



# Article The Usage of UCG Technology as Alternative to Reach Low-Carbon Energy

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**Abstract:** Countries of the European Union have stated transition to carbon-neutral economy until the year of 2050. Countries with a higher share of coal-fired power generation currently have no solution to end their combustion and use clean, emission-free energy immediately. The solution to this problem in the energy industry appears to be the increased use of natural gas, which significantly reduces CO<sub>2</sub> emissions. In this article, we investigated the possibility of using coal in situ, using UCG (underground coal gasification) technology. We focused on verified geological, hydrogeological, and tectonic information about the selected brown coal deposit in Slovakia. This information has been assessed in research projects in recent years at the Technical University. From the abovementioned information, possible adverse factors were evaluated. These factors affect the rock environment around the underground generator by UCG activity. As part of the process management, measures were proposed to eliminate the occurrence of pollution and adverse effects on the environment. In the final phase of the UCG technology, we proposed to carry out, in the boreholes and in the generator cavity, water flushing and subsequent grouting. The proposed are suitable materials for solidification and stabilization. Results of this article 's solutions are crucial in the case of usage of this so-called clean technology, not only in Slovakia but also worldwide.

**Keywords:** low-carbon energy; UCG technology; grouting; solidification soil; soil air; statistic model; soil contamination; atmospheric geochemical survey; environmental burden

# 1. Introduction

The European Union has set itself an ambitious target for the transition to a carbonneutral economy. In 2050, some countries are expected to be carbon-neutral without any problems. However, in time, Europe will have to acknowledge that each country has started from a different position, with a different background in history. Energy is a sector where investment is made for decades to come. It is assumed that there will also be countries, such as Poland, which currently obtain more than 80 percent of their energy from coal. It is unrealistic to change the structure from full coal to carbon-free energy in 30 years, in addition to the impending social consequences. Moreover, the current disparities between the energies of the EU's western and eastern countries could create tensions in certain critical situations, and also determine the future and integrity of the European Union (EU).

The direction of European energy policy is determined mainly by the German economy. The Czech Republic and Slovakia have to adapt to the fact that the time for national selfsufficient energy has ended. Related to this is the transition to carbon-free technologies, although it is not yet clear what energy will look like after 2050. If Slovakia manages to put into operation the nuclear units in Mochovce, it should not have problems with the transition to emission-free technologies in the production of electricity. The Czech Republic and Poland may be in a more difficult position, in which the share of coal in production



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). is more significant. The problem is also expected in the eastern part of Germany when switching to a carbon-neutral economy.

However, the situation in Slovakia has changed in recent years. In 2010, the Government of the Slovak Republic passed Resolution No. 47/2010, approved under the General Economic Interest, directing the volumes of production and supply of electricity and heat from domestic coal [1].

At the same time, this support also had a significant social dimension, which consisted in maintaining employment in the Horna Nitra and Zahorie region. This measure ensured the optimal level of coal mining and higher security of electricity supply as well as lower energy dependence of the Slovak Republic for the period until 2020 and prospectively until 2035. The largest consumer of coal was Slovenské elektrárne, a.s.—Novaky Power Plant (ENO) [2].

The security of energy supplies is important, of course, all in the context of international obligations, in particular, those relating to climate change and the environment, especially air protection [3].

The change occurred in 2018 with the adoption of the Government Resolution No. 580/2018, when there was a fundamental change: the end of support for the production of electricity from domestic coal in 2023. In practice, this means the premature closure of mining operations 7 years earlier than the original concept [4].

The government has already set targets where, after 2020, it will gradually replace classical extraction methods by underground coal gasification, thereby ensuring synthesis gas for electricity and heat or, more precisely, production for chemical use [5].

Measures have been set to achieve the objectives of:

- executing in situ research on underground coal gasification (2015);
- regularly assessing, in cooperation with the regulatory authority, the costs and benefits
  resulting from supporting electricity generation, optimizing costs, and increasing the
  efficiency of its production; and
- maintaining the general economic interest for the production and supply of electricity produced from domestic coal during optimization of electricity generation, as well as ensuring, through an appropriate regulatory framework, the return of investments necessary for fulfillment with the obligations under Directive 2010/75/EU on industrial emissions [5,6].

In order to achieve carbon-free energy, it is primarily necessary, traditional, and nonrenewable sources such as coal, natural gas, and oil that need to be replaced by alternative energy sources such as photovoltaic, wind, and nuclear energy [7,8].

The abovementioned situation in the developing low-carbon energy forces Slovakia and other countries to think about the use of other technologies, in an effort to ensure the required conditions. The key question to be answered in order to make a significant contribution to environmental protection is: Which types of fuels would be the best to reduce nitrogen oxides' emissions and, at the same time, avoid the growth of other gaseous pollutants?

