Management Systems in Production Engineering

2014, No 3 (15), pp 126-134

DOI 10.12914/MSPE-07-03-2014

RESEARCH OF LEVEL OF SPONTANEOUS COMBUSTION ON COAL HEAPS GENESIS DANGER

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Abstract:
The article presents the summary of information about the spontaneous combustion of brown coal mass on coal heaps. It describes the procedure "The evaluation of the degree of the danger for the genesis of the spontaneous combustion of coal on coal heaps". The evaluation includes analysis of important influencing factors. The conclusion of this article contains definite text of the proposition. It will be verified in the last year of the solution of this project TA01020351 – program ALFA.

***Key words**: lignite, brown coal, dump, heap, coal self-ignition*

BASIC APPROACH TO THE PROPOSAL „EVALUATION OF THE SPONTANEOUS COMBUSTION PROCESS OF BROWN COAL MASS ON THE DUMPS (CRITERION MHU)

The proposal of „The evaluation of the spontaneous combustion process for brown coal on coal heaps" is based in the maximal extent on our knowledge and experiences gained at the evaluation of the level of danger of this process at the high wall mining – criterion MF – utilized in the OKR mining company today [1, 2]. The evaluation scoring scale is set by this way, that the (maximum) critical threshold is 35 points. If the rate exceeds the risk of spontaneous combustion after the sum of all scores referred to the critical value, then the technical measures for its reduction has to be done.

The assessment procedure quantifies gradually the pointers, which most directly affect the risk of the self-ignition in landfills and which are, for the purpose of a better understanding, divided into the following "groups" or factors:

1. **Coal parameters (internal** factors) – related to the properties of the coal. For the purpose of the proposed evaluation these parameters are referred to as „U".
2. **Technological parameters** (**storage** factors) – related to the geometry and the construction of the dump. For the purpose of the proposed evaluation these parameters are called "T".
3. **Parameters of environment (meteorological/ weather** factors) – related to the localization of the landfill in a given environment. For the purpose of the proposal evaluation, these parameters are referred to as "P".
4. **Additional parameters** – related to measures to reduce the risk of self-ignition. For the purpose of the proposed evaluation these parameters are referred to as "D".

The individual groups (factors) are broken down in more detail on the rated characteristics, which have been designed on the basis of experience and knowledge about the behavior of coal dumps. The selection of individual indicators was (except workers VUHU) discussed with the experts on the spontaneous combustion of coal and coal dumps from OKR (Ing. Z. Michalec, Ing. M. Špok).

U: Coal parameters (internal factors) – related to the properties of the coal
U1: Predisposition to spontaneous combustion of coal (oxireactivity);
U2: Content of humidity
U3: Granularity (size distribution)
U4: History of coal treatment before dumping

T: Technological parameters (**storage** factors) related to the geometry and the construction of the dump
T1: Height of the heap (dump)
T2: Degree of compacting
T3: Angle of the slope tilt
T4: Subgrade (subsurface) of the dump
T5: Technological construction of dump and processing procedure
T6: Season of the year in which the dump was constructed
T7: Average time of coal dumping

P: Parameters of environment (**weather** factors) related to the localization of the dump (landfill) in a given environment
P1: Orientation of the dump related to the winds
P2: Protection of the landfill from the rain
P3: Shielding of the landfill from the Sun

D: Additional parameters – related to measures to reduce the risk of self-ignition
D1: Barrier against direct impacts of the winds on the dump
D2: Monitoring of the landfill status (thermovision, gas probes)
D3: Treatment of coal by an inhibitor

The resulting value of the criteria MHU is obtained by aggregating scores for each of the indicators. The scores of the individual indicators are based on the results of the detailed analytical investigations (including modelling), as they are described in detail in the following (main) part of this work. The resulting proposal for evaluation is then given in the last final part of this study.

ANALYSIS OF THE INDIVIDUAL PARAMETERS (FACTORS) INFLUENCING THE FORMATION OF SPONTANEOUS COMBUSTION PROCESS ON THE COAL LANDFILLS

U. Coal parameters (internal factors)

U1: Predisposition to spontaneous combustion of coal (oxireactivity)

It is generally known that the reactivity of brown coal to oxygen is much higher than of the hard coal. This fact is clearly demonstrated by the results of the measurement method of pulse flow calorimetry (PPK) [3]. The PPK method allows the direct measurement of the heat released by a chemical reaction of oxygen with coal – the heat of oxidation q30, whose value is an essential indicator for assessment of the coal self-ignition predisposition [3]. The values of the heat of oxidation q30 correspond to the heat of chemical interaction released by one gram of fresh coal during its contact with oxygen at 30°C and the ambient pressure (index 30 in the designation of the q30 has therefore two meanings, both expressed in temperature of measurement °C/and the time of the contact of coal with oxygen/min). The dimension of the oxidative heat q30 is usually expressed in J/(g) of coal (with the knowledge that the heat is released within 30 minutes), respectively, in W/kg of coal (the translation relation: 1 J/g (30 min) = 0.5555 W/kg).

The relationship of the coal oxireactivity with the coal type is clearly shown in Fig. 1a, when the coal carbonization is characterized by the value of carbon content in the combustible part of coal – C daf (%C – dry ash free sample). The water contents for individual samples of coal used for the calorimetric measurements are given in the bottom part of the image (1b).

