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Soviet experience of underground coal gasification focusing on surface subsidence

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Abstract: Global coal mining activity is increasing due to demands for cheap energy and the availability of large coal deposits around the world; however, the risks associated with conventional coal mining activities remain relatively high. Underground coal gasification (UCG), also known as in-situ coal gasification (ISCG) is a promising alternative method of accessing energy resources derived from coal. UCG is a physical-chemical-geotechnical method of coal mining that has several advantages over traditional mining, for example, its applicability in areas where conventional mining methods are not suitable and reduction of hazards associated with working underground. The main disadvantages of UCG are the possibility of underground water pollution and surface subsidence. This work is focused on the latter issue.

A thorough understanding of subsidence issues is a crucial step to implement UCG on a wide scale. Scientists point out the scarce available data on strata deformations resulting from UCG. The former Soviet Union countries have a long history of developing the science related to UCG and experimenting with its application. However, the Soviet development occurred in relative isolation and this makes a modern review of the Soviet experience valuable. There are some literature sources dealing with Soviet UCG projects; however, they are either not up-to-date or do not focus on aspects that are of particular importance to surface subsidence, including geological profiles, strata physical-mechanical properties, thermal properties of geomaterials and temperature spreading. The goal of this work is to increase the knowledge on these aspects in the English-speaking science community.

Key words: Underground coal gasification, Surface subsidence, Thermal properties of geomaterial

1 Introduction

Towards the end of the 20th century, coal was losing its position as the world's most prolific energy source. A number of coal mines were closed, including for example, the Pyramiden on the archipelago of Svalbard, Norway, and the Seredeiskaya mine in the Moscow basin. However, coal has regained its position as a key energy supplier due to three advantages that it has over oil and gas, namely lower price per energy unit, different geopolitical distribution of reserves, and a higher reserves-to-production ratio (Kavalov and Peteves, 2007). Unfortunately, the mining and burning of coal is not environmentally friendly and much of the coal in the ground is either too deep or too low in quality to be mined economically (Walter, 2007).

Underground Coal Gasification (UCG) is a solution at least to the last problem. It is one of the physical-chemical-geotechnical methods of coal mining. The method is not restricted to purely burning coal; some successful experiments on Underground Sulphur and Shale Burning have also been conducted (Miller, 1964; Arens, 1986).

UCG has several advantages over traditional mining. Its benefits include applicability in areas where conventional mining methods are not suitable and that it reduces or even eliminates human work underground. In the simplest scheme, only two boreholes are required — one for oxygen ignition and the other for production. The product of coal gasification, synthesis gas or syngas, is easy to handle and can be used as fuel. Moreover, the method can be coupled with carbon capture and storage (CCS) by injection of CO_2 in the void left after UCG. According to MacDonald (2010), UCG is the cheapest way to produce electricity in comparison with traditional mining.

2 Surface subsidence

Ali *et al.* (2012) emphasised that ground subsidence is probably the most important single obstacle to the commercialisation of UCG. This phenomenon may cause swamping the territory. Ground deformation caused by UCG has the potential for large-scale detrimental effects, including initiation of flow paths between underground aquifers and damage to surface structures and buried infrastructure. Zhukov (1963a) points out the importance of the knowledge of surface subsidence for gas generator design and technology of the gasification. For example, Zhukov *et al.* (1963) argued that wells located in the middle of the trough have less possibility to be damaged.

The magnitude and form of subsidence depends on multiple aspects, such as a seam depth, its thickness and dip angle, physical-mechanical properties of the geomaterials above and under the seam, the initial stress conditions, in-situ fractures and groundwater. Skafa (1960) indicated four types of surface subsidence behaviour after UCG: no ground surface movements; smooth bending; bending with fractures; and crater (sink hole).

There are several aspects which differentiate surface subsidence during UCG from the conventional mining methods. During UCG, rocks are subject to one or both of mechanical and thermal loads. In addition, because coal burning occurs from the bottom to the top of the seam, vertical displacements are observed to occur at a slower rate compared with conventional mining (Turchaninov, 1957a). As a result of this, the bulking factor of the overburden rock is smaller (Turchaninov, 1957a) hence greater surface subsidence is expected. However, during UCG the void is filled with slag and ash which can also mitigate the surface sag.

It can be concluded that subsidence during UCG is a complicated process which deserves further investigation. Tian (2013) pointed out the need for broader knowledge on high-temperature mechanical behaviour of coal, the underground temperature distribution during UCG, and field measured surface subsidence data. Zamzow (2010) argued that the subsidence behaviour from industrial scale projects was not clear. The overview on the Soviet UCG projects presented here extends the knowledge on these issues.

3 Soviet USG projects

Gregg *et al.* (1976) summarised the Soviet experience at that time and came to the conclusion that "the amount of UCG research effort expended by the Soviets far exceeds the summation of research efforts by other nations". The detailed history of the gas and coal industry in the Soviet Union was described by Gregg *et al.* (1976), Antonova *et al.* (1990), Klimenko (2009), Matveichuk and Evdoshenko (2011) and Kopytov (2012). The history of UCG in the Soviet Union began quite early and one of the first scientists to mention the possibility of coal extraction without conventional mining was Dmitri I. Mendeleev in the early 1880s (Mendeleev, 1939). Kuprin (1971), the famous Russian writer, mentioned the UCG process in one of his stories in 1899. This idea was accepted with great enthusiasm by Lenin (Lenin, 1973) and this was one of the decisive factors that drove UCG development in the Soviet Union. The Krutovskaya station was the first UCG project in the Soviet Union which was unsuccessfully conducted in 1932 (Kolesnikov, 1935; Gregg *et al.*, 1976). Later efforts were more successful. The experience was not limited by one horizontal coal seam, but includes steeply dipped coal seams (Kazak, 1965; Kreinin, 2010) and several interleaved coal seams (Lazarenko *et al.*, 2006). The effect of permafrost on UCG has also been studied (Gusyatnikov, 1940).

