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VALORIZATION OF NON-BALANCED COAL RESERVES IN SERBIA FOR UNDERGROUND COAL GASIFICATION

by

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In the name of a better and safer energy future, it is our responsibility to focus our knowledge and activities to save on imported liquid and gas fossil fuels, as well as coal on which energy security of Serbia is based. The rationalization in the use of available energy resources certainly positively affects economy and the environment of a country. This paper indicates motivations for the application of the underground coal gasification process, as well as surface gasification for Serbia. The goal is to burn less coal, while simultaneously utilizing more gas from the onsite underground coal gasification, or by gasification in various types of gas generators mounted on the surface. In both cases, from the obtained gas, CO_2, NO_x, and other harmful gases are extracted in scrubbers. This means that further gas combustion byproducts do not pollute the atmosphere in comparison with traditional coal combustion. In addition, complete underground coal gasification power requirements could be offset by the onsite solar photovoltaic power plant, which furthermore enhances environmental concerns of the overall coal utilization.

Key words: *coal, gasification, environmental protection, storage, solar*

Introduction

Underground coal gasification (UCG) is an onsite gasification process that converts coal into a useful gas, usually carried out in non-mined coal layers using injection of oxidants and steam. The product gas is transferred to surface through wells drilled from the surface, fig. 1.

World experiences in UCG indicate that the primary form of coal energy should be treated much more rationally. The effects of the UCG application have resulted in significant enhancement in terms of energy, economics and environmental issues.

When it comes to energy efficiency, it is appropriate to reference that with traditional mining (*e. g.* in underground coal mining), coal utilization is no more than 20-25%, while in UCG it is about 72-96%, taking into account the useful volume of coal. In addition, it should be kept in mind that the UCG method mainly utilizes non-balanced deposits and excavated residues of balanced reserves.

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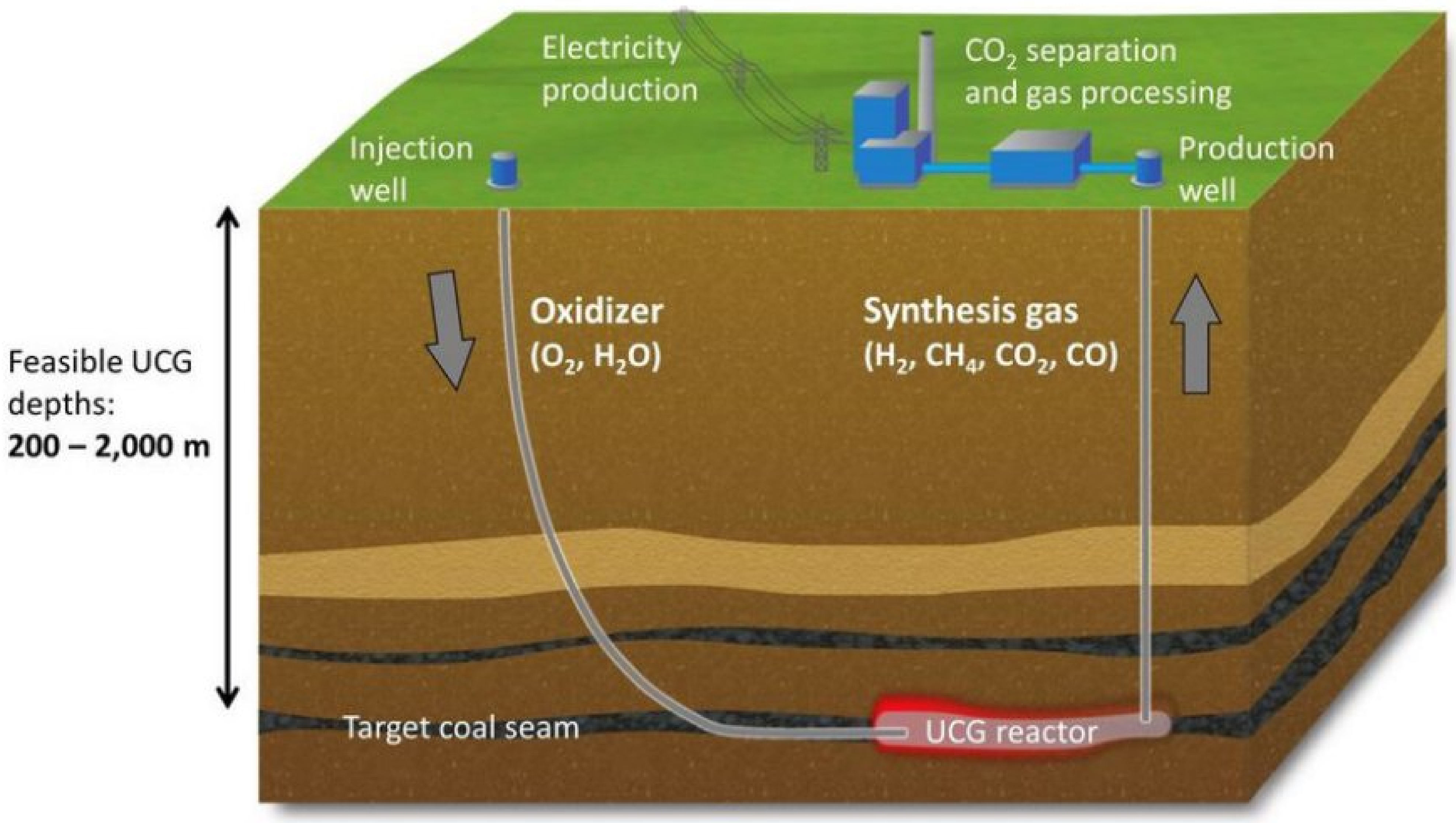

Figure 1. Underground coal gasification [1]

The UCG implies a controlled, quiet and incomplete onsite combustion, without any personnel involved, and equipment placed underground. Also, there is no need for investments in expensive process equipment, as well as conveyer or tube transportation systems for slag and ash to landfills. Considering these benefits indicates how significant economic effects of the UCG application are.

In parallel, environmental benefits are also exceptional. Utilization of UCG method does not generate any slag and ash, there is no degradation of the terrain comparing to the underground exploitation of coal, and also no special needs for terrain recultivation. During gas combustion in burners there are no solid particles emitted into the atmosphere through exhaust mufflers.

During the gasification of solid fuel at normal pressure, obtained is a gas or gas mixture that consists of CO, CO_2, and H_2, and at elevated pressures and temperatures (in particular with the current UCG systems), CH_4 is also present. Generated gas mixture is similar to natural gas.

If a vapor-oxygen mixture is used as a gasification agent instead of air, the optimal ratio should be about 7-8 kg of steam per m_n^3 of O_2. If only oxygen is used, the calorific value of the gas from such UCG process would be 2-2.5 times higher than that of air gasification [2].