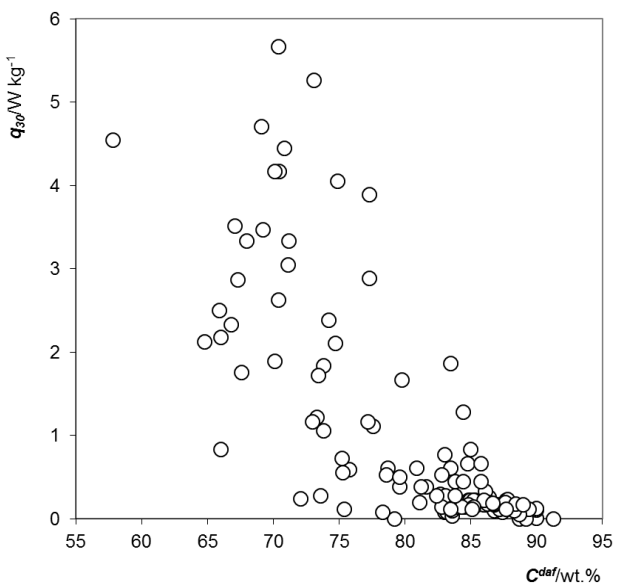

Fig. 1 Dependency of oxidation heat (a) or the moisture content (b) on the content of carbon in coal

The Figure 1 obviously demonstrates the decreasing tendency of the heat of oxidation **q30** with the increasing carbon content, i.e. with the increasing carbonization of coal. The highest value **q30** of all measured coal samples was determined for a sample of brown coal from the mine Handlová (Slovakia) and also Turkish lignite and it was approx. 15 J/g = 8 W/kg (Fig. 1, these values are not plotted).

Coal is classified into one of three categories of the predisposition to self-ignition according to the values of the heat of oxidation q30, the limit values of categories were determined for brown coal to measure a range of samples of Czech and Slovak coal types.

Naturally, there is a valid direct proportion, the higher the oxireactivity is the higher the danger of the spontaneous combustion of the respective coal and this parameter is very significant and influencing the danger of the self-ignition of the brown coal landfill.

The proposal for the "Evaluation of the brown coal spontaneous combustion process on landfills" is for this indicator based on this logic. Coal falling into the category I of "highly reactive coal" was assigned a point value of 10, coal from the category II received a point value of 5 and the category III received then a point value of 2 points. If the oxireactivity of the coal has not been established yet, it is appraised by a point value of 10 points.

U2: Moisture content

Water is an essential component of natural coal, which inseparably accompanies natural coal. The content of the water in coal is very different - from a few percent (hard coal types) through the levels of around 30% (brown coal) up to the contents of the moisture in excess of 50% (lignite). Therefore, talking about self-ignition (oxidation) of coal in situ, it actually refers to a system of "coal-oxygen-water". The resulting behavior of the coal to the oxygen also includes the information about the possible interaction of present water. (Completely dry state of coal can be realized only in laboratory conditions.)

With regard to the dominant importance of moisture/water on the self-ignition process of brown coal, the moisture (implicitly) is taken into account in more evaluation indicators of this proposal. In addition to the U2 parameter, it plays role in further indicators – U4, T5 or P2. The indicator U2 evaluates the moisture content of the coal, which is dumped in a landfill, and that comes imminently into contact with air oxygen.

The influence of the moisture content of coal at its oxireactivity (expressed using the heat of oxidation q30) was within the framework of this project studied last year, when the samples of brown coal from the mines Centre and CSA were measured [4].

These measurements confirmed the fundamental influence of moisture on the resulting value of the heat of oxidation, while this impact is not obviously "monotonous". While reducing the moisture content of coal from the original values (about 28%) to the lower levels of humidity leads at the beginning to a significant increase of the heat of oxidation, further drying causes the apparent decrease in this heat (see Fig. 2).

Figure 2 illustrates that the most intense oxidation process runs at the content of moisture around the values 15%, the status of coal (**Wmax**). Such a behavior was already observed previously [5] and apparently truly captures the behavior of chemical reaction of oxygen with brown coal types in the whole range of the humidity.

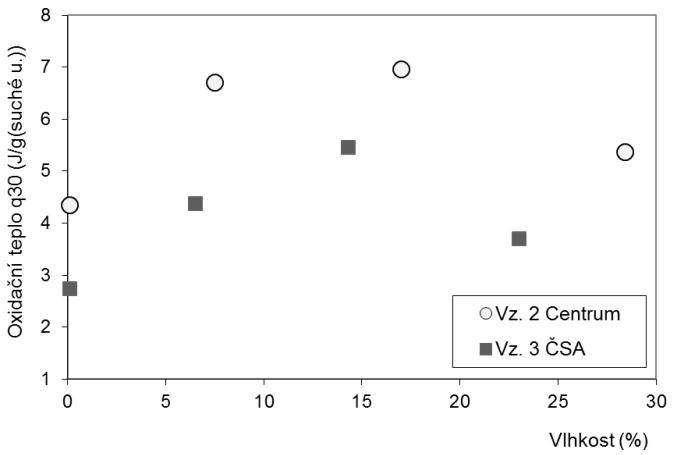

Fig. 2 Dependency of oxidation heat on the moisture content in coal

The value **Wmax**, for which the speed reaches its maximum, is known as hygroscopic [6] or critical [5] moisture content. Its value may be regarded as a constant and this found value of **Wmax** around 15% coincides with the published data.

The existence of maxima in the relationship of q30 vs. W could be explained from the perspective of the chemistry of coal oxidation by the formation of hydroperoxides: the conditions for the formation of hydroperoxides are optimal at the moisture content of Wmax. The reduction of the heat q30 below Wmax can be understood as a gradual deficit of moisture for the progress of the hydroperoxides formation. The decline in the values of the q30 over the value of Wmax again reflects the impeded access of O_2 to the reaction sites on the surface of coal as a result of the growing content of condensed water.

In the context of an addiction of the intensity of the oxidation process of brown coal on its humidity we propose for the purposes of the "Evaluation of the self-ignition process of brown coal on landfill" to distinguish three levels of humidity of (just) dumped coal.

