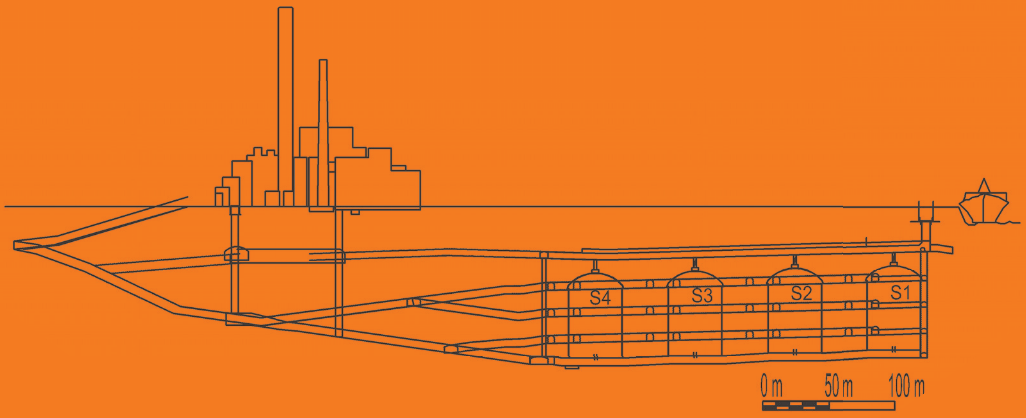
**Department of Engineering Design and Production**

# Emerging risk issues in underground storage of bituminous coal

**Juha Sipilä**



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# Emerging risk issues in underground storage of bituminous coal

**Juha Sipilä**

A doctoral dissertation completed for the degree of Doctor of Science in Technology to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall 121 in Puu2- building (Tekniikantie 3, Espoo) on 19th November 2013 at 12 o'clock noon.

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# Abstract

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**Abstract**

This thesis aims to address the root causes and means of prevention, mitigation and other improvements to the challenges from smouldering fires, coal freezing and occupational risk in an underground storage silo built into granite bedrock. In addition, appropriate performance indicators are suggested, and the benefits of the recommended or adopted actions are estimated. The issues and observed incidents demonstrate hazards that are largely classified to represent issues of emerging risk.

To reduce the fire risk, successful measures included bottom maintenance door sealing and modified design of silo filling and discharge. The assessed benefits of these actions suggest a payback period of only about 10 days, assuming that, without these measures, a fire like the one in 2008 could occur once in four years. Additional recommendations are made to reduce air flow through the coal bed and near the silo ceiling, and to improve nitrogen purging at the hoppers.

Filling with subzero coal can freeze silo drains, resulting in water inflow and further freezing to hamper discharge. As the heat flow is unlike any previously known cases of coal freezing, conventional mitigation e.g. by freeze conditioning agents, would not help. After implementing modified filling procedures for cold coal, no severe freezing cases have occurred.

Safety advantages from the automated and remotely controlled operation do not necessarily apply under exceptional circumstances requiring human involvement. As preventive measures, protection has been sought from additional technical barriers and training effort. The rarity of serious incidents is a challenge in demonstrating success, but also emphasizes the importance of using leading (not only lagging) safety performance indicators for measurable safety promotion.

In contrast, suitable leading performance indicators of the fire risk have been suggested for deliveries as an index of coal properties and for storage (gas emissions and temperature). Suggested leading indicators of the freezing risk can be based on adverse weather along the transport route, delivery of wet cold coal, and the flow rate of seepage water entering silos with cold coal.

**Keywords** coal, underground storage, silo, self-heating, smouldering fire, freezing, performance indicator, safety, risk, prevention, mitigation

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# Tiivistelmä

**Tekijä**
Juha Sipilä

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Maanalaisen kivihiilivaraston uudet riskitekijät

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## Tiivistelmä

Tämä työ tarkastelee kallioon louhitun maanalaisen kivihiilivarastosiilon kytöpalojen, hiilen jäätymistapausten ja työtapaturmien syitä, torjuntaa ja vaikutusten lieventämistä. Lisäksi työssä esitetään suositeltavia toimenpiteitä, niiden tunnuslukuja ja toteutettujen toimien hyötyjä. Tarkastelu koskee suurelta osin uuden teknologian vaaratekijöitä, jotka edustavat nousevia (emerging) riskejä.

Tulipalojen vähentämiseksi on toteutettu siilojen pohjaovien tiivistys sekä parannettu siilojen täyttö- ja tyhjennysmenettely. Arvion mukaan toimenpiteiden takaisinmaksuaika on vain noin 10 päivää, olettaen että vastaava palo kuin 2008 voisi esiintyä ilman toimenpiteitä kerran neljässä vuodessa. Lisäsuosituksia on tehty hiilen läpi ja siilon yläpäässä esiintyvän ilmavuodon vähentämiseksi sekä typpisuojan parantamiseksi purkusuppilolla. Kytöpalon ennakoiviksi tunnusluvuiksi on esitetty hiilen hankintaan lämpenemistaipumusta kuvaavaa indeksiä ja varastoinnin aikana mitattua kaasupitoisuutta ja lämpötilaa.

Täyttö hyvin kylmällä hiilellä voi jäädyttää siilon vuotovesikanavat ja johtaa vuotoveden jäätymään hiilen sekaan suuriksi paakuiksi, jotka estävät hiilen purkua. Lämpövuon suunta on tällöin ulkoa hiileen päin eli päinvastainen kuin aiemmin tunnetuissa hiilen jäätymistapauksissa, joten perinteiset torjuntamenetelmät kuten jäänestolisäaineet eivät auta. Kylmän hiilen parannetun vastaanoton ja käsittelyn jälkeen ei vakavia jäätymistapauksia ole esiintynyt. Hiilen jäätymisen tunnusluvut voivat perustua kuljetusreitin säätilaan, hiilen kosteuspitoisuuteen ja lämpötilaan sekä siilokohtaiseen vesivuotoon.

Automaattisen etäkäytön turvallisuushyödyt pienenevät tilanteissa, jotka vaativat ihmistyötä varastossa. Lisäturvaa varten on kehitetty teknisiä turvaesteitä ja henkilökunnan koulutusta. Vakavat tapaukset ovat sitä harvinaisempia mitä paremmin turvallisuustyössä onnistutaan, joten keskeisiä toiminnan tunnuslukuja ovat edistymistä ennakoivat mittarit.

Uusia haasteita voidaan odottaa biopolttoaineista, joissa on korkea itsesyttymistä edistävä haihtuvien aineosien pitoisuus, jäätymistä helpottava korkea kosteuspitoisuus sekä alhainen lämpöarvo, joka lisää kuljetuksen ja varastoinnin volyymia ja sitä kautta kaikkia em. riskejä.

**Avainsanat** kivihiili, maanalainen varasto, siilo, itselämpeneminen, kytöpalo, jäätyminen, toiminnan tunnusluku, turvallisuus, riski, torjunta, lieventäminen

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# Preface

The research work for this thesis was carried out at the Department of Engineering Design and Production of Aalto University during 2010–2013 as a result of interdisciplinary collaboration continued on the topics covered in my Master of Science thesis.

I would like to acknowledge Professor Kalevi Aaltonen for his open-minded supervision of the work. I am grateful to Lic. Tech. Pertti Auerkari for being the indispensable instructor of the dissertation. I would also like to express my gratitude to the other co-authors, Professor Mikael Rinne (Aalto University), Dr. Iris Vela (BAM, Berlin), Professor Ulrich Krause (Otto von Guericke University, Magdeburg), Dr. Anna-Mari Heikkilä, Mr. Yngve Malmén, Mr. Risto Tuominen, Dr. Stefan Holmström (VTT), and Mr. Jyrki Itkonen (Helsingin Energia) for their essential contribution to the publications within this work. For the opportunity and support to conduct and complete this work and the dissertation, I would like to thank my colleagues and superiors from Helsingin Energia: Mr. Rauno Kontro, Mr. Mikko Sillanpää, Mr. Mauri Rautiainen, Mr. Tomi Wilén, Mr. Kari Pilkkakangas, Ms. Arja Jurasch, and Mr. Sami Mustonen. Also, I would like to express my appreciation to the numerous employees of Helsingin Energia for their kind help in solving the technical details of the work. I would also like to acknowledge Dr. Ilkka Satola and Mr. Jussi Haiko from the Geotechnical Division of the City of Helsinki. For the opportunity of constructive cooperation, the technical support of the European project iNTeg-Risk of the 7th Framework Programme (grant agreement no. 213345) of the European Union and VTT is also acknowledged.

I wish to express my warmest gratitude to my parents and to my friends. Their permanent encouragement and support have been essential during the past years.

Helsinki, September 30, 2013

Juha Sipilä

# Contents

# List of abbreviations and symbols

| | |
|---|---|
| A | Rate constant of creep (of ice) |
| D, G | Constants |
| GAG | Górniczy Agregat Gaśniczy (Polish), a jet engine inertisation unit for coal mine fires |
| $d\varepsilon/dt$ | Strain rate |
| FCA | Freeze conditioning agent |
| KPI | Key performance indicator |
| $k$ | Slope of strength-moisture curve at zero strength |
| LHV | Lower heating value |
| $m$ | (Total) moisture |
| $m_o$ | Moisture at zero strength |
| N | Number of batches |
| n | Creep exponent of the Norton creep law |
| $n_1$, $n_2$ | Rate exponents of oxidation |
| P(U) | (Accident) probability |
| Q | Activation energy (of creep) |
| R | Gas constant (8.314 kJ/molK) |
| SGI | Smith-Glasser index |
| T | Temperature |
| $\sigma$ | Stress |
| $\sigma_i$ | Strength of ice |
| $\sigma_c$ | Strength of frozen coal |
| $\nu$ | Dry content of volatiles |

# List of Publications

This thesis consists of an overview of the following publications, which are referred to in the text by their Roman numerals:

**I** Juha Sipilä, Pertti Auerkari, Anna-Mari Heikkilä and Ulrich Krause. Emerging risk of autoignition and fire in underground coal storage. *Journal of Risk Research, 16 (2013) 447-457*

**II** Juha Sipilä, Pertti Auerkari, Yngve Malmén, Anna-Mari Heikkilä, Iris Vela and Ulrich Krause. Experience and the unexpected: risk and mitigation issues for operating underground storage silos for coal fired power plant. *Journal of Risk Research, 16 (2013) 487-500*

**III** Juha Sipilä, Pertti Auerkari, Anna-Mari Heikkilä, Risto Tuominen, Iris Vela, Jyrki Itkonen, Mikael Rinne and Kalevi Aaltonen. Risk and mitigation of self-heating and spontaneous combustion in underground coal storage. *Journal of Loss Prevention in the Process Industries, 25 (2012) 617-622.*

**IV** Juha Sipilä, Pertti Auerkari, Stefan Holmström, Jyrki Itkonen and Kalevi Aaltonen. Observations on the Smith–Glasser index for self-heating of bituminous coal. *Journal of Fire Sciences, 30 (2012) 331-338*

**V** Juha Sipilä, Pertti Auerkari, Risto Tuominen, Jyrki Itkonen and Kalevi Aaltonen. Safety issues in an underground coal storage. *5th iNTeg-Risk Conference, Stuttgart 21-22 May 2013. 14 p.*

**VI** Juha Sipilä, Pertti Auerkari, Stefan Holmström, Jyrki Itkonen and Kalevi Aaltonen. Freezing of coal in the underground storage of a power plant. *Cold Regions Science and Technology, 79-80 (2012) 38-42*

## Author's contribution

The author of this thesis has had the main responsibility for Publications I - VI, particularly in planning and analysing the research ideas, results, conducting the background literature study and writing the draft papers. Publication I mainly involves the author's analysis of field observations and conclusions on major autoignition incidents. In Publications II and V, the author contributed technical data to the fault and event trees and other analysis of fire, freezing and safety related incidents. The author also performed data collection and analysis from the database of the on-site laboratory in Publications III, IV and VI. Furthermore, the author designed and implemented the model on frozen coal strength in Publication VI together with co-authors P.A. and S.H. The author also conducted the operator interviews on the experience related to the incidents in the coal storage facility.

# Publications in short

### Publication I

The paper describes an incident of a smouldering fire in an underground coal storage facility. Nitrogen injection was found to be useful for extinguishing controllable fires, and three-phase foams and oxygen-displacing exhaust gases appear preferable against uncontrolled fires. Fire extinction during power plant operation can be challenging, as any air ingress may feed the fire. One of the root causes was found to be air leakage, and it is believed that similar events are reduced or prevented by tight sealing of bottom/wall openings and hoppers. To avoid similar events, selecting and maintaining proper grade and temperature of the stored coal also remain important.

### Publication II

The unique rock silo storage facility of the Salmisaari power plant has distinct advantages against external disturbance but it has, nevertheless, experienced events of coal autoignition and freezing. The risks and the safety system of the storage are described, as well as suggested performance indicators related to autoignition. Also, an unexpected disturbance due to frozen coal is described, with incoming cold coal freezing the silo drains and allowing seepage water to enter and form large clumps of icy coal, blocking the hoppers. This emerging risk is characterised by fault and event trees for lost fuel supply due to frozen coal, and suggested performance indicators are given for this type of incidents.

### Publication III

Issues of importance have been considered and compared in this paper for three types of closed coal storage facilities regarding self-heating and spontaneous combustion. Fault and event trees to describe and assess this risk have been developed from the experience on the incidents of the Salmisaari storage facility. Options for the prevention and extinguishing of fires are discussed in the light of known solutions in different types of closed storage facilities. Recommendations are given on cost-effective preventive, corrective and mitigating action for minimising fire risk and promoting storage availability.

### Publication IV

The paper deals with intrinsic (coal-related) factors in self-heating in storage. In particular, the performance and potential use of the Smith-Glasser index (SGI) is discussed as an indicator of the self-heating propensity of bituminous coals. The particular advantage of SGI is that it only requires determination of moisture and volatile contents of coal. The results suggest that the index can even be applied in a modified form using total moisture instead of the inherent one. The evaluated distributions of modified SGI appear consistent with the observed incidences of self-heating in storage.

**Publication V**

The remotely operated underground storage in Salmisaari has the advantages of reducing employee exposure to dust and noise and, in principle, to many other hazards. However, the new storage technology also implies more limited access in case of fires or other disturbance, and the challenge to safety can further increase under exceptional circumstances like during construction, maintenance and process deviations. The effort of hazard reduction involves a range of activities with the principle of continuous improvement in the safety system. The observed incidents have arisen from variable causative details, and improvements have been sought from reduced exposure in addition to considering the lessons from the individual incidents. The post-incident experience in the areas of the case examples appears to demonstrate safety benefit.