Analyzing UCG process as a way of obtaining a suitable and useful energy source, some of the advantages are:
- the absence of heavy mining in underground, as well as in surface mining conditions,
- minimum costs of transporting gas to consumers,
- significantly lower cost of the final product (normalized to 1 MJ of energy),
- there is no significant degradation of the terrain, since all the non-combustible substances (slag or ash) remain in the deposits beneath the surface of the earth,
- there is no substantial pollution of the environment and the working environment, as there are no solid residues in the combustion of gas from UCG process in the boiler furnace,
- there is no need for storing about 50% of the total mass is waste material (slag and ash remain underground),
- there is no need to secure significant areas necessary for the collocation and disposal of slag and ash,

– there is no combustible dust that additionally pollute the atmosphere by the products of self-ignition on the landfills, and
– there is no need for recultivation of the terrain, since after the completion of the gasification, the terrain again resumes the same purposes from before gasification, and considerable areas are used during the UCG in continuity with agro-cultural activities.

Some features of the UCG

The commercial sustainability of the UCG process will primarily depend on geological constraints. The UCG with the obligation to separate CO_2 from the gas mixture of UCG, and its possible storage carbon capture and storage, depends on the technological development of the separation and storage of CO_2 [3].

Syngas can be used to produce a number of usable products, such as electricity, liquid fuels and chemical raw materials. The competitiveness of these products is changing with the cost of technology, or the level of development of this technology.

Today's economic, energy and environmental effects have highlighted outstanding interests for the future of clean and renewable energy resources. While the world is looking at alternative energy resources to meet many of the imposed challenges, fossil fuels (primarily natural gas and gases related to it) will likely remain an important part of global energy consumption for a long time.

Underground gasification also has some possible risks, such as potential pollution of groundwater (as well as reduction of groundwater), and the dangers of possible shuffling of the terrain surface. Such risks can be mitigated by the quality selection of the site for gasification.

Regarding climate change and other environmental concerns, significant investments in *clean coal* technologies are evident in the world, with the aim of making rational use of this significant and relatively inexpensive energy source, while at the same time reducing its negative impact on the environment.

Coal in the global thermal energy balance participates close to 80%. Fossil fuels (solid, liquid and gaseous) are involved with 96%, while 4% are currently generated by renewable energy sources [4].

In essence, the UCG process releases energy from coal layers located deeper underground, which are not economical for mining exploitation. Therefore, the use of these resources with a properly defined technology has a central place in the overall feasibility of this technology.

Particular attention should be devoted to the special drilling techniques to facilitate the gasification process. After the boreholes are formed (two vertical wells: one injection and one production), the gasification initiator (oxidant and possibly steam) from the compressor station at high temperature would be pumped to catalyze gasification reactions and transport the resulting gas mixture through production well. The final quality of gas – syngas depends on many influential parameters related to drilling options, geological characteristics and coal quality.

Technological process of UCG

The technological process of UCG involves the preparation of a coal gasification layer and consists of drilling vertical wells or boreholes that follow the coal layer. Pipes are placed into wells up to the top of the coal layer, and the contact of the pipe with the surrounding area is cemented, while borehole is not placed in the tube that is passing through the coal bed.

The connection between drilled boreholes can be accomplished in following ways:
- by connecting them to the compressed air line (p = 50 bar), or even nitrogen,
- by water pressure with a pump set, and
- by establishing a link with hydraulic fracturing, by means of high-pressure injection of the fluid (such as water, gel or foam), containing send or other proppants suspended with various agents. Hydraulic fracturing creates cracks in the deep rock formations through which gases flow.

The coal layer is usually ignited by inserting a hot coke through the borehole and blowing the low pressure air. Instead of firing coal layer with the coke at high temperatures, a burned textile soaked with petroleum could be used by throwing it into the injection borehole under the pressure of the gasification agent such as air or oxygen.

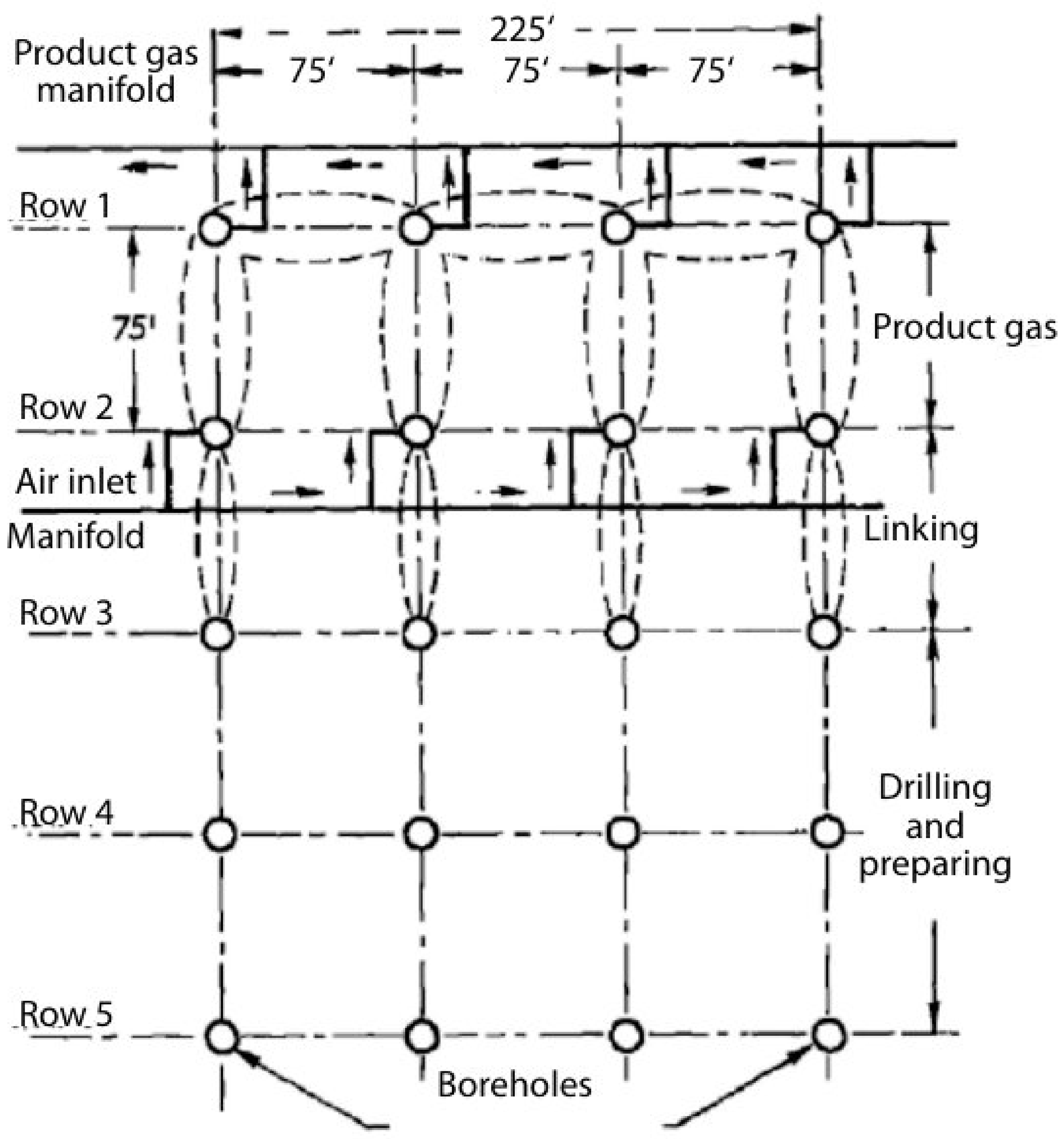

Figure 2. Plan view of the grid between boreholes [5]

To start the UCG process, the bottom of the borehole is adjusted to about 0.5 m from the bottom of the coal layer. To form a channel between the boreholes, a directed drilling is performed by creating nearly horizontal borehole drilled through the coal layer, which connects the vertical boreholes.