Unfortunately, access to the UCG material is complicated because the papers are almost unavailable as electronic copies and not presented in the international journals because the Soviet science was mostly conducted with the scientists in solitude (Kapitsa, 2010). However, there is some evidence of collaboration on UCG between the Soviet Union and the USA; for example, a licence agreement with Licensintorg (the international technology exchange enterprise) of the Soviet Union and the American company 'Texas Utilities' for technical documentation and assistance in underground coal gasification (Clements, 1977). Clements (1977) reported that they had obtained documentation with data on UCG in various types of coal deposits and visited two sites in different geological basins but the outcomes could not be disclosed. There is a summary of the Soviet studies focused on surface subsidence in English done by Gregg (1979), but the author was limited by the availability of the translations from the Russian language and this makes a present review of the Soviet experience valuable.

The Soviet UCG activities were mainly focussed in four basins at Angren, Moscow, Donetsk and Kuznetsk. The first three letters of their names and the word "basin" with double "s" due to the Russian language pronunciation constitute alternative second names for the latter three basins — the Mosbass, Donbass and Kuzbass. In the literature available in English, both names are used. Table 1 presents the UCG stations with the seam characteristics in these basins.

Table 1 Soviet UCG stations

Station/Reactor or seam name	Start date	Thickness, m	Inclination, degree	Depth, m
Moscow basin				
Krutovskaya	1932[*8]	1.8[*5]	0[*5]	—
Podmoskovnaya	1940[*8]	2.5[*5]	0[*5]	40—50[*2]
Shatskaya	1955[*4]	2.6[*5]	0[*5]	45[*4]
Kuznetsk basin				
Lenin pit	1933[*8]	—	—	—
Yuzhno-Abinsk	1955[*1]	9.2—9.8[*7]	68—70[*7]	43[*3]—53[*7]
Stalinsk	1960[*8]	—	—	—
Donetsk basin				up to 400[*8]
Lisichansk	1933[*8]	—	—	
Bobrovskiy	—	0.75[*5]	30—40[*5]	
K_8	—	1.8—2.1[*5]	40—60[*5]	
l_8	—	—	41[*5]	
Shakhta	1933[*8]	0.8[*5]	—	
K_4 Rozoviy	—	0.4[*5]	15-18[*5]	
Gorlovka	1935[*8]	—	—	
Derezovka K_3	—	2.0[*5]	80[*5]	
Kamensk	1960[*8]	—	—	
Angren basin				
Angren	1960[*6]			
upper		0.3—3.8[*6]	—	—
interlayer (clay)		0.7—4.7[*6]	—	—
lower (main)		2.0—7.3[*6]	5[*6]	115—126[*6]

[*1]Semenenko and Turchaninov, 1957; [*2]Turchaninov (1957a); [*3]Turchaninov and Zabrovsky (1958); [*4]Turchaninov and Sazonov (1958); [*5]Kazak and Sememenko (1960); [*6]Zhukov and Orlov (1964); [*7]Ovchinikov *et al.* (1966); [*8]Gregg *et al.* (1976);

4 Measurements at the sites

Almost the same field measurements were organized for all sites. For example, in the Moscow basin, the initial vertical fractures were measured in the rock outcrops. They were generally non-uniform; however there was some regularity of the directions (Vinogradov, 1963). According to Valentsov V.G. (Vinogradov, 1963), the production well and the injection well connected better in the directions of the fractures. Thus, the rates of coal burning in different directions could be a hint of the orientation of the fractures. The control of surface and underground space deformation and observation of the underground space after UCG was also conducted. In the Podmoskovnaya station in 1949, a square geodetic net of reference points were established with a spacing of 5—10 m that covered a gasified area of 70 000 m^2 along with deep reference points installed in boreholes which measured vertical deformations of different layers (Fokin, 1954). In 1952—1954, the strata were studied by new boreholes or shafts dug into the used UCG reactors (Semenenko and Turchaninov, 1957; Kazak and Sememenko, 1960). Ovchinnikov *et al.* (1966) reported about a geodetic net and deep reference points in five boreholes as well as excavating the gas generator after 60% coal gasification at the Yuzhno-Abinsk station. The results of the measurements will be discussed and analysed in the following sections.

5 Strata deformations

5.1 Overview

The reported magnitudes of surface subsidence resulting from UCG in different basins range from 0.5 m to 10 m (Table 2) due to different seam depths, seam inclinations (from 0° to 80°), seam heights, seam widths, ash content in the coal and different geological profiles. These factors will be discussed further in subsequent sections.

Table 2 Maximum subsidence in the different basins

Basin	Subsidence	Source
Moscow	1.2 m	(Turchaninov and Sazonov, 1958)
Kuznetsk	2.2 m	(Ovchinnikov *et al.*, 1966)
	collapses up to 10 m	(Turchaninov and Zabrovsky, 1958)
Angren	1.0 m	(Zhukov and Orlov, 1964)
Donetsk	0.5 m	(Semenenko and Turchaninov, 1957)

Horizontal deformations are also important to study together with settlement depths. Horizontal strata movements reduce maximum subsidence depth but increase the size of the affected area. At the Kuznetsk basin, the tensile horizontal deformations were +220 mm/m and compressive horizontal deformations were −160 mm/m (Ovchinnikov *et al.*, 1966). After a field study of the damaged strata using the exploitation boreholes at the Angren station, it was noticed that the horizontal displacements played a crucial role in the distortion of the boreholes (Zhukov *et al.*, 1963). It also should be highlighted that horizontal deformations can impact on the measurements of surface settlements.

