CAUSES OF SELF HEATING AND SPONTANEOUS COMBUSTION IN COAL

Rosemary Falcon
February 2014
Contents

1. Significance of Self heating
2. Mechanisms of self heating
3. Inherent Factors
4. External Factors
5. Conclusions
SIGNIFICANCE OF SELF HEATING

Self heating leading to spontaneous combustion has long been known.

It occurs in mines, on seam faces, in underground pillars, in shallow seams, in stockpiles, shipments, train loads, silos and ducts.

All coals are liable to self heating but not all coals do, in fact, do so.

It is responsible for millions of rands worth of damage annually and, in certain circumstances, has lead to serious ill health and death. Now serious emissions are being considered too.

Shipping companies have long been aware of the dangers and a safety protocol (Code of Practice) has been in place for some time.

Guidelines for stockpile management have been compiled.

Banks funding new mines are also beginning to ask for risk assessments.
Severity of the cases at sea

Deaths
• 2 deaths in Suez Canal – 3 weeks at sea – ex Maputo
• 5 deaths off Cape Town (US Shipment of coke for Far East)
• 16 deaths of Port Elizabeth – ex Richards Bay
• and others (one recently)

Damaged beyond repair
• 1 ship due to be scuttled at sea, all holds burning

Costs
• Hundreds of millions of dollars to date (e.g. 1 ship in 1990 – 18 legals in
  3 teams, 6 million US dollars, 19 months to complete)

Nature and source of the cargos
• Coking coal
• Thermal coal
• Coke (Chinese)

Countries of origin
• South Africa, USA, Colombia, Venezuela, Indonesia, China

Consequences
IMO SAFETY COMMITTEE
Increasing Asian demand for High Grade Steam coal will stimulate ‘new’ flows, for High Grade Steam coal.

South African High Grade Steam Coal exports (14% ash) to Europe are declining.

Approximately 20% of SA export steam goes to the EU – down from 88%.

>60% of SA export steam coal now goes to the Far East.
Since 1990, 25 hot coal shipping incidents have been investigated, 9 resulting in costly arbitrations in Europe.

25 hot coal shipment cases in 11 years 1990-2001 – and still on-going
BURNING DUMP – SEEN FROM HELICOPTER
STOCKPILES AT COAL MINE
A huge stockpile of burning coal –R4 million insurance claim for each of two stockpiles; both 250 000 tons)
STOCKPILES AT PORT
Burnt-out stockpile area (NB: damaged side wall tiles)
Damaged tiles from fire in the stockpile at port
Damaged tiles from fire in the stockpile
Burnt out front-end loader from fire in a stockpile at port
Contents

1. Significance of Self heating
2. **Mechanisms of self heating**
3. Inherent Factors
4. External Factors
5. Conclusions
FUEL COMBUSTION TRIANGLE

KEY FACTORS FOR SUCCESSFUL COMBUSTION

TEMPERATURE
- External Source (open flame, hot fuel)
- Internal Source (self-heating)

IGNITION COMBUSTION

FUEL
COAL:
- High reactivity
- Medium reactivity
- Low reactivity

OXYGEN
AIR:
- Internal source
- External source

Falcon 1990
CAUSES OF SELF HEATING IN COAL

SELF HEATING LEADING TO SPONTANEOUS COMBUSTION OCCURS AS A RESULT OF

(i) **OXIDATION** AND (ii) **HEATS OF RE-WETTING** OF

COAL PARTICLES AND PYRITE NODULES

---

**Diagram:**

- **OXIDATION**
- **CHEMICAL PROCESS**

\[ C + O_2 \rightarrow CO / CO_2 \]

**Rate of Oxidation is determined by:**
- Availability of \( \text{Air} / O_2 \)
- Nature and extent of surface areas
- Temperature

**Absorption / Chemical Conversion = Energy / T°C**

**In the presence of \( O_2 \) heat process continues**

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Falcon 1990
CAUSES OF SELF HEATING IN COAL

SELF HEATING LEADING TO SPONTANEOUS COMBUSTION OCCURS AS A RESULT OF

(i) **OXIDATION** AND (ii) **HEATS OF RE-WETTING** OF

COAL PARTICLES AND PYRITE NODULES

---

(i) **OXIDATION**

Chemical Process:

\[ \text{C} + \text{O}_2 \rightarrow \text{CO} / \text{CO}_2 \]

Rate of Oxidation is determined by:
- Availability of \( \text{O}_2 \)
- Nature and extent of surface areas
- Temperature

Absorption/Chemical Conversion = Energy / \( T^\circ C \)

Heat Process Continues

(ii) **HEATS OF RE-WETTING**

Physical Process:

Dry Coal \( \rightarrow \) Water \( \leftarrow \)

Source of Moisture:
- Moist/Fresh Coal
- Rain
- Humidity

Adsorption = Energy / \( T^\circ C \)

Once equilibrium (moisture) is achieved, process ceases.

