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# OVERVIEW OF RESEARCH STUDIES ON UNDERGROUND COAL GASIFICATION IN SLOVENIA

# PREGLED RAZISKAV V ZVEZI S PODZEMNIM UPLINJANJEM PREMOGA V SLOVENIJI

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**Keywords:** coal gasification, lignite, research overview, UCG, underground

## Abstract

The first concepts regarding the commercial processing of lignite date back to 1948, and in 1961 the EKK power plant was formally established. It was liquidated in 1968, due to low oil and gas prices on the world market. In 1962, the first Slovenian research project analysing underground coal gasification (UCG) technologies was published. In 1980, the activities that should be taken to perform the first Slovenian UCG test in 1984 were specified. From 1983 to 1987, the first laboratory experiments were conducted. The purpose of the experiments was to study the impact of operating parameters on coal combustion and gas quality. Since 2000, interest in UCG technology has been rising again. Research has been funded by the CMV and implemented by ERICo, IREET, FNT, NIC and CMV. The main purpose of these studies was to obtain information on the state of the art in the world regarding UCG technologies and the geological characterization of coal seams appropriate for UCG. From 2010 to 2012, the CMV produced a study on the efficiency of a power plant using gas produced by lignite UCG. In 2011, the RCE started a project under which the first Slovenian gasification test is planned to be carried out in-situ in 2014.

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## Povzetek

Prve ideje o komercialni predelavi lignita datirajo v leto 1948. Energetsko kemijski kombinat EKK je bil formalno ustanovljen leta 1961 in leta 1968 likvidiran, zato ker tehnologija pridelave plina ni bila konkurenčna ceni nafte in plina na svetovnem trgu. Leta 1962 je bila opravljena prva raziskava, ki posega na področje PUP. V letu 1980 so izdelali projekt aktivnosti za izvedbo prvega testa uplinjanja premoga v Sloveniji, ki naj bi ga izvedli leta 1984. V letih 1983-1987 so se izvajali prvi laboratorijski poskusi. Namen teh poskusov je bil določiti vpliv obratovalnih parametrov na potek nastajanja izgorevalne votline, sestavo nastalega premogovega plina in njegovo kalorično vrednost. Po letu 2000 se je zanimanje za tehnologijo PUP zopet povečalo, raziskave je financiral PV izvajali pa so jih ERICo, KI, IREET, FNT in PV. Namen teh študij je bil predvsem informiranje s stanjem tehnike v svetu in geološka opredelitev potencialnih ležišč primernih za PUP. V letih 2010 do 2012 je PV izdelal študijo o energetski učinkovitosti obrata, ki bi baziral na plinu, pridobljenem pri podzemnem uplinjanju lignita. Leta 2011 je RCE pričel s projektom v okviru katerega naj bi prišlo tudi do prvega testnega uplinjanja premoga v naravi v letu 2014.

## 1 INTRODUCTION

At the end of 19th century, underground coal gasification (UCG) was known as a technology suitable for the exploitation of coal layers. Initially, the main purpose of UCG was to reduce heavy smoke emissions from coal-fuelled industrial plants, to relieve the miners of difficult work underground and to explore the coal layers that remained unexplored after the abolition of mining operations. Recently, UCG has been emerging as an alternative technology for the production of energy and fuels, and as an alternative technology of oil production. With the development of drilling methods, the coal seams that were unreachable by traditional mining methods, due to their specific location, depth or lack of coal thickness, have become available. The development of drilling techniques has led to improvements in UCG technology that ensure constant quality and constant amounts of gas produced in a single reactor over a long period. The principles of traditional and current state-of-the-art UCG technology are schematically presented in Figure 1. The main differences are in the gasification site preparation, the size of the resulting underground reactor and the direction of the combustion front propagation.