5.2 Role of coal seam inclination in subsidence

The seam inclination plays an important role in the type of the surface subsidence. For horizontal deposits, the bending mechanism of subsidence is typical, whereas for synclined deposits, a crater type subsidence is generally observed. According to the description of the subsidence by Ovchinnikov *et al.* (1966) and by Turchaninov and Zabrovsky (1958), it can be concluded that the Yuzhno-Abinsk station with a 70° dipped seam had a crater type subsidence with fractures propagating up to the surface. Ovchinnikov *et al.* (1966) reported shear fractures at the ground surface and Zabrovsky (1959) observed gas on the surface which indicated that the fractures spread to the surface. Opposed to this, Turchaninov and Sazonov (1958) observed that at the Shatskaya station with a horizontal seam, fractures did not propagate to the surface. According to the contour maps of the subsidence by Turchaninov and Sazonov

(1958), it can be concluded that the Shaskaya could be characterised by the second (smooth bending) and third (bending with fractures) types of the subsidence. At the same basin, the Moscow basin, the Podmoskovnaya station has the same type of the subsidence according to the contour maps of the subsidence by Skafa (1960). The contour maps of the subsidence by Zhukov and Orlov (1964) show that the Angren station with a seam dipped at a small angle of 5° also showed the second and third types of the subsidence.

5.3 Role of coal seam thickness in subsidence

The coal seam thickness influences the subsidence depth directly. This is illustrated by considering the Kuznetsk basin, where Table 1 shows the thickness of the coal seam is largest (9.2—9.8 m) and Table 2 shows that this basin also has the largest subsidence (2.2 m).

The coal seam thickness impacts on the height of the distressed zone which is a combination of fractured and caved zones above the gas generator, which is one of the factors affecting subsidence behaviour. Kazak and Semenenko (1960) suggested that if the coal seam is 0.4—0.5 m, the vertical deformation of the seam roof is smooth, without failure. Skafa (1960) postulated that the height of the distressed zone for the Lisichansk station was ten times the coal seam thickness. For this station, Kazak and Semenenko (1960) reported almost the same values — the distressed zone was six— eight times the coal thickness and no failure was observed.

After laboratory experiments Zhukov (1963b) came to the conclusion that the thickness of the coal seam plays an important role in fracture opening within the caved zone. A 1:100 scale model of the Angren station showed that gasification of a coal seam up to 4 m thick caused fractures 15—20 m up from the seam, with small openings observed. For a 4—6 m thick coal seam, a net of fractures, sometimes with wide openings was observed, and for a 6—8 m thick coal seam, fractures with wide openings were observed. Kazak and Semenenko (1960) reported the absence of the fracture net and through fractures at the Podmoskovnaya station with a 2.5 m thick coal seam.

5.4 Role of strata in subsidence

5.4.1 Role of weak strata in subsidence

The existence of a weak strata decreases the time of the response of the ground surface to the UCG. At the Shatskaya station with weak strata (refer to the borehole log in Table 3), the first surface subsidence was observed on the 34th day after ignition (Turchaninov and Sazonov, 1958). At the Yuzhno-Abinsk station with mostly rock material profile, the first surface deformation was noticed eight months after ignition (Ovchinnikov, 1966).

Table 3. Borehole log at the Shatskaya station (Turchaninov and Sazonov, 1958)

Mean depth	Thickness, m	Geo-material	Aquifer
4 m	2.0—6.0	Loam	
14 m	2.0—7.0	Clay	
18 m	2.0—6.0	Limestone	Aleksinsky
21 m	2.0—3.0	Clay	
23 m	1.0—2.0	Limestone	Up-per-Tulsky
31 m	7.0—10.0	Clay	
35 m	3.0—4.0	Limestone	Mid-dle-Tulsky
37 m	1.5—3.0	Clay	
39 m	1.0—2.5	Limestone	Low-Tulsky
41 m	1.0—2.0	Clay	
43 m	1.0—3.0	Sand	Above coal
45 m	2.0—4.0	Coal	
	0.2—0.4	Soil	Coal
48 m	1.6—2.5	Coal	
51 m	2.0—4.0	Clay	
52 m	1.0—2.0	Sand	Under coal
54 m	2.0—2.5	Limestone	Uspensky

5.4.2 Role of sand in subsidence

The gasified area at the Shatskaya station was further spread from the production wells due to the presence of sand in the roof and floor of the seam, which conducted oxygen and increased the area of the burn (Turchaninov and Sazonov, 1958). This distance was wider at the Shatskaya station (15 m) than at the Podmoskovnaya station (6—8 m) (Turchaninov and Sazonov, 1958). However, the depths of the surface subsidence for both of these stations (in the Moscow basin) do not differ significantly.

5.4.2 Role of limestone in subsidence

A layer of limestone (being relatively strong) above the burn tends to smoothen the subsidence trough; however, the state of the limestone is also important. The Shatskaya and Podmoskovnaya stations are in the same basin. The profile of the Shatskaya station (see the boreholelog in Table 3) includes more limestone (24% of the vertical profile) whereas the Podmoskovnaya station has a vertical profile that includes only 10% limestone (Turchaninov and Sazonov, 1958). The schematic borehole log given by Semenenko (1965) shows the locations of the limestone are at mean depths between 19.0 m and 30.0 m, which are 18 m and 29 m above the coal seam. Turchaninov (1957b) did not notice any significant difference between both these sites and concluded that the limestone did not influence the trough development because it was weakened by fractures. For the Lisichansk station, Kazak (1965) presented three roof borehole logs from the Donetsk basin (Table 4); one was before UCG and the other two were after. Limestone is presented along the whole profile and contributes to the shallow subsidence of 0.5 m (Semeneko and Turchaninov, 1957). According to the contour map of the subsidence by Semenenko and Turchaninov (1957), a smooth subsidence trough was observed. The difference between Boreholes 2 and 3 will be discussed later.