- the moisture content is less than 12%..... 3 points,
- the moisture content is in the range of 12-18%.... 6 points,
- the moisture content is greater than 18%..... 3 points.

U3: Granularity (size distribution)

It is known that the powdered coal is subject to oxidation far more easily than the coal in pieces. In General, the coal is finer, the risk of spontaneous combustion of the landfill grows. But some authors have demonstrated that this applies only to certain critical grain size. A similar conclusion we basically found on the basis of our own investigations of brown coal from the mines of the CSA and the Centre [4], for a fraction under 1 mm in diameter we found de facto the independence of the values of the heat of oxidation q30 on an average size of coal grain.

Practically, this means that the additional grinding of brown coal with a grain size of 1 mm does not lead to the uncovering of the new surface, and thus to make accessible new reaction sites (oxygen is able to reach all reaction centers already in the tests with the grain fractions of coal of 1 mm). In that context it should be pointed out that the used experimental device did not allow to measure coal fractions with a granule size greater than (just) 1 mm.

Therefore from the standpoint of the safety of coal dumps against the spontaneous combustion, we consider as the decisive parameter the presence/quantity of the coal grit in the landfill. As the crushed brown coal (grit) we consider coal with a diameter of 3 mm and smaller grains (limit 3 mm – in comparison with the experimentally observed diameter 1 mm – is designed for the safety reasons with regard to the fact that the used experimental device enabled us to measure coal fraction with the size of grains only under 1 mm).

In the context of the above given details, we propose for the purposes of the „Evaluation of the self-ignition process of brown coal on landfill" the following scoring:

- coal dust (= coal with a diameter under 3 mm) is in the composition of coal landfill represented more than 5 percent. ... 7 points,
- coal dust (= coal with a diameter under 3 mm) is in the composition of coal landfill represented less than 5 per cent. ... 3 points.

U4: History of coal treatment before dumping

This parameter is evaluated to take into account the time that has elapsed since the extraction of coal to its dumping on the landfill. Experiments have clearly demonstrated that the effects of oxygen on fresh coal samples proved the reduction of the heat of the chemical interaction with O_2. Figure 3 clearly demonstrates such a typical trend, as it has been found for a fresh sample of brown coal from Slovakia (Handlová).

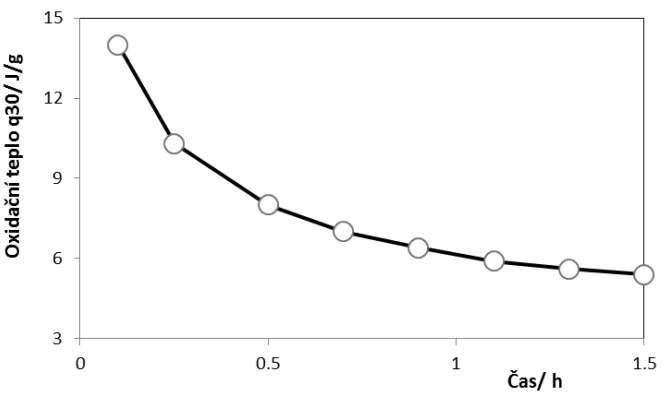

Fig. 3 Dependency of oxidation heat on the time of oxidation (brown coal Handlová)

The picture apparently indicates that the initial significant decrease in the heat of oxidation is soon damped and the heat is then changing only very slowly. It corresponds to the approaching the respective steady state in the behavior of oxygen with coal, as it was described even earlier [8]. However, even a prolonged long-term exposure of oxygen does not lead to the saturation of all the reaction sites on coal and to the termination of the oxidation process. For example, a given sample of brown coal from Handlová reached after the 30-day air oxidation the value q30 of 0.4 s/g (from the original value of 14.5 J/g) and even after three years of storage in the laboratory, this sample had not been on the zero level of the heat, it was q30 ~ 0.07 J/g.

For the purposes of the „Evaluation of the self-ignition process of brown coal on the landfills" we propose to distinguish the "age" of landfilled coal in two point levels:

- the dumped coal was extracted within the time of less than 1 week. ... 5 points,
- the dumped coal was extracted within the time more than 1 week. ... 3 points.

T: Technological parameters (storage factors)

T1: Height of the landfill (dump)

In order to assess the importance of the dump height on the self-ignition process of coal a series of computer simulations of coal oxidation in a landfill with a constant amount of blank space of 12% and a slope 40° was carried out. The height of the dump varied in the range 5-20 m [9]. The figure 4 summarizes the results, which indicate that the height of the heap actually has not a significant effect on the length of the periods of time to achieve the tipping point of spontaneous combustion to the stage of uncontrollable burning. In all cases, this time being modeled around 34 + 4 days.

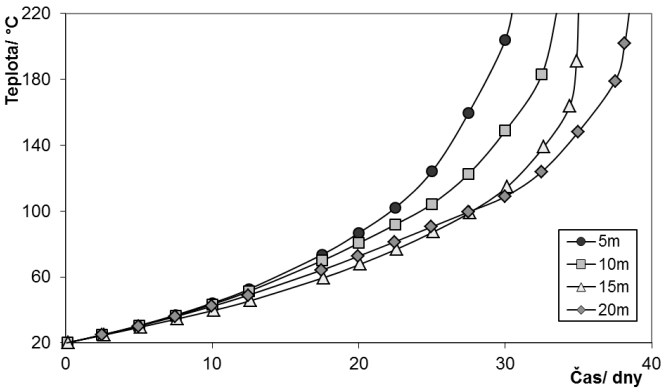

Fig. 4 Influence of the dump height on the self-ignition process dynamics

The height of the landfill (dump) in the reference interval of 5-20 m does not significantly affect the conditions of the development of self-ignition process of coal. It is necessary to mention the fact that there is a generally adopted meaning that the minimum height of the landfill must be exceeded for the formation of spontaneous combustion process. As such the height it is referred the value of 2 m [10] (in this light, therefore, computer simulations were performed for the height of the heap, which in all cases were higher than "critical" minimum height).