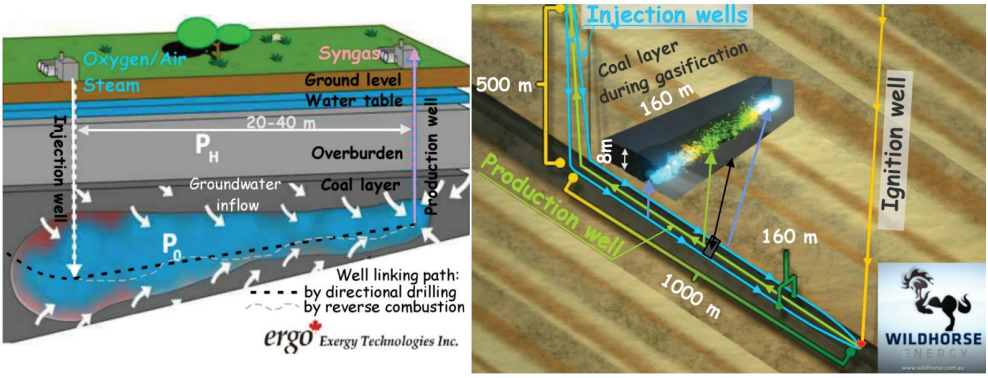


***Figure 1:*** *Comparison between different UCG technologies. Linked vertical wells (LVW) technology (left) and parallel controlled retracting injection point (CRIP) technology (right).*

The traditional linked vertical wells (LVW) method is based on two vertical wells drilled from the surface toward the coal layer at a distance of 20–40 m. In the coal layer, a linking between wells is obtained mostly with the reverse combustion method or with directional drilling. For the parallel CRIP method, the gasification site is prepared by directional drilling only. Since the drilling costs increase with the depth, the parallel CRIP method is preferable after exceeding a certain depth. During gasification with the LVW method, the combustion front spread three-dimensionally. To ensure a constant quality of produced gas, operating at a variable feed rate or performing UCG in multiple locations at the same time is required, but at different stages of cavity formation, which assures constant quality of produced gas and, therefore, a suitable supply for an integrated energy and processing plant. Parallel CRIP technology provides that, during the exploitation of coal beds, the non-stationary conditions are only at the initial stage of combustion; afterwards, the combustion front retains its shape during the gasification of the entire layer (theoretically up to a period of two years), which allows a direct connection to a power plant or an integrated chemical processing plant.

The scope of studies and investments in new technologies for coal processing is linked to the price of other energy sources. From the data presented in Figure 2, it is clear that a rise in oil prices increases the interest in investing in research of coal gasification, which is reflected in the increased occurrence of phrases 'coal gasification' and 'underground coal gasification' in the titles of articles, abstracts of articles and related keywords. Slovenia has also followed this trend.

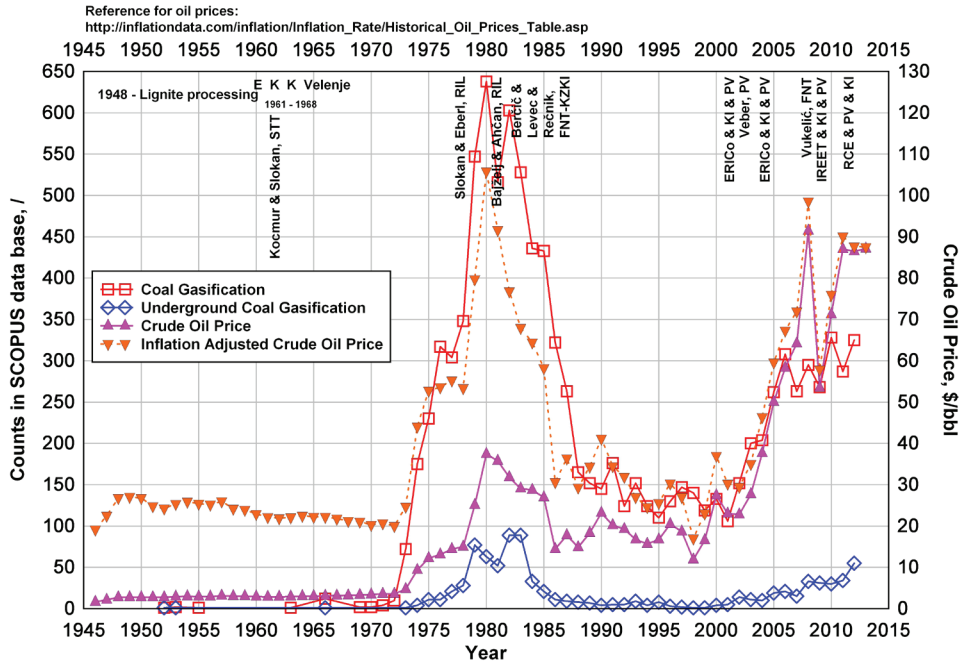


**Figure 2:** *Influence of oil prices on research of coal gasification technologies.*

In Figure 2, the relevant Slovenian research works concerning UCG technology are labelled chronologically under the upper x-axis. The first initiative to commercially process lignite from the Velenje

