

Geotechnical and Physical Aspects of Eliminating Seats of Fire on Coal Waste Dumps

Abstract

Complex analysis of thermal and gaseous state of chosen coal dumps performed by the author made it possible to initially evaluate risk of spontaneous combustion of these objects and their classification based on indicators of certain risk group. Thanks to the observation of coal dumps using ground thermovisual camera, non-contact visualization of temperature distribution of the coal dump was obtained in form of colored thermograms, which led to identification of areas of higher thermal activity. Use of thermovisual camera is an example of adaptation of modern technology in research purpose. Properly planned measurement, swift development and comparison of results gives complex information about object structure and thermal reactions on its surface. Analysis of thermal anomalies found on coal dumps allows drawing conclusions on causes of these events occurrence and repeating characteristics of environmental physicochemical conditions variability accompanying such events.

Process of endogenic fire formation is very complex mechanism that is not yet fully understood. Doubts were dispelled in the matter of main spontaneous combustion reason, which is oxidation process of coal, which is the main burning by-product material of mining operation. However, reason of activation process of self-heating and leading coal substance to critical temperature (60–80 °C) is not fully understood. According to that, author reviewed knowledge related to experiences with spontaneous combustions of coal dumps. Learning individual stages of thermal anomalies development on coal dumps allow introduction of more effective prevention methods as well as fighting already existing fires.

In early chapters of thesis characteristics of coal waste have been shown. The most significant combustible particles that stimulate spontaneous combustion have been taken under the scope. Thermophysical properties of accompanying rocks have been highlighted. Scale of the fire problem related to coal dumps have been shown. There has been estimated number of burning objects and places with highest density of anthropogenic formations have been shown on the maps. Reader was offered with statistical data providing knowledge about mining waste management.

Next chapters bring up issues concerning influence of burning coal dumps in the environment. First, hazards of toxic products of burning have been characterized. Presented values let one realize how important the issue of fire gas emission is for the surrounding and how catastrophic the results may be. Subject has been risen about influence of carbon dioxide emission on the climate change. Moreover, author reminded few tragedies from the past, where direct cause was explosive mixture of gases gathered inside anthropogenic cones. Few words have been said about excessive dust emission of burning dumps. One of the most spectacular phenomenon has been discussed, which is loss of stability of the scarp caused by fire. It has also been mentioned what risks await building, which foundations have been located close to burning coal dump. Apart from information about burning out and degradation of

vegetation and soil there is also mention of plant gigantism and pioneer species of plants and animals that inhabit tops of coal dumps. Chemical reactions have been shown, which lead to acidification of meandering waters in coal dump area. Factors leading to oxidation of sulfides and modifications related to draining of coal dumps have been schematically illustrated. Author have introduced the world of technogenical minerals, which were created due to temperature changes that occur in burning slopes of coal dumps. Successive generation of coal dumps have been checked as well as newest ideas for reclamation of these objects.

Afterwards general characteristic of fire hazard on coal dump has been presented. Author have focused on spontaneous combustion causes, on theories and research on spontaneous combustion of waste and on the process of endogenic fire formation and factors stimulating its development. In the next part fire preventative measures and issues concerning firefighting have been the main interest.

Using extended knowledge about self-heating phenomenon of post carboniferous waste, author engaged in clarification of complex analysis of thermal-gaseous state. Particular attention has been paid to procedures of creation and interpretation of thermograms of coal dumps. Technical parameters have been shown for the equipment needed to perform research. Author have also conducted review of innovative research concerning thermal-gaseous activity of large size objects formed from coal waste.

Keywords: coal waste dumps, spontaneous combustion, endogenic fire, thermovisual camera

Geotechniczne i fizyczne aspekty eliminacji ognisk pożarowych na zwałowiskach odpadów powęglowych

Streszczenie

Przeprowadzona przez autora kompleksowa analiza stanu termicznego i gazowego wybranych zwałowisk zbudowanych z odpadów górnictwa węgla kamiennego pozwoliła na wstępną ocenę narażenia tych obiektów na samozapłon i zakwalifikowanie ich na podstawie wskaźników do określonej grupy ryzyka. Dzięki obserwacji zwałowisk przy pomocy naziemnej kamery termowizyjnej uzyskano bezkontaktowe zobrazowania rozkładu temperatury zwału w formie barwnych termogramów, co przyczyniło się do zidentyfikowania obszarów o wzmożonej aktywności termicznej. Użycie kamery termowizyjnej jest przykładem zastosowania współczesnej technologii w celach badawczych. Odpowiednio zaplanowany pomiar, szybkie opracowanie oraz porównanie wyników daje kompleksową informację o budowie badanego obiektu oraz o reakcjach termicznych występujących na jego powierzchni. Analiza anomalii cieplnych spotykanych na zwałowiskach powęglowych pozwala na formułowanie wniosków o przyczynach powstawania tych zjawisk oraz o powtarzających się cechach charakterystycznych zmienności fizyko-chemicznych warunków środowiska towarzyszących takim zjawiskom.

Proces powstawania pożarów endogenicznych jest mechanizmem bardzo złożonym i jeszcze nie do końca zrozumianym. Wątpliwości zostały zburzone jedynie w kwestii głównego powodu samozapłonu, jakim jest proces utleniania węgla, który stanowi podstawowy materiał palny ubocznego produktu procesu wydobywczego. Niezrozumiana do końca jest przyczyna aktywacji procesu samozagrzewania oraz doprowadzenie substancji węglistej do temperatury krytycznej (60–80 °C). Wobec tego autor książki dokonał przeglądu dotychczasowej wiedzy związanej z doświadczeniami nad samoistnymi zapłonami zwałowisk powęglowych. Poznanie poszczególnych etapów rozwoju anomalii cieplnych występujących na hałdach pozwala na wprowadzenie skuteczniejszych metod prewencyjnych, profilaktycznych, a także zwalczania ognisk pożarowych.

W początkowych rozdziałach pracy przedstawiono charakterystykę odpadów z górnictwa węgla kamiennego. Pod lupę wzięto najistotniejsze cząstki palne przyczyniające się do stymulacji samozapłonu. Zwrócono uwagę na własności fizyko-termiczne skał towarzyszących pokładom węgla kamiennego. Przedstawiono skalę problemu związanego z pożarami zwałowisk powęglowych. Podano szacunkowe liczby zapożarowanych obiektów oraz pokazano na mapach miejsca o największym zagęszczeniu antropogenicznych tworów. Zaoferowano czytelnikowi statystyczne dane dostarczające wiedzy o gospodarowaniu odpadami wydobywczymi.

Następne rozdziały dotyczą zagadnień związanych z wpływem palących się hałd na środowisko. Najpierw scharakteryzowano zagrożenia dotyczące oddziaływania toksycznych produktów spalania. Przedstawione wartości uzmysławiają jak poważnym problemem dla otoczenia jest emisja gazów pożarowych i jakie mogą wystąpić katastrofalne skutki. Poruszono kwestię związaną z wpływem emisji dwutlenku węgla na zmiany klimatyczne. Ponadto przypomniano kilka tragedii sprzed lat, w których bezpośrednią przyczyną była wybuchowa mieszanka gazów zgromadzona wewnątrz antropogenicznych stożków. Powiedziano też kilka słów o fakcie

związany z nadmiernym pyleniem zapożarowanych usypisk. Przedyskutowano jedno z nadzwyczaj spektakularnych zjawisk, jakim jest utrata stabilności skarpy na skutek pożaru. Powiedziano też, jakie zagrożenia czyhają na konstrukcje budowlane, których fundamenty postawiono nieopodal zapożarowanej hałdy. Prócz informacji o wypaleniu i degradacji szaty roślinnej oraz gleby napomknięto o zjawisku gigantyzm roślin i pionierskich gatunkach roślin i zwierząt, jakie skrywają się na wierzchołkach. Przedstawiono reakcje chemiczne, które powodują zakwaszenie wód meandrujących w obrębie zwału. Schematycznie zilustrowano czynniki przyczyniające się do utleniania siarczków i modyfikacji związanych z odwadnianiem hałd powęglowych. Wtajemniczono się w świat minerałów technogenicznych, które powstały na skutek zmian temperaturowych, jakie zachodzą na płonących zboczach zwałowiska. Sprawdzono jak wyglądały kolejne generacje zwałowisk i jakie są najnowsze pomysły na rekultywację tych obiektów.

W następnej kolejności przedstawiono ogólną charakterystykę zagrożenia pożarami na zwałowiskach odpadów powęglowych. Skupiono się na przyczynach zapłonu, teoriach i badaniach nad samozapalnością odpadów oraz na procesie powstawania pożaru endogenicznego i czynnikach stymulujących jego rozwój. W dalszej części zainteresowano się metodami profilaktyki pożarowej i problematyką zwalczania występującego pożaru.

Wykorzystując poszerzoną wiedzę o zjawisku samozagrzewania się odpadów pokarbońskich zaangażowano się w doprecyzowanie kompleksowej analizy stanu termiczno-gazowego. Szczególną uwagę poświęcono procedurom wykonania oraz interpretacji termogramów zwałowisk powęglowych. Przedstawiono parametry techniczne aparatury potrzebnej do wykonania badań oraz przeprowadzono przegląd innowacyjnych badań związanych z problematyką aktywności termiczno-gazowej wielkogabarytowych obiektów uformowanych z odpadów powęglowych.

Słowa kluczowe: zwałowisko odpadów powęglowych, proces samozagrzewania, pożar endogeniczny, badania termowizyjne

1. Introduction

Underground deposits operation performed in Upper Silesian Coal Mining Area (GZW – pl. *Górnośląskie Zagłębie Węglowe*) has a negative influence on fundamental components of the environment. The greatest and most eye-catching changes concern landscape. The signs of these changes are anthropogenic forms of terrain, which have not existed before, called coal dumps or coal waste dumping grounds. Black bodies of artificial hills, waste heaped up over the years these are known in Silesia as “hałdy” or rather “hołdy” (germ. *Halde*). Zbigniew Kadłubek, professor at the University of Silesia in Katowice, reminds us of alternative names of this place created thanks to foreign languages influence e.g. hałda in Czech is called, “halda” or „výsypka”. Silesian folk have a saying that “No heaping up – no hołda. Silesia seen from plane looks like it has a rash” Coal dumps are places transformed by human hands, in France known under a quaint name, “montagnes de la peine” – „mountains of toil”. Lunar landscape of coal dumps of so called “Black Silesia” is on one hand a subject of disdain and on the other – admiration. Even grim dumps of gangue can prove both beautiful and colourful, can possess charm, however you need to have certain type of sensitivity like outstanding painter and graphic Franciszek Starowieyski, who called dumps “the most beautiful mountains in Poland”. One can familiarize himself with the artist's thoughts on Silesian coal dumps in essay “O burzeniu najpiękniejszych gór Polski” [*About demolition of Poland's most beautiful mountains*] [37]. Article has been published in so called Silesian edition of now legendary Cracovian magazine “NaGłos” (1994, No 15/16, pages 39–43). Starowieyski writes “What he observes in Silesia is not destruction of the landscape, but its creation [...]. Here can be seen thousands, millions of tons of soil displaced, moved, ripped from the inside, heaped up into mounds, scattering in the wind”. How accurate are words spoken by Dr. Jacek Kurek, who says: “Coal dumps are places where fires rages in hiding. Places of poisonous exhalations, but also places that are safe haven for the poorest” Area surrounding Home, where generations have risen. Waste, impurity, but also one of Silesia allegories. And testimony of life-giving industrial boom that once took place here”.

Looking at dictionary definition of term “hałda” place in Karłowicz, Kryński and Niedźwiecki lexicon from 1900, one of the most interesting and unique descriptions can be found: “Hałda, Chalda, Halda, Warpa, Warpia, Warpisko, Warchwa, Warfa, mining: heap of hollow stones and gangue soils, from mine extracted and near the shaft lying”. Analysing Stanisław Staszic's chosen works, anybody can think that scientist would classify coal dumps as manifestation of “earth-birthing” that means, something that earth gave birth to and man extracted as redundant material and brought to the surface. Modern dictionaries unanimously define coal dump as anthropogenic form of terrain transformation. There is no doubt, that in Poland “hałda” in mining terminology is called “zwał”.

Mine is an industrial enterprise that is based on extraction of the mineral resource that we are interested in. However, there is also redundant extracted material accompanying mined minerals, so called gangue. Waste is created at every phase of

mine development and deposit mining operation, beginning from creation of mine shafts, decks ending with mining operation, as well as in every other technological operation that concern enrichment of minerals brought to the surface [60].

Waste created in operation and processing of coal is called coal waste or mining waste. Excavation sites, due to specific conditions of coal mining in Poland, cause access mine workings – vertical, horizontal or sloped, that is shafts, tunnels, cross-cuts, adits and sloping tunnels – to run through gangue and because of that all the material extracted at the time of their creation is considered a waste. Currently for every ton of extracted coal there is about 0.4–0.5 Mg of waste material, which makes dumping great amount of redundant material on the surface, a necessity.

Anthropogenic material that coal dumps are made of is unusual and coarse-grained, characterized by features of both coarse and fine grained soils. Among extracted rock fragments, shales and mudstones are the most common, the rest consist of coal slates, sandstones and pebble conglomerates, occasionally there are limestones and other conglomerates. Remains of coal and pyrite mixed with gangue heaped up on coal dumps can combust spontaneously in favorable conditions, which leads to long-lasting fire that is hard to control. Contents of the most important combustible components in polish mining waste located on older dumps, can reach up to 30% of coal substance and up to 8% pyrite. There are also dumps of coal slurry, created in coal treatment process, which is a waste people were unable to use once.

In the past years, due to technological restrictions and undeveloped options for the use of gangue, waste was absent-mindedly gathered in random places near mines and processing plants. Decision on where the dump should be placed has been made based on transport costs and availability of the dumping ground, with no consideration of the potential harm it may cause to the environment. Lack of waste segregation, proper grain size selection or its density as well as failure to comply with any fire preventative measures during both building of coal dump and after the dump has been formed are currently reason of common spontaneous combustions on coal dumps. Smoking slopes of dumps mean that there is internal fire inside them. Accumulation of incredibly high temperatures takes place, up to 1200 °C. Volume of gathered material is getting reduced due to thermal transformations, which causes cracking of the top of the coal dump. These cracks are zones of gases exhalation that takes toll on both natural environment and human health [80, 81].

The problem of thermal events on coal dumps is still the current. In last decade at least 21 fire occurrences were observed, mainly endogenic. It also applies to reclaimed objects [184]. Newest research performed in under the Cool's project (2007–2013) show thermal activity of 15 coal dumps. It has been estimated that fire susceptible surface of coal dumps constitutes 2.5% of total coal dump surface [196, 128]. At the same time, it has to be stated that in Upper-Silesian Coal Mining Area there are 220 coal dumps.

Analysis of ongoing thermal activity in object subjected to reclamation and old coal heaps created from coal mining waste lead to conclusion about causes of thermal anomalies and repeating characteristics of environmental physicochemical conditions variability accompanying such events. Main classification factor of fire hazard of coal dump is scope and frequency of thermal state observation. Chronological monitoring

eliminates fire risk, because any alarming event can be spotted on time and proper preventative measures can be taken [15].

In this book particular emphasis has been put on research related to complex analysis of thermal and gaseous state of coal dumps build from coal waste. Conclusions were drawn based on thermovisual observations, temperature measurement and gaseous atmosphere composition inside coal dump located in Czerwionka-Leszczyny that belong to “Dębieńsko” Coal Mine (*KWK Dębieńsko*).

2. Characteristics of Coal Mining Waste

2.1. Classification and description of groups of waste deposited on coal dumps

Coal mining waste, also called coal waste, is classed as mineral processing waste created by mining, enrichment and ore processing. In the light of new law regulations previously used, widely used division is now outdated. Despite that it is still important for having correct understanding and conducting proper waste recycling. Traditional mineral processing waste are divided into four groups considering technical characteristics of these waste as well as mining operation and technological processes from which they are created.

- **accompanying minerals**, in other words mineral resources that may occur in coal deposit or its surroundings, which can be selectively exploited or separated in processing and other procedures; it is decided in regard with both economic and ecological reasons;
- **mining waste** also called exploitation waste, are rocks coming from mining operation and preparation works, which make main deposit available, but primarily overburden and interburden (fig. 2.1);

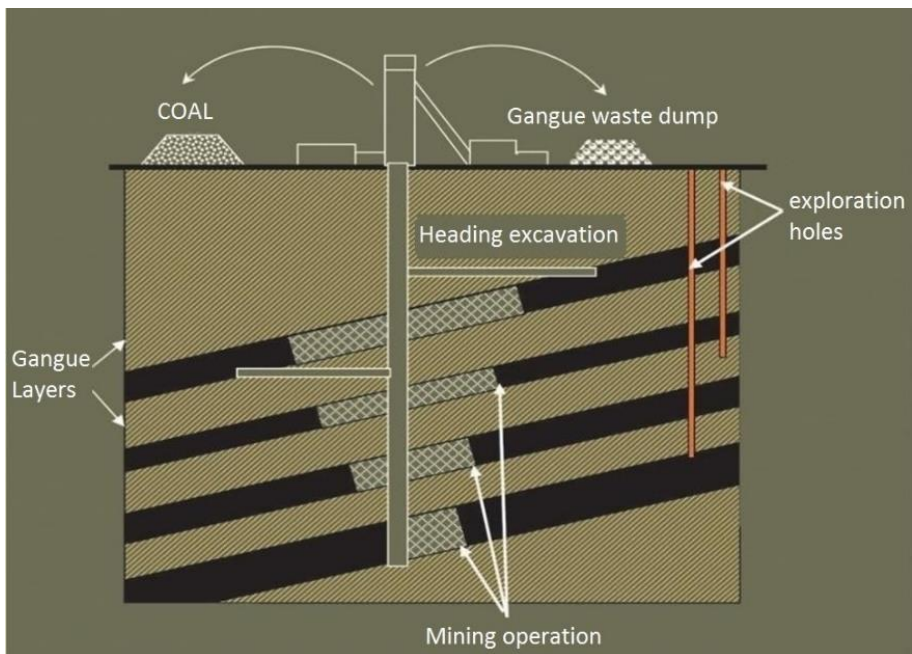


Fig. 2.1. Waste sources in coal mines [113]

- **processing waste** include rock material exploited with main mineral that is separated in mineral enrichment process (i.e. while sorting, grinding, washing and flotation, fig. 2.2);

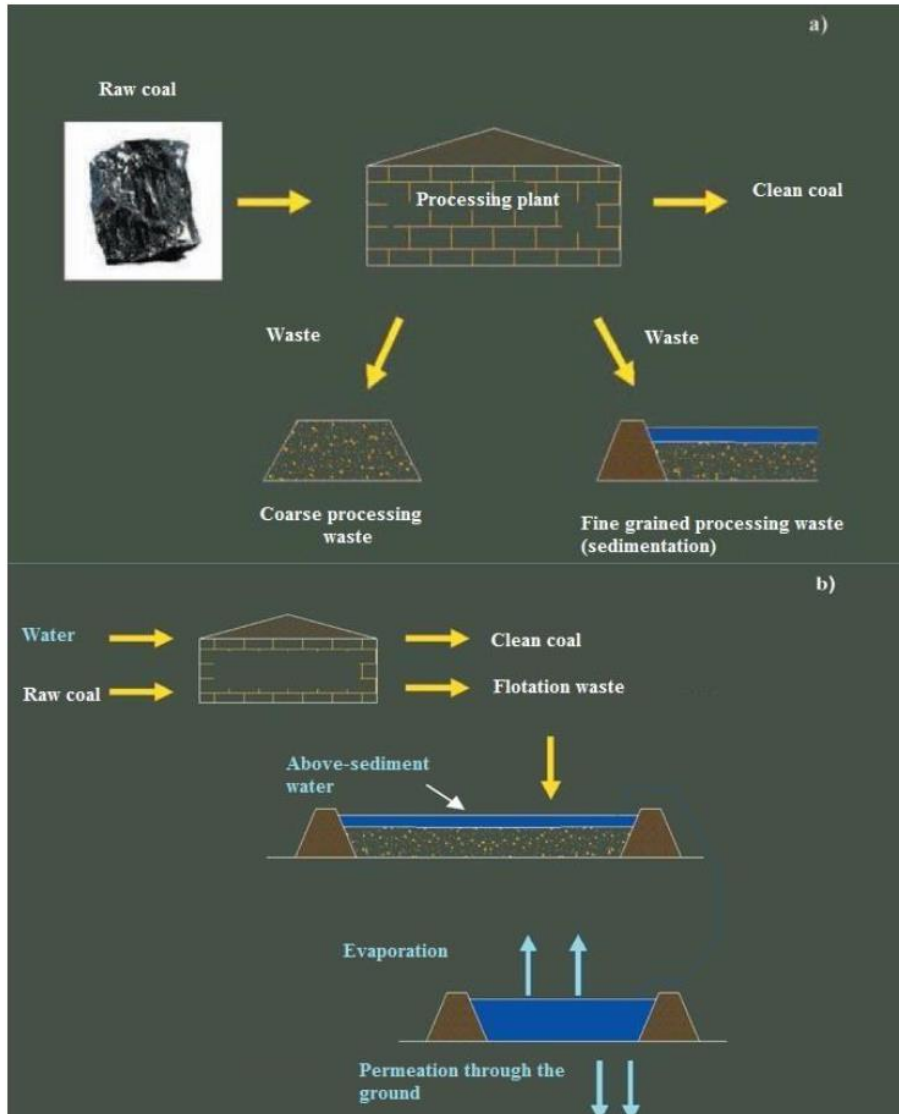


Fig. 2.2. Waste types in processing plant: a) energetic coal, b) coking coal [113]

- **secondary processing waste** are remainder of main mineral processing created during production of final trade products (including coal silt).

According to Minister of the Environment decree from 27th September 2001 in case regarding waste catalogue (Dz.U. [Journal of Laws] from 2001 No. 112, item 1206) mining waste were classified into [86]:

- **Group 01** – waste created during prospection, extraction, physical and chemical processing of ores and other minerals:
 - subgroups 01 waste from mineral extraction,
 - subgroup 04 waste from physical and chemical processing of mineral other than metallic ores.

The biggest amount of waste created in coal mining is coded accordingly:

- **01 01 02** waste from extraction of minerals other than metallic ores – rock waste, coarse, coming from preparation works performed in mines:
 - grains ranging from 20 mm to 200 mm,
 - uniform mineralogical composition,
 - coal substance content 5–15%,
 - total sulfur content below 1%,
 - water contents 4–6%,
- **01 04 12** waste created during washing and purification of minerals other than described in 01 04 07 and 01 04 11 – these are waste created in mechanical processing from coal washing and manual sorting:
 - grains below 20 mm,
 - uniform mineralogical composition,
 - higher coal substance content than in coarse waste,
 - higher total sulfur content (above 1%),
 - higher water content (10% to 12%),
- **01 04 81** waste created after flotation enrichment process other than described in 01 04 80, these are fine grained waste created in mechanical coal processing plants:
 - very fine grains, high total sulfur content,
 - high water content (above 20%),
 - high coal substance content,
 - remainder of flotation process – flotation reagents,
 - remainder of sedimentation process – flocculants.

By contrast act from 10th July 2008 regarding mining waste (Dz.U. [Journal of Laws] from 2008, No. 138, item 865) introduces only terms such as [137]:

- **processing waste** – exploitation waste in form of solid or sludge, which are left after mineral processing, conducted as a result of mechanical, physical, biological, thermal or chemical processes as well as through merging of those processes;

- **mining waste** – waste created from prospection, extraction, processing and storing of minerals from deposits.

Coal mining waste can be disposed of in so called mining waste disposal objects that is objects meant for storing mining waste in form of solid, liquid, solution or suspension. These includes dams, coal dumps and settling ponds; mining excavations or mine headings and workings filled with mining waste for technological or reclamation purposes are not considered disposal objects.

There are also different divisions shown in literature regarding waste from mining and processing coal. Figure 2.3 shows one of the general division, which includes waste deposited on coal dumps. Coal dumps in many cases consists of mix of different waste described in this register.

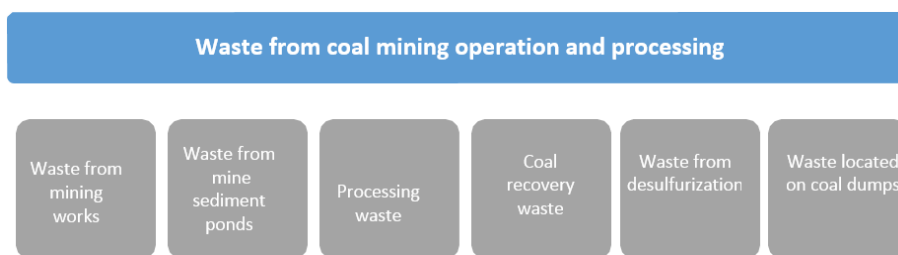


Fig. 2.3. Division of coal-dump waste from mining and processing of coal [72]

In book titled „*Antropogeniczne przeobrażenia środowiska przyrodniczego konurbacji górnośląskiej*” [Anthropogenic caused changes in the environment of Upper Silesian conurbation] Stefan Źmuda classifies coal dumps considering their shape and size [189]. Following types of dumps are distinguished:

1. terraced dumps – flat peak hills with steep slopes on depositing side (dump expansion side),
2. flat – with flat peak surface and steep slopes,
3. ridged – shaped like levee or dike,
4. domed – convex, often differentiated peak surface and gentle slopes,
5. coned – high, pyramidal, steep dumping grounds covering relatively small surface, rising to considerable heights up to several dozen meters and sometimes exceeding 100 m.

Variety of shapes and even color of dumps is the result of diverse factors, most important are [189]:

1. origin of waste material,
2. structure of waste material,
3. waste material deposition techniques,
4. terrain and spatial condition of areas covered by dumps.

In regards to dump placement on diverse terrain level, they are divided into [112, 113]:

- above-level – created on flat land. Drawbacks of such localization are distortion of the landscape and high ash pollution. Advantages are easy exploitation and dehydration.
- below-level – created in old workings and land dips. Below the level dumps are characterized by high costs and difficulties with their dehydration but at the same time they have small impact on the environment.
- partially above and below level. Drawbacks are the necessity of ground works and difficulties with draining polluted water. Advantages are high storing capacity and smaller ash ejection.
- lateral – these are near scarp or leaning on the slopes dumps divided into deep-seated and surface. Can be found in following forms: flat, prism, heaped, flat-scarped and shapeless.

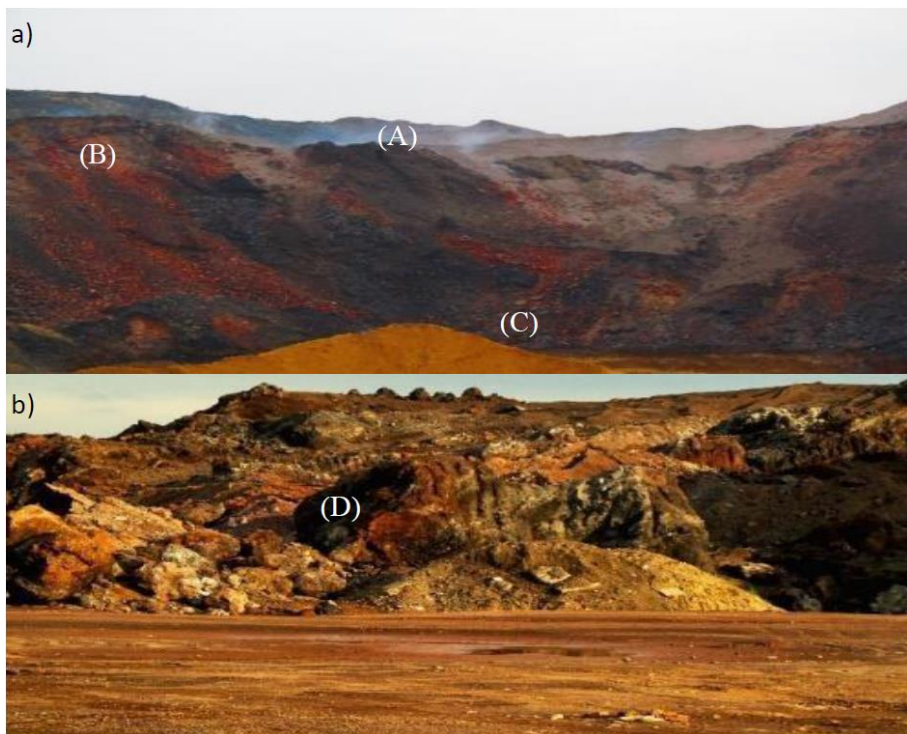


Fig. 2.4. Operation scarp (Ajska Świętochłowice dump) – zones with different grade of thermal transformations: a) (A) macroscopically unchanged zone, (B) moderately thermally transformed zone, (C) scree at the foot of scarp; b) (D) intensely transformed zone (sinters) (pic. Damian Cyfka)

Dumping grounds can also be divided considering:

- localization in regards to proximity to industrial plants (company and central),

- vertical form (storied, coned),
- in regards to water conditions (effluent, non-effluent),
- rock type (dominance of sandstones, mudstones, shales, mixed),
- mineralogical and chemical composition (considering percentage of mineral phases and chemical compounds),
- foliage density (reclaimed, partially reclaimed, not reclaimed).

Negative process accompanying coal waste deposition on the surface is self-heating of gangue and as the result of that initiation and later escalation of fires. Old dumps, where there was a considerable amount of thermal activity are characterized by varying degree of thermal transformations of waste (fig. 2.4). Surface of these objects can be divided into three zones:

- first zone (macroscopic thermal transformation, unburned). Characterized by high amount of organic material (coal) and minerals typical of carboniferous rocks of Upper-Silesian Coal Mining Area (GZW – *Górnośląskie Zagłębie Węglowe*).
- second zone (moderate thermal transformation, burned). Organic material is not present or low and there is an oxidation of minerals containing Fe, making waste of this zone brick red color.
- third zone (highly transformed, sinters). Observations show complete vanishing of clay minerals, replaced by high temperature minerals, typical of contact metamorphism, as well as glass.

In regards to thermal activity, there are:

- burning dumps, which are thermally active dumps, regardless of their burning or smoking,
- inactive dumps, where deposition process is complete and thermal activity stopped or never took place,
- thermally passive dumps that can be ignited.

Typical feature of coal waste located on dumps is their vulnerability to physical and chemical erosion. Erosion degree is thought to be dependent on material type as well as time of its deposition (waste material age). Taking this feature into consideration waste has been divided into [144]:

- fresh (from 0 to 0.5 year),
- relatively fresh (from 0.5 to 1 year),
- partially eroded (from 1 to 3 years),
- eroded (from 3 to 15 years),
- highly eroded (from 15 to 30 years and longer).

2.2. Coal-dump waste contents contributing to spontaneous combustion

The most important burning parts content in polish mining waste located on older coal dumps can reach up to 30% of coal substance and up to 8% of pyrite. These are components, which when combined with air oxidize naturally with simultaneous raise in temperature. In the table 2.1 indicative mineralogical composition has been shown for coal waste created in Poland and other countries.

