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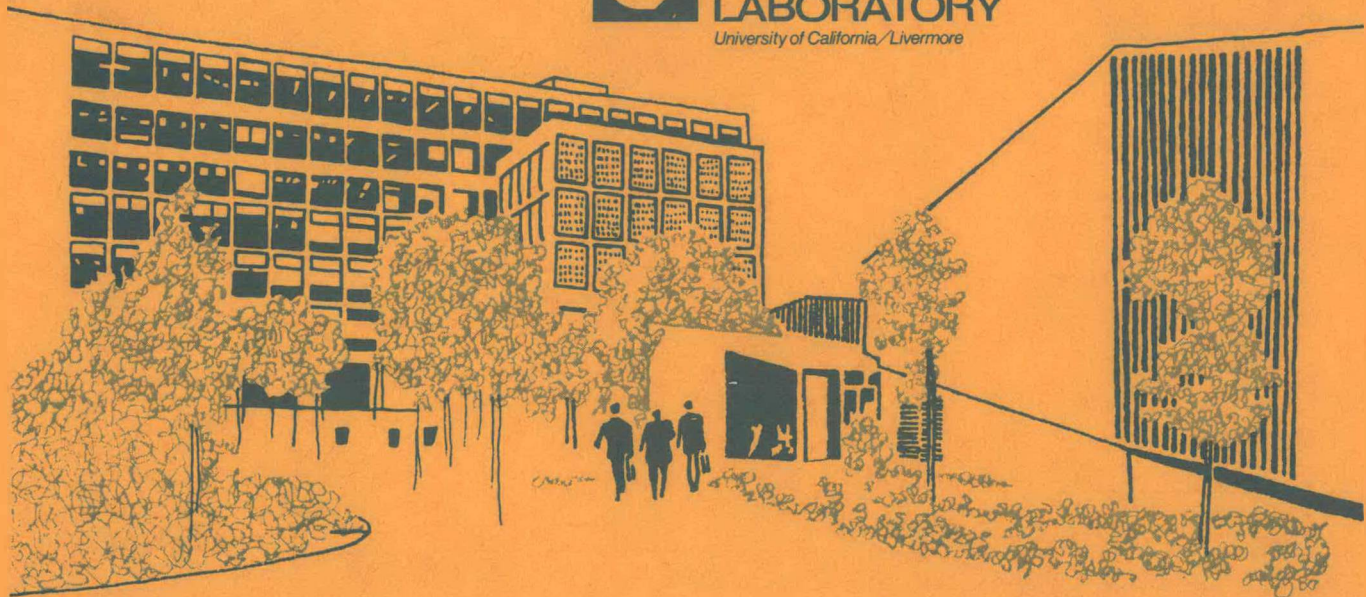
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GROUND SUBSIDENCE RESULTING FROM UNDERGROUND GASIFICATION OF COAL

David W. Gregg

March 29, 1977

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GROUND SUBSIDENCE RESULTING FROM UNDERGROUND GASIFICATION OF COAL

Abstract

Ground subsidence has been found to be a very significant physical phenomenon that must be dealt with in the design and operation of an underground coal gasification process. This report deals with the types of subsidence that one might expect,

and how they affect the process. A brief theory of bending subsidence is presented, and the experience the Soviets had while operating their commercial underground gasification stations is reviewed.

Introduction

One goal of underground gasification of coal is to utilize the total resource in the area being processed. When this is done there is no coal left to support the overlying material, and this roof material must of necessity subside into the void below. Therefore, it is important to understand how the subsidence occurs, its effect on the process, and possible environmental consequences in terms of surface movement and aquifer contamination or mixing. This report first addresses the forms of subsidence that might be expected from basic subsidence theory and experience. This information is then applied to what we can expect in a coal gasification system, which is finally compared to subsidence observed primarily in the

Soviet Union.

