Cordillera. Canadian Institute of Mining and Metallurgy Bulletin 75, 76-83.

Bustin, R.M., Cameron, A.R., Grieve, D.A., Kalkreuth, W.D., 1983. Coal Petrology, its Principles, Methods and Applications. Geological Association of Canada, Short Course Notes Volume 3, 273 pp.

Bustin, R.M., Cameron, A.R., Grieve, D.A., Kalkreuth, W.D., 1985. Coal petrology, its principles, methods, and applications. Geological Association of Canada, Short Course Notes, Vol. 3, Cardott, B., J., 1989. A petrographic survey of high-volatile bituminous Oklahoma coal beds. Oklahoma Geology Notes 49(4), 112-124.

Butakova, V.I., Popov, V.K., Posokhov, Yu. M., Kuznetsova, N.P. 2013. Initial stage in the low-temperature oxidation of coal in air. Coke and Chemistry, 56(7), 225-234.

Cagigas, A., Escudero, J.B., Low, M.J.D., Pis, J.J., Tascon, J.M.D., 1987. A comparison of various characterization techniques for low-temperature oxidation of coal. Fuel Processing Technology 15, 245-256.

Calemma, V., del Piero, G., Rausa, R., Girardi, E., 1995. [Changes in optical properties of coals during air oxidation at moderate temperature](http://www.sciencedirect.com/science/article/pii/001623619593471O?_rdoc=11&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231995%23999259996%23185697%23FLP%23display%23Volume)&_docanchor=&_ct=24&_refLink=Y&_zone=rslt_list_item&md5=9cbc655d65d547a8a150a94e43d9e8c8). Fuel 74(3), 383-388.

Calemma, V., Rausa, R., Margarit, R., Girardi, R., 1988. [FTIR study of coal oxidation at low temperature](http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V3B-498MD00-VP&_user=919745&_coverDate=06%2F30%2F1988&_rdoc=6&_fmt=high&_orig=browse&_origin=browse&_zone=rslt_list_item&_srch=doc-info(%23toc%235726%231988%23999329993%23447049%23FLP%23display%23Volume)&_cdi=5726&_sort=d&_docanchor=&_ct=30&_acct=C000048079&_version=1&_urlVersion=0&_userid=919745&md5=74b8c3cff994a20fd88e26fdff2a2164&searchtype=a). Fuel 67(6), 764-770.

Carras, J.N., Young, B.C., 1994. Self-heating of coal and related materials: models, applications and test methods. Progress in Energy and Combustion Science 20(1), 1-15.

Casal, M.D., Gonzalez, A.I., Canga, C.S., Barriocanal, C., Pis, J.J., Alvarez, R., Diez, M.A., 2003. Modifications of coking coal and metallurgical coke properties induced by coal weathering. Fuel Processing Technology 84(1-3), 47-62.

Chakravaty, S.L., 1960a. Journal of Mines, Metals and Fuels. Auto-oxidation of Indian coals. Part II. Mechanism of oxidation. Journal of Mines, Metals and Fuels 1, 10-15.

Chakravaty, S.L., 1960b. Auto-oxidation of Indian coals. Part I. Influence of variables on the formation of peroxidic bodies. Journal of Mines, Metals and Fuels 9, 1-4.

Chalishazar, B.H., Spooner, C.E., 1957. A rapid method for the determination of peroxide groups on coal. Fuel 36, 127-128

Chandra, D., 1958. Reflectance of oxidized coals. Economic Geology 53, 102-108.

[Chandra, D., 1962](http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V8C-4GG8VFG-1&_user=919745&_coverDate=08%2F19%2F2005&_alid=1617651018&_rdoc=1&_fmt=high&_orig=search&_origin=search&_zone=rslt_list_item&_cdi=5867&_sort=r&_st=13&_docanchor=&view=c&_ct=1&_acct=C000048079&_version=1&_urlVersion=0&_userid=919745&md5=2e90773141009cbbb8642fc430923707&searchtype=a#bbib5). Reflectance and microstructure of weathered coals. Fuel **41**(2), 185-193.

Chandra, D., 1966. Effect of storage of coals on reflectance and petrological composition. Economic Geology 61, 754-759

Chandra, D., Srivastava, G.P., 1978. Reflectance of burnt coals. Fuel 57(4), 251-252.

Chandra, D., 1982. Oxidized coals. In Stach, E., Mackowsky, T-Th., Teichmüller, M., Taylor, G.H., Chandra, D., Teichmüller, R. (Eds.) Stach`s textbook of coal petrology. Gebrueder Borntraeger, Berlin, pp. 198-206.

Chen, X.D., Stott, J.B., 1993. The effect of moisture content on the oxidation rate of coal during near-equilibrium drying and wetting at 50°C. Fuel 72(6), 787-792.

Choudhury, D., Srivastava, S.K.,Prasad, R.S, (2009) Studies on Preparation of adsorbent Precursor From Coal; Using Oxidative Technique. Indian Journal of Environmental Protection, 29 (4), 359-368.

Cimadevilla, J.L.G., Alvarez, R., Pis, J.J. 2003. Photoacoustic FT-IR study of weathered stockpiled coking coals. Vibrational Spectroscopy 31(1), 133-141.

Cimadevilla, J.L.G., Alvarez, R., Pis, J.J., 2005. [Influence of coal forced oxidation on technological properties of cokes produced at laboratory scale](http://infosys.korea.ac.kr/outlink/periodicals/vol_view.php?seq=692032&start=0&number=1&jourid=85&jname=Fuel%20Process.%20Technol.&vol=87&num=1&totalcount=11). Fuel Processing Technology 87(1), 1-10.

Clarkson, C.R., Bustin, R.M., 1997. Variation in permeability with lithotype and maceral composition of Cretaceous Coals of the Canadian Cordillera. International Journal of Coal Geology 33(2), 135-151.

Clemens, A.H., Matheson, T.W., Lynch, L.J., Sakurovs, R., 1989. Oxidation studies of high fluidity coals. Fuel 68(9), 1162-1167.

Clemens, A., Matheson, T., Rogers, D., 1991. [Low temperature oxidation studies of dried New Zealand coals](http://www.sciencedirect.com/science/article/pii/0016236191901554?_rdoc=12&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231991%23999299997%23447716%23FLP%23display%23Volume)&_docanchor=&_ct=22&_refLink=Y&_zone=rslt_list_item&md5=27c24871ebe4fc4524f8ff4e99eff029). Fuel 70(2), 215-221.

Clemens, A.H., Matheson, T.W., 1992. [Further studies of Gieseler fluidity development in New Zealand coals](http://www.sciencedirect.com/science/article/pii/001623619290008C?_alid=1788990754&_rdoc=3&_fmt=high&_origin=search&_docanchor=&_ct=11&_zone=rslt_list_item&md5=8af4ed54e32b682139842e41b789dfb8). Fuel 71(2), 193-197.

Cloke, M., Lester, E., 1994. Characterization of coals for combustion using petrographic analysis. Fuel 73(3), 315-320.

Copard, Y., Disnar, J.R., Becq-Giraudon, J.F., 2002. Erroneous maturity assessment given by Tmax and HI Rock-Eval parameters on highly mature weathered coals. International Journal of Coal Geology 49(1), 57-65.

Copard, Y., Disnar, J.R., Becq-Giraudon, J.F., Laggoun-Defarge, F., 2004. Erroneous coal maturity assessment caused by low temperature oxidation. International Journal of Coal Geology 58(3), 171-180.