The first step in drilling involves the drilling of injection and production boreholes. In order to achieve the most efficient use of coal resources, the borehole grid is drilled through the ground in the selected exploitation field, fig. 2.

Connections between injection and production boreholes require additional activities to ensure the predicted path of the generated gas through the reaction zone to the production borehole [5]. Coal of lower porosity and increased density requires special attention to ensure the smooth and easy flow of the syngas.

The continuous retraction injection point (CRIP) developed by Lawrence Livermore National Laboratory in the 1980's, significantly helps to establish that channel or reaction zone, fig. 3.

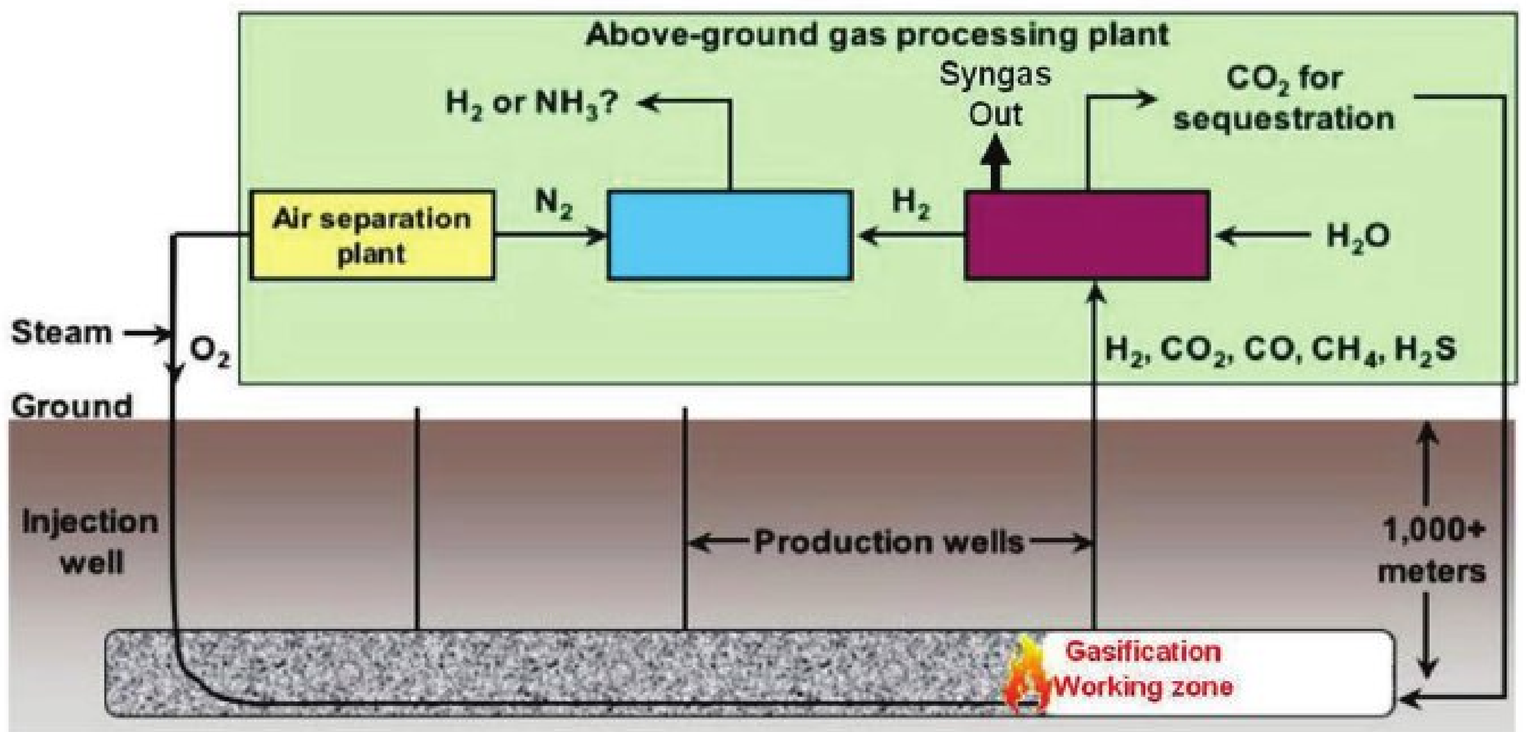

Figure 3. The CRIP process [6]

The injection boreholes are drilled vertically through a semicircular rounded layer prior to entering the part of the coal layer and continues horizontally to the production wells which are necessarily vertical [6]. When horizontal connections are established, the ignition starts at the end of the injection. At the end of the treatment of this reaction zone, the reaction cavity-zone is automatically formed in the same way, on the next third, fourth, *etc.*, fig. 4, [7].

In order for the gasification process to be performed more efficiently by the CRIP method, the mentioned half round layer in the injection borehole help to avoid possible problematic geological structures of the coal bed, as well as coal roof and coal floor.

Coal gasification chemistry includes seven primary reactions occurring within the layer. The primary reaction that happens is the displacement reaction of the generated water vapor (H_2O) and gas, where water vapor and carbon from the coal generate H_2, and CO. In order to improve the quality of the gas obtained, the concentrations of H_2, CO and CH_4 are of prime importance, since CO_2 is an inert gas without calorific value, tab. 1, [7].