A description of typical underground coal gasification systems for both horizontal and steeply dipping coal seams has been presented by Gregg and Olness.^{1,2} All of these systems are constructed by first forming a pattern of parallel, highly permeable channels along the bottom of the coal seam and intersecting them periodically with pipes leading to the surface, which are used for air injection and product gas removal. When gasification takes place, the coal is removed by carrying out partial combustion in the channels that grow in diameter and extend up into the coal seam until they eventually merge. Initially, when the channels are small, they can form stable, open

channels supported by an arched roof. However, as they grow wider and approach merging, subsidence is unavoidable. The size to which the channel grows before the beginning of subsidence depends critically on the physical properties of the formation layers above the coal as well as the precise geometry of the opening. Hard rock roofs can support wide arches before they collapse, whereas soft clay roofs will sag into the void while the channels are still relatively small. All conditions between these extremes are possible.

Due to the importance of room and pillar mining, the ability of predicting quantitatively the limiting sizes of stable arches has been under very intensive investigations.^{3,11} The

mathematical treatments used are beyond the scope of this report and therefore will be referenced only. Such treatment, however, is important only when the coal has a competent roof and the cavern is supported on two sides. When the coal is overlaid by a thick layer of soft, flowable clay, as is often the case, we can assume that the roof flows or bends into the void almost as soon as the void in the channel extends from the bottom of the seam to the roof. Also, if initial collapse has already occurred, further gasification will probably result in the roof bending into the void almost immediately—even for competent materials—as it is supported on one side only.

Basic Principles of Subsidence

When subsidence (roof collapse) occurs, it can come about in at least four distinctly different modes. This depends upon the precise nature of the overlying formation as well as on the geometry of the cavern or parallel caverns. A measurable surface deformation may or may not result. The four modes are stoping or bulking subsidence (caving), chimneying, bending subsidence, and plug failure.¹⁴

STOPPING OR BULKING SUBSIDENCE

In this type of subsidence, chunks of rock fall sequentially from the roof into the void. It is a type of progressive failure, by spalling, whereby the roof of the void gradually moves towards the surface as the void is filled with rubble. In this case, there is a certain amount of bulking whereby the rubble occupies a larger volume

than it does when it is part of the roof. Depending upon the depth, bulking fraction, and size of the cavity, this bulking effect can dramatically reduce the surface subsidence to a small fraction of the initial void at depth or result in no measurable surface subsidence at all. This type of failure requires that the overburden be a brittle material, perhaps rock with preexisting fractures, as opposed to a malleable clay. Such a material has a tendency to form an arch. However, the failure occurs when the cavity reaches a size where the arch can no longer support the full pressure of the overburden and fails by spalling into the cavity. In an underground coal gasification system, arch failure may be abetted by the heat of the reaction drying and weakening the roof.

Clearly, the degree of bulking that occurs as the rock falls into the void varies in different situations. A good average assumption is that the fallen rock contains approximately 25% void, starting from essentially no void space.¹¹ As the fracture zone progresses, the arch span decreases, eventually forming a fracture zone that approximates an elliptical shape.^{7,11} Once the added bulk of the fallen rock equals the volume of the initial cavity, the fracture zone ceases to move further up into the overburden. If this happens before

the zone reaches the surface, little or no surface subsidence is observed. The primary effects that this type of subsidence has on a coal gasification process is to introduce gas leakage, through the rubble zone, to higher lying formations or possibly to the surface. This also would allow water from higher lying aquifers to drain into the gasification zone.

When the fracture zone, moving towards the surface, intersects a thick, malleable formation such as clay, further subsidence from the point of intersection to the surface will be dominated by bending subsidence. Refer to section on Bending Subsidence.

CHIMNEYING¹⁴

Chimneying is a type of caving subsidence that starts over a relatively small area and, by a succession of failures or sloughs, creates a hole or chimney that progresses rapidly to the surface. Over the length of the chimney the cross sectional area usually remains constant, and the diameter may be as small as 10 feet. Chimneys can progress through 1000 feet of cover in a matter of days, provided, of course, that the rubble is removed fast enough. The mechanism that causes chimneying may not be entirely different from the mechanism that produces the progressive type of caving described in the previous section of this report.