Falcon 1990
**Normal conditions:**
Oxidation — inherent self heating leading to hot spots (normal factors e.g. wind, size segregation; hot climate, etc)

**Inherent capacities of coal to self heat** under standard conditions:
A – Most reactive
to
E - Least reactive
COAL REACTIVITIES OR SHELF LIFE – TRIGGER ACTIONS

COAL ELEVATED TO 50°C THEN TO 80°C

Trigger Mechanisms:

Heats of wetting – re-wetting coal and pyrite (dry-wet interface; oxidised-fresh interface)

Oxidation – coal and pyrite (external heat sources e.g. proximity to boiler room on board ship).

Normal conditions:

Oxidation – inherent self heating leading to hot spots (normal factors e.g. wind, size segregation; hot climate, etc)

Inherent capacities of coal to self heat under standard conditions:

A – Most reactive
deto
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FACTORS THAT INFLUENCE SELF HEATING

Inherent factors within the coal

- **TYPE** - organic matter constitution – maceral type (reactives)
- **GRADE** - inorganic matter constitution – minerals (pyrite, clay)
- **RANK** - level of maturity of coal
- **WEATHERING** - degree of oxidation
- **PARTICLE SIZE** - natural arising fines
**Type of Coal: Organic Matter in the Seam**

- **Seam Coal**
  - **Bright**
  - **Banded**
  - **Dull**
  - **Massive**
    - Conchoidal Dull (Tobanite, Cannel, etc.)

- **Humic Coal**
  - Stratified

- **Sapropelic Coal**
  - Non-stratified

**Macroscopically Defined Terminology**
- **Hand Specimen**
  - Vitrain
  - Clarain
  - Fusain Durain

**Microscopically Defined Terminology**
- **Vitrinite**
  - \( \text{Vitrinite} > 65\% \)
  - \( \text{Vitrinite} < 65\% \)
  - Inertinite \( 17.5\%-55\% \)
  - Liptinite \( < 17.5\% \)

- **Clarite +**
- **Inertite**
  - Inertinite \( < 55\% \)
  - Vitrinite \( < 65\% \)
  - Inertinite \( 17.5\%-25\% \)
  - Liptinite \( < 17.5\% \)

- **Liptite**
  - Liptinite Exinite \( > 25\% \)

**Lithotypes**
- **Micro-lithotypes**
- **Macerals**
COAL TYPE – Organic matter - MACERAL GROUPS

VITRINITE –
HOMOGENOUS AND SMOOTH (V)
Highly reactive

INERTINITE –
FIBROUS WOODY TISSUE (I) – white
Highly inert, unreactive
EFFECT OF MACERALS ON SELF HEATING AND COMBUSTION

INERTINITE
- Slow to oxidise/heat
- Low / no volatiles
- No swelling
- Limited surface area
- Poor ignition
- Slow combustion
- Poor burn-out

VITRINITE
- Fast to oxidise/heat
- Higher volatiles
- Good swelling
- High surface area
- Easy ignition
- Fast burn-out

Internal volatiles breaking through wall, Creating pores in the cenosphere
Vitrinite - Highly porous char - fast burn-out

Inertodetrinite - Mixed char - moderate burn-out

Inert Inertinite - Dense char - long burn-out
Behavour of Coal Types to Low Temperature Oxidation and Self Heating

Raw Coal on Exposure to Air and Heating:

- Rapid Self Heating
  - Highly Porous Char
  - Mixed Char
  - Dense Char
  - Ash-Coated Char
- Slow Self Heating
  - Dilutes, Encapsulates, Reduces Combustion
- Limited to No Self Heating Unless Fragmented and Exposed
RUN-OF-MINE FROM WHOLE SEAM OR SELECTED PARTS OF THE SEAM