Table 4. Bottom height of the layers above the coal seam at the Lisichansk station (Kazak, 1965)

Geomaterial	Before UCG	After UCG	
	Borehole 1	Borehole 2	Borehole 3
Limestone	14.40 m	13.55 m	13.40 m
Shale	12.07 m	10.74 m	10.78 m
Shale with limestone	10.13 m	9.80 m	9.57 m
Shale	9.19 m	8.88 m	8.44 m
Coal	9.04 m	8.70 m	8.27 m
Shale with limestone	7.15 m	6.75 m	6.0 m
Shale with higher amount of limestone	6.72 m	6.31 m	5.46 m
Sandy shale-shale	6.22 m	5.95 m	5.14 m
Sandy shale	6.12 m	5.85 m	5.04 m
Sandy shale-shale	4.36 m	4.03 m	3.93 m
Shale	4.21 m	3.93 m	3.67 m
Sandy shale-shale	3.24 m	3.15 m	3.07 m
Shale	2.76 m	2.42 m	2.89 m
Limestone	2.61 m	2.30 m	2.71 m
Shale	1.73 m	1.92 m[*1]	2.08 m
		1.42 m[*2]	
Sandy shale-shale	1.43 m	1.12 m[*2]	1.70 m[*1]
		0.37 m[*3]	
Coal/Slag	0.80 m	0.75 m	1.40m[*2]

[*1]warmed; *[2]fired and fractured; *[3]failed.

5.5 Rate of surface subsidence

The rate at which surface subsidence occurs (typically in mm/day) is important because it can provide a hint to how the UCG process has advanced and organize mitigation measures to minimise effect of subsidence on near-surface structures and infrastructure. The subsidence velocity can also give an idea of the overburden strata's bulking factors.

A strong overburden stratum can reduce the subsidence velocity. In the Moscow basin with weak strata, the subsidence velocity was the highest when compared to the other three basins. At the Shatskaya station, the mean subsidence velocity was 25 mm/day with a maximum of 40mm/day (Turchaninov and Sazonov, 1958). In the Kuznetsk basin, the maximum subsidence velocity reached the mean velocity in the Moscow basin — 25 mm/day (Ovchinnikov *et al.*, 1966). In both basins the depths of the coal seams were approximately 50 m below the surface but the Kuznetsk basin has stronger strata than the Moscow basin.

The subsidence rate also reduces with an increase in depth of the coal seam. At the Angren site, the coal seam is at a depth of 110—120 m and the subsidence was slower than in the basins described above, with a maximum of 5mm/day (Zhukov *et al.,* 1963). In the Donetsk basin, the subsidence velocity was the slowest, 1 mm/day (Semenenko and Turchaninov, 1957). Possibly, this is because it has the deepest coal seam (up to 400 m).

The presence of the strong limestone in the profile causes a constant subsidence velocity over time. Table 5 presents two borehole logs which are located at a distance of 450 m from each other in the Angren basins. The table shows that the location of the limestone is far away from the failure zone and near the surface in the Angren basin. However, the process of the surface subsidence had a constant velocity, and this is believed to be due to the limestone layer (Zhukov *et al.*, 1963).

Table 5. Two borehole logs in the Angren basin (Zhukov, 1963)

Geo-material	Borehole 1 Depth, m	Borehole 2 Depth, m
Clay	0	0
Limestone	17	13
Sandstone	—	27
Clay	—	34
Sandstone	31.5	39
Clay	39.5	45.5
Sandstone	46	52
Clay	53	58
Sandstone	59.5	62.5
Clay	65.5	67
Sandstone	70.5	68.5
Clay	74.5	72.5
Sandstone	76.5	74.5
Kaolinite	80	78
Sandstone	87	85
Kaolinite	89	86.5
Sandstone	101.5	99
Kaolinite	103.5	101
Sandstone	108.5	105.5
Clay	112	109
Sandstone	121	120
Clay	122	—
Sandstone	123.5	—
Clay	122	121
Sandstone	126.5	124
Clay	128	128
Coal	130	131

6 Impact of coal burning in-situ

6.1 Thermal geomaterial conductivity

The main differences between UCG and conventional coal mining are exposure of the geomaterial to the high temperatures and the products of burning that are left in the void. According to Turchaninov (1956), the temperature was more than 1500°C in the generators in the Donetsk basin. However, Turchaninov (1956) believed the temperature was lower in the Moscow basin due to the coal's lower heat conductivity and because the air was injected instead of oxygen.

The high temperature impact of UCG is a complicated process. The information about thermal geomaterial conductivity, calculation of heat losses for heating wet soil and strata physical-mechanical properties under thermal conditions will be discussed. The ash properties will be also considered.

Semenenko and Turchaninov (1957) claim UCG heats rock and soil over only a relatively small distance away from the UCG generator. Russo and Kazak (1958) agree with this fact but point out that the spread of the heat mainly occurs due to the convection of hot gas through the fractures that appear near the generator.

The energy conductivity of the coal in the seam is very small (Kolesnikov, 1935), but the real conductivity could be much higher due to fractures. Kolesnikov (1935) reported 10° temperature decrease per a meter at the Moscow basin. Kazak and Semenenko (1960) give some data on soil heating at the Lisichansk UCG station.

Fig. 1 shows that the temperature reduces to less than 100°C at a distance of 3 m above the seam and 4 m below (the lowest depth where measurements were conducted). At a distance of 10 m above the seam, the thermal effects from UCG were not observed.