Correa da Silva, Z.C., Pereira Neto, J., 1993. Oxidation effects on macerals of the Candiota coal, Rio Grande do Sul State, southern Brazil, stocked in piles. 45th Annual Meeting of ICCP at Chania,Crete, Greece, September 26-02 October, 1993. ICCP News 8, p. 13.

Cox, J.L., 1984. Concern over coal samples. Fuel 63(7), 1030-1031.

Cox, J.L., Nelson, C.R., 1984. Coal weathering: causes, effects and implications. Division of Fuel Chemistry American Chemical Society 29(1), 102-107.

Crelling, J.C., Schrader, R.H., Benedict, L.G., 1979. Effects of weathered coal on coking properties and coke quality. Fuel 58(7), 542-546.

Crelling, J.C., 2008. Coal Carbonisation. In I. Suárez-Ruiz and J.C. Crelling, (Eds.) , Applied coal petrology: the role of petrology in coal utilization: New York, Academic Press, p. 173-192.

Cronauer, D.C., Ruberto, R.G., 1979. Investigation of mechanism of reactions involving oxygen-containing compounds in coal hydrogenation. EPRI Final Report AF-913. Final Report on Project 713-1, March 1979.

Cronauer, D.C., Ruberto, R.G., Jenkins, R.G., Davis, A., Painter, P.C., Hoover, D.S., Starsinic, M.E., Schlyer, D., 1983a. [Liquefaction of partially dried and oxidized coals: 2. Coal characteristics](http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V3B-498TM17-FY&_user=919745&_coverDate=10%2F31%2F1983&_rdoc=4&_fmt=high&_orig=browse&_origin=browse&_zone=rslt_list_item&_srch=doc-info(%23toc%235726%231983%23999379989%23447614%23FLP%23display%23Volume)&_cdi=5726&_sort=d&_docanchor=&_ct=30&_acct=C000048079&_version=1&_urlVersion=0&_userid=919745&md5=9a00e2427e4c98681a8740152c8f7315&searchtype=a). Fuel 62(10), 1124-1132.

Cronauer, D.C., Ruberto, R.G., Silver, R.S., Jenkins, R.G., Ismail, Y.M.K., Schlyer, D., 1983b. [Liquefaction of partially dried and oxidized coals: 1. Coal characteristics](http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V3B-498TM17-FY&_user=919745&_coverDate=10%2F31%2F1983&_rdoc=4&_fmt=high&_orig=browse&_origin=browse&_zone=rslt_list_item&_srch=doc-info(%23toc%235726%231983%23999379989%23447614%23FLP%23display%23Volume)&_cdi=5726&_sort=d&_docanchor=&_ct=30&_acct=C000048079&_version=1&_urlVersion=0&_userid=919745&md5=9a00e2427e4c98681a8740152c8f7315&searchtype=a). Fuel 62(10), 1116-1123.

Cronauer, D.C., Ruberto, R.G., Silver, R.S. , Jenkins, R.G. , Davis, A., Hoover, D.S., 1984. [Liquefaction of partially dried and oxidized coals: 3. Liquefaction results](http://www.sciencedirect.com/science/article/pii/0016236184902588?_alid=1791083767&_rdoc=1&_fmt=high&_origin=search&_docanchor=&_ct=18&_zone=rslt_list_item&md5=76034b88014120ca02b1f71c43305b45). Fuel 63(1), 71-77.

Davidson, R.M., 1990. Natural oxidation of coal. IEACR/29, IEA Coal Research, London pp. 57-60.

Davidson, R.M., 1991. Natural oxidation of coal: University of Kentucky Center for Applied Energy Research, Energeia 2(2), 1-4.

Davis, R.C., Noon, S.W., Harrington, J., 2007. The petroleum potential of Tertiary coals from Western Indonesia: Relationship to mire type and sequence stratigraphic setting. International Journal of Coal Geology 70(1-3), 35–52.

Dawson, K.M. 1967. The microscopic examination of oxidized char. Fuel 46: 159-167.

Diessel, C.F.K., 1985. Fluorometric analysis of inertinite. Fuel 64(11), 1542-1546.

Dunlop, N.F., Johns, R.B., 1999. Thermally induced chemical changes in the macromolecular structure of an Indonesian coal. Organic Geochemistry 30(10), 1301-1309.

Dryden, I.G.C., 1963. Chemical constitution and reactions of coal. In: H. H. Lowry (Ed.). The Chemistry of Coal Utilization. Supplementary Volume, p. 232-295.

Edwards, A.H., Jones, J.M., Newcombe, W., 1964. The extraction by nitric acid of pyrites from vitrains and coal samples. Fuel 43, 55-62.

Estevez, M., Juan, R., Ruiz, C., Anders, J.M., 1990. Formation of humic acids in lignites and subbituminous coals by dry air oxidation. Fuel 69(1), 157-160.

Ferrari, B., 1938. Die Entstehung von Grubenbränden nach Untersuchungen auf kohlenpetrographischer Grundlage. Glückauf 74, 765-774.

Fieldner, A.C., Fisher, P.L., Steiner, W.A. 1945. Relative spontaneous heating tendencies of coals. Technical paper No. 681. Bureau of Mines, United States Department of the Interior, Washington, DC.

Francis, W., 1961. Coal, its formation and composition. Edward Arnold, Ltd., London, 806 pp.

Fredericks, P.M., Warbrooke, P., Wilson, M.A., 1983. Chemical changes during natural oxidation of a high volatile bituminous coal. Organic Geochemistry 5(3), 89– 97.

Freyer, F.J., Szladow, A.J., 1973. Storage of Coal Samples. Alberta Research Council Information Series 66, 1-7.

Fuchs, W., Sandhoff, A.G., 1942. Theory of coal pyrolysis. Industrial and Engineering Chemistry 34(5), 567-571.

Fujijoka, Y., Nishifuji, M., Saito, K., Kato, K., 2006. Analysis of thermal decomposition behaviour of coals using thigh temperature infrared spectrophotometer system. Nippon Steel Technical Report 94, 58-62.

Furimsky, E., MacPhee, J.A., Vancea, L., Ciavaglia, L.A., Nandi, B.N., 1983. Effect of oxidation on the chemical nature and distribution of low temperature pyrolysis products from bituminous coal. Fuel 62(4), 395-400.

Fuerstenau, D.W., Rosenbaum, J.M., Laskowski, J., 1983. Effect of surface functional groups on the flotation of coal. Colloids and Surface 8, 153-173.

Garcia, A.B., Moinelo, S.R., Martinez-Tarazona, M.R., Tascon, J.M.D., 1991. Influence of weathering process on the flotation response of coal. Fuel 70(12), 1391-1397.

Gentzis, T., Goodarzi, F., McFarlane, R.A., 1992. Molecular structure of reactive coals during oxidation, carbonization and hydrogenation - an infrared photoacoustic spectroscopic and optical microscopic study. Organic Geochemistry 18(3), 249-258.

Gerus-Piasecka, I., Jasieńko, S., 1989. Zmiany własności węgla płomiennego i odmian petrograficznych w procesach wietrzenia. Changes of flame coal properties and its petrographic components in the process of weathering. Koks Smola Gaz 34, 31-36. (in Polish).

Gethner, J.S., 1985. Thermal and oxidation chemistry of coal at low temperatures. Fuel 64(10), 1443-1446.

Gethner, J.S., 1986. Coal oxidation and thermal chemistry. Americal Chemical Society, Division of Fuel Chemistry 31(4), 103-110.