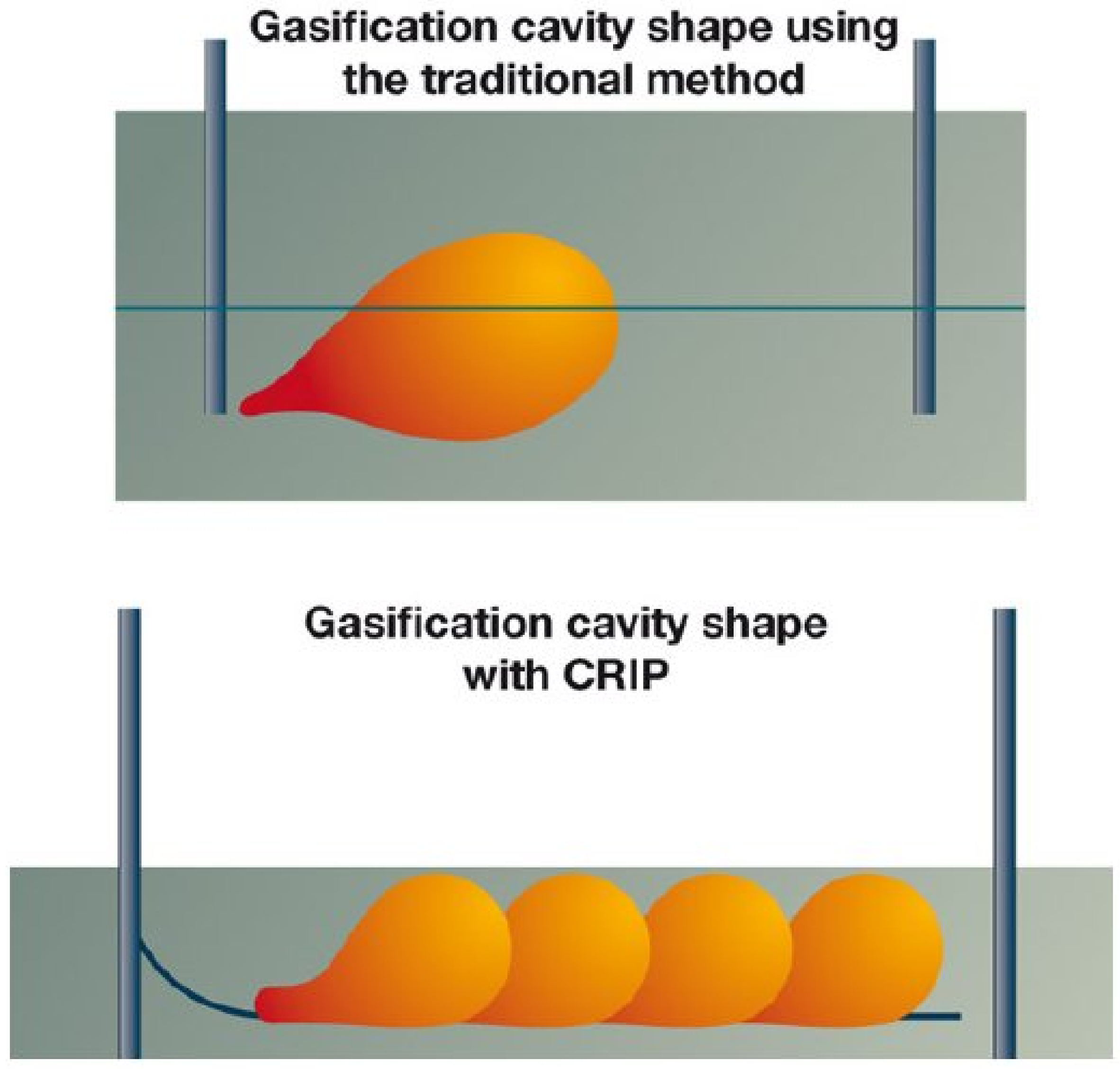

Figure 4. Schematic of CRIP process compared to traditional methods [8]

Table 1. Gasification reactions [6]

Reaction	Enthalpy [kJmol^{-1}]
(1) Heterogeneous water – gas shift reaction $C + H_2O = H_2 + CO$	$\Delta H = +118.5$
(2) Shift conversion $CO + H_2O = H_2 + CO_2$	$\Delta H = -42.3$
(3) Methanation $CO + 3H_2 = CH_4 + H_2O$	$\Delta H = -206.0$
(4) Hydrogenating gasification $C + 2H_2 = CH_4$ (5) Partial oxidation $C + 1/2O_2$ - CO	$\Delta H = -87.5$ $\Delta H = -123.1$
(6) Oxidation $C + O_2 = CO_2$ (7) Baudouard reaction $C + CO_2$ - 2CO	$\Delta H = -406.0$ $\Delta H = +159.9$

The concentrations of various gases relative to the total amount of gas mixture dictate the constitution of the characteristic zones in the total reaction zone, fig. 5, [7].

The gas stream coming out of the production borehole contains the components mentioned, but also a certain amount of impurities. They are necessarily removed, as they could cause potential environmental hazards (soil and atmosphere), if they would be uncontrolled wandering. All of this is now successfully regulated by the application of appropriate gas separation technique, or with a system of various scrubbers within the complex of UCG.

For the opening of the coal layers, vertical, inclined and curved (directed) boreholes and channels in the coal layers are used. Channels are used to accommodate the functioning of reaction zones in the layer, to blowing the gasification agent into it, as well as to obtain gas.

In order to successfully perform the UCG test, it is necessary to ensure the fracturing of the coal layer that will be gasified. This can be done by the air compressor with the certain characteristics:

– working pressure 50 bar and
– capacity up to 50000 m_n^3 of gas/h,

or a fracturing plant that could be leased if its procurement would represent a significant burden on the projected investment [9].

The following parameters of air must be provided for the coal layer gasification process itself:

– working pressure 2-3 bar and
– capacity up to 4000 m_n^3 of gas/h.

And for the gas parameters are:

– quantity of produced gas up to 100000 m_n^3 of gas/h,
– gas pressure 0.2 bar, and
– gas temperature 200-400 °C.