The answer may be: Natural gas and propane-butane both serve as widely available gaseous fuels. This would not create problems regarding the size and distribution of pollutant particles and many others that need to be taken into account when testing solid fuels [9].

One of the possibilities could be underground coal gasification in situ. The article was designed in such a way to draw attention to important properties of the deposit, which are closely related to the possibility of using UCG technology in the conditions of Slovakia.

The main advantages of the technology mentioned include reduction of two major greenhouse gases, namely, methane and carbon monoxide. All the technologies for capturing of methane are appreciated these days, as methane is emission gas that has up to 20 times greater effect in the atmosphere than  $CO_2$ . In the case of UCG technology, no emission gas is consumed, but the idea of bringing UCG is interesting, as well as the possibility of  $CO_2$  storage in the incurred cavity after coal gasification [10,11].

The UCG center at the China University of Mining and Technology in Beijing is also testing UCG in abandoned coal mines. A technical center for UCG has been set up in the University of Beijing, and technical exchange of information on UCG is taking place in the UK [12].

From 1997 through 2003 the Chinchilla project was made in Chinchilla, Queensland, Australia. It was the largest UCG project to date in the western part of Australia. Project layout, design, and operation of the UCG plant were done with the help of Ergo Exergy Technologies Inc., Montreal, Canada (Ergo Exergy) [13].

UCG technology points to the need to know the geology, hydrogeology, and tectonic faults of the deposit and its surroundings. These can affect the rock environment around the underground generator.

The current idea of underground coal gasification is pointed out here, also due to the fact that, according to the currently valid calculations, there are a number of reserves that are impossible to be extracted by current technologies or they were recovered with high losses. The new way of using lignite reserves should contribute to reducing the negative impacts on the elements of the environment and increasing the usage of own resources of mineral wealth.

Mining has a real impact on the environment and on the morphology of the whole region. Manifestations of mining activity are of different characters. Depending on the thickness of the overlying rocks and their composition, there is a decline in the terrain above the excavated area. These morphological deformations have various characteristics and manifestations, from simple cracks that close after a few months to extensive ground disturbances such as soil subsidence, landslides, and rifts.

Larger landslides result in the flooding of the area with water. Local wetlands are created, where new habitats with variable representations of plants and animals are present. Local landslide areas are also formed, especially in hillside areas [14].

Undercutting of unstable slopes has been shown to reactivate slope landslides. The slopes of the Vtacnik mountain range are primarily disturbed by landslides. They are characterized by sensitivity to even minimal interventions in the stability system.

The danger of UCG and general effects are summarized in Table 1.

Main Dangers	Adverse Effects of UCG Technology
- carcinogenic waste (coal tar) - contaminating layers creating water	- dust and air pollution at the time of production
- the danger of underground explosions	- inhabited areas are not suitable for research
- gas emissions may come to the surface	- delayed redevelopment of the area
- subsidence may occur even after several years	- the threat of un-controlled expansion of groundwater contamination

Table 1. Main dangers and adverse effects of UCG technology [15].

At present, according to the mining laws, extensive remediation works are being carried out to adjust the affected areas so that they are economically usable and minimize the adverse effects on the environment.

## 2. Material and Methods

The article addresses the issue of underground coal gasification, using knowledge of geology, hydrogeology, and tectonic faults of the coal deposit. Gasification is a chemical process of converting solid or liquid fuels into gaseous fuels, which takes place in gasifiers (generators, reactors).

The principle of UCG technology is based on the existence of at least two wells (often a series of wells), namely, injection and production wells, drilled into the coal seam. After ignition of the seam, the oxidizer is blown into the injection borehole and low to medium calorific gas is gathered by the production well. In the bearings, chemical reactions similar to those in conventional gasifying generators run. The extracted gas has a diverse quality, which is dependent on the quality of coal, the type of oxidant, and coping with the process [16,17].

The UCG is a transformation of heavy, liquid fuels into gaseous fuels, which occurs in a coal bed. The gasification of coal under high temperatures causes decomposition of organic substance, and tar, gas, cinder, and ashes are produced. During the UCG, controlled burning occurs under the ground in the coal seam [18,19].

As already mentioned, at least two wells are injected into the coal layer (injection and production). Through the injection well, the layer is burned with gasification medium. By the second-production well, the produced gas gets to the surface (see Figure 1) [20,21].



Figure 1. Scheme of UCG technology [22].