For the purposes of the „Evaluation of the self-ignition process of brown coal in landfills", we propose to take into account the height of the coal heap scoring just with regard to the crossing the "critical" minimum height of the heap that we consider to be 2 m.

- the height of the landfill is less than 2 m. ... 1 point,
- the height of the landfill is higher than the 2 m. ... 3 points.

T2: The degree of compacting (permeability, porosity) of landfill

Degree of compacting (= permeability, porosity) of the landfill is the parameter that absolutely fundamentally determines the conditions for the formation of the self-ignition process. The larger is the porosity, the smaller is the resistance to penetration of airs inside of the landfill and generally higher the risk of the self-ignition. The investigation of the influence of compaction of the landfill on the development of coal oxidation was carried out using a mathematical model [9] for the value of the permeability of space in the range 8-30%. Permeability 8% corresponds to the highest degree of compacting of landfills that could be achieved technically for the given granularity of coal. The results of the simulations are summarized on the Figure 5 with the time trends of the maximum temperatures for each value of permeability.

Figure 5 demonstrates that the landfill compaction slows down the dynamics of the temperature rise time. At the compaction with the permeability value of 8% the maximum temperature in the stored coal does not reach even after two months the level of critical temperature of spontaneous combustion (100°C), and just in this simulated case it was possible to avoid the transition process from pre-ignition phase into the phase of non-controlled spontaneous combustion. On the contrary, the compacting the landfill on the permeability of 20-30% proved to be inadequate as the tipping point of self-ignition process to his uncontrollable phase has been reached in approximately 2 weeks. In general terms we can conclude that the decrease in the permeability obviously suppresses processes leading to spontaneous combustion of stored coal.

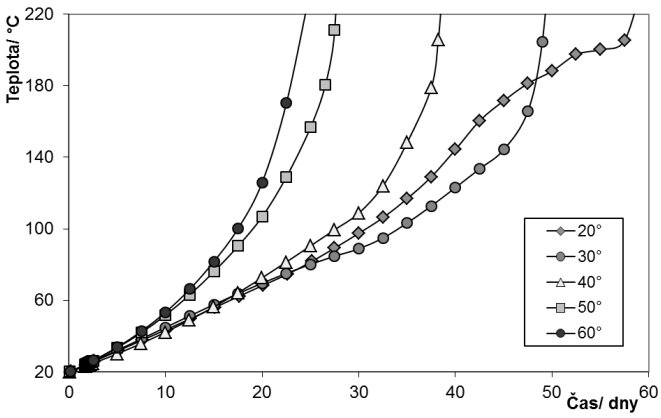

Fig. 5 Influence of the dump height on the self-ignition process dynamics

For the purposes of the „Evaluation of the self-ignition process of brown coal in landfills", we propose to take into account the degree of compaction of coal in the evaluated heap in two point levels. For a non-compacted landfill, we expect permeability more than 20%, for a compacted landfill then less than 20%. We decided using the (only) two-stage assessment level due to the fact that, in operational practice, for which the system is primarily intended for the proposed Evaluation is the quantification of the permeability of the dump (without more detailed measurements) rather complicated and so it is necessary to rely exclusively just on the qualified (approximate) estimation of the responsible worker.

- the landfill is in bulk, it is not compacted. ... 8 points,
- the landfill is compacted (e.g. by movement of wheeled mechanisms importing coal to landfill or in some other way).... 3 points.

T3: Angle of the slope tilt

The investigation of the influence of the angle of inclination of side slopes of the landfill (in the range from 20 to 60°) was carried out using a mathematical model for the single permeability of landfill of 12% and a constant height of 20 m. The results are graphically summarized in Figure 6 which clearly demonstrates that shrinking of the landfill slope obviously slows down the time of coal oxidation temperature rise. By reducing the angle of slope of the landfill from 60° to 30° the time to reach the tipping point of self-ignition to the stage of rampant burning is roughly doubled. However, the dynamics of the temperature rise for the smallest modeled angle 20° faded out of this trend – without the typical temperature curve with the steep increase, see Fig. 6.

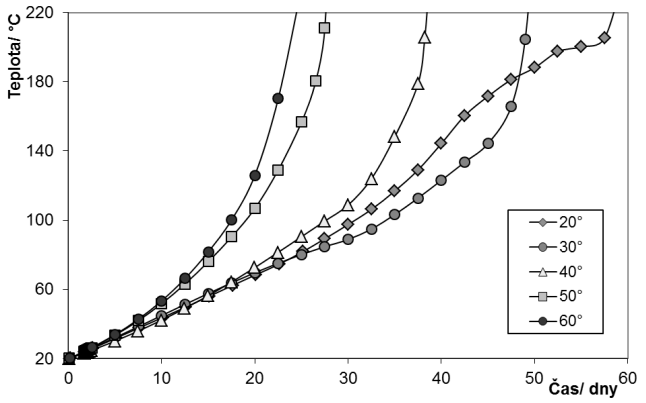

Fig. 6 The influence of the inclination of the landfill slope on the dynamics of the self-ignition process

In this context, we can confirm a certain continuity of the knowledge of AGKUNA with ESSENHIGHEM that for the formation of self-ignition process is a critical angle of 26° degree, under this value the process of spontaneous combustion of coal on the landfill no longer occurs. Other authors, however, as a "critical" degree for the formation of spontaneous combustion indicate the value of 15° and 18°.

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills“ we take into account the slope angle of the heap in two point levels, while we consider the crucial crossing of the "critical mass" of slope angle of 20°:

- slope angle of the landfill is less than 20°… 1 point,
- slope angle of the landfill is greater than 20°... 3 points.