**Publication VI**

Compared to any previously known or reported cases of coal freezing in transport or storage, the freezing incident in the Salmisaari silo represents an unexpected direction of heat transfer from storage wall to coal. This means an additional challenge in mitigation as, for example, freeze conditioning agents added to coal would be unlikely to help much. To quantify the challenge of blocked hoppers, the compressive strength of frozen coal has been modelled as a function of moisture content, ambient temperature in Helsinki, loading (strain) rate, and the limiting strength of ice. The input variables as realistic distributions have been used in a Monte-Carlo analysis of the developed strength model for frozen coal. The results suggest that this strength would frequently be sufficient in winter to render immediate remedial action at the hoppers tedious, explaining the observed challenge to plant operation at the time of the incident.

# 1 INTRODUCTION

## 1.1 Background: the underground storage facility

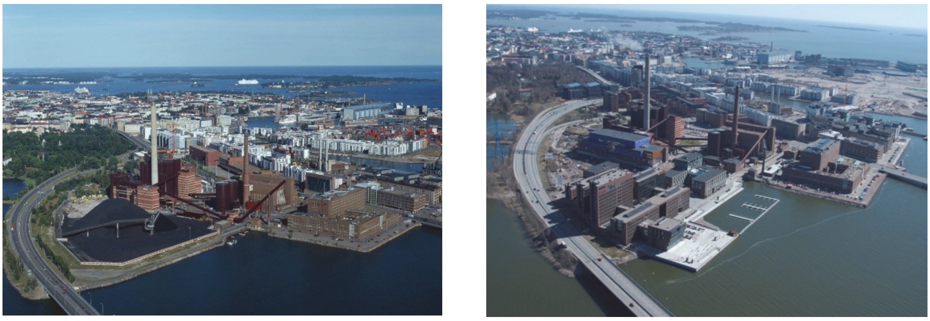
This work was sparked by incidents of spontaneous combustion and freezing of coal in the Salmisaari automated coal storage, which is a first-of-a-kind facility with large underground rock silos. As the cases demonstrated hazards that were not expected to manifest themselves the way they did, they were classified as issues of emerging risk (here the risk issues refer to sources of risk, and emerging when carrying new or significantly growing risk). With the fortunate opportunity to conduct a study in cooperation with the European project iNTeg-Risk (www.integrisk.eu-vri.eu), the incidents were taken as case examples of more general and conceptual development in the area of emerging risk, including the aspects of prevention, mitigation and other improvement in the operation of the storage facility.

Self-heating and spontaneous combustion of coal represent a well-known issue and are generally under control in mining, transport and storage in above-ground stockpiles (Porter and Ovitz 1912, Carpenter et al. 2003, Nalbandian 2010), but there is little published experience on closed storage, and practically nothing on underground rock silos (Quest 2011). Freezing of coal was another subject of intensive studies in late 1970s and early 1980s (H.G. Engineering 1978, Colijn 1980, Glanville and Haley 1982, Boley 1984, Carpenter et al. 2003), but again not for underground rock silos. As occupational safety is included in the important subjects of the iNTeg-Risk project (Jovanovic 2009, Duval and Dien 2010), safety at the storage facility is also an issue of interest in this study.

The storage facility at the Salmisaari combined heat and power plant (Figure 1) has been operational since 2004, replacing an earlier above-ground open stockpile. The storage has a total capacity of 250 000 tons, which corresponds to about half of the yearly fuel consumption of the plant. The storage consists of four silos, ∅ 40 m x 65 m each, with the silo bottom at a depth of -120 m. A cross-section of the storage facility is presented on top cover of the dissertation. Coal is discharged from the silos to the boilers via horizontal and vertical conveyors through day bunkers. The vertical conveyor is an important vulnerable component with a maximum allowable operating temperature of 70°C, and the delivery time of a new vertical conveyor is approximately eight months.

The advantages of closed underground storage in comparison to the earlier above-ground stockpile include automated operation, greatly reduced dust, noise and loss of heat content, less air ingress to the stored coal, and improved aesthetics. The new storage facility also provided an opportunity for the City of Helsinki (utility owner) to free up approx. 100 000 $m^2$ of urban real estate close to the city centre. A potential disadvantage could be the less convenient access to the stored fuel whenever such a need may arise.

Maintenance campaigns are typically conducted in summer when the need for district heating is minimal and the price of electricity is low. During the summer outage the silos should be empty, because at that time no heated coal can be simply burned in the boiler, and it is not as easy to remove heated coal as from an above-ground stockpile.



a) b)

**Figure 1.** Salmisaari power station a) before and b) after construction of the underground coal storage facility. Photos: Helsingin Energia

### 1.2 Problem setting and objectives

During the short service history of the underground storage, unexpected events of operational interruption and lost availability have been observed due to the triple challenge of smouldering fires, freezing of coal, and occupational incidents. As the the associated risks could be seen as potentially new or emerging, this work was initiated with the following objectives:

- to address the root causes to the challenges from smouldering fires, coal freezing and occupational incidents in the underground coal storage,
- to recommend appropriate leading and performance indicators, and means of prevention, mitigation or other improvements to deal with the associated risk, and
- to assess the benefit from the action recommended and taken so far.

# 2 STATE-OF-THE-ART

## 2.1 Self-heating and spontaneous combustion

Even in absence of an external heat source, provided that the balance of the rates of heat produced by the chemical reactions and heat losses from the system allows for it, exothermic oxidation of coal can result in gradual heating of a coal mass up to a point of ignition. The resulting self-heating and spontaneous combustion (Figure 2) can be a threat to reliable operation in mining, transporting and storing coal, and has been a recognised challenge for more than a century (Porter and Ovitz 1912, Carpenter et al. 2003, IMO 2009, Nalbandian 2010).

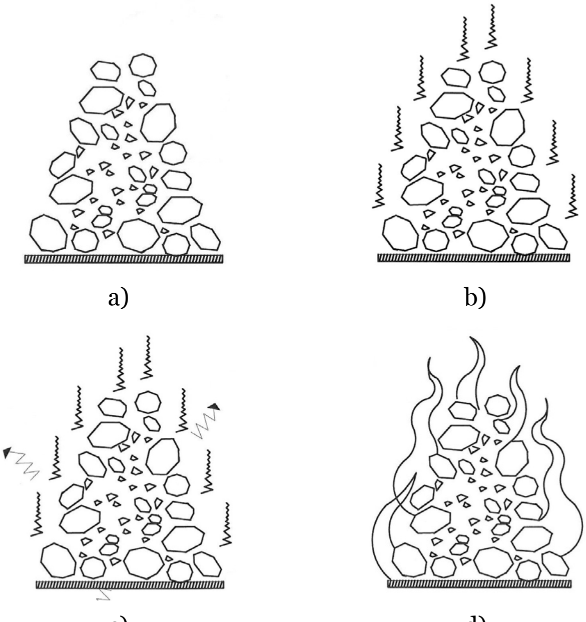


**Figure 2.** Steps leading to spontaneous combustion: a) coal pile at an ambient (low) temperature; b) initial self-heating by oxidation with air ingress; c) continuing self-heating exceeding heat loss by conduction, convection and radiation; d) heating to a critical temperature to ignite a fire (adapted from DOE HDBK-1081 1994).

Conventional above-ground stockpiles allow for a straightforward solution to extract the hot spots for cooling and self-extinction, as an open fire is generally not sustained due to heat loss to the environment (Nalbandian 2010, Figure 3).


a) b)

**Figure 3.** a) Excavation and removal of burning hot spot in an open coal stockpile; b) spreading out burning coal for self-extinction. Photos: Keijo Kotirinta/Helsingin Energia

Because of more limited access, the same approach is not as easy in a closed storage. Therefore, when sufficient air ingress is available to feed self-heating, other means are needed to identify, locate and size (assess) the hot spot, and to combat it. The principles and critical factors in self-heating and spontaneous combustion such as the condition of the environment and quality of coal are fairly well known (Bowes 1984, Smith and Lazzara 1987, Davidson 1990, Fierro et al. 1999, DMT/BAM 2000, Ray et al. 2000, Carpenter et al. 2003, IMO 2009, Nalbandian 2010), although may only provide partial help in fire prevention. The classical model of thermal explosion for the purpose assumes unlimited reactants and implies two alternative future paths for a body of self-heating material: it will either show progressively increasing temperature, or establish a steady-state temperature excess in the body (van't Hoff 1884, Semenov 1928, 1940a, 1940b, Frank-Kamenetskii 1938, 1969).

For a cylindrical body of porous reactive solid, or a cylindrical fuel silo, the one-dimensional heat balance of unsteady temperature $T$ at time $t$ can be expressed as (Frank-Kamenetskii 1969, Bowes 1984)

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c_p}\nabla^2 T + \frac{k_0 H_0}{c_p} \cdot \exp\left[-\frac{E}{RT}\right] \qquad (1)$$

where $k_o$ is the pre-exponential or frequency factor to be experimentally determined, $\rho$ is the effective density (for bituminous coal somewhat below 1000 kg/m$^3$), $H_o$ is heating value (heat of reaction, see publication IV), $\lambda$ is the effective thermal conductivity (of the order of 0.1 W/mK), $c_p$ is the specific heat capacity (about 1 kJ/kgK), $E/R$ (also experimentally determined, roughly $10^4$ K) is the apparent activation energy normalized by the gas constant, and the operator $\nabla$ is of the form $[\partial^2 T/\partial x^2 + (1/x)(\partial T/\partial x)]$. The ambient temperature is initially on average about 9°C at the silo wall of the Salmisaari storage. In reality the process of coal oxidation consists of varying contributing reactants at different temperature ranges, with corresponding activation energies and pre-exponential factors. However, here the main interest is in the early stages of self-heating at relatively low temperatures, and this would constrain the effective activation energy and other factors in Eq. (1).

Various experimental arrangements have been used to assess the critical temperatures and time to sustained self-heating and ignition of coal (Smith and Lazzara 1987, Beamish et al. 2001, Wang et al. 2003, Malow and Krause 2004, Lohrer 2005, Krause et al. 2006 & 2009, Garcia-Torrent et al. 2012). Experimental laboratory methods to characterize self-heating of coal are mostly using a coal samples subjected to controlled heating and feed of the oxidizing gas flow. The most common methods are the following:

*Adiabatic heating* (calorimetry) is a method where a ground coal sample is heated in an adiabatic oven (calorimeter, with walls of low thermal conductivity) with constant oxygen carrying gas feed. The approach can be used to indicate the maximum temperature rise during self-heating, the effective activation energy ($E/R$) and the pre-exponential coefficient ($k_o H_o/c_p$). A typically reported characteristic measure of self-heating propensity of a coal batch is R70, which is the rate (°C/h) in the linear part of the temperature-time curve for the sample to self-heat from 40°C to 70°C under given test conditions (Humphreys et al. 1981, Beamish et al. 2001).

*Crossing-point temperature* (CPT) is the temperature of self-heating coal, when it equals (crosses) the temperature of the reaction vessel that is heated at a constant rate (usually about 1°C/min). CPT corresponds to the point where the conduction term ($\nabla^2 T$) in Eq. (1) is zero, and CPT is then assumed to be a measure of the onset of significant self-heating (Nubling and Wanner 1915, Zhang and Sujanti 1999).

*Differential thermal analysis* (DTA) is used to obtain simultaneously the temperature records of a coal sample and an inert reference when both are identically heated at a selected rate. The results can be applied to analyse heat evolution and the related chemical reactions (Banerjee and Chakravorty 1967).

*Thermogravimetric analysis* (TGA) involves weighing of a coal sample during heating with controlled oxygen feed. The results can be used to assess kinetic parameters like reaction rate constants, often in combination with DTA (Marinov 1977, Chen et al. 1995).

*Oxygen adsorption* technique can be applied to determine the time-dependent rates of gas adsorption and desorption from the partial pressure records of oxygen and oxidation products for adsorption equilibrium at given temperature (Carras and Young 1994). In a faster modification of the original static approach, an isothermal flow reactor is used to analyse the gases and partial pressures and to determine the dynamics of the reactions from oxygen consumption and emission of product gases (Krishnaswamy et al. 1996).

*Basket heating* approach is using a pre-shaped e.g. metal wire basket filled with coal. The basket is placed in an oven at selected constant oven temperature and oxygen feed, and the temperature of the basket centre is monitored. If there is no runaway reaction, the test is repeated at a higher temperature until by iteration a critical runaway or self-ignition temperature ($T_{SI}$) is found for the given test volume. With a series of experiments using different basket sizes, the corresponding values of logarithmic volume-to-surface ratios (characteristic dimension) are plotted against reciprocal $T_{SI}$ values and extrapolated to the ratio (dimension) of interest, for example to the size of the coal storage, to obtain the relevant value of $T_{SI}$. To estimate the self-ignition temperature and the corresponding time to self-ignition, this is the simplest graphical pseudo-Arrhenius technique of the standard EN 15188 (2007) that is originally intended for assessing the ignition behaviour of dust accumulations. By similarly extrapolating the logarithmic volume-to-surface ratios plotted against logarithmic values of the time to self-ignition up to the actual storage size gives the predicted induction time to self-ignition.

The graphical method can lead to relatively large uncertainty in the predictions, and an alternative approach is using the Frank-Kamenetskii (FK) simplification of Eq. (1) for an experimental analysis of the reaction rates (Frank-Kamenetskii 1969, Bowes 1984, Jones 1999). This model can be expressed as

$$\ln\left[\frac{\delta_c T_{SI}{}^2}{r^2}\right] = \ln\left[\frac{E}{R}\cdot\frac{k_0\cdot\rho\cdot H_0}{\lambda}\right] - \frac{E}{RT_{SI}} \tag{2}$$

where $\delta_c$ is the critical value of FK number (geometry-dependent, e.g. $\delta_c$ = 2.76 for a cylinder with height = diameter), and *r* is the characteristic dimension of the coal bed.

Again, an Arrhenius plot with extrapolation to real storage volume can be made to fit the experimental data from the oven tests of different test volumes, giving a linear correlation between logarithm of $\delta_c(T_{SI}/r)^2$ and reciprocal $T_{SI}$, with $E/R$ as the slope, to yield the predicted $T_{SI}$ for the coal storage. The prediction can be further refined by including a correction for finite values of the heat transfer coefficient, but even then the approach does not include time as a variable, and cannot predict the induction time. To allow for more general analysis of any boundary condition, geometrical configuration and self-heating history up to ignition, Eq. (1) can be solved numerically by finite element analysis (FEA) to describe the evolution of the temperature field.

