Strategies for preventing Spontaneous Combustion of Coal Cargos carried at Ports & Shipping

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Abstract

Coal is the world’s most plentiful fossil fuel which has been burned for centuries as a source of heat and energy. For more than 100 years coals have been shipped in bulk by ships. It is expected that the worldwide coal consumption to grow by more than 40 per cent between 2001 and 2025. Nowadays, coals are shipped in bulk every year across the oceans of the world. While the vast majority of these shipments are made without incident, there have been a number of serious casualties which resulted not only in the loss of the ship but also in loss of life. The most important hazards regarding is self-heating. The fire incidents involving coal cargoes have been serious problematic for centuries. It was a much-feared hazard in the days of wooden sailing ships, and has continued on since the advent of modern ships. This paper inspects the spontaneous combustion of coal and provides appropriate strategies to reduce and prevent this risk in maritime transportation.

Keywords: Coal, spontaneous combustion, IMO regulation, port, shipping

Introduction

Originally coal was used as a source of heat and powers at homes and industries. During 1950s and 1960s cheap oil curtailed the growth of the coal use, but uncertainties of oil supply in 1970s led to a resumption in coal consumption and a rapid growth in international coal [1]. Today coal accounts for 25% of the global primary energy and 40% of the global electricity production [2].

In total, coal is used in four possible ways:

- As a primary input to produce electricity or a secondary/tertiary fuel that is used elsewhere or sold - this is referred to as use in the Transformation Sector; e.g., coking coal used to produce coke in a coke oven, steam coal used to produce electricity
- As a fuel used to support (but not used in) a transformation process - this is referred to as use in the Energy Sector; e.g., coke oven gas used to heat the coke oven, steam coal used to operate the power plant
- As a fuel consumed in manufacturing industry, mining and construction, in transport, in agriculture, in commercial and public services and in households - this is referred to as use in the Final Consumption Sectors; E.g. steam coal used to produce heat in cement kilns, steam coal used to produce industrial process steam
- As a raw material - this is referred to as non-energy use, e.g. Coal used to produce carbon electrodes for the aluminum industry [3].

In Iran, as we are one of the world’s top producer of oil and gas the use of coal as fuel is about 1% of total energy consumption (fig 1). The main consumption of coal in Iran belongs to the steel manufacturing sector.

Figure 1: Iran’s total energy consumption share by fuel, 2010[4]

Coal is the dangerous cargo to keep and transport. The most important danger that the maritime world encounter related to coal is spontaneous combustion. It is consider that spontaneous combustion is the cause of 14 percent of the fires of coal cargoes, and the risk becomes greater with broken coal, in either transit or loading [5].

Spontaneous combustion is the process of self-heating of coal by oxidation of exposed coal surfaces which occurs at or near ambient temperature producing heat energy. On exposure to air, coal undergoes a continuous oxidizing reaction. A hazard exists when the rate of heat production by this exothermic reaction exceeds the rate of cooling, produced mainly...
by the convective effects of air. The coal can then increase in temperature until combustion takes place. This paper describes the mechanism of spontaneous combustion then reviews the relevant rules on marine transportation of coal and finally investigating implementation of new strategies in ports to reduce the coal’s spontaneous combustion.

MECHANISM OF SPONTANEOUS COMBUSTION

When coal is exposed to air it absorbs oxygen at the imposed surface. Some fractions of the exposed coal substance absorb oxygen at a faster rate than others and the oxidation results in the formation of gases, mainly CO, CO₂ and water vapor along with evolution of heat during the chemical reaction. The process takes place even at normal atmospheric temperature but it is slow and the heat evolved is not perceptible as it is carried away by the air unless the latter is stagnant. If, however, the rate of dissipation of heat is slow compared with the evolution of heat by oxidation, there is a gradual build-up of heat and slow rise in the temperature of coal. At the raised temperature the process of oxidation is slightly accelerated and some other fractions of coal become susceptible to oxidation. A stage is reached when the build-up of heat and the rise of temperature reaches the ignition point of coal which then catches fire. A good air current will effectively prevent undue increase of temperature; absence of air will prevent oxidation; and somewhere between these two extremes conditions may permit marked heating to take place. Once the coal reaches its ignition point (as distinct from slow oxidation), the air supply to it will only increase the combustion. The ignition temperature of bituminous coal is nearly 200°C and of anthracite coal, nearly 398°C. The coal may be smoldering in the beginning but it may soon break up into flames if sufficient oxygen or fresh air feeds the hot coal. This process of self-heating of coal resulting ultimately in its combustion is known as spontaneous combustion. The different stages in which this process continues is shown below:

![Figure 2: Stages in spontaneous heating of coal](image)

FACTORS AFFECTING SPONTANEOUS HEATING OF COAL

The main reason for the difficulties in understanding the mechanism of spontaneous combustion is the presence of many internal and external factors affecting the initiation and development of the phenomenon (Table 1). These factors have been reviewed by various researchers (Kroger and Beier, 1962; Guney, 1968; Chamberlain and Hall, 1973a; Feng et al., 1973; Beier, 1973; Kim, 1977; Banerjee, 1982; Didari, 1988; Goodarzi and Gentzis, 1991; Didari and Ökten, 1994). The main factors which have significant effects on the process are summarized below:

<table>
<thead>
<tr>
<th>Table 1: Factors affecting spontaneous combustion of coal [7].</th>
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</thead>
<tbody>
<tr>
<td><strong>Comparatively accelerated oxidation (up to 80°C)</strong></td>
</tr>
<tr>
<td><strong>Evolution of oxides of carbon (up to 180°C)</strong></td>
</tr>
<tr>
<td><strong>Active combustion leading to ignition (beyond 275°C)</strong></td>
</tr>
<tr>
<td><strong>Self-sustained process of combustion (up to 275°C)</strong></td>
</tr>
<tr>
<td><strong>Steady-state oxidation due to removal of moisture (up to 120°C)</strong></td>
</tr>
<tr>
<td><strong>Very slow oxidation (up to 50°C)</strong></td>
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<tr>
<td><strong>Coal + oxygen</strong></td>
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<tr>
<td><strong>Thermal decomposition (up to 220°C)</strong></td>
</tr>
</tbody>
</table>

Figure 2: Stages in spontaneous heating of coal [6]
<table>
<thead>
<tr>
<th>Intrinsic Factors</th>
<th>Extrinsic Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Nature of Coal)</td>
<td>(Atmospheric, Geological, and Mining Conditions)</td>
</tr>
<tr>
<td>Pyrites</td>
<td>Temperature</td>
</tr>
<tr>
<td>Moisture</td>
<td>Moisture</td>
</tr>
<tr>
<td>Particle size and surface area</td>
<td>Barometric pressure</td>
</tr>
<tr>
<td>Rank and petrography constituents</td>
<td>Oxygen concentration</td>
</tr>
<tr>
<td>Chemical constituents</td>
<td>Bacteria</td>
</tr>
<tr>
<td>Mineral matter</td>
<td>Coal seam and surrounding strata</td>
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<tr>
<td></td>
<td>Method of working</td>
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<td></td>
<td>Ventilation system and air flow rate</td>
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<td>Timbering</td>
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<td>Roadways</td>
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**Regulation of IMO for the safe carriage of coal**

Self-igniting coal has changed the course of history and the demographics of the maritime industry. It led to the explosion of the USS Maine in Havana harbor in 1898 at the Spanish-American War and continues to be a great hazard today. The incidents related to spontaneous combustion of coals asked for a harmonized industry-wide reaction to prevent such mishaps. The result was adoption of regulation by the IMO for the safe carriage of coal by ships. During the course of time this regulation proved to be inadequate thus IMO revised and amended it several times. The current detailed recommendations for the safe carriage of coal are contained in Appendix 1 of the International Maritime Solid Bulk Cargoes (IMSBC) Code [8], which became mandatory worldwide on 1 January 2011. The code should be a familiar reading for all deck officers serving on bulk carriers and other types of ship that carry bulk cargoes, even if only occasionally.