Gethner, J.S. 1987a. Kinetic study of the oxidation of Illinois No. 6 coal at low temperatures: Evidence for simultaneous reactions. Fuel 66, 1091-1096.

Gethner, J.S., 1987b. The mechanism of the low-temperature oxidation of coal by O2: observation and separation of simultaneous reactions using in situ FT-IR Difference Spectroscopy. Applied Spectroscopy 41(1), 50-63.

Ghosh, T.K., 1997. Petrography and metamorphism of the lower Gondwana (Permian) coal of Rangit Valley, eastern Himalayas, India. International Journal of Coal Geology 33(4), 351-368.

Given, P.H., 1976. [The use of daf and dmmf ultimate analyses of coals](http://www.sciencedirect.com/science/article/pii/0016236176901022?_rdoc=22&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231976%23999449996%23447606%23FLP%23display%23Volume)&_docanchor=&_ct=33&_refLink=Y&_zone=rslt_list_item&md5=6ab71a07e3bc749bb277323251e82cb1). Fuel 55(3), 256-256.

Goodarzi, F., Murchison, D.G. 1973. [Oxidized vitrinites — their aromaticity, optical properties and possible detection](http://www.sciencedirect.com/science/article/pii/0016236173900276?_rdoc=1&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231973%23999479997%23447175%23FLP%23display%23Volume)&_docanchor=&_ct=24&_refLink=Y&_zone=rslt_list_item&md5=2754ba4e7af7558bbb22cc768169a4ed). Fuel 52(2), 90-92.

Goodarzi, F., Hermon, G., Iley, M., Marsh, H., 1975. Carbonization and liquid-crystal (mesophase) development. 6. Effect of pre-oxidation of vitrinites upon coking properties. Fuel 54(2), 105-112.

Goodarzi, F., Murchison, D.G., 1976. [Petrography and anisotropy of carbonized preoxidized coals](http://www.sciencedirect.com/science/article/pii/0016236176900119?_rdoc=11&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231976%23999449997%23446986%23FLP%23display%23Volume)&_docanchor=&_ct=21&_refLink=Y&_zone=rslt_list_item&md5=859b112cd8cb686c5da1452543d54ee6). Fuel 55(2), 141-147.

Goodarzi, F., 1986. Optical properties of oxidized resinites. Fuel 65(2), 260-265.

Graham, J I, 1914. The Absorption of Oxygen by Coal, Part V: The Influence of Temperature on Rates of Absorption by Different Parts of the Barnsley Bed, Transactionsof the Institution of Mining Engineers, Vol. 48, 521-534.

Graham, J.I., 1915. The absorption of oxygen by coal. Part VII.- The influence of moisture upon the rate of absorption, and the question of bacterial oxidation. Transactionsof the Institution of Mining Engineers. 49: 35-43.

Gransden, J.F., Jorgensen, J.G., Manery, N., Price, J.T., Ramey, N.J., 1991. Application of microscopy to coke making. International Journal of Coal Geology 19(1-4), 77-107.

Gray, R.J., Rhoades, A.H., King, D.T., 1976. Detection of oxidized coal and the effect of oxidation of the technological properties. Transaction of SME (AIME) 260, 334-341.

Gray, R.J., Krupinski, K.C., 1976. Use of microscopic procedures to determine the extent of destruction of agglomerating properties in coal. Proc. Coal Agglomeration and Conversion Symposium, Sponsored by West Virginia Geological and Economic Survey and Coal Research Bureau, West Virginia University, pp. 37-62.

Gray, R.J., 1982. A petrologic method of analysis of nonmaceral microstructures in coal. [International Journal of Coal Geology](http://www.sciencedirect.com/science/journal/01665162) 2(1), 79-97.

Grint, A., Marsh, H., Clarke, K., 1983. Co-carbonisation of oxidized coals with petroleum pitches. Fuel 62(11), 1355-1358.

Guyot, R.E., Pollard, F., 1974. Effects of oxidation on coal properties related to

industrial use. Australian Coal Industry Research Laboratories, Report 74-18.

Haldane, J.S., Makgill, R.H., 1934. The spontaneous oxidation of coal and other organic substances. Journal of the Chemical Society, Indus (London) 53T, 359-367.

Hao, F., Chen, J., 1992.The cause and mechanism of vitrinite reflectance anomalies. Journal of Petroleum Geology **15(3)**, 419–434.

Havens, J.R., Koenig, J.L., Kuehn, D., Rhoads, C., Davis, A., Painter, P.C. 1983. Characterisation of coals and coal oxidation by magic angle 13C NMR spectroscopy. Fuel 62, 936-941.

Hoover, D.S., Schweighardt, F.K., 1989. Analytical techniques for monitoring coal sample storage, in R. Klein and R. Wellek, eds., Sample selection, aging, and reactivity of coal: New York, John Wiley & Sons, p. 443-461.

Huffman, G.P., Huggins, F.E., Dunmyre, G.R., Pignocco, A.J., Lin, M.C., 1985. Comparative sensitivity of various analytical techniques to the low-temperature oxidation of coal. Fuel 64(6), 849–856.

Huggins, F.E., Huffman, G.P., Kosmack, D.A., Lowenhaupt, D.E., 1980. Mossbauer detection of goethite in coal and its potential as an indicator of coal oxidation. International Journal of Coal Geology 1(1), 75-81.

Huggins, F.E., Huffman, G.P., Lin, M.C., 1983. Observation on low-temperature oxidation in minerals in bituminous coals. International Journal of Coal Geology 3(2), 157-182.

Huggins, F.E., Huffman, G.P., Dunmyre, G.R., Lin, M.C., 1985. Correlative investigation of the effects of oxidation on the minerals, macerals, and technological properties of coal. Final report to Gas Research Institute, GRI-85/108; NTIS PB85-246437.

Huggins, F.E., Huffman, G.P., Dunmyre, G.R., Nardozzi, M.J., Lin, M.C., 1987. Low temperature oxidation of bituminous coal: its detection and effect on coal conversion. Fuel Processing Technology 15, 233-244.

Huggins, F.E., Huffman, G.P., 1989. Coal weathering and oxidation: Early stages. In: Nelson, C.R. (Ed.), Chemistry of Coal Weathering Coal Science and Technology, 14, 33-60.

Iglesias, M.J., de la Puente, G., Fuente, E., Pis, J.J., 1998. [Compositional and structural changes during aerial oxidation of coal and their relations with technological properties](http://www.sciencedirect.com/science/article/pii/S0924203198000174?_rdoc=3&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235293%231998%23999829998%2320485%23FLA%23display%23Volume)&_docanchor=&_ct=9&_refLink=Y&_zone=rslt_list_item&md5=2876d8460f2aeb5160ad52de50b8f386). Vibrational Spectroscopy 17(1), 41-52.

Ignasiak, B.S., Nandi, B.N., Montgomery, D.S., 1970. [Oxidation studies on coking coal related to weathering: (1) Chromatographic analysis of pyrolysis gases as a method for studying coal weathering](http://www.sciencedirect.com/science/article/pii/0016236170900414?_rdoc=11&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231970%23999509997%23447155%23FLP%23display%23Volume)&_docanchor=&_ct=19&_refLink=Y&_zone=rslt_list_item&md5=310bc34d8292c013565967b3ed0c5115). Fuel 49(2), 214-221.