Coal Mine dates back to 1948. In 1961, the EKK (Energo-Chemical Plant) was formally established, but it was liquidated in 1968, because the technology for gas production from the lignite was not competitive with the prices of oil and gas on the world market. In 1962, the first survey on implementation of UCG technologies was carried out by the Institute for Separations within the Trbovlje Machine Factory. In 1980, the Ljubljana Institute of Mines started a project which should lead to the first UCG test in Slovenia in 1984. Unfortunately, the project was not implemented in accordance with the planned schedule and scope of works. During the 1983–1987 period, laboratory experiments were conducted at the Department for Chemical Engineering (KZKI) within the Faculty for Natural Sciences and Technology (FNT). The purpose of these experiments was to determine the effect of operating parameters on the formation process of the combustion cavity, on the composition of the resulting gas from coal and its calorific value. After the year 2000, interest in UCG technology increased again. The research was funded by the Velenje Coal Mine and conducted by the ERICo (Environmental Research & Industrial Cooperation, Velenje), the IREET (Energy, Ecology and Technology Research Institute, Ljubljana), the FNT, the KI (National Institute of Chemistry, Ljubljana) and the PV (Coal Mine Velenje). The purpose of these studies was to obtain information on the state of the art of UCG in the world, a theoretical analysis of the implementation of the UCG process in the layer of lignite and the geological definition of the Slovenian coal seams suitable for UCG. From 2010 to 2012, the Velenje Coal Mine produced a study on the efficiency of a power plant that would use gas obtained by the underground gasification of lignite. In 2011, the RCE (Research Center Energy) started the project under which the first coal gasification test should be performed in situ.

## 2 REVIEW OF THE FIRST REPORTS ON IMPLEMENTATION OF UCG TECHNOLOGY IN SLOVENIA

As early as the 1950s, the lignite from the Velenje coal basin was considered to be the main raw material and energy source in Slovenia, [1]. Due to a large content of non-combustible materials (ash and water), ideas about the lignite gasification emerged immediately after the Second World War. Gasification would significantly reduce the energy transport costs and reduce pollution in the vicinity of industrial facilities. The preliminary gasification tests with the lignite were carried out at the Most power plant in Czechoslovakia in 1948. The proposal for building a large gasification plant in Velenje was continuously supported and defended by the Velenje Coal Mine and the Šoštanj Termal Power Plant. At the request from the Velenje Coal Mine, the Boris Kidrič Chemical Institute Ljubljana and the Industrial Office Ljubljana prepared an investment study for the construction of a large gasification plant in Velenje in 1960, [2]. In 1961, the trade association for the construction of a large gasification plant in Velenje was registered, and the procedures for construction, selection of a proper technology and procurement of equipment started. However, the financial construction of the project was always problematic. In the 1960s, on the global market of energy sources, oil and natural gas started to replace coal and, therefore, the financial construction of a large gasification plant EKK became economically questionable. In 1968, the Slovenian government decided liquidate the business association for the construction of EKK; this also ended the efforts to implement technologies based on coal gasification in Slovenia. In 1962, the Trbovlje Institute for Separations of Machine Factory (STT) issued a first report on the underground coal gasification technology. The authors, engineer Janez Kocmur and Prof. Karel Slokan, [3], reported in detail the principles of underground coal gasification, the course of gasification and the methods used in the world. They also presented the methods of construction and the connection of holes needed for UCG and the background chemistry of the gasification process. They showed results of the experimental study of the influence of flow of

gasification gasses on the composition of formed gas and the variation of produced gas composition when passing coal seams on the way out. In their report, the authors also gave a detailed summary of the research and results obtained during UCG tests carried out in the Soviet Union, Italy, Belgium, France, England, the United States and Czechoslovakia. In their conclusions, they pointed out that the problem of underground coal gasification cannot be solved within a single institute and that the integrated efforts of several mining research institutions are needed for a success. Together, they should first carefully examine the work and results of the gasification processes in other countries and, on the basis on this and their own experiences, set the suitable locations for underground coal gasification and choose one of them for carrying out the initial experiments.