The operational parameters of the gasifying agent (air or oxygen) have a significant impact on the UCG process efficiency and could also affect its economic performance [23] and gasification indexes including the syngas quality and yield, by regulating its injection method, mixing ratio, and volume to meet different needs [24,25].

During coal gasification, the action of the gasification medium at high temperatures leads to the decomposition of organic substance. The result is gaseous products, tars, and a solid residue, which is cinders or ash. After cleaning, gaseous products are used for the production of electricity or as a raw material for the production of chemical products.

The extracted gas normally contains more than 80% of methane. The gas composition, particularly the methane content, is decisive for its use. It is commonly used to produce electricity. However, with a high content of methane, over 90%, its use is the same as for natural gas and the gas is pumped into pipelines [26,27].

The underground coal gasification is based on the same principle as classic gasification with the only difference being the place of gasification in the coal seam [28].

UCG technology was verified in Slovakia within the projects, only in laboratory conditions, for several experiments. The experiments differed in the methods of coal storage, the use of different oxidants, and the methods of disposal. Experimental coal gasification in laboratory conditions, which took place during the solution of applied research projects, allowed us to gain knowledge about this process. We analyzed useful but even harmful products of this so-called "clean technology".

Currently, the biggest environmental polluters in the district of Prievidza are Power Plants Slovenské elektrárne, Novaky Power Plant, Zemianske Kostolany Plant, The Novaky Chemical Plant, and Novaky and Upper Nitra Coal Mines [4]. Based on the projects solved so far at the Technical University in Košice dealing with the use of UCG technology in Slovakia, the Mines Cigel and Upper Nitra Coal Mines Prievidza were determined to be the most technically suitable.

From the methodology point of view, we stated for our research specific parameters:

- Geology: geological-structural characteristics of the deposit;
- Hydrogeology: hydrogeological characteristics of the deposit and hydrochemical characteristics of the deposit; and
- Tectonic structure of the deposit.

We stated benefits of this technology based on the accomplished operational trials abroad.

We analyzed the possibility of influencing the rock environment by UCG activities according to specific geological, hydrogeological, and tectonic conditions. Three models of possible situations of behavior of the underground UCG generator on the surrounding environment according to specific conditions were determined.

We proposed measures to eliminate the occurrence of pollution and adverse effects on the environment.

#### 3. Results

# 3.1. Geological and Hydrogeological Conditions in the Mining Area of the Cigel Mine

There are significant coal deposits in the Upper Nitra Basin. Deposits of caustobiolith (brown coal and lignite) represent a significant raw material potential. Brown coal is situated in the locality of the Handlová deposit and lignite is situated in the Novaky deposit. Three mining areas are registered on two deposits: Cigel Mine, Handlova Mine, and Novaky Mine (see Figure 2).



**Figure 2.** Definition of the territory, studied area: wider surroundings of mining areas (DP) of brown coal deposits Novaky, Cigel, and Handlova [29].

The basic development of the coal basin was formed in the lower and middle Miocene. In this environment, a massive formation of epiclastic rocks originating from the destructive Baden strato-volcano from the southern part of the basin was deposited. The emerging, fluvial-limnic environment created favorable conditions for the formation of rich plant vegetation, from which coal seams were formed. Diagenesis of vegetation layers formed coal seams in the central part of the basin [29].

3.1.1. Geological-Structural Characteristics of the Mining Area Cigel

The Cigel mining area covers the western part of the Handlova Coal Deposit, where the Mine Cigel operates. In the northern part of the mining area is located the VII mining section. The rock mass was built by a complex of Neogen rocks. The top cover was formed by clays, clay stones, and andesite breccia of the highest part of the Sarmat. Part of the filling of the area consists of rocks of volcanic-detrital formation with an average thickness of about 20–50 m. The direct overburden of the productive formation was created by gray Kos-overburden clays. The total thickness of overburden (Kos) clays is variable, from 150 to 230 m.

The productive coal formation consists of several coal and clay layers. It has a total thickness of about 20–55 m. The uppermost coal position is defined as the upper coal seam (h<sub>1</sub>). The geological thickness of the layer is about 5–6 m. The total thickness of coal is about 4–4.5 m. The calorific value of coal is about 13.0 MJ·kg<sup>-1</sup>. The compressive strength of the coal deposit ranges from 17 to 21 MPa. The subsoil of the upper layer was formed by the so-called interlinear sandy clays consisting of fine psammitic, illitic clays of varying thickness and strength. Clays have the ability to swell in the presence of water. In the lower part of the formation there is a lower layer-seam (h<sub>2</sub>). The calorific value of coal is about 12 MJ·kg<sup>-1</sup>, the compressive strength is from 12 to 18 MPa, and the geological thickness is from 4 to 5 m. The bedrock below the lower layer consists of various tufitic clays, clay stones, and sandstones (stone formations).