Table 2.1. Indicative percentage mineralogical composition of coal waste in different countries [144]

Mineral	Belgium	Czech Republic	Spain	Germany	United Kingdom	Russian Federation	Poland
Illite	80	10–45	20–60	41–66	10–31	5–30	28–82
Kaolinite	12	20–45	3–30	4–25	10–40	1–60	9–65
Chlorite	5	0–15	0–7	1–3	2–7	–	0–10
Quartz	8	10–50	5–57	13–27	15–25	–	3–37
Pyrite	0.5	0–25	–	0.5–5	2–10	0.2–8	0–8
Substance coal	10	0–25	4–30	5–10	5–25	8–40	15–30

Table 2.2. Chemical composition of mining waste containing carboniferous rocks – average values [144]

Ordinal	Components	Content [%]		
		Sandstones	Claystones one	Mudstones
1	SiO ₂	66.7	48.0	54.0
2	Al ₂ O ₃	13.5	23.0	20.0
3	Fe ₂ O ₃ + FeO	5.1	4.5	6.0
4	CaO	2.5	0.9	1.0
5	MgO	2.1	1.3	2.5
6	K ₂ O + Na ₂ O	4.9	4.1	3.0
7	TiO ₂	0.6	0.4	–
8	P ₂ O ₅	0.2	0.2	–
9	MnO ₂	–	0.07	–
10	SO ₃	–	0.4	0.2
11	C	–	5.6	–
12	H ₂ O + CO ₂	3.6	8.8	–
13	other	0.8	2.7	13.3

Chemical composition of mining waste regarding its origin and production process is varied [144]. Indicative has been shown in table 2.2. It is important considering creation of secondary products and potential environmental hazards (washing out soluble salts, e.g. chlorides and sulfates). Sulfates can be found mostly in shales, mudstones and marlstones in form of calcium, magnesium and sodium salts. Chlorides content in polish carboniferous waste is low and between 0.002% and 0.006%. These amounts are not hazardous for the environment only when the ground on the dump is properly condensed. Limiting infiltration results in reduction in water dissolving and washing out chlorides.

The most basic component of mining waste dump is gangue (basically incombustible), created mainly during preparation, extraction and enrichment processes. Waste material is characterized by high petrographic and chemical diversity, dependent on lithological formation of exploited layers [144].

Rocks accompanying coal seams (table 2.3) originating from ceilings, floors and intergrowths, genetically diverse and characterized by diverse mineralogical composition: qualitative and quantitative. This type of rocks has been presented the most thoroughly by J. Kuhl [79].

Table 2.3. Classification of coal accompanying rocks using example of Upper Silesian carboniferous rocks [79]

Group	Rock type
I	Coal rocks: coal shales, coal clays, swelling coal clays
II	Clay rocks: kaolinite clays, kaolinite-illite clays, kaolinite-albite clays, kaolinite-sericite-quartz clays, kaolinite-chlorite-sericite clays, crystalline non-plastic clays, tonsteins
III	Mudstones: normal mudstones, siderite mudstone
IV	Sandstones: very fine-grained sandstones, powdery sandstones, lime-dolomitic or siderite-dolomitic, fine-grained sandstones, fine-grained dolomitic or ankerite-dolomitic sandstones, medium-grained sandstones, coarse-grained sandstones
V	Conglomerates: fine-grained conglomerates, coarse-grained conglomerates
VI	Limestones: lime marlstones, sandy limestones
VII	Tuffites

Table 2.4. Petrographic composition of coal waste in Poland [144]

Rock type	Coal Basin	
	Upper Silesian [%]	Lubelskie [%]
Claystones	40–98	31–65
Mudstones	2–40	34–47
Coal Shales	2–25	–
Sandstones	0–33	16–18
Coal	3–10	6–8

In overall balance of coal mining waste, the highest percentage of total mass comprise of, as follows, claystones, mudstones, coal shales, sandstones and pebble conglomerates. From time to time limestones and coarser conglomerates. Table 2.4 also shows, percentage of typical waste deposited on polish coal dumps.

Some of the highlighted rocks are shown in fig. 2.5 and described in tab. 2.5.

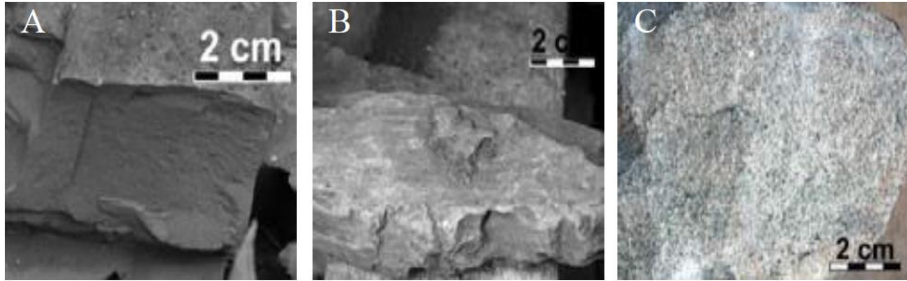


Fig. 2.5. Sedimentary rocks (A) coal accompanying mudstone (B) coal accompanying shale (C) coal accompanying sandstone [49]

Table 2.5. Shortened petrographic description of coal accompanying rocks [49]

Rock	Description	Notes
Shales	Sedimentary rock, dendritic, black colored, rarely dark gray, layered in texture (slated), aleurite-pelitic, varying layer thickness	Relatively low mechanical resistance, fissility
Mudstone	Sedimentary rock, detritic, color ranging from dark gray to black, homogeneous, texture directionless, compact, massive and aleuritic, intermittently appearing siderite bulges (siderite concretion – sedimentary limestone, gray-brown to brown-yellow, high density with compact massive, directionless texture	This rock has varying mechanical resistance depending on coal content
Sandstone	Sedimentary rock, detritic, light to dark gray, homogeneous, texture is directionless, rarely layered, compact, massive, psammitic sometimes with small mix of psephitic grains, it has high mechanical resistance, which highly depends on	Sandstone's matrix (the more clay minerals the less resistant it is)

It has been estimated that coal content in clays and mudstones rich up to several percent, however coal shales may contain about 40% coal [137]. According to foresight data (2009) average coal content in coarse waste is around 8%, in fine-grained around 10% and in flotation waste may even exceed 20%.

Considering importance of coal in self-combustion process and its varying percentage content in different waste rocks, it's worth to mention few things about coal petrography.

Coal is flammable rock of organic origin, mostly plant-based. There are four coal lithotypes (petrographic forms): vitrain (lustrous coal), clarain (semi-lustrous coal), durain (dull coal), and fusain (fibrous coal).

Lithotypes shown in coal seam are present in form of intrusions or interbeddings. Coal shale, which is often accompanying in the seam, contains 20–70% of mineral components. Rock above 70% of mineral components is considered to be a gangue, e.g. coal claystone. Coal lithotypes are built out of different macerals (petrographic components) distinguished under the microscope, characterized by specific morphological and optical features, showing different chemical composition. Macerals found in humic coal are divided into groups of vitrinite, liptinite and inertinite. According to scientists the vitrinite is the most vulnerable to oxidation. In case of Upper Silesian Coal Basin, the most prone to self-combustion are low-carbonized coals contain above 30% of fusinite and semifusinite thus macerals of inertinite group.

Carbonization level and seam macrostructure prove to be important features. It is widely accepted that the most prone to self-combustion are low-carbonized seams containing thick-layered vitrine.

Mineral content, especially sulfides (pyrite and marcasite), is also significantly affecting thermal processes on coal dumps [34]. During mechanical processing significant amount of FeS_2 goes into waste material because of high density difference between pyrite and coal. Sulfides amount deposited on coal dump grows with decrease in grain size of processing waste [165, 142].

Pyrite is found in form of encrusting, filling insides of structural cells of coal micro components, pseudomorphs of coal components cells, most of all in form of sockets, lenses and bulges not connected to coal material (fig 2.6).



Fig. 2.6. (A) Pyrite on coal, (B) Sulfide mineralization – pyrite, sphalerite inside carbonate vein, (C) Carbonate hydrothermal vein with visible pyrite [229]

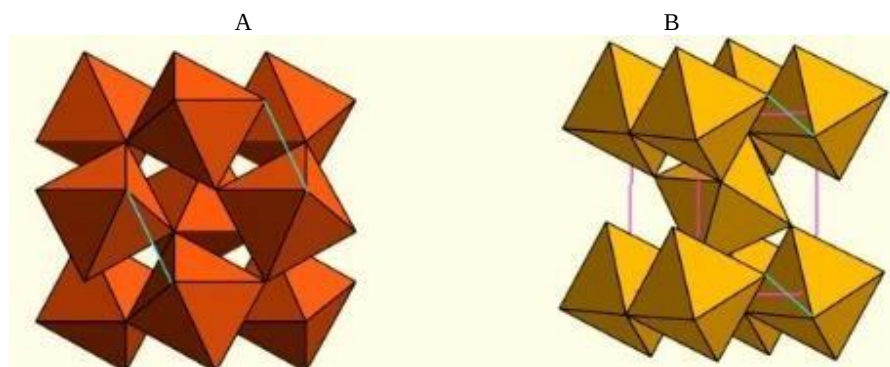


Fig. 2.7. Crystallographic forms: (A) pyrite FeS_2 and (B) marcasite FeS_2 [231]

Cubic crystal system pyrite is clearly dominating in ore mineralization of coal in comparison with marcasite, which crystallizes in orthorhombic system (fig. 2.7) that oxidize much easier than pyrite [2].

There are four basic types of pyrite accompanying coal seams [13]:

- euhedral crystals (5–10 μm),
- coarse-grained pyrite (> 25 μm) that replaces plant-based components,
- coarse-grained laminar pyrite that fills cracks and fractures in the rocks,
- framboidal pyrite – clusters or spheres around 25 μm in size.

When looking for the most reactive form of pyrite, framboidal pyrite should be brought to attention. It is featured by specific surface and high porosity (fig. 2.8).

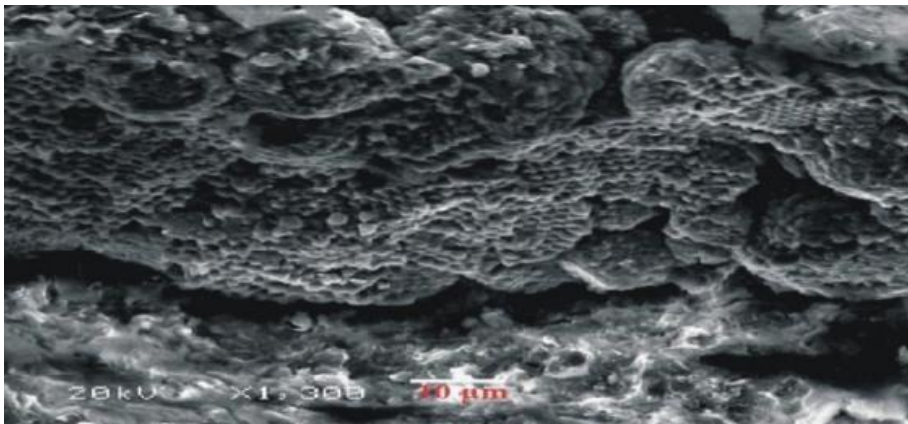


Fig. 2.8. Framboidal pyrite [160]

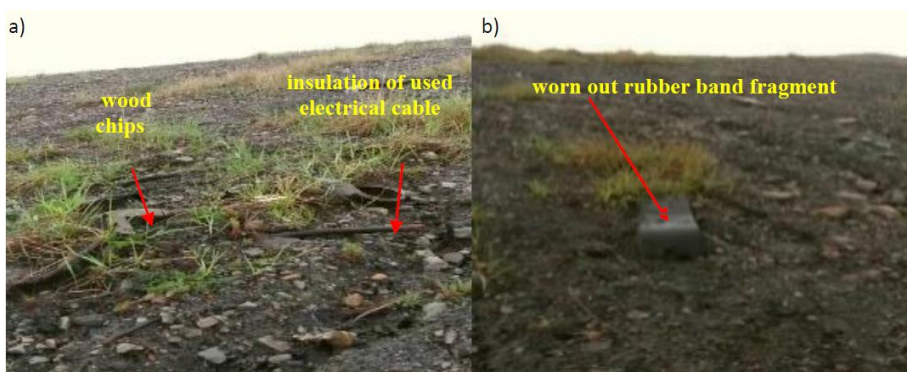


Fig. 2.9. Unsegregated coal-dump waste occurrence on dump: a) wood and electrical cable; b) rubber band [source: own]

Additionally, in material cross-section of gangue dump, small amounts of non-sorted waste of different origin can be found of constructional nature. These waste contain rubber bands (fig. 2.9b), wood chips, sawdust, working clothes fragments, rags soaked in grease and oils, steel scrap, rubble, plastics, cable insulation, hoses and rubber waste, cables and power plant dust and similar materials (fig. 2.9a). Admittedly, these material content is relatively small, as it doesn't exceed 0.2% of coal dump volume, but there is a potential risk of local gathering of flammable material [14].

2.3. Coal-dump waste thermophysical properties

Previous research considering thermal properties of rocks accompanying coal seams gave us knowledge, which let for identification of thermophysical features to a good degree [79, 21, 20]. However, taking of the topic of thermal objects properties, which are built out of coal mining waste, it is important to relate to waste mass as if it was a mix of different kinds of rocks. In this case, recognition of thermal properties is not so accurate. Additional complication is varying mineral composition, grain sizes, differences in origin and oxidation level.

As the most basic parameters describing physical properties of rocks and rock waste we can consider:

- volumetric density ρ ,
- bulk density ρ_n ,
- porosity p ,
- specific surface area S .

Numeric values of above parameters have been show in table 2.6 [144, 138].

Table 2.6. Physical properties of carboniferous rocks of Upper-Silesian Coal Mining Area (GZW – *Górnosławskie Zagłębie Węglowe*) that can be found in coal waste [144, 138]

Properties	Slates and shales	Mudstones	Coal shales	Sandstones	Coals
Volumetric density ρ_p , 10^3 kg/m^3	2.14–2.75	2.14–2.65	1.43–2.24	2.04–2.75	1.09–1.87
Mass density ρ , 10^3 kg/m^3	2.45–2.85	2.34–2.85	1.63–2.85	2.54–2.85	1.24–1.96
Porosity p , %	–	0.05–9.86	–	0.08–21.5	3.74–13.24

The main technical parameters of rocks are:

- thermal conductivity λ ,
- thermal diffusivity a ,
- heat capacity c_{wl} .

Rocks conduct heat in regards to their natural properties, namely: structure, texture, mineral composition, porosity, degree in which media are filling up pores, pressure and thermal anisotropy. Variability of these features causes difference in thermal energy flow. Rock's ability to conduct heat is described by **thermal conductivity coefficient λ** . This physical quantity has specified value in certain state of water

saturation and in certain thermal state of rock. It is physical parameter characterizing the ability to conduct heat described as total heat stream conducted through unit of rock surface (coal waste) of the fixed thickness when its opposite faces differ in temperature by one kelvin, in the unit of time during given conduction of heat [21].

Heat stream carried on the way of conduction (in case of one dimensional fixed conduction) is calculated according to Fourier's Law [138]:

$$Q = -\lambda F \frac{\Delta T}{\delta} t \quad (2.1)$$

where: Q – amount of heat energy [J], ΔT – temperature difference [K], F – surface [m^2], t – time [s], λ – temperature conductivity [W/mK]:

$$\lambda = -\frac{\dot{Q}\delta}{F\Delta T} \quad (2.2)$$

$$\lambda = -\dot{q} \frac{\delta}{\Delta T} \quad (2.3)$$

where: $\dot{Q}$ – heat flux [W], $\dot{q}$ – heat flux density [W/ m^2].

Table 2.7. Average thermal conductivity for various carboniferous rocks and stratigraphic members of Upper-Silesian Coal Mining Area (GZW – *Górnosławskie Zagłębie Węglowe*) ($\lambda_{\parallel}$ – coefficient designated in parallel to layering, $\lambda_{\perp}$ – coefficient designated perpendicularly to layering) [21]

Rock type	Layers									
	libiąskie and łaziskie		orzeskie		rudzkie		siodłowe		porębskie	
	$\lambda_{\parallel}$	$\lambda_{\perp}$	$\lambda_{\parallel}$	$\lambda_{\perp}$	$\lambda_{\parallel}$	$\lambda_{\perp}$	$\lambda_{\parallel}$	$\lambda_{\perp}$	$\lambda_{\parallel}$	$\lambda_{\perp}$
Pebble conglomerates and coarse sandstones	1.937	1.108	3.762	3.092	3.849	2.698	4.498	3.231	4.051	3.463
Sandstones medium and fine grained	1.313	0.948	3.447	2.605	3.479	2.695	3.402	2.660	3.685	2.506
Mudstones and claystones	1.384	1.276	2.353	1.858	2.452	1.629	2.720	1.723	3.155	2.192
Claystones and coal claystones	1.980	1.416	2.229	1.661	2.431	1.569	2.427	1.473	3.228	1.885
Coals	0.443	0.398	0.673	0.490	0.528	0.490	0.652	0.437	0.669	0.565

Research on thermal conductivity of carboniferous rocks of Upper Silesia have shown that variability of thermal conductivity in regards to temperature changes are conditioned by structure and mineral composition of the rock. Furthermore, increase in coefficient value when temperature increased has been observed. In practice coefficient λ is considered to be a constant value, which does not depend on temperature. For calculations averaged value is accepted.

Thermal diffusivity coefficient a , describes ability of unit of volume to change temperature in a unit of time during heat transfer. In other words, value of this coefficient decides the speed of temperature diffuses in the events of non-stationary heat transfer [117]:

$$a = \frac{\lambda}{c_{wt}} \rho \quad \left[\frac{m^2}{s} \right] \quad (2.4)$$

where: c – heat capacity [J/kgK].

Heat capacity c is the amount of energy expressed in joules that 1 kg of mass need to raise its temperature by 1 K. It is described by following formula:

$$c = \frac{Q}{m \cdot dT} \quad \left[\frac{J}{kgK} \right] \quad (2.5)$$

where: dT – temperature raise of material (rock) [K].

Numeric values of basic thermophysical properties of coal mining waste (table 2.8) shown amongst others in work of Saranczuk [141].

Table 2.8. Thermophysical properties of coal waste [141]

Property	Range of variation	Average
Specific heat c , 10^3 J/kgK,	0.933–1.235	
Thermal conductivity coefficient λ , W/mK	0.169–0.567	
Apparent density ρ_n , kg/ m ³	1610–2180	1835 – flat dumps 1970 – from processing plants
Bulk density ρ_n , kg/ m ³	1280–1700	1500 – flat dumps 1440 – from processing plants
Porosity P , %	14.0–33.5	18.0 – flat dumps 27.2 – from processing plants
Specific surface area S , m ² /m ³	495–1820	1080 – flat dumps 1450 – from processing plants

Problem associated with designation of thermal conductivity coefficient for material built of coal waste has also been discussed in PhD thesis of Z. Róžański [138]. Thanks to the research conducted on coal dump near mining shaft “Skalny” of “Bolesław Śmiały” Coal Mine (*KWK Bolesław Śmiały*), values of thermal conductivity coefficient have been designated. They ranged between 0.406 W/mK and 1.09 W/mK. Whereas average value of this coefficient has been estimated at 0.642 W/mK. Some building materials have also been observed to have similar properties when it comes to heat conduction, among other popular red brick.

Comparing relatively low value of thermal coefficient and equally low specific heat of waste matter (around 4 times lower than specific heat of the water) it is believed that heat created, e.g. in self-heating or sunlight heating process has an impact on high temperature raise, that slowly disperses [138].

2.4. Scale of the problem of potential thermal hazards in coal mining waste

Fire hazard is one of the biggest environmental problems considering coal dumps. Smoldering wastes are not only dangerous to the surrounding of the dump but also impact sanitary condition of the air. Thermal activity is observed mainly on older coned objects and dumps that were created relatively recently, where fire preventative measures were not sufficient [118, 42].

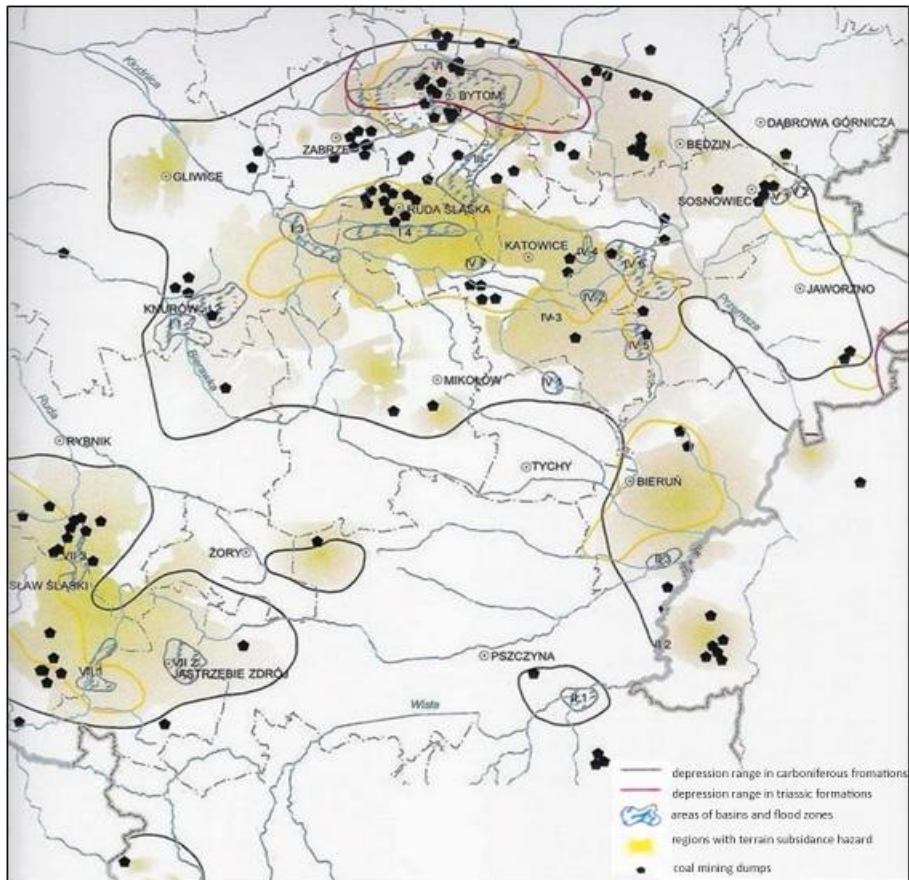


Fig. 2.10. Coal dumps in Upper-Silesian Coal Mining Area (Górnośląskie Zagłębie Węglowe) [143]

In last decade at least 21 cases of fire have been observed, mainly endogenous. This also applies to reclaimed structures [184]. Capt. Aneta Gołębiowska from Regional Headquarters of National Fire Department in Katowice seems to confirm number of fires, informing in one of the newspapers that between 1998 and 2007 fire department had 30 interventions on coal dumps. Among these interventions only there was only 18 cases of self-combustion of the dump. The rest lied in extinguishing of burning trash or grass that grew on the dump [32].

The newest research conducted in under the project Cool's (2007–2013) shows thermal activity on 15 coal dumps. Burning surface of the coal dumps is calculated to be around 2.5% of total surface of coal mining dumps in Poland, which is around 4 thousand ha [194, 125]. Other source provides information that at the moment in Poland more or less advanced thermal states are observed on around 30 structures of total burning surface of around 100 ha [88].

At the same time, it needs to be mentioned that in Upper-Silesian Coal Basin area there are around 220 coal dumps (fig. 2.10).

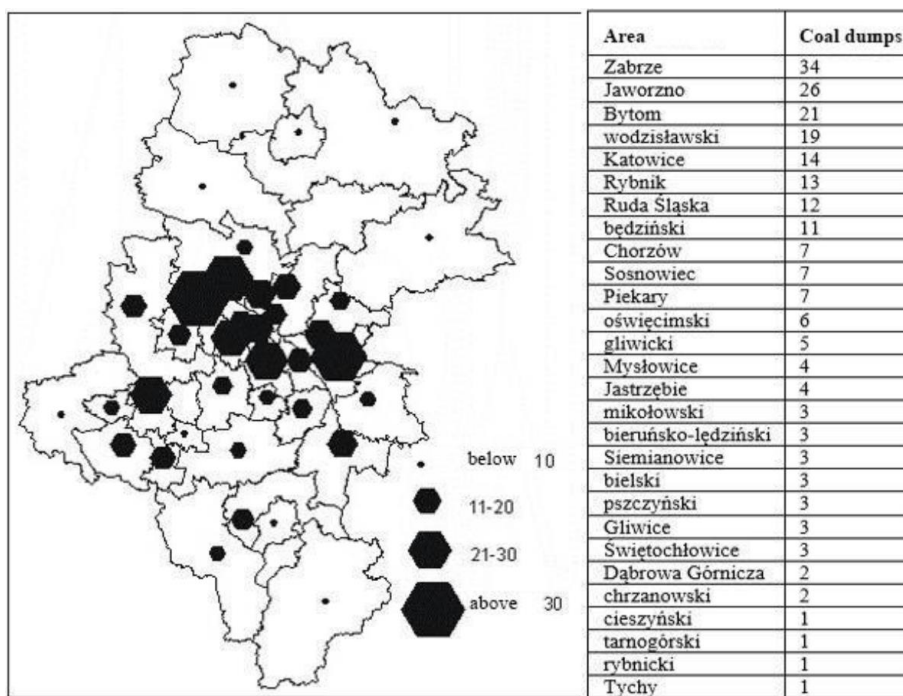


Fig. 2.11. Coal dumps density in Upper-Silesian Coal Mining Area [41]

On coal dumps there are waste from mining that have been gathered for 200 years as well as waste from mechanical processing of coal. There is significantly higher density of anthropogenic structures (above 80) in central part of Upper-Silesian

Coal Mining Area. In Zabrze area there are 34 dumps, in Bytom – 21 dumps, in Katowice – 14 dumps and in Ruda Śląska there are 12 dumps. Big cluster of coal mining waste “cones” is located in the Rybnik Coal Area. Next, distinguished area is within the borders of Sosnowiec, Dąbrowa Górnicza, Czeladź and Będzin. Other area of significant dump density is region of Tychy, Brzeszcz, Łaziska, Czechowice and Łędziny. PhD Łukasz Gawor, who impresses with his competence give us exact number of dumps in different areas of Upper-Silesian Coal Mining Area (fig. 2.11).

2.5. Coal mining waste management

According to the data of Central Statistical Office, coal mining in Poland decrease in the last 8 years by 20 Mt (fig. 2.12), to reach in 2013, 76,45 Mt [110, 130, 113].

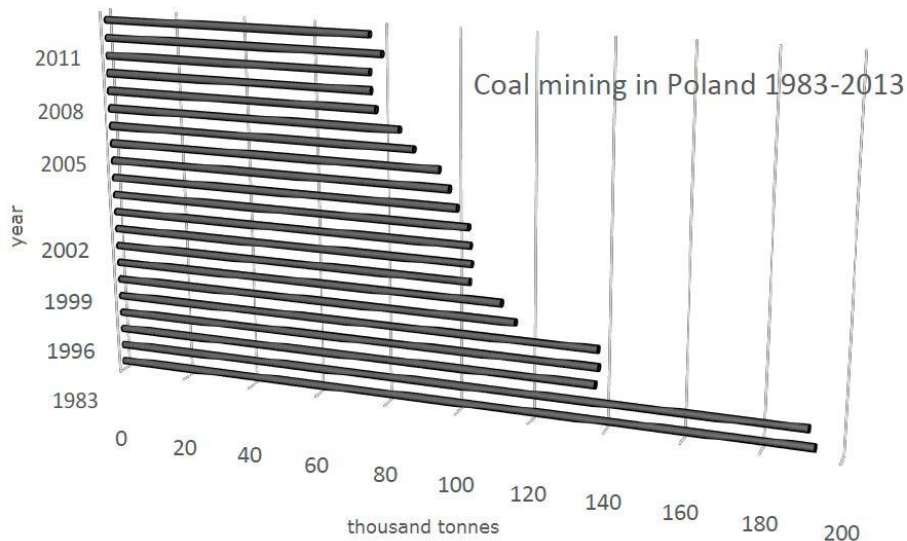


Fig. 2.12. Coal yield in Poland between 1983 and 2013 [110, 130, 113]

In 2012 total production in Poland reached 123.1 Mt of the waste material. Big share, 38.4 Mt, therefore 31.2% consisted of mineral waste created during mining and processing of coal (fig. 2.13)

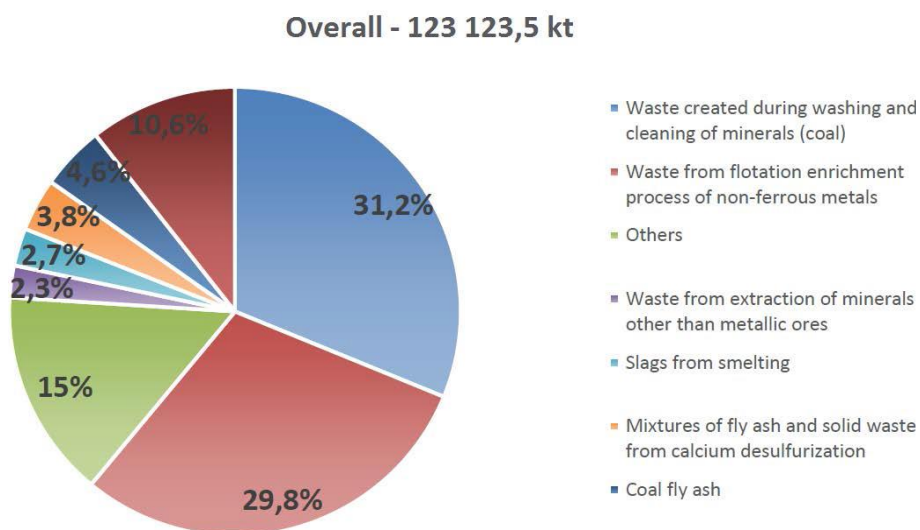


Fig. 2.13. Waste amount (without communal) produced by types in 2012 [110, 130, 113]

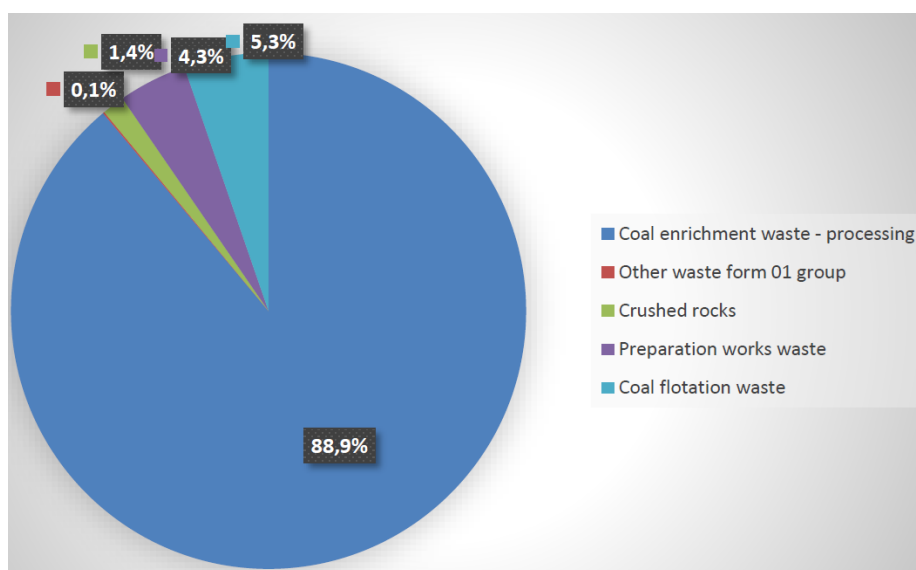


Fig. 2.14. Percentage of different coal-dump waste types produced in 2007 in coal mines of Upper-Silesian Coal Basin [110, 130, 113, 86]

Figure 2.14 presents percentage of different waste types produced in 2007 in coal mines of Upper-Silesian Coal Basin.