Raw product with contamination from roof, floor or partings

- Hanging wall
- Upper dull coal
- Mid-seam parting
- Lower bright coal
- Foot wall

Whole seam mining

Selective mining

Dull coal is inertinite rich and poorly reactive

Bright coal is vitrinite rich and reactive
### WASHED PRODUCTS

*Different products with varying maceral, ash, volatile matter and calorific values*

#### HMS BENEFICIATION PROCESS

<table>
<thead>
<tr>
<th>PRODUCTS</th>
<th>ASH %</th>
<th>VOLATILE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low ash</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>Middlings 1</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>Middlings 2</td>
<td>25</td>
<td>18</td>
</tr>
<tr>
<td>Discard</td>
<td>75</td>
<td>10</td>
</tr>
</tbody>
</table>

**High Risk**

**Low Risk**
RANK - Conditions for increasing rank in coal formation

(Cairncross, 2005)
RANK OF COAL

Lignite

Sub-bit

Bituminous C

Bituminous B

Semi-Anthracite

Anthracite

INDICATED BY COLOUR AND REFLECTANCE OF LIGHT IN VITRINITE (V)

RAPID SELF HEATING

SLOW SELF HEATING
Three coal samples:
All 18% volatiles ad
CHARACTERISTIC REFLECTOGRAMS OF SPECIFIC COLLIERY PRODUCTS AND THEIR IDENTIFICATION IN A BLEND

Low rank, highly reactive ...................... high rank, low reactivity, heat sink
BLEND OF COALS OF DIFFERENT RANKS

A – BITUMINOUS COAL
Fast oxidation, high volatiles

B – ANTHRACITE
Slow oxidation, heat sink
MINERALS IN COAL – IMPACT ON SELF HEATING
# Forms of Pyrite and Other Fe-S Minerals

<table>
<thead>
<tr>
<th>Form</th>
<th>Microns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-fine granules</td>
<td>1-3</td>
</tr>
<tr>
<td>Small granules</td>
<td>10-20</td>
</tr>
<tr>
<td>Large nodules</td>
<td>100-150</td>
</tr>
<tr>
<td>Composite multi-nodule - frambooid</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Woody cellular infillings</td>
<td>500-1000</td>
</tr>
<tr>
<td>Cleats in fractures</td>
<td>5-30 wide, Long and complex</td>
</tr>
</tbody>
</table>

*Pyrite oxidises and self heats up to 10 x faster than coal*
PYRITE GRAINS INDICATING SIGNS OF SELF HEATING COAL DURING OXIDATION

(NB: pyrite heated faster than coal as shown by gas pores adjacent to pyrite grains; coal still softening, non-porous.)
MINERAL CONTENT: NB: Quartz sparks with friction
NB: Clays create steam wet hot

CARBONACEOUS SHALE
Quartz and clay (brown and black) with highly oxidised inert organic fragments (white)

Scale: 200 microns across the width of the photograph

Varying proportions of clay in high ash coals
THERMAL SPLITTING (DEFLAGRATION) OF HIGH ASH RICH COALS

COAL
Inertodetrinite
Particles of organic matter (white and grey) mixed with mineral matter (black)

CHAR
Inertodetrinite
Particles of organic matter (white and grey) mixed with mineral matter (black)

Creates fines with high surface area
IMPACT ON OXIDATION AND SELF HEATING
Weathered coal cracks, presents high surface areas, dries out the moisture and oxidises the exposed surfaces.
Secondary Mineral formed in burnt coal in an Old Stockpile
## IMPACT OF INHERENT FACTORS ON SELF HEATING