At the end of 1975, the Research Community of Slovenia approved the research project 'Options for Underground Coal Gasification in the SRS (Socialistic Republic of Slovenia)'. The study should examine the international professional literature and present the latest information in the field of underground gasification, find suitable coal seams and categorize parts which are suitable for underground gasification. The task was carried out in the 1976–77 period by the Ljubljana Mining Institute under the project entitled 'Underground coal gasification and its possible applications in the Slovenian coal mines' [4]. The holder of the assignment was Prof. Slokan. The final report was made on the basis of the report which Prof. Slokan had already made for the STT. The information about coal gasification trials in West Germany and a review of the Slovenian resources suitable for underground coal gasification were added. The report gave also detailed analysis of stocks, options and methods for underground gasification in the Coal Mine Velenje, coal mines in Zasavje (Dol-Hrastnik, Ojstro-Trbovlje and Zagorje), and coal seams around Lendava. In their guidelines for further research, the authors stressed that relevant Slovenian research and scientific institutions and Slovenian companies producing energy should join in the research and implementation of underground coal gasification technology.

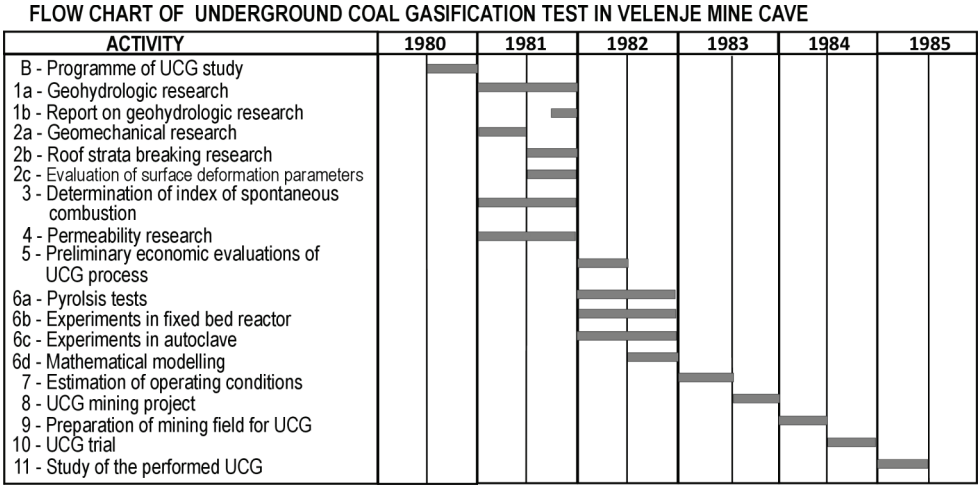


***Figure 3**: Flow chart of research activities planned under the project entitled Underground Gasification of Lignite in Velenje Mine Cave [5].*

In 1980, the SOZD of the Joint Electric and Economy Companies of Slovenia and the Ljubljana Mining Institute concluded a contract assigning the Ljubljana Mining Institute to provide a study 'Underground Gasification of Lignite in Velenje Mine Cave ', [5]. According to the plan, the study was to

last five years and result in a test gasification of coal at a selected location in 1984. The time course of the study is in the form of a bar graph shown in Figure 3.

It turned out that the timetable of the project was too ambitious and unrealistic regarding the capacities of research institutions involved. Activities under numbers 1-5 were carried out and presented in the report by the Mining Institute in 1981, [6]. Implementation of chemical engineering research (Items 6a to 6c) ended in 1987 with the diploma thesis by Aleksander Rečnik, [7]. However, chemical engineering research could not be carried out using the existing experimental equipment, since it was necessary to construct every single piece of equipment, which resulted in a prolonged experimentation period. Moreover, there were no researchers with the experimental experience from similar fields, which certainly would have sped up development of the experimental apparatuses. The results of chemical engineering research are given independently in the form of reports of the Department of Chemical Engineering and as an integral part of the subsequent reports of the Mining Institute.