Risk of spontaneous combustion of coal led to IMO provides regulations for reduction the risk in the marine transportation. This section reviews regulation related to maritime transport of coal. Carriage of coal at sea. During a voyage When coal cargo start to oxidize, it spontaneously generates heat and toxic gases such as carbon monoxide. This may lead to a flammable atmosphere in the hold, depletion of oxygen in those spaces and corrosion of metal structures. Thus monitoring of coal cargo during the voyage is an important task that should be done.

**Cargo monitoring during the voyage**

Based on the IMSBC code the following cares must be taken during the voyage when carrying coal:

1. Monitoring the hold atmospheres for methane, carbon monoxide, and oxygen at least once a day more frequently if the carbon monoxide and/or methane concentrations begin to rise steadily. Maintain a proper record of these measurements.
2. a reduction of the oxygen concentration in a well-sealed hold is to be expected.
3. Below an oxygen concentration of about 10%, most instruments in common use will not provide reliable readings of the methane %LEL. (Check your instrument manufacturer’s recommendations on the use of a ‘splitter’ at low oxygen levels and/or seek expert advice if there is cause for concern)

4. Temperatures measured by lowering thermometers into sounding pipes may be useful in general terms but should not be relied upon to reflect any changes occurring in the bulk of the cargo as temperature monitoring via sounding pipes will only detect heating coal in the immediate vicinity and will not provide information on the bulk of the cargo

5. If methane in excess of 20% of the LEL is detected; use surface ventilation in accordance with the Code but only for the minimum time necessary to remove the methane. If this concentration of methane is detected after the oxygen has fallen below 10%, seek expert advice before ventilating

6. If carbon monoxide concentration in a closed cargo hold exceeds 30ppm; the Code recommends that the frequency of measurement is increased to twice daily. If the carbon monoxide exceeds 50ppm the Code recommends the owner should be notified to call for expert advice. With Indonesian coal the carbon monoxide level can be significantly higher than these values without indicating the presence of self-heating but the owner should still be notified.

   The upper guidelines emphasize the monitoring and control of cargo temperature during voyage as it is fluctuating. Finally the special precautions relate to coals emitting methane and self-heating coals are followed:

   1. If the shipper has advised that the cargo is liable to self-heat, the master should seek confirmation that the precautions intended to be taken and the procedures intended for monitoring the cargo during the voyage are adequate.

   2. If the cargo is liable to self-heat or analysis of the atmosphere in the cargo space indicates an increasing concentration of carbon monoxide, then the following additional precautions should be taken:

      2.1. The hatches should be closed immediately after completion of loading in each cargo space. The hatch covers can also be additionally sealed with a suitable sealing tape. Surface ventilation should be limited to the absolute minimum time necessary to remove methane which may have accumulated. Forced ventilation should not be used. On no account should air be directed into the body of the coal as air could promote self-heating.

      2.2. Personnel should not be allowed to enter the cargo space, unless they are wearing self-contained breathing apparatus and access is critical to the safety of the ship or safety of life. The self-contained breathing apparatus should be worn only by personnel trained in its use (see also section 3 and appendix F).

      2.3. When required by the competent authority, the carbon monoxide concentration in each cargo space should be measured at regular time intervals to detect self-heating.

      2.4. If at the time of loading, when the hatches are open, the temperature of the coal exceeds 55°C, expert advice should be obtained.

      2.5. If the carbon monoxide level is increasing steadily, a potential self-heating may be developing. The cargo space should be completely closed down and all ventilation ceased. The master should seek expert advice immediately. Water should not be used for cooling the material or fighting coal cargo fires at sea, but may be used for cooling the boundaries of the cargo space.

      2.6. Information to be passed to owners.

   The most comprehensive record of measurements will always be the log used to record daily results. The coal cargo monitoring log for the voyage should be communicated to the vessel’s owners.