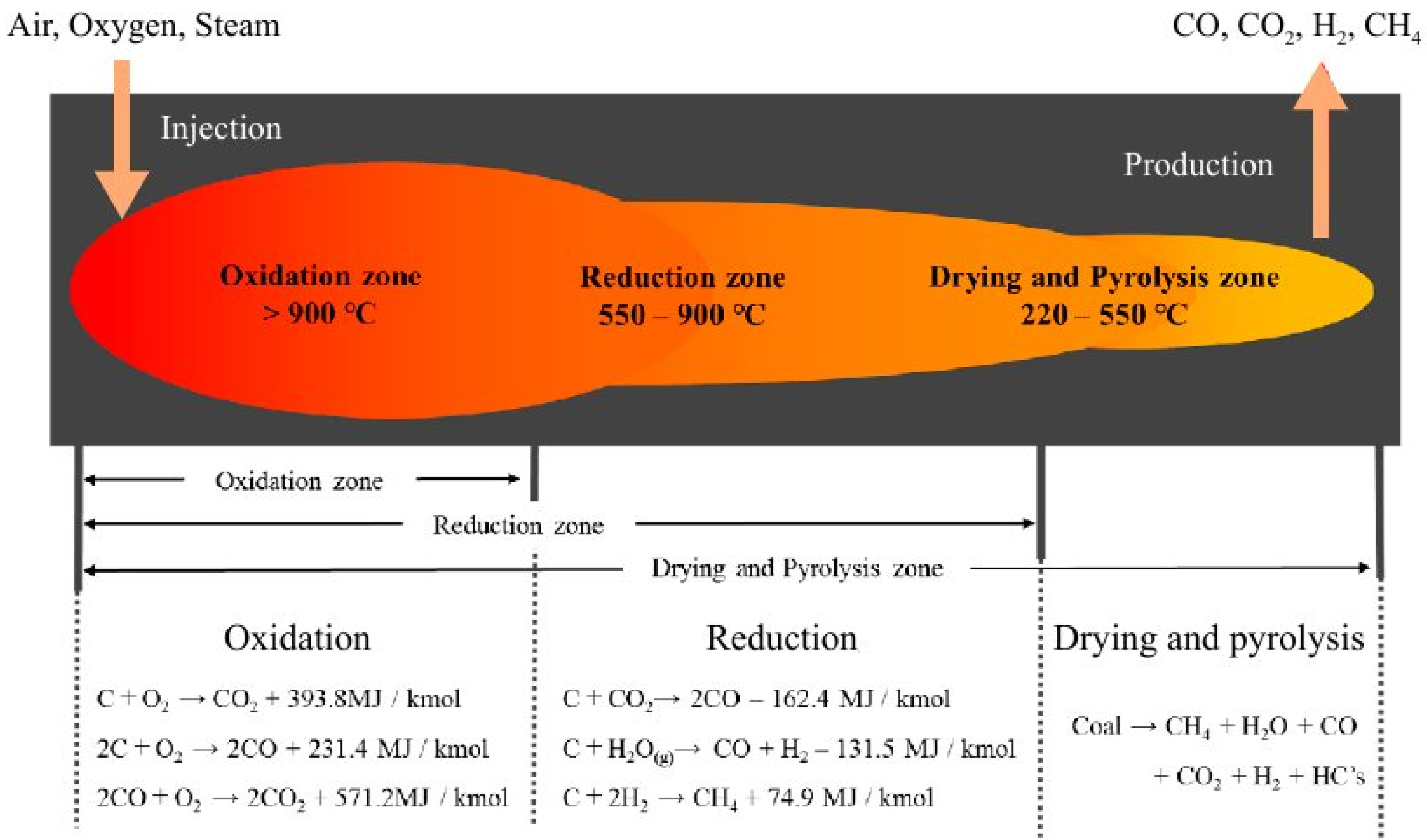

Figure 5. Schematic representation of an UCG reaction zone [7]

The flame zone (reaction zone) is formed around the coal-burning point where it extends simultaneously in several possible directions (direct, reversed and radial).

The velocity of the firehead spreading in the reaction zone is positively affected by the separation of the gases from the cracks of the coal layer, which are in contact with heated air in the channel additionally burn and accelerate the development of the firehead in the layer.

The process of initiating the combustion of a gas generator basically comes down to the following:

– usually a coke and a cartridge for ignition is introduced into the channel, which is intended for initiating the combustion (bottom of the injection borehole for introducing the gasifying agent),
– water is removed from the place where the combustion is initiated occurs by blowing the air, and
– during the air supply, the coke cartridge is activated, and the coke burns the surrounding coal and forms the reaction zone.

Exothermic reactions (at t > 600 °C) are predominantly occurring in UCG process, and the resulting gas mixture can contain 8-20% CO_2, 5-20% CO, 10-20% H_2, and 2-5% CH_4. If the gas mixture contains too much CO_2 and possibly water vapor, the UCG gas (syngas) can be introduced into the reduction zone in special scrubbers [6], where a significant part of the exothermic reactions is taking place in terms of the extraction of CO_2 from the gas.

There are numerous applications of the gas generated from the UCG process. It could be utilized as a fuel in thermal power plants (TPP), as well as district heating plants, in chemical industry, in systems for the hydrogen generation, and also for obtaining petroleum products as fuels. In Australia, in the beginning of this century, when the prices of oil fuels were high, diesel fuel has been manufactured from coal. The cost of such generated diesel fuel was about $28 per barrel, which included entire production process from coal, to gas and the oil at the end.

Twenty years ago the UCG process was exploited in only 6-7 countries in the World. Today there are more than 40 countries which is dealing with UCG. Some of the countries are only involved from the perspective of research and applied investigations, while some are developing semi-industrial systems, and others are already at the stage of the full industrially proven manufacturing set-up [4].

Components of the syngas

Nitrogen in the form of nitrogen compounds (NO_x, NH_3, *etc.*) in the gas mixture obtained by UCG, is generated by combustion of coal at high temperatures, where NO_x are formed with nitrogen from the air and with the oxygen. The NO_x also appear somewhat during the combustion of nitrogen particles from fuel (mainly at $t > 1700$ °C).

Total amount of NO_x are distinguished in the appropriate elements of the scrubbing system (NO_x amount will be significantly lower if oxygen is used as a gasification agent instead of air). In any case, in exhaust gases coming through the TPP chimneys, there will be significantly less of these harmful gases if the UCG gas is burned during combustion of coal in the boiler furnace.

Nitrogenous substances from the fuel in the process of gasification often produce certain amounts of NH_3, which is removed (and used for various purposes) through the scrubber system in the UCG process.

The gaseous fuel does not contain nitrogen compounds at that time, and NO_x can only be formed by the oxidation of nitrogen from the air (if the gasification agent is air). The NO_x depends on the adiabatic stoichiometric combustion temperature, which can be reduced by bringing cold (inert) matter to the reaction zone (CO_2 that is already a part of UCG gas is quite suitable for the reduction of NO_x emissions) [10].

The occurrence of SO_2 is very rare, but it could appear in very small quantities. Otherwise, if it were in greater quantity, the gas mixture would be carried out through the SO_2 reactor, where the 96% conversion of SO_2 into SO_3 is carried out with the assistance of catalyst:

$$2SO_2 + O_2 \rightarrow 2SO_3 \ (+98 \text{ kJ/mol}) \tag{1}$$

The released heat increases the temperature of the gas by about 19 °C, and the cooled process gas exits the reactor, while SO_3 is reacting with the water vapor:

$$SO_3 + H_2O \rightarrow H_2SO_4 \ (+101 \text{ kJ/mol}) \tag{2}$$

In the next part of the process system, 92-97% of H_2SO_4 is condensed without any accompanying products.

Such purified gas becomes a suitable fuel for TPP, as well as for district heating power systems, refineries, coke ovens, pulp and paper industry, brickworks, *etc.* In addition purified gas could be converted into liquid fuel.

The released heat during cooling of the process gas is used for the production of dry steam at the certain pressure. From the gas waste, using desulphurization by catalytic oxidation of sulfur hydrogen – H_2S, H_2SO_4 is generated with a concentration of up to 95% (not taking into the account previously mentioned 92-97% of H_2SO_4).

Reduction of the amount of water from the gas generator prior to the ignition is done by the previous drainage or by blowing the air of a certain pressure and temperature, with the aim of water extraction. Neglecting hydrogeological research can lead to congestion of gasification, or to a potential reduction in the UCG process effects.

Preliminary calculation indicators for possible application of UCG in Serbia

Ćirikovac coal deposits and the overall area of the nearby TPP Kostolac is considered to be investigated for the UCG application. For the implementation of UCG process in the proposed Pilot Plant, fig. 6, it is necessary to pump the air (or some other agent) in quantities of 8000-9000 m_n^3 of gas/h, under pressure of 2.5-3 bar. For the preliminary decomposition or fracturing of coal, a pressure of 50 bar is needed, in quantities of up to 50000 m_n^3 of gas/h. [7, 8, 10, 11-13].