## 3 OVERVIEW OF THE MAIN EXPERIMENTAL WORK REGARDING THE FUNDAMENTALS OF UCG

The experimental work took place primarily in the industrial laboratory of the Department of Chemical Engineering within the Faculty for Natural Sciences and Technology in the 1983–1987 period. In accordance with the work programme, we carried out pyrolysis tests, experiments in a fixed bed reactor, and experiments in an autoclave. In the scope of pyrolysis tests, the thermogravimetric analysis of different coals were made. The temperature range of physicochemical changes and weight losses during the controlled heating treatment of selected types of coal were defined. We also carried out tests in a small fixed bed reactor in order to determine the amount, composition and heating value of the gases released during the pyrolysis of different coals, [8]. In a fixed bed reactor, the continuous layer of crushed lignite was gasified at different operating pressures and at different flow rates of steam and oxygen. We determined that the quality of gas produced by gasification of lignite was comparable to published results. In the most favourable case (pressure = 5 bar, $H_2O$: $O_2$ = 4.9), the calorific value of gas was 5.6 MJ/Nm3, [9]. The most relevant results were obtained by the coal gasification tests carried out in autoclave (Figure 4), as these data should give insight into what happens in a layer of coal during gasification.

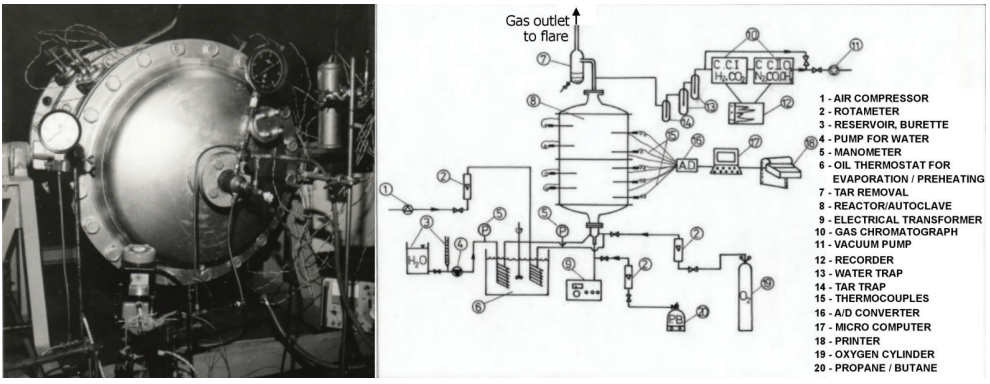


**Figure 4:** *Picture and scheme of experimental apparatus for coal gasification in an autoclave, [10].*

In the preparation of a representative layer of coal for experiments in autoclave, we concluded that we should prepare a synthetic piece of coal, because the Velenje Coal Mine could not deliver a sufficiently large single piece of coal to fill the entire volume of the reactor. When putting together a larger piece of coal from several smaller pieces [10], we determined that the combustion cavity spread unrealistically on the contact surfaces between two pieces; therefore, new synthetic pieces of coal were prepared in the Coal Mine Velenje by pressing crushed coal of various fractions into a cylinder with a diameter of 50 cm and a length of 100 cm. With compressed pieces of coal, Rečnik completed ten experiments, including seven under his thesis, [7]. Table 1 contains data on the composition of gas obtained during the conditions of pseudo-steady state. In most cases, the gasification experiments were carried out with a mixture of oxygen and water vapour. Calorific values of produced gas were between 7.2 and 7.9 MJ/m³, through gasification with pure oxygen even 8.79 MJ/m³.

***Table 1:*** *Results of gasification tests of compressed lignite blocks*

| Experiment | VLN-1 | VLN-2 | VLN-3 | VLN-4 | VLN-5 | VLN-6 | VLN-7 | VLN-8 | VLN-9 | VLN-10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $H_2O:O_2$ | 1.0 | 2.0 | 1.0 | 1.0 | 1.5 | 1.5 | 1.0 | Air | Air : $O_2$ 1:1 | $O_2$ |
| $H_2$ | 40.1 | 19.4 | 28.7 | 28.1 | 35.1 | 22.5 | 31.5 | 9.2 | 23.9 | 33.2 |
| CO | 14.9 | 9.6 | 15.1 | 20.1 | 16.4 | 12.8 | 12.3 | 4.2 | 15.1 | 28.7 |
| $CH_4$ | 2.1 | 2.1 | 2.8 | 2.8 | 2.7 | 3.4 | 3.7 | 0.8 | 2.2 | 2.2 |
| $CO_2$ | 42.9 | 68.9 | 53.4 | 49.0 | 45.8 | 61.3 | 52.7 | 19.0 | 28.8 | 32.0 |
| Calorific value | 7.84 | 4.53 | 6.69 | 7.24 | 7.63 | 5.84 | 7.02 | 2.0 | 5.85 | 8.79 |