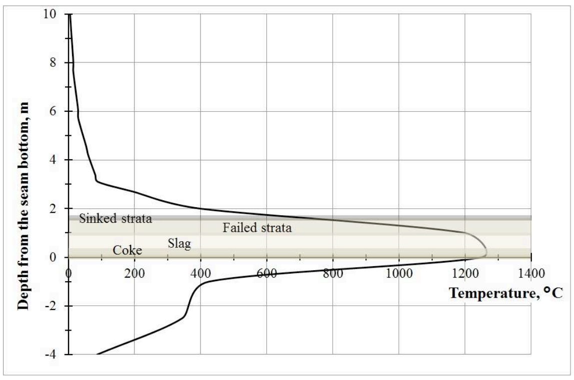

Fig. 1 Distribution of soil temperature after UCG at the Lisichansk station (modified after Kazak and Semenenko, 1960)

Kazak *et al.* (1990) observed at the Yuzhno-Abinskaya station that the temperature dropped sharply from 1000°C to 400°C in the lower, non-structured, part of the caved zone because the geomaterial fell from the roof to the bottom of the seam, then the temperature does not change significantly for the rest of the caved zone. Kazak *et al.* (1990) explain that the geomaterial of the lower part falling from the roof piece by piece is exposes more coal to direct burning and that other material is subsequently heated due to conduction. Kazak *et al.* (1990) suggest an equation for heat loss during conduction:

$$\frac{Q_1+Q_2}{Q}=\frac{350}{q_y}\cdot\frac{m_c}{m}+\frac{100.7\sqrt{l}}{m\sqrt{v}\,q_y} \tag{1}$$

where Q_1 = the convective heat losses in joules; Q_2 = the conductive heat losses in joules; Q = the general heat produced by UCG in joules; m_c = the thickness of the isothermic area in m, l = the width of the isothermic area in m, m = the thickness of the gasified area in m, v = the velocity of the face development in m/day, and q_y = the heat of the coal burn in joules/m^3.

6.2 Calculation of heat loss due to evaporation

The magnitude of heat loss due to evaporation in wet ground during UCG has been considered. Based on the assumption by Stefan (Riemann and Weber, 1927), Lykov and Pomerantchev (1935) analytically showed that the evaporation surface would expand into the soil according to the equation:

$$s=\alpha\sqrt{t} \tag{2}$$

where t = the time in hours and α = a coefficient which depends on the thermal heat conductivity coefficient, dry soil density, absolute soil moisture, soil surface temperature, soil temperature, and vaporisation temperature.

After modification, it is possible to obtain Eq. (3) to determine the amount of the evaporated water (kg/m^2).

$$w=\alpha\,\rho_1 W_a\sqrt{t} \tag{3}$$

where ρ_1 = dry soil density in kg/m^3, and W_a = absolute soil moisture.

In two calculations involving heat loss in soils, α was taken as 0.0455 and 0.0480. These values were estimated based on mathematical calculations using the parameters characterising the heating technique and for the prescribed physical constants.

6.3 Strata under thermal impact

During UCG, the strata are subject to both mechanical and thermal loads. Gerdov (1940) argued that the thermal impact on different strata could be very different and each case needs to be studied individually.

Under high temperatures, the strength of the geomaterial can either increase or decrease. Generally, over the range of the UCG temperatures, the laboratory tests show that the geomaterial strength increases. The uniaxial compression strength of shale at the Lisichansk station was shown to increase from 7.7 MPa to 40.7 MPa after UCG (Russo and Kazak, 1958). According to Russo and Kazak (1958), the strength of a sample of shale with high SiO_2 from the Lisichansk station increased from 24.2 MPa at 0°C to 87.0 MPa at 900°.

Fig. 2 shows the relationship between temperature and strength of clay at the Mosbass, and rock of the Donbass and Kuzbass. The common trend is that mainly the strength increases with the temperature until a particular temperature, for example, 800°C for the sandy clay and 1000°C for the organic clay with high coal content, so-called coaly clay. After these temperatures, the strength decreases due to the agglomeration of the soil particles (Semenenko and Turchaninov, 1957). The strength of the sandy clay increases more rapidly until 400°C due to water evaporation (Semenenko and Turchaninov, 1957). In Fig. 2, the rocks increase in strength less than the soils; however, the coaly clay has the opposite behaviour. At the beginning of burning, the strength decreases until 400°C is reached because the coal particles burn and fracture (Semenenko and Turchaninov, 1957). This agrees with Ruschinsky (1952) who concluded that the compressive strength of the Moscow basin coal reduces from 2.02—1.61 MPa to 0.70—0.75 MPa under the thermal impact and after coal burning, the left ash has strength of only 0.02—0.04 MPa. Fig. 2 also shows the strength of the clay increases almost linearly with temperature. Semenenko *et al.* (1952) pointed out that the clay lost its plastic properties under high temperatures.

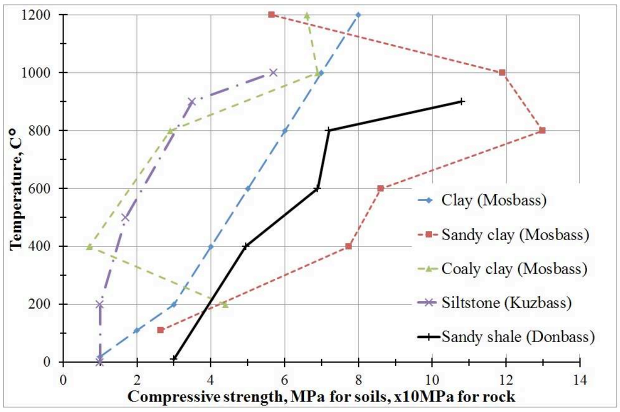

Fig. 2 Compressive strength under different temperatures (for soils modified after Semenenko and Turchaninov, 1957; for rock modified after Antonova et al., 1990)

6.4 Change in volume

The other effect of the thermal impact on the strata is volume change. This expansion or contraction in the strata volume can markedly reduce or increase surface subsidence. Table 5 shows two different borehole logs after a UCG event. Borehole 2 has 0.75 m of slag, and borehole 3 has 1.4 m of slag. The deformation of the strata over borehole 3 was insignificant and failure was not observed (Kazak, 1965). Kreinin and Kogan (1963) observed that for the coal, the highest rate of the increase in volume was between temperatures of 350—450°C.