Right now for every ton of extracted coal there is around 0.4 Mg of waste mass. Gradual modernization of mining waste management rules, consisting, among others, of collecting fees for their deposition on coal dumps led to abandoning of common practice of storing waste in the in favor of their utilization [34].

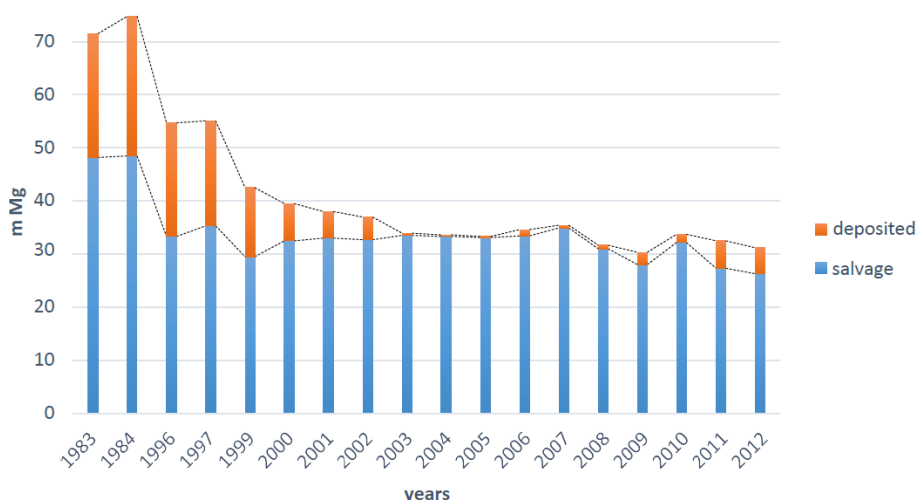


Fig. 2.15. Mining waste management in Polish mining industry in selected years between 1983 and 2012, source own acc. to [110, 130, 113, 86]

Recently, share of waste deposited to the total amount of waste produced has been reduced significantly and right now is around 5%. The fact that waste deposition on coal dumps is several percent doesn't mean that waste amount that is already on the surface got reduced in similar fashion. It has been calculated that industry utilizes only 30% of the mining waste, while 70% is used for engineering works (leveling or reclamation of post-industrial areas). In the figure 2.15 changes in coal mining waste management have been presented in years between 1983–2012. Coal waste are in used mostly in different forms of reclamation, while the remainder is deposited in the environment (deposited or stored) [49]. To prevent this there is an act from 10th July 2008 about mining waste, which within its scope implements regulations of European Parliament and Council directive 2006/21/WE from 15th March 2006 [167]. Act obliges waste producers to utilize them and to properly manage them in industrial installations, excluding some of the previously used methods of management such as deposition.

Coal mining activity that lasted several hundred years led to many changes in the environment. Newly created anthropogenic dumps together consist of nearly 500 Mt of carboniferous waste and cover total surface of around 4000 ha. Nowadays degraded areas are subject of reclamation or dismantling, while burned waste thanks to the newest technologies gain value of mineral resources. Older coned dumps were most of the time burned in result of endogenous fires, however thermal activity on

these type of structures is characterized by longevity and tendency to start anew. Carboniferous dumps can cumulate temperatures up to several hundred degrees, while processes of dying out of thermal activities may take several decades [118].

3. General Characteristics of Fire Hazard on Coal Waste Dumps

3.1. Causes of combustion of coal-dump waste deposited on dumps

To understand the essence of the processes and phenomena that take place on thermally active dumps, it is necessary to find out about their origin. Causes of combustion can be divided into two categories: endogenous and exogenous.

Exogenous combustions occur in the result of interference of other heat sources. In most cases initiators of these kind of fires are people acting irresponsibly on coal dumps. Usually the causes are human-lit fires, not properly secured welding works, hot and smoldering materials. Combustion can also be result of random causes such as lighting strike or fire from surrounding woods. Underground and on-ground electric wiring may also prove dangerous. Prevention of exogenous fires is based on regulation of human actions in the dump area in form of action banning signs (fig. 3.1), e.g. fire starting, throwing flammable materials or certain investments bans.



Fig. 3.1. Sign forbidding entrance to the area of waste rock dump belonging to “Ziemowit” Coal Mine (KWK Ziemowit) [source: own]

Endogenous combustions are result of low temperature oxidation of flammable substances (mainly coal, pyrite and markasite). This process is characterized by significant temperature emission which leads to spontaneous combustion of waste material and creation of so called hot spots.

3.2. Theories and research on coal spontaneous combustion

Process of starting endogenous fires is very complex mechanism, not entirely understood. There are no doubts only when it comes to the main reason of self-combustion that is process of coal oxidation, which is the primary flammable material of secondary products created during extraction process. However, the cause of the self-heating activation and achieving by coal critical temperature is not yet understood (60–80 °C). In regards to this using current knowledge of coal self-combustion seems substantiated as foundation for explaining thermal events on coal dumps. Research points to several possible theories about coal self-combustion, these include:

- **Bacterial theory**

Theory was based on assumption that significant role in self-combustion should be attributed to biological processes involving microorganisms (fermentation). Probable microbiological mechanism of self-combustion relies on bacterial methane exhaustion that is then catalytically burning. Further research undermined this theory's role, because even sterilized material, devoid of microorganisms, still had an ability to spontaneously combust. Bacterial theory found its uses in regards to self-combustion of organic substances such as hay, straw, wool, sawdust (lignin, cellulose), grain and oils [9, 137]. Fermentation processes may cause temperature raise in the inside the dump only when we are talking about wood chips deposited along other coal mining waste.

- **Phenol theory**

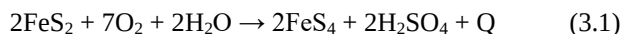
Theory considers coal self-heating under influence of energetic absorption of oxygen by unsaturated phenols with simultaneous heat emission [64, 137, 163].

- **Theory of coal-oxygen complex**

Theory focused on coal ability to adsorb and chemisorb oxygen with simultaneous heat emission. According to this theory, adsorption of oxygen by coal in standard temperature condition can get to 0.4 cm³/g [64, 137]. Theory takes under consideration significance of factors such as humidity and presence of fusain in coal.

- **Pyrite theory**

Pyrite (FeS₂) under atmospheric conditions oxidizes into iron (II) sulfate (FeSO₄) and sulfuric acid (H₂SO₄). these reactions are strongly exothermic. Advocates of pyrite theory treat self-heating of coal as process caused by catalysts (pyrite oxidation products) scattered in coal material. Following formula shows pyrite exothermic oxidation reaction:



Heat (Q), emitted during this reaction raises temperature of coal material and under certain conditions leads to coal combustion. Heating of coal can be initiated by pyrite especially if its content is higher than 5% and when it's fragmented and scattered with sufficient humidity [137, 163].

However, this theory is undermined by the fact that coals that do not contain pyrite also have an ability of self-combustion [9]. Regardless of mentioned aspect its worth noting, that presence of pyrite in coal intensifies self-heating process, because due to its oxidation it increases its volume. It results in crushing of coal and widening of gaps, which positively affects oxidation process.

It's also important to take under consideration the hypothesis that younger coal is more susceptible to self-combustion than the older one. Main arguments are that younger coal has higher percentage content of components such as:

- humins – amorphous, non-crystalline substances, colored brown or black generated in result of long lasting natural decomposition of plant material,
- humic acids (soil), $C_6H_4O_3$ – brown, amorphous acidic substances created in result of natural fermentation process of plant material,
- oxygen.

Oxidizing humins and humic acids have an ability to dynamically absorb oxygen, which leads to exothermic reactions emitting enough heat energy to initiate coal self-combustion [142, 163].

In attempt to find middle ground between theories shown above, we can bring out consistent approach to coal self-heating as a process of coal oxidation in oxygen environment. Oxidation reactions take place even at low temperatures. The specific heat of coal being four times lower than water and coal's small thermal conduction coefficient (around $0.3 \text{ W/m}^3\text{K}$ – in room temp.) mean that heat emitted in its oxidation process leads to relatively high thermal growth [163]. High water content in coal slows down self-heating process because of heat loss connected to water evaporation. Thus it is thought that coal water content – if it's small – accelerates self-heating process and if it's high – slows it.

Research conducted on coal are based on a series of methods specifying coal tendency for self-heating determining amount of heat and water vapor emitted from coal sample (adiabatic calorimetry) or measuring coal ability of coal to absorb oxygen in set conditions [25]. Different method of measuring self-combustion relies on heating the sample in bath using constant temperature raise. Sample's heat in entry phase is equal to the temperature of bath and later it starts to exceed it as a result of exothermic reactions. Measure of coal's susceptibility to self-combustion is time that passes before heat of the sample exceeds the value of bath heating it.

In 1990 Cairney [10] proposed a method allowing for determining temperature growth and smoldering of coal waste risk. During research it was observed that mixture of coal mining waste with soil couldn't be effectively combusted, despite the fact that it was characterized by (supercritical) calorific value ranging $9000\text{--}16\,000 \text{ kJ/kg}$. Suggested test of potential spontaneous combustion allows to obtain good information about ability of coal mining waste for combustion and its actual deposition environment. Apparatus construction allows for choosing of various flow velocity of air to go through the sample and identifying of critical flow, predisposing to waste combustion. During the test sample is being made with density that is found on existing coal dump. Analyzed coal mining waste gets heat up simultaneously with reference sample until they achieve temperature of $600\text{--}700 \text{ }^\circ\text{C}$. Temperature increase graph lines for both samples are drawn parallel to each other if researched sample doesn't show any sign

of potential for self-combustion (fig. 3.2a). When graph of temperature increase of researched sample is verging significantly and it's crossing with graph of reference sample then it is evidence for hypothetical probability for occurrence of spontaneous combustion (fig. 3.2b). The higher the heat, which intensifies temperature gradient of researched sample, the more prone to self-combustion is the sample.

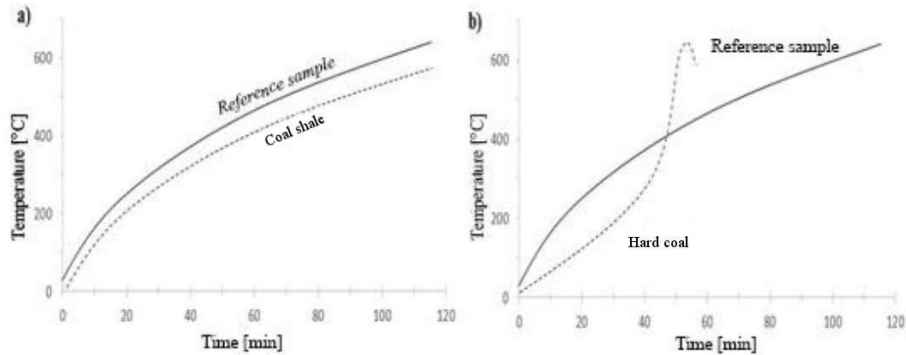


Fig. 3.2. Graph model of temperature increase in samples heated up to 600 °C, with airflow of 2,5 l/min: a) reference sample and coal shale sample b) reference sample and hard coal sample [144]

Some worrying concept for cause and susceptibility of coal to ignite itself are presented by measurements provided by OTA method (Oxyreactive Thermal Analysis) [64, 15]. OTA analysis is the method that relies on observation of reaction progress in sample while its being heated [22]. It is type of generally used differential thermal analyses (derivatographic) [16]. Research are conducted in specifically chosen course factors of heating process.

Active atmosphere transition of combustion chamber is used during sample analysis. It is performed for retrospection of environment conditions where processes that initiate the fire take place on coal dumps. Additionally, it is ensured that the sample is highly fragmented and distributed in a fine layer on the series of plates in order to increase oxygen availability to the upper end of the reacting particle of researched waste. Mass increase or decrease reactions (TG curve), heat emission or absorption (DTA curve), temperature, mutual causality and reactions duration speed let for apparent diagnosis of researched waste material. Measurement of differential of TG curve supporting DTG curve is registered in minimal heating time intervals. It is done in order to show highest degree of reaction for waste substance mass loss or increase [16, 11].

OTA captures both quantity and quality of coal material with incredible accuracy. It registers the amount of pyrite, clay, carbonate and sulfate minerals. It is especially important considering that this type of substances and mineral phases gets into coal mining waste in particular. Simultaneity of substances presented and scoping their behavior with temperature increase in result of spontaneous combustion of flammable material on coal dumps is a fundamental direction of thermal analysis [23, 22].

Different method of research used for studying coal dump waste material's susceptibility to spontaneous combustion is attempt to use a solid-bed reactor for ignition point evaluation.

The method relies on heating up samples to determined starting temperature, designated based on preliminary research. Spontaneous temperature increase is observed afterwards. Atmosphere inside the reactor is a mixture O_2 and N_2 selected in such a way that it resembles natural composition of air. In the meantime, gaseous products such as CO , CO_2 , H_2 and O_2 are measured at the reactor's outlet. Correlating measurement results allows to present a concept of three-stage fire development on coal mining dumps. Method show has been used to study spontaneous combustion of waste on dumps: „Waleska” – „Bolesław Śmiały” coal mine, „Wrzosey” – „Rydułtowy-Anna” coal mine, „Szyby Zachodnie” – „Jas-Mos” coal mine, coal dump on Bielszowicka street in Zabrze after the of „Zabrze” coal mine and coal dump „Ruda” in Zabrze-Biskupice.

3.3. Endogenous fires starting process on coal dumps

Spontaneous combustion of coal dumps can be summarized as multi-staged, self-accelerating burning and/or smoldering process. Content of main flammable components in polish mining waste deposited on coal dumps can even go up to 30% of carbonaceous substance and up to 8% pyrite and markasite [136]. Endogenous fire hazard on mining waste utilization structures can occur when three conditions are met simultaneously (fig. 3.3) [118, 30, 34, 144, 98, 106, 62–64, 131].

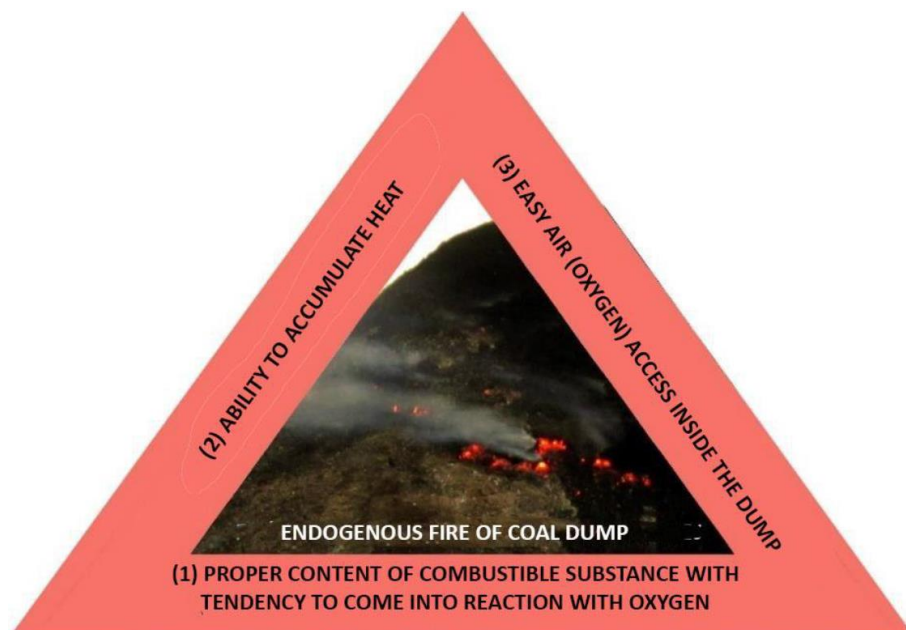


Fig. 3.3. Conditions necessary for fire occurrence on coal dump [source: own]

Flammable substances deposited on coal dumps along with rock waste material are exposed to atmospheric conditions and weathering (weathering). At the same time series of hypergenic processes start (fig. 3.4) activating coal waste mass [9, 106, 107]. Endogenous fire is the final result of chain of events preceding it.

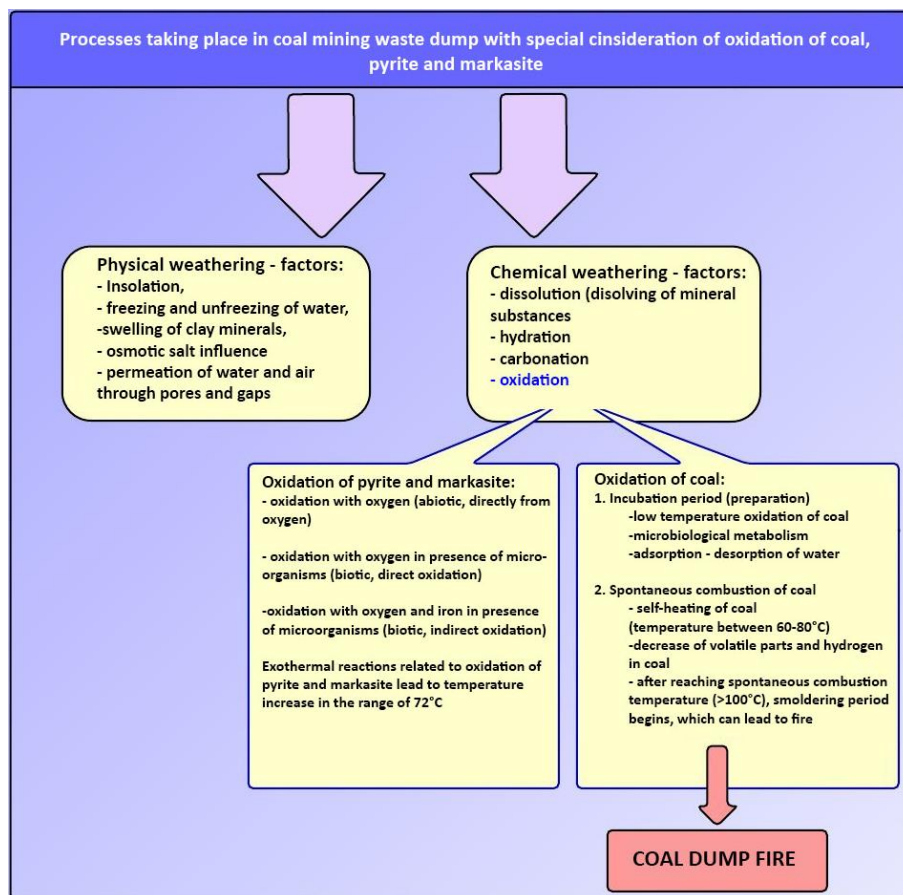


Fig. 3.4. Processes taking place on coal dumps, source: own acc. to [105, 107]

Depending on temperature range and oxygen availability we distinguish following processes of coal spontaneous combustion (fig. 3.5):

- auto-oxidization,
- smoldering,
- annealing,
- open fire.

The least known is the process of auto-oxidation, which is described based on various theories, hypothesis and research (the most important has been discussed in chapter 4.2). Auto-oxidation process is probably molecular chain reaction. Each particle or atom group in a particle, that came into reaction, create active particle (one or few), which then react and catalyze neighboring particles. This process is enabled and last for certain time in low temperature (it is so called incubation period). Oxidation is superficial in nature because chemical composition of oxidized coal doesn't change [7, 137]. Smoldering and annealing processes and can be considered in regards to heat explosion theory.

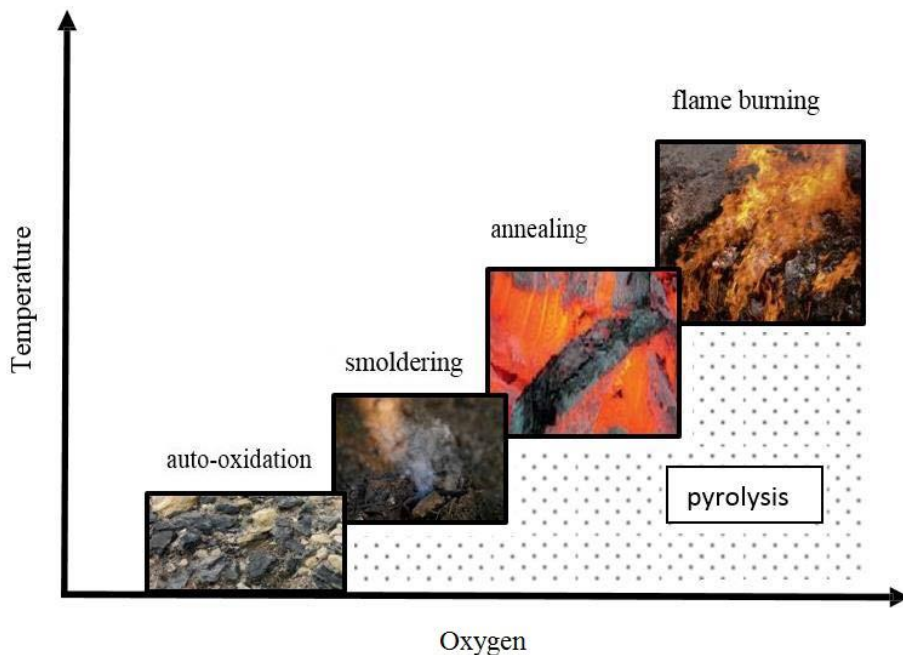


Fig. 3.5. Processes of reaction with air during deposition of solid fuels, source: own acc. to [9]

Long-term experiences gained in coal dump fire research allowed to distinguish two periods in their self-ignition process. Analogically to self-ignition mechanism in mines and on dumping heaps (fig. 3.6) [51]. First period, known as incubation on preparation, is characterized by slow oxidation of organic material and temperature close to the surrounding temperature (T_0) with minimal tendency for temperature increase. Research on coal particle surrounded by rock material show that transporting (bringing combustion products in and out) take place fast enough to provide enough oxygen to coal particle (limiting factor is the kinetics of the reaction). When it comes to efficiency of heat dissipation it is stated that it sufficient for dispersion of energy

created from chemical reactions. Lack of tendency for temperature increase is specific. It is a result of processes that take place and temperature changes very slowly and rely heavily on temperature changes around the coal particle.

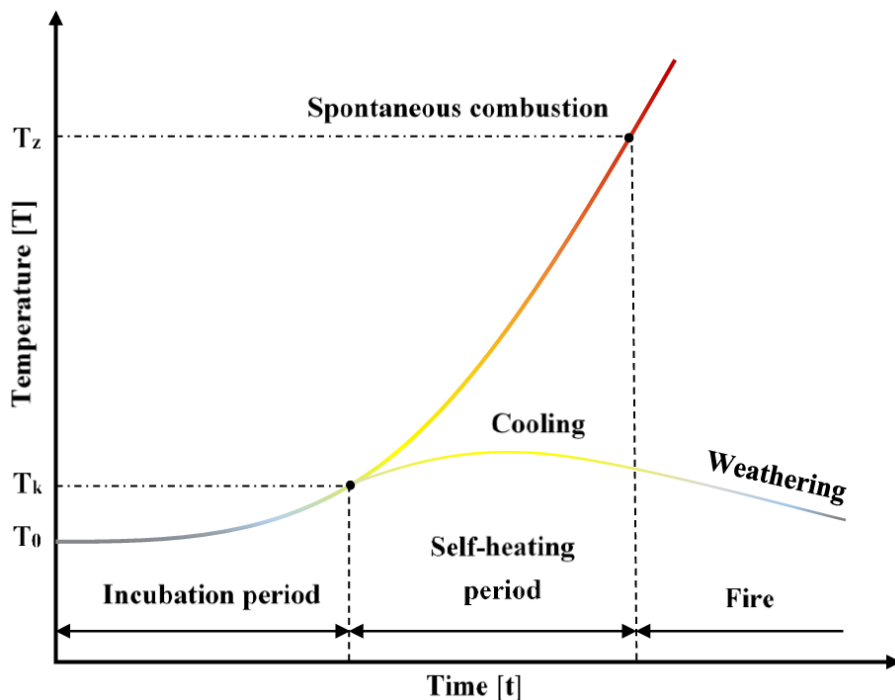


Fig. 3.6. Curve of coal spontaneous combustion on dump T_0 – initial temperature, T_k – critical temperature, T_z – spontaneous combustion temperature [142]

Low temperature oxidation in starting phase take place on macropores surface in neighborhood of outer surface of grains and gaps (fig. 3.7). According to Adamus [1], total volume of pores in coal can exceed $20 \text{ mm}^3/\text{g}$, while statistical proportion of macropores ($50 \text{ nm} < \phi \leq 7500 \text{ nm}$) to micropores ($50 \text{ nm} < \phi \leq 7500 \text{ nm}$) ratio is 2:3. It is also observed that total free flow of gas molecules doesn't take place until $10 \text{ }\mu\text{m}$ ($10\,000 \text{ nm}$). However, in situation where coal is a subject to some difference of aerodynamic potentials and escalation of flow (migration) of air, the oxidation – if it still occurs proceeds into micropore area [163].

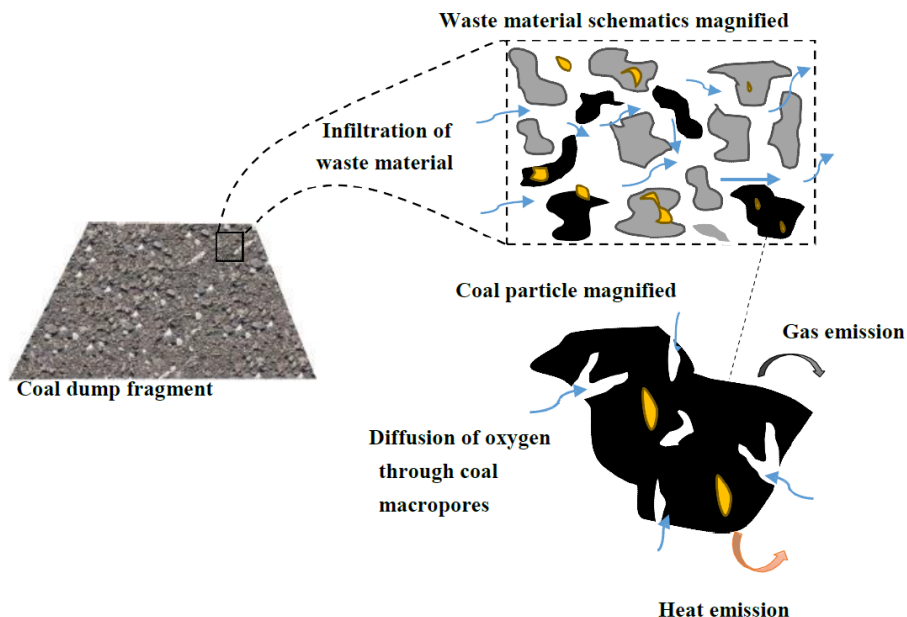
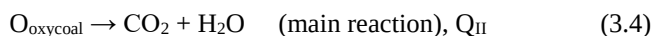
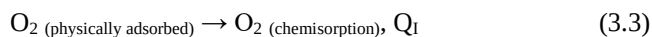


Fig. 3.7. Illustration showing basic phenomena occurring during low temperature oxidation of coal, acc. to [170]

Low temperature coal oxidation in range up to around 150 °C can be represented by following chemical reactions [9]:



where: O_{oxycoal} is oxygen adsorbed on coal surface.

Heat ($Q_I + Q_{II}$) emitted as a result of reaction is estimated at 33.4–36.1 MJ/kg of coal. Thermodynamical data can be a base for estimation of waste dump thermal stability loss due to slow coal oxidation according to some mathematical models [145, 9].

During analysis of thermal events causes on Rybnik area coal mining dumps [14] assumption has been made that coal contained in waste is characterized by so called “oxyreactivity”. It is a tendency for creating “oxycoal” where free valences of combined coal particles, in favorable conditions with available oxygen, join in the oxygen particle. This phenomenon is characterized by absence of carbon monoxide and carbon dioxide emission. Research also leads to conclusion that in starting phase, heating up of carboniferous waste take place in result of the biochemical reactions with thermophilic bacteria participation. It’s indicated by identical character of biochemical processes that happen during composting. Analogy can be seen in:

- temperature increase that does not exceed 60–70 °C in the first stage,
- lack of CO or CO₂ emission,
- reaction progression with access to oxygen (O₂, N₂),
- high humidity of waste material,
- tendency for heat accumulation inside structure.

During incubation period coal is activated and chemical reaction take place that emit significant amount of heat. From chemical point of view, spontaneous combustion of coal can be divided into three stages, which are oxidation (3.6), spontaneous combustion (3.7), burning (3.8–3.12) [85, 56]:

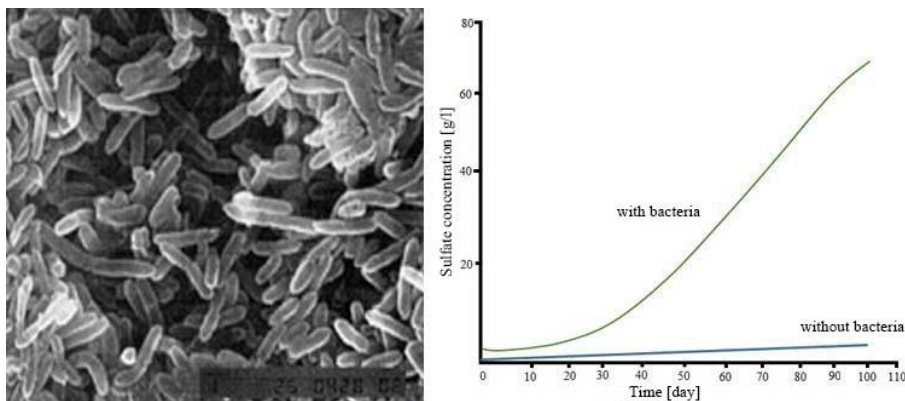
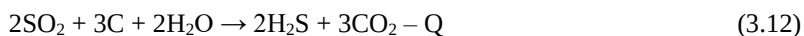
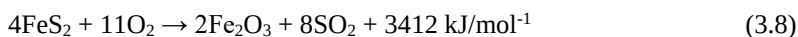
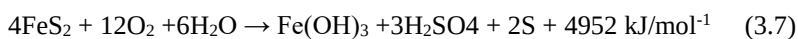
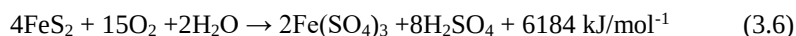


Fig. 3.8. On the left, view of Thiobacillus-Ferrooxidans bacteria [191]. On the right, graph showing speed of pyrite oxidation (for sulphide mining waste, temp. 21 °C, pH = 3) with and without bacteria presence [2]

Oxidation of coal, accompanying pyrite and markasite, is of utter importance in initiation and acceleration of thermal events [142]. The most reactive sulfide is framboidal pyrite, which can be distributed in waste mass in form of fine grained, micrometer sized grains. Iron sulfides, coal and organic matter oxidation occur in presence of atmospheric oxygen in wind aeration zone and oxygen that is dispersed

in water infiltrating the dump. Pyrite also weather in no-oxygen condition due to the presence of trivalent iron (Fe^{3+}). It happens thanks to bacteria from *Thiobacillus* genus namely *Thiobacillus-Ferrooxidans* (fig. 3.8) [149, 157].