*Concentrations of gases are in mol%; calorific values of produced gas in MJ/m³.*

In Figure 5, the reconstructed sizes of six combustion chambers on the basis of a sequence of photographic images taken during excavation of coal from the block in autoclave are shown. In the case of VLN-7, the coal block was prepared from lignite particles having a diameter up to 30 mm, while in all other cases particles of a diameter up to 10 mm were used. From the presented forms of the resulting combustion cavities, it can be concluded that the composition of the gasification agent (ratio oxygen/steam) affects the shape of the cavity created. In some cases, an atypical prolongation of cavity in the vertical direction was observed, which presumably resulted from mechanical failure, and it was not a result of gasification. On the basis of the carried out tests, we cannot make quantitative conclusions since the individual pieces of synthetic coal block were not made from the same coal. For the same reason, we cannot verify the repeatability of experiments, which would allow us to distinct between the influence of operating conditions and defects in the structure on the shape of the resulting cavity.

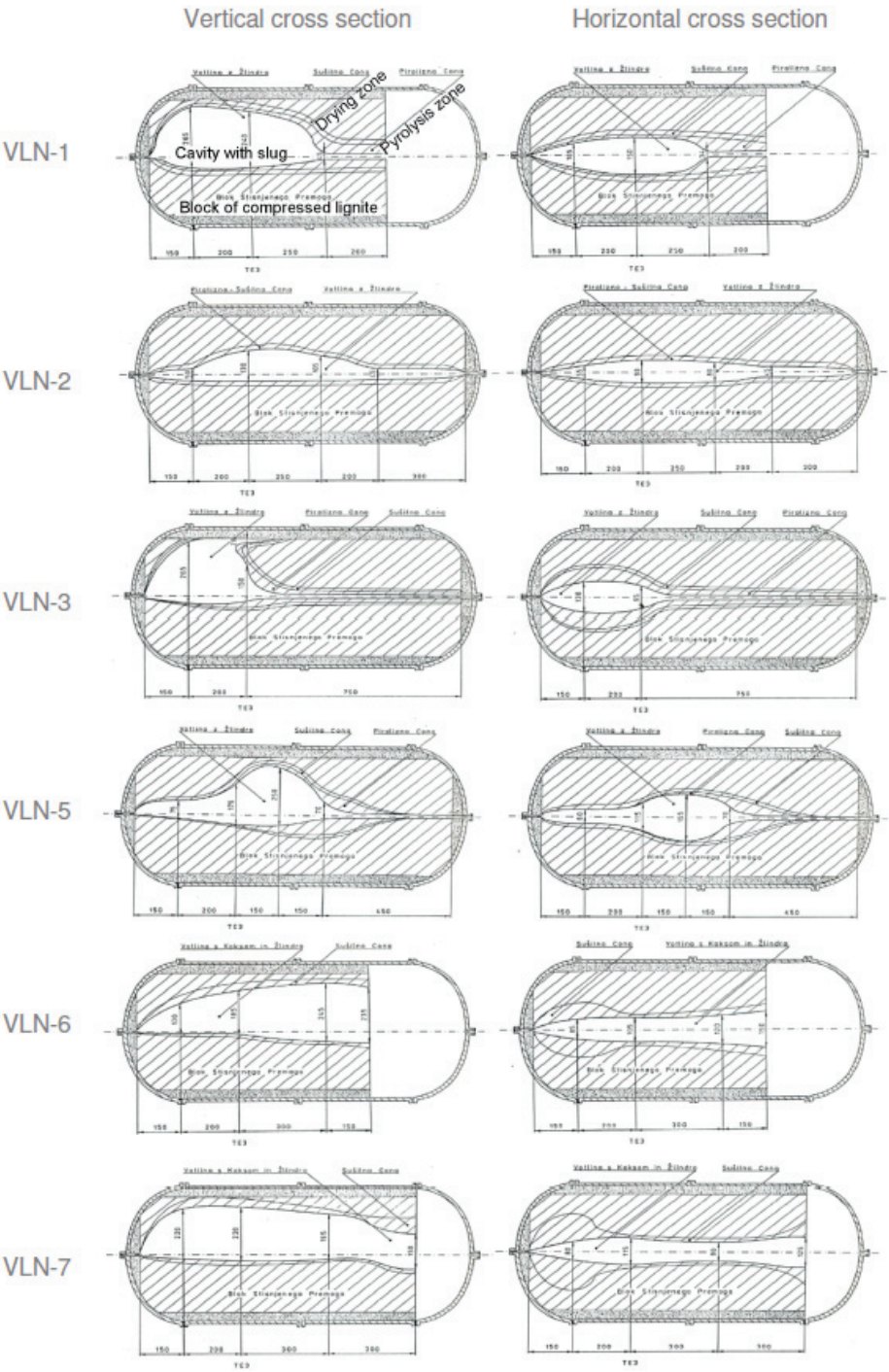


***Figure 5:*** *Comparison of formed cavities during gasification of compressed lignite blocks at different operating conditions [7].*

# 4 RESEARCH ACTIVITY AFTER 2000

Since the year 2000, the Velenje Coal Mine, in the frame of development of clean coal technologies, had been the main Slovenian financier of research activities on underground coal gasification. In 2001, ERICo, [11], produced a scoping study on UCG, in which an overview of developments in the UCG technology was given. The technology of UCG was presented together with the site preparation techniques and guidelines for UCG. The review of mathematical models describing UCG was also presented. The previously performed Slovenian research activities on UCG were briefly summarized. The problems of environmental protection were outlined and an overview of the factors that may affect the economics of the process was also given. In a 2003 study (ERICo, [12]), the physical, chemical and mineral characterizations of lignite from the two most suitable locations for UCG, i.e. Tičnica and Leženj, [13], were made. The technological requirements for the process were given, and the reasons for the selection of CRIP gasification methods were discussed. The results of thermodynamic prediction of equilibrium composition for the system lignite-oxygen-steam were presented for different operating conditions. The strategy of UCG process control based on the calculation of hypothetical equilibrium temperature in underground coal gasifier using inlet conditions, the measured composition of produced gas, and the estimated water influxes were presented. In a 2007 study, Vukelić, [14], gave