Gerdov (1940) conducted several thermal experiments on the strata samples from the Donetsk and the Moscow basins. The 50 mm long and 35 mm diameter cylindrical samples were kept in a stove and under no load as well as a constant load of 0.5 MPa. Gerdov (1940) came to the following conclusions:

- The Donetsk basin limestone. The 600×45×55 mm sample starts sagging while set on two supports without load at a temperature of 1295°C. At a temperature of 1365°C sagging reaches 50 mm. The sample becomes powder (CaO) at a temperature of 1395°C and loses about 50% volume.
- The Moscow basin clay. The melting temperature is quite high at 1730°C and an initial soil increase in volume is observed at temperatures of 600—800°C.
- The Donetsk basin shale starts deforming at 860—940°C under a constant load of 0.5 MPa with

plastic deformation starting at 1000—1140°C. The deformation ends at 1030—1250°C and at 1470—1580°C the rock melts. The shale of the Moscow basin starts deforming, increasing in volume at almost the same temperature of 970°C. Fractures appear at temperatures of 970—1100°C without exfoliation, and melting starts earlier at 1000°C.

The laboratory experiments by Russo and Kazak (1958) showed that the coefficient of the volume increase, the so-called swelling coefficient, for the shale of the Lisichansk station rises non-linearly over temperatures of 1000—1200°C (see Fig. 3) and the plastic state is reached at 1200°C. The swelling coefficient can be as high as 2.2. Moreover, the in-situ volume increase is greater than the theoretical extrapolation of this value because of the increase of fractures and porosity in the bulk material (Russo and Kazak, 1958).

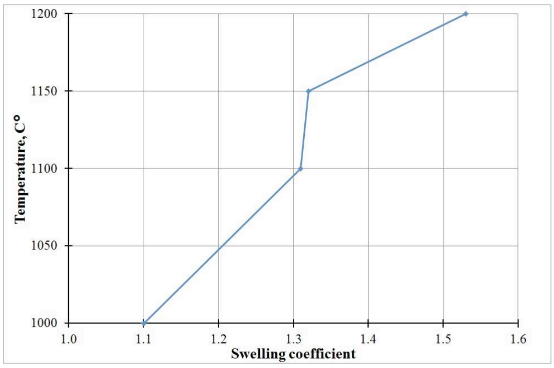

Fig. 3 Swelling coefficient under different temperatures (modified after Russo and Kazak, 1958)

Porosity is partly responsible for the volume change in a geomaterial which is an important factor of soil deformation (Chen *et al.*, 2014). Fig. 4 shows that within the sandy clay (the Moscow basin) porosity does not change greatly with increasing temperature. However, the clay porosity increases at low temperatures (200°C—600°C) and decreases at higher temperatures (600°C—1200°C).

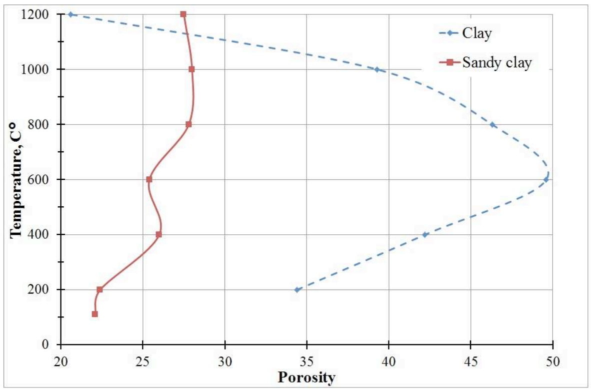

Fig. 4 Changes of porosity under different temperatures (modified after Semenenko and Turchaninov, 1957)

6.5 Role of the ash in subsidence

One more feature of UCG is that the void is partly filled with ash after the underground burn of the coal. Turchaninov (1956) pointed out that the physical-mechanical ash properties can have an impact on the ground surface subsidence. According to Gregg *et al.* (1976), the coal in the Moscow basin has the highest ash content of up to 60%, whereas the others have approximately 10% ash content. Turchaninov (1956) gives ash shrinkage vs pressure curves (Fig. 5) for two samples of 14.1% and 21.0% ash contents taken at the Podmoskovnaya station, the Moscow basin.

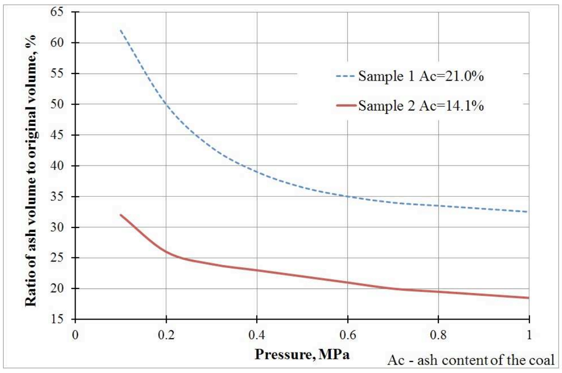

Fig. 5 Ash shrinkage vs pressure (modified after Turchaninov, 1956)

Fig. 5 shows that ash shrinkage decreases with pressure and at pressures greater than 1 MPa very little change in volume occurs. Turchaninov (1956) provided Eq. (4) to determine the volume of remaining ash (V_{ash}) after the UCG burn based on experimental results.

$$V_{ash} = 0.014 A_c V_y \tag{4}$$

where A_c = ash content in the coal in %; V_y = volume of the gasified coal in m^3.