T4: Subgrade (subsurface) of the dump

The character of the coal dump subsoil can to a certain extent influence the progress of the spontaneous combustion process. There are two fundamental aspects: (i)) thermal insulation properties of subgrade; (ii)) the integrity of the subsoil with regard to the existence of possible communication paths for the supply of air oxygen.

The effect of insulating properties of the subsoil on the development of the self-ignition process of coal is demonstrated by the dependencies shown in Figure 7, the set of computer simulations. They clearly show that the insulating nature of the subsoil contributes to the development process.

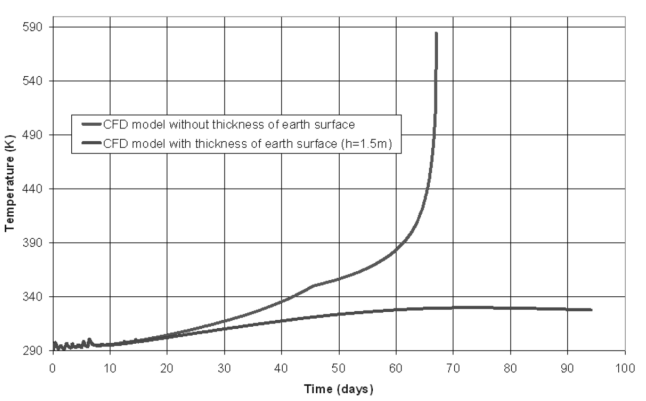

Fig. 7 The effect of the landfill isolation character on the dynamics of the self-ignition process

The importance of the integrity of the bedrock we can point out ("only") on the basis of our own (or passed) experience. The investigation of the causes of the self-ignition problems on the hard coal landfill the Lazy demonstrated that the center of the spontaneous combustion usually occurs near a tectonic rift (decline), which passes through the body of the landfill, violates the coherence of the dumped coal and so obviously constitutes a significant factor for the easier communication of dumped coal with the surrounding environment. In another case (ultimately), the effort to create flat and firm surface under the future landfill with the use of rectangular concrete segments proved to be negative. After loading the such established base by dumped coal, the individual components gradually opened a gap between them creating new important communication paths for oxygen supply. This led to the formation of self-ignition problems, which were not observed in landfills without this "concrete" base.

For the purposes of the “Evaluation of the self-ignition process of brown coal on landfills”, we propose to take into account mainly an integrated character of the landfill base, which we consider more important aspect than the insulating properties of the subsoil:

- the bedrock of the landfill is solid, no tectonic infringements and the unspoiled nature of the bedrock's retains even after a load by coal. ... 1 point,
- the bedrock of the landfill is not too hard, with possible irregularities (dips), which emphasizes after the loading by coal. ... 3 points.

T5: Technological construction of dump and processing procedure

The formation of the self-ignition process can be influenced by the way the landfill site is established and operated. The basic technological choices which could be considered for the establishment of the landfill in the SHR are i) (free) loading of coal using a mobile belt conveyor and ii) loading of coal from the wheel mechanisms (trucks). In the first case the dumped coal is compacted only by its weight, in the second case the landfill compaction is done by the travel of mechanisms over the surface of the dumped coal. The different degree of compaction of these technologically different types of landfills is the main cause for the different scores within the criteria of the MHU as the permeability of the loaded material is a major factor affecting the conditions of formation of spontaneous combustion process (see T2).

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills“, we propose to take into account the technology of landfill foundation and operating as follows:

- the landfill was based by technology using coal belt conveyors... 4 points,
- the landfill was established by loading from the wheel mechanisms. ... .. 1 point.

T6: Season of the year in which the dump was constructed

This indicator should take into account the effect of the temperature (initial) of dumped coal on the spontaneous combustion process as the temperature is generally considered to be a significant parameter influencing the oxidation reaction.

To quantify the effect of temperature on the development of the oxidation process, the heats of oxidation were measured for samples of brown coal (Centrum, Hrabák) from the temperature of 30°C to 120°C. The measurement results are graphically presented for the sample from Centrum in Figure 8.

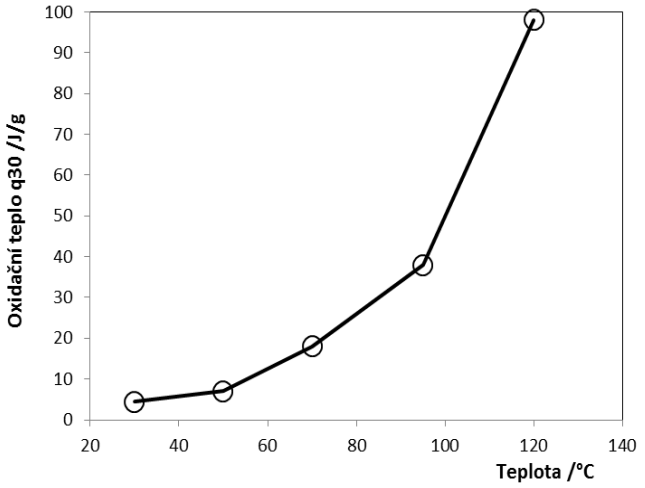

Fig. 8 Dependence of the heat of oxidation on the temperature (sample of brown coal from Centrum)

The carried out monitoring proved according to the expectations a clear increase of the heat release with the increasing temperature.