Ignasiak , B.S., Szladow, J., Montgomery, D.S., 1974. [Oxidation studies on coking coal related to weathering. 3. The influence of acidic hydroxyl groups, created during oxidation, on the plasticity and dilatation of the weathered coking coal](http://www.sciencedirect.com/science/article/pii/0016236174900258?_rdoc=5&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231974%23999469998%23447163%23FLP%23display%23Volume)&_docanchor=&_ct=18&_refLink=Y&_zone=rslt_list_item&md5=0a061f0e0fea38f6fecc9941ac8144cc). Fuel 53(1), 12-15.

Ingram, G.R., Rimstidt, J.D., 1984. Natural weathering of coal. Fuel **63**(3), 292–296.

Isaacs, J.J., Liotta, R., 1987. Oxidative weathering of Powder River basin coal. Energy and Fuels 1(4), 349-351.

Itay, M.H., Hill, C.R., Glasser, D., 1989. A study of the low temperature oxidation of coal. Fuel Processing Technology 21(2), 81-97.

Jackman, H.W., Eissler, R.L., Reed, F.H., 1957. Weathering of Illinois coals during storage. Illinois State Geological Survey Circular 227, 22 p.

Jacob, H., 1964. Über Steinkohlen-Oxyhumodile aus Afghanistan, Ägypten, Kolumbien und dem Iran-Kohlevarietäten der Verwitterungszone von Steinkohlen. I. Die Verwitterungs von Steinkohlen und Rolle der Oxidation, makropetrographischer Befund und mikroskopische Untersuchung. Brennstoff-Chemie 45: 26-29.

Jones, R. E.,Townend D. T. A., 1945. Mechanism of the oxidation of coal.Nature,155,424-425.

Jones, R.E., Townend, D.T.A., 1949. The oxidation of coal. Journal of Society of Chemical Industry 68(7), 197-201.

Josten, K.H., 1956. Die Kohlen im Pfälzer Bergland. NotizblattdesHessischen Landesamtes für Bodenforschung zu Wiesbaden 84, 300-327.

Jüttner, B., 1956. The wet oxidation of bituminous coal. Brennstoffchemie 37, 70-74.

Kalemma, W.S., Gavalas, G.R., 1987. [Changes in coal composition during air oxidation at 200–250 °C](http://www.sciencedirect.com/science/article/pii/0016236187902341?_rdoc=3&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231987%23999339997%23447041%23FLP%23display%23Volume)&_docanchor=&_ct=31&_refLink=Y&_zone=rslt_list_item&md5=669c380c65a9dd63237e629f44058dda). Fuel 66(2), 158-164.

Kam, A. Y., Hixson, A. N., Perlmutter, D. D., 1976. The Oxidation of Bituminous Coal-I. Development of a Mathematical Model, Chemical Engineering Science 31(9), 815-819.

Keogh, R.A., Chawla, B., Tailbee, D., Davis, B.H., 1989. In: Proceedings of the International Conference on Coal Science, 23-27 October 1989, Tokyo, Japan, NEDO Japan, 683-686.

Khan, M.R., Usmen, R., Newton, E., Beer, S., Chisholm, W., 1988. ESR spectroscopic study on the chemistry of coal oxidation. Fuel 67(12), 1668-1673.

Kister, J., Guiliano, M., Mille, G. and Dou, H., 1988. Changes in the chemical structure of low rank coal after low temperature oxidation or demineralization by acid treatment. Fuel, 67, 1076-1081.

Klein, R. Welleck, R., 1989. Sample Selection, Aging and Reactivity of Coal. Wiley, New York, 481 pp.

Klika, Z., Kraussova, J., 1993. Properties of Altered Coals Associated with Carboniferous Red Beds in the Upper Silesian Coal Basin and Their Tentative Classification. International Journal of Coal Geology 22(3-4), 217-235.

Kochi, J.K., 1973. Free Radicals Volume 1, Wiley Interscience, New York, pp.690.

Kojima, K., Ogoshi, H., 1973. Petrographic consideration of weathered coal. J. Fuel Soc. Jpn., 52(56), 885-895.

Kolker, A., Huggins, F.E., 2007. Progressive oxidation of pyrite in five bituminous coal samples: an As XANES and 57Fe Mössbauer spectroscopic study. Applied Geochemistry 22(4), 778-787.

Kona, N.R., Fairbanks, N.V., Leonard, J.W., 1968. Low temperature oxidation of coal. Fuel 57(3), 177-183.

Korte, de, G.J., 2001. Beneficiation of weathered coal. Report Coaltech 2020-4.6.2. pp. 20.

Kosina, M., Hrncir, J., 1983. The properties of macerals in Czechoslovak coals rich in inertinite. International Journal of Coal Geology 3(2), 145–156.

Kruszewska, K.J., du Cann, V.M., Labuschagne, B.C.J., 1992. New petrographic method for the detection of the incipient oxidation of coal. Report No. ENER-C 92037. Division of Energy Technology CSIR.

Kruszewska, K.J., du Cann, V.M., 1996. [Detection of the incipient oxidation of coal by petrographic techniques](http://www.sciencedirect.com/science/article/pii/0016236195002642?_rdoc=18&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231996%23999249993%23103659%23FLP%23display%23Volume)&_docanchor=&_ct=22&_refLink=Y&_zone=rslt_list_item&md5=5cc1c34078e9d98aceb07b3b7272d750). Fuel 75(6), 769-774.

Kukharenko, T.A., Ryzhova, Z.A., 1956. Certain aspects of weathering of coal in relation to its petrographic composition. Khim. I Tekhnol. Topliva 4, 20-30; Chem. Abst. 50: 12440b.

Kus, J. Meyer, U., Jianwei, M., Chen-Brauchler, D., 2010. Oxidation and carbonisation of coals: a case study of coal fire affected coals from the Wuda coalfield, Inner Mongolia, China. In: General Assembly of the European Geosciences Union 2010 Vienna, Austria, 02-07 Mai 2010. Geophysical Research Abstracts vol. 12 (EGU2010-11851).

La Grange, C.C., 1950. Spontaneous heating of coal – summarised extracts from the literature. Report No. 9. Fuel Research Institute of South Africa.

La Grange, C.C., 1951. Storage of coal with special reference to quality deterioration and spontaneous combustion. Fuel Research Institute of South Africa. Report No. 28.

Landais, P., Monthioux, M., Meunier, J.D., 1984. Importance of the oxidation/maturation pair in the evolution of humic coals. Organic Geochemistry 7(3-4), 249–260.

Landais, P., Rochdi, A., 1993. In situ examination of coal macerals oxidation by micro-FT-IR. spectroscopy. Fuel 72(10), 1393–1401.

Larsen, J.W., Lee, D., Schmidt, T., Grint, A., 1986. Multiple mechanisms for the loss of coking properties caused by mild air oxidation. Fuel 65(4), 595-596.

Leythaeuser, D., 1973. Effects of weathering on organic matter in shales. Geochimica et Cosmochimica Acta37(1), 113-120.

Lin, M.C., Huggins, G.P. Huffmann, F.E., Lowenhaupt, D.E., 1983. A Correlative investigation of the effects of oxidation on the minerals, macerals and technological properties of coal. American Chemical Society, Division of Fuel Chemistry 28(4), 1-7.

Liotta, R., Brons, G., Isaacs, J., 1983. [Oxidative weathering of Illinois No.6 coal](http://www.sciencedirect.com/science/article/pii/0016236183900285?_rdoc=5&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231983%23999379992%23447749%23FLP%23display%23Volume)&_docanchor=&_ct=24&_refLink=Y&_zone=rslt_list_item&md5=842a804a3ad7fad29c0fdf2694714523). Fuel 62(7), 781-791.