an estimate of the suitability of coal resources in Goričko and in NE Slovenia for UCG based on the results and analysis of samples collected by drilling wells during searching for the Slovenian oil and natural gas resources. A region between Strukovci and Kuzma was preferred, where a 10–12 m thick layer of brown coal with calorific value of 17.5MJ/kg was found at a depth of 150 m. A similar coal layer was found also in the vicinity of the borehole Slatine HR-1 at a depth of 600–700 m. As a suitable location for UCG, the following locations were mentioned: Gačani, Beltinci, Rakičan, Križevci, Moščanci and Bukovnica where the coal layer thickness is about 2 m. Nevertheless, additional research drillings will be necessary to identify further proceedings regarding the conduct of UCG on the proposed locations. In 2009, IREET, [15], produced the latest scoping study on UCG, which describes all the parameters that are crucial for the characterization of potential coal seam, provides an estimate of all products generated during UCG and analyses environmental acceptability of the process. The possibility to capture and store generated $CO_2$ (or $CO_2$ from other sources) in a formed reactor cavity is also analysed, and the results and locations of recent pilot tests of UCG are mentioned. In the chapter on the energetic efficiency of UCG, the method for the calculation of a mass flow of reactants and products generated on the basis of thermodynamic equilibrium, steady-state assumption and processing scheme proposed by the company Carbon Energy, [17], is introduced. The aforementioned method was also used in the producing of the report *Sizing and economics of power plant based on reserves, products and energy utilization of UCG process*, [16], which was prepared by PV as an enclosure to a study of IREET, [15]. In it, costs are specified for the installation, maintenance and operation of virtual energetic plant that would operate on lignite and use process scheme proposed by the Carbon Energy. A default size of the gasification field was assumed to be 600 m × 180 m × 8 m and the rate of progression of the combustion front was set to 3 cm/hour. Figure 6 presents a flow chart for determining the flow rates of reactants and products that meet the assumed rate of progression of the combustion front during the gasification of lignite through gasification mixtures that have different steam to oxygen ratios. It should be noted that the calculation is based on the assumption of thermodynamic equilibrium and, therefore, at lower temperatures, a higher flow of gasification gases is needed since the part of the lignite that decomposes due to temperature is smaller. In order to assure constant progression velocity of the combustion front, the gas flow rates should be increased at lower temperatures. The horizontal lines denote 60% and 80% transfer ef-