The influence of temperature on the chemical reaction is the most commonly analyzed using the familiar Equation of ARRHENIUS [3], whose importance is given by the possibility of quantifying the value of activation energy (E), simply introducing an energy barrier that must be exceeded to start the reaction (the lower value of E enable easier start of reaction). The value of activation energy (E) = 34 kJ/mol was determined for the reference coal from Centrum, which means that when we change the temperature by 15°C, the speed of the development of oxidative heat (roughly) doubles. Based on this considerations, it is clear that the landfill based in the summer with the expected temperature of dumped coal of 30°C will be subjected to more than doubled intense oxidation reaction than the coal on the site based in the winter, when the temperature of the coal can be expected around 10°C. This logic based the following scoring design:

- the landfill was founded in the summer. ... 6 points,
- the landfill was based on spring or autumn. ... 3 points.
- the landfill was founded in winter.. ... 1 point

T7: Average time of coal dumping

This pointer is trying to describe the increasing risk of spontaneous combustion process depending on the time for which coal remains on the landfill. Though the intensity of the oxidation reaction of coal decreases with time (see U2), it is simultaneously obvious that with a monotonically increasing time increases the total amount of the developed (oxidation) heat. The total amount of oxidation heat developed for time t could be described by the Elovich equation, whose shape can be used for the development of oxidation heat from calorimetric measurements in equation (1):

$$q = \beta \cdot log(t + 25) - 1{,}4 \cdot \beta \qquad (1)$$

where:

q – indicates the heat of oxidation released in a given time t,

β – is a constant.

The form of the equation (1) implies that (for the validity of the Elovich equation) experimental data in the coordinate system q vs. log (t + 25) show a linear progress.

From a practical point of view we can consider that with the increasing time of storage of coal increases the risk of spontaneous combustion process.

So-called incubation period was introduced as a criterion of exposure to oxidative process for the self-ignition of hard coal, which represents a time interval in which the spontaneous combustion process of coal gets into advanced (uncontrollable) phase (the term "low-temperature oxidation of coal" is a synonym for the incubation period of the oxidation process,). The incubation period (generally) in the interval from 3 weeks to about two months is used for hard coal. We did not meet the concept of the incubation period for the spontaneous combustion process of brown coal, but with regard to the significantly higher oxireactivity of brown coal (compared to hard coal, see U1) we can expect a clearly lower time of disposition for their secure storage. This "logic" is used for the proposal.

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills“, we propose to take into account the average time of coal deposition on the landfill site as follows:

- coal is deposited on the site for longer than 14 days. ... 3 points,
- coal is deposited in a landfill for a period shorter than 14 days. ... 1 point.

P: Parameters of environment (weather factors)

P1: Orientation of the dump related to the winds

One of the generally accepted knowledge about characteristics of the self-ignition process of coal in landfills is the fact that the center of the spontaneous combustion process originates exclusively on the landfill upwind site at a depth of about 0.5-3 m under the surface of the landfill. A vital role in the formation of the self-ignition process have winds that "face" on the walls of the landfill and that represent the major source of the oxygen needed for the development of the spontaneous combustion process. The importance of the wind velocity on the dynamic development of the spontaneous combustion process of dumped coal was clearly confirmed by computer simulations and it is illustrated on the Figure 9.

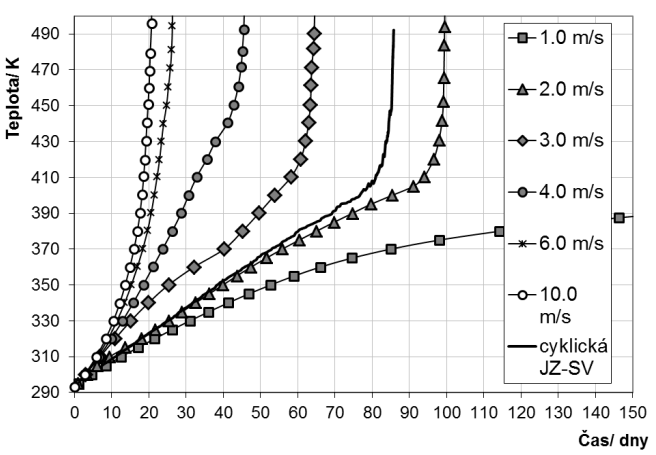

Fig. 9 The influence of wind velocity on the dynamics of self-ignition process

Figure 9 convincingly shows that with the increasing wind speed the time development of the spontaneous combustion process into its uncontrollable stage is shortened.

The influence of the winds, as extremely serious parameter, is in the design of the assessment directly contained in

the two indicators. In the framework of the (later described) indicator D1, the level of the shading of the landfill against the impact of the winds (P1) will be evaluated. The indicator P1 takes into account the orientation of the landfill to the direction of the prevailing winds. The wind is considered to be the force vector, whose power is maximally manifested at a perpendicular impact against the wall of the landfill. The most dangerous (in terms of the formation of the self-ignition) is the perpendicular orientation of the long (the longest) side wall of the landfill to the (predominant) direction of the wind flows.

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills“, we propose to take into account the orientation of the landfill of coal dump to the direction of the prevailing winds, as follows:

- the long side of the landfill is oriented vertically to the predominant wind direction (with a tolerance of + 20°) 3 points,
- the long side of the landfill is oriented in a different direction than perpendicular to the predominant wind direction (orthogonal direction = 90° + 20°) 1 point.

P2: Protection of the landfill from the rain

Water, as a fundamental component accompaing the coal mass, have already been addressed in the framework of indicators U2, which assesses the importance of the current moisture content of coal in its interaction with oxygen (see U2). The influence of water on the spontaneous combustion process of coal, however, is more complex. A considerable amount of the heat can be released simply by contact of liquid water with coal – without necessary presence of oxygen. We are talking about the wetting of coal and in a real environment of the coal dump it actually corresponds to the "rain fall" on the coal dump. The fact of the importance of the released heat we can explain using the Figure 10, where the thermal effects released by the contact of water with dried coal are plotted against its degree of carbonization (= carbon content in combustible matter).