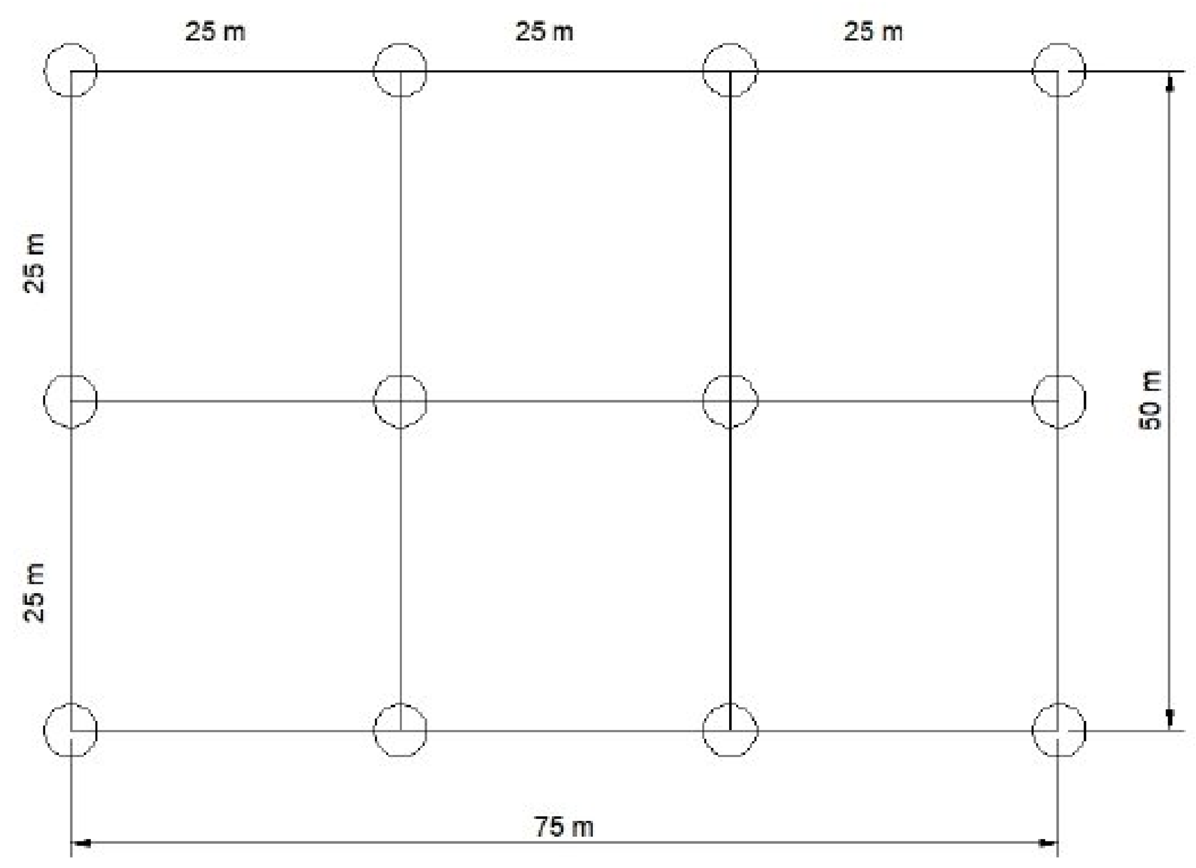

Figure 6. Exploitation Pilot Plant field for UCG in Serbia

For the assumed UCG exploitation field, fig. 5, the Pilot Plant (with thickness of the coal layer h = 6 m; ρ_n = 1.3 t/m^3) needs to be processed by gasification:

$$Q_u' = 75 \cdot 50 \cdot 6 \cdot 1.3 = 29250 \text{ t of coal} \quad (3)$$

If such a quantity of coal would be excavated with the traditional underground method, 20-25% of it would be utilized:

$$Q_u = 0.25 \cdot 29250 = 7313 \text{ t}, \quad Q_\text{u} = 7313 \text{ t} \quad (4)$$

The available energy potential from this amount of coal (H_{D_u} = 9922 kJ/kg – lignite Ćirikovac) [14] would be:

$$E_{u_r} = Q_u H_{(D_u)} = 7313 \cdot 10^3 \text{ kg} \cdot 9922 \cdot 10^3 \text{ J/kg} = 72560 \text{ GJ}$$

which is

$$E_{u_r} \cong 20 \text{ GWh} \quad (5)$$

As an example, for TPP Kostolac A+B, the total installed capacity of 1007 MW generates energy of 6256 GWh, which is ≅ 6.21 GWh.

Previously calculated available energy potential of 20 GWh, is equivalent to a power of 3.22 MW. For this available energy potential, coal consumption would be:

$$\dot{m}_u = \frac{N}{H_{D_u}} = \frac{(3.22 \cdot 10^3 \text{ kJ/s})}{(9922 \text{ kJ/kg})} = 0.324 \frac{\text{kg}}{\text{s}} = 1168 \frac{\text{kg}}{\text{h}} \quad (6)$$

where N [kJs^{-1}] – the power that would ensure the subject exploitation field, H_{D_u} [kJkg^{-1}] – the lower thermal value of coal.

To provide the power of 3.22 MW (out of a total of 1007 MW), 7313 t of coal would be consumed annually. That amount of the coal would, at current market prices, bring a profit to the coal supplier (with price of $C'_u = 4000$ RSD/t) of:

$$C_{u_{uk}} = Q_u C'_u = 7313\ \text{t} \cdot 4000 \frac{\text{RSD}}{\text{t}} = 29252000.00\ \text{RSD}, \quad C_{u_{uk}} = 248000\ € \tag{7}$$

If this exploitation field (75 × 50 m) would be gasified, the proposed Pilot Plant, using 29250 t of coal, would use 80% for the UCG, which leads to total that will be used efficiently:

$$\text{Q}_{\text{u}_{\text{gasif}}} = 29250\ \text{t} \cdot 0.80 = 23400\ \text{t} \tag{8}$$

The planned technological investigation at the proposed Pilot Plant (with gas yield of at least $\text{PRG} = 1.9^3_\text{n}\text{m}^3_\text{n}/\text{kg}$ for lignite, $\eta_\text{gasif} = 65\%$) will generate the following amount of syngas:

$$\text{Q}_\text{g} = Q_{u_{\text{gasif}}} \cdot PRG \cdot \eta_\text{gasif} = 23400 \cdot 10^3\ \text{kg} \cdot 1.9 \frac{(\text{m}^3_\text{n})}{\text{kg}} \cdot 0.65 = 28889 \cdot 10^3\ \text{m}^3_\text{n}$$

$$Q_g \cong 29 \cdot 10^6\,\text{m}^3_\text{n} \tag{9}$$

The available energy potential from this amount of UCG generated gas, taking into account the assumed surface of the exploitation field (75 × 50 m, h = 6 m, H_{D_g} = 3140 kJ/m^3_n for gas from lignite) will be:

$$E_{gr} = Q_g H_{D_g} = 29 \cdot 10^6\,\text{m}^3_\text{n} \cdot 3140\ \text{kJ/m}^3_\text{n}, \quad \text{E}_\text{gr} = 25\ \text{GWh} \tag{10}$$

where H_{D_g} [kJm^3_n] is the lower thermal value of gas, Q_g[m^3_n] – the quantity of the received syngas.

This corresponds to the power of 4.02 MW, which would ensure the annual supply of energy – gas in the amount of $29\cdot10^6$ m^3_n.