The risk of self-heating and spontaneous combustion is influenced by both storage system-related and coal-specific (intrinsic) factors. Known intrinsic factors to promote the process include, for example, low rank, high volatile content, high active surface area (porosity and small particle size) of coal, and high alkali content in ash (Van Krevelen 1993, Beamish et al. 2001, Quick and Brill 2002, Beamish and Arisoy 2008, IMO 2009, Nalbandian 2010, Sipilä and Auerkari 2010). When considering the early or low-temperature stages (below 70-80°C) of self-heating, the rate of oxidation reaction can be expressed as (Smith and Glasser 2005)

$$r = k \cdot C_{coal}^{m} \cdot C_{O_2}^{n} \qquad (3a)$$

$$\text{with } k = k_0 \cdot \exp(-E/RT) \qquad (3b)$$

where $m$ is the order of reaction with respect to coal and $n$ the order of reaction with respct to oxygen, and $C$ refers to the corresponding concentration. The rate constant $k$ includes a temperature dependence with activation energy $E$ and pre-exponential factor $k_o$, similarly as in Eq. (1) for comparable coal, oxygen concentration and temperature regime. At low temperatures the observed reaction rates for a wide range of coals are insensitive to many variables including particle size, petrographic details of coal and contents of other constituents than volatiles and inherent moisture. By regression analysis of 23 such variables on tested oxidation rates in laboratory, Smith and Glasser concluded that the low-temperature reaction rate $r$ is best predicted by

$$\log(r) = 0.89 \cdot m^{0.14} \cdot v^{0.43} \qquad (4)$$

where $m$ is the inherent moisture content and $v$ the volatile content of coal. If true, this appears in many ways attractive and fortunate, since it would dramatically constrain the amount of information that has been assumed to be influential for the propensity of coal to self-heat (Van Krevelen 1993, Beamish et al. 2001, Quick and Brill 2002).

No fire will occur without oxygen, but it is generally challenging to exclude air ingress to the storage. As long as the temperature remains below about 40-50 °C, oxidation of coal is slow. Above this temperature level, the reaction rate progressively increases, although initially slowly, until a self-sustaining combustion can be expected at about 200-250 °C. As the coal bed is also an effective obstacle to heat transfer, the critical temperature for a self-sustained reaction can be as low as 70-80 °C for bituminous coal (DOE HDBK-1081 1994, Jones et al. 1998, Jones 1998, Walker 1999, Ren et al. 1999, Sujanti et al. 1999, Nalbandian 2010). The likelihood of self-ignition will depend on coal type and storage time, and is usually highest before 6 months after entering storage. The oxidation rate is reduced by a partly protective (absorbed) layer on the coal particles, while the oxidation products are typically released as carbon dioxide, carbon monoxide, and water or steam (Wang et al. 2003, Nalbandian 2010). The process will typically result in smouldering fires that can be challenging to detect and extinguish at an early stage.

In principle heating and autoignition can be revealed by the emission of odour, gaseous reaction products, and heat. The challenge lies in sufficiently early detection as the signals may be delayed by diffusion and mass transfer through the bed between the hot spot and the detecting sensor. In closed storage facilities like above-ground silos, CO, CH4 and O2 (gas) sensors are used together with ambient air temperature monitoring. Also, thermal imagers and pyrometry can indicate heated coal but only at or near surfaces of the coal bed (Sipilä 2009, Rosner and Röpell 2011). These indicators are also used in the Salmisaari storage.

Beyond these methods, only few techniques appear to be available for detecting hot spots, such as the measurement of electric resistance. In this approach, the hot spot is indicated from its temperature-dependent change in the electrical conductivity, so that the distribution of electrical potential corresponds to the intensity and distribution of the heat source (Tanaka et al. 2004, Li et al. 2005).

When excessive heating or fire is detected, cooling or extinguishing can be carried out with water, particularly if the hot spot is near the surface. In such cases sufficiently abundant water flow should be used to avoid significant water gas reaction from producing a flammable gas mixture (hydrogen and carbon monoxide) at the hot spot. Otherwise, nitrogen injection can be applied, typically combined with discharge of the heated coal from the silo when possible. These extinguishing methods are also available in the Salmisaari storage. Efficient fire extinction during power plant operation can be also challenging, as any air ingress tends to feed the fire and result in losses of the extinguishing agent and the heating value of coal (Hull et al. 1997a, 1997b, Tuomisaari et al. 1998, Vierro et al. 2001, Nijhof 2007, Sipilä and Auerkari 2010, Auerkari et al. 2011, Lerena et al. 2013, Zhu et al. 2013). A fire in the rock silo may also heat the rock wall so that adjacent coal can re-ignite faster.

The propensity analysis and prevention of coal fires are in principle analogous for coal mines and underground storage, with important differences. In particular, coal mines require more detailed analysis of the coal grade (and possible flammable gases) because of the natural variation and needs to characterize and possibly treat or blend the product. In contrast, power plant storage only needs to confirm the compatibility to the fuel specifications, the fuel stock is limited to the storage, and there is much reduced hazard of e.g. methane explosions.

In the present work the emphasis is on avoiding excessive self-heating from the point of view of a power plant utility that receives specified coal to store. In-plant data is utilized as much as possible on the delivered coal batches and the operational experience from the underground storage, rather than on detailed ignition studies like those typically applied in coal mining and supply industry. Nevertheless, the experience derived from work supported by the mining and supply side is also to be acknowledged.

## 2.2 Freezing of coal

The subzero temperatures of the northern winter can be challenging for the handling, transport, storage and end use of solid fuels. In case of coal, this happens when freezing water in contact with coal forms ice that binds coal particles together and to external surfaces. The rock walls of the silos can be weakened by variation in temperature, humidity (moisture), and permeability. Expansion of freezing water can promote cracking of rock or concrete (Hall et al. 2002), but due to the associated increase in pressure, undercooling well below 0 °C is needed for complete freezing in a crack. Additional weakening can arise from multiple freezing-thawing cycles (Takarli et al. 2008, Matsuoka 2008), but more importantly, ice segregation occurs when the temperature gradient in the freezing coal or rock drives unfrozen water through a porous medium (rock, concrete drains and coal bed) towards freezing sites to grow lenses or layers of ice (Murton et al. 2006). For coal handling, freezing problems are unlikely as long the surface moisture content remains below about 4-5% (H.G. Engineering 1978, Colijn 1980, Taglio 1981, Richardson et al. 1985, Jones 1998). With sufficient surface moisture, the freezing challenge is increased by higher content of fine particles, particularly those smaller than 2 mm grain size (Jones 1998). Generally in all reported cases of coal freezing the heat flow is in the direction from coal to the environment (Colijn 1980, Sargent and Wold 1981, Glanville and Haley 1982, Carpenter et al. 2003).

Freezing of coal has been a subject of intensive studies in the 1970s to the 1980s (Glanville and Haley 1982), resulting in the development of, e.g. freeze conditioning agents (FCA) as preventive additives (EIA 1979, Martin 1980, Moaveni and Stewart 1980, Schlaff 1981, Green 1982, Boley 1984, Richardson et al. 1985). This approach is better than thawing by heating that can be challenging because of the associated cost and the low thermal conductivity of crushed coal (whether frozen or not). The previously adopted solutions like FCA have mainly been for transport by conveyors and open space rail cars, and for storage in open stockpiles, where access for preventive or corrective measures has been reasonably easy. Access to the stored fuel is much more limited in closed storage, for which recorded or published freezing incidents have been rare, and completely absent in case of underground storage to the knowledge of the author.

One of the major sources of disturbance involving frozen coal is the mechanical strength of the ice-coal aggregate, at least when FCA is not used. High strength translates to tedious mechanical removal by breakup or crushing, and the upper limit, particularly in compression, is generally given by the strength of freshwater ice. At ambient winter temperatures ice is near its melting point, and the relevant compressive strength can be often taken to be creep strength (Fletcher 1970). Creep data of freshwater ice is available e.g. from Gold (1977), Sinha (1981), Arakawa and Maeno (1997), Jones (2007), and Kim and Keune (2007). For constant grain size, at stress (strength) $\sigma$ and absolute temperature $T$, the classic Norton power law gives for strain rate

$$d\varepsilon / dt = A\sigma^{n} \exp(-E / RT) \qquad (5a)$$

or for creep strength

$$\sigma = \exp\left[n^{-1}(\ln(d\varepsilon / dt) - \ln A + E / RT)\right] \qquad (5b)$$

where $A$ is a rate constant, $R$ is the gas constant, $n$ is the creep exponent and $E$ is the apparent activation energy for creep. The commonly reported value for $n$ = 3 to 5 and for $E$ = 61-80 kJ/mol (Barnes et al. 1971, Durham et al. 1983, Arakawa and Maeno 1997, Jones 2007) for freshwater ice at strain rates below $10^{-3}$ 1/s. For example, for ice with a grain size of 1 mm and ductile failure under compression, $A = 2.7 \cdot 10^7$ 1/s, $n = 3.7$ and $E = 69.9$ kJ/mol at strain rates of $4 \cdot 10^{-6}$ to $4 \cdot 10^{-4}$ 1/s (Arakawa and Maeno 1997). The compressive strength of ice increase up to the strain rate of about $10^{-3}$ 1/s, then decreases to about $10^0$ 1/s and increases again at higher strain rates (Schulson 2001, Jones 2007, Kermani et al. 2007). At high strain rates in compression brittle failure mode can be expected up to high temperatures close to the melting point. Under tension the failure mode is consistently brittle and strength lower, not more than about 1.0-1.5 MPa almost independently of strain rate and temperature (Schulson 1999 and 2001, Mohamed and Farzaneh 2011).

In terms fracture mechanics, i.e. strength of material containing macroscopic defects, the fracture toughness ($K_{Ic}$) of polycrystalline freshwater ice is typically about 0.1 to 0.25 MPa√m in short-term tests above -25°C (Goodman 1980, Tromans and Meech 2004, Timco and Weeks 2010).

Because of significant mechanical strength of ice and materials like frozen soils, these can be used in arctic and other cold regions as structural materials for e.g. bases of buildings, mining and transport lines (Neuber and Wolters 1977, Lai et al. 2013). For similar reasons, ice and frozen solids like coal can represent mechanical obstacles in processes that are not designed for them.

Subzero winter temperatures are common in Helsinki, but the yearly mean rock temperature around the underground storage is permanently about +9°C, and therefore freezing incidents in the storage require much colder material from outside. After the zero-strength threshold of 4-5% moisture, the strength of frozen coal will initially increase in proportion to the moisture content of coal (H.G. Engineering 1978, Colijn 1980, Richardson et al. 1985). This is the starting point for modelling the strength of frozen coal in Publication IV, to consider the impact of frozen coal in the underground storage from the information available for the power plant operator. In the present work the emphasis is on explaining the extent of likely trouble in case of very cold or frozen coal entering the storage, and on considering the associated consequences, potential leading indicators, and mitigation or prevention. Cases or experience are compared below with findings of the study.

## 2.3 Occupational safety

In comparison to an above-ground stockpile, the closed underground coal storage has reduced emissions of dust, CO2 and noise, and limited employee exposure through automated remote operation. On the other hand, a closed underground storage provides more limited access at times of safety challenge. Incidents that may result in personnel injury are often associated with some exceptional circumstances during construction, maintenance or process disturbance (Jo and Park 2003, Sonnemans et al. 2010). For incidents with widely variable causes, the preventive measures and policies may mainly target the hazard exposure rather than the individual initiating causes which however also need to be analysed for the actually occurred incidents and near-miss cases (Khanzode et al. 2010, Anderson and Denkl 2010). For investigating the occurred incidents, guidelines exist for helpful advice on procedures to follow (e.g. AIChE 2003).

Accidents typically do not happen without a combination of causal and contributing conditions and events, so that a harmful consequence requires penetration of all individually sufficient safety barriers (Figure 4). Especially under exceptional circumstances, easier or temporary opportunities for penetration may easily appear (Reason 1990, 1997 & 2008, Hollnagel 1998, 2009 and 2010, Perneger 2005, Ren et al. 2008, Weissenborn 2011) if there is insufficient effort to maintain intact barriers. An automated and remotely controlled normal operation of the underground storage does not call for direct human involvement. Hence, exposure to safety hazard can be expected to concentrate on the periods or events of process disturbance or maintenance requesting human intervention (Figure 5).

According to reported statistics and experience from power plants (Williams 1986 & 1988, Jo and Park 2003), under certain conditions the likelihood of human error can be expected to increase. Such conditions include in decreasing order of impact:

- unfamiliarity with rare or new hazards
- short time for error detection and correction
- easy override of the safety precautions at times of disturbance
- mismatch between views of the operator and designer or on views between perceived and real risk
- operator inexperience, and
- loss of information in communication.

The related experience strongly suggests that important remedial actions include training and coaching to promote risk awareness and safety culture (Swain and Guttman 1983, Ricci and Rowe 1985, Gertman et al. 2005).

The design and operation involves a range of measures to deal with the recognised or anticipated health and safety hazards that are listed in brief with the outlined mitigation measures in Table 1. The safety system has been designed to protect the personnel and equipment, with features described in Table 2.

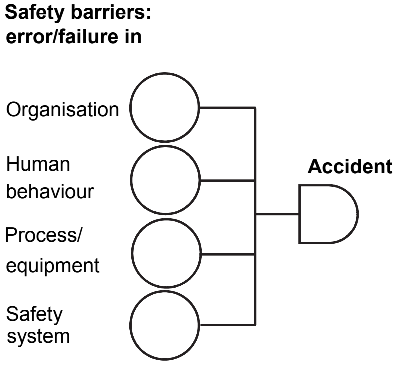


**Figure 4.** Fault tree of an accident that requires simultaneous errors or failures in organisational performance, human behaviour, process/equipment and safety system (partly adapted from Jo and Park 2003)

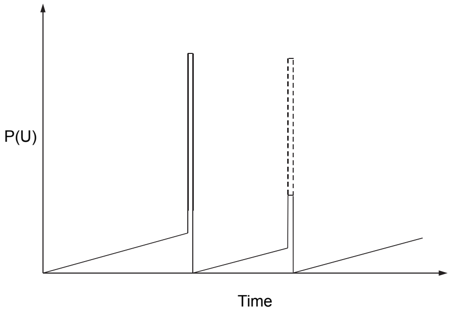


**Figure 5.** Increased accident probability P(U) in exceptional circumstances (e.g. process disturbance or maintenance) compared to normal operation with a conventional approach in the first event and reduced P(U) for the second event with added safety measures (schematic, adapted from Jo and Park 2003)

**Table 1.** Recognised health and safety issues and mitigation measures (Sipilä and Auerkari 2010)

| Hazard | Control / mitigation | Notes |
|---|---|---|
| Coal fire | Alarms, sealed air access, extinguishers, avoid heated coal | Early alarm, training to avoid escalation |
| Oil fire | Alarms; diesel vehicles only; avoid storing much oil underground | Fire-resistant oils to be preferred for e.g. hydraulics |
| High CO and/or $CO_2$ | Alarms, ventilation, safe exits | |
| Oxygen < safety limits | Alarms, ventilation, safe exits | $N_2$ purging will reduce $O_2$ |
| Dust explosion | Cleaning and coal selection | Water wash, crusher cyclone |
| Gas explosion | Protected electrical equipment | Also use of diesel vehicles |
| Burns and other injuries | Use of protective equipment | According to instructions |
| Smoke from coal fire, car or other flammables | Venting, booster fan (on trailer); only diesel vehicles allowed | Booster fan used by city fire brigade |
| Coal dust (health) | Cleaning, coal selection | Limited human presence |
| Reduced light in storage (accident hazard) | Maintenance: emergency lighting with battery backup (60 min) | Additional lights may be needed at points of working |
| Limited opportunities for communication | Underground base station network to support mobile phones | Fire service phone socket in all 65 service points |
| Limited number of and lengthy routes to exits | Design for short term exit at least in two directions | Exit directions indicated by emergency lighting |
| Time to access points for mitigating action | Service points with water, electricity, compressed air, alarms | Mean distance to a service point 75 m |
| Hot work, e.g. welding, grinding, heat treatment | Hot work permit, communication, post-confirmation of no ignition | Fire alarms to be reactivated if disconnected for hot work |