Exothermic reactions connected to pyrite and markasite oxidation to Iron(II) sulfate and sulfuric acid lead to temperature increase of surrounding up to $72\text{ }^{\circ}\text{C}$ [34]. All fine grained rock materials are treated as heat insulators and sustain temperature that has been reached. Created heat energy is high enough that it reaches borderline of so called critical temperature (T_{cr}), which are considered between $60\text{--}80\text{ }^{\circ}\text{C}$ for open coal dumps [142, 9]. At this moment curvature of graph line for spontaneous combustion is reliant on conditions favorable for dispersion or accumulation of heat [142, 34, 123, 105, 106]. According to Saranczuk process of self-heating up to critical temperature can take from around two months up to two years [140]. Further oxidation of flammable substances can have three stages:

- Stage I: relies on situation when temperature of organic substance does not reach critical temperature or when after reaching it conditions for dispersion of heat are met. Then spontaneous combustion mechanism gets interrupted and cooling starts. Further air flow causes coal to weathering and loss of its ability to ignite itself;
- Stage II: flammable substance activity stays on the same level;
- Stage III: Occurs when temperature accumulation take place and critical temperature is exceeded (T_{cr}). Spontaneous combustion of organic substance reaches next stadium called self-heating period. At that time high temperature increase is observed, which influences acceleration of oxidation processes and increases bacterial activity.

It is believed that controlling factor for oxidation speed of coal and pyrite on coal dump is oxygen presence inside the dump mass, free convection and direction and strength of the wind.

Free convection – described as main mechanism for transport of oxygen, reagents and heat (fig. 3.9 and 3.10). Low density degree and favorable shape of dump, facilitate creation of convection current inside its bulk, which enables further spontaneous combustion processes [80, 81]. Autopsy suggest that self-heating process starts on the steepest slopes at around 3–4 m deep from near surface layer. It follows that with improper density of slopes or when steep slope has not been condensed at all, conditions for spontaneous combustion are favorable even when the rest of the structure has been built correctly [118]. On the other hand, Wagner's and Králík's [169, 73] observations prove that endogenous fires start under near surface weathered layer from 0.2 m to 0.5 m deep and rarely deeper – up to 5 m. However, Drenda notes that burning areas of coal dump have higher surface temperature than air temperature, usually more than few degrees or in case of open fire up to several hundred degrees Celsius. Still, the deeper from the surface layer the higher dynamic temperature increase value. In hot spot (8–10 m deep) it can reach up to $1000\text{ }^{\circ}\text{C}$ [116]. By contrast research on thermally active structures of former USSR prove that seats of fires where highest temperatures of waste material have been observed ($500\text{--}1000\text{ }^{\circ}\text{C}$) are located on small depths of 1.5–2.5 m from the surface of coal dump [140]. Suchariwskij noticed that on flat dumps, areas of highest thermal activity are usually located near steep

slopes of the dump where oxygen can infiltrate bulk of the dump in relatively easy way [156]. Different scenario is thermal activity on flat surface of dumps where thermal anomalies occur especially near gaps and cracks of the structure. Then, depths at which hot spots are located can be bigger than 5–6 m.

Direction and strength of the wind – initiation of thermal anomalies and their highest intensity in most cases occur on scarp from windward side. Strong winds fuel thermal processes. Along with reaching temperature that exceeds 60 °C, supremacy of coal oxidation occurs, while in coal dump atmosphere CO and CO₂ is observed. There are many observed instances of intense temperature increase, when in 1–2 days there is rapid growth of thermal phenomena in near surface layers of steep windward side during strong winds. Rybnik’s “Stožki” are proof of such occurrence, when temperatures observed there increased from around 50–60 °C up to 800 °C in a very short time. It has been emphasized that rapid growth may take place after exceeding 130 °C [14].

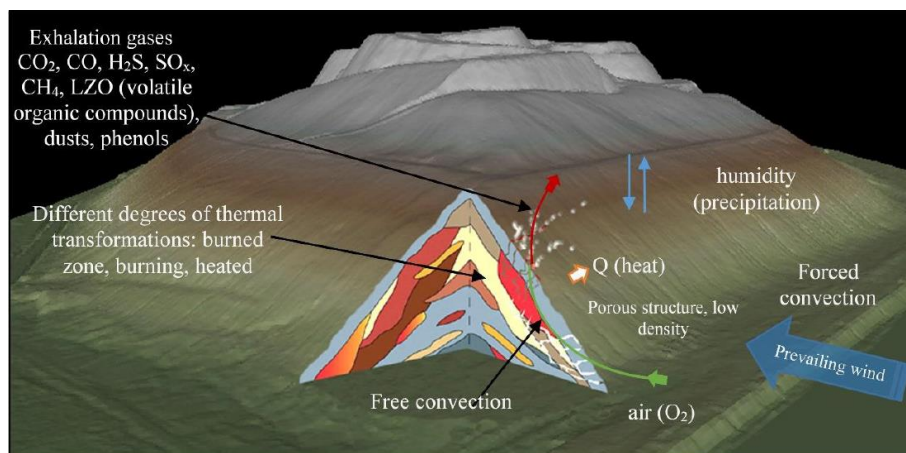


Fig. 3.9. Schematic of burning coal dump with convection mechanisms taken into account [source: own]

Further progress of fire fueled by convection current is shown in fig. 3.10 [101].

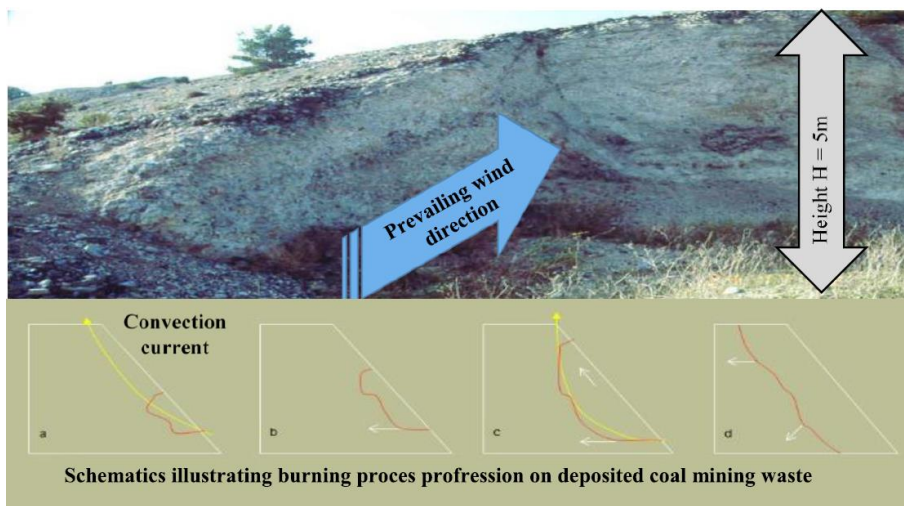


Fig. 3.10. Propagation of combustion of coal-dump waste fueled by convection current [93]

Two parallel processes are worth mentioning, during oxidation of carbonaceous substances [163]:

- activation, which is raise in number of active seats of fire on the surface of dump during humidity loss and heat increase;
- deactivation, which is wearing-out of active seats of fire on the surface of dump as a result of oxygen sorption.

Intensity of mentioned processes has a significant influence on self-heating. Increasing coal heat, depending on its carbonization stage, reaches combustion temperature ranging between 250–350 °C [25]. On the other hand, when studying temperature of ignition, depending on fragmentation of coal, it has been designated between 330–360 °C when grain size is in the range of 1.5–2 mm. In case of grain sizes above 1mm, ignition temperature drops to 190–220 °C [90, 163]. Higher fragmentation of coal allows for easier oxygen access to coal material, in result increasing contact surface with oxygen, thus making self-heating and spontaneous combustion processes easier.

There is an assumption that imply that final stage of self-heating, which is spontaneous combustion of coal waste, is connected to spontaneous combustion of elemental sulfur fumes, emitted during oxidation of pyrite contained in waste. This phenomenon can occur in air near heated surface of rock that reached its heat level thanks to chemical reactions of oxygen leaching of pyrite, raising temperature to 248–261 °C. At the same time there is risk of combustion of methane desorbing from sulfur [183].

Appearance of gases such as CO or H₂ is an indicator that dump reached state of combustion initiation [48]. However, it sometimes happens that high temperature inside coal dump doesn't have to indicate occurrence of fire, because simultaneous lack of CO, average CO₂ content (around 6–10%) and oxygen content up to 10% leads

to conclusion that dump reached post-fire state, which results in cooling of deposited material [118].

Urbański and Granowski [166, 50] distinguish three fire progression stages depending on temperature of waste material:

- heating of coal dump, temperature of deposited waste ranges between 40 °C and 150 °C,
- low or medium intensity fire, temperatures of deposited waste ranges between 150 °C and 300 °C,
- intensive fire, temperature of deposited waste exceeds 300 °C.

Initiated endogenous fire ends bacterial activity, however thermal processes progress extremely fast. Decrease of sensitivity to temperature of surrounding of dump becomes distinctive feature of spontaneous combustion [140]. Seat of fire is spreading to the next areas of dump and further progress relies on oxygen access as well as organic material content in waste.

Example of temperature changes of air and waste material at different depths in heating stage during one-year time, has been shown in fig. 3.11(A). At the same time fig. 3.11(B) illustrates isotherms distribution on vertical cross-section of coal dump.

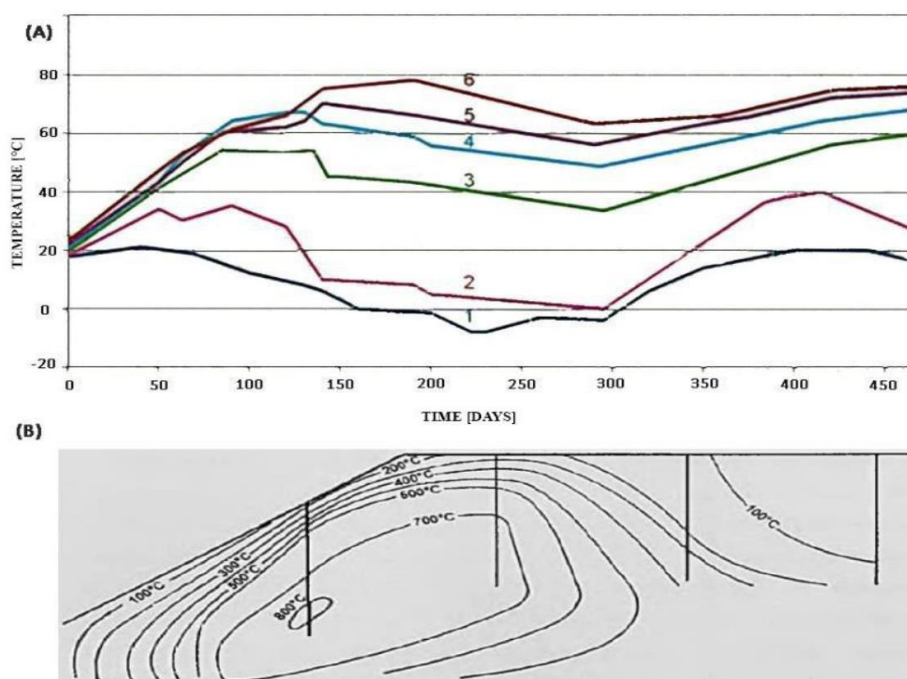


Fig. 3.11. (A) Air temperature changes (1) and waste material in its heating phase on a surface (2), depth of 0.5 m (3), 1.0 m (4), 1.5 m (5) and 2.0 m (6) on one of dumps of the former USSR. (B) Temperature distribution in zone with high thermal anomalies [140, 137]

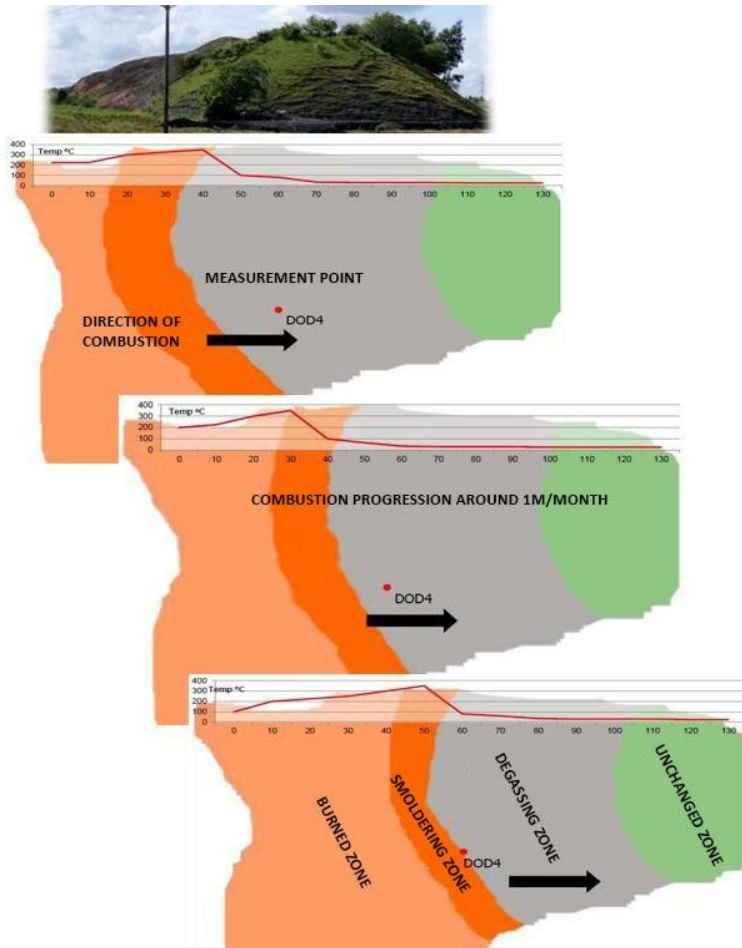


Fig. 3.12. Burning progression in case of smoldering waste (Bogside Bing, Scotland) [162]

Limited oxygen access to the waste bulk results in particular form of fire observed on dumps that is smoldering or even coking (fig. 3.12). Because of that burning of dump can last for many years. Heat created during smoldering of waste reaches values exceeding 500 °C while oxygen concentration in burning zone can decrease from 20% to 0.1–2.5% [137, 116, 30, 31].

Confirmation of smoldering of coal waste is [162]:

- flameless burning of waste material,
- low peak temperature, around 600 °C,
- low combustion heat, around 5 kJ/g,
- progression of waste smoldering (~0.1 mm/s),
- endothermic pyrolysis and exothermic oxidation,

- in depth burning in porous media,
- burning reaction is usually incomplete,
- presence of CH_4 and H_2O in gas measurements,
- increased temperature in range of smoldering material,
- sustaining of own heat,
- burning out of organic material and oxidation of ferrous compounds results in red-orange color of gangue (cause by thermally transformed, finely distributed hematite).

Stored waste contains significant amount of sulfur and organic compounds, which when come in contact with high temperature and humidity, in low oxygen condition, undergo thermal breakdown (pyrolysis) with emission of gaseous products (volatiles) and liquid (tar). Solid coke remainder is called char (fig. 3.13).

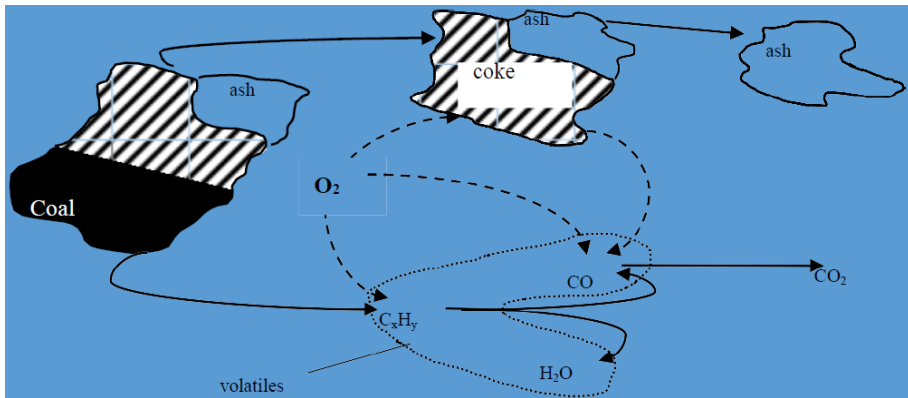


Fig. 3.13. Coal metamorphism during burning [9]

Pyrolysis of coal contained in mining waste is different to pyrolysis of industrial coal, which is performed in controlled environment. Despite that it is acceptable to compare overlapping mechanisms in both processes [38].

Pyrolysis process is complex and depends on many external factors (temperature, heating rate, and atmosphere) and on coal type. Tar and volatiles emission relies on carbonization: in case of low carbonized coals gaseous products of pyrolysis come forefront while tar is dominant product for highly carbonized coals [55, 9].

Turns out that pyrolysis mechanism is radical. Heat increase lead to degradation of less stable coal bonds and creation of free radicals. Part of them reacts with hydrogen, forming volatile and liquid products, while other (in polymerization, condensation and recombination processes) create solid coke remainder [9].

Medium carbonized coals go through plastic state, which is important in degassing mechanism (fig. 3.14). Generally, three characteristic phases of thermal breakdown of coal can be distinguished:

- I. coal – metaplast,
- II. metaplast – semicoke + tar (primary degassing in 350–500 °C),
- III. semicoke – coke + gas (secondary degassing above 500 °C).

In the first phase most emitted are water vapor, CO₂, H₂S and some other flammable gases as well as tar. In the second phase tar is intensively produced and emission of gases increase. The third phase is characterized by breakdown of solid substance – semicoke. The most dynamic degassing of semicoke is connected to hydrogen emission and take place at temperature in the range of 670–720 °C [161, 150].

Quantity and composition of volatiles depends on coal type, petrography, pyrolysis conditions (pressure, temperature, atmosphere). Typical for volatiles is high CO₂ and H₂O content. Flammable components, excluding carbon monoxide and hydrogen, are mainly hydrocarbons [9].

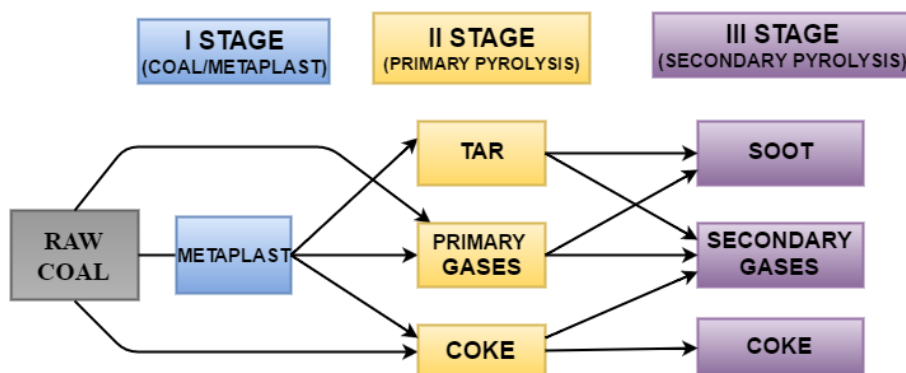


Fig. 3.14. Pyrolysis of coal diagram [158]

Coal dump burning process progresses slowly and can take many years, but with its intensification temperature can locally reach 1200 °C [142, 129]. Temperature accumulation inside the waste bulk and presence of porous water and gases containing products of slow coal oxidation (CO, CO₂), have beneficial effect on gasification process of coal material remainder in dump micro-areas.

Carboniferous waste heat can cause dump fires to show in form of flaming fires that is observable on the surface of dump.

So high thermal effects lead to thermal transformations of organic and mineral material. Transformations mentioned above depend on waste material properties (composition: coal, hydrogen, sulfur, sodium, chlorine, iron and calcium), temperature and its duration. Observations of burning coal dumps prove that temperature distribution inside dump mass is very variable. It also confirms highly varied intensity of transformations in waste mass [106, 107, 135, 136, 80, 81]. It should be noted that content of sodium, chlorine, iron and calcium in waste, thermally aid transformations of minerals, functioning as fluxes. Fluxes have properties reducing temperature needed for melting. Feature shown also influences rate of burning of carboniferous rocks, eliminating their energy demand needed for thermal transformations. Fluxes

are considered high temperature transformation catalysts in dump bulk area [80, 81]. Thermal transformation taking place on coal dumps causes decrease in volume of deposited waste by 40–60% [102]. Result of that are series of cracks reaching upper layer of dump. Fire gases, created in self-oxidation and self-heating processes, migrate through cracks into the atmosphere.



Fig. 3.15. Flame burning on coal dump Orzeł Biały – Brzeziny Śląskie (pic. Damian Cyfka)

3.4. Factors inducing thermal processes on coal dumps

Geochemical processes that take place inside thermally active dumps are complex and depend various factors, which can be divided into two groups [98]:

- genetic factors (internal), describing reaction ability of coal dumps material in comparison to air oxygen in low temperatures and
- external factors.

Genetic factors are material composition of dump with consideration of flammable components, structure of coal components and presence of oxidation inhibitors. External factors consist of parameters influencing filtration abilities of coal dump and their heat balance. Fire occurrence inside dump in result of self-heating is possible only when three main and long known conditions are met, namely:

- 1) proper content of flammable material (coal) with tendency to react with oxygen from atmospheric air;
- 2) facilitated air access (oxygen) into a dump;
- 3) proper heat accumulation conditions inside a dump.

Elimination of even one of mentioned conditions prevents possibility of spontaneous combustion (endogenous fire).

3.4.1. Conditions necessary for fire occurrence of coal dump Coal waste components that contribute to stimulation of endogenous fires have already been detailed in second chapter of this book. However, in this part, attention is focused on conditions connected to problems of aerological nature and dumps ability to accumulate heat.

Ease of infiltration of air flowing around the dump influences changes in pressure distribution on the structure's surface. One of the most important factors responsible for thermal activity is susceptibility of some area of dump to high pressure gradients. In massive above-level coal dumps daily changes of pressure causes air exchange up to 2 m depth. It turns out that rapid changes of pressure don't cool surface layer of the structure, but supply it with oxygen needed for oxidation processes. In regards to the fact that amount of air getting inside that way is low, burning process is incomplete.

Strong winds cause intensive aeration of dump steep scarps, while on leeward side there are zones of dynamic under pressure. Schematics shown in fig. 3.16 illustrates which zones of dump are the most influenced by effects of atmospheric pressure and winds [16, 8].

Strong wind periods escalate thermal events. Instances of intensive dump heating happened many times. In few days there was rapid increase of thermal processes. Such situation took place on "Starzykowice" dump, where in 1–2 day time sudden temperature increase had been observed in outer layer of windward scarp from 50 °C to more than 800 °C (visible red flame) [15].

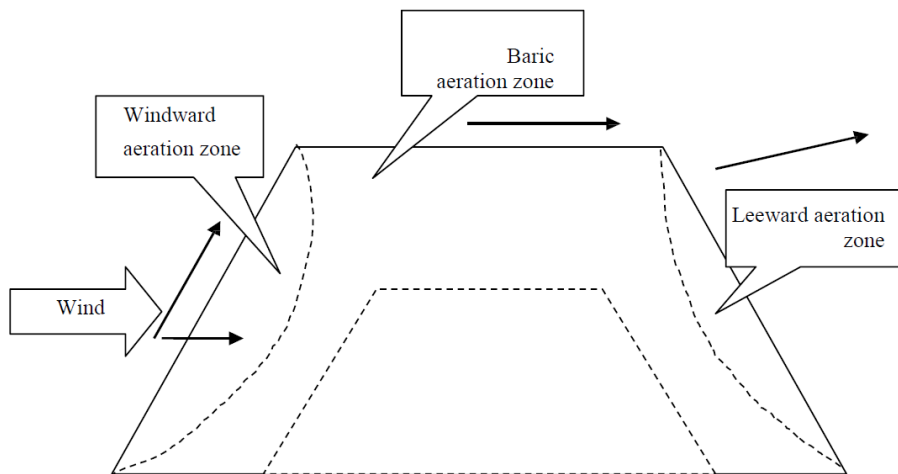


Fig. 3.16. Baric aeration zones, wind and leeward in coal dump acc. to [62]

Heat accumulation in coal dump is term understood as a case, where heat level created exceeds the heat vented outside the dump. Additional factor influencing accumulation of heat is the shape of object, which stores waste. It turns out that big solid structures (several thousand m³ and above), where surface to volume ratio of

deposited waste is small, are structures that are good at accumulating heat. Next factor is the rate of waste deposition. Depositing a lot of waste, on a small surface, in a small time span, in the range of few to several thousand tons a day, can significantly limit primary oxidation of coal substance [34].

3.4.2. Factors increasing probability of fire hazard on coal dumps

Besides conditions necessary for fire occurrence on coal dump, there are also factors sharing responsibility for thermal activity. Most important have been shown in fig. 3.17.

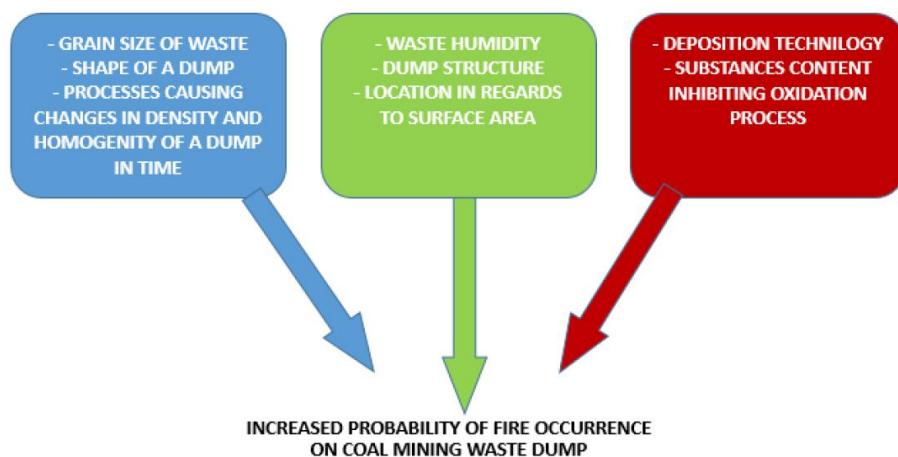


Fig. 3.17. Factors influencing increase of fire risk [source: own]

Factors associated with grain size of waste

Waste that can be found on mining waste dumps are usually a merger of different rock fragments that vary in grain size. In regards to origin, coal waste can be divide into two groups [119]:

- 1) waste that come directly from preparation works and operation of coal seams; coarse with grain sizes up to 500 mm,
- 2) waste created in coal enrichment process:
 - coarse washing waste from slurry separators, grain sizes of 10–50 mm,
 - fine washing waste from jigs, grain sizes of 0.5–30 mm,
 - flotation, grain sizes below 1 mm.

Smaller grain size fraction in comparison to coarse waste contain higher amount of flammable material. However, it doesn't mean that content of fine grained material instantly increases fire hazard. Objects structure that consist of significant amount of smaller fractions can cause partial sealing thus limiting the air infiltration into the dump. On the other hand, fire hazard increases when waste is being deposited in a way allowing natural grain segregation. Old dumps had been heaped up, which lead to grain segregation. Result of that was gathering of fine grains in upper and inner

part of the dump, while coarse fraction slid down the slopes in lower and outer areas. Such structure made it easier for air to infiltrate the object [166, 136, 137].

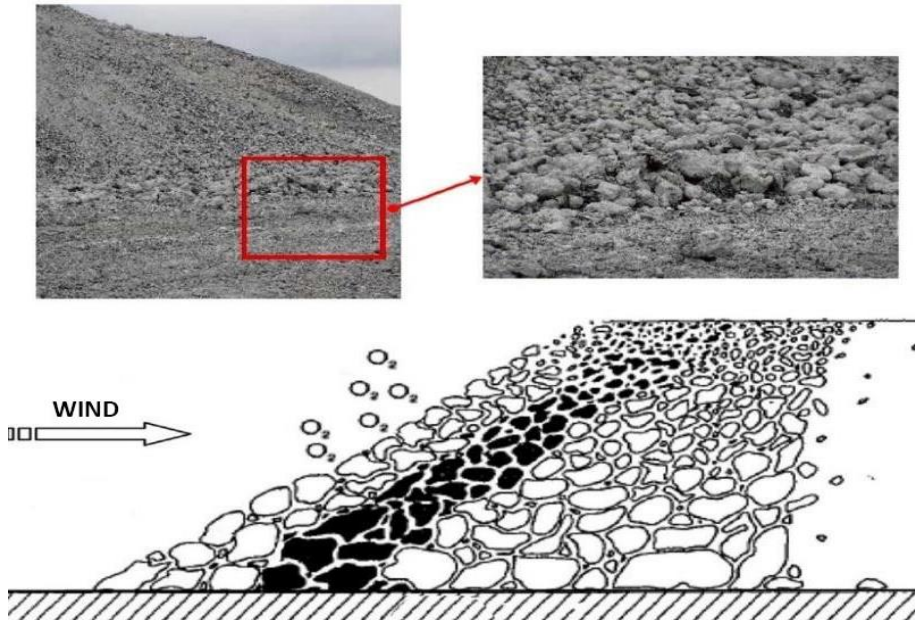


Fig. 3.18. Natural grain segregation [source: own]

Furthermore, granulometric composition changes as the dump ages. On newly heaped dumps, dominating fractions are cobbles and gravel while there is a lack of fine grains. In old waste as a result of oxidation, finer material is present and amount of fraction below 1 mm increases.

Factors associated with humidity

Turns out that humidity of waste is not a factor, which neutrally influences development of seats of fire. Presence of water from precipitation and air oxygen access in waste, helps in grain disintegration (crumbling) processes. Grain breakdown leads to further access of atmospheric oxygen allowing more contact with coal and pyrite grains. Escalation of such processes proceeds roughly two years after finishing of waste deposition, usually during late fall and winter (December, January) [15].

It also happens that water stops development of seats of fire. Situation like this occurs when amount of heat needed for vaporizing of water is higher than heat produced by oxidation of coal and pyrite.