Lo, H.B., Cardott, B.J., 1995. Detection of natural weathering of Upper McAlester and Woodford shale, Oklahoma, USA. Organic Geochemistry 22(1), 73–83.

Loison, R., Peytavy, A., Boyer, A.F., Grillot, R., 1963. In: A Chemistry of Coal Utilization, Supplementary Volume, (Ed.) Lowry, H.H. John Wiley & Sons, Inc. New York, Chapter 4.

Lopez, D., Sanada, Y., Mondragon, F., 1998. Effect of low temperature oxidation of coal on hydrogen transfer capability. Fuel 77(14), 1623-1628.

Lowenhaupt, D.E., Gray, R.J., 1980. The alkali-extraction test as a reliable method of detecting oxidised metallurgical coal. International Journal of Coal Geology 1(1), 63-73.

Lowry, H.H., 1963. Chemistry of Coal Utilisation. John Wiley and Sons, New York, pp. 272-289.

Ludvig, M.M., Gard, G.L., Emmett, P.H. 1983. Use of controlled oxidation to increase the surface area of coal: Application to a bituminous and a semi-anthracite coal. Fuel 62(12), 1393-1396.

MacPhee, J.A., Nandi, B.N., 1981. 13C N.M.R. as a probe for the characterisation of the low-temperature oxidation of coal. Fuel 60(2), 169-170.

MacPhee, J.A., Giroux, L., Charland, J.-P., Gransden, J.F., Price, J.T., 2004. Detection of natural oxidation of coking coal by TG-FTIR-mechanistic implications. Fuel 83(13), 1855-1860.

Mahajan, O.P., Komatsu, M., Walker, P.L., 1980. Low-temperature air oxidation of caking coals. 1. Effect on subsequent reactivity of chars produced. Fuel 59(1), 3-10.

Malony, D.J., Jhenkins, R.G., Walker, (Jr.) P.L., 1982. [Low-temperature air oxidation of caking coals. 2. Effect on swelling and softening properties](http://www.sciencedirect.com/science/article/pii/0016236182902319?_rdoc=15&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231982%23999389997%23447733%23FLP%23display%23Volume)&_docanchor=&_ct=23&_refLink=Y&_zone=rslt_list_item&md5=bf0290e1c438581d5289fb339892b726). Fuel 61(2), 175-181.

Mangena, S.J., du Cann, V.M., 2007. Binderless briquetting of some selected South African prime coking, blend coking and weathered bituminous coals and the effect of coal properties on binderless briquetting. International Journal of Coal Geology 71(2-3), 303-312.

Mao, J.-D., Schimmelmann, A., Mastalerz, M., Hatcher, P.G., Li, Y., 2010. Structural features of a bituminous coal and their changes during low-temperature oxidation and loss of volatiles investigated by advanced solid-state NMR spectroscopy. Energy Fuels 24, 2536-2544.

Marchioni, D.L., 1983. The detection of weathering in coal by petrographic, rheologic and chemical methods. International Journal of Coal Geology 2(3), 231–259.

Markova, K., Valceva, S., 1983. Oxidation of some Bulgarian coals. Influence of low-temperature oxidation on the microhardness and reflectivity of some brown coals. Fuel 62(8), 942-945.

Martinez, M., Escobar, M., 1995. Effect of coal weathering on some geochemical parameters. Organic Geochemistry 23(3), 253-261.

Mastalerz, M., Solano-Acosta, W., Schimmerlmann, A., Drobniak, A., 2009. Effects of coal storage in air on physical and chemical properties of coal and on gas adsorption. International Journal of Coal Geology 79(4), 167-174.

Mathews, W.H., Bustin, R.M., 1984. Changes associated with natural in situ weathering of a coking coal from southwestern British Columbia. Fuel 63(4), 548-550.

Mastalerz, M., R.M. Bustin, and M.N. Lamberson, 1993, Variation in chemistry of vitrinite and semifusinite as a function of associated inertinite content: International Journal of Coal Geology, v. 22, p. 149-162.

Mavor, M.J., Pratt, T.J., 1993. Improved methodology for determining total gas content volume 1. Canister gas desorption data summary, Topical Report No. GRI-9310410.

McHugh, E.A., Diessel, C.F.K., Kutzner, R., 1991. Use of fluorescence microscopy in the detection of low level oxidation in bituminous coals. Fuel 70(5), 647-653.

McHugh, E.A., 1992. The influence of oxidation on the fluorescence properties of coking coals. 20th Newcastle Symposium Proceedings. Advances in the Study of the Sydney Basin. University of Newcastle, Newcastle, 66-70.

Menendez, R., Marsh, H., Pis, J.J., Alvarez, R., Lorentara, J.L., 1989. Proceedings of International Conference on Coal Science, 23-27 October, Tokyo, 591-599.

Meuzelaar, H.L.C. Harper, A.M., Hill, G.R., Given, P.H., 1984. [Characterization and classification of Rocky Mountain coals by Curie-point pyrolysis mass spectrometry](http://www.sciencedirect.com/science/article/pii/0016236184901601?_rdoc=12&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231984%23999369994%23447629%23FLP%23display%23Volume)&_docanchor=&_ct=34&_refLink=Y&_zone=rslt_list_item&md5=3756c6373266cefb825f022923330a64). Fuel 63(5), 640-652.

Miller, J., Smooke, M., Green, R., Kee, R., 1983. Kinetic modeling of the oxidation of ammonia in flames. Combustion Science and Technology 34(1-6), 149-176.

Misz, M. Fabiańska M., Ćmiel, S., 2007. Organic components in thermally altered coal waste: preliminary petrographic and geochemical investigations. International Journal of Coal Geology **71(4)**, 405-424.

[Misz-Kennan M., Fabiańska,](http://www.sciencedirect.com/science/article/pii/S0146638010001063%22%20%5Cl%20%22bbib5) M., 2010. Thermal transformation of organic matter in coal waste from Rymer Cones (Upper Silesian Coal Basin, Poland). International Journal of Coal Geology 81(4), 343-358.

Mochida, I., Furano, T., Korai, Y., Fujitsu, H., 1986. Studies Reveal Shot Coke

Microstructure, Suggest Ways to Minimize Its Formation. Oil and Gas Journal

84(5), 51-56.

Monthioux, M., 1988. Expected mechanisms in nature and in confined-system pyrolysis. Fuel 67(6), 843-847.

Moore, B., 1931. The behaviour of solid fuel during oxidation. Part IV. The combustion of the banded ingredients-vitrain, clarain, durain and fusain. Fuel 10, 205-211.

Moore, B., 1932. Behaviour of solid fuels during oxidation. Part VIII. Ignition and combustion properties of cokes. Fuel 11, 267-273.

Moreland, A., Patrick, J.W., Walker, A. 1988. Optical anisotropy in cokes from high-rank coals. Fuel 77, 730-732.

Murata, T., 1981. Wettability of coal estimated from the contact angle. Fuel 60, 744-746.

Murchison, D.G., 1966. Properties of coal macerals: infrared spectra of resinites and their carbonized and oxidized products. in R.F. Gould, ed., Coal Science: American Chemical Society Advances in Chemistry Series 55, 307-331.

Mukherjee, P.N., Lahiri, A., 1957. T h e role of moisture in the oxidation of coals at low temperatures. Brennstoff-Chemie 38, 55-58.

Nakayanagi, Y., 1956. Microscopic study of outcrop coal - a microscopic study of the grades of coalification on the weathered coal sampled from outcrops. Journalof Coal Research Institute (Japan), 1, 225-232.