   The following minimum information is essential if an accurate assessment of the situation is to be achieved.

   (a) Identity of the holds involved; monitoring results covering carbon monoxide, methane and oxygen concentrations;

   (b) If available, temperature of coal, location and method used to obtain results;

   (c) Time gas samples taken (monitoring routine);

   (d) Time ventilators opened/closed;

   (e) Quantity of coal in hold(s) involved;

   (f) Type of coal as per shipper’s declaration, and any special precautions indicated on declaration;

   (g) Date loaded, and ETA at intended discharge port (which should be specified); and

   (h) Comments or observations from the ship’s master.

   All aspects of shipping receive considerable attention toward safety of carriage of coal at sea. In the last decades, maritime industry have seen more and more legislations promulgated with relation to the safe carriage of coal but still there are incidents. It well known that approximately80% of accidents caused by human (i.e. seafarers and other crew of ships). To solve this problem and to reduce accidents and for efficient implementation of the rules, the modern technology is used. In the following, a summary of this methods and technologies is going to be discussed.
MANAGEMENT PRINCIPLES

The basic process to be followed with any coal material, and particularly with coals suspected of being liable to self-heating, can be categorized in three basic areas namely: Prevention, Detection, and Control.

In this paper we elaborate on the main strategies that needed to be taken for implementation of these factors.

IMPLEMENTATION STRATEGIES

In this section we discuss the management principles in detail.

Prevention

Spontaneous combustion is a time dependent phenomenon. Early attention to potential sources of problems may well prevent occurrences.

1. Tailings

Tailings dams should be capped with at least one meter of inert (non-carbonaceous) material, top soiled.

2. Coarse reject

Problem material should be placed in layers and compacted using a roller, particularly on the edges of the dump, so that infiltration of oxygen is minimal. The total layer thickness should be no greater than 5 meters and each layer should be covered by a one meter thick layer of inert (non-carbonaceous) material. The final landform should be such that erosion and runoff is minimized and new areas of coal are not exposed to the atmosphere. Short living trees (Such as wattle) should not be planted where roots will penetrate the material as, following the tree’s death, the roots will rot and leave airways into the Spoil heap. Coal reject should not be used in the construction of dam walls when such material has a potential for spontaneous combustion.

3. Spoil

Accumulations of coal material, particularly if pyritic, should be buried under inert spoil.

4. Product Coal

Product stockpiles should not be left longer than the incipient heating period. An indication of the length of this period can be obtained from specific test work. Both Run of Mine (RoM) and saleable product coal have been known to be susceptible to spontaneous combustion. Particular caution should be taken.

Where there is segregation of material sizes due to the stockpiling/dumping technique. A layer/fringe of coarser particles at the base and edges of stockpiles allows enhanced ventilation. The situation is particularly aggravated by prevalent hot, moist winds in a favorable direction. Stockpile/dump shape and orientation may then become important issues. The height of stockpiles and dumps may also be a critical site-specific consideration. When the technique is feasible, considerable benefit can be obtained by building dumps in relatively thin compacted layers. Longer term stockpiles, particularly of product coal, can be further safeguarded by spraying the surfaces within a thin (bituminous) coating to exclude air.

Open Cut Coal Faces

Coal spilling from the coal face should not be allowed to remain against the face. If the coal is liable to spontaneous combustion, loose coal should be cleared away and/or the face buttressed with spoil material if it is to be left for an extended period. At the end of the mine life such coal faces should be effectively sealed with water, clay or thick blanket of inert spoil.

Detection

Spontaneous combustion fires may be detected fairly early in their development, i.e. before the obvious smoke and/or flame. Any of the following may assist in early detection, depending upon the particular circumstances:

Temperature Difference

Heat haze and ‘steam’ plumes may be observed on cold mornings and in times of high humidity. ‘Hot spots’ may also be detected by infrared monitoring instruments or photography. Routine surveying of stockpiles using infrared scanning devices is a wise precaution in situations where spontaneous combustion may be likely to occur. Efflorescence due to decomposition of pyrites and sublimation of sulphur is a strong indication of heating in pyritic (high sulphur) coals.