Storage conditions of the coal formation in area VII sections are variable, with the lowest points in the central part of the section. In general, the whole area is slightly sloping to the SW. As a result of active subsidence movements of the entire deposit area, sedimentation anomalies occurred in local deposits, resulting in smaller deposits of caustobioliths. In area VII, the section of Cigel Mine has a registered coal thickness of approx. 30–35 m above the upper layer, overlying the coal seam, h<sub>0</sub>.

The morphology of the surface is of hilly character with a slope from east to west. The coal formation in the given locality is situated at a depth of 190 to 430 m. After the exploitation work, various modifications of tensile cracks appeared on the surface (individual cracks are up to 1.0 m wide and about 20 m long), which closed after a certain period and left a mediumly devastated surface (smaller sliding areas, disturbed original vegetation, surface defects, and others) [30].

#### 3.1.2. Tectonic Structure of the Deposit

Endogenous processes created a complex tectonic structure consisting of subsidence and reverse fault defects.

The Handlova coal deposit represents a complex, asymmetrically developed ridge with different tendencies of fractures, which are approximately in the NE-SW direction. The prevailing opinion is that the foundation of the tectonic structure of the deposit has a very close connection with the volcanic activity of the Vtacnik mountain range.

The basic network of tectonic fault forms elongated lenticular blocks of various lengths and widths from a coal deposit. The vertical displacement between the individual blocks is very variable and reaches values from decimeters to several tens of meters. The predominant type of tectonic structure is a declining tectonic fault.

The genesis of subsidence failures is evident in the fact that, in areas with volcanic processes, different tensions arise in the foundation, but also in the higher parts of the rock massif. As a result of these unequal tension states, some parts of the mountain massif are displaced (raised, fall) in some areas, which can evoke various disjunctive surfaces in the fragile coal and plastic clay layers.

By penetrating volcanic bodies into the base rocks, they can cause various vertical movements of the rock layers, thus creating a basis for tectonic rock failure. These areas of instability can very often be combined with the gravitational descent of the broken blocks and can form a combined system of breakage in the rock layers.

The inclination of the disjunctive surfaces varies according to the character of the rock layer from  $15^{\circ}$  to  $60^{\circ}$ . Some tectonic faults may be of pre-sediment origin, as they can only be identified in the base rocks without penetrating the productive layers. The second groups of tectonic structures are tectonic faults in the coal seam itself. Another group of disjunctive lines are those that disrupt the entire productive complex of strata (from the subsoil through the coal seam to the overlying clays).

Important knowledge about the genesis of tectonic defects was obtained from the area of coal seam bifurcation. Another type of tectonic fault was found in the given locality, where one tectonic line tends to disrupt the coal seam twice, but with opposite inclinations of disjunctive surfaces (so-called paired tectonic faults).

A genetically separate part of the tectonic fault is the reverse fault tectonics, which occur in areas VII and VI of Section B. It is not possible to identify the origin and development of shears and dips. The genesis of the reverse fault in the northern region of the deposit is explained by the active penetration of magma into the productive complex of strata. The tangential component of the pressure vector induced by volcanic processes caused shifts in the upper part of the coal complex of the strata. In the southern part of the deposit there is a shear structure that breaks the entire coal formation. This rearrangement system has genesis in the area of the plutonic body, which is located at the southern boundary of the coal deposit. The guide length depends on the intensity of the stress forces [30].

#### 3.1.3. Hydrogeological Characteristics of the Deposit

The mine "Bana Cigel" mining area belongs to the Nitra river basin. The most important streams flowing through the deposit are Mostenica, Ciglianka, Takov, and Mraznica, which flow into Handlovka. The productive complex of strata is located above the erosive base of the Nitra River with an elevation of about 250 m above sea level.

The area of the entire mining area and its surroundings is actually an infiltration area. Atmospheric precipitation, which seeps into the rock environment and penetrates the volcanic-detrital formation to an impermeable layer of overlying clays, which in an intact state form an impermeable barrier. In the area of the absence of overlying clays, the impermeable layer forms a coal seam. The general inclination of the impermeable subsoil of the volcanic-detritic formation directs the underground filtration flow, which does not run linearly but adapts to the relief of the overlying clays formed by erosion. In addition, it is also affected by the position of individual tectonic blocks.

Streams forming local erosive bases located above the deposit are an important factor in the saturate of the overburden.

Overall, we can determine the following causes of overburden flooding:

- (1) permanent underground flow toward the erosive base of the Nitra River,
- (2) streams that form local erosive bases and water supply volcanic-detritic formation,
- (3) water supplying the volcanic-detrital formation through a series of tectonic faults oriented approximately perpendicularly to the direction of the filtration flow.