Humidity of coal waste depends on grain size and atmospheric conditions. Humidity of material from Upper-Silesian Coal Mine is from 4 to 19%, where [119]:

- fresh waste $w = 4\text{--}10\%$,
- waste from new dumps $w = 4\text{--}13\%$,

- waste from old dumps $w = 5\text{--}19\%$.

Factors associated with deposition technology

The least beneficial technology of deposition is heaping up cones with steep slopes. Waste material is transported directly from conveyors or funiculars with fixed attachment of car to cable, which is led through the block on top of the dump and counterweighted. The counterweight is usually second funicular. This technology has been forbidden in the 60ties, because dump structure formed that way created favorable conditions for air infiltration into the dump thus starting oxidation of coal substance and pyrite. Technologies practiced in the past did not take into account fire preventative measures. Some of them are presented in figure 3.19.

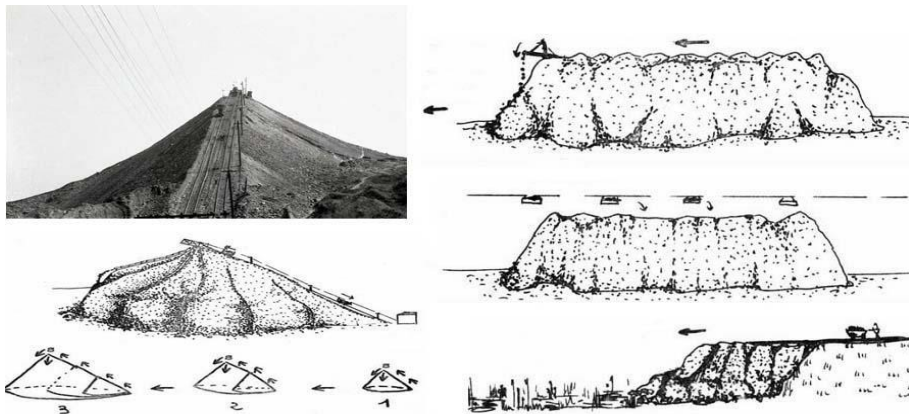


Fig. 3.19. Deposition technology of waste through creation of conical heap near main mineshaft “Ziemowit” in the fifties (pic. Jacek Filipiak) and schematics of other technologies used at that time [196]

The second, equally adverse technology, is transport of waste material using rail, its unloading and finally scattering of waste outside scarp edge using bulldozers. This technology is unfavorable as it leads to natural grain segregation and also makes it impossible for real time condensation.

The third known waste deposition system is performed using excavator, conveyor belt and stacker. It’s a niche system, which is favorable due to layered deposition of waste. The disadvantage is insufficient condensation and sealing of deposited material.

The last, most commonly used system is deposition of waste using dump trucks. This method allows for versatility in dump bulk formation as well as use of any fire prevention measures.

Right now, deposition of waste on surface dumps is conducted in two ways – frontal and backward. Frontal deposition relies on waste being transported to the head of dumping ground and then scattered in its slopes with highest inclination of the scarp

of 33%. Backward deposition technique relying on transportation of waste to the foot of dump, then moving them up slopes. The inclination is equal to 33% as well.

Factors associated with shape of coal dump

It turns out that shape of the dump (fig. 3.20) is not as insignificant for development of thermal processes. Scarps characterized by high inclination, especially the ones, standing in a way of prevailing winds, are much more endangered by fire possibility than gently sloped scarps. That is why scarps located windward shouldn't be frontal ones and should have possibly small inclination relative to the surface (to 30°). Height of an object influences thermal aspect as well [166].

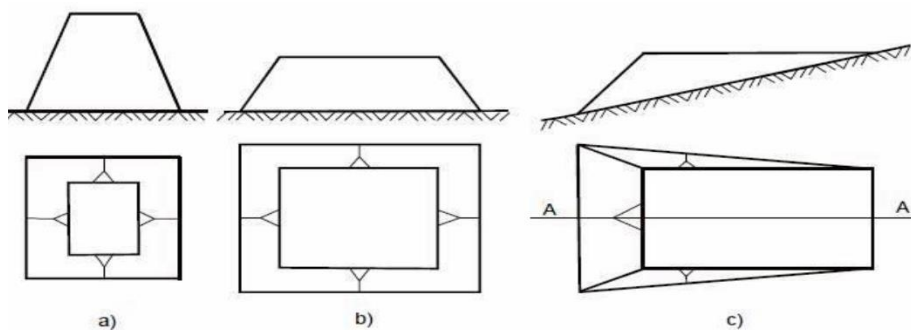


Fig. 3.20. The most often used forms of above level dumps and dumps a) cone b) heap c) slope pile [165]

Factors associated with location of an object in relation to the surface

In regards to location of an object in relation to the surface, four types of dump can be distinguished: below-level, above-level, partially above and partially below level and lateral. Issue has been discussed more broadly in chapter 2.1. Fire hazard relates more to above-level dumps, especially objects higher than 20 m. In case of below-level dumps fire hazard is significantly smaller because oxygen access into the waste is reduced.

Factors associated with proper construction of the dump

During construction of the dump, preventative measures should be taken into consideration. It is important to properly choose shape of the dump that excludes possibility of erosion and allowing for correct retention of rain water. Improper rain retention (fig. 3.21a and 3.21b) causes series fissures and channels to appear on the surface of dump. Correct condensation of waste material and choice of proper, fine grained materials, that seal the dump, should also be taken into account. Materials – good sealants – there are clay, fly ash, industrial silt, mud, etc. Sealing process can be conducted on surface or internally, e.g. through injections, filter swales or mixing mentioned fine grained materials with waste.



Fig. 3.21. A result of rain caused ablation processes on waste rock dump surface of “Ziemowit” Coal Mine (KWK Ziemowit) a selection of distinctive erosion forms such as a) erosion notches or b) channels and in their outlet – alluvial fans [source: own]

Factors associated with oxidation inhibitors content

Substances inhibiting oxidation process are called antipyrogens or inhibitors. There are various theories about activity of coal burning inhibitors. For example, presence of some chemical substances in waste mass decreases coal affinity towards oxygen, while breakdown products of some compounds such as free chlorine, have extinguishing properties.

Antipyrogens are:

- calcium compounds, e.g. $\text{Ca}(\text{OH})_2$, $\text{Ca}(\text{HCO}_3)_2$, CaCO_3 , CaCl_2 ,
- some silicon, aluminum, iron and magnesium compounds,
- ammonium salts, phosphates,
- industrial waste containing amines, phenol and its derivatives.

Processes causing changes of density and homogeneity of dump over time

- chemical weathering (in rapid air and water exchange environment in particular),
- suffosion (mechanical washing out of grains and mineral particles from sediment by aquifer infiltrating rock or soil),
- biological activity (creation of voids as a result of settling of animals or plants on dump),
- cold weathering (type of physical weathering, relying on bursting or crushing of rocks, as a result of pressure created by repeatedly freezing and unfreezing water contained in cracks and pores of rocks).

Other factors have been shown in figure 3.22 presenting interactions of factors stimulating thermal processes on coal mining waste dumps. While creating schematic, efforts were made to consider all factors found in professional literature.

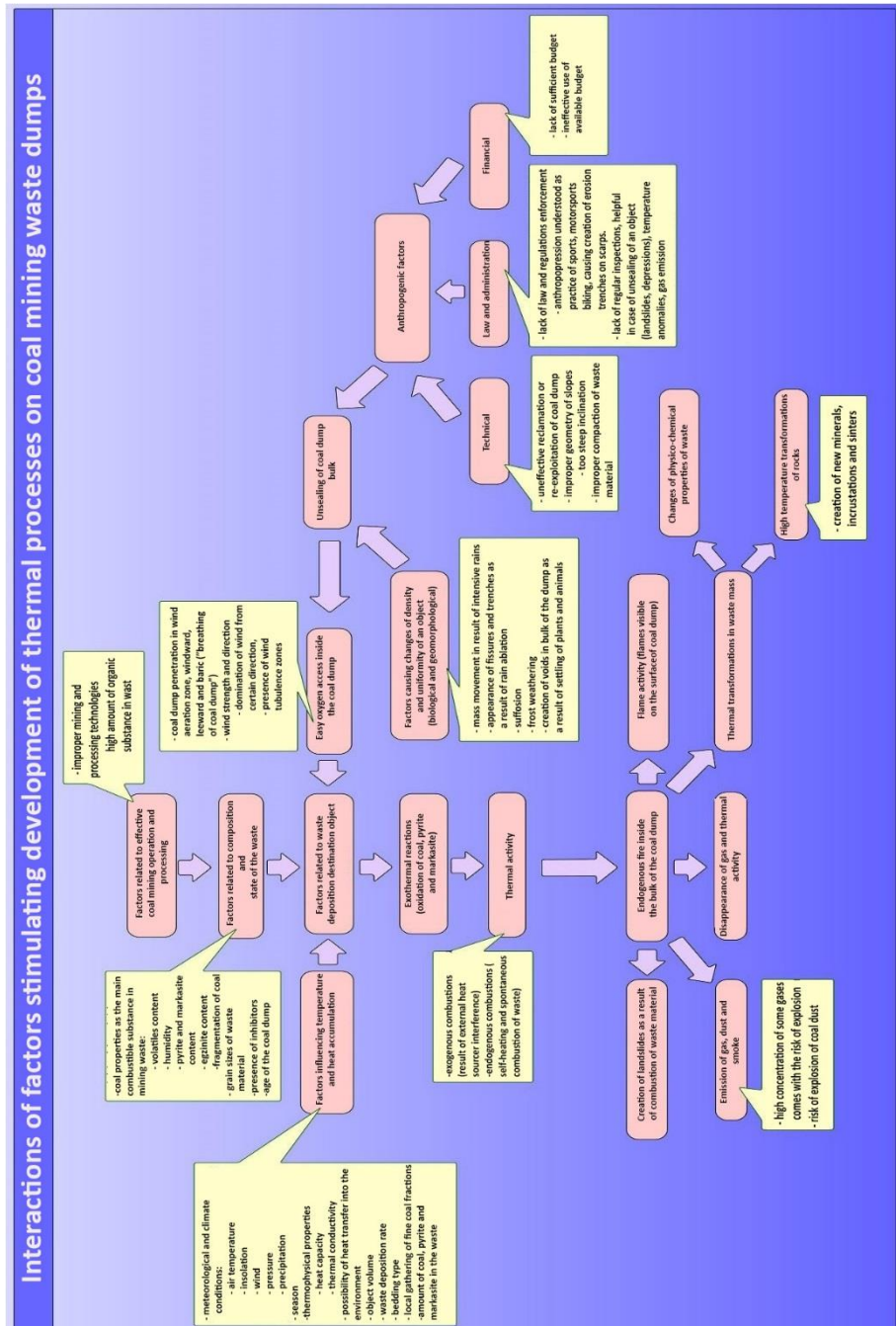


Fig. 3.22. Interactions between factors stimulating development of thermal processes on coal dumps [source: own]

4. Fire Prevention and Firefighting

Methods of preventing hazards of fires on coal dumps are associated with taking appropriate actions already on building stage. Preventing occurrence of exogenous fire is relatively easy as only avoidance of causes is necessary, that i.e. starting fires, burning grass in the area or neighborhood of dump etc. Despite this local community does not always possess proper knowledge of the problem and there are cases of fires started this way. Preventing endogenous fires, which start and develop in a latent way, relies on excluding and minimizing at least one of its causes. Following actions can be undertaken: decrease of substances in waste that are active towards oxygen, limiting oxygen access into the dump or decreasing heat accumulation abilities [30, 31].

In fact, it is impossible to completely remove flammable substances from waste. Safe limits of coal and pyrite contents couldn't be set as well [118]. It's also hard to prevent accumulation of heat in dumps considering their huge volume and mass. The easiest way is to reduce air infiltration into the dump.

Analyzing preventative methods for fighting endogenous fires on coal dumps, division can be made, as shown in fig. 4.1.

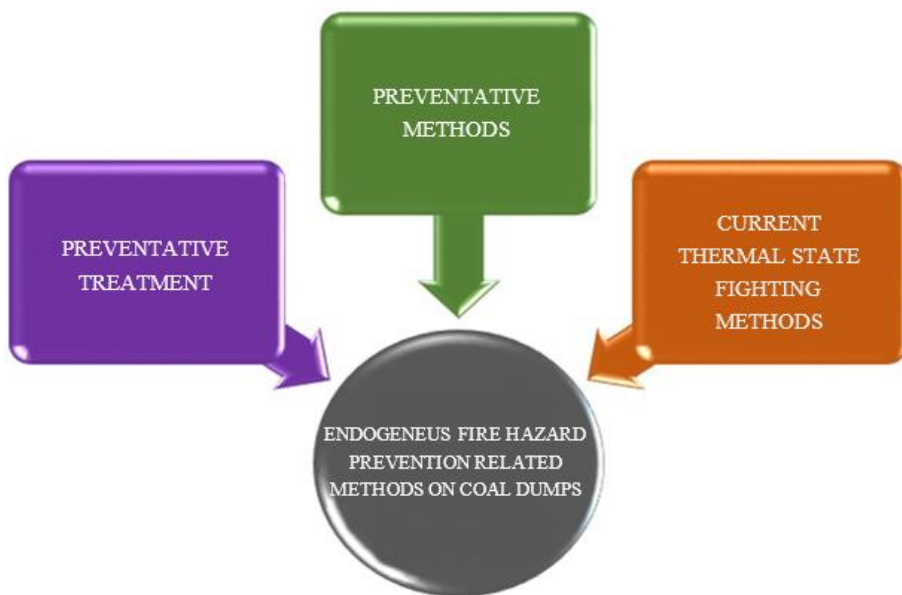


Fig. 4.1. Preventative methods of fighting endogenous fires on coal dumps source: own acc. to [89]

4.1. Preventative methods

Preventative methods allow to avoid thermal activity generation on coal dumps. Fire prevention should be taken into account already on designing stage and during mining operation. Basic rules associated with prevention are:

- ensuring the use of proper grain size and waste material compaction on dump,
- highest possible reduction of coal content in deposited material,
- choice of technology offering the best waste compaction coefficient on dump,
- observation, during construction stage, as well as post-construction phase.

Ensuring the use of proper grain size and waste material compaction on dump

The best hermeticity of dumps can be achieved through the choice of proper grain size of waste mass. Advantage of mixture with optimal grain size curve (fig. 4.2) is good compaction rate and minimized price of ground works. It helps limiting air access into the dump, which in turn reduce self-heating hazard. Proper parameters regarding tightness can be obtained with [89]:

- depositing of material of graining non-uniformity $U = d_{60}/d_{10} > 15$, and minimally $U > 5$),
- achieving volumetric density of waste mass that is in range of $1.7\text{--}1.9 \text{ Mg/m}^3$,
- achieving compaction coefficient in range of 0.95.

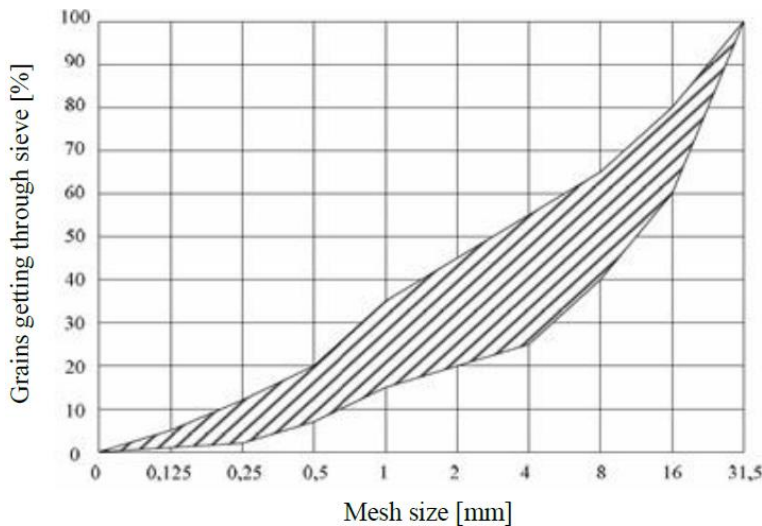


Fig. 4.2. Zone of good grain size for maximum size of aggregate grains of 31.5 mm [89, 47]

Maximum volumetric density of solid particles ρ_{ds} and optimal waste humidity w_{opt} rely on grain sizes, endurance of rock fragments, time of deposition and research methods. Maximum volumetric density and optimal coal waste humidity designated using standard Proctor's method, equal [119]:

- for fresh waste $\rho_{ds} = 1.62\text{--}1.9 \text{ g/cm}^3$, $w_{opt} = 7\text{--}14.5\%$,
- waste from new dumps $\rho_{ds} = 1.6\text{--}1.9 \text{ g/cm}^3$, $w_{opt} = 9\text{--}16\%$,
- waste from old dumps $\rho_{ds} = 1.2\text{--}2.0 \text{ g/cm}^3$, $w_{opt} = 11\text{--}19\%$.

Highest possible reduction of coal content in deposited material

Significant role in self-heating phenomenon, plays the coal substance content. Previous research does not give specific percentage content of coal, which allow to state that waste mass doesn't show tendency for endogenous fire. Thus, all reduction of coal substance is considered to lower the risk of spontaneous combustion.

Reduction of coal substance can be achieved through adding substances bereft of flammable parts. Such substances are usually byproducts of burning, mostly fly ashes from power plant. These also include clays.

Reduction of flammable substance can also be achieved through professional technologies and processes associated with coal reclamation. One of these technologies is washing using heavy medium.

In 1988–1997 GRP company started reclamation of coal on southern side of Smolnica coal dump. Decision about work was fully justified, because coal substance content in waste material reached up to 17%. Plant annually processed 1.5 m^3 , which considering 10% of assumed coal reclamation from waste gave 150 thousand Mg on average, Mg coal/year. Technological process of coal reclamation proceeded according to schematic shown in fig. 4.3.

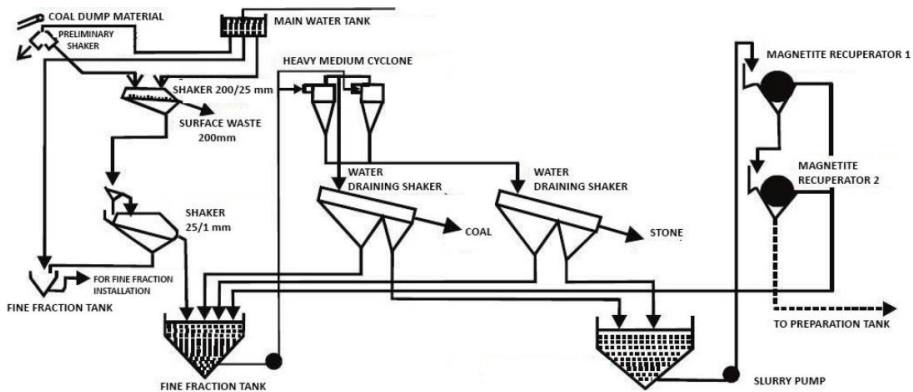


Fig. 4.3. Technological process schematics of coal reclamation [154]

Choice of technology offering the best waste compaction coefficient on dump

Current technical solutions associated with coal waste mass deposition, rely mainly on pursuing the highest possible compaction of materials on the dump. High compaction coefficient is achieved as a result of [89]:

- layered incorporation of material (layers up to 0.5 m max)
- proper shape of dump, clearing of steep scarps,

- avoiding to put seasoned waste material in contact with fresh one,
- avoiding deposition of gangue in a way that could cause grain segregation of material,
- compaction of different layers using professional equipment,
- using grain mixtures that positively affect grain size curve.

4.2. Preventative treatment

Preventative treatment methods are mainly associated with dumps that have already been formed. There are two major preventative treatment methods: injection wells and method that relies on covering of waste material with reclamation layer.

Injection well method considers injecting, into the dump waste mass, substance consisting of byproducts of burning, e.g. power plant ash and water. Mixture of water and ash is supplied via boreholes. This procedure aims to isolate existing fire and limiting air access to its seat.

Injection holes used on coal dumps are designed as piped down to 1–1.5 m below the surface. Below this depth they are “bare”. Casing pipe diameter should equal at least 160 mm. In situation, when there are problems with reaching anticipated injection range, e.g. caused by too dense layer of waste mass with small number of intergranular voids, there is necessity of increasing diameter of boreholes or condensation of boreholes mesh. Injection holes are drilled using spiral drill with highest maximum diameter from the viewpoint of casing pipe. Casing pipe should be properly sealed using mixture of water and calcium in 1:2 ration or with laitance. Efficiency of this method relies on following parameters:

- distribution of injection holes,
- depth of injection holes,
- direction of holes,
- injection method,
- type of injectate,
- injection pressure.

Injection holes are created in rows with shift. Distance of rows and distance of holes in rows are established based on absorptivity research in created earlier surveillance holes. Calculations of holes’ distances are performed using formula (4.1):

$$V = \pi R^2 D \left(1 + \frac{R}{b} c_2 \right) \quad (4.1)$$

where: V – total absorptivity of hole, c_2 – shape coefficient based on height of upper and lower surface restricting injected zone ($c_2 = 4/3$ for sphere, $c_2 = 1/2$ for flattened surface similar to oblate spheroid), b – height of cylindrical surface restricting injection range, D – substitute – fissures width, R – injection range radius.

Injection slurry should be injected under pressure ranging from 0.2 Mpa to 0.6 Mpa. Injection is performed in specified time intervals using slurry of proper density (viscosity). Emphasis is also put on providing continuity of injection, that’s

why before the beginning of injection operation. It should be ensured that there is enough mixture for the procedure.

Completing of injection process take place after injecting more than 10 m³ of injectate per meter of injection hole and after total loss of absorptivity, which manifests by flowing out of the slurry in neighboring hole or penetration of surface.

Covering surface area with reclamation layer in order to increase tightness of dump and create conditions for flora development. Thickness of reclamation layer should range between 30 cm and 50 cm, unless attempts of forestation were made, then thickness can reach up to 80 cm. Seeding can be performed directly on spread reclamation layer. In areas particularly endangered by erosion and weathering, e.g. scarps, staking (fig. 4.4a and 4.4b) procedure is used as well as reinforcing meshes. During seeding process, trees with taproot system should be avoiding to prevent them from loosening the deep lying layers of the dump, which in turn can cause spontaneous combustion.



Fig. 4.4. a) Staking on dump near main mineshaft “Ziemowit” [source: own], b) dump in Katowice – Welnowiec [23]

4.3. Methods of fighting present thermal state

Present thermal state fighting and self-extinguishing methods are usually a series of technical and coordination procedures. Basically most of these procedure come down creation of hermetic isolation screens that prevent or significantly slow down air access into the dump. It leads to gradual decline of coal material oxidation located in waste mass. Following methods can be distinguished:

Injection well

Injection well is considered to be minimally invasive. Used especially, where keeping of waste mass shape intact is necessary or in situation when environment need special attention. Broader description of injection well has been presented in section “Preventative treatment”.

Trench barrier technology (filter swales)

Core of this method is sealing of thermally active area using extinguishing medium, which is poured into trenches created in advance (fig. 4.5a, b, c). During swale

creation there is a significant interference in dump structure and burning areas. This filter swale is considered invasive method, that has to be preceded by environmental analysis necessary to ensure that creation of swale will not be to troublesome for local inhabitants, neighboring the coal dump.

Practical creation of trench is performed using professional equipment, e.g. excavator. Depth of the trench is dependent on thickness of the dump, however considering equipment restrictions it doesn't exceed 6 m. Hole's cross-section is trapezoidal. Width is in the range of few meters. Barrier trenches are created in short sections so that bigger fragment of the scarp is not dug at once and to have possibility to quickly fill it with prepared medium. Swales should also be instantly filled with ash slurry with ash to water ratio of 1:1.5. Useful thing is mixing power plan ash with calcium (around 10%). During filling section of trench with injectate, slightly solidified slurry mixed with incombustible grains sizing 20–120 mm, and compacted using heavy-duty construction equipment. Slurry that has been prepared correctly should seal heaps of the dump well, filling intergranular voids and cause temperature decrease of dumped material.

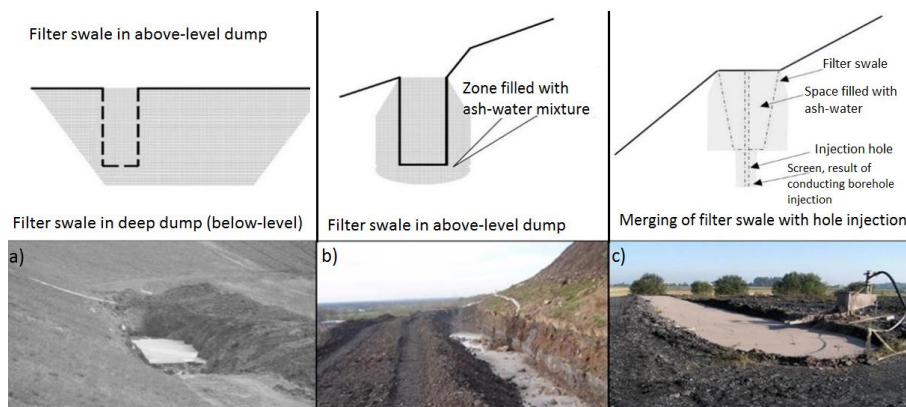


Fig. 4.5. Idea of an absorption trench on different coal dump types [64]

Groundworks technology

In the time, when there is necessity of modification of burning area's shape or one that is adjacent, extinguishing tasks are executed using groundworks technologies. These works are related to:

- digging out burning material, extinguishing and reconstruction (fig. 4.6),
- covering waste mass with layer of incombustible material (fig. 4.7),
- construction – around the coal dump – of isolating embankment with very high compaction coefficient, along with filling of the area between burning coal dump and highly compacted, newly created embankment, with ash-water slurry (fig. 4.8–4.9).



Fig. 4.6. Dismantling of burning coal dump “Wrzosey” [199]

Reconstruction of thermally active layer starts with the digging out burning material with heavy equipment and temporary moving it beyond the active area so that it can cool down. This operation brings extreme improvement of thermal situation. Although it should be noted that in every case, thermal processes have tendency to restore themselves. Covering of coal dump surface with layer of isolating material, e.g. ash-water slurry (fig. 4.7) aims for reduction of oxygen access into the object and securing it from self-heating of waste material. Emulsifier is created on site in special hydraulic-pneumatic heads.

Slurry is spread evenly on whole surface, after solidifying, it forms a crust, about 5 cm thick.



Fig. 4.7. Covering of fire site surface with insulating layer [244]

Afterwards, compacted embankment is constructed around the coal dump. Mixture of loose rocks and soil or only soil is used as an isolating material, which is then put in form of minimum 2 m thick layer above fire zone. To avoid material sliding of slopes, their inclination shouldn't exceed 27° [42].



Fig. 4.8. Creation of reclamation dyke – dump Skalny, “Bolesław Śmiały” Coal Mine (KWK Bolesław Śmiały) [source: own]

Isolating layer constructed like this is also called “sarcophagus”. Drawback of this method is that it is impossible to transfer heat outside the coal dump.

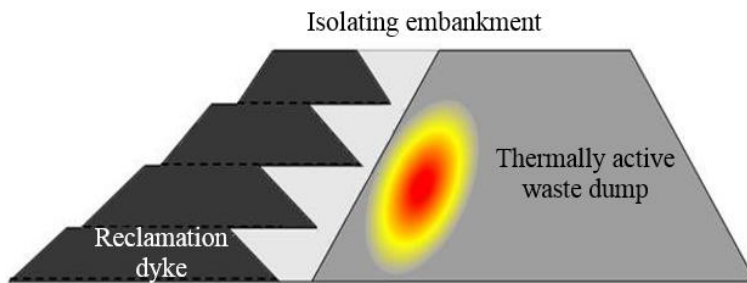


Fig. 4.9. Schematics of reclamation dyke around dump with implementation of insulating trench [source: own]

Application of liquid CO₂

Liquid CO₂ technology is used in coal mines for some time now as a preventative method as well as in rescue missions. Apart from its basic property, which is cooling of the waste mass, carbon dioxide also has extinguishing properties. It happens due to its ability to displace oxygen in the atmospheric air. This method was used on “Waleska” coal dump. It relied on creating series of holes in structure of the object and pouring liquid CO₂ inside them (pumping operation has been shown in fig. 4.10). As a pressure dropped gas started solidifying, followed by slow sublimation with simultaneous draining of heat from sides of the drill hole. At the same time, amount of oxygen in the waste mass decreased (specific weight of gaseous CO₂ is higher than specific weight of atmospheric air), slowing down oxidation processes of combustible material. On surface and slopes and in their direct neighborhood, over a dozen holes were made, 125 mm in diameter and 6–8 m deep. In their outlets, casing pipe sections were embedded and cemented. Into the holes prepared that way, liquid CO₂ was

pumped. At one-time some holes were filled with up to 120 dm^3 of liquid gas (into the most absorptive, liquid CO_2 was pumped sever times. After that, holes were eliminated by filling them with ash-water slurry. That method proved incredibly effective. Fire zones were cooled by $50\text{--}60^\circ\text{C}$ and practically anaerobic area has been created inside the coal dump [63–65, 87].



Fig. 4.10. Injection of CO_2 on Waleska dump of “Bolesław Śmiały” Coal Mine (KWK Bolesław Śmiały) [source: own]

Antipyrogens application

In literature, there are many different theories about how antipyrogens are functioning, i.e. substances stopping self-heating of coal. One of these theories says that antipyrogens cause decrease in surface of reaction between coal and air oxygen. Antipyrogens found use on gangue dumps in old USSR, especially in form of lime water. Poland succeeded in creating effective antipyrogens containing oxalic acid and oxalates. Following antipyrogens can be distinguished: polyacrylamide, alkali sulfite, oxalic acid, some oxalates, sodium chloride or natural saline solution, calcium chloride and magnesium chloride. Antipyrogens, in form of powder, can be used to extinguish small, as well as big areas reaching several hundred square meters.

Their advantage is the possibility to be used in situation where there is no other effective method or when it is unprofitable. Application of antipyrogens took place on Waleska coal dump (fig. 4.11).



Fig. 4.11. Application of antipyrogens on Waleska dump of “Bolesław Śmiały” Coal Mine (KWK Bolesław Śmiały) [source: own]

Controlled burning of the dump

Controlled burning is method, which relies on monitored burning out with simultaneous suctioning and filtration of fumes (fig. 4.12). Different method considers combustion of waste mass, screening them, using coarse and fine grained waste.