**Table 2.** Features of the safety system

| Issue | Action / features | Notes |
|---|---|---|
| Training before allowing access | All personnel working underground | Also subcontractors & fire brigade |
| Confirmation of training success | Passing a written exam | Proficiency and competence |
| Monitoring of presence, use of safety equipment | Log of personnel, gas sensor, rescue hood, mobile number | Log of entering & returning personnel at control room |
| Preventing ingress of smoke/ toxic gases to emergency exits | Overpressure in shafts and lifts | To provide safe exiting time |
| Safety information system | Visualised hot spots, air flow, fire shutters, smoke fans, gases | Visual mapping, to help e.g. firemen to assess the current situation |
| Technical service points | Alarms, lights, water, phone, electricity, pressurised air, ventilation | 65 service points (every 75 m) for fire brigade |
| Emergency stop of ventilation | Fire: shutdown of fans, closure of fire shutters in ventilation channels | Manual from the control room; fire shutters only close in extensive fire |
| Gas / danger alarms | Silo alarm lights and sound | High CO, $CH_4$, low $O_2$ |
| Alarms on conveyor start | Alarm light and sound | Short alarm only |
| Emergency lighting | Battery back-up | 60 min reserve |
| Smoke removal | Boosted by power fan (on trailer) | Managed by city fire brigade |
| Sprinkler system + water posts | Water spray for tunnels & conveyors | Water posts at service points |
| Nitrogen and foam systems | Above (both) and below ($N_2$) silos | |
| Post-fire / heating control | Removal of heated coal | Monitor (thermal imaging) |
| Thermal (infrared) sensors | Before and after silos | Sensitive to dust, dirt, moisture |
| Ventilation & monitoring of gases | Ventilation of CO, $CH_4$, $H_2$ / silo roof | Monitoring of CO, $CH_4$, $O_2$ |
| Prevention of dust explosions | Cleaning of coal dust (water wash) | Also cyclone at coal crusher |

The recorded cases in the coal storage (see Sipilä et al. 2013) are consistent with the types thought to be most likely, i.e. incidents involving relatively simple types of “slips, trips and falls from height” or “caught between”, or “struck by” incidents, affecting in each case singular individuals only. Assuming that the hazard and related statistics are sufficiently comparable, it may be appropriate to describe the associated risk in a hierarchical way (see Wright and van der Schaaf 2004, Anderson and Denkl 2010, Khanzode et al. 2010, Kleindorfer et al. 2012). As outlined in Figure 6, fatalities in such incidents are much less common than injuries leading to lost working time, but the consequences of fires and coal mine incidents may be particularly severe. A common lagging (historical) safety indicator in e.g. large construction projects or in large companies can be the number of incidents per million work hours. Leading or forward-looking indicators can be related to safety walks, observed adherence to safety instructions, and rewarding of safety-promoting initiative (Eiden 2013, Pust and Müller 2013). Note however that reduction of personnel through automation can also reduce the yearly work-hours to such an extent that it may become a challenge to measure the safety indicators to a satisfactory accuracy.

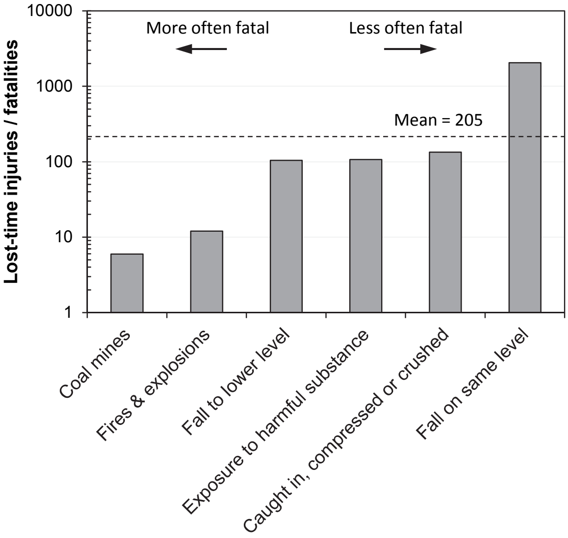


**Figure 6.** Ratio of injuries to fatalities: data from Indian coal mines (with "serious injury" only, 1981-2004, Khanzode et al. 2010), other data including the indicated mean of 5657 fatalities and 1158870 lost-time injuries recorded by the US Bureau of Labor Statistics in 2007, as quoted by Anderson and Denkl (2010); note that the categories of "caught in etc.", "fall to lower level" and "exposure to harmful substance (or environment)" could be relevant to the example cases of the present work (see Sipilä et al. 2013).

# 3 MATERIALS AND METHODS

## 3.1 Self-heating and spontaneous combustion

After the first major spontaneous combustion incident in 2008, an investigation was launched by the operator to evaluate the causes and procedures of extinguishing coal fires (Sipilä 2009). This initial effort was extended to a further assessment of subsequent autoignition incidents, the fault and event trees, associated risk and contributing factors such as properties and condition of transported coal and the silos (Publications II-IV). The information and experience of the plant personnel from the incidents were collected by interviews in 2009 and 2010. The observed fire incidents were used to highlight the complexities in avoiding and extinguishing smouldering underground fires. The incident experience was used to develop a risk matrix and a proposed set of leading and performance indicators for smoldering fires. To assess the potential influence of coal grade, the properties were reviewed for more than 600 bituminous coal batches (shiploads) delivered to the operator over a period of ten years (2001-2010). This amounted to a total of about 7.5 million tons, consisting of about 3 million tons of Polish and 4.5 million tons of Russian coal with a similar mean heating value of about 7.85 MWh/ton (LHV) delivered as batches (shiploads) of 2000-31 000 tons. Each batch was characterised in an on-site laboratory for e.g. moisture and volatiles content, and heating value. Before entering the silos, coal is crushed so that the maximum size of the smallest dimension is 30 mm (for more details see Publication IV). For improvement, the emphasis was in seeking methods and approaches that could be applied as much as possible with the existing facilities and for the specified coal grade.

## 3.2 Freezing of coal

Observed incidents of coal freezing in the Salmisaari storage have first been described by Sipilä and Auerkari (2010) and in Publication II, and further analysed in Publication VI. Fault and event trees have been created to describe the causes and progression of events leading to discharge blockage and operational disturbance of the storage facility (Publication II). To understand the mechanical characteristics of frozen coal responsible for the blockage and its resistance to attempts of clearance, the strength of frozen coal has been modelled (Publication VI) by combining a creep rupture model of freshwater ice and the available strength data for ice from Gold (1977), Sinha (1981), Arakawa and Maeno (1997), Jones (2007), and Kim and Keune (2007), and for frozen coal from H.G. Engineering (1978), Colijn (1980), and Richardson et al. (1985), the measured moisture content of bituminous coal batches delivered to the storage before the freezing incidences, and sub-zero temperature data of Helsinki in 1971-2000, provided by the Finnish Meteorological Institute. For comparison and background information, operator experience of the coal freezing incidents was gathered by interviewing the power plant personnel and operators in 2009 and 2010. The results were used to propose a risk matrix and a set of leading and performance indicators for coal freezing, also to consider the future development of the associated risk.

## 3.3 Safety issues of the storage facility

Safety is an obvious issue of interest for all fuel storage facilities, largely but not exclusively due to the fire hazard. This work is addressing the experience, prevention, impact and mitigation of safety related incidents in the storage facility. The most common expected type of accident in the storage facility involves relatively simple occupational events, such as “slips, trips and falls from height” or “caught between”, or “struck by” type of incidents, leading in the worst case to injury or death of one or a few individuals (cf. Attwood et al. 2006). Based on the recorded and mostly also previously published incidents (TVL/TOT 2003, TVL/TOT 2009), case examples of selected hazards and observed accidents have been analysed and described in terms of fault and event trees, and discussed for improvement of safety by preventive, corrective and mitigating measures (Publication V). Also, leading and performance indicators have been considered for the purpose.

# 4 REVIEW OF THE FINDINGS

## 4.1 Self-heating and spontaneous combustion

In case of the Salmisaari storage facility, CO, CH4 and O2 (gas) sensors, and ambient air temperature monitoring, are mostly used. In case of doubt, hand-held thermal imagers and pyrometry can also be applied, for example, to detect heated coal on conveyors (Publications I-IV).

Beyond these methods, only few techniques appear to be available, such as the measurement of electric resistance (Tanaka et al. 2004, Li et al. 2005), which is not used in Salmisaari. In this approach, the hot spot is detected from its temperature-dependent change in the electrical conductivity, so that the distribution of electrical potential corresponds to the intensity and distribution of the heat source.

When excessive heating or fire is detected, cooling or extinguishing is carried out with abundant water if the hot spot is near the surface. Otherwise, nitrogen injection can be applied, typically combined with discharge of the heated coal from the silo when possible.

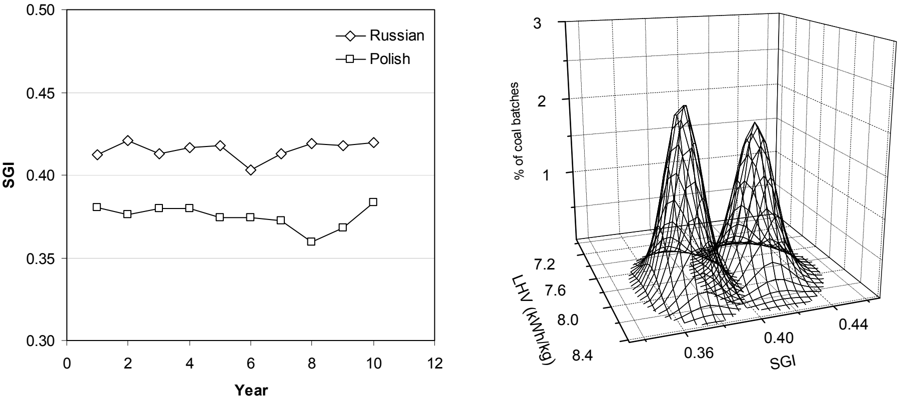
The complexities in avoiding and extinguishing underground fires are highlighted by the case example, describing the observations and outcome of an extended smouldering fire in 2008 (Publications I-III). The principles and critical factors in self-heating and spontaneous combustion such as the condition of the environment and quality of coal are fairly well known (Smith and Lazzara 1987, Davidson 1990, Fierro et al. 1999, DMT/BAM 2000, Ray et al. 2000, Carpenter et al. 2003, IMO 2009, Nalbandian 2010), but may only provide partial help in fire prevention. Efficient fire extinction during power plant operation can be also challenging, as any air ingress tends to feed the fire and result in losses of the extinguishing agent and the heating value of coal (Hull et al. 1997a, 1997b, Tuomisaari et al. 1998, Vierro et al. 2001, Sipilä and Auerkari 2010, Auerkari et al. 2011, Lerena et al. 2013).

### 4.1.1 **Factors affecting the likelihood of self-heating and spontaneous combustion of coal**

Methods have been sought to assess the (intrinsic) self-heating propensity of bituminous coals. One challenge is that all coal-specific properties that can influence the likelihood of self-heating and autoignition (see Publication I) are not routinely measured from commercial deliveries. It has been shown that the content of volatile matter and intrinsic moisture reflect the self-heating potential of coal of a given particle size (Smith and Glasser 2005). Decreasing the particle size can promote self-heating, but the effect is not initially significant before considerable heating well above the room temperature (Smith and Glasser 2005, Fei et al. 2009). To explore the applicability of this approach, the recorded properties of more than 600 coal batches (shiploads; about 7500000 metric tons in total) were reviewed and compared to the experience on incidences of self-heating and autoignition (see Publications II-IV). Moisture is partly held relatively tightly in the coal particles and their pores and microcapillaries (intrinsic moisture), and only partly externally on the outer surfaces and between particles (Karthikeyan et al. 2009). The intrinsic moisture correlates with the reactive surface area, and the volatile content roughly indicates the extent of lighter and more easily flammable combustibles in coal than carbon. These variables appear to stand out as the most significant indicators in a statistical evaluation of early self-heating (Smith and Glasser 2005). Unfortunately unlike total moisture, intrinsic moisture (see ASTM D 1412-99) is not routinely recorded for commercial deliveries. Nevertheless, a comparison of the literature information (Publication IV) suggests a reasonably constant ratio (1.5 to 2.5) of total to intrinsic moisture content for a given type of coal. Accordingly, a modified Smith-Glasser index (SGI) was proposed as

$$SGI = 0.89 \cdot m^{0.14} \cdot v^{0.43}, \qquad (1)$$

where $m$ is the (total) moisture (%) and $v$ is the dry content of volatiles (%) in coal. A comparison is shown in Figure 7, suggesting a consistently higher index for Russian than Polish coal. It is notable that all significant fire incidents in the Salmisaari storage facility have involved Russian coal or its batch interface. It is hence suggested that the modified Smith-Glasser index (SGI) can serve as a leading indicator of the self-heating propensity.



a) b)

**Figure** 7. a) Mean modified SGI (using total moisture) in 2001-2010; b) normalised distributions of modified SGI for all coal batches 2001-2010 (left side: Polish coal); Publication IV

More complex indices can be constructed for the ignition propensity, but these will also require additional measurements (Wang et al. 2009, Mohalik et al. 2009, 2010, Auerkari et al. 2011), and for quick screening and comparison of coals, the simplicity of modified SGI appears attractive.

With evolving technology, new risk issues may emerge (cf. IRGC 2010). New challenges could arise from the increasing use of biomass fuels that similarly to low-rank coals have relatively high volatile and moisture contents, ignite easily when dry, and have low heating values and densities such that high volumes are needed for an equivalent energy content. It remains to be seen whether the modified SGI could also be used to rank the intrinsic self-heating propensity of such fuels.

The overall likelihood of self-heating will naturally involve other than purely intrinsic factors. Coal entering conveyors and storage can already be heated, and heating may be further promoted by the excessive ingress of air to the coal bed. In such cases, it is important to extract heated coal and divert it to combustion as soon as possible, and to seal off the air leaks, particularly if leakage occurs from below.