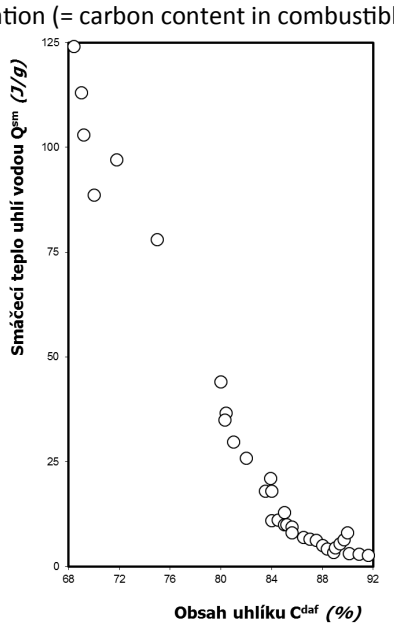

Fig. 10 The values of the heat of wetting of dry coal by water depending on the content of carbon

Figure 10 clearly demonstrates the fact that the wetting of (dry) less carbonized brown coal releases the heat of more than 100 J/g, which (assuming adiabatic) conditions may represent an increase of the system temperature about the tens of degree (°C) by "purely non-oxidative way". Obviously, this can significantly increase the temperature level of the oxidized coal and as a result, it can be (naturally) expected to speed up the spontaneous combustion process of "wetted" coal. This fully corresponds to the knowledge of the practice. The values of the heat of wetting from the Figure 11, however, have been measured for dried coal, and from this perspective, the data represents the maximal value. The value of the heat of wetting (of course) are progressively reduced with increasing moisture content of coal, see Figure 11.

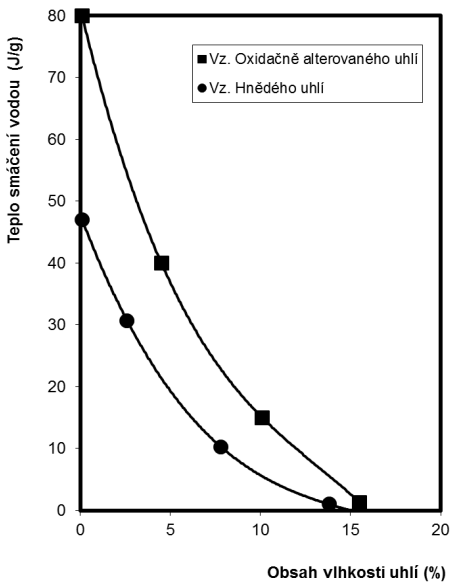

Fig. 11 Dependence of heat of wetting on the moisture content of coal

It is so obvious that the current moisture content of coal plays a crucial role for the importance of the heat of wetting of coal as one of the aspects supporting the development of spontaneous combustion process together with the possibility of direct contact of coal with rainfall.

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills“, we propose to take into account the acceleration of the process as a result of its "wetting" (= wetting by liquid water) as follows:

- the landfill is not protected against rainfall and the moisture content of the coal is less than 12%.... 6 points,
- the landfill is not protected against rainfall and the moisture content of the coal is more than 12%... 3 points,
- the landfill is protected against rainfall. ... 1 point.

P3: Shielding of the landfill from the Sun

This pointer (again) takes into account the influence of temperature on the process of the coal self-ignition, this time as a result of the additional heating of coal by direct sunlight. Temperature, as a significant parameter influencing the oxidation reaction, is scaled (already) using the earlier indicator T6. The indicator T6 shows that the temperature increase of approx. 15°C leads to a doubling of the speed of oxidation of the coal samples. The investigation on coal heaps proved that on the sunlit places the surface temperature of substrate materials can exceed the level of 60°C, which represents the "non-oxidating" heating (approximately) 30°C higher compared to the coal in shadow. This may establish a different ("more advantageous") temperature conditions for the "kick start" of the self-

ignition process in such places. Therefore from the perspective of the risk reduction of the self-ignition process is certainly preferable to establish a landfill on the shadowed site or the surface of the landfill protect by addition shading precautions.

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills“, we propose to take into account the possibility of an increase in the temperature of the spot site of coal by direct sunlight, as follows:

- the landfill is not protected from direct sunlight. ... 3 points.
- the landfill is protected from direct sunlight (at least ¾) ... 1 point.

D: Additional parameters

D1: Barrier against direct impacts of the winds on the dump

The fundamental significance of the winds on the dynamics of expression of spontaneous combustion process of landfilled coal was previously commented (see P1), the pointer P1 was previously established to account for the orientation of the landfill to the direction of the prevailing winds. The indicator D1 evaluates the situation on the landfill assessed with regard to its protection against the immediate impact of the winds. These "wind barrier" can be both a purely natural origin (trees, buildings), as well as obstacles established and additionally implemented (barriers, fences, cover of the surface of the landfill by the eddying "curtain"). To cover the windward site of coal dumps by "protective shield" and the construction of wind-resistant barriers (more generally) is recommended as a preventive measure to avoid the formation of self-ignition process. A layer of clay or plastic foil can be used as a protective shield against the blowing winds. Due to the character of this precaution as the precautionary measure, the scoring of this indicator is for the first time subtracted from the total sum (= the score is in negative points). The additional wind shielding is an option how to decrease the adverse scoring of the spontaneous combustion risk (MHU) on the given landfill.

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills", we propose to take into account the level of protection of the landfill from the immediate impact of the winds, as follows:

- the landfill is not protected from the direct impact of the winds ... ... 5 points.
- the landfill is protected by natural obstacles from the direct impacts of the winds …. 0 points.
- the landfill is protected from the impact of the winds by additional screens. ... -4 points.