Smell

Mine fires are readily recognizable by their distinctive smell. Oxidation of the coal causes the release of large volumes of noxious and flammable gases which in themselves may also represent a hazard, due to asphyxiation, poisoning or fire/explosion.
Notable toxic gases include: Sulphur Dioxide (SO₂), Oxides of Nitrogen (NOₓ), Hydrogen Sulphide (H₂S), and Carbon Monoxide (CO) of which the latter two are also flammable. The gases that are most likely to be present during a heating and that are flammable are: Methane (CH₄), Hydrogen (H₂), and Carbon Monoxide (CO) [9].

**Control**

Effective control of spontaneous combustion may often be achieved by use of a combination of the following techniques.

**Mill Fire Detector**

Monitors the levels of carbon monoxide inside the mill and storage silos. A rapid rise in the levels indicates that combustion is underway. If CO levels reach the pre-set limits then alarms are triggered and preventative action can be taken before a fire starts or an explosion occurs. Fires and explosions can lead to mills having to be replaced, surroundings being repaired (or replaced) and extensive amounts of downtime. The mills reject box should also be monitored.

**Coal Pile Fire Detector**

Storing coal in large piles has the inherent risk of spontaneous combustion. There are many industry guidelines to the best method for storing coal in piles. These guidelines include: Avoidance of spontaneous combustion with regard to pile angles, compression and surface smoothing. Even strict adherence to these guidelines (particularly with the more volatile coals) may in some circumstances not be enough. An early warning system to prevent the onset of fire remains the best and most reliable solution.

**Portable Thermal Imager**

Thermal imaging has multiple uses around any coal handling or processing plant. Checking the thermal integrity of the bunker or silo for insulation failures is only one application. Where there is the potential for over-heating and damage as a result, a high resolution thermal image provides the best possible early indication.

**Conveyor Fire Detector**

A scanning temperature measurement system which looks at the entire width of the conveyor at any one time is an ideal solution. It scans at a wide angle (the entire conveyor width), at high Speed and with a fast response. Every hot spot can be detected as the all surface coal is viewed. The scanner outputs the hottest temperature on the conveyor directly to a suitable customer Alarm system.

**Railcar Fire Detector**

The system scans the coal as it drops from the railcar through under-track grates into a storage hopper (track hopper). Any hotspot or smoldering coal is detected and fire prevention action can be taken. As each rail car arrives at the plant and unloads the coal, the curtain of falling coal is Temperature checked using an infrared temperature scanner. This is located trackside and mounted horizontally to view the passing coal as it leaves the railcar. Any hot spots are picked up and used to trigger alarms to prevent widespread fire in the storage hopper or the subsequent conveyor system.

**IR Coal Fire Monitor**

While carbon monoxide (CO) detection offers an earlier warning, infrared thermometry can provide a low cost alternative in the bunker/hopper and the mill reject box. The thermometer can be mounted to view the coal inside the hopper/bunker and give a rapid indication of temperature rise - a warning that fire is imminent. Where thermocouples are used in the reject box, the thermometer is a real alternative, with faster response and greater longevity.[10]

**Conclusion**

Coal is very liable to spontaneous heating when carried at sea. If there is sufficient oxygen available in holds combustion is likely to take place. The amount of heating that takes place depends on the type of coal and how much heat can be dispersed by ventilating the coal. It is consider that spontaneous combustion is the cause of 14 percent of the fires in coal cargoes, and the risk of explosion becomes greater with broken coal, in either transit or loading. The IMO
code provides one of the best guidelines for preventing coal related incidents but as we discussed in this paper managing the implementation of the code is the key factor to prevent incidents/fire… It worth noting that recent Sinking of 60,000 DWT coal carrier that occurred near Mumbai due to penetration of water into her holds in 2011 is an example which shows us that the Self heating although the most important but is not the only danger related to carrying coal.

Reference