### 4.1.2 Fire incident in 2008

A smouldering fire in silo no. 4 was first indicated by elevated CO levels on 15th September 2008, and lasted for four months. The silo contained mainly Russian coal, with an approximately one metre layer of old Polish coal at the bottom. Nitrogen injection (Figure 8) was initiated but was not fully successful before discharging the silo completely. Thermal images showed two hot spots on the silo surfaces, one next to a maintenance door and another at nearly the opposite side of the silo (Figures 9 and 10). Upon discharging, a relatively strong steam flow was observed next to the bottom maintenance door and the concrete wall (Sipilä 2009).

**Figure 8.** Nitrogen injection at the Salmisaari plant during the worst fire incident in 2008. Photo: Juha Sipilä/Helsingin Energia

Inhabitants in the vicinity of the plant complained about the noise of the ventilation fan and a smell of hydrogen sulphide. No production limits were introduced during the incident, but personnel traffic in the storage was only allowed with oxygen breathing support. During discharge, a thin bottom layer of cool coal from another silo was sufficient to protect the conveyor belt from the impact of heated coal. Otherwise, the belt was watered for additional cooling using a sufficient water flow to prevent significant formation of explosive gas mixtures.

Cracking and spalling of the shotcrete in the silo wall was observed in an area corresponding to about one third of the wall area, which is in contact with coal when the silo is full. A temperature difference of approximately 120˚C in the adjoining layers was estimated to spall the shotcrete of the rock surface, not necessarily requiring that the fire would touch the wall. The damage at the bottom maintenance door (Figure 10) with partly burnt coal, ash and hard slag around the opening suggest a nearby hot spot where this provided air ingress during the fire. The measured surface temperature on the door was 350˚C, which was enough to damage the seal of the door frame. The concrete surfaces near the silo also suffered damage near the discharge cone, silo ceiling and nitrogen injection tubes. The bellows of the discharge cone had nearly completely burnt, providing additional air ingress.

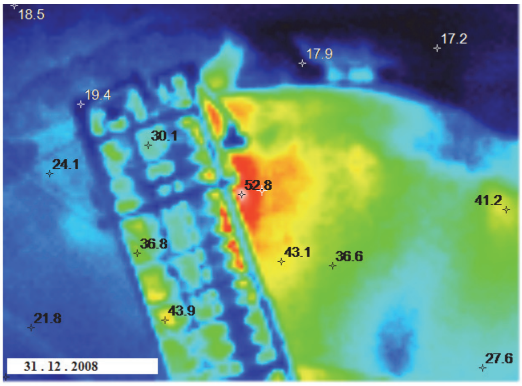


**Figure 9.** Thermal image of a hot spot in the silo. Photo: Mikko Sillanpää/Helsingin Energia

**Figure 10.** Inside appearance of the bottom maintenance door opening after a smouldering fire in the silo. Photo: Juha Sipilä/Helsingin Energia

### 4.1.3 Fire risk management: prevention and mitigation

The current system to extinguish fires in the Salmisaari silos is using nitrogen which however is relatively costly, takes time (delivery, filling, holding and venting of N2) and prevents human presence in the storage during the extinguishing work cycle of about two days. Ventilation afterwards with smoke venting fans is noisy and disturbing to people in the plant vicinity. Relatively small smouldering fires have been successfully extinguished using water with a fire hose, for example, by directing the water flow near the silo wall drains that appear to facilitate air ingress. The advantages of water include good availability, low cost and no need for subsequent venting or limits to personnel access. Water is only suitable for extinguishing fires on conveyor belts or close to the top surface layers of coal in the silos. Water on conveyor belts tends to encourage the sticking of fine coal particles to the belt, potentially disturbing belt alignment and cleaning during operation.

For example fly ash mixed with water can be useful for fire prevention by sealing coal beds from air ingress in open stockpiles (Kenneth et al. 2006), but it has not been tested for the top side of a closed storage. A closed storage facility can be easier to seal, but it may provide less cooling than open stockpiles if the air flow is only through leaks from drains or other channels of the coal bed. Increasing time in storage for up to approximately six months also appears to enhance the hazard of self-heating and autoignition (Carpenter et al. 2003, Nalbandian 2010). In principle the probability of autoignition can be reduced by ensuring that the storage is dry, cool and clean. Coals with highly differing qualities and grain sizes should be stored separately, and strongly self-heating coals should be used first (Fierro et al. 2001).

Table 3 shows a comparison of the experience from the Salmisaari facility with that of the Värtan underground facility in Sweden (Alsparr 2000) and of the Tiefstack above-ground silo storage in Germany (Rosner and Röpell 2011). Table 4 compares typical fire retardant and fire fighting media.

**Table 3.** Comparison of selected closed storage facilities (Alsparr 2000, Sipilä and Auerkari 2010, Publication I, Rosner and Röpell 2011), in all cases last in first out (i.e. oldest coal last out); for more details see Publications II and III)

| Issue or feature | Salmisaari (FI, underground) | Tiefstack (DE, above-ground) | Värtan (SE, underground) |
|---|---|---|---|
| Principles of excluding or reducing air access | Coal to silos in thin even layers, closed storage, tight doors, drains, etc. | Coal to silos in 0.2 m layers, closed storage, tight doors, drains, etc., gel or sand bags on top | As free-standing piles in storage caverns |
| Observed or suspected air ingress from | Maintenance door, hopper, bellows, drain pipes, loose coal | Inspection doors, drain pipes and fittings | See above |
| Thermal draft in silo | Anecdotal evidence only, along rock walls and wall drains | Air leaks amplified by draft due to heated coal and low outside temperature | See above |
| Self-heating & fire detection from | CO, CH4, O2 detectors + odour (human nose) | CO, CH4, O2 detectors + thermal imager | CO detectors |
| Alarm indication by | Mainly CO, odour | Mainly CO | Mainly CO |
| Observed incidents | Reported cases of self-heating and fires | Only self-heating cases reported | Self-heating occurred |

**Table 4.** Comparison of media used against self-heating and fires in closed storage facilities

| Medium | Advantages | Limitations | Notes |
|---|---|---|---|
| Water (spray) | Cheap, widely available, with cooling effect | To be applied in large quantity, reduces the heating value, can reduce coal flow | Can form flammable water gas ($CO+H_2$) if not used in abundance |
| Fire-fighting foam | Relatively cheap, easy to apply, with cooling effect | Reduces the heating value, can reduce coal flow | Can make substrate surfaces greasy or sticky |
| Nitrogen | Fully inert, cooling medium, replaces oxygen, can be introduced from below | Expensive, diluted if not contained in a gas-tight system, will limit personnel access | Requires venting afterwards |
| Fire-retardant gel | Reduces through-bed air flow and loss of heating value, low tendency to reduce coal flow, cheaper than $N_2$ | Requires proper and even spreading to be effective | Prevents quick water evaporation and formation of $CO+H_2$ on hot coal surfaces |

An explosion can occur in flammable gases, such as methane, CO, hydrogen and light hydrocarbons, in coal dust, or both together (hybrid explosion). Coal dust can ignite as a suspended dust bed in air, or as a precipitated dust layer, with the igniting energy that can be provided by a spark or even human static discharge. For prevention, dust formation can be controlled by process design, but the amount of coal dust usually remains small with a typical water content of about 8-12% (Grossman et al. 1995, Carpenter et al. 2003).

Some self-heating in the Salmisaari storage will probably occasionally occur also in future. To reduce or avoid autoignition events, selecting and maintaining a proper grade, grain size and temperature of the stored coal remains important. Sufficient air tightness should be provided particularly for the lower parts of the silos. From the consequence point of view, a worst case fire could damage the main conveyors, disabling the storage and the power plant during the critical winter months.

The fault and event trees (Figures 11a and 11b) aim to show in an abbreviated manner the incident of the autoignition case. The essential causative factors promoting self-heating and spontaneous combustion include air ingress, high moisture and volatiles (reactivity) of coal, and extended time in silo (or in transport) to self-heat. These factors will also provide the basis for the suggested leading indicators of smouldering fire.

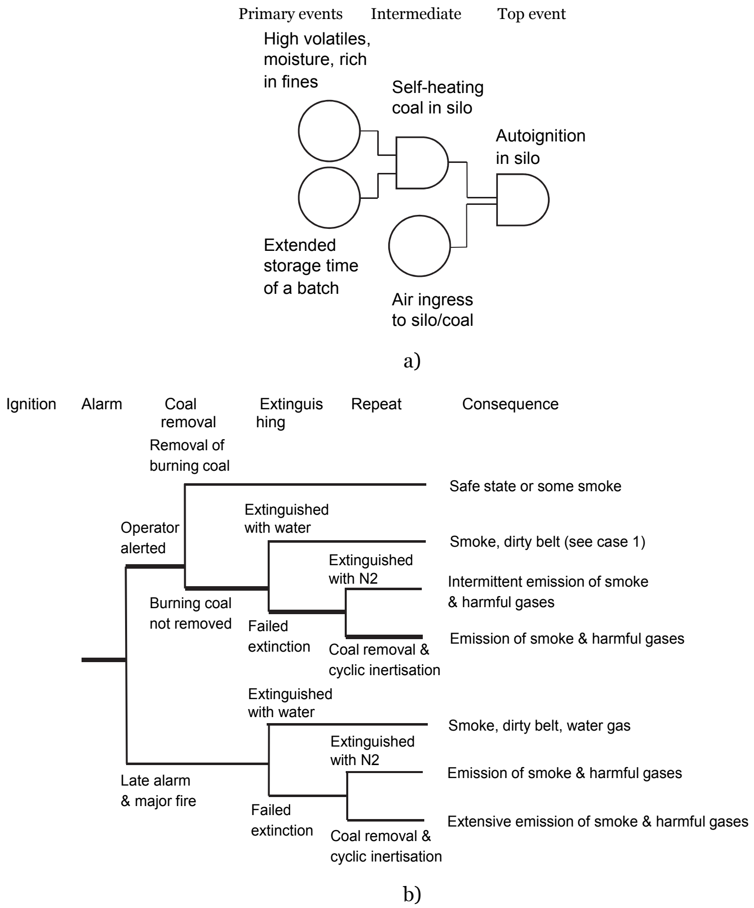


**Figure 11.** Abbreviated a) fault tree and b) event tree presentation for assessing the risk of self-heating and autoignition incidents in the underground storage silos; the thick line shows the event path of the case example (adapted from Publication III)

A tentative 4 x 4 risk matrix related to in-storage fire incidents was developed in cooperation with the plant personnel, and is shown in Figure 12, with an estimated position of the 2008 fire incident. The experience suggests that, with attention to the coal grade and handling, suitable order and timing of silo filling and discharge, and well maintained capabilities of both equipment and personnel, the fire risk has been significantly reduced from the time of early operation and the most severe fire incident.

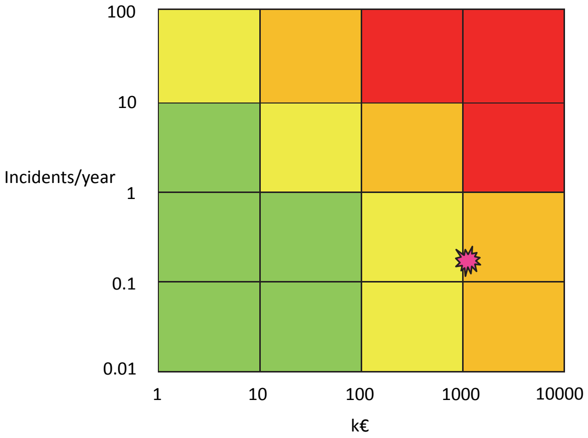


**Figure 12.** Suggested risk matrix for self-heating and spontaneous combustion incidents in a closed coal storage facility; red = immediate action required; orange = action required within defined time; yellow = tolerable; green = minor to negligible risk; the marker shows the estimated position of the 2008 fire incident (adapted from Auerkari et al. 2013).

## 4.2 Coal freezing

To assess the accompanied risk and options, the strength of frozen coal has been modelled from the expected behaviour bounded by the extremes of moisture content. Based on the strength model and realistic distributions of the input variables (Publication VI), a Monte Carlo analysis has been used to assess the expected strength of frozen coal under the local winter climate (Figure 13). The results suggest that the strength of frozen coal in the discharge hoppers is typically sufficient to render immediate remedial action tedious and problematic, explaining the observed challenges to plant operation.

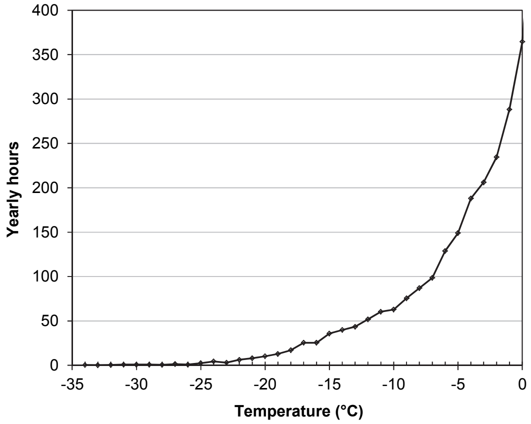


**Figure 13.** Distribution of subzero temperatures in Helsinki (1971-2000; data from the Finnish Meteorological Institute; Publication VI)

### 4.2.1 Coal freezing incidents

The relatively cold winter of 2009-2010 was reflected in a high demand for district heating from the Salmisaari plant, and in corresponding coal consumption. In February 2010, two of the storage silos were unavailable, and two batches of cold coal with total moisture of 14% and 10% were introduced to the remaining two silos when the outside temperature was -8°C and -15˚C, respectively. After a few days, initiated discharge from the silos with cold coal was interrupted by large frozen ice clumps that blocked the discharge hoppers above the horizontal conveyor. The buckets of the vertical conveyor were also blocked and required repeated manual cleaning work. Manual unblocking and thawing by heating was not sufficient to restore fuel flow to the power plant, and additional truck transport from another above-ground stockpile was initiated. In addition, the reserve fuel of heavy fuel oil was not available either due to the cold weather that rendered the necessary oil heating system insufficient. The disturbance resulted in added costs due to power derating and external energy supply, additional labour and maintenance, and transport of replacement fuel. The disturbance was only ended with the arrival of a shipment of unfrozen coal. It turned out that icy clumps were forming within cold coal from the groundwater leaking to the coal bed from the surrounding rock after the wall drains were first frozen by cold coal. An unexpected feature of the incident was freezing with heat flow from the surrounding rock of the storage wall into coal (Publication VI). As far as is known, in all other reported cases of coal freezing, the heat flow is in the opposite direction, i.e. from coal to the environment (see e.g. Colijn 1980, Sargent and Wold 1981, Glanville and Haley 1982, Carpenter et al. 2003).