In their natural state, overlying rocks are drained by various types of springs and surface flows. However, the established natural hydrogeological regime is significantly affected by mining activities. Drainage and pumping of water from the underground creates new artificial drainage points, which cause changes in the flow of groundwater.

The geological structure of the overburden and the height position of the seam zone in the mining areas of the mine "Bana Cigel" and Handlova conditioned, from the point of view of mining safety, the need to drain mainly rocks of the overlying horizon of volcanic-detritic formation and andesite.

The underlying water bearing in VII section has only local significance. In this area there are layers of tuffites, the irrigation of which is tied to the near infiltration area (Handlova, Morovno Prievidza). The tuffites continue toward the so-called negative zone to the subsoil of the Novaky deposit, where they are intensively drained.

In relation to the seam zone, three hydrogeological units are separated on the deposit: overlying, inter-layer, and underlying. The overlying irrigated horizon with a maximum thickness of up to 400 m is represented by Quaternary sediments, products of overlying volcanism, volcanic detritic formation, and the overlying formation of overburden. The Quaternary is not essential from the point of view of deposit hydrogeology. The products of overlying volcanism are tuffites, tuffo-breccia, and especially andesites of various types. They predominate in the southern part of the deposit, where they reach up to 350 m and here their thickness increases in the east–west direction. The groundwater of neovolcanics is bound to more intensively cracked parts of volcanic massifs, to broken fault lines, and to their contact with low-permeable positions of volcanoclastics. The filtration coefficient (k) of andesites has a wide range:  $1 \times 10^{-7} \text{ m} \cdot \text{s}^{-1}$  to  $1.58 \times 10^{-3} \text{ m} \cdot \text{s}^{-1}$ . Cracked rock with signs of hydrothermal transformation, with the occurrence of tectonic zones at the base, predetermines the intensive replenishment of the seam zone with water. Individual hydrogeological boreholes, whether surface or mining, are not, in most cases, goundwater levels related, and flow occurs in more locally permeable areas and positions. In most cases, groundwater levels are not continuous between individual hydrogeological boreholes, whether surface or mining, and the flow occurs in more locally permeable positions.

The volcanic-detrital formation is petro graphically and granulometrically very diverse. It is a rock complex characterized by great heterogeneity. It is built of gravel conglomerate sands, clays with sandstones, and tuffits, and tuffites are sporadically represented. The clays are sandy in places. In contact with water they quickly change their consistency from a solid state to a plastic one.

In gravel, conglomerate was found, k from  $3.8 \times 10^{-5}$  to  $5.7 \times 10^{-8}$  m·s<sup>-1</sup>, and it had more cracked than porous permeability. Pyroclastic-tuffitic breccia tuffaceous-conglomerate has a verified k of  $1.97 \times 10^{-7}$  m·s<sup>-1</sup> and a combined fissure-porous permeability.

In general, we can speak of a complex water-bearing strata system. The storage part of the system consists of several water-bearing collectors, in which the level is either free or tense. The thickness of the clay to the clay layer separating the seam zone from the volcanic-detritic formation is important for the safe operation of the deposit.

At the southern, eastern, and northwestern edges of the deposit, erosion occurred and there, in direct overburden of seam level, is placed a volcanic-detritic formation or, more precisely, andesite. Overlying clays and clay stones serve as passive hydrogeological protection and, from this point of view, it is important that they are intact and non-disintegrating in contact with water or, more precisely, they stay waterproof.

The inter-seam, water-bearing assise is developed locally. At the bifurcated seam its thickness is max. 32 m. Inter-seam sediments are represented by silica sands, sandy clays, clays, and tuffites with  $k_f$  from  $6.5 \times 10^{-8}$  to  $9.82 \times 10^{-6}$  m·s<sup>-1</sup> [30].

# 3.1.4. Hydrochemical Characteristics of the Deposit

The chemical composition of groundwater is influenced by the time of water circulation in the rock, geochemical reactions during the mutual mixing of different types of water, and changes in rock environments, temperature, and pressure conditions during water flow. The chemical composition of water is, therefore, variable over time, not only by the action of primary genetic factors but also secondarily by human activities.

Based on physicochemical analyzes, we can define two basic types of water:

- the basic calcium bicarbonate type with a transition to the calcium sulphate and magnesium sulphate types, which is characteristic of Quaternary rocks, overlyingoverburden volcanism, volcanic-detrital formation, and aged water;
- (2) the basic sodium bicarbonate type, which is characteristic of the waters of inter-seam sands and the underlying assise but with higher mineralization [30].