Nandi, B.N., Ciavaglia, L.A., Montgomery, D.S., 1977. The variation of the microhardness and reflectance of coal under conditions of oxidation simulating weathering. Journal of Microscopy 109(1), 93-103.

Neavel, R.C., 1976. Liquefaction of coal in hydrogen-donor and non-donor vehicles. Fuel 55(3), 237-242.

Neavel, R.C., 1982. Coal Plasticity Mechanism: Inference from Liquefaction Studies. In: Gorbaty, M. L., Larsen, J. W., Wender, I., (Eds.) Coal Science; Academic Press: New York, 1982; Vol. 1, 1-19.

Nelson, C.R., 1989. Coal weathering: chemical processes and pathways. Chemistry of coal weathering. In: Nelson, C.R. (Ed.) Coal Science and Technology 14. Elsevier, Amsterdam, pp. 1-32.

Noel, R., 1958. Contribution à l̉̉̉̉ etude des charbons du Congo Belge, Revue Industrie Minérale, Numéro Spécial: 32-40.

Nötzold, E., 1940a. Erforschung der Selbstentzündung der Kohle auf kohlenpetrographischer Grundlage. Glückauf 76(28), 381-389.

Nötzold, E., 1940b. Erforschung der Selbstentzündung der Kohle auf kohlenpetrographischer Grundlage. Glückauf 76(29), 393-397.

Orchin, M., Golumbic, C., Anderson, J.E., Storch, H.H., 1951. Studies of

the extraction and coking of coal and their significance in relation to its

structure. U.S. Bureau of Mines Bulletins 505. 15 pp.

Oreshko, F., 1949. Oxidation of coals. Izvest. Akad Nauk S. S. S. R., Otdel. Tekh. Nauk, p. 249-57; Chemical Abstracts, 1950, v. 44, col. 2200i.

Oreshko, F., 1950. Oxidation of hard coal under nonisothermal conditions: Zhur. Priklad. Khini. (J. Applied Chem.), v. 23, p. 306-16; Chemical Abstracts, 1951, v. 45, col. 2174h.

Osborne, D.G., 1988. Flotation, agglomeration and selective flocculation. Coal Preparation Technology. Graham & Trotman, London, pp. 452-454.

Ota, H., Takarada, T., 2001. Low-temperature oxidation of coal using 18O2 isotope and cakeing property of coal oxidized. Nippon Enerugi Gakkai Sekitan Kagaku Kaigi Happyo Ronbunshu 38: 87-90, (in Japanese).

Painter, P., Rhoads, C., 1981. ACS Division of Fuel Chemistry Preprints, 26(1), 35-41.

Painter, P.C., Snyder, W., Pearson, D.E., Kwong, J., 1980. [Fourier transform infrared study of the variation in the oxidation of a coking coal](http://www.sciencedirect.com/science/article/pii/0016236180902094?_rdoc=1&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231980%23999409994%23447280%23FLP%23display%23Volume)&_docanchor=&_ct=21&_refLink=Y&_zone=rslt_list_item&md5=0bb04320ad000865cf93aca00be77a03). Fuel 59(5), 282-286.

Painter, P.C., Snyder, R.W., Starsinic, M., Coleman, M.M. Kuehn, D.W., Davis, A., 1981. Concerning the application of FT-IR to the study of coal: A critical assessment of band assigmenemts and the applications of spectral analysis programs. Applied Spectroscopy 35(5), 475- 485.

Panaseiko, N.P., 1974. Influence of moisture on the low-temperature oxidation of coals. Solid Fuel Chemistry 8, 21-24. (Translated from Khimiya Tverdogo Topliva 8(1), 26-30).

Pandolfo, A.G., Buchanan, A.S., Johns, R.B., 1995. Chemical changes occurring during aerial oxidation of a bituminous coal. In: Pajares, J.A., Tascon, J.M.D. (Eds.) Coal Science. Elsevier, Amsterdam, p. 477.

Parr, S.W., Francis, C.K., 1908. The Modification of Illinois Coal by Low Temperature Distillation. University of Illinois Engineering Experiment Station, Bulletin No. 24.

Parr, S.W., 1925. Deterioration and spontaneous combustion of coal in storage. Industrial and Engineering Chemistry 17(2), 120-121.

Parr, S.W., Coons, C.C., 1925. Carbon dioxide as an index of the critical oxidation temperature for coal in storage. Industrial and Engineering Chemistry 17(2), 118-120.

Parr, S.W., Milner, R.T., 1925. The oxidation of coal at storage temperatures. Industrial and Engineering Chemistry 17(2), 115-116.

Patrick, J.W., Green, P.D., Thomas, K.M., Walker, A., 1989. The influence of pressure on the development of optical anisotropy during carbonization of coal. Fuel 68(2), 149-154.

Pawlewicz, M.J., Barker, 1989. Vitrinite reflectance of Tertiary coal across the surface of the northern Powder River basin, Wyoming-Montana. 1989 Montana Geological Society Field Conference, 341-351.

Pearson, D.E., Kwong, J., 1979. [Mineral matter as a measure of oxidation of a coking coal](http://www.sciencedirect.com/science/article/pii/0016236179900541?_rdoc=13&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231979%23999419998%23447152%23FLP%23display%23Volume)&_docanchor=&_ct=23&_refLink=Y&_zone=rslt_list_item&md5=7806b79b9bdb9a71edaa1e19e64d122e). Fuel 58(1), 63-66.

Pearson , D.E., Creaney, S., 1981. Reflectance of carbonized vitrinite as a measure of oxidation of a coking coal Fuel. 60(3), 273-275.

Pietrzak, R., Wachowska, H., 2003. [Low temperature oxidation of coals of different rank and different sulphur content.](http://www.sciencedirect.com/science/article/pii/S0016236102003642?_rdoc=11&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%232003%23999179993%23380566%23FLA%23display%23Volume)&_docanchor=&_ct=15&_refLink=Y&_zone=rslt_list_item&md5=8f358def7f1299c1fe85a54d3e47aeb2) Fuel 82(6), 705-713.

Pis, J.J., Cagigas, A., Simon, P., Lorenzana, J.J., 1988. Effect of aerial oxidation of coking coals on the technological properties of the resulting cokes. Fuel Processing Technology 20, 307-316.

Pisupati, S.V., Scaroni, A.W., Stoessner, R.D., 1991. Combustion characteristics of naturally weathered (in situ) bituminous coals. Fuel Processing Technology 28(1), 49-66.

Pisupati, S.V., Scaroni, A.W., 1993. Natural weathering and laboratory oxidation of bituminous coals: organic and inorganic structural changes. Fuel 72(4), 531–542.

Pisupati, S.V., Scaroni, A.W., Hatcher, P.G., 1993. Devolatilization behaviour of naturally weathered and laboratory oxidized bituminous coals. Fuel 72(2), 165-173.

Podgajni, O.A., 1961. Beitrag zur petrographischen Untersuchung oxidierter Kohlen. Bulletin/ Institute for Geological and geophysical Research, Belgrade, 19, 267-276.

Prado, J.G., 1972. Microscopia de carbones oxidados. PhD Thesis. University of Oviedo, Spain, pp. 150.

Prado, J.G., 1977, Optical properties of oxidized vitrinite and exinite. Journal of Microscopy 109(1), 85-92.

Quick, J.C., Davis, A., Lin, R., 1988. Recognition of reactive maceral types by combined fluorescence and reflectance microscopy. Proceedings Ironmaking Conference 47, 331-337.