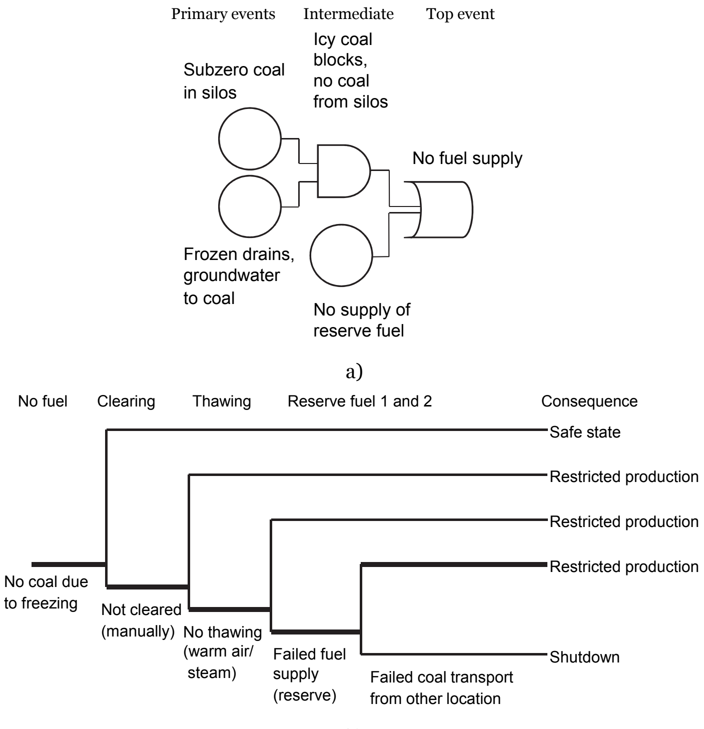
The following winter was also colder than average, and a batch of coal with 12% total moisture was partly frozen in December 2010 at the harbour hoppers during discharge from ship. Operating the coal feed to crusher and further to the underground storage became too slow at an ambient temperature of -19°C, even when attempting to assist the coal flow by manual clearance and steam thawing (Figure 14). Unlike in the freezing event of the previous winter, the coal batch apparently already included frozen clumps that could not pass the hopper grills, and the incident represented the more conventional case of freezing due to heat flow from coal to the environment. Neither case apparently involved a third possible mechanism that may occur e.g. inside hoppers, when coal includes freezing slosh (partly liquid water) that adheres together under compression rather like a snowball. For receiving and storing individual batches of coal arriving by marine transport to Salmisaari, freeze-conditioning agents (FCAs) have not been considered cost-effective. However, a partly new situation was created by the commencing of underground storage in 2004. FCAs would be less likely to fully prevent freezing of the inward flowing seepage water in the case of the first incidence.

**Figure 14.** Steam thawing (here almost completed) of a harbour hopper blocked by frozen coal; note residual frozen lumps on the grille. Photo: Juha Sipilä/Helsingin Energia (Publication VI).

### 4.2.2 Modelling for coal freezing hazard

The hazard of coal freezing can be affected by the modes of transport as, e.g. the transport equipment may add some water, ice or snow already before loading, during transport or in intermediate storage. Layers of frozen coal may be produced by refreezing and thawing, so that even after crushing solid icy blocks form to hamper end user operation. Coal transported in subzero weather may be so dry that it is not prone to freezing. However, as shown for the Salmisaari facility (Publications II and VI), very cold coal can freeze the silo drains, resulting in clumps of ice to effectively block the coal flow at the bottlenecks of the transport system, such as the discharge bins and conveyors.

Proposed fault and event trees for the freezing incident in Salmisaari are shown in Figure 15. In this case the critical event is failed supply of coal and reserve fuel (heavy fuel oil) to the power plant.



a)

b)

**Figure 15.** Abbreviated a) fault tree and b) event tree for lost fuel supply due to frozen coal; the thick line shows the event path of the case example (adapted from Publication II).

The essential contributing factors in coal freezing are the temperatures of coal and the environment, cooling rate, (surface) moisture and particle size (Taglio 1981). For the bituminous coals considered here, the distribution of moisture content was reasonably normal, with the mean at 11% (Figure 16).

For frozen coal to become problematic, it must have sufficient mechanical strength. A relatively wide distribution of particle sizes is generally more of a freezing challenge than more evenly coarse-grained coal, since fine particles filling the interparticle spaces can help to form ice bridges (Taglio 1981). Otherwise, higher surface moisture (at least 4%), faster loading, decreasing solute content, reduced bubbles or other defects, and decreasing temperature will increase the compressive strength of frozen coal (H.G. Engineering 1978, Colijn 1980, Taglio 1981, Richardson et al. 1985).

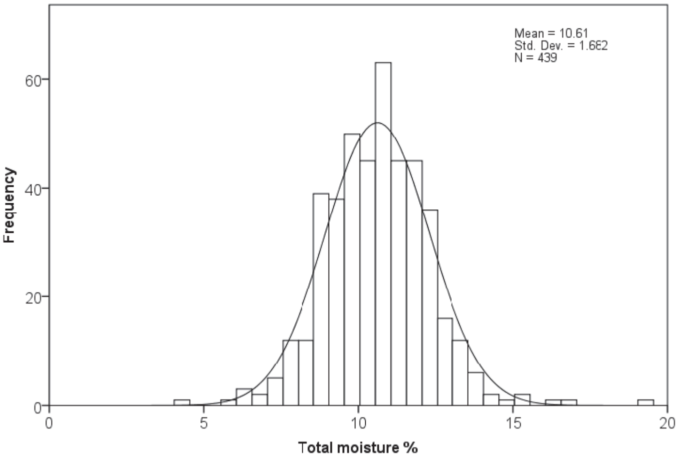


**Figure 16.** Distribution of measured total moisture of the coal batches (Russian coal; Publication VI)

To model the compressive strength of frozen coal, the upper limit was taken to correspond to the strength of freshwater ice, with data from Gold (1977), Sinha (1981), Arakawa and Maeno (1997), Jones (2007), and Kim and Keune (2007). For ice with a constant grain size, at stress (strength) σ and absolute temperature T, the common Norton law gives for strain rate $d\varepsilon/dt = A\sigma^n \cdot \exp(-Q/RT)$, where A is a rate constant, R is the gas constant, n is the creep exponent, and Q is the apparent activation energy. For example, for ice with a grain size of 1 mm and ductile failure under compression, $A = 2.7 \cdot 10^7$ 1/s, n = 3.7 and Q = 69.9 kJ/mol at strain rates of $4 \cdot 10^{-6}$ to $4 \cdot 10^{-4}$ 1/s (Arakawa and Maeno 1997). The values of n and Q are within the commonly reported range with n = 3.2-5.1 and Q = 61-80 kJ/mol (Barnes et al. 1971, Durham et al. 1983, Arakawa and Maeno 1997, Jones 2007) for freshwater ice at strain rates below $10^{-3}$ 1/s. The strength of frozen coal is taken to be initially proportional to the moisture content *m* above a critical moisture level that corresponds to zero strength (H.G. Engineering 1978, Colijn 1980, Richardson et al. 1985). To comply with the asymptotic behaviour towards low and high moisture content, the suggested model for the compressive strength of frozen coal (Publication VI) is

$$\sigma_C = \sigma_i \cdot \left[ \frac{2}{1 + \exp\left[-2k(m - m_0)/\sigma_i\right]} - 1 \right] \tag{1}$$

where $m_o$ is moisture content at zero strength and *k* is the slope of the strength-moisture curve at this point. Close to $m_o$, the predicted strength increases nearly linearly with *m*, and approaches the strength of ice at high values of *m* (Figure 17). In general, the compressive strength of ice increases up to the strain rate of about $10^{-3}$ 1/s, then decreases up to the strain rate of approximately $10^{-1}$ 1/s and finally increases again at higher strain rates (Schulson 2001, Kermani et al. 2007, Jones 2007). At high strain rates, ice will show brittle failure up to temperatures close to the melting point. The failure mode is also brittle under tension, with a much reduced and nearly constant strength, about 1.0-1.5 MPa practically independently of the strain rate and temperature (Schulson 2001, Mohamed and Farzaneh 2011). The tensile strength of frozen coal (in MPa) can be approximated by

$$\sigma = D \cdot m - G \tag{2}$$

where with a tensile strength of 1.3 MPa for ice, D = 0.0363 and G = 0.15, independently of strain rate (above $10^{-4}$ 1/s) and temperature at least above -20°C (Schulson 1999, Mohamed and Farzaneh 2011).

The predicted compressive strength of frozen coal from the Eq. (1) is shown as a function of total moisture in Figure 17 for the upper and lower range of published test data (H.G. Engineering 1978, Colijn 1980, Richardson et al. 1985) at -20°C and a strain rate of $4 \cdot 10^{-4}$ 1/s. The corresponding tensile strength according to Eq. (2) is also shown in Figure 17 for strain rates of at least $10^{-4}$ 1/s. As the packing density, particle size distribution and ice crystal adherence can introduce much scatter to the levels corresponding to the strength range of Figure 17, the lower limit of the compressive strength can be negligible even with sufficient moisture in a subzero environment. However, winter transport to Salmisaari may well provide enough time for ice bridging between coal particles, and as seen from Figure 16, as a rule there is sufficient (> 6%) moisture content in most batches received.

In reality, the variables of the strength model (1) can vary within a certain range, and hence the strength is better characterised by a distribution of expected values. Assuming a range of the values for strain rate, moisture, temperature and model constants according to observations and experience, the corresponding strength distribution can be extracted using the model and the Monte Carlo approach (here with $5 \cdot 10^4$ repeats). This has been done in Figure 18 for the strength model of Eq. (1), using a strain rate evenly distributed in the range $4 \cdot 10^{-6}$ to $4 \cdot 10^{-4}$ 1/s, a strength level evenly distributed between the upper and lower lines of Figure 17, observed distribution of the total moisture content of the coal batches (Figure 16), and an ambient subzero (below 0°C and below -10°C) temperature distribution in Helsinki (cf. Figure 13). The results shown in Figure 18 suggest that the most likely level of compressive strength is about 1.8 MPa for all subzero temperatures, and about 2.2 MPa for temperatures below -10°C. The distributions are upwards biased, so that the expected strength is higher than these values in more than 50% of the cases. The expected values of compressive strength are thought to be well sufficient to make frozen coal tedious to remove when confined by the hopper walls. The situation can be even worse if blocks of pure ice can form within the coal bed, since at challenging subzero temperatures below -10°C and at high strain rates (like in crushing), the expected compressive strength of pure ice is approximately 3-20 MPa (Jones 2007), i.e. much higher than that shown in Figure 18 for frozen coal (see Publication VI).

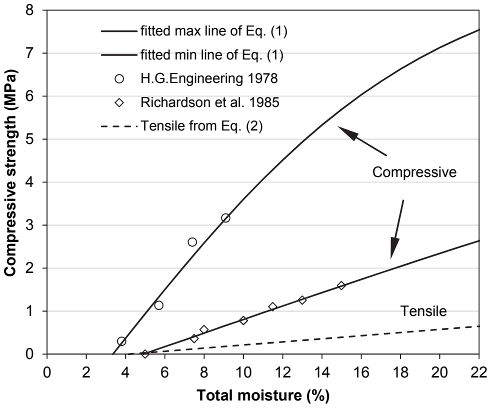


**Figure 17.** Predicted strength of frozen coal for the upper (H.G. Engineering 1978, Colijn 1980) and lower bound (Richardson et al. 1985) of test data at -20°C, with fitted lines from the model Eq. (1) at strain rates of about $10^{-4}$ 1/s (Publication VI)

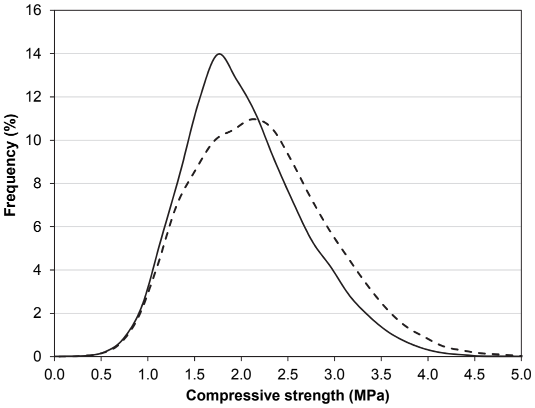


**Figure 18.** Compressive strength of frozen coal from the Monte Carlo prediction using Eq. (1) with evenly distributed ranges of k and $m_0$ between max. and min. strength lines, an evenly distributed strain rate of $4 \cdot 10^{-6} \ldots 4 \cdot 10^{-4}$ 1/s (Publication VI); moisture content distributed as in Figure 16, and ambient temperature distributed as in Helsinki (Figure 13, solid line for all subzero temperatures and dashed line for temperatures below -10°C).

### 4.2.3 Freezing risk management

A tentative risk matrix related to storage freezing incidents is proposed as outlined in Figure 19, with the estimated position of the first 2010 freezing incident. So far, the experience suggests that, with attention to the appropriate risk indicators, the freezing risk has been contained to a significantly reduced level in comparison to the time of early operation of the storage facility. This requires proper sourcing and timing of wintertime deliveries, to avoid receiving very cold coal batches that could result in drain freezing. A useful sign of an overly cold batch can be an unusually high dust emission that may indicate lack of dust-binding unfrozen water at subzero harbour discharge.

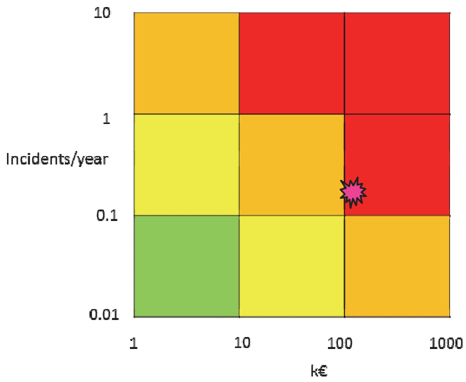


**Figure 19.** Suggested risk matrix for in-silo coal freezing incidents; red = immediate action required; orange = plan/implement preventive/mitigating action; yellow = tolerable; green = negligible risk; the marker shows the estimated position of the first 2010 freezing incident.

If a very cold batch is received, but it cannot be redirected and stored elsewhere, it is preferably stored in silo no. 4 that shows the lowest drain water flow rate (about tenth of that in silo no. 1; see Table 5). In this silo the maximum water flow (in 2010) and therefore also the ice formation rate would be about 2.7 tons per week.

Mechanical crushing (assuming strain rates of 1 $s^{-1}$ or more) may facilitate transport of frozen coal to or from the silos but should be designed to overcome a compressive strength of both frozen coal and pure ice, or some 15-20 MPa.