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>PARAMETER</th>
<th>IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RANK</strong></td>
<td>RoV% Vitrinite Reflectance</td>
<td>Rate of reactivity, $T^\circ C$ of heats of wetting; $T^\circ C$ of devolatilisation and combustion; inherent moisture level; microporosity; source of $\text{CH}_4$; heat retention capacity; blending by rank</td>
</tr>
<tr>
<td><strong>TYPE</strong></td>
<td>Vitrinite %</td>
<td>Rate of reactivity; $T^\circ C$ of devolatilisation and combustion; microporosity; source of $\text{CH}_4$</td>
</tr>
<tr>
<td><strong>MINERAL MATTER</strong></td>
<td>Total S, Pyritic S%</td>
<td>Creates ToC rise through oxidation and heats of wetting</td>
</tr>
<tr>
<td>• Pyrite proportion</td>
<td>Microscopic form, size, shape%</td>
<td></td>
</tr>
<tr>
<td>• Forms of pyrite</td>
<td>Microscopic liberation %</td>
<td></td>
</tr>
<tr>
<td>• Degrees of exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CONDITION</strong></td>
<td>Microscopic analysis</td>
<td>Dries out inherent moisture leading to heats of wetting; creates fines and increased surface area</td>
</tr>
<tr>
<td>• Weathered degree/form</td>
<td>Inherent moisture %</td>
<td></td>
</tr>
<tr>
<td><strong>MOISTURE</strong></td>
<td>Inherent Moisture %</td>
<td>Once dried out, replacement leads to heats of wetting</td>
</tr>
<tr>
<td>• Inherent Moisture</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RELATIVE DENSITY</strong></td>
<td>Relative density of sample RD</td>
<td>High densities act as a heat sink, leading to increased reaction rate</td>
</tr>
<tr>
<td><strong>FRIABILITY</strong></td>
<td>Hardgrove Index</td>
<td>Leads to increased surface area and therefore higher reaction</td>
</tr>
<tr>
<td><strong>POROSITY</strong></td>
<td>Degree of macro/micro porosity by microscopic assessment</td>
<td>High surface area for reaction, may store water; when dry could lead to heats of wetting</td>
</tr>
<tr>
<td><strong>SIZE DISTRIBUTION</strong></td>
<td>Particle size distribution %</td>
<td>Affects compaction, segregation; voidage,</td>
</tr>
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Contents

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External factors imposed upon coal

- Particle size distribution – segregation during storage
- Environment during storage – access to air
- Climate – temperature, humidity
- Time – length of exposure
- Compatibility of blends – wet-dry; fresh-weathered;
- Degree of beneficiation – low-ash to high-ash or discards
- External heat sources – proximity to boilers (on ships), flames or sparks
EXTERNAL FACTORS AFFECTING SPONTANEOUS COMBUSTION AND THE FORMATION OF HOT SPOTS

Particle size distribution – THE IMPACT OF HOMOGENEOUSLY-SIZED COAL

PARTICLE SIZE

LARGE LUMPS
AIR PASSES THROUGH SUFFICIENTLY FAST TO DISSIPATE THE HEAT

MEDIUM LUMPS
AIR PASSES THROUGH JUST FAST ENOUGH TO DISSIPATE HEAT

SMALL LUMPS
- AIR PASSES THROUGH TOO SLOWLY TO DISSIPATE HEAT,
- HIGH SURFACE AREA FOR OXIDATION TO TAKE PLACE
- TEMPERATURE RISE THROUGH OXIDATION IS Retained AND WILL CONTINUE TO INCREASE IF NOT STOPPED

FINE LUMPS
- AIR UNABLE TO PASS THROUGH
- LUMPS TOO TIGHTLY COMPACTED
-- MATERIAL STABLE IF COMPACTION IS RETAINED
EXTERNAL FACTORS AFFECTING SPONTANEOUS COMBUSTION AND THE FORMATION OF HOT SPOTS

SEGREGATION - THE IMPACT OF NON-HOMOGENEOUSLY-SIZED COAL

VOIDAGE AND SURFACE AREA

LAYERS OF DENSELY PACKED FINE COAL – NO AIR PENETRATION

LAYER / SPOT WITH IDEAL % AIR FLOW FOR HEAT GENERATION BUT TOO LITTLE AIR FLOW FOR HEAT DISSIPATION – HOT SPOT

LAYER OF FINE COAL CLOSE TO SOURCE OF AIR WITH GOOD HEAT DISSIPATION

IDEAL PACKING - FINES BETWEEN COARSE – NO VOIDAGE FOR AIR
EXTERNAL FACTORS AFFECTING SPONTANEOUS COMBUSTION
THE FORMATION OF HOT SPOTS

THE IMPACT OF NON-HOMOGENEOUSLY-SIZED COAL

SIZE, VOIDAGE AND SURFACE AREA

Figure 29 Particle size segregation in a conical stockpile (Cudmore and Proudfoot, 1988)

Figure 30 Air flow through the segregated stockpile (Cudmore and Proudfoot, 1988)
OTHER EXTERNAL FACTORS AFFECTING THE SELF HEATING OF A COAL STOCKPILE (Carras and Young, 1994)
# IMPACT OF EXTERNAL FACTORS ON SELF HEATING