The price of that gas could be 1/10 (even 1/15) of the price of natural gas. This is because H_D of the UCG generated gas is about 10 times lower than the natural gas. The price of natural gas is around 40 RSD/m^3_n, which leads to:

$$C'_g = \frac{1}{10} \cdot 10 = 4\ \text{RSD/m}^3_\text{n} \tag{11}$$

Revenue from the delivered amount of gas is:

$$C_{g_u k} = Q_g C'_g = 29 \cdot 10^6\,\text{m}^3_\text{n} \cdot 4\ \text{RSD/m}^3_\text{n}, \quad C_{g_{uk}} = 983 \cdot 10^3\ € = 983000\ € \tag{12}$$

This price of the gas can also be corrected up to the 1/15 of the UCG gas price if:

$$C'_g = \frac{1}{15} \cdot 40 = 2.67\ \text{RSD/m}^3_\text{n}, \quad C_g = 29 \cdot 10^6\,\text{m}^3_\text{n} \cdot 2.67\ \text{RSD/m}^3_\text{n}$$

$$C_g = 656 \cdot 10^3\ € = 656000\ € \tag{13}$$

The cost of gasification depends on the price of production of the 12 planned boreholes, as well as other significant investments in equipment and installation of the necessary plant gear on the given exploitation field.

The timeline to work on the gas production, when performing a technological test, would be (with assumed capacity of the Pilot Plant of 10000 m^3_n/h):

$$T = \frac{Q_g}{Q_{(g_{\text{hour}})}} = \frac{29 \cdot 10^6 \,\text{m}_\text{n}^3}{10000 \,\text{m}_\text{n}^3/\text{h}} = 2900 \text{ hours} = 120 \text{ days}, \quad T = 120 \text{ days} = 4 \text{ months} \tag{14}$$

If in 4 months (120 days) amount of the burned coal is: $75 \cdot 50 \cdot 6 \cdot 3 = 29250$ t, then with UCG the amount of gas will bet 29 mil. m_n^3, which is:

$$\dot{m}_g = \frac{29 \cdot 10^6 \,\text{m}_\text{n}^3}{120 \text{ days}} = 241667 \,\text{m}_\text{n}^3/\text{days}, \ i.\,e. \ 10070 \,\text{m}_\text{n}^3/\text{h}, \quad \dot{m}_g = 10070 \,\text{m}_\text{n}^3/\text{h} \tag{15}$$

Sometimes in calculations and various design checks it is sometimes operated with the parameter of the gas production per 1 m thickness of the layer. Calculating per 1 m of the layer thickness, this gas production becomes 1783 $\text{m}_\text{n}^3/\text{h}$.

The obtained gas production, $\dot{m}_g$, for the coal layer is 70 × 50 × 6, and it corresponds to the initial assumption of the capacity of the UCG Pilot Plant.

If we analyze all of the above, it is not difficult to get to the conclusion why 40 countries in the world are engaged in the development of the UCG processes. Specific preliminary calculations are given in the following tab. 2.

Table 2. Comparison between the classical method of exploatation and USG

	Using classic methods	With UCG
The amount of coal that is being exploited	$Q_u = 7313$ t	$Q_{u_{gas}} = 23400$ t
Capacity – time production of energy	$\dot{m}_u = 1235$ t/h	$\dot{m}_g = 10070 \,\text{m}_\text{n}^3/\text{h}$
Available energy potential of energy source	$E_{u_r} = 20$ GWh	$E_{g_r} = 25$ GWh
Total value of the obtained energy source	$C_{u_{uk}} = 248000$ €	$C_{g_{ug}} = 983000$ €
Working time for energy production	T = 120 days = 4 months	

Potential impacts of UCG on the environment

Professionals involved in energy engineering, as well as the consumers of energy are aware of the fact that an ecological completely clean source of energy does not exist.

When it comes to the possible application of the UCG, it should be noted that despite the significant advantages of its application in regard to conventional coal mining methods, both from the energy and economical perspective, world experience also points to improved effects from an environmental aspect. It is necessary, in all this, to master the effects and possible problems that could manifest if several important items are not taken into account, such as:

– insufficient knowledge of the geology of the planned location for the UCG,
– possible inability to drill the required wells, often with higher accuracy (high level of precision is possible nowadays),
– work with possible inadequate parameters of the UCG, because the work on the application of the UCG requires multidisciplinary teams (miners, geologists, mechanical and electrical energy engineers, technologists, geophysicists, hydrogeologists, ecologists, *etc.*), and
– lack of a full understanding of the impact of the gasification process of underground cavities or the displaced zones.

Today, there are industrially proven commercial UCG facilities in Uzbekistan, USA (two locations), China, South Africa, and Australia (two locations); as well as semi-industrial

UCG setups in over 35 countries (New Zealand, India, China, Canada, Japan, Great Britain, some countries of the EU, *etc.*). In the last few years, the Russian Academy of Sciences has been developing projects for possible UCG application at the six new locations.

To address various challenges in applied research UCG projects today, several systems have been developed to initiate the UCG reactions control, including the CRIP developed by the US National Laboratory, Lawrence Livermore (LLNL). This was initially developed for coal near land surface, while today in Europe this is advanced for coal deeper below surface.

If possible adverse environmental effects are addressed, it should be pointed out that there are two basic environmental threats related to the UCG process:
- possible subsidence of the terrain and
- potential negative effect on the groundwater.

Both problems, according to LLNL, can be significantly mitigated by carefully selecting the location and with process management. These potential negative impacts on the environment can be reflected in the quality of groundwater resources, while the surface subsidence of the terrain may be caused by the cavities generated by the onsite coal combustion. Moreover, such problems are increasingly less pronounced with increasing depth of layer laying.

To be able to additionally strengthen the environmental aspect of UCG application in Serbia various additional renewable energy resources have been considered. The key one are solar photovoltaic systems that are proposed to be utilized to provide necessary onsite clean energy generation option [15]. Stand-alone or grid-connected photovoltaic systems could be installed to deliver onsite power for running dedicated pumps, and other UCG process equipment creating complete UCG energy generation furthermore environmentally friendly.

Preliminary studies are showing that the planned photovoltaic system can completely power all the required onsite UCG loads. Needless to mention, solar photovoltaic systems are completely environmentally friendly, generating power cleanly onsite and without any noise or any other negative effects on the environment.

Possible subsidence of the terrain

It is well known that the terrain subsidence of the UCG utilization at the surface (up to 50-60 m deep) is less prominent, because there are generally small thicknesses of layers, often uninteresting for UCG. Especially if they are about 0.6 m thick (lower limit for UCG exploitation), or often lower.

If these layers are more pronounced, the subsidence from the surface to the depths is less manifested with increasing depth of recovery. If the composition of the bottom of the layer, and especially the roof layers for gasification, is suitable, this significantly mitigates the overall possible field subsidence or ecological disturbance. Generally, with increasing depth of subsidence, the subsidence on the surface of the field is becoming less pronounced [16, 17].

A special advantage, which is related to the danger of subsidence of the terrain, is that in the gasified area slag and ash remain in the scattered area. This happens even up to 2/3 of the height of that treated space, which tolerates the possibility of terrain subsidence to be minimized [13].