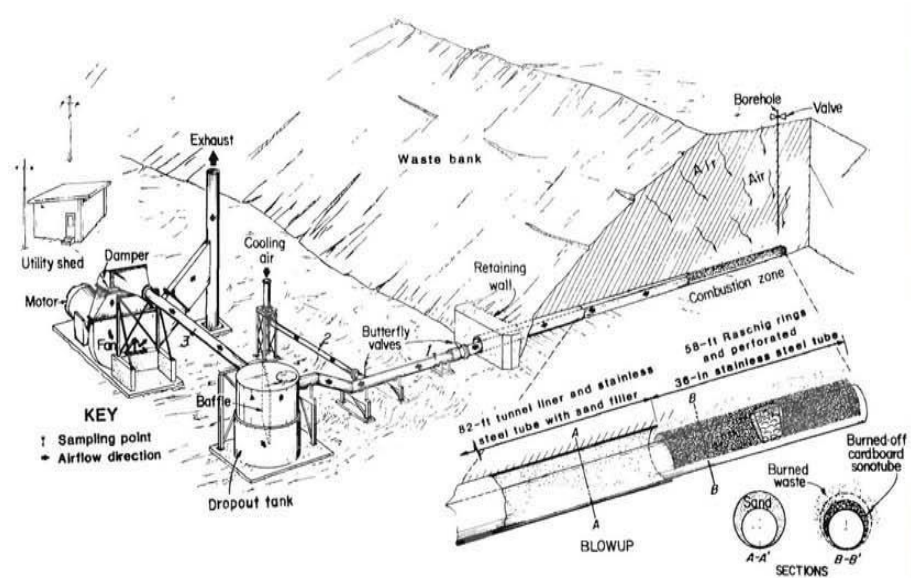


Fig. 4.12. Schematic of installation used in burning out waste mass deposited on coal dump in Aberfan (West Virginia, USA) [17]

The first of mentioned methods was attempted to be applied during extinguishing of seats of fire on “Skalny” coal dump in Łaziska Górne, where Swedish concept was used that relied on controlled leading oxygen inside it, followed by suctioning and filtering of fumes. As for the method, no restriction was introduced, however it hasn't been used anywhere. In case of “Skalny” coal dump, the reason for abandoning it, was probably the magnitude of coal dump fire.

Second method mentioned found its use on “Wrzosa” coal dump in Pszów. Cone of the coal dump was divided into two part: “warm”, thermally active and “cold” Built from production waste. Both part was divide by safety screen, which was simultaneously supposed to improve air flow conditions through burning part (view of isolating trench is shown in figure 4.13). The disadvantage of burning coal dump that way is high gas emission [30, 31, 89].



Fig. 4.13. Trench insulating burning part of dump and controlled burning out – Wrzosey “Rydułtowy-Anna” Coal Mine (KWK Rydułtowy-Anna) [source: own]

Less often used methods of fighting endogenous fires on coal mining dumps are:

Flooding the surface of burning dump with water – it’s one of the first methods used for fighting fires on coal dumps. Supplying water as extinguishing medium can occur through spraying the surface of coal dump or injecting water via drilling holes. Flooding radically improve thermal situation, however not permanently. Extinguishing with water is associated with many negative aspects such as washing out finer material from between coarser grains and erosion of dumps surface. Consequence of that is air getting inside the dump and restoring thermal activity. Coal dump building material after soaking with water is susceptible to landslides, which leads to disruption of slopes balance. Moreover, while heating in low temperature (up to about 70 °C), water presence is beneficial to self-heating processes that usually occur in high humidity conditions. These are the reasons why this method has been abandoned [42, 15].

Sealing surface of the object with clay pulp – method relies on covering thermally active coal dump with ten centimeters thick layer of clay pulp, limiting access of atmospheric air. It turned out that using this technology lets only for suppressing seats of fire. Although the clay layer effectively limits the ability to dissipate heat but as the time goes, visible cracks in isolation appear, which cause progress of fire once again.

Merging few smaller dumps into one bigger – it is preventative technique relying on merging few small dumps, after using other methods of extinguishing fire. During performing this method, it is possible to work on reclaim coal from the waste. This procedure is justifiable in case, when coal substance in waste material is at least 7–9% [42].

Using pipe heat exchangers – research on acquiring heat energy from thermally active dumps proved that temperature of waste material can be significantly decreased using pipe heat exchangers by which cooling medium (water) flows through [116, 137].

Maximum efficiency in firefighting on coal dumps is achieved using several different technologies. Methods used have to be properly chosen considering construction of the dump and its technical conditions. The most often practiced

preventative methods, treatment and extinguishing techniques used on coal dumps have been shown in tables 4.1 and 4.2.

Table 4.1. Technologies and preventative methods used on coal dumps [89]

Procedures/ technologies	Shortened technology description	Equipment used	Extinguishing factor/medium	Pros/Cons	Examples of use
Preventative methods					
Optimal grain size choice	Preparation and modification of grain sizes of deposited material in a way that allows for their maximum compaction and sealing of coal dump	Mixers, sieves, heavy equipment	Material compacted through use of optimal grain sizes	Non-invasive method, low or medium pollution, decreasing deposition costs	Object "Pochwacie" KWK Zofiówka
Decrease in percentage of coal and combustible substances in material	Preparing and modification of deposited materials through decreasing of combustible particles content, e.g. by adding UPS	Heavy equipment: bulldozer, vibration rollers, mixers	Compacted material with decreased coal content by using additives	Non-invasive method, low or medium pollution, possibility of utilization of other waste	Object "Panewniki" KWK Halemba
Groundworks with high compaction of waste	Complex building works with high compaction of material	Heavy equipment: bulldozers, vibration rollers	Compacted and properly built-in material	Invasive method, often highly polluting, the most optimal costs	Coal dump „Skalny” and „Waleska” in Łaziska Górne
Preventative treatment					
Injection well	Into drilled holes (in fire zone) extinguishing medium is pumped, which fills void inside the dumps cutting of oxygen access	Driller, device for medium production, medium mixer (pulp/slurry), injectate pump, equipment for transport and moving into places of pumping	Slurry created from water and fine grained material (ashes from conventional and fluidized-bed boilers, desulfurisation of fumes, other)	Non-invasive method, small interference with bulk integrity of an object, very low dust pollution into the atmosphere, high costs	Coal dump "Skalny" and "Waleska" in Łaziska Górne, coal dump 6/4 on "Piast" field in Nowa Ruda, coal dump "Ruda" in Zabrze, coal dump 7/4 on field "Słupiec" in Nowa Ruda
Implementation of surface reclamation cover	Coal mining waste are covered with layer of inert material (clay or sandy clay) and introduced with plant life	Heavy equipment	Layer of inert material along with sealing, vegetation cover stabilizing object	Non-invasive method, reduces dusting, object reclaimed for environmental use	"Skalny" and "Waleska" coal dumps in Łaziska, coal dump, "Wysoki Brzeg" in Jaworzno, coal dump KWK Klimontów in Sosnowiec, many other reclaimed coal dumps

Priority of preventative methods, treatment and extinguishing techniques is securing or extinguishing of thermally active areas while minimizing damage to the environment and neighborhood. Cost of the undertaking is also important as well as

Table 4.2. Extinguishing technologies used on coal dumps [89]

Procedures/ technologies	Shortened technology description	Equipment used	Extinguishing factor/medium	Pros/Cons	Examples of use
Extinguishing methods					
Filtering swales	Dug up trenches, usually trapezoidal in cross-section, flooded with solidifying extinguishing medium that divides fire zones and causes cutting off air access	Heavy equipment: diggers, bulldozers, device for medium production (slurry), medium mixer	Slurry created from water and fine grained material (ashes from conventional and fluidized-bed boilers, desulfurization of fumes, other)	Invasive method, high interference with dump bulk integrity, highly polluting (dust emission), high costs	Coal dump „Skalny” and „Waleska” in Łaziskach, coal dump KWK Marcel in Radlin, coal dump 7/4 on field „Ślupiec” in Nowa Ruda,, coal dump KWK Rydułtowy in Rydułtowy
Groundworks: material shaping (dump disassembly), covering with incombustible material, construction of highly compacted isolating embankments	Configuration change of fire zone or adjacent area using heavy construction equipment, building around thermally active dumps	Heavy equipment: diggers, bulldozers, vibration rollers, devices for spreading and transport of extinguishing mixtures	Ash-water mixtures, incombustible materials (clay, soil), highly compacted coal mining waste	Often, the most invasive among methods used, significant impact on the environment, high costs, which can be partially compensated by production of aggregates or coal reclamation	Coal dump KWK Makoszowy in Zabrze, coal dump „Skalny” and „Waleska” in Łaziska Górne, coal dump KWK Marcel, coal dump of Ibbunburen (Germany) mine, coal dumps located in South Africa, other
Antipyrogens application	Burning dump is covered in antipyrogens that cuts off oxygen access	Equipment needed for spreading and applying antipyrogens on coal dump	Foam concrete, ammonium phosphate, urea, acidic calcium carbonate, borax, calcium chloride	Applied methods were usually used casually, adoption of new antipyrogens in burning coal dumps condition requires new research	Lime water is often used on burning coal dumps since 80ties
Burning part of the coal dump	Burning coal dump or its parts, screening them, using coarse and fine grained waste	Heavy equipment: diggers, bulldozers, transportation equipment	Coarse grained material and fine, incombustible material	Invasive method, fairly cheap, during burning of coal dump there is high emission	Coal dump „Wrzosey” in Pszów, coal dump Rydułtowy
Application of inert gases	Into the drilled holes, liquid carbon dioxide or nitrogen is pumped These gases receive heat and most of all, decrease oxygen amount in dump – vanishing of fires	Drilling equipment, machines for transport and injection of liquid CO ₂ or nitrogen	Liquid carbon dioxide, liquid nitrogen	Very costly method, non-invasive, no negative impact on environment Used experimentally	Coal dump “Waleska” in Łaziska Górne
Controlled burning of the dump	Supplying the dump with air, followed by suctioning and purification of fumes	Method relies on construction of complicated installation supplying air and draining fumes	–	Experimental method, very high costs, even considering energy reclamation, very high gas emission to the atmosphere	Controlled burning method was attempted to be used on “Skalny” coal dump in Łaziska Górne.

technical capabilities of the executor. Table 4.3 defines two types of factors, external and internal, as for external factors, availability of materials for preventative and extinguishing works and distance from residential buildings should be distinguished. Internal factors are described by intensity of thermal phenomena, surface of the object subjected to thermal activity and terrain.

The essence of this issue is finding dependency between external and internal factors and technologies used and confirming or denying, presence of certain parameters, leading the choice of specified technology. External and internal factors in regards to technology used have been presented in table 4.3.

Table 4.3. External and internal factors regarding technology used [89]

Object /coal dump	Intensity of thermal activities	Surface of the object subjected to thermal activity	Terrain	Material availability for preventative and extinguishing works	Distance from the closest buildings	Preventative and extinguishing methods used
“Skalny”	very intensive – internal temperature up to 900 °C	big – few hectares	difficult: steep slopes with inclination 1:2 narrow shelves	fly ashes and decarbonization lime from nearby power plant, processing water available in the object area	< 100	injection, filter swales, partial dismantling
“Waleska”	medium – internal temperature up to 300 °C	medium – single fire < 1 ha, several fires to 150 m ²	difficult: steep slopes with inclination 1:2 narrow shelves	fly ashes and decarbonization lime from nearby power plant, processing water available in the object area	200–300	injection, filter swales, pumping of liquid CO ₂
“Wrzosey”	medium – internal temperature up to 300 °C	big – intensively burning middle area coal dumps – several hectares	difficult: steep slopes with inclination 1:1, no technical shelves	No direct proximity of UPS, no water on the object	100–200	collector trenches
“1/R”	medium – internal temperature up to 390 °C	big – thermals on significant area of scarp and top surface – several hectares	easy – gentle slopes, big top surface	UPS and water transported in tanks	< 100	injection, filter swales, partial dismantling
“Ruda”	very intensive – temperature up to 600 °C	big – most of the top surface and scarp burning – over a dozen hectares	easy: big top surface, low scarps	UPS transported by tanks, processing water from the river at the foot of coal dump	200–300	injection, surface isolation, surrounding with sealed embankment

5. Analysis of Thermal and Gaseous State of Coal Dumps Built from Coal Mining Waste

Requirements associated with monitoring of deposited waste is regulated by Ministry of the Environment act from 9th December 2002 in regards to scope, time, method and conditions of waste dump monitoring (Dz.U. [Journal of Laws] from 2002, No. 220, item 1858). Monitoring and assessment of coal dump thermal activity include:

- piezometers control that include depth measurement of water table and physico-chemical studying of these waters according to type deposited waste;
- control of sewage that relies on physico-chemical studying of sewage and measurement of their amount in the time of their sampling;
- quality control of surface water under the influence of coal dump, relying on physico-chemical study of waters and measurement of their amount in the time of their sampling;
- measurement of precipitation;
- monitoring of gaseous environment and thermal state of the coal dump;
- control of dump surface subsidence using surveying methods by authorized specialists based on set benchmarks;
- slope stability control – geotechnical methods.

The most current solutions in regards to evaluation of thermal state of dumps built from coal mining wastes has been shown in method developed by Central Mining Institute in 2012. “Metoda oceny zagrożenia pożarowego na terenach lokowania odpadów powęglowych” [*Method of assessing fire hazard in areas of coal mining waste deposition*] [47].

According to the mentioned method, fundamental factor allowing to classify fire hazard of coal dump is scope and frequency of thermal state observation. Chronological monitoring eliminates fire occurrence risk, because whenever any alarming event takes place, it is noticed in the right moment and proper steps are taken that eliminate that event.

5.1. Procedure of creation and interpretation of thermograms of coal dumps

As for now, there is no standard, which would describe studying procedure focused on thermovisual monitoring of coal mining waste dump. However, there is relatively big base of research projects and expertise, which gather many valuable remarks and experiences needed for proper thermal imaging of coal dumps. These documents have not only been developed by scientific-research units (Silesian University of Technology, AGH University of Science and Technology, and Central Mining Institute), but also professional design companies.

One of well described measurements of this type in Poland has been created at the end of 2003 in the area of “Skalny” coal dump in Łaziska Górne. Infrared thermovision was used in this case, for localizing not fully extinguished seats of fire. Development of this method and gained experience allowed for using thermovisual observation as a tool for monitoring of thermally extinguished and reclaimed coal dump [65].

Modern thermovisual cameras usually include built-in photo camera and infrared overlay function. Camera used during measurement on “Skalny” coal dump didn’t have such function. This issue was solved by making pairs of photos – one in visible spectrum and other in infrared (fig. 5.20). This simple procedure is used considering difficulties that researcher have to deal with while reporting on studied area basing on multiple and often very similar thermograms.

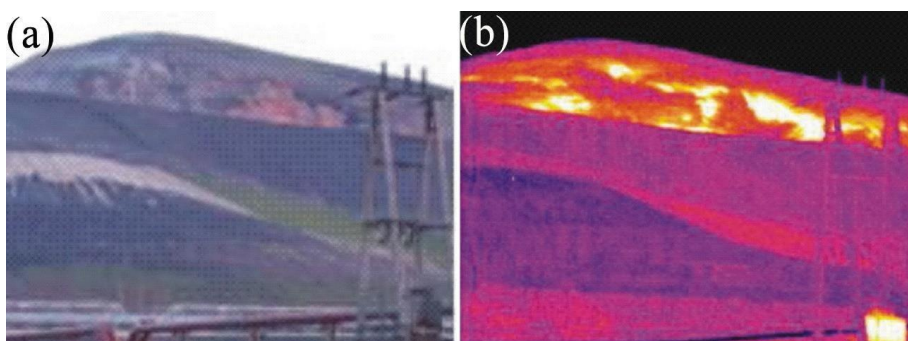


Fig. 5.1. Pictures of “Skalny” dump in visible spectrum (a) and in infrared (b), 2003 [65]

Modern thermovisual cameras are equipped with proper software, which allows for creation of panoramic thermograms. Widescreen imaging have big significance in regards to large size coal dumps formed from materials with tendencies for spontaneous combustion. Thermogram of coal dump with under-surface fire zones has been shown in figure 5.2, where yellow and red color demonstrate evident seats of fire.

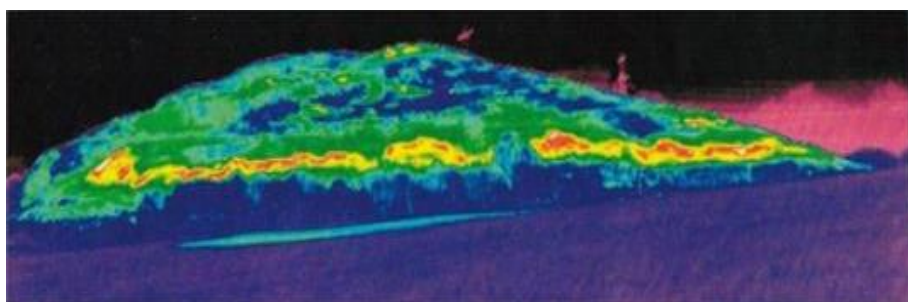


Fig. 5.2. Thermogram of coal dump with visible burning areas [180]

One of the results of these research, conducted by A. Wróbel, is suggestion that thermovisual measurement of coal dumps for thermal conditions control, were performed before reclamation process begins [83, 84].

Microbolometric detectors of the cameras work in area of infrared radiation, which is not visible for human eye. Because of that it is possible to detect thermal anomalies on the surface of coal dump before fire even begins. Apart from that, thermovisual technique allows for identification of both quantity of materials subjected to heating as well as its intensity [142]. Advantages also include the speed of measurement, mobility and limited number of samplers needed for the study. Thanks to observation of coal dump using terrestrial thermovisual camera you obtain, without contact, images of temperature distribution in form of colored thermograms. Basically it is the only method that let for complex study of an object. Admittedly it is possible to use infrared thermometer (pyrometer), which is reliable and very useful for point measurement of temperature, but does not work well in case of large coal dumps. During detection of this type of objects from further away, i.e. several dozen meters, it is easy to overlook key locations, such as exhalation fissures. Moreover, pyrometric results from further distances are suffer from inaccuracy and big errors (mistakes) [171, 174, 83, 84, 65].

In case when measurement from greater distance is impossible, person conducting a study proceeds with inspection of the area (usually refers to top surface of the coal dump). Thermovisual camera operator simultaneously to moving up to higher tiers of an object, observes the distribution of temperature on the surface, on the camera screen.



Fig. 5.3. Thermovisual measurement near thermally active scarp [source: own]

Thermograms are created in strips, 3–5 m thick, and if needed they are saved in cameras memory. Conducted this way, thermal imaging, covers all the area of the

dump with special consideration of steep and high slopes. Forwarder, after noticing areas, which seem to be especially endangered by thermal events and after observing places with clear, thermal anomalies, attempts to perform measurement from closer distance, i.e. 1–10 m (fig. 5.3). Measurement of surface temperature of the dump using no-contact method, should be conducted at least once a quarter.

Below studying procedure has been shown, based on standard PN-EN 13187:2001, which targets buildings and building objects. Course of action has been supplemented by conclusions obtained from experiences associated with conduction of thermovisual measurements of objects built from coal mining waste. Procedure of thermovisual studies conduction, constructed like this, goes as follows [105]:

Stage I – organization stage, which most important part is:

- identification of object formed from coal mining waste – local vision with evaluation of technical possibilities for measurements and getting to the dump,
- becoming familiar with available technical documentation,
- establishing location of coal dump according to directions of the world,
- determination of emission coefficient for waste material,
- careful planning of scope, date and conditions of measurement,
- keeping eye on weather forecasts, taking notes about air temperature outside 2–3 days before and during the measurements,
- creating data protocols referring to overcasts, precipitation, relative humidity of air outside, strength and direction of the wind in days preceding and during the measurement.

Stage II – main measurement stage, relying on thermovisual study of the coal dump. This stage consists of following tasks:

- setting thermovisual camera according to producer’s indications and entering necessary parameters into the camera’s system, i.e. surface emission coefficient, temperature measuring range, air temperature, radiation temperature, distance from an object, relative humidity of air, etc. in order to receive the highest possible thermal resolution in measurement conditions and for precise temperature evaluation,
- stabilizing of thermovisual camera for about 30 min before proceeding with measurement,
- creation of thermograms from chosen areas of studied coal dump,
- during measurement:
 - ✓ registering temperature and relative humidity of air, registering other meteorological events occurring while conducting study and having impact on results, temperature changes outside should be registered within fixed intervals, e.g. every 15–20 minutes,
 - ✓ mark on plan and number every next measuring point, number thermograms, note (or record) any remarks and distances from every point

- and object as well as other information that may be useful for thermograms interpretation,
- ✓ attach every thermogram to the plan included with measurement report,
- ✓ take photos of studied areas of coal dump apart from the ones taken with thermovisual camera, which has worse picture quality,
- processing of thermograms, their analysis, interpretation and development of conclusions and recommendations for the ordering party,
- because range of tasks is quite extensive it is recommended that research party consisted of at least two people.

Stage III – creating a report from the studies:

- evaluation of heat isolation of top layer of the coal dump, identification of thermal bridges, infiltration of air areas and gas exhalations along with explicit interpretation of thermograms,
- establishing the causes of anomalies present,
- giving conclusions and recommendations from conducted research and analyses.

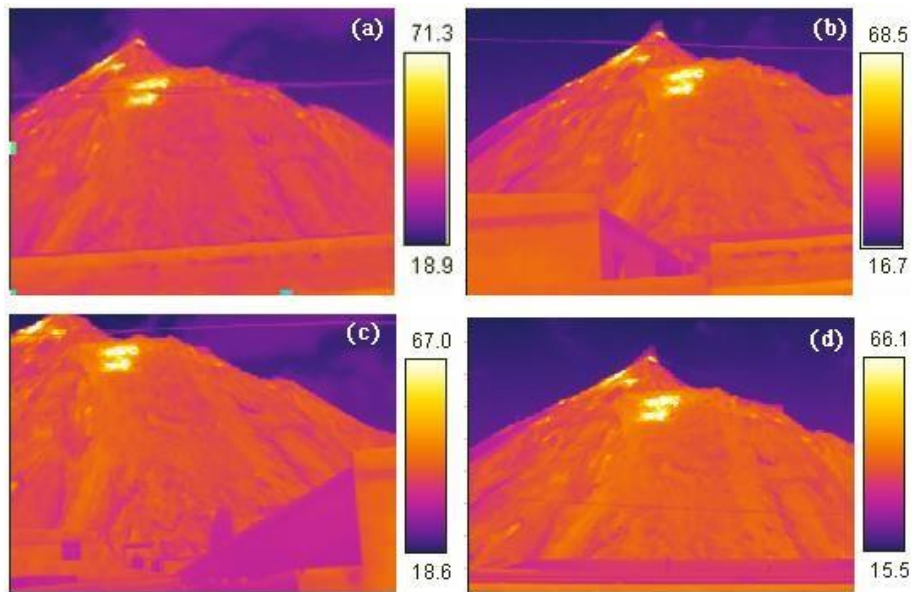


Fig. 5.4. Making of thermograms of the same area at different time with visible gradual decrease in thermal processes dynamics [181]

Report from thermovisual survey can be supplied with registered data about correctness of conducted studies, i.e. temperature course 2–3 days before and during measurement, registered relative humidity of air, speed and direction of wind, information about time of the survey (date, hours of start and completion), information

about lack of precipitation, etc. as well as document that certify calibration of camera [105].

Apart from that, when it's possible, comparison between thermograms obtained during measurement with thermogram considered to be reference model, so called "reference thermogram", which has been created for identical waste mass but does not show signs of thermal anomalies, gas exhalations or any other factors telling about fire on the coal dump.

In studying of thermal state of coal dump, a helpful procedure might be conduction of series of thermographic research in set time period. Thanks to that, analysis of process course dynamics and characterizing of their development or disappearance, is possible. This type of research has been used during monitoring of coal mining waste dump "Gangue" in China (fig. 5.4).

Interpretation of thermograms comes down to identification of properties directly related with gangue dump – it regards to explanation and commentary on theoretical and measured field of temperature on studied surface in relation to coal dump properties and conditions that determine heat transmission. Any, thermogram made correctly, shows two basic information about the state of studied coal dump. It provides temperature value in certain point of studied area and it shows range of isothermic areas.

During interpretation of thermal imaging, features related directly to coal dump, such as shape and size, should be taken into consideration. Mining waste dumps are part of group of objects, which are large enough that are not hard to identify and for interpretation of thermograms, provided that during measurement there is enough of necessary thermal contrast, i.e. differentiation in intensity of thermal radiation between studied object and surrounding [105].

Limitations of thermovisual observation of coal dumps

Radiation received by thermovisual camera does not come only from the observed coal dump. Ground (soil), clouds or sky and surrounding objects (buildings) radiate. Radiation reflected from dump falls on camera's detector through the lens. Furthermore, radiation progressing from coal dump is interfered by atmosphere. Atmosphere suppresses radiation propagation and degree of suppression depends on current atmospheric conditions (impact of rain, snow or fog). Atmosphere is a source of radiation by itself, which overlays with radiation from coal dump. Ranges of electromagnetic waves that "penetrate" atmosphere are called atmospheric windows. Only these are useful during thermal imaging. Other limitation is related to the instance, when dump is in large distance from thermal camera operator, then air turbulence, reducing picture quality, has significant impact on ability to survey and register data. All of the mentioned limitations must be taken into account in complex process of thermal analysis of an object. Single components of radiation reaching the camera have been shown in figure below [175, 57].

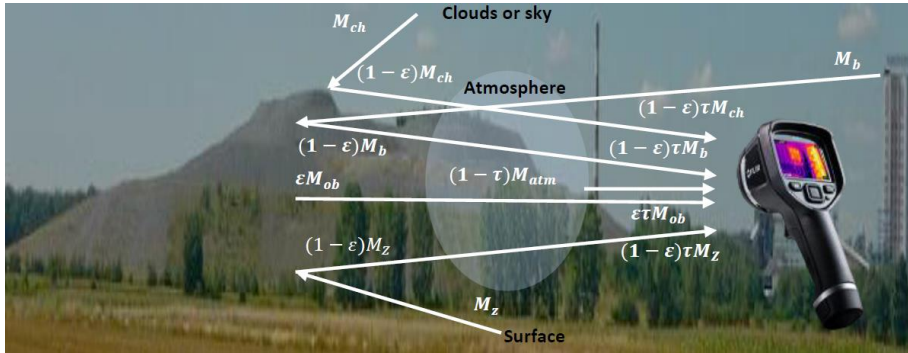


Fig. 5.5. Radiation components measured by thermovisual camera in real life conditions [source: own]

Looking at figure 5.5, it becomes obvious that the signal s generated by thermovisual camera is the effect of absorption of different radiation components by the camera, which is, in simplified way, represented by equation (5.1). Simplification comes down to replacing of all components of objects radiation in measurement environment, with single replacement value, radiant exitance of the surrounding M_a .

$$s = A[\varepsilon\tau M_{ob} + (1 - \varepsilon)\tau M_a + (1 - \tau)M_{atm}] \quad (5.1)$$

where: ε – emissivity of studied object; τ – transmission coefficient of the atmosphere; M_{ob} , M_a and M_{atm} – exitance of an object, surrounding and atmosphere corresponding to spectral exitance of black body for objects temperature, replacement surrounding temperature and atmosphere; A – camera's constant, resulting from conversion of radiation inside the detector and amplification of signal through electronic reading circuit.

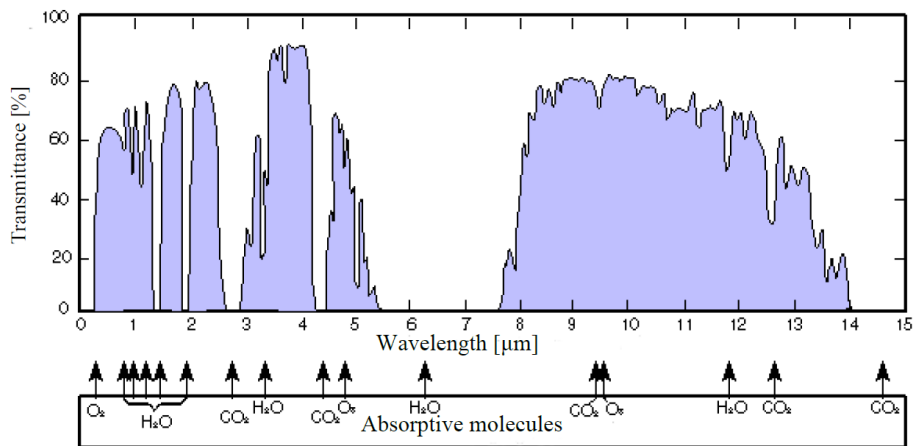


Fig. 5.6. Transmittance of earth atmosphere at 1 nautical mile at sea level [53]

Solid and liquid bodies give constant heat radiation spectrum, while gases radiate and absorb heat radiation selectively. Absorption of radiation emitted from studied surface and passing through layer of atmospheric air (gas) between object and camera's lens, can clearly influence the result [75, 76]. Radiation dissipating in earth atmosphere is suppressed to varying degrees, depending on wavelength. For thermovisual research, so called measurement windows are used in infrared range for wavelength of 3–5 μm and 8–14 μm , where H_2O and CO_2 suppression is particularly small. In figure 5.6 transmissivity of the atmosphere has been shown on sea level at distance of 1.8 km. Looking at mentioned graph, there is noticeable, high suppression of infrared radiation by water vapor for wavelength of 6–7 μm and local minimums in medium wavelength infrared range MWIR. On the other hand, presence of CO_2 in the atmosphere causes strong suppression of radiation for wavelengths of 2.7 μm and 4.2 μm . Generally, it can be said that in long wavelength infrared range (LWIR, 8–14 μm) atmosphere is more transmitting for radiation than in medium wavelength infrared range (MWIR, 3–5 μm) [175, 65, 170, 171, 174].

Table 5.1 shows ranges of wavelengths, for which there is an occurrence of absorption of radiation by water vapor and carbon dioxide. At the same time gases within these bandwidths are radiation active and emit their own radiation. Boundaries given are in some way contractual, because transition from transparency ranges to absorption ranges changes gradually and not rapidly.

Table 5.1. Bandwidths of radiation of water vapor and carbon dioxide [66]

Bandwidth	Wavelength ranges [μm]	
	H_2O	CO_2
1	1.7–2.0	–
2	2.2–3.0	2.4–3.0
3	4.8–8.0	4.0–4.8
4	12–30	12.5–16.5

It is easy to observe that in wavelength range 3–5 μm , there is an active band 4.0–4.8 μm for carbon dioxide. However, percentage of CO_2 in the atmosphere is essentially fixed, this there is no need for evaluation of this parameter every time. More perturbations come from water vapor, as its content is related to atmospheric conditions. That's why it is necessary to measure air humidity before every thermovisual measurement.

Ability of gases to emit and absorb radiation is varying and depends on particle composition of gas. Every gas containing particles built of only one atom, so called monoatomic gases, and also almost all diatomic gases, excluding CO and HCl are close to be perfectly transparent. Their ability of emission and absorption of radiation is basically irrelevant in regards to energy. Triatomic gases, such as CO_2 , H_2O , SO_2 , and gases with even higher number of atoms in a particle (e.g. NH_3 , CH_4) clearly take part in radiation, thus emitting and absorbing it (fig. 5.7).

It is characteristic for gases that emission and absorption occurs within its whole volume and not on some surface like in case of solids. Whatever radiation energy stream passes through gas, gets absorbed as it comes in contact with another gas particle. Absorption is more efficient, the higher number of particles that come in contact. Absorptivity of gases is dependent on density of studied gas layer, wherein absorptivity of such layer is of course different from its emissivity. Number of particles in contact with radiation depends on distance, partial pressure of considered gas and from the temperature of that gas [117].