## 3.2. Advantages of UCG Technology

Most countries with large coal reserves have almost 85% of known coal reserves, which cannot be extracted using known mining methods. UCG technology can be the solution to take full advantage of this valuable resource. Many experts argue that this could double the availability of coal worldwide, which is currently expanding the number of UCG projects.

The UCG principle is based on the existence of a minimum of two wells (more often a series of wells), specifically injection and production wells, drilled into the coal seam. After igniting the seam, an oxidizer is injected into the bearing through an injection well and low to medium calorific gas is obtained by production. Chemical reactions in the deposit

take place similarly to conventional gasification generators. The obtained gas has different quality and depends on the quality of coal, type of oxidizer, process control, etc. [28].

UCG technology has a less negative impact on the environment because all the coal remains underground and there are fewer emissions and fewer surface footprints because no surface gasification is needed and the gas is processed to remove harmful particles, including  $CO_2$  capture. This process is safe and economical, which also meets the requirement of secure gas supply for domestic and industrial use. Hence, the potential environmental concerns related to UCG need to be addressed and understood to allow for its commercialization [31].

According to operational experiments abroad, the benefits of this technology are summarized in the following points:

- low operating costs of the entire technological process,
- minimal surface changes above or around the deposit during and after mining,
- minimal danger to operating personnel,
- no ash from surface combustion, as in surface gasification,
- significantly lower CO<sub>2</sub> emissions, and
- no surface or underground contamination related to technological processes that have yet been recorded and only minimal reclamation is required after mining [28].

#### 4. Discussion

# 4.1. Possibility of Influencing the Rock Environment by the Activities of UCG "Underground Coal Gasification"

The possible influence of the rock environment in the vicinity of the underground generator results from the following assumptions:

(1) Contaminants remain in a movable form in and around the generator.

The process of gasification, heating while there is absence of air, proceeds as follows. At temperatures around 100 °C, part of the water is released as well as absorbed gases. Up to 300 °C, a substantial part of the water and a certain amount of gases, mainly carbon dioxide, are released from the brown coal, which releases, in particular, oxygen, a very small amount of nitrogen, and carbon monoxide. By further heating in the range of 300–350 °C, the splitting of bound water and oxygen continues and flammable gases (methane) begin to appear. Only ballast, non-flammable substances are released to this temperature.

Above 350 °C, the decomposition of the carbonaceous component occurs and flammable gases, hydrocarbon vapors, and tars, which occur here in the gas phase, begin to be released. The highest production of vapors of hydrocarbons and tars, which, after cooling, give a liquid fraction, can be obtained at a temperature of about 600 °C. At high temperatures (1000 °C) most of the product is released in the form of gas and their amount decreases rapidly after exceeding a temperature of 800 °C. In terms of solids, a porous residue is formed in connection with the release of gas and vapor, which, if the heating temperatures did not exceed about 600 °C, is referred to as low-temperature coke (semi-coke), when heated to temperatures higher (up to 1000 °C and more) than coke. Higher temperatures cause coal to decompose, resulting in a gaseous fraction and a solid residue [25].

By cooling these gases and vapors, a condensate is formed, which consists of a hydrocarbon and an aqueous fraction. Their chemical character is identical to the fractions of combustibles, which we mentioned as part of the composition of coal. Thus, in hydrocarbon fractions it is the same as in oil: gasoline, diesel, paraffins, light and heavy oils, and asphalt materials. Furthermore, there are aqueous fractions, soluble compounds that are formed by the thermal decomposition of coal. It is mainly ammonia, a certain amount of sulfur substances, and a wide range of organic compounds such as phenols, ketones, and other polar substances. Pure ammonia and nitrogen fertilizers can be obtained by treating ammonia waters. [32] In the period from 2007 to 2010, experiments with coal gasification were carried out at the Technical University in Kosice as part of a grant project. Figure 3 shows the temperatures that occurred during the experimental coal gasification.



**Figure 3.** Development of temperatures after the cross section of the generator in time and in laboratory conditions, 1–181 time in hours. The perpendicular axis shows the length of the generator, 0.3 m to 2.6 m [33].

The Environmental Protection Agency (U.S. EPA) has determined the 16 PAHs that were located in the tar. Hydrocarbons are the following: acenaphthene, phenanthrene, anthracene, fluoranthene, pyrene, benzo (a) anthracene, chrysene, benzo (b, k) fluoranthene, benzo (a) pyrene, dibenzo (a, h) anthracene, benzo (g, h, i) perylene, and indeno (1,2,3-c, d) pyrene. Samples contained other pollutants and volatile compounds: TOC and BTEX [34,35].