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<tr>
<th>TOPIC</th>
<th>PARAMETER</th>
<th>IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of compaction</td>
<td>Controlled by handling and storage</td>
<td>Impacts upon access of air</td>
</tr>
<tr>
<td>Source of air</td>
<td>Wind, draught, imposed pressure</td>
<td>Leads to increased oxidation</td>
</tr>
<tr>
<td>Source of heat</td>
<td>Artificial (boiler, welding, match, etc0</td>
<td>Leads to increased rates of oxidation</td>
</tr>
<tr>
<td>Source of moisture</td>
<td>Rain, humidity, fresh coal</td>
<td>Leads to increased heats of wetting on dry coal</td>
</tr>
<tr>
<td>Level of ambient ToC</td>
<td>Ambient variations, ToC;</td>
<td>Initiates rise in temperature</td>
</tr>
<tr>
<td>Length of time of exposure</td>
<td>Days to weeks to months to years</td>
<td>Leads to weathering (if not covered, compacted)</td>
</tr>
<tr>
<td>Degree of segregation</td>
<td>Controlled by handling and storage</td>
<td>segregated</td>
</tr>
<tr>
<td>Degree of degradation</td>
<td>Controlled by careful mining, handling and storage</td>
<td>Leads to increased surface area; dry surfaces and ultimately heats of wetting</td>
</tr>
<tr>
<td>Form of mixing/blending</td>
<td>Dry/Wet; Low/High rank; Fresh/weathered; small/large sized layers</td>
<td>Affects compatibility of blends; leads to hot spots on or near contact</td>
</tr>
<tr>
<td>Degree of beneficiation</td>
<td>Ash content; total S content %</td>
<td>Leads to degradation of particles; increased heat during oxidation (S)</td>
</tr>
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**FUEL COMBUSTION TRIANGLE**

**KEY FACTORS FOR SUCCESSFUL COMBUSTION**

**TEMPERATURE**
- External Source (open flame, hot fuel)
- Internal Source (selfheating)

**IGNITION COMBUSTION**

**FUEL**
- COAL:
  - High reactivity
  - Medium reactivity
  - Low reactivity

**OXYGEN**
- AIR:
  - Internal source
  - External source

Falcon 1990
FACTORS THAT INFLUENCE SELF HEATING

Inherent factors within the coal

- Organic matter constitution – maceral type (reactives)
- Rank - level of maturity of coal
- Inorganic matter constitution – minerals (pyrite)
- Weathering - degree of oxidation
- Particle size - natural arising fines

External factors imposed upon coal

- Particle size distribution – segregation during storage
- Environment during storage – access to air
- Climate – temperature, humidity
- Time – length of exposure
- Compatibility of blends – wet-dry; fresh-weathered;
- Degree of beneficiation – low-ash to high-ash or discards
- External heat sources – proximity to boilers (on ships), flames or sparks
AN INTEGRATED RISK ASSESSMENT BASED UPON THE PARAMETERS DISCUSSED FOR THE LIABILITY OF SELF HEATING LEADING TO SPONTANEOUS COMBUSTION HAS BEEN DEVELOPED.

THIS WILL BE PRESENTED IN A SECOND PAPER LATER TODAY.
KEY LOCATIONS WHERE EXTERNAL FACTORS CAN LEAD TO SELF HEATING CAN TAKE PLACE

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SELF HEATING IN OTHER CIRCUMSTANCES

- HOPPERS
- DUCTS
- CHUTES
- MILLS

- DUST EXPLOSIONS IN MINES (following methane explosions, electrical sparks etc)
- PF EXPLOSIONS IN BOILERS (following flame outs)
Coal Dust Explosions

Example of impact at Kloppersbos Explosion Research Tunnel, North of Pretoria
Coal dust explosion ex the short tunnel
Coal dust explosion out of the large tunnel – the response of only 150kg of coal dust, once ignited.
Aftermath of the dust explosion in the long tunnel
Middelbult Mine Disaster
mid 1990s

56 people were killed in one section underground due to a methane explosion followed by a dust explosion
Prevention of such disasters underground is undertaken, in part, by stone-dusting (white-washing roof, walls and floor)
Conclusion

Great care must be taken in handling, transporting and stockpiling coal for the

- Prevention of coal degradation through weathering, mishandling and self heating
- Promotion of safety for personnel, plant and products
Thank you