ficiency of chemical energy from lignite to the produced gas. By drawing a vertical line through the intersection between the curve presenting power carried by the produced gas and the line showing the energy efficiency of gasification gas, the thermodynamic quasi-equilibrium temperature can be determined. In fact, the velocity of combustion front propagation can be calculated from the carbon mass balance and energetic efficiency from the flow rate and composition of produced syngas. In a real case, the iteration procedure should be included since the water balance must be compensated with the underground water inflow. The estimated quasi-equilibrium temperature aids in adjusting operating conditions, i.e. mainly the ratio between oxygen and water in order to assure desired gasification conditions.

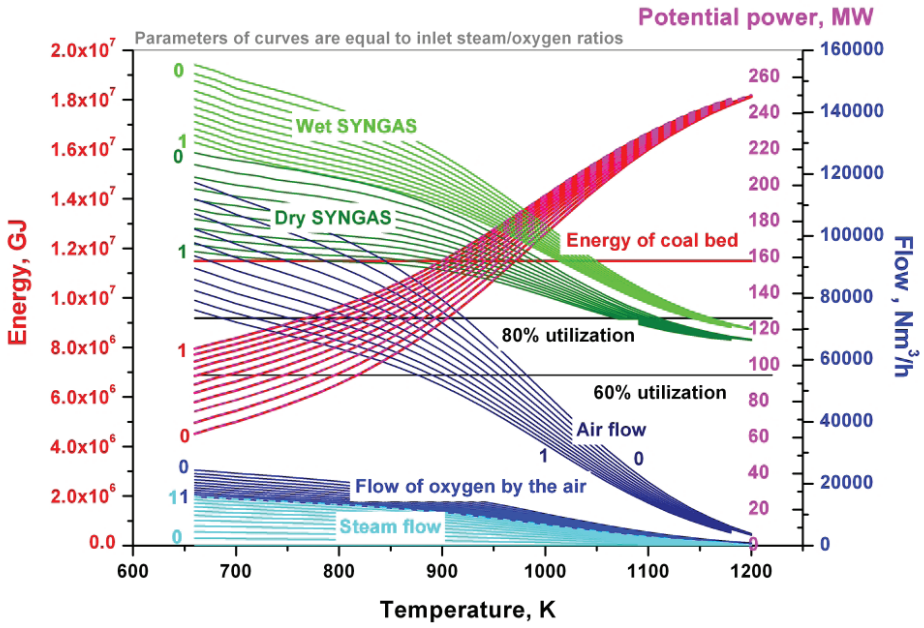


***Figure 6**: Diagram for graphic determination of flow rates of reactants and products for assumed combustion velocity of 3 cm/h at different thermodynamic equilibrium temperatures, [16].*

## 5 CONCLUSION

The main purpose of this article was to provide a short overview of all research activities regarding UCG in Slovenia. The emphasis is given to relevant experimental results and to theoretical approaches that could be applied during gasification experiments. From the abovementioned research activities, it is evident that a part of the Slovenian expert public has always been aware of UCG technology potentials and its possibility to explore untapped coal resources. The mentioned research projects show that we occasionally 'refresh' our theoretical knowledge about UCG technology and developments on the field of UCG; however, despite the immense potential that UCG certainly has, we have not managed to carry out a field experiment in one of the selected locations. Nevertheless, the opportunity to carry out the first field gasification test has now been opened since the RCE recently started to execute the research and development project entitled *Under-*

*ground Coal Gasification*. The project is funded by the Slovenian Ministry for Economy and the EU Structural Funds. One of the main goals of this project is also a field experiment, which will be performed in 2014 at a location of Tičnica.

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