Additionally, atmosphere has different composition dependent on external conditions, such as altitude, temperature, location on earth of pollution.

If coal mining waste dump is treated as large body emitting heat radiation then it turns out, that it is possible to create thermal image of studied object using thermovisual camera. In attempt to measure it should be known that thermograms show the heat of surface waste layer and not the inside of the bulk. Considering this fact, thermal anomaly view is possible only in case of near surface thermal activity [170, 171, 83].

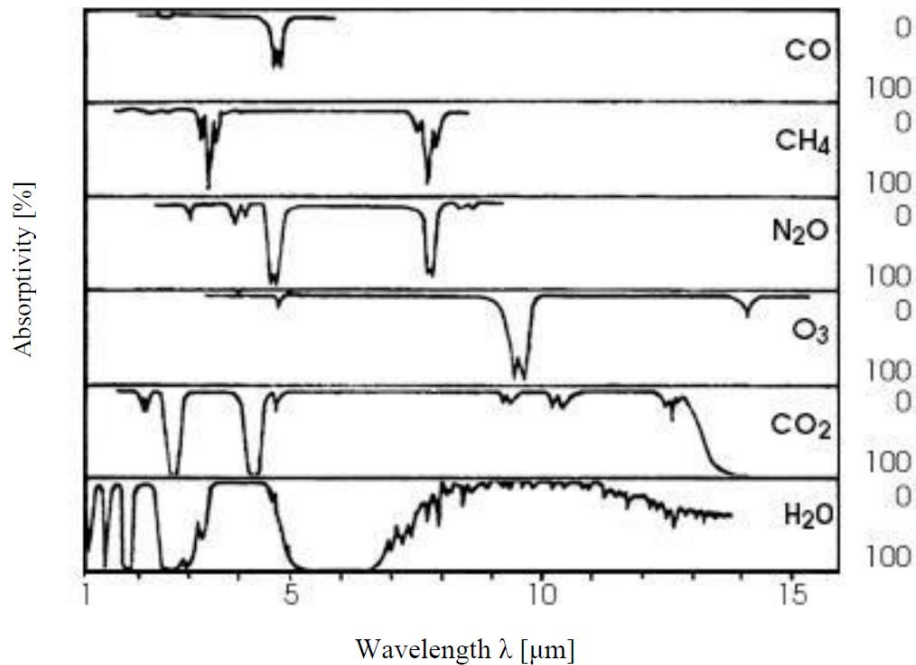


Fig. 5.7. Absorption of radiation by different gases in the atmosphere [92]

Furthermore, coal dump monitoring can be limited by interfering factors. Biological reclamation of anthropogenic creations, leads to gradual development of herbs and trees, which during the measurement may prove to be sources of thermal interference. Thus it is suggested that on this type of objects, there should be regular

agricultural engineering works, especially mowing of grass. Moreover, this procedure is justified by research on temperature distribution on the surface with use of thermovisual imaging conducted by S. Mularz and A. Wróbel [180]. Scientists stated that:

- temperature of uncovered soil is higher than foliage; at night slightly, during a day up to over a dozen degrees,
- at late evening hours, temperature of uncovered soil equalizes with air temperature,
- temperature of foliage, late in the evening is slightly lower than the air temperature, and in a day higher by several degrees,
- the most equal temperatures of: uncovered soil, foliage and air are at dawn.

Thermograms registered by researches were analyzed using Thermacam software, where temperature was calculated regarding correction of:

- suppression of radiation in the atmosphere, dependent on distance of imaging,
- effective emissivity coefficient (emissivity coefficient designated using spectrometric method equals 0.95 for both soils and foliage). Value of this coefficient is also used for measurement of coal dumps,
- influence of background radiation (as surrounding temperature, air temp. has been accepted).

Optimal measurement condition according to practitioners are [105, 240]:

- overcast before and during the measurement,
- stable weather conditions (at least 2–3 days before measurement, no high external temperature fluctuations, temperature course should be stable and be range from about +5.0 °C to about –5.0 °C),
- it is unacceptable for measurement to be conducted during a day. Exception are the days, when there is whole day long overcast with cumulus clouds, between November and February. In October, March and April, even with completely overcast sky, there is risk of too strong influence of dispersed sun radiation, which can disrupt measurement result,
- during measurement there cannot be any precipitation, fog or smog,
- on the route of measurement there cannot be any obstacles and smoke,
- surface of measured object should be dry (low humidity), without thermal interference (e.g. leaves, high grass, trees or gaps in the surface),
- speed of wind should not exceed 2 m/s, measurement is not advised when speed is higher than 5 m/s, optimal weather conditions are either windless or low wind speed up to 1 m/s,
- proper measurement location, that avoids high angles of camera towards the object. Angle between normal to studied surface and camera lens axis should equal maximum of 30° and in special situations it should not exceed 45°. That is why special care should be taken during measurement of steep slopes of coal dump,

- the beneficial conditions for thermovisual studying of objects are during complete overcast and temperature of air around 0 °C.

Then, there are small temperature fluctuations, usually throughout several days. In such conditions, temperature of the surroundings of the coal dumps is also stable.

Burning coal dumps, are different, special case that deviating from conventional hear emitters. For this reason, additional factor influencing deviations and observation errors appear. Self-heating occurrence is accompanied by intensive evaporation from the surface of dumps, which causes distortion of measurements (fig. 5.8). It happens because heat absorbed by water evaporation causes local, temporary temperature decrease. During analysis of thermograms awareness should be raised in regards to zones that show lower temperature than surrounding. Also emission of hydrocarbons emission, which in self-heating stage can disrupt the results. Air pollution such as dust, soot, smoke and some fumes have high emissivity and are practically impenetrable. That means that they can disrupt the measurement, emitting their own infrared radiation, which is received by thermovisual camera. Furthermore, only a part of infrared radiation of measured object can get into the thermovisual camera, because it gets dispersed and absorbed by floating matter.

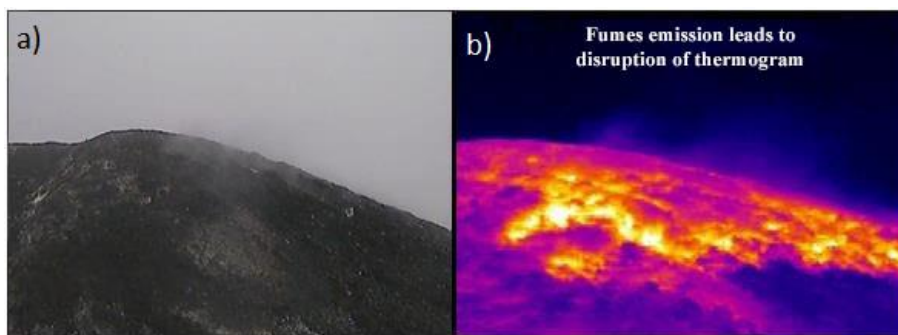


Fig. 5.8. a) Gas emission from burning dump area; b) distortion of thermovisual image caused by gas emission from burning dump area [source: own]

Other factor, which multiplies difficulties in thermogram evaluation is color, texture and structure of certain surrounding layers. During intensive activity of sun rays, objects of different structure, heat up in different way. That is why it is the best to create thermograms right after dawn (also due to the need of synchronized taking pictures in visible spectrum). Thermovisual measurements at dawn are recommended considering that at night there is an equalization of temperature on coal dump surface that was earlier heated by sun [63, 65, 83, 84].

In case of thermovisual temperature measurement of objects located in open area, surrounding of studied object is partially sky and partially ground surface along with some buildings. These elements are usually varying in temperature value, while thermovisual camera have ability to apply only one surrounding temperature in order

to provide internal corrections of surrounding temperature influence on measurement result. This issue occurs during thermal diagnostic of coal dumps, building and any other object located in open area [76].

Thermovisual camera operator must face difficulties of capturing the image of coal dump in such a way that does not include fragment of the sky or building. In reality it is a complicated procedure, which ends in failure almost every time. It causes disruption in thermogram, as the sky has the temperature completely different from analyzed coal dump. Apart from that, temperatures, dependent on season and time of the day can fluctuate between over a dozen to several dozen degrees, which causes significant interference in scale of measured temperatures. Another issue that operators face during thermograms registration is heating up of the surface layer of deposited material by sun rays. It is not surprising that temperatures registered on top surface of coal dump can reach up to 50–55 °C on sunny days [241]. It causes difficulties in measurement due to high contrasts between surface temperature and sky [83, 84, 65, 76]. Encountering such an issue, surrounding temperature in thermovisual camera should be set. Designation of replacement surrounding temperature based on radiation of clouds, sky, ground and other object in proximity of studied structure is difficult. It requires careful analysis of radiation heat exchange and evaluation of value of so called configuration coefficient. Value of this temperature depends on mutual orientation of studied object in relation to other radiating bodies in proximity of camera. The easiest method for assessing surrounding temperature during studies conducted outside, for vertical objects with consideration of only clouds and ground is to average value of these temperatures, e.g. for temperature of ground $T_1 = 3\text{ °C}$ and sky $T_2 = -15\text{ °C}$, value of surrounding temperature, that should be entered to the camera before starting the study should equal $T_a = -6\text{ °C}$ [176].

It is worth mentioning that during temperature measurement of sky temperature, even experienced operators may interpret the results incorrectly. Sometimes, comments can be found, stating that according to thermogram, sky temperature equals, e.g. from -40 °C to -80 °C . It should be highlighted that thermogram shows “spectral temperature of the sky”, measured in range of thermovisual camera, e.g. $7.5\text{--}13\text{ }\mu\text{m}$. So called “average radiation temperature of the sky” for total range of spectral thermal radiation ($3.0\text{--}50.0\text{ }\mu\text{m}$), thus full radiation range of influence on buildings (coal dumps) in cloudless conditions, for flat surface can be lower than air temperature by around $20\text{--}25\text{ °C}$ [105].

5.2. Measurement of temperature and gaseous atmosphere composition inside the object

Based on near-surface temperature distribution, places of increased thermal activity are located (hot spots). In these zones study fields are designated and inside them a grid of measurement holes is planned out. Next stage relies on creating drill holes, at least 1 m deep. In order to do this, equipment is used, e.g. drillers adapted to work on steep slopes or in rare cases, primitive tools such as metal spades or a steel pole with knob, 1.1 m long. Next step is use of professional measurement equipment, consisting of digital measurer of temperature along with probe (fig. 5.9). Thanks to this, samplers are able to measure temperature inside the coal dump. In sensitive

places it is recommended to thicken the grid. Suggested frequency of measurement is every half year.

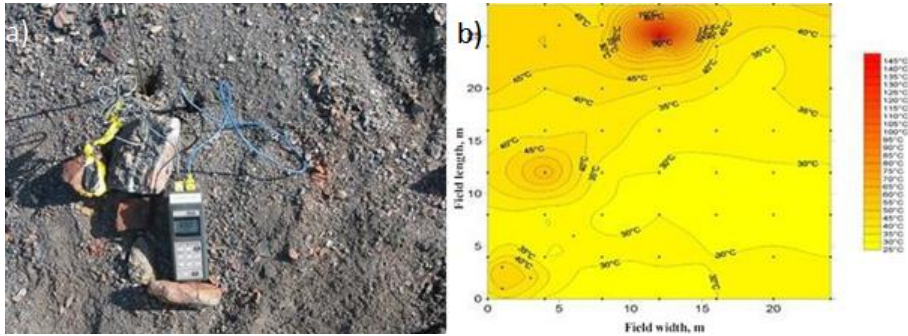


Fig. 5.9. a) Use of Delta OHM HD 9016 thermometer for in depth measurement of dump.
b) Temperature distribution in measuring field on dump surface has been designated using Surfer software [source: own]

For measurement of temperature inside the coal dump, thermovisual camera can also be used. This however involves, digging in special measurement pipe into the dump (fig. 5.10). During embedding of the pipe, it should be remembered to seal it from the top, because leaving unsecured hole open, allows oxygen to access the hot spot [171, 174].

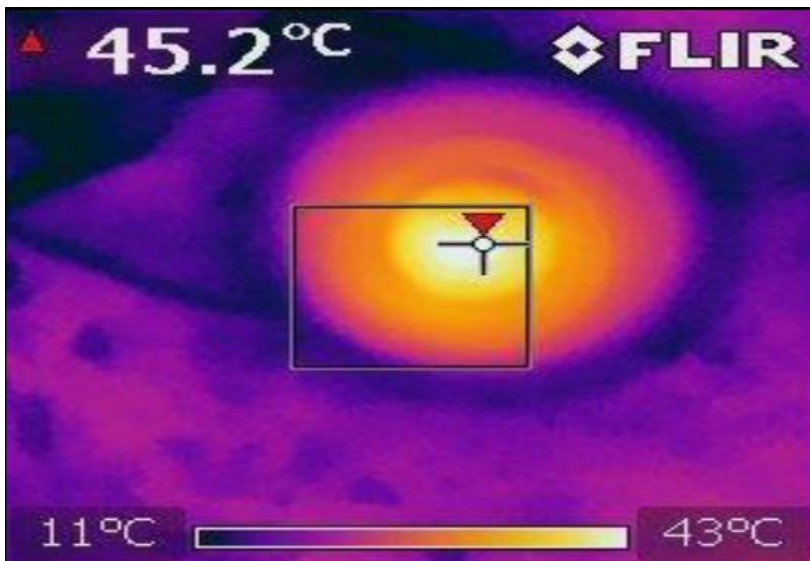


Fig. 5.10. Temperature distribution inside the pipe dug in dump area, characterized with significant thermal anomalies [source: own]

Studies on gas composition inside the coal dump are conducted using professional analyzer. Values of gas concentrations are shown on a digital display of the device and saved in its memory. Samples are gathered from the same holes, where temperature of the inside of coal dump was measured. Following designations of concentration are performed:

- designation of carbon monoxide CO concentration [% vol.],
- designation of carbon dioxide CO₂ concentration [% vol.],
- designation of oxygen O₂ concentration [% vol.].



Fig. 5.11. Measurement of gas concentration using Dräger X-am7000 detector

Other method allowing to measure composition of atmosphere inside the dump considers sampling of gases and performing chemical analysis in chromatographic laboratory. Figure 5.12 presents APG-1 type device, which can be used for taking samples of air and gases using pressure method from thermally active coal dumps and other places, where air composition or concentration of gas may be harmful or hazardous for people and their surroundings.

APG-1 type device consists of following elements:

- suction conveying pump with displacement of 45 cm,
- extension cord 570 mm to 2000 mm long,
- needle valve with manometer,
- single valve small pipettes with volume of 40 cm³ – 10 units,
- dual valve large pipettes with volume of 65 cm³ – 10 units,
- bag – for transportation.

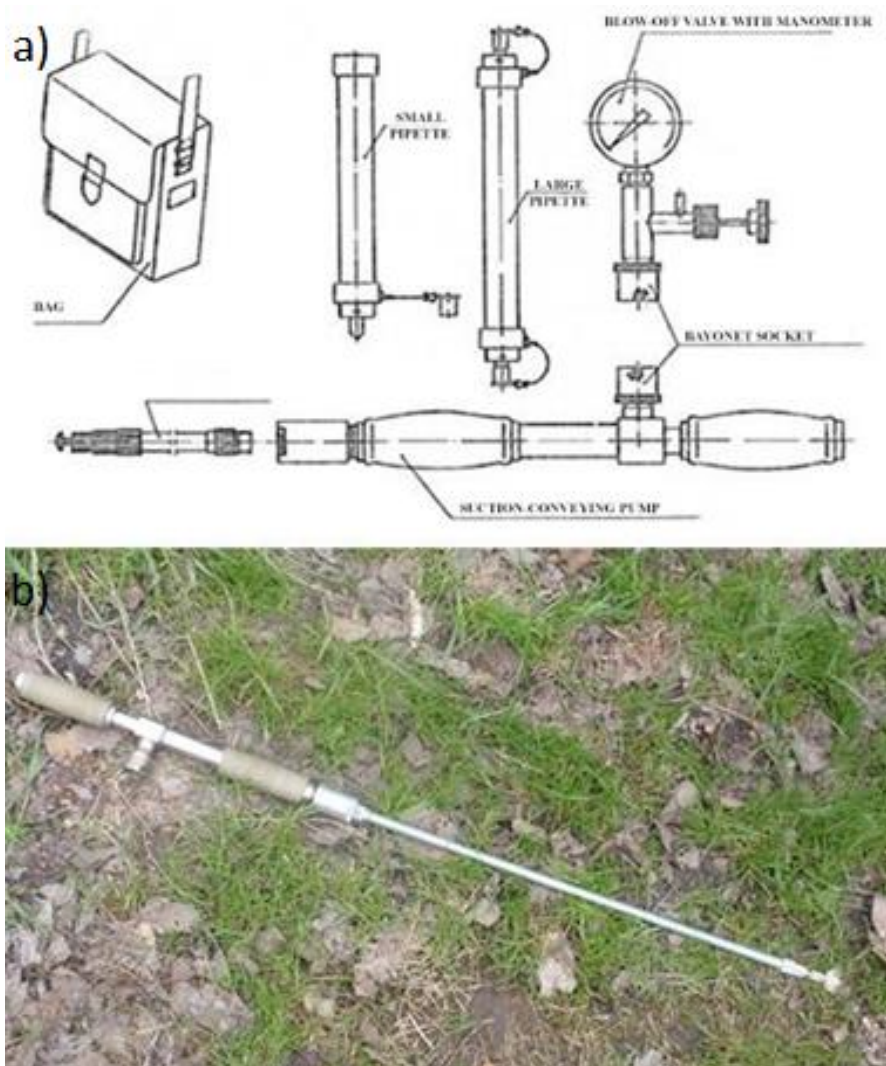


Fig. 5.12. a) APG-1 device, used for taking samples of air and gases using pressure method and b) view of force and lift pump [254]

In his time Z. Róžański [138] attempted to designate gas emission in exhalation zones, appearing on the surface of thermally active mining waste dump “Skalny” in Łaziska Górne. Studies of gas concentration has been performed using a tent set on the surface of coal dump. Tent allowed for taking samples of gas, which were later subjected to chromatographic analysis. Outlet of cone-shaped tent let for measurement of gas stream coming out of the tent into the atmosphere. Potential emission of gases into the atmosphere was calculated, based on studies result. Similar way of gas emission designation has been used on dumps in Australia (fig. 5.13).

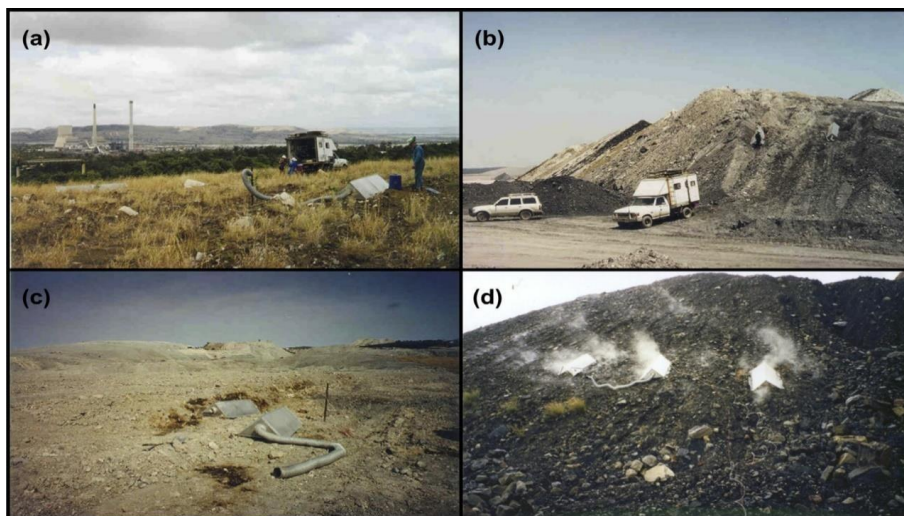


Fig. 5.13. Measurement of gas emission from the surface of dump with different level of thermal activity: (a) reclaimed dump, (b) dump without signs spontaneous combustion, (c) dump with significant, near-surface, thermal anomalies, particularly visible near cracks and fissures, (d) burning dump with visible gaseous exhalation. Length of tent visible in fig. (c) and (d) is 2 m (fig. Ferenc Szemes)

Gas emission has been measured in hundreds of places in many different coal dumps. Gathered results shown that there is very broad range of gas emission, which depends highly on degree of thermal activity of the dump. As a consequence, it has been divided into three categories [46]:

1. Intensive fire, characterized by high emission of smoke. Visible cracks and discoloration on the surface. Emission coefficient around 8200 kg CO₂ per annum for every m².
2. Self-heating of waste without clear signs of thermal activity. Emission coefficient around 95 kg CO₂ per annum for every m².
3. No signs of self-heating. Emission coefficient around 13 kg CO₂ per annum for every m².

In comparison, in France, in-situ method for measuring fire gases is used (operation in place of gas emission). In this method, analyzer is used, which is mounted on a vehicle adapted for this task in particular. Thanks to mobile laboratory (fig. 5.14) instant analysis of following gases is possible: O₂, CO₂, CO, SO₂, NO_x and hydrocarbons.

To reliably analyze thermal state of the coal dump, proper series of research should be conducted throughout certain amount of time. Only this way, scientists are able to describe the dynamics of thermal processes on coal dump as well as the character of these processes (development or disappearance).

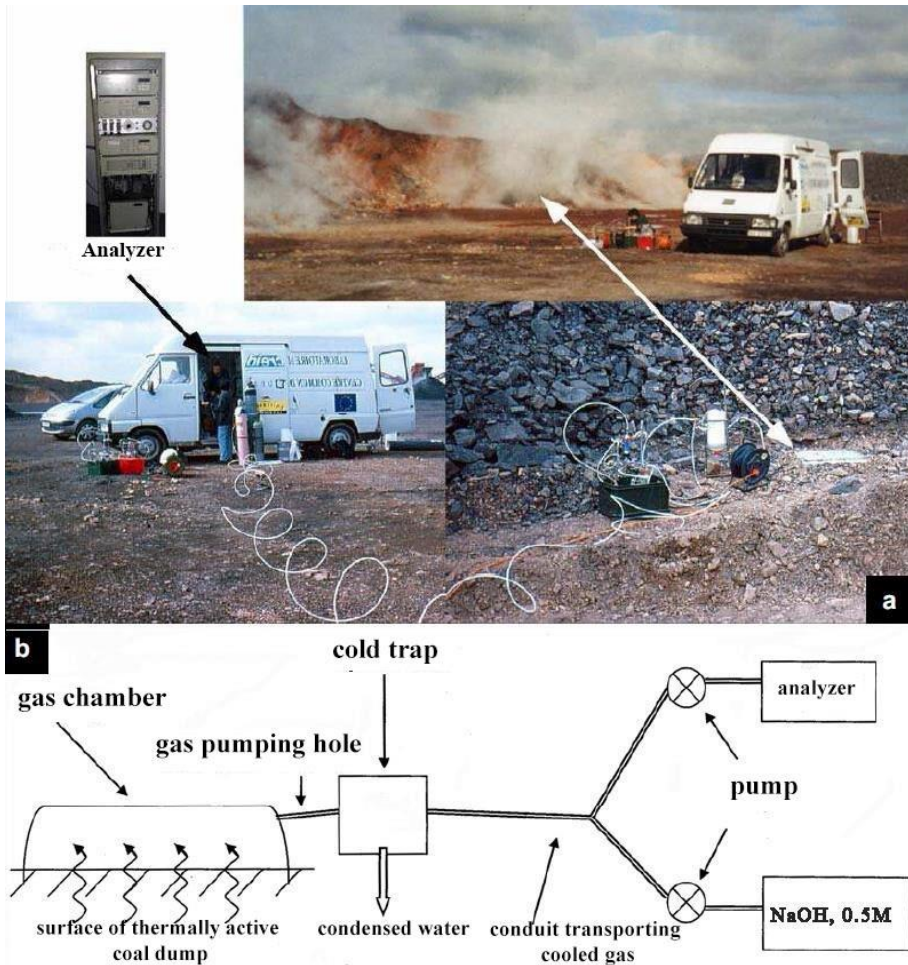


Fig. 5.14. Coal dump No. 76 Avion (France 2002), a) Gas measurement using in situ methods, b) Gas sampling device schematics [101]

5.3. Diagnosis of incubation state and fire progression

Progression of fire degree inside the mining waste dump is evaluated based on three stages. First is isothermic, spontaneously accelerating oxidation, which later progress into self-heating stage and ends in spontaneous combustion of the coal dump. Each of these stages is characterized by specific symptoms that allow to diagnose thermal state. These symptoms and associated approximate temperatures inside the coal dump have been presented in table 5.2.

Table 5.2. Symptoms along with approximated temperatures inside the coal mining waste dump [170]

Stage	Temperature (approximate)	Symptoms
Isothermic spontaneously accelerating oxidation	> 35 °C	Decrease in oxygen content
	> 45 °C	Increase in CO ₂ content
	> 55 °C	Appearance of CO
	> 70 °C	Increase of CO content
	80 °C	“Sweating” of material
	110 °C	Appearance of methane and ethane
	120 °C	Appearance of hydrogen
	130 °C	Slight stench
	150 °C	Appearance of ethylene
Self-heating	> 150 °C	Temperature increase
	200 °C	Fog – delicate evaporation
	200–250 °C	Strong smell of engine fuel
	> 250 °C	Release of higher hydrocarbons
	> 300 °C	Light gray smoke
Spontaneous combustion	370 °C	Strong tar-like smell (stench)
	430–450 °C	Dark smoke
	550–600 °C	Open fire

Additional factors that have to be taken under consideration in evaluation of thermal state algorithm on coal dumps, are:

- type of coal dump tendency of waste for spontaneous combustion,
- range and frequency of monitoring,
- compaction coefficient of dumps,
- physical properties of waste (compactibility).

Table 5.3 shows proposed options for each individual factor. It has been accepted that each analyzed factor can be characterized by two options. First factor is satisfactory option, which is synonymous with decrease of fire hazard and marked with plus symbol. Second factor is unsatisfactory option, which is synonymous with increase of fire hazard and marked with minus symbol.

Table 5.3. Factor options, prognostic of fire hazard [47]

Ordinal	Factor	Higher hazard (+)	Lower hazard (–)
1	Type of dump	below-level	above-level
2	Earlier instances of spontaneous combustion of waste (waste tendency for spontaneous combustion)	no occurrence (low)	occurred (high)
3	Range and frequency of monitoring	sufficient	insufficient
4	Compaction coefficient	sufficient	insufficient
5	Physical properties of waste (compactibility)	compactible	incompactible

After gathering information about factors mentioned and after scientific analysis of the coal dump, classification of fire hazard of coal dump comes next. Classification should be conducted based on set algorithm, which has been shown in the figure 5.15.

After choosing proper algorithm path and reading of classification, one should proceed with familiarizing with table 5.4, where preventative-repair actions are pointed out to be completed for certain category.

Table 5.4. Classification of fire hazard on coal mining waste dumps [47]

Category	Hazard	Subcategory	Minimal range of preventative-repair actions
I	small	–	Special actions for specified object
II	medium	a	Extending monitoring range or improvement of monitoring, other special actions
		b	Sealing/compaction of dumps
III	large	a	Extending monitoring range or improvement of monitoring, sealing/compaction of dumps
		b	Adding material of specified grain size to the waste, sealing/compaction of dumps
		c	Extending monitoring range or improvement of monitoring, adding material of specified grain size to the waste, sealing/compaction of dumps
IV	very large	–	Extending monitoring range or improvement of monitoring, Adding material of specified grain size to the waste, sealing/compaction of dumps

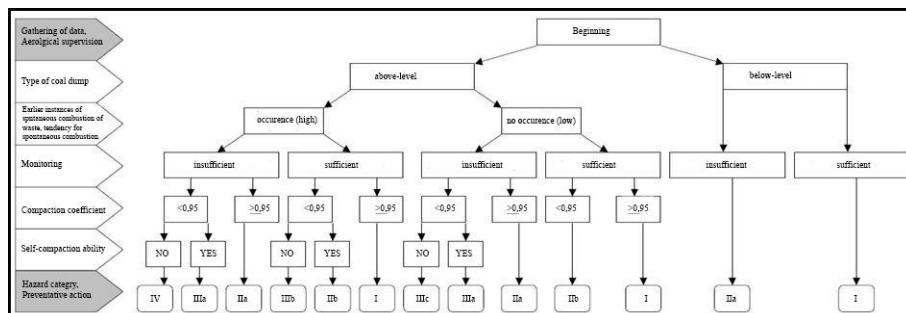


Fig. 5.15. Algorithm of evaluation method and classification of fire hazard in coal-dump waste dumps [47]

5.4. Assessing compaction index of dumps

Assessing compaction index of specified parts of dump proves necessary for overall evaluation of thermal state. Compactibility index I_s is described as measurable parameter representing compaction of waste mass. It is recommended that compaction of waste mass oscillated in range of $I_s = 0.95$. According to that, during evaluation of already constructed coal dumps, this parameter is considered appropriate for correct tightness of the dump. If this index is smaller than 0.95 then tightness is considered to be insufficient. Compaction index for coal dumps designated areas is calculated in at least 10 points (in a grid 50 m × 50 m in size), using method applied to make grounds. One of such methods is measuring of the ground with Light Weight Deflectometer (fig. 5.16).



Fig. 5.16. Measurement of soil compaction using Light Weight Deflectometer [source: own]

5.5. Parameters necessary for correct evaluation of dump thermal levels

Evaluation of thermal state of coal mining waste dump is conducted according to parameters set by GIG, based on variability of coal dump surface temperature and carbon monoxide content inside the coal dump. These parameters can also be verified during measurement. Basic criteria for thermal state evaluation have been shown in table 5.5.

Table 5.5. Thermal state evaluation criteria

Thermal state	Δt [°C]	CO [% vol.]
1. no signs of coal dump self-heating	$\Delta t < 3$	$CO \leq 0.002$
2. coal dump self-heating	$3 \leq \Delta t < 10$	$0.002 < CO \leq 0.015$
3. low intensity coal dump fire	$10 \leq \Delta t < 20$	$0.015 < CO \leq 0.05$
4. intensive coal dump fire	$\Delta t \geq 20$	$CO > 0.05$

where: Δt – difference between coal dump surface temperature and surrounding temperature; CO – carbon monoxide concentration in gas sample from the inside of coal dump.

Correction should be taken for measurements conducted in summer season, as temperature of the surface may not show the real temperature inside the coal dump. It happens due to intensive sunlight. At that time, even on thermally inactive dumps, values of Δt can well exceed 3 °C.

Sometimes, high temperature inside coal dump does not have to show signs of fire occurrence, because simultaneous lack of CO emission, average (about 6–10%) value of CO₂ and oxygen content up to 10%, indicates fire state, which leads to cooling of deposited material [118].

5.6. Technical parameters of instruments needed for research

To conduct complex analysis of coal dump thermal state, according to method created by GIG, one should use following devices: thermovision camera, pistol-shaped pyrometer and gas analyzer [12].