Qian, Z., Marsh, H., 1984. The co-carbonization of oxidized coals with pitches and decacyclene. Fuel 63(11), 1588-1593.

Radspinner, J.A. Howard, H.C., 1943. Determination of surface oxidation of bituminous coal. Journal of Industrial and Engineering Chemistry: 15th Analual Edition, 566-570.

Rees, O.W., Coolican, F.C., Pierron, E.D., Beeler, C.W., 1961. Effects of outdoor storage on Illinois steam coals. Illinois State Geological Survey Circular 313, 10 p.

Rhoads, C.A., Senftle, J.T., Coleman, M.M., Davis, A., Painter, P.C., 1983. Further studies of coal oxidation. Fuel 62(12), 1387–1392.

Roy, M.M., 1965. Studies on coal macerals. III. Aerial oxidation of macerals. Economic Geology 60(6), 1213-1217.

Ruiz, B., Parra, J.B., Pajares, J.A., Pis, J.J., 2001. Study of porous development in pyrolysis chars obtained from a low volatile coal. Journal of Analytical and Applied Pyrolysis 58-59, 873-886.

Ruiz, B., Parra, J.B., Pajares, J.A., Pis, J.J., 2006. Effect of coal pre-oxidation on the optical texture and porosity of pyrolysis chars. [Journal of Analytical and Applied Pyrolysis](http://www.sciencedirect.com/science/journal/01652370) 75(1), 27-32.

Sánchez, A.E., Rincón, J.M., 1997. Oxidation paths of a coking coal and comparison of its oxidized product with a non-caking coal. Fuel 76(2), 1137-1142.

Savage, W.H.D., 1951. Weathering tests on coking coals. Report No. 2. Fuel Research Institute of South Africa.

Schmal, D., 1989. Spontaneous heating of stored coal. In: Nelson, C.R. (Ed.), Chemistry of coal weathering. Elsevier, Amsterdam, pp.133-215.

Schmidt, L.D., Elder, J.L., 1940. Atmospheric oxidation of coal at moderate temperatures. Industrial and Engineering Chemistry 32, 249-256.

Schmidt, L.D., 1945. Changes in coal during storage. In Lowry, H.H. (Ed.) Chemistry of coal utilization. Volume 1. New York, John Wiley and Sons, Inc., p. 627-676.

Seki, H., Ito, O, Lino, M., 1990. Effect of mild oxidation of bituminous coals on caking properties. Fuel 69(3), 317-321.

Sen, R. Sricastava, S.K., Singh, M.M., 2009. Aerial oxidation of coal-analytical methods, instrumental techniques and test methods: a survey. Indian Journal of Chemical Technology 16, 103-135.

Senftle, J.T., Davis, A., 1984. Effect of oxidative weathering on the thermoplastic and liquefaction behaviors of four coals. International Journal of Coal Geology 3(4), 375-381.

Seyler, C.A., 1938. The past and future of coal — the contribution of petrology. Proceedings of the South Wales Institute of Engineers 63, 213-243

Smith, A.C., Lazzara, C.P., 1987. Spontaneous combustion studies of U.S. coals. Repot of Investigation No. 9079, US Bureau of Mines, Pittsburgh pp. 16-18.

Smith, J.W., Ahmed, M., Phan, D., 2001. Reactions accompanying loss of coking ability during the aerial oxidation of coal. Organic Geochemistry 32(10), 1233-1240.

Sommers, H., Peters, W., 1954. Die Kinetik der Kohlenoxidation bei mäßigen Temperaturen. Chemie Ingenieur Technik 26, 441-453.

Stach, E., Mackowski, M.-Th., Teichmüller, M., Taylor, G.F. Chandra D., Teichmüller, R., 1975. Stach's Textbook of Coal Petrology. 2nd edition. Gebrüder Borntraeger, Berlin pp. 428.

Stach, E., Mackowsky, M.-Th., Teichmiiller, M., Taylor, G.H., Chandra, D., Teichmiiller, R., 1982. Coal Petrology. 3rd edition. Borntraeger, Berlin, 535 pp.

Stopes, M.C., Wheeler, R.V., 1923a. The spontaneous combustion of coal in relation to its composition and structure. Fuel 2, 29-41.

Stopes, M.C., Wheeler, R.V., 1923b. The spontaneous combustion of coal in relation to its composition and structure. Fuel 2, 83-92.

Stopes, M.C., Wheeler, R.V., 1923c. The spontaneous combustion of coal in relation to its composition and structure. Fuel 2, 122-132.

Stopes, M.C., Wheeler, R.V., 1924. The spontaneous combustion of coal. Colliery Guardian, London, pp. 125.

Suárez-Ruiz, I., Ward, C.R., 2008. Basic factors controlling coal quality and technological behavior of coal, in I. Suárez-Ruiz and J.C. Crelling, eds., Applied coal petrology: the role of petrology in coal utilization: New York, Academic Press, p. 19-59.

Swann, P.D., Evans, D.G., 1979. [Low-temperature oxidation of brown coal. 3. Reaction with molecular oxygen at temperatures close to ambient](http://www.sciencedirect.com/science/article/pii/0016236179901364?_rdoc=7&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231979%23999419995%23447154%23FLP%23display%23Volume)&_docanchor=&_ct=17&_refLink=Y&_zone=rslt_list_item&md5=fb354eca717bf4c78be613f14d29200d). Fuel 58(4), 276-280.

Szadeczky-Kardoss, E., 1944. Spontaneous combustion and decomposition of coal from a petrographic point of view. Banayasz. es Kohasz., Lapok, 77: 241-247; 253-260. Chemistry Abstracts 1948, vol. 42, col. 2084a.

Taylor, S.R., Miller, K.J., Deurbrouck, A.W., 1981. Surface chemical problems in coal flotation. In: B.R. Cooper and L. Petrakis (Editors), Chemistry and Physics of Coal Utilization-1980. American Institute of Physics, New York, N.Y., pp. 344-356.

Taylor, G.H., Teichmülller, M., Davis, A., Diessel, C.F.K., Littke, R., Robert, P., 1998. Organic Petrology, Gebruder Borntraeger, Berlin, page 198.

Teo, K.C., Finora, S., Leja, J., 1982. [Oxidation states in surface and buried coal from the Fording River Deposit](http://www.sciencedirect.com/science/article/pii/0016236182902952?_alid=1788951401&_rdoc=4&_fmt=high&_origin=search&_docanchor=&_ct=4&_zone=rslt_list_item&md5=1025deb6246f1c178ba073cfb6edcb1b). Fuel 61(1), 71-76.

Teichmüller, M., Teichmüller, R., 1948. Das Inkohlungsbild des Niedersächsischen Wealden-Beckens. [Zeitschrift der Deutschen Gesellschaft für Geowissenschaften](http://www.schweizerbart.de/journals/zdgg) 100, 498-517.

Teichmüller, M., Teichmüller, R., 1950. Das Inkohlungsbild des niedersaechsischen Wealden-Beckens. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften. 100, 498-517.

Thomas, K.M., Tytko, A.P., Mulligan, M.J., Green, P.D., 1992. The effect of oxidation on the thermoplastic and coking properties of coal at elevated pressures. Fuel 71(2), 169-181.

Thompson, R.R. 2000. History of applied coal petrology in the United States: III. Contributions to applied coal and coke petrology at the Bethlehem Steel Corporation. [International Journal of Coal Geology](http://www.sciencedirect.com/science/journal/01665162) 42(2-3), 115-128.

Tideswell, F.V., Wheeler, R.V., 1920.Oxidation of banded bituminous coal. Transactions of Chemical Society 117, 794-801.