The pressure on the goaf increases with the distance from the face during conventional mining. In Fig. 6, there is dependence between the pressure and the distance from the face after failure at the Moscow basin. Turchaninov (1956) suggested that it is the same for UCG but the transition should be smoother.

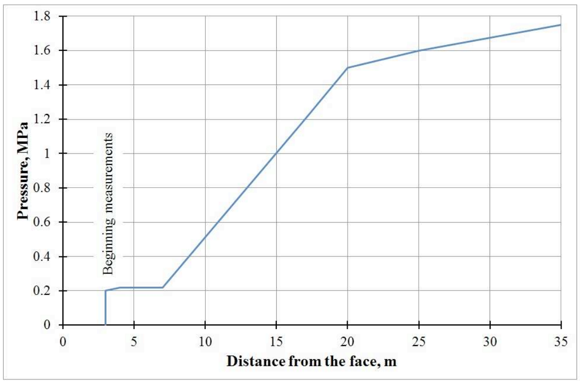

Fig. 6 Pressure vs the distance from the face (modified after Ruschinsky, 1952)

6.6 Groundwater

The temperature and mineralization of the groundwater can be a key to the UCG thermal effect and it should be investigated thoroughly (Kreinin *et al.*, 1991). According to Kreinin *et al.* (1991), the UCG area has an abnormally high water temperature and this can be seen 20 years after the burn at the Yuzhno-Abinsk UCG station. Also, higher groundwater mineralization was noticed near the UCG reactor (Kreinin *et al.*, 1991).

6 Conclusions

This paper has provided a review of some literature describing the Soviet experience of the UCG, with the main emphasis on ground movements. The main source of the literature was the National Library of Russia in Saint Petersburg. The papers reviewed were rather old, some being issued before World War II, and most of them are only available as hard copies. Two additional libraries could be useful sources to obtain further information: the Russian State Library in Moscow and the Library of the Russian Academy of Sciences in Saint Petersburg (access is limited). In this work, the focus is on early work on UCG because more recent developments have shifted from the countries of the former Soviet Union to other regions mainly due to discovery of the large natural gas deposits in the Soviet Union. Today, there is only one station, Angren station in Uzbekistan still operates by Yerostigaz, a subsidiary of Linc Energy and recently it has been announced that CBM Partners, a subsidiary of Red Mountain Energy launched the first UCG project in Russia for many years.

References

Ali, S.M., Pattanayal, P., Shubhra, 2012. Underground coal gasification techniques, problems and its solutions. *International Journal of Engineering and Innovative Technology (IJEIT)*, **2**(3):129-134.

Antonova, R.I., Bezhanishvili, A.I., Blinderman, M.S., *et al.*,1990. Underground coal gasification, Moscow, Central Research Institute of Economics and Scientific-Technical Information of Coal Industry (in Russian).

Arens, V. Z. 1986. Mining by boreholes, Moscow, Nedra (in Russian).

Chen, X.X., Luo, Z.J., Zhou, S.L., 2014. Influences of soil hydraulic and mechanical parameters on land subsidence and ground fissures caused by groundwater exploitation. *Journal of Hydrodynamics, Ser. B,* **26**:155-164. [doi:10.1016/S1001-6058(14)60018-4]

Clements, B.R., 1977. Progress report for the Texas utilities UCG program. In: Proceedings of the third annual underground coal conversion symposium. California: Lawrence Livermore Laboratory, p.81-82.

Fokin, D.A., 1954. Implementation of deep reference points for studying strata deformation at the Podmoskovnaya station. Underground coal gasification, 3 (in Russian).

Gerdov, M.A., 1940. Some results of the thermal study of the strata bearing coal seams. The bulletin on the issues of underground coal gasification, 1 (in Russian).

Gregg, D.W., Hill, R.W., Olness, D.U., 1976. Overview of the Soviet effort in underground gasification of coal. California: Lawrence Livermore Laboratory.

Gregg, D.W., 1979. Ground subsidence resulting from underground gasification of coal. [Includes analysis of USSR experience]. *In Situ* **3**(1):53-81.

Gusyatnikov, S.P., 1940. Permafrost and underground coal gasification. The bulletin on the issues of underground coal gasification, 1 (in Russian).