**Table 5.** Drain water flow rates (m³/day) in nearly empty storage silos; measured 16.8.2010/23.8.2012 [1)]

| Location | Silo 1 | Silo 2 | Silo 3 | Silo 4 |
|---|---|---|---|---|
| Drain 1 | 3.40/ - | 1.24/ - | 0.76/0.09 | 0.39/0.006 |
| Drain 2 | 0.82/ - | 0.39/ - | 2.42/1.44 | 0.00/0.0001 |
| Total | 4.22/ - | 1.63/ - | 3.18/1.53 | 0.39/0.007 |

[1)] Not properly measurable in 2012 because of excess extinguishing water

## 4.3 Safety issues

Compared with an above-ground stockpile, the underground storage has reduced the emissions of dust, CO2 and noise, and limited employee exposure through automated remote operation. On the other hand, a closed underground storage provides more limited access at times of incidents that may challenge safety, and creates a closed environment to potentially accumulate harmful gases like CO. Case examples of such incidents can highlight the impact of exceptional circumstances during construction, maintenance and process disturbances, consistent with the expected type of events that may result in personnel injury (Jo and Park 2003, Sonnemans et al. 2010). As such incidents can have very variable causes, preventive measures are more effective when targeting the hazard exposure rather than the individual initiating causes (Publication V). The systematic effort in hazard reduction should be conducted with vigilant persistence and continuous improvement, even under a continuously changing environment for business and operation. Power plants typically represent a long term investment and relatively slow shift in technology, and the related conservatism can also help to provide time and an opportunity for conscious promotion of the safety culture. For minimising the risk of occupational incidents, protective and precautionary measures are included in the system design, operational procedures and other guidelines of the storage facility (see Publications I-II and V).

### 4.3.1 Safety during operation and periods of disturbance

Here four case examples have been taken from the recorded and published safety related incidents in the underground storage at Salmisaari to show the characteristics of the hazard and risk of accidents to moments and periods of exceptional circumstances rather than to times of normal operation. For all case examples, abbreviated fault and event tree presentations of the incidents can be found in Publication V.

The first example incident (TVL/TOT 2009) occurred when coal was sticking and accumulating on a horizontal conveyor belt and its supporting roller, resulting in belt misalignment and conveyor stoppage by limit switch action. An experienced operator of the fuel supply system went to clean the roller with a steel bar from below the moving conveyor, and was fatally injured after being caught between the roller and the belt. According to the operating guideline, the conveyor must be stopped for cleaning. There was a protective steel grid fence in front of the roller-belt gap, but it was possible to bypass it (Figure 20). An emergency stop line runs along the conveyor but is not accessible from under the belt. Coal particles can accumulate on the rollers from residual water and coal sludge on the belt, e.g. after extinguishing a self-ignited fire on the belt or in silos. Additional safety measures, such as an improved protective fence and further training of storage operators on safe operational practices were implemented after the incident, and no similar or comparable incident has occurred thereafter.

The second case example (TVL/TOT 2003) is from the time of construction of the underground storage. An experienced worker was drilling rock holes for lift shaft reinforcement on a wooden platform, without using a protective harness, which was not considered compulsory when working on the platform. Due to a faulty gripping handle of the original rock drill, the operator switched to another tool, which included a pneumatic cylinder foot for additional drilling force. For this purpose, he attached the cylinder head to the working platform, which was not designed to take the horizontal force. With likely ice formation in the control valve, the pneumatic cylinder did not function well, and after further opening of the valve, the cylinder suddenly pushed the platform so that the operator slipped and was fatally injured by falling approximately 30 m down the open lift shaft. In this case, proper drilling equipment would have helped to avoid the accident, but the unsafe attachment of the pneumatic cylinder on the working platform was also against the user instructions. No similar or comparable incidents have occurred later during the operation of the facility.

The third example is a case of an assumed credible hazard, which so far has not resulted in any accident. At the bottom level of each silo is a door to the service tunnel and, during an inspection to check for possible thermal draft through the coal bed, the inspector noted that his portable gas sensor indicated low oxygen content. An outward air/gas flow was found to take place through the seals of the door frame in the dead space where ventilation is relatively poor. Further measurements with a more accurate sensor indicated an oxygen content of only 15% next to the bottom door frame. As reduced oxygen content in the silos can occur even without fire, it is important that the seals to every opening are tight and that no personnel will work without adequate sensors, indicators, protection and/or supervision at locations of poor ventilation.

**Figure 20.** Due to repeated disturbance of belt operation, a fuel supply operator went below the moving conveyor belt to clean the belt turning roller and was fatally caught between the belt and the roller. The location was covered by a steel fence, but it was possible to bypass it during operation. The space between the floor and the lower roll is about 70 cm (TVL/TOT 2009).

The last case example refers to a persistent smouldering fire in a storage silo, resulting in damage to hopper bellows and wall shotcrete in one silo, and intermittent nitrogen injection for a total period of four months (Publications IV and V). In spite of the lengthy period of disturbance, the storage was sufficiently available for power plant operation during the incident, without any serious injury. After introduction of a better seal against air ingress, no fires have occurred on a similar scale, in spite of leaving e.g. the sensor and alarm systems, use of the storage, related practices and the equipment unchanged. Nevertheless, fires can carry potential health and safety issues including the potential impact of noxious flue gases.

### 4.3.2 The safety system and potential for development

Although some safety hazards and incidents were encountered in the new storage, replacing the previous open stockpile by an automated and remotely controlled underground facility has provided expected and realised benefits (Publication V). The observed safety related cases involved relatively simple types of “slips, trips and falls from height” or “caught between”, or “struck by” incidents, affecting in each case singular individuals only. Assuming that the hazard will remain sufficiently comparable, it may be appropriate to describe the associated risk in a hierarchical way (see Wright and van der Schaaf 2004, Anderson and Denkl 2010, Kleindorfer et al. 2012), as outlined in Figure 21.

To minimise the risk of such incidents, it is thought to be important to

- reduce hazard exposure at times of exceptional circumstances such as construction, maintenance and process disturbance;
- promote and maintain adherence to safe working practices and attitude also during normal operation (“innate immunity”); and
- reduce the risk related to observed incidents or deviations from safe practice by a root cause analysis and a subsequent review of instructions, working practices and training (“adaptive immunity”).

Systematic risk reduction by maintaining and upgrading training, guidelines, process control and other safety barriers can provide a response to the safety challenges, even when relatively rare, and to remain prepared for necessary action through a proper safety culture. The observed incidents and the related new (emerging) risk also required a more detailed causative assessment, as described previously. In particular, when addressing the hazard through minor but frequent incidents according to the Heinrich pyramid principle (Heinrich 1931, Heinrich et al. 1980), one may miss cases that are potentially severe but not well represented by the more frequent events, or otherwise the fatal and non-fatal accidents are differently distributed (Salminen et al. 1992, Anderson and Denkl 2010). This could also be the case when looking at new or emerging risks that by definition may not be well represented in the incident statistics or accident history.

The post-incident experience appears to demonstrate safety improvements. Considering the four incident cases described above, this conclusion is justified not only by the fact that no similar incidents have occurred since, but also by the following exposure-reducing actions and observations of success:

- concerning the first incident case, the safety fences of the conveyors have been upgraded to prevent access to operating belts, and personnel training includes added emphasis on working next to moving equipment and underground.
- concerning the second case, no similar construction work is expected, but to some extent comparable working conditions are conceivable during maintenance or upgrading of underground facilities; strict adherence to the use of safety harnesses under such work conditions is emphasised in safety reviews and training.
- for the third (low oxygen under silo) and fourth (smouldering fire) incident cases, observed improvement is thought to be largely due to a second sealing maintenance door at the silo bottom to drastically reduce gas leakage in and out of the silos.

The success can also be described in terms of the payback period of the related investment. For example, assuming that a fire comparable to that in 2008 would under similar conditions occur once in four years, causing an average loss of about 700 000 euros, and the preventive action by installing the sealing maintenance doors costing approximately 5000 euros, corresponds to a payback period of only approximately 10 days. In this case, the preventive measure successfully addressed both the smouldering silo fires and the low oxygen hazard under the silos.

A common and good ultimate goal is a zero accident rate, particularly for fatal or severe injury. Success may be measured as a reducing accident rate which however is a historical (lagging) performance indicator. For a proactive approach one must strive for continuous improvement by an effort to develop and maintain a proactive safety culture, active learning from the best practices and caring of the fellow team members (Anderson and Denkl 2010, van Selm 2011, Sundell 2011).

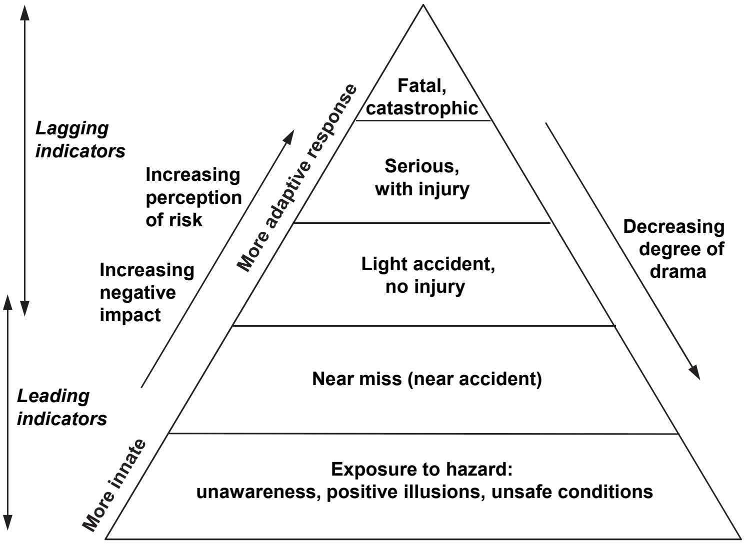


**Figure 21.** Schematic hierarchy of incidents: more serious incidents are less frequent than those of less severe consequence, and provided that causes are comparable, the latter may better work as leading indicators; partially adapted from Anderson and Denkl (2010), Kleindorfer et al. (2012)

# 5 PERFORMANCE INDICATORS

The performance of any system is only understandable and communicable if the related criteria are defined, measurable or at least comparable for the defined purposes, such as an evaluation of past operations or expectations for the future. In practice, the requirement to measure or compare will need indicators that also must be defined for the system of interest.

## 5.1 Definitions

Traditional risk assessment largely relies on historical incident data and existing experience with particular risks that can only provide posterior or lagging indicators of the expected, i.e. using such indicators one takes a reactive approach and assumes that future risk is reasonably well represented by that in the past. Not surprisingly, such lagging (key) performance indicators or (K)PIs are not always suitable to analyse new or emerging risks. Both for emerging and existing or known risks, there is a need for a more proactive approach.

The risk issues can in principle be identified and mitigated before an unwanted incident occurs by using appropriate leading indicators, to be applied instead of or together with more traditional lagging indicators. Ideally, the indicators should be applicable through a technology or facility life cycle. For example, inherent safety can be addressed by indicators for design, while indicators for operation could be applied during a later service phase by the operators and management.

Conventional risk assessments have often focused on technical aspects, such as failure of engineering equipment, facilities or systems. Whether risks are known or new (emerging), aspects related to the interfaces of human activity, technology and organisation can also be important. Leading performance (or risk) indicators can address the issues related to the interfaces, and a systematic assessment with such indicators can account for human and management, policies and regulatory, technological and governance aspects in the applied framework (ISO 31000:2009, IRGC 2010, Duval et al. 2009, Duval and Dien 2010, Jovanovic 2010). Successfully selected leading (or early warning) indicators are hence particularly attractive for issues associated with new or emerging risk.

## 5.2 Leading indicators

Suggested leading or early warning performance (or risk) indicators on unwanted events are summarised in Tables 6 and 7. Table 6 is grouped according to the issues of concern in the example cases, i.e. for fires from self-heating, coal freezing and occupational safety. In Table 7, seleted issues and potential leading indicators are listed from the point of view of other unwanted events or features. Some of the indicators have been further elaborated and quantified for the Salmisaari storage (Auerkari et al. 2011, Sipilä et al. 2012).

**Table 6.** Suggested leading (early warning) indicators of risks of fire, freezing and safety issues (Auerkari et al. 2013, Sipilä et al. 2013)

| Issue of concern | Leading indicators | Notes |
|---|---|---|
| Self-heating and autoignition of coal | CO > 10 ppm[1) ], indicated odour, coal temperature > 40°C, <u>SGI > 0.42, storage time > 1 year</u> | High sensitivity needed to detect initiation in a thick coal bed; early indicators underlined |
| Coal freezing | Cold weather in filling (<-10°C), cold/frozen coal to silos with high seepage water flow | Early indication from cold transport route; risk reduced by unfrozen coal in other silos |
| Occupational safety | Deviation from norms, observed exposure to hazard[2)], or severe disturbance | E.g. in safety walks: improper safety equipment, toxic emission, untidy work environment etc. |

[1)] extinguishing when CO > 30 ppm

[2)] e.g. normal work limits CO > 30 ppm during 8 h or > 75 ppm during 15 min

**Table 7.** Suggested additional leading indicators for selected risk issues (Publications II-III)

| Issue of concern | Leading indicators | Notes |
|---|---|---|
| $CO_2$, other emissions from storage | CO, $CH_4$ content, temperature | Help from cool & closed underground silos |
| Disturbed fuel flow, plant shutdown | Fuel supply rate (difference to demand), temperature | Risk from fires or freezing |
| Extra wear & tear | Temperature, fuel blockage, coal bridging/arching | E.g. due to accepting of heated or too cold coal |
| Safety hazard | Unauthorised entry | Access control, monitoring |
| | Dust build-up | Cleaning, overtime control, |
| | Unplanned maintenance | correct work methods & tools |
| | | Challenge to train for rare events |

## 5.3 Lagging indicators

In principle, lagging (longer term) performance indicators offer the wisdom of hindsight, or experience, when available. Although experience is rare or nonexisting for truly new events or risks, some guidance may be sought from parallel technology, temporally or geographically distant sources, or in combination with presumed leading indicators. However, when faced with new risks, potentially symptomatic incidents may start to provide evidence and imply lagging indicators for future risk management. Suggested lagging performance indicators are summarised in Tables 8 and 9. In Table 8, the issues are grouped according to the example cases, i.e. fires, freezing and safety, largely in accordance with the experience from the Salmisaari storage (Publications II and III). In Table 9, selected additional issues and lagging indicators are suggested from the point of view of the unwanted event.