Additionally, thermovision camera operator should be equipped with other necessary scientific gear, namely, camera, laser rangefinder, anemometer with wind speed recorder, air relative temperature and humidity recorder, thermocouple with recorder, spare camera batteries, tripod, black, mat, duct tape with known emissivity coefficient. Additional accessories are used for measurement and recording of important auxiliary parameters, which are necessary for measurement control and interpretation of thermograms [105].

Below, general characteristic has been presented, of devices suitable for use in temperature anomalies condition, found on coal dumps [125].

1. For temperature measurement of waste material on coal dump surface:
 - a) thermovision camera:
 - minimal measurement range: –20 °C to 600 °C,

- detector: matrix 320×240 pixels or higher,
- minimal measuring accuracy: 2% size of measurement ± 2 °C,
- thermal sensitivity: 0.05 °C,
- operation temperature -10 °C to 50 °C;
- b) portable temperature measurer using infrared radiation method (pyrometer):
 - measurement range: -30 °C to 1200 °C or higher,
 - measurement precision: 1% size of measurement ± 1 digit,
 - resolution: 1 °C while measuring differences of 0.1 °C,
 - reaction time: about 1 sec,
 - measuring cycle: minimum 4 measurement/s,
 - permissible surrounding temperature: 0 – 50 °C;
- 2. For temperature measurement of waste material on depth of 0.8 – 1.0 m below object's surface and for measurement of carbon monoxide CO, carbon dioxide CO₂ and oxygen O₂ concentration:
Fumes analyzer with following features:
 - measurement ranges: for CO – 0 to 10% vol.; for O₂ – 0 to 20.9% vol.; for CO₂ – 0 to 25% vol.,
 - reading accuracy: for CO 10 ppm; for CO₂ 0.1% ; for O₂ 0.1% ,
 - work environment temperature: from -20 °C to 50 °C,
 - powered by built in battery,
 - resistance to harsh environment.

5.7. Example of thermal state analysis of coal dump in Czerwionka-Leszczyny belonging to KWK “Dębieńsko”

5.7.1. Characteristics of coal dump „Dębieńsko”

Coal dump KWK “Dębieńsko” is located in the area of Czerwionka-Leszczyny municipality in Silesian voivodeship, powiat Rybnicki. Object was formed for many years when mining operation was conducted by Kopalnia Węgla Kamiennego [Coal Mine] “Dębieńsko”. Total surface of the objects is 140 ha and covers coned coal dumps, flat dump and mud sedimentation basin. On coal dumps around 37 m tons of waste were deposited, which came from mining operations, consisting mainly from rocks and coal processing waste. Coned dumps reach height up to 351 m above sea level, whole flat dump and sedimentation basins range between 270 m and 280 m above sea level and even 290 m in some places.

Deposition was performed using technology based on transportation of material by rail. After delivery of material to the location, it was spread by bulldozer on coal dump with simultaneous shaping of inclination with angle of natural slopes.

Area of the dumping ground include five cones, sedimentation basins and flat coal dump. Today, there are reclamation works on two cones, whole other cones remain untouched. Deposited on flat dump, coarse grained waste is subject to secondary exploitation in order to reclaim coal present in deposited waste. Estimated percentage of coal in waste material is between 10 – 12% . Technological procedure of coal reclamation relies on separation of coal from waste using physical methods. This

technology includes, crushing of deposited material, mixing, transportation and in the end sieving using vibrating sieves, washing, desilting, enrichment in heavy medium and finally storing of reclaimed resource.



Fig. 5.17. I, II and III cones from the distance [source: own]



Fig. 5.18. Terrain map of coal dump. Red line marks the area where mining operation is performed. Yellow line marks cones in natural state source: own

5.7.2. Characteristics of deposited waste

Waste deposited on dump located in Czerwionka-Leszczyny, mostly come from mining operations. They consist of rocks, mixed with smaller fractions of coal and processing waste that include washing stone and silt gathered in sedimentation basins. Waste structure was dominated by coarse grained waste (cobbles and gravel), while fine grained waste comprised 10% of total mass. In averaged waste, gravel fraction is dominating and is on average 76% of the material mass. In case of cobble fraction,

situation is slightly different, as it is 14% on average. Sand fraction comprise 9% average, while contribution of silt and clay fraction is unsubstantial and averages 0.16%. Granulometric composition of certain waste is varied. Waste that came from preparation works are distinguished by high range of grain sizes between 0–300 mm. While using DISA concentrators, waste is characterized by certain amount of super – and subgrains. In grain composition of these waste dominating was fraction ranging 80–50 mm and 50–30 mm. Waste from jigs achieved grain sizes of 1–10 mm in post-flotation waste – 1 mm [182, 61].

Waste deposited on dump in regards to their petrographic composition, contained claystone of three main types:

- solid, kaolinite-sericite-quartz (type a)
62.7–82.5%, average 72.2%,
- with bands of coal kaolinite (type b)
9.7–27.8%, average 17.6%,
- soft, swelling illite-montmorillonite (type c)
0.5–4.0%, average 1.5%,
- siderite (type d)
2.7–1.2%, average 7.8%,
- sandstone with transition to coarse mudstone (type e)
0.0–5.5%, average 1.9%.

It has been stated that dominating claystones comprise of, solid kaolinite-sericite-quartz 72.2% on average and kaolinite with bands of coal, on average 17.6%. In mineral composition the dominating minerals are kaolinite, illite and mixed illite-montmorillonite layers. Prevailing form of sulfur in waste is pyrite, which make up 0.9% of chemical composition.

Table 5.6. Mineral composition of dominating type a [144]

Mineral	Percentage [%]
Kaolinite	44.4
Sericite	4.4
Illite	13
Quartz	10
Siderite	3.2
Biotite	2.4
Pyrite	0.9
Goethyt	1.1
Coal	20.5

In case of chemical composition of accumulated waste material, it is characterized by prevalence of potassium over sodium and magnesium over calcium.

Table 5.7. Chemical composition of dominating type a [144]

Chemical name	Percentage [%]
SiO ₂	49.9
Al ₂ O ₃	25.11
Fe ₂ O ₃	5.53
CaO	0.30
MgO	1.44
Na ₂ O +K ₂ O	2.47
Sc	0.44
CO ₂	2.44
H ₂ O	7.07
C _{pal.}	5.33

Older coal dumps where weathered coal mining waste lie, are characterized by increased sulfate sulfur content, which is result of pyrite oxidation process. This phenomenon influence self-heating of waste mass.

**Fig. 5.19.** Coal-dump waste deposited on KWK “Dębieńsko” dump [source: own]

5.7.3. Thermal state research in order to localize an experimental field

From February to May 2014, own research was conducted on coal mining waste dump KWK “Dębieńsko”. These measurements were performed using professional equipment.

Measurements were made on three cones. After preliminary overview studies, highest thermal activity was found on cone I. In case of cone II, only one thermally active place was found while cone II did not show any signs of thermal activity.

During measurement in February temperature reached 0 °C, overcast, moderate, with humidity of 85%. Next studies performed at the turn of March and April, were in cloudy days, when average humidity ranged 70% and temperature was around 10 °C.

There was deep temperature measurement on three studied cones. Probe was placed on 15 cm and 1 m deep. 30 measurements total, were made, which shown the biggest thermal activity on cone I. Measurement results and conclusions from research sessions have been discussed in following chapters.

5.7.3.1. Equipment and tools necessary for conducting research

For measurement necessary were devices:

- Infrared thermometer IRtec MicroRay HVAC (pyrometer),
- Thermometer Delta OHM HD 9016 along with probes,
- Thermovisual camera Trotec ICO80V,
- Hammer and chisel.

Pyrometer IRtec MicroRay HVAC (fig. 5.20) was used for measuring surface temperature of the coal dump, chosen for conduction of more detailed thermal research.



Fig. 5.20. Pyrometer IRtec MicroRay HVAC (in the middle) [source: own]

Technical specification:

- measuring range $-30\text{ }^{\circ}\text{C}$ to $500\text{ }^{\circ}\text{C}$,
- optics 15:1,
- accuracy $\pm 1.5\text{ }\%$ for reading or $\pm 1.5\text{ }^{\circ}\text{C}$,
- emissivity coefficient default 0,95 (set according to needs).

Thermometer Delta OHM HD 9016 (fig. 5.21) along with probes was later used in studies of temperature measurement inside the object. Thanks to probes place on depth of 1 m and 15 cm, it was possible to read temperature measurement.



Fig. 5.21. Thermometer Delta OHM HD 9016 with probes during measurement [source: own]

Technical specification:

- measuring range $-200\text{ }^{\circ}\text{C}$ to $1800\text{ }^{\circ}\text{C}$,
- precision of the device
 - $0\text{ }^{\circ}\text{C} - 199.9\text{ }^{\circ}\text{C} \pm 0.1\text{ \%}$ for reading or $0.4\text{ }^{\circ}\text{C}$,
 - $200\text{ }^{\circ}\text{C}$ to full scale or $-0.1\text{ \%}$ do $-200\text{ }^{\circ}\text{C} \pm 0.2\text{ \%}$ reading $\pm 1\text{ }^{\circ}\text{C}$.

Precision relates to environment temperature that is $25\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$:

- comprises two inlets for probes,
- power (battery IEC 6LF22 9 V) 100 h of work,
- weight (280 g).

Thermovisual camera Trotec ICO80V (fig. 5.22) used for preliminary localization of hot spots and designating their temperature.



Fig. 5.22. Thermovisual camera Trotec ICO80V [source: own]

Technical specification:

- measuring range $-20\text{ }^{\circ}\text{C}$ to $600\text{ }^{\circ}\text{C}$,

- screen refresh rate 50/60 Hz,
- geometric resolution 2.2 mrad,
- thermal sensitivity 0.1 °C,
- minimum measuring distance 10 cm.

5.7.3.2. Thermovisual study

Thermovisual study was conducted on three cones. After thermogram analysis, the highest thermal activity was demonstrated on cone I. In case of other two cones I and III, activity was negligible. thanks to thermovisual camera research, places were located, where area of considerable thermal activity are visible, and places where temperature distribution didn't change significantly.

5.7.3.3. Comparison analysis of completed thermograms

Thermovisual studies done in four-month time (from February to May) proved that cone I is featured by highest thermal activity. In February overview studies were done aiming at localizing of hot spots. During measurement, temperature was 3 °C, while humidity of air reached 85%. During measurement, the highest temperature hot spot found was 68 °C.

In March, during measurement, temperature of air was 10 °C and humidity at 75%. In that month, average temperature of studied thermograms was 36.6 °C. In highest measuring point temperature reached 72 °C. Next month, that was April, decrease in average temperature of measured thermograms was noted, which was 26.2 °C. It could have been caused by atmospheric conditions, temperature during April measurement was 9 °C, with humidity of 60%. In March it was sunny, while at the day of measuring there was complete overcast. The last measurement month on cone I was May, when temperature during the day reached 14 °C, with humidity of 75%. Weather was sunny, however there was gusty wind which also influenced the measurement with thermovisual camera. Average temperature of studied thermograms equaled not much less than in March, that is 35.4 °C. However, worrying sign was observed maximum temperature on one of the thermograms, which was 85 °C.

In April research were also conducted on second field which was cone II. Studies were done in April when temperature of air reached 9 °C and humidity was at 60%. There were over a dozen thermovisual measurements, which for the most part, did not show that on cone II, there are hot spots present. There was only one area where temperature was slightly increased. Average temperature of thermograms done in April in the area of cone II was 11.6 °C.

Also own research was conducted on cone III. Measurements were done in March in sunny weather with temperature of 10 °C and humidity of 75%. There were three deep measurements and several thermovisual. Similarly, to cone II no hot spots were found. Average temperature of thermograms was 22.3 °C. Field was lacking in terms of clean foliage. In the surface there was a lot of dry wood, that heats up rapidly in sunny days, which could lead to inflation of average temperature of studied thermograms.

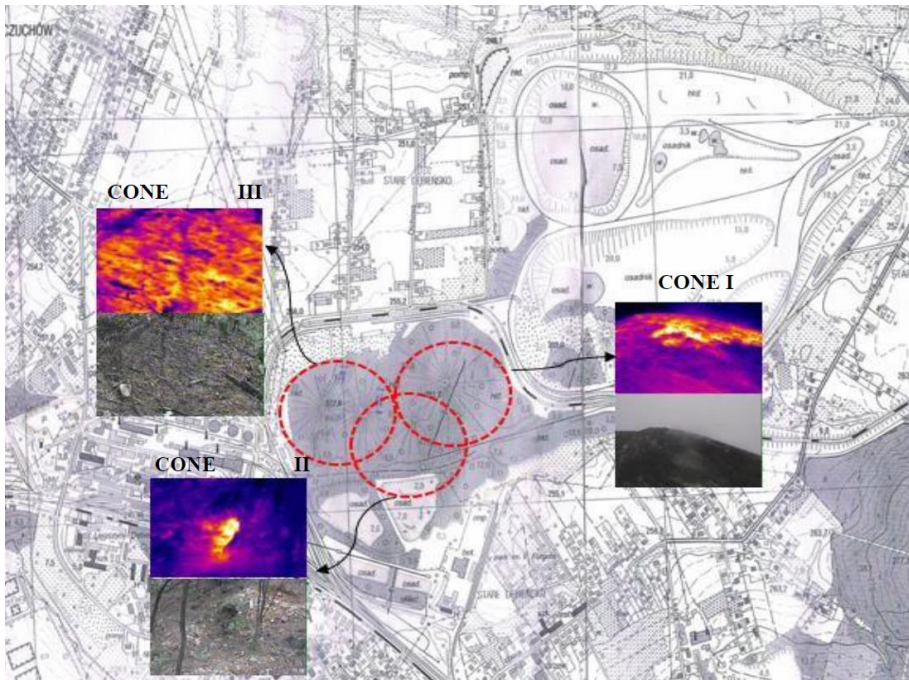


Fig. 5.23. Localization of areas observed with thermovisual camera and view of exemplary thermograms [source: own]

After thermovisual studies were done it could be stated that cone I featured the highest thermal activity, which should be immediately controlled, while cones II and III did not show such activity.

5.7.3.4. Measurement of temperature inside the coal dump

Based on own thermovisual measurements (fig. 5.23), also deep temperature measurements were done in research area. On the surface of cone I there was overall 17 measuring holes, several of them in the same place to find out how temperature changes over the course of few months. On cone II, 5 and on cone III 3 holes. In fig. 5.24 locations of measuring points have been shown.

First research area – CONE I

Cone I is located in north-west part of the waste dump after old coal mine “Dębieńsko”. Measurements completed using thermovisual camera showed increased thermal activity at the top of cone and surface of higher parts.

Between February and May, there were over a dozen measurements of temperature inside the coal dump at depth of about 15 cm and over a dozen 1 m deep. At certain day there were five measurements on average. Measurements in next months have been done at the same location that the previous one to determine potential changes occurring inside.

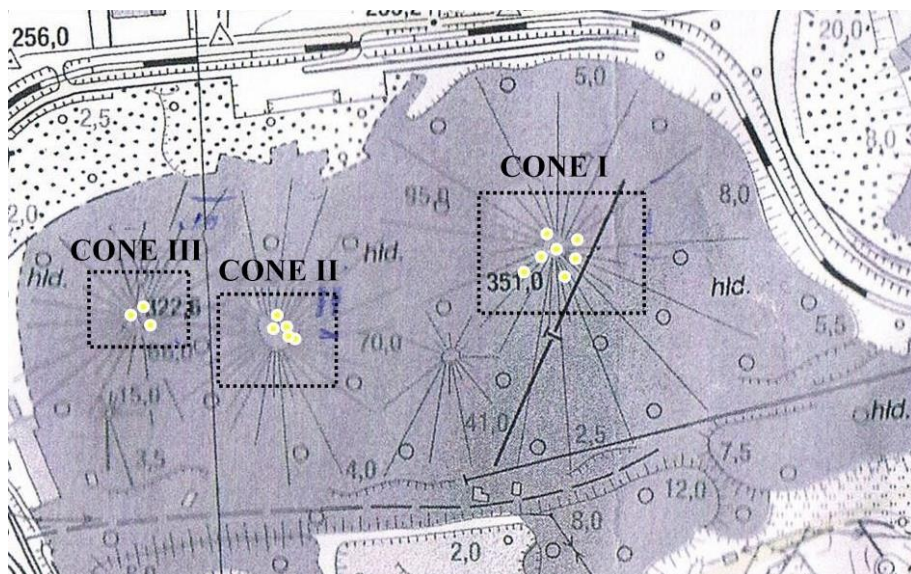


Fig. 5.24. Localization of boreholes on I, II and III cones [source: own]

First session was conducted in February. Field research were performed in morning hours, during complete overcast and temperature of surrounding that equaled 3°C . During measurements at 15 cm, the highest value has been recorded on south-eastern, top part of the cone I and it was 79.15°C with surface temperature of 59.7°C , while lowest value was in south-western, top part of the cone I and it was 42.5°C with surface temperature of 21.5°C . The next step in field research was creation of holes, 1 m deep and readings of temperature. At greater depth of 1m, maximum value was found in south-eastern area of the top of cone I, temperature reached 86.1°C , with surface temperature of 74.1°C . Lowest temperature was noted on south-western, top part of the cone while in lower part it was 58.1°C , with surface temperature of 38.7°C .

According to table 5.5, it can be accepted that we have to deal with intensive fire of coal dump. Difference between maximum recorded surface temperature in measuring point and maximum temperature of coal dump surrounding (3°C) was 71.1°C .

Next month of measurement was March. On 28.03.2014 there was sunny weather with small overcast, temperature of surrounding was 10°C . Five measurements were done in the same areas that in February. Maximum value recorded by probe was 72.3°C , at 15 cm, with surface temperature of 36.9°C . Minimal value was 18.1°C , with surface temperature of 23.7°C . It can be observed that minimal value decreased in relation to measurements from February. In case of increased depth measurements at 1 m, maximum value near top of the cone I was 82.7°C , with surface temperature of 36.9°C , minimal temperature recorded below the top in lower parts and equaled 20.3°C , with temperature of surrounding of 23.7°C .

According to table 5.5 it can be acknowledged that we deal with intensive fire of the coal dump. Difference between maximum recorded surface temperature in measuring point and maximum temperature of coal dump surrounding (10 °C) was 16.9 °C.

Another measurement was performed 9th April 2014 in the morning with complete overcast, while surrounding temperature was 9 °C. At depth of 15 cm probe recorded maximum temperature equal to 73.6 °C in south-eastern area, very close to the top of cone. Temperature of surface in this area was 19.5 °C. Minimal value was observed in lower top part of the cone and it was equal to 41.9 °C, with temperature of surrounding of 21.1 °C. After increasing depth to 85 cm, maximum value near the top was 78.1 °C, with surface temperature of 25.5 °C. Minimal value equaled 51.2 °C, with surface temperature of 21.1 °C.

According to chapter 5.5 it can be accepted that we deal with low intensity coal dump fire. Difference between maximum recorded surface temperature in measuring point and maximum temperature of coal dump surrounding (9 °C) was 25.5 °C. Weather conditions, day before measurement, should be taken into consideration. On April 8th, in the area of the dump there were some small intensity precipitation that could cause temporary cooling of the surface of the dump.

Last month of measurement was May. On May 10th, surrounding temperature was at 13 °C and there was partial overcast. This day few more measurements were done than in previous month in order to obtain even more detailed data about thermal state of cone I. Measurement of the top of cone I was done in a place where highest temperatures were recorded both in case of 15 cm probe as well as 1 m probe. Maximum temperature at 15 cm reached values of 85.8 °C, and for 1 m probe 88.3 °C. Temperature of the surface near these holes was at 36 °C. Minimal values were recorded in eastern part of cone I and lower parts of the top. With surface temperature of 33.6 °C, shorter probe recorder temperature equal to 42.5 °C, and the long one 45.5 °C.

According to table 5.5. It can be acknowledged that there is intensive coal dump fire, difference between maximum recorded surface temperature in measuring point and maximum temperature of coal dump surrounding (13 °C) was 23.4 °C.



Fig. 5.25. Motorsports and cycling on dump leads to creation of erosion trenches, which help providing oxygen to waste mass that is necessary in self-heating processes [source: own]

Cone I is a place often visited by people riding bikes. Fans of motorsports, riding on top of the coal dump, uncover the surfaces that oxygen can access, thus fueling fire raging inside. Out of open measurement holes, unpleasant smell comes out.

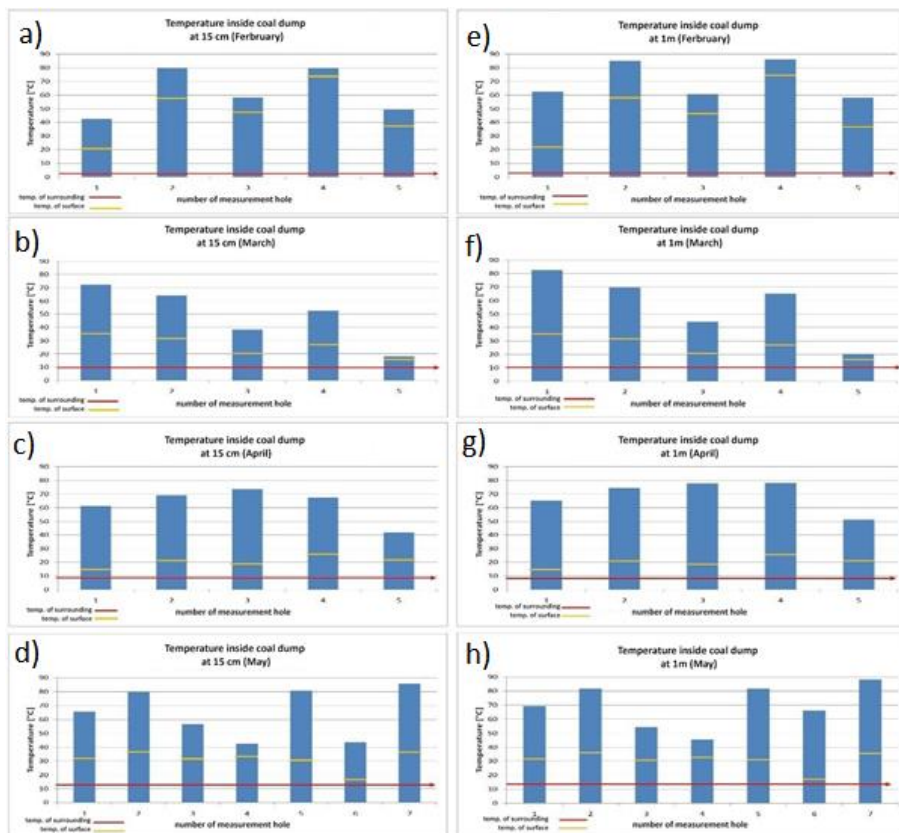


Fig. 5.26. Temperature analysis of the inside of mine waste dump KWK “Dębieńsko” at the depth of 15 cm (a, b, c, d) and 1 m (e, f, g, h). Research field covers area of cone I. Measurements registered between February (a and e) and May (d and h) were taken into account [source: own]

Second research field – CONE II

Another area covered by thermal studies, was cone II, which is located near cone I from south-western side. This area was not subject to fire zones as intensive as cone I, that is why in this zone only overview studies were conducted. In case of studies done with thermovisual camera in the area f cone II, only one place was located where thermal state was high and where exhalation of gas occurred. According to table 5.5 it was accepted that in second area there is a self-heating of the coal dump but it can't

be said that there is fire. Difference between maximum recorded surface temperature in measuring point and maximum temperature of coal dump surrounding was 4.5 °C.

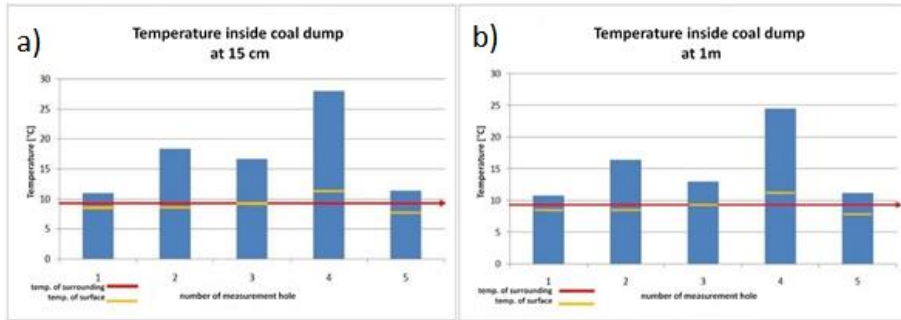


Fig. 5.27. Temperature analysis of the inside of mine waste dump KWK "Dębieńsko" at the depth of a) 15 cm and b) 1. Research field covers area of cone I. Measurements registered in April were taken into account [source: own]

Third research field – CONE III

The last object where studies of thermal state were conducted was cone II located in the line of the last two cones. Although deep measurements performed in this area excluded presence of hot spots, however in preliminary stage it wasn't clear.

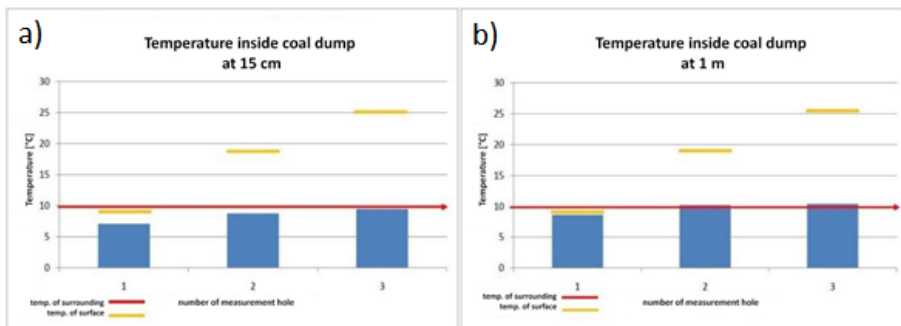


Fig. 5.28. Temperature analysis of the inside of mining waste dump KWK "Dębieńsko" at the depth of a) 15 cm and b) 1 m. Research field covers area of cone I. Measurements registered in March were taken into account [source: own]

If one would follow only the data shown by thermograms, the conclusion could be made that surface of the coal dump show signs of thermal anomalies. However, from the start there was a belief that thermal images may be biased. Reasons for biased measurement can be found in weather conditions. Pictures were taken during sunny weather that caused self-heating of waste material on the top of cone (figure 5.29). Additionally, in measurement area a lot of wooden material could be found that heat

up much faster when exposed to sunrays and inflate real temperature of an object. Because of that thermovisual camera measurements were also inflated.

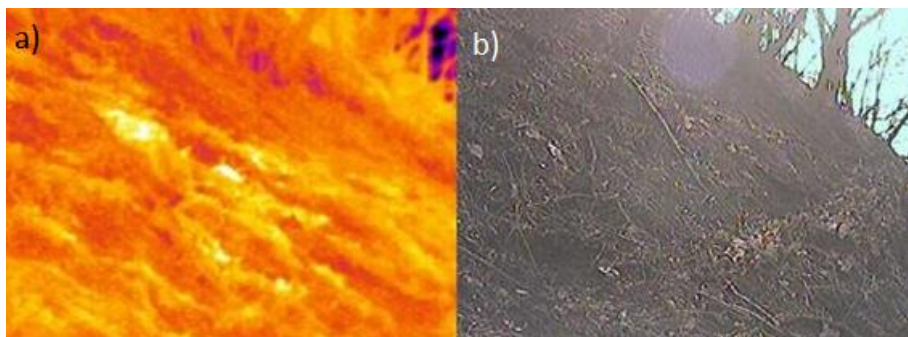


Fig. 5.29. Sunrays during cloudless day heat up the surface of dump (b), preventing preparation of correct thermogram (a) [source: own]

It is understood that thermovisual camera operation cannot limit himself only to operation of equipment and creating of thermograms – his general task is complete and profound interpretation of thermal imaging and formulating of conclusions and recommendations. That's why recommendations and procedures should be followed, as presented in chapter

5.7.3.5. Conclusions based on performed research

1. High content of combustible substance in deposited waste on coal dump KWK „Dębiesko” in Czerwionka-Leszczyny town, exposes object to constant fire hazard.
2. Thermovisual studies helped in localization of areas showing high thermal activity.
3. Difference of temperature between surface of coal dump and surrounding in first research field (cone I) was showing signs of intensive fire. Temperature inside cone I reached, in places, 89 °C.
4. Difference of temperature between surface of coal dump and surrounding in first research field (cone II) was showing signs of self-heating of deposited material. Temperature inside cone II reached, in some measuring points, 25 °C.
5. Thermovisual camera measurement proved that cone III is subject to low intensity fire, however, measurements of the inside of dump excluded such possibility. Maximum recorded value equaled 10.4 °C.
6. Necessary preventative action range that should be undertaken is to apply surveillance. It is also needed to start working on condensation of dumps, especially in places where fissures show up. Beneficial operation would be securing the dump by putting signs or enclosing the area. It would reduce to minimum participation in motorsports on coal dump, causing creation of erosion trenches on the slopes.

7. To fight thermal activity on coal dump it is necessary to undertake proper preventative and extinguishing actions.
8. Creation of filter swales, filled with water-ash slurry allows for overcome fire hazard and reduce contaminants emission into the atmosphere.
9. Pumping in liquid CO₂ inside the most thermally active cone I, can be an efficient method of firefighting. It allows for effective suppression of thermally active zones. Hole injection used in case of cone II. can significantly reduce possibility of fire and reduce temperature of self-heating waste material.
10. Pressure differences on the surface of coal dump can additionally influence development of thermal processes inside the coal dump.
11. For complete thermal analysis, higher number of measurements with detailed consideration of weather conditions, is necessary.
12. Thermal processes occurring inside the coal dump cause increase of surface temperature and as a result, negative impact on environment by reduction of foliage on cone I.
13. Waste dump after old “Dębieńsko” Coal Mine (*KWK Dębieńsko*) in short time may prove important issue for local administration, considering the emission of stinking substances into the air. It is fairly cumbersome for local housing.

6. Summary

The aim of this elaboration was to present the issue of thermal phenomena on coal mining waste dumps, in possibly, the broadest context. Showing such important topic in interdisciplinary background, allowed for demonstration of complexity of an issue that, for the surface, are fires initiated on coal waste dumps.

Because of direct impact of thermally active coal dumps on the surface, proper elimination of threats and reclamation, translates to safety of people, buildings, terrain infrastructure as well as quality of life in Upper Silesian Coal Basin, heavily degraded by mining activity lasting for hundreds of years.

Of course, striving to show the reader, an overall image of the “burning coal dumps” problem, elimination of that hazard and reclamation of the area, affects the detail level of each single issue discussed. Relatively extensive, however, considering how huge are the achievements in this field, incomplete bibliography that has been presented to the reader, gives the ability to expand knowledge about topics raised in this book.

This book should be useful especially to the students of mining, construction and spatial planning faculties, as well as others, who are thematically related to the issues of influence of thermally active mining waste dumps on the surface, as these are also places of potential investment value.

That is why, this book is also addressed to the wide group of potential building investors, including private investors, taking on challenge of constructing residential and industrial buildings in the areas where widely understood elimination of seats of fire (thermally active) and reclamation took place – as an investment adaptation measure.

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