Kapitsa, S.P., 2010. Lecture. What should be done with the

science. Moscow (in Russian).
Kavalov, B., Peteves, S.D., 2007. The Future of Coal. Netherlands: DG JRC Institute for Energy (in Russian).
Kazak, V.N., Semenenko, D.K., 1960. Study of geological factors determining the underground coal gasification process. Management of the seam roof under Underground coal gasification. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **1**:72-82 (in Russian).
Kazak, V.N., 1965. Mechanism of rock performance under underground coal gasification of the thin, slightly sloping and sloping coal seams. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **13**:43-52 (in Russian).
Kazak, V.N., Kapralov, V.K., Kreinin, E.V., 1990. Ways of reducing heat losses under underground coal gasification. *Physical-chemical problems of mining,* **6**:91-96 (in Russian).
Klimenko, A.Y., 2009. Early ideas in underground coal gasification and their evolution. Energies, **2:**456-476.
Kolesnikov, P.T., 1935. To the question about stratum thermal conductivity. *Underground coal gasification,* **2**:9-11 (in Russian).
Kopytov, V.V., 2012. Gasification of condensed fuel: retrospective review, state-of-the-art affairs and development prospects. Moscow: Infra-Engineering. (in Russian)
Kreinin, E.V., Antonova, R.I., Dvornokova, Y.V., *et al.*, 1991. Underground coal gasification and preservation of the environment. In: Proceedings of the Skochinski Mining Institute, p.199-207 (in Russian).
Kreinin, E. V. 2010. Underground coal gasification. Bases of theory and practice, innovations, Moscow, Korina-ofset (in Russian).
Kreinin, E.V., Kogan, M.Y., 1963. Heaving of Southern Abinsk coal in the canal. Underground coal gasification. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **11**:38-46 (in Russian).
Kuprin, A.I., 1971. Collection in 9 volumes, Khud. Literatura (in Russian).
Lazarenko, S.N., Mazakin, V.P., Trizno, S.K., *et al.*, 2006. Underground coal gasification in Kuzbass: new possibilities, Kemerovo: Institute of Coal and Coalchemistry SO RAN (in Russian).
Lenin, V.I. 1973. Full collection of the essays, Moscow: Politizdat (in Russian).
Lykov, A.V., Pomerantchev, A.A., 1935. Calculation of heat losses for heating the wet soil under underground coal gasification. Underground coal gasification, **9**:3-14 (in Russian).
Macdonald, M., 2010. UK Electricity generation costs update. UK: Mott MacDonald.
Matveichuk, A.A., Evdoshenko, Y.V., 2011. The origins of the Russian gas industry. 1811-1945 Historical Essays, Moscow: Granitsa (in Russian).
Mendeleev, D.I., 1939. Essays, Leningrad: Literaturnoe nasledie (in Russian).
Miller, W.S., 1964. Burning process for recovering sulfur from the earth. Google Patents.
Ovchinnikov, V., Tyutin, F., Semenenko, D., *et al.*, 1966. Features of the rock deformation and its performance under underground gasification of the steep coal seam at the Kuznetsk basin (Kuzbass). *Underground coal gasification at the Kuzbass* **1**:130-146 (in Russian).
Riemann, B., Weber, H., 1927. Differentialgleichungen der Physik. Ph. Frank and R. von Mises, Braunschweig, 2 (in German).
Ruschinsky, M.V., 1952. Changes of the rock pressure in the longwall face of the mine #33 of Moscow coal. Collection of VUGI, 7 (in Russian).
Russo, Y.V., Kazak, V.N., 1958. Changes of physical-mechanical properties of the coal seam roof under underground coal gasification. *Underground coal gasification*, **4**:36-40 (in Russian).
Semenenko, D.K., Fokin, D.A., Turchaninov, I.A., 1952. Study of strata behaviour during UCG. Scientific-technical report. VNII Podzengasa (in Russian).
Semenenko, D.K., Turchaninov, I.A., 1957. Rock performance under underground coal gasification. *Underground coal gasification*, **3**:31-39 (in Russian).
Semenenko, D.K., 1965. About rock loosening under underground coal gasification at the Podmoskovny basin. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **13**:32-35 (in Russian).
Shtumpf, G.G., 1994. Mechanical properties of rock of the Kuznetsk basin and regularities of their change. *Physical-Chemical Problems of Mining,* **4**:43-50 (in Russian).
Skafa, P.V., 1960. Underground coal gasificaion, Moscow: Gosgortechizdat (in Russian).
Tian, H., 2013. Development of a thermo-mechanical model for rocks exposed to high temperatures during underground coal gasification. Doctor's Thesis, RWTH Aachen University.
Turchaninov, I.A., 1956. About some physical-mechanical properties of the ash residue under underground coal gasification at the Podmoskovny basin. *Underground coal gasification,* **7**:55-58 (in Russian).
Turchaninov, I.A., 1957a. About nature of underground coal gasification and deformation of the rock under underground coal gasification at the Podmoskovny basin. *Underground coal gasification,* **2**:74-78 (in Russian).
Turchaninov, I.A., 1957b. Ways of the solution for management of the top under underground coal gasification. *Underground coal gasification,* **2**:39-41 (in Russian).
Turchaninov, I.A., Sazonov, V.A., 1958. Some features of coal seam gasification and shifting overburden rock under underground coal gasification at the Shatskaya station. *Underground coal gasification,* **3**:11-16 (in Russian).
Turchaninov, I. A., Zabrovsky, A. S. 1958. Rock deformation and its influence on the process of underground gasification of the thick and steep coal seam. *Underground coal gasification,* **2**:7-11 (in Russian).
Vinogradov, B. G. 1963. About nature of rock fracturing in the area of the Shatskaya station. Underground coal gas-

ification. Scientific Work of All-Soviet Research Institute of Underground Coal Gasification, **10**:82-90 (in Russian).

Walter, K., 2007. Fire in the Hole. Underground Coal Gasification. Science & Technology Lawrence Livermore National Laboratory.

Zabrovsky, A.S., 1959. Conditions of seal saving of the underground gas generators in the steep medium-thickness seams. *Underground coal gasification,* **3**:6-10 (in Russian).

Zabrovsky, A.S., 1960. Seal failure of the underground gas generators in the steep seams and fighting against this phenomenon. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **3**:52-60 (in Russian).

Zamzow, K.L., 2010. Underground Coal Gasification: history, environmental issues, and the proposed project at Beluga, Alaska.: Center for Science in Public Participation.

Zhukov, V.V., 1963a. About possibility of interpretation of gasification of thick coal seam of Angrensk field by ground subsidence. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **11**:47-53 (in Russian).

Zhukov, V.V., 1963b. Preliminary results of the study of the rock massif disturbance during excavation of the Angren coal seam with different thicknesses. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **10**:77-82 (in Russian).

Zhukov, V.V., Ovchinnikov, V., Loshkin, E.L., *et al.*, 1963. To the question about influence of strata movement under underground gasification of the Angren coal seam on disturbance of the casing pipes of the underground gas generators boreholes. *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **10**:85-90 (in Russian).

Zhukov, V.V., Orlov, G.V., 1964. Ground subsidence under underground gasification of the coal seam at the industrial gas generator #3 at the Angren station "Podzemgaz". *Scientific Work of All-Soviet Research Institute of Underground Coal Gasification,* **12**:68-74 (in Russian).