Valentim, B., Lemos de Sousa, M.J., Albelha, P., Boavida, D., Gulyurtlu, I., 2006. The identification of unusual microscopic features in coal and their derived chars: Influence on coal fluidized bed combustion. International Journal of Coal Geology 67(3), 202-211.

Valia, H.S., 1990. Effects of coal oxidation on cokemaking. Proceedings Ironmaking Conference, 49, 199-209.

Valceva, S.P., Markova, K.I., Rouschev, D.D., Bekyarova, E.E., 1976. Oxidation of petrographic ingredients of lignite and its inhibition with phenol. Fuel 55(3), 173-176.

van Krevelen, D.W., 1961. Coal: typology-chemistry-physics-constitution. Elsevier, Amsterdam. pp. 514.

Van Krevelen, D.W., 1981. Chemistry of coal weathering and spontaneous combustion, in Coal: typology - chemistry - physics - constitution: New York, Elsevier Scientific Publishing Company, pp. 238-262.

Van Krevelen, D.W., 1982. Development of coal research – a review. Fuel 61(9), 786-790.

Van Krevelen, D.W., 1993. Coal: Typology–Physics–Chemistry–Constitution, 3rd edn. Elsevier, Amsterdam, 979 pp.

Van Krevelen, D. W., and Schuyer, J., 1957, Coal Science: Aspects of Coal Constitution. New York, Elsevier, 352 p.

Vessey, S.J., Bustin, R.M., 1999. Coalbed methane characteristics of the Mist Mountain Formation, southern Canadian Cordillera: effect of shearing and oxidation, in M. Mastalerz, M. Glikson, and S.D. Golding, eds., Coalbed methane: scientific, environmental and economic evaluation: Boston, Kluwer Academic Publishers, p. 367-384.

Wachowska, H.M., Nandi, B.N., Montgomery, D.S., 1974. [Oxidation studies on coking coal related to weathering. 4. Oxygen linkages influencing the dilatometric properties and the effect of cleavage of ether linkages](http://www.sciencedirect.com/science/article/pii/0016236174900143?_rdoc=14&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%231974%23999469996%23447073%23FLP%23display%23Volume)&_docanchor=&_ct=20&_refLink=Y&_zone=rslt_list_item&md5=e715966ae5ed3e376a8cff6c433f1c8b). Fuel 53(3), 212-219.

Wagner, N.J., 1998. The effect of weathering on stored discard coals and the impact on combustion. Unpublished PhD Thesis, University of the Witwatersrand, South Africa.

Wagner, N.J., 2007. The abnormal condition analysis used to characterize weathered discard coals. International Journal of Coal Geology 72(3-4), 177-186.

Walker, I.K., 1967. The role of water in spontaneous combustion of solids. Fire Research Abstracts and Reviews 9(1), 5-22.

Walker, S., 1999. Uncontrolled fires in coal and coal wastes. International Energy Agency,London Report CCC/16, pp. 72.

Wang, H., Dlugogorski, B.Z., Kennedy, E.M., 2003. Role of inherent water in low-temperature oxidation of coal. Combustion Science and Technology 175(2), 253-270.

Wang, W., Qin, Y., Sang, S., Jiang, B., Yingming, Z., Guo, Y., 2007. [Sulfur variability and element geochemistry of the No. 11 coal seam from the Antaibao mining district, China](http://www.sciencedirect.com/science/article/pii/S0016236106003619?_rdoc=20&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235726%232007%23999139994%23640184%23FLA%23display%23Volume)&_docanchor=&_ct=36&_refLink=Y&_zone=rslt_list_item&md5=84b961dc35a11d7c7e5fc0419a203a3f). Fuel 86(5-6), 777-784.

Wen, W.W., Sun, S.C., 1976. An electrokinetic study of the amine flotation of oxidized coal. SME-AIME Fall Meeting and Exhibit on World Mining and Metals Technology, Denver, Colorado,01-03 September 1976, pp. 1-3.

Wender, I., Heredy, L.A., Neuworth, M.B. Dryden, I.G.C., 1981. Chemical Reactions and the Constitution of Coal. In: M. A. Elliott, (Ed.) Chemistry of Coal Utilization, Second Supplementary Volume, New York, John Wiley and Sons Inc., p. 425-495.

Wheeler, R.V., Woolhouse, T.G., 1932. Effect of oxidation on co

king properties of coal. Fuel 11, 44-55.

Whitehurst, D.D., Mitchell, T.O., Farcasiu, M., 1980. Coal liquefaction. The chemical and technology of thermal processes. Academic press, New York, 378 pp.

Worasuwannarak, N., 2002. Effect of pre-oxidation at low temperature on the carbonisation behaviour of coal. Fuel 81(11-12), 1477-1484.

Wu, M.M., Winschel, R.A., 1986. The effects of low-temperature weathering on flotation and thermoplastic properties of coal. Proceedings of the 3rd Annual Pittsburgh Coal Conference, Pittsburgh, Pennsylvania, 08-10 September 1986, pp. 591-607.

Wu, M.M., Robbins, G.A., Winschel, R.A., Burke, F.P., 1987. The effects of weathering on flotation and thermoplastic properties of coal. American Chemical Society, Division of Fuel Chemistry 32(1), 408-416.

Wu, M.M., Robbins, G.A., Winschel, R.A., Burke, F.P., 1988. [Low-temperature coal weathering: its chemical nature and effects on coal properties](http://pubs.acs.org/doi/abs/10.1021/ef00008a009?prevSearch=%2528Winschel%2529%2BNOT%2B%255Batype%253A%2Bad%255D%2BNOT%2B%255Batype%253A%2Bacs-toc%255D&searchHistoryKey=). Energy and Fuels 2(2), 150-157.

Yohe, G.R., 1958. Oxidation of coal. Illinois State geological Survey. Report of investigations 207, p. 51.

Yokono, T., Marsh, H., Yokono, M., 1981a. Carbonisation and liquid-crystal (mesophase) development. 19. Co-carbonisation of oxidized coals with model organic compounds. Fuel 60(6), 507-512.

Yokono, T., Miyazawa, K., Sanada, Y., Marsh, H., 1981b. Nuclear magnetic proton relaxation studies of oxidised coals. Fuel 60(7), 598-602.

Yun, Y., Meuzelaar, H.L.C., 1991. [Development of a reliable coal oxidation (weathering) index - Slurry pH and its applications](http://www.sciencedirect.com/science/article/pii/037838209190100Q?_rdoc=5&_fmt=high&_origin=browse&_srch=doc-info(%23toc%235243%231991%23999729997%23444156%23FLP%23display%23Volume)&_docanchor=&_ct=7&_refLink=Y&_zone=rslt_list_item&md5=7acd1c66f3d8b23252464ee16296b3b3). Fuel Processing Technology 27(2), 179-202.

Zhang, Y. Wu, J., Chang, L., Wang, J., Xue, J., Li, Z. 2013. Kinetic and thermodynamic studies on the mechanism of low-temperature oxidation of coal: A case study of Shendong coal (China). International Journal of COal Geology 120, 41-49.

Zelkowski, J., 2004. Kohlecharakterisierung und Kohleverbrennung. 2 Auflage. Essen, VGB PowerTech e.V. Essen, VGB - B 008.

Zimmerman, R.E., 1968. Wet concentration of fine coal. Part 3. Froth flotation. In: J.W. Leonard and D.R. Mitchell (Editors), Coal Preparation. American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, N.Y. pp. 10-66 to 10-90.