During the experiments of brown coal gasification in the mentioned two generators in laboratory, tar samples were taken and analyzed in an accredited laboratory [36]. Table 2 shows a chemical analysis of the individual components of tar from about 650 kg of brown coal, and they were compared with the threshold values for synthetically produced pollutants. According to [33], in mine "Bana Cigel", the amount of reserves for underground gasification is about 200,000 t.

Experiment	1	2	Limit Values for Syntheticaly Produced
Indicator	Value [µg/L]	Value [µg/L]	Polluting Waters [µg/L]
NPEC IR	1,324,000	144,900	
TOC	2,824,000	22,656	
Benzén (BTEX)	3.80	393.90	0.75
o-xylén (BTEX)	3.00	41.00	212 5
m,p-xylén (BTEX)	4.75	76.20	512.5
Toluen (BTEX)	3.20	199.90	437.5
Acenaftén (PAH)	3.08	1022.19	
Acenaftylén (PAH)	2.36	3766.27	
Antracén (PAH)	2.61	880.49	
Benzo(b)flourantén (PAH)	0.00	29.67	
Benzo(a)antracén (PAH)	0.34	358.28	
Benzo(k)flourantén (PAH)	0.00	15.64	
Benzo(g.h.i)perylén (PAH)	0.00	11.58	
Benzo(a)pyrén (PAH)	0.00	44.35	0.00625
Dibenzo(a,h)antracén (PAH)	0.00	5.48	
Fenatrén (PAH)	16.72	2299.92	
Flourantén (PAH)	3.20	1036.90	
Flourén (PAH)	4.92	1162.52	
Chryzén (PAH)	0.38	363.43	
Indeno(1,2,3-c,d)pyrén (PAH)	0.00	20.83	
Naftalén (PAH)	1.77	2894.26	
Pyrén (PAH)	2.26	660.04	
$\Sigma$ PAH	41.102	14,784	0.0625
Amount of tar [liter]	21.8	10	

Table 2. Values of pollutants in tar samples (NPEC IR, TOC, BTEX, PAH) [28,37] and authors.

In conversion, with a tar production of 31.8 L/650 kg, it represents a total tar production of 9800 L. Such an amount of tar poses a threat of contamination to the rock environment. The use of tar as a gasification product is expected in the chemical industry and, therefore, it is necessary that most of its components are removed from the generator, preferably in gaseous form. By controlling the gasification process, it is necessary to ensure that the condensation of the gaseous components of the tar does not take place in the generator. If this requirement is met, the risk of contamination of the rock environment will also be reduced [38].

High levels of tar cause carcinogens that are dangerous to living organisms.

(2) Contaminants in the generator and in its surroundings get into motion and water enters the generator.

Based on the characteristics of the rock environment given in the previous part 3 it can be stated that in the overburden of productive layers (coal seams) is placed the detrital-volcanic formation, which is water bearing. The productive layer is separated from the detrital formation by a layer of clays with good isolation properties (the filtration coefficient has low values).

Overburden clays and clay stones serve as passive hydrogeological protection and, from this point of view, it is important that they are intact and non-disintegrating in contact with water. The thickness of the clay layer separating the seam zone from the volcanicdetrital formation is important for the safe implementation of the gasification process. Equally important is the tectonic dysfunction that extends into the clay formation because there is a risk of water penetrating the generator and moving the contaminants.

(3) There are communication paths for moving contaminants out of the generator.

As in the previous point, based on the characteristics of the rock environment, it can be stated that the isolating layer of clays forms an impermeable barrier to the exit of contaminants from the generator. However, due to the existence of tectonic lines, the escape of contaminants cannot be completely ruled out.

After analyzing the assumptions of the impact on the rock environment, it is possible to draw the following partial conclusions to minimize the adverse effects on the environment:

- Before carrying out the gasification process, the site in question must be assessed geologically and hydrogeologically. The risks of rock and environmental contamination have to be assessed.
- (2) To minimize contamination of the rock environment, it is necessary to focus on reducing the amount of contaminants left in the generator.
- (3) After the end of the activity in the generator, reduce the content of residual pollutants.
- (4) Carry out the injection of the generator premises in such a way that the source of pollutants is modified (physico-chemical), in such a way to limit the mobility of contaminants and their ability to pass into the transport medium.

#### 4.2. Proposal of Measures to Eliminate Pollution

#### 4.2.1. Rinsing with Water

In the third and final phase of gasification (Figure 4), the boreholes are liquidated. In case of possible contamination, it is recommended to rinse the cavity with water before disposing of the underground generator and boreholes, in order to minimize possible contamination of the environment and water around the resulting cavity. Potentially contaminated water can be treated in a surface sewage disposal plant. At the end of the process, long-term monitoring of the created cavity and its surroundings is necessary [28].