Subsidence of the terrain is sometimes caused by the exploitation of groundwater. At that time it is necessary to define what the priority is. The UCG should not be foreseen at all costs. Due to the lowering of the level of groundwater, there is an increase in the soil's own mass in the reduction zone, which leads to subsequent subsidence of the terrain in the wider area. This is one of the reasons for the presence of hydrogeologists in the UCG development team.

Due to all this, after the termination of the UCG development in a certain location, the land is returned to its original purpose without any need for the special field recultivation. A significant part of these areas between the pipelines and other infrastructure on the ground is used during the underground gasification itself.

Potential negative effects on groundwater

During the treatment of groundwater the problem of wastewaters, which have already been contaminated during some of the processes, are exposed to further pollution in their circulation. Pollutants are all organic, inorganic and similar substances, or components that are in natural or artificial conditions brought into the underground aquifer, or they are continuously introduced into the aquifer. Their origin can be the result of the basic processes of forming the aquifer in the natural conditions of the environment, to artificial, deliberate or unintentional introduction of them into the outlet waters.

In the treatment of wastewater, there is sometimes a need for additional, detailed research which should clarify the hydrogeological and hydro-chemical environment immediately in the parts of the terrain where appropriate measures for protection will be built or undertaken (investigative works, experimental filtration field tests, laboratory tests, water and rock chemical analysis, *etc.*).

Free groundwater in the walls of the massif, unlike surface waters, have been exposed to significantly different physical-chemical conditions and interdependencies, where the concentration of dissolved substances in them is much more diverse and changes according to the specific rules all the time. This is especially the case with the flow of aquifer waters, where the pollution process itself, with all the consequences it carries, differs significantly from the pollution of surface waters [16].

When collecting data and the aforementioned studies of possible sources of pollution in the given area, it is necessary to consider some other tests as necessary, such as:
– the amount of necessary existing surface and groundwater,
– status of the existing sewage network, drainage channels and other facilities in regard to the possibility of outflow of industrial wastewater and other solutions from them, and
– locations and measurements of the waste water discharge point.

Concrete solutions to this issue must address a number of issues related to the protection of the aquifer, such as:
– at what distance and during what time contaminated waters may occur from the pollution site,
– whether there is a possibility for disappearing of some pollutants, through the natural purification of those polluted waters, and
– the length of the journey or the time needed to reduce the concentration of pollutants to the allowed values according to the adopted norms, which are of interest from the perspective of the forecast of changes in the water quality of the aquifer.

Measures of preventive character are those that can prevent the possibility of contamination of groundwater. In addition to these groundwater protection measures, localization and liquidation measures are also applied. Those along with preventive measures need to elaborate methods and solutions for the localization of pollution hotspots, and where possible their liquidation.

Prevention of contamination of groundwater implies, among other things:
– liquidation or purification of gas-smoke products,

– deep disposal of particularly harmful products for which the economic justification of their purification or liquidation is determined, and
– establishment of protective zones in the area of existence of groundwater with the implementation of strict measures during the construction of appropriate facilities.

Waste waters or technological solutions, as well as possible unexpected gases from UCG plants, which can be infiltrated into the aquatic environment, should be gathered by the appropriate drainage system and forced towards sewage type of collection tank, from where they are removed or accepted for purification.

Localization measures for the protection of groundwater are applied in cases where part of the aquifer is already contaminated. The formed source of pollution in the aquifer may, even after liquidation of the sources of pollution, spread to the underground flow directed towards various water ways, thereby causing their pollution. Localization measures that prevent the spreading of pollution over the aquifer can be carried out, depending on the hydrogeological conditions, with various physical barriers that constrain further dissemination.

The aim of reconstruction measures is to liquidate the pollution of the aquifer and establish the natural quality of groundwater. This can be done by pulling out of the polluted content from the contaminated layer using drainage boreholes, or by intensive flushing of the layer through the injection and pumping of water or special solutions through the system of injection borehole for drainage.

In most cases, reconstruction measures are very costly, especially when pumping contaminated water must be moreover purified for further use. In addition, the time necessary for the complete removal of pollutants from the layer is usually very long. It may be considered that reconstruction measures should be carried out only in the localization of sources of pollution.

When it comes to the pollution of groundwater by certain accidental particles of the gas mixture obtained by the underground gasification of coal, some special gel can be injected to certain areas of the UCG, which would then seal the boundary surfaces, so that groundwater could not penetrate it. Such cases are extremely rare. There is a known case of such activities performed on the industrial UCG complex in Iran, and it was generally positively assessed [18, 19].

In the case of the possible UCG on Ćirikovac deposit, for the considered framed exploitation field (size 75 × 50 m, layer thickness 6 m), the amount of gas that would be obtained is $Q = 29 \cdot 10^6$ m_n^3, valued at $Cg_{uk} = 983000$ €. If CO_2 (≈15%) was extracted from the gas mixture in the scrubber, that would amount to $4.3 \cdot 10^6$ m_n^3, which would already be interesting for industrial applications. Noticeably the remaining gas that is released from CO_2 contains significantly more powerful energy value, because CO_2, as well as N_2 are inert gases [20]. When CO_2 and N_2 are removed from the UCG process gas in scrubbers, then the gas is cleaner and more energy-efficient, since inert gases represent over 70% of syngas. Such purified syngas consists of the 100% CO, H_2 i CH_4 mixture, and the thermal power of this clean gas mixture can be 3-4 times higher than that of untreated gas. The mentioned calculations refer to the use of UCG at the location of Ćirikovac, and similar could be done for other coal deposits.

Conclusion

It is well known that the syngas generated from the UCG process can be used as an energy gas in TPP, as well as district heating plants. Also it can be utilized as technology gas in chemical industry, for fractional distillation of crude oil refining, to obtain hydrogen, *etc.*

The energy gas from the proposed UCG at Ćirikovac deposit near TPP Kostolac, or similar deposits for other TPP, is extremely convenient because UCG method mainly utilizes non-balanced deposits and excavated residues of balanced reserves. In regard to energy efficiency, it is appropriate to reference that with traditional underground mining, coal utilization is no more than 20-25%, while in UCG it is about 72-96%, taking into account the useful volume of coal.

Proper location selection for the UCG site, as well as the application of the necessary protective measures does not result in any significant pollution of the environment. There are no solid residues comprised during the syngas combustion in TPP burners, nor sulfur oxides. Sulfur, which would possibly find itself near the gasification zone, will remain bound in the form of down-forming sulfide compounds through the accompanying reactions in the UCG.

To additionally support the environmentally friendly aspect of UCG in Serbia, solar photovoltaic energy generation systems have been explored. Solar power is proposed to be utilized to providing necessary onsite clean energy generation option, which could deliver on-site power for running dedicated loads of the UCG process equipment. Ćirikovac deposit near TPP Kostolac is considered to house a dedicated photovoltaic power plant that can completely power the proposed UCG plant.

In addition to everything previously considered, it would be adequate to take into account the exceptional interest for the UCG in the world, and especially in Europe. There are various current EU research funder projects that are tackling UCG applications, and especially utilization of hydrogen generated in the UCG process. Serbia possesses coal deposits with such a great potential for UCG utilization.

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