D2: Monitoring of the landfill status (thermovision, gas probes)

The basic measure for the detection of self-ignition process of coal already in its early stages is to use appropriate methods to monitor the current status of the landfill. The elemental concept of the system behavior – "coal + oxygen = oxidized coal + exhaust gasses + heat of reaction" – clearly indicates that the monitoring methods may be either gas detection, in principle – the detection of the increased content of oxidative products in air, or thermal detection – with localization and monitoring of spaces with increased temperature compared to the ambient temperature.

To assess which of the monitoring techniques is more sensitive (more suitable) for indication of the beginning of the self-ignition process is not easy. For example, our own experience based on the investigation on the brown coal mine in Handlová showed that the thermovisual imaging of the surface temperatures is more sensitive to indicate the places of the spontaneous combustion process than the gas detection methods in easily accessible places of the coal landfill.

This experience is based on the situation, when using the thermovision helped to localize the beginning of the spontaneous combustion process in the ceiling of the corridor with a range of more heated faces approx. 10 m^2 of space. The affected area was characterized by a slightly increased surface temperature of 30-40°C (the temperature of the rocks in the original location at 25°C) and by exhalations of CO directly from the surface of the place ~ 50-200 ppm. The result of the analysis of the sample taken from the total ventilation stream did not warn about the emerging anomalous situation. The concentration of CO in the exhaust does not exceed the value of 25 ppm (which in the given flow of the winds indicated just the “non-spontaneous” volume growth of 7.5 l CO/min) and the concentration of ethylene and propylene, as basic indicative gases, was below the detection limit of the chromatographic analysis – less than 0.1 ppm. A "positive" outcome of the chromatographic analysis of the air sample taken on the exhaust was found just immediately after an outbreak (denudation) of the self-ignition center by direct intervention, when traces of ethylene were detected in the concentration level of approx. 0.3 ppm.

For the purposes of the „Evaluation of the self-ignition process of brown coal on landfills“, we propose to take into account whether "some" technique to monitor the landfill is deployed or not. Application of the monitoring methods is taken into account as the deduction of the evaluation points (= negative points). In the deployment of monitoring techniques on the landfill provides an additional option to reduce the value of the total scoring of the risk of spontaneous combustion process on the landfill. Specific point value depreciation reflects the type of applied monitoring technique, we consider as the most suitable the thermal monitoring and as the worst suitable a discontinual operational analysis of gases:

- the landfill is continuously or at regular intervals not exceeding two days monitored by thermovision ... -6 points.
- the landfill is continuously or at regular intervals not exceeding two days monitored by contact thermometers ... -4 points.
- the landfill is continuously monitor.ed by the carbon monoxide detector .... -4 points.
- the landfill is at regular intervals not exceeding two days sampled for gas chromatographic analysis .... -2 points.

D3: Treatment of coal by an inhibitor

One of the ways how to (additionally) affect the spontaneous combustion of coal is chemical impregnation of coal by additives, which slow down the oxidation process of coal with air oxygen (inhibitors). We studied the inhibitors suitable for use for black and brown coal quite in detail in past, when we gradually tested the inhibitive potential of 14 different compounds (additives). To express the quantitative extent of the inhibitive effect of the additive, the value of inhibition efficiency, IU (%), was introduced, whose value is determined by comparing the value of the heat of oxidation indicated for impregnated coal (q30 (inhibitor)) with the value of the heat of oxidation for the original unim-

pregnated coal (q30 (coal)). The value of the IU (%) is then calculated using the following relationship:

$$IU = (1 - q30\ (inhibitor)\ q30\ (coal) \cdot 100 \quad (2)$$

The higher value of the pointer "IU" indicates *more effective* inhibition of the spontaneous combustion process by this substance.

The fundamental results of the investigation can be summarized as follows:

- we can hardly recommend "some" inhibitor as an universally applicable for any type of coal. The suitability of the inhibitor for the type of coal must be assessed individually,
- **calcium chloride** and **urea** (applied to the coal in the form of 10% aqueous solutions) was evaluated as the most promising for chemical inhibition of oxidation of coal,
- on the contrary, some chemicals were detected not to inhibit but accelerate the oxidation process of coal (although their use for "inhibition" was described) – for example thiourea.

For the purposes of the „Evaluation of the spontaneous combustion process of brown coal on landfills", we favor the application of a chemical inhibitor on the coal substrate. The score is (again) taken into account as the deduction of the evaluated points (= negative points). As inhibitors for an operational use, we suggest calcium chloride or urea. The more preferred variant (with higher scoring) is an individual assessment of an appropriate inhibitor on the basis of laboratory tests:

- dumped coal was treated with solution of calcium chloride or urea as inhibitors of spontaneous combustion process. ... -4 points,
- dumped coal has been treated with a solution of inhibitor that has been recommended for the coal from laboratory tests .... -8 points.

CONCLUSION

Four groups of parameters (factors) are evaluated separately – see chapter No. 1, which are directly related with the danger of the formation of the spontaneous combustion process on the landfill site.

The scoring scale is set by the way to have the critical threshold of 35 points (this requirement will ensure "compatibility" with the assessment of the degree of danger of the spontaneous combustion process in underground shafts according to the criteria MF used in OKR). Pointers from the group D are rated with "negative" points (= reducing the risk), and thus represent a way to mitigate the negative point loads of the landfill.

The score is determined by the evaluation of the individual indicators for quantifying the degree of danger and the resulting emergence of spontaneous combustion – MHU – is then given as the sum of:

$$MHU = U1+U2+U3+U4+T1+T2+T3+T4+T5+T6+T7+P1+P2+P3+D1+D2+D3$$

If the risk of spontaneous combustion determined by criterion "MHU" exceeds a critical value of 35, it is necessary to design the technical measures for its reduction.

ACKNOWLEDGEMENT

This paper was written in the frame of the ALFA program – the project no. TA01020351 with financial support from the public sources of the Technological agency of the Czech Republic – TAČR.

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