4.2.2. Grouting with Subsequent Solidification and Stabilization of Materials in the Generator

One of the possibilities of filling boreholes and cavities after gasification is the principle of secondary use of waste for solidification and stabilization. The basic precondition for implementation is to design such an injection mixture that meets the requirements for:

- suspension stability, good penetration into the environment, and good pumping.
- leachability of harmful substances

The penetration ability can be assessed using Darcy's law and the filtration coefficient *k*.

$$k = \frac{Q.L}{S.\Delta h} \left[ \text{m.s}^{-1} \right] \tag{1}$$

where:

*Q* is flow of penetrating suspension  $[m^3.s^{-1}]$ ,

*L* is distance between places A and B,

*S* is the area over which the flowing suspension flows  $[m^2]$ , and

 $\Delta h$  is the pressure difference at the point of inflow and outflow of the suspension [m] [39].

leachability of harmful substances.

The basic criterion in assessing the impact of mining and construction materials on the environment is the assessment of the leachability of harmful substances from the filling mixture into mining waters. In the natural environment, leachability is a function of the physical and chemical properties of the base mixture and the hydrogeological and geochemical characteristics of the place where it was used for the mining-building material. The basic factors influencing leachability include:

The basic factors influencing leachability include.

- surface area of the base mixture (granulometric compound of waste) and its permeability,
- the chemical composition of the solution in which the leaching takes place,
- pH of the leaching solution,
- leaching time,
- leaching temperature, and
- liquid to solid phase ratio.

Due to the usability of the solidificate, cementation methods, which have been used abroad for many years for the disposal and utilization of waste containing mainly heavy metals, are the most suitable for mining conditions. These methods are based on the fixation and immobilization of pollutants in the silicate matrix. It is a physico-chemical treatment of waste by homogenization with suitable components so that no pollutants are released into the natural environment [40].

As with every product, also base mixtures have to meet the criteria for chemical and physical properties that determine the utility value of the product. These criteria can be divided into basic groups:

- assessment in terms of specific use,
- evaluation from the point of view of transport and injection technology, and
- assessment of the impact of mining material on the environment.

Whether the base mix-mining building materials meet the abovementioned criteria has to be verified by tests under such conditions as they are used at the place after solidification. The leachability test has to be carried out in the state in which it arises after use and after stabilization and solidification (not a ground sample), as in the case of a construction product.

In order to prepare base mixes meeting the above criteria, we need to know the chemical and physical properties of the waste, as these determine the final formulation of the mix, which must guarantee that chemical substances are stabilized in the production and subsequent solidification process [39]. It is the method that, by its nature, meets the requirements of environmental protection and labor safety [41,42].

# 5. Conclusions

The district of Prievidza is one of the most industrially developed and urbanized regions of Slovakia, with a predominance of fuel, energy, mining, and chemical industries. This concentration of industry was reflected in the state of the environment, the quality of which ranked the district among the districts with the most polluted environment in Slovakia. As a result, part of the district was included in one of the eight congested areas of Slovakia–Ponitrianska congested area [33].

In the case of using the so-called clean technology, underground coal gasification, the article draws attention to the possible impact of pollution, taking into account the geological, hydrogeological, and tectonic conditions in the selected locality of mine "Bana Cigel". Attention was focused on pollution from underground coal gasification in situ, taking into account the amounts of gasified coal based on sampling after simulated gasification and chemical analyses of tar. The question remains how these tars will affect the groundwater and surface water in this area, which has long been burdened by the mining and chemical industries.

Based on the analysis of the produced gas (syngas), a mixture of tar and water, the article pointed out the energy properties of the products as well as hazardous substances that may endanger the environment. The laboratory gasification of coal, which took place on the surface, within the solved projects, in the proposed generators, made it possible to monitor individual useful but also harmful products of this so-called clean technology.

The proposed measures to mitigate adverse effects after in situ gasification aim to minimize these adverse effects. It was pointed out here to select suitable materials for the implementation of filling/grouting of spaces that will remain empty after gasification and around the wells.

The presented results and the difference between our experimental data and data acquired in some other studies indicate the need for further research.

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# Abbreviations

$CO_2$	carbon dioxide
BTEX	benzene, toluene, ethylbenzene, xylene
UCG	underground coal gasification
ГОС	total organic carbon
PAH	polycyclic aromatic hydrocarbons
NPEC IR	non-polar etxtractable compounds spectrophotometric method in the infrared
	region of the spectrum

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