**Table 8.** Suggested lagging performance indicators of risks of fire, freezing and safety issues (Publications II and III)

| Issue of concern | Lagging indicators |
|---|---|
| Self-heating and autoignition (fires) | Number of recorded fires/10 y<br>Number (trend) of true alarms/1, 5 & 10 y<br>Time to extinguish from alarm (mean, max, no. of attempts)<br>No. of deviations from the storage utilisation plan / y<br>Extent of related public reactions<br>Losses (€) |
| Coal freezing | No. of related incidents limiting supply to/from storage /10 y<br>No. (trend) of related disturbances requiring extra maintenance/clearing / 1, 5 & 10 y<br>Time to end disturbance (from alarm)<br>Extent of related public reactions<br>Losses (€) |
| Occupational safety | Number of injuries & lost work time due to fires, freezing or dust explosions /1, 5 & 10 y<br>Overtime hours / y for unplanned maintenance<br>Number of deviations from safety norms / y |

**Table 9.** Suggested additional lagging indicators for selected risk issues (cf. e.g. Nalbandian 2010, Eiden 2013)

| Issue of concern | Lagging indicators | Notes |
|---|---|---|
| $CO_2$, other emissions from storage | (Coal turnover rate) | Possibly insensitive |
| Disturbed fuel flow, plant shutdown | Total difference of fuel supply and demand /y | Leading to shutdown or derating |
| Extra wear & tear | Added cost / y | |
| Safety hazard | Number of unauthorised entries/y<br>Dust buildup/untidiness: no. of deviations from norm/y | |
| Communication & development | No. of initiatives for improvement (fires, freezing, safety) | To include rewarding for adopted practices |

# 6 DISCUSSION AND CONCLUSIONS

During the relatively short operational history of the Salmisaari underground storage facility, smouldering fires, coal freezing and occupational accidents have emerged as occasional challenges to reliable operation. This work aimed to address the root causes in these challenges, to define useful means of prevention, mitigation and other improvement, including performance indicators for the outcome, and to assess the benefits as far as they can be indicated (for an outline, see Figure 22). The results, recommendations and selected aspects of foreseen future developments are discussed below in the order of the challenges of fires, freezing and occupational safety. The recommendations naturally aim to be compatible with the general objectives of the organisation related to quality, continuous improvement and environmental management (ISO 14001: 2004, ISO 9001:2008). In general, the developments, successes and remaining challenges can be seen as a part of the evolving storage design for solid fuels. In particular, there is still a significant scope for improvement in terms of fire and freezing risk in the current type of underground rock silos. In terms of safety, the targets are clear but quantifying the current level of risk (say, as incidents per million work hours) is made more difficult by the low absolute rate from the automated remotely controlled operation, and modest number of yearly work hours in the storage.

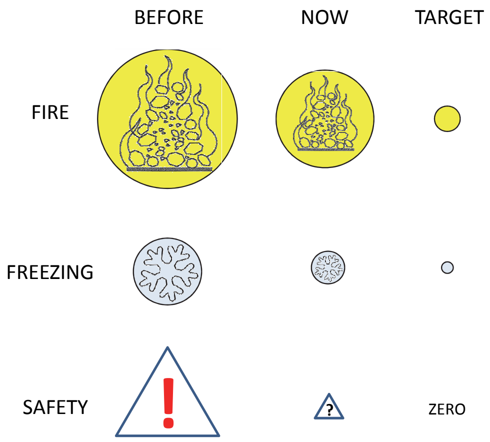


**Figure 22.** Schematic outcome of the effort described in the present work in comparison to the initial risk (approximated by relative change in area) and near-future targets for smouldering fires, freezing and occupational safety

## 6.1 Self-heating and spontaneous combustion

The root causes of the smouldering fire incidents are clear: combined air ingress, coal reactivity and sufficient time in closed storage will create conditions of accelerated heating and finally autoignition due to sufficient rate of heat generation and insufficient rate of heat loss. The estimated level of the associated risk is indicated in Figure 12 for the most severe observed fire incident in 2008. The improvement until present has not been very impressive, and the underground silo design with the first in, last out principle has not become popular elsewhere, i.e. the Salmisaari storage type remains unique.

The experience with the warning (alarm) indicators of odour, gas (CO) and temperature monitoring of the process of spontaneous combustion has shown both potential for improvement and limitations in the underground rock silos (Publications III and IV, Sipilä et al. 2012). In particular, coal ranking using the modified SGI can be evaluated from the currently applied batch-specific quality control analysis of each shipped delivery (Publication IV). The earliest warning indication is obtained as a combination of SGI, time in storage and temperature of coal at silo entry (see Table 6), so that when everything proceeds as planned, a satisfactory safe storage (incubation) time of about one year can be expected even for the more reactive Russian coal (Auerkari et al. 2013). However, deviations from the expected process have not yet been excluded, and smouldering fires can continue to occur. Hence further preventive and mitigating measures like additional oxygen barriers are still needed, although sealing of the bottom access with secondary doors was successful in reducing the fire risk (Publications II and III). It remains also important to avoid heated coal from entering the storage (Publications I and II). In addition, the risk of spontaneous combustion can be reduced by suitable scheduling (minimal incubationtime) and layering (minimal air ingress) in filling and discharge. Selected additional actions proposed to minimise or avoid self-heating and resulting fires are listed in Table 10. These include application of fire-retardant gel on the top layers to stop air flow through coal, following the experience at closed silos elsewhere (Rosner and Röpell 2011), and nitrogen purging at the hopper side. The silo ceiling could be sealed with a water- and fireproof membrane for corrosion protection and to avoid air channelling by drip water. The last recommended action in Table 10 aims to provide an element of continuous improvement by systematic review of quantified objectives and performance indicators.

Suitable (key) performance indicators for the fire risk remain important, in particular the leading indicators of Table 6. The benefit from a reduced rate of smouldering fire incidents has been assessed above, suggesting a payback period of only about 10 days, if a fire like the one in 2008 occurred without additional measures once in four years, with an conservative estimated loss of about 700 000 euros, and that the cost of the preventive action (sealing maintenance doors) was 5000 euros. The action would also simultaneously address the low oxygen hazard under the silos. New challenges could arise from the increasing use of biomass fuels with high volatile contents to facilitate relatively easy autoignition.

**Table 10.** Recommended actions to avoid/manage self-heating and spontaneous combustion, with advantages and possible limitations, to be implemented with training and communication (Alsparr 2000, Rosner and Röpell 2011, Publications I-III, V-VI)

| Action | Advantages | Limitations | Notes |
|---|---|---|---|
| Add fire retardant gel to top | Reduced air ingress, less fire incidents, reduced need for $N_2$ purging | Applied at discharge stop, reduces locally the heating value | Stops air ingress through coal bed |
| Add silo sealing top membrane | Prevents water drip channels in coal and corrosion in structures | May limit visual inspection of the rock ceiling | Fire retardant membrane available |
| Hopper ($N_2$) inertisation | To reduce coal oxidation rates at the hopper | Needs modification to the existing system | Could be introduced by using $N_2$ bottles |
| Check fire indications in every shift | Early alarm makes mitigation easier, reduces cost and occupational risk | Sensors may miss odours detectable by human operator | Safety case example no. 4; monitor adherence |
| New goals, KPI's and continuity | Systematic goal review to avoid incidents & maintain/ improve performance | Rare events may challenge alertness & motivation | Possibly to be integrated into a wider system |

## 6.2 Freezing of coal

The root causes of coal freezing are also clear: combined subzero weather conditions in transport and discharge to silos (low coal temperature) to facilitate blocked conveyor transport to or from the silos. The estimated level of the associated risk is indicated in Figure 19 for the most severe observed freezing incident in 2010. In spite of some improvement, the freezing risk during adverse weather and transport condinditions remains significant, and this is clearly related to the unique storage design.

The suggested leading indicators for freezing are observed as subzero weather, wet or frozen coal in the system, and seepage water entering silos with cold coal (Table 6, see also Publication II). Coal batch-related risk factors to freezing have been considered in Publication VI. Again, prevention of freezing related trouble is much better than solving problems resulting from blocked fuel flow, and selected actions are proposed to manage the associated risk (Table 11). In particular, avoiding suspect batches or directing them elsewhere can prevent trouble before coal enters the silos. In addition, the freezing trouble is much alleviated if unfrozen coal is available from at least some of the other silos.

The most severe freezing incident in 2010 was considered to represent a new, unique type of emerging risk in terms of the contributing mechanisms (Publications II and VI). Filling with subzero coal froze the silo drains for seepage water, resulting in leakage into the silo to form icy lumps and prevent discharge. Compared to any previously known cases of freezing, the unexpected direction of heat transfer from the storage wall to coal means an additional challenge in mitigation, as for example freeze conditioning agents would be unlikely to help. Nevertheless, the implemented measures are expected to reduce the likelihood of recurring problems, and even the unexpected reduced fuel supply during the worst freezing incident did not lead to the extreme consequence of full plant shutdown. The relative rarity of the freezing incidents may also pose some challenge in keeping the organisation alert and responsive. The climate models suggest that in spite of general warming, all extreme cold spells are unlikely to disappear (Hansen et al. 2012). Furthermore, renewable solid fuels tend to have higher moisture content than coal and may freeze even more easily (unless sufficiently self-heating). Replacing a significant fraction of coal with such fuels will increase the scale of associated transport and storage activities, as a low heating value will translate to a correspondingly high fuel volume.

Suggested leading indicators of the freezing risk are those listed in Table 6: adverse weather, wet or cold coal, and seepage water entering silos with cold coal. The benefit from a reduced rate of freezing incidents will arise from avoided plant derating, avoided added cost of replacement fuel and personnel overtime, and reduced risk of occupational hazard from unplanned heavy clearing work. As noted above, the risk from freezing is reduced by the availability of unfrozen coal from other silos. Some freezing challenges in the future may arise from the increasing use of biomass fuels with high moisture content.

**Table 11.** Recommended actions to prevent/manage coal freezing, with expected advantages and possible limitations, to be implemented with training and communication (Publications I-III, V-VI)

| Action | Advantages | Limitations | Notes |
|---|---|---|---|
| Avoid deep subzero transport 1) | Reduced freezing risk at unloading and in silos | Cold spells only, in shipping or land transport | Compounded by high water content in coal |
| Redirect problem coal elsewhere 1) | Reduced freezing risk at unloading and in silos | Requires an alternative site for storage and means of transport | Currently discharge only to combustion |
| New goals, KPI's and continuity | Systematic goal review to avoid incidents & maintain/ improve performance | Rare events may challenge alertness & motivation | Possibly to be integrated into a wider system |

1) Unattractive option when running out of coal in storage

## 6.3 Occupational safety

The root causes were assessed for four recorded and published safety related incidents in the Salmisaari storage. The cases are variable but show common characteristics of hazard confined to periods of exceptional circumstances rather than to times of normal operation. While the automated and remotely controlled operation of the storage is expected to provide distinct safety advantage, it does not necessarily extend to the exceptional circumstances requiring human involvement. This is also demonstrated by the most serious belt/roller gap incident that occurred during operation but only when the guidelines were not followed and the protective safety measures were circumvented. To prevent a similar operator error, the protective fence was redesigned to prevent bypass, and strict adherence to the proper way of belt roller cleaning is emphasised in training of the operators and other personnel involved, including those of external contractors. No similar incident has occurred after the case example, but the leading indicators are considered more important: the unsafe method of belt cleaning has not been used after the accident.

On the other hand, the occurred incidents, corresponding precautions or indicators need not be fundamentally unlike those in some other industrial systems. For example, it is plausible that belt conveyors may represent rather similar hazards in coal fired power plants and coal mines (see e.g. Khanzode et al. 2010, Khanzode et al. 2012). The suggested leading or early warning indicators are the monitored adherence to safety precautions, and the extent of hazard exposure during disturbance (Table 6).

With no harmful incident so far, the case example on low underground oxygen content represents a credible hazard but the improved seals of the silo maintenance doors have reduced the associated risk to the personnel. Monitoring of local oxygen/CO/$CH_4$ level provides a leading indicator of this risk, and also of that of smouldering fires. Considering lagging indicators only, no similar extensive fires as in 2008 have occurred since introducing the improved door seals, and this is thought to indicate a parallel reduction of safety hazard (Publication V).

The recommended actions to manage the safety risk are summarised in Table 12. These actions concentrate on safe work practices, using protective equipment, carrying indicators of harmful or toxic gases when working underground, with attention to potential fire indications during every workshift and recurrent attention to continuous improvement.

**Table 12.** Recommended actions to prevent/manage autoignition, with expected advantages and possible limitations, to be implemented with training and communication (Publications I-III, V-VI)

| Action | Advantages | Limitations | Notes |
|---|---|---|---|
| Use safe work-practices, protective harness/ equipment | Reduced incident rate, less sick days, better corporate image | May require change of safety culture, applies also to contractors | Case examples 1 & 2; monitor adherence |
| Use personal gas indicators in storage facility | Indicates if toxic atmosphere is present in storage (CO, $CH_4$, low $O_2$ ) | May be seen as nuisance by personnel | Case examples 3 & 4; monitor adherence |
| Check fire indications in every shift | Early alarm makes mitigation easier, reduces cost and occupational risk | Sensors may miss odours detectable by human operator | Case example 4; monitor adherence |
| New goals, KPI's and continuity | Systematic goal review to avoid incidents & maintain/ improve performance | Rare events may challenge alertness & motivation | Possibly to be integrated into a wider system |

All case examples represented relatively infrequent incidents, except for self-heating of coal that may not be as uncommon as one would hope for. Rare alarms may reduce the alertness and ability of organisations to respond to unusual initiating events that can become weak signals even for the experienced personnel. Continuous improvement towards a zero incident rate will by definition make the incidents less common and hence more challenging to anticipate, unless the alarm signals, leading indicators, training, communication, or other features of the safety system will compensate for the trend.

Considering the future option of biomass fuels, apart from the potential fungal growth and spore formation, no major new health and safety issues are expected to emerge, assuming that closed storage continues to be applied (Saidur et al. 2011).

## 6.4 Suggested future work

Regarding the self-heating and autoignition risk of the delivered coal batches, possible further development could be introduced by measuring and recording the intrinsic moisture of coal in addition to the total moisture. This would allow for more accurate follow-up of SGI and possibly better control in cases of self-heating. The results could be used in automatic accounting of SGI and amounts of the coal batch layers in each silo, to assess the self-heating propensity and its relation to the applied leading and lagging fire risk indicators. Nevertheless, emergency transfer of heated coal from the silos to above-ground extinguishing and cooling should also be made possible. It would be good for tracking if more accurate accounting of the individual coal batches were possible than at present in spite of varying amounts of coal entry and discharge form individual silos during the winter season.

Considering coal freezing, a potential measure to indicate on-going freezing and ice accumulation in a silo could be a reduced flow of the drainage water. Therefore, continuous measurement of the drain water flow rates may provide a useful leading though not very early indicator of the freezing risk. In contrast, the drain water flow rate is not expected to significantly change by self-heating, and the occasionally observed condensing steam during self-heating incidents is thought to originate from the moisture in coal rather than from drain water. In principle the drain water flow to the coal bed could be prevented by an additional liner at the silo wall.

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The coal-fired Salmisaari power plant has provided heat and electricity for the city of Helsinki for over 50 years. For almost the entire period, the fuel was stored in an unsightly above-ground stockpile. However, as of 2004, the fuel has been stored in a first-of-a-kind automated underground storage facility. The new storage facility has a number of advantages, but it has also experienced unanticipated incidents of fire and freezing, as well as occupational incidents that are considered to represent issues of emerging risk. Options for prevention, mitigation and other improvement are discussed from the point of view of preparing for rare or unforeseen events, and for future operation. Key performance indicators are suggested to help in managing the emerging risk related to issues of fire, freezing and safety.

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