Since the affected area is so small, the rate of progress to the surface so fast, and the time and place that a chimney will develop so unpredictable, it makes this procedure appear to be unique.

Rice¹⁵ described a chimney cave resulting from opening a 14-by-28-ft roof area in a relatively incompetent graphitic slate, dipping at approximately 60°. The cave was created to provide backfill material; as the broken slate was drawn, the cave progressed vertically through 900 feet of cover, to surface in approximately one year's time. The cross section of the cave, through the rock, was about equal to the size of the initial underground opening. Chimney caves frequently develop in the cover overlying block-caving operations, usually before any other gross indication of surface subsidence. This type of cave has occurred in such dissimilar rock as highly jointed limestone and highly fractured porphyritic granite. In both rock types, the development of the cave was first realized when small trees were found underground in the broken ore. In both of these cases it was also inferred that the diameter of the cave was small all the way to the surface, as the volume of caved material did not cause an appreciable dilution of the ore. When chimneys develop over block-caving operations, the surrounding surface

area usually subsides shortly thereafter and, as this more general subsidence continues, the chimney may become obscure.

If chimneying were to occur in an underground coal gasification system, it would create a gas leakage path that might extend all the way to the surface. The Soviets apparently experienced this type of subsidence when they gasified thick, steeply dipping beds, which will be discussed later in this report. They had to stop the leaks by filling the resulting holes with mud at the surface, using a bulldozer.

BENDING SUBSIDENCE

Bending subsidence (trough subsidence) results when the overburden simply bends or sags into the underground cavern. One of the most significant features of this type of subsidence is that there is very little bulking, with the result that—above a critical cavern size—a large fraction of the underground displacement is observed at the surface, regardless of cavern depth.⁵ This type of subsidence is most likely to occur when the roof material is a soft clay. However, it can also come about with rock overburden, for much wider caverns, when the rock is strong with minimal naturally occurring fractures.¹²

The depression that develops at the ground surface, as a result of bending subsidence, is generally characterized by both vertical and horizontal displacement.^{5,13} Vertical displacements generally extend beyond the boundaries of the extraction area, as shown in Fig. 1. Distance AB in Fig. 1(a) is commonly called the draw and the angle α is called the angle of the draw. The zone of material that shifts as a direct result of the excavation is referred to as the zone of influence.

The surface profile that develops as a result of subsidence, for a given angle of draw, depends on the ratio of the lateral extent of mined area to the depth of deposit. See Fig. 1 for the three stages of mining subsidence commonly referred to as subcritical, critical, and supercritical. The meaning of these terms is made clear by considering the surface movement at point P as a result of increasing the lateral extent of excavation. For a small excavation, point P will sink by some value, S. In this region, S depends upon the area of extraction; this is called the subcritical stage. When the size of the extraction is increased laterally, the sinking of point P will increase continuously until it reaches some maximum value, S_{\max} , as shown in Figs. 1(a) and 1(b). The area of extraction associated with the maximum

depression of P (e.g. when $S = S_{\max}$) is called the critical area. Further increases in the mined area have no effect on point P. Thus, the mining operations have now reached the supercritical stage.

Distribution of surface displacement over a two-dimensional extraction area is expressed mathematically in terms of a profile function.¹³ This expression for the profile is typically a function of the maximum subsidence possible at a particular point (S_{\max}), the depth of deposit (h), the angle of draw (α), and the horizontal position (x) of the point on the surface.⁵ Due to the symmetry around the center axis of the subsidence crater, the profile function is an equation for only half of the subsidence surface. It ranges thus from full subsidence to zero subsidence.

One commonly accepted profile function for coal mining is given by the expression^{5,13}

$$S(x) = \frac{S_{\max}}{2} \left[1 - \tanh \left(\frac{2x}{h \tan \alpha} \right) \right] \quad (1)$$

for subsidence in the critical and supercritical stage, and by the expression

$$S(x) = \frac{S_{\max}}{2} \times \left[\tanh \frac{2(x+d)}{h \tan \alpha} - \tanh \frac{2x}{h \tan \alpha} \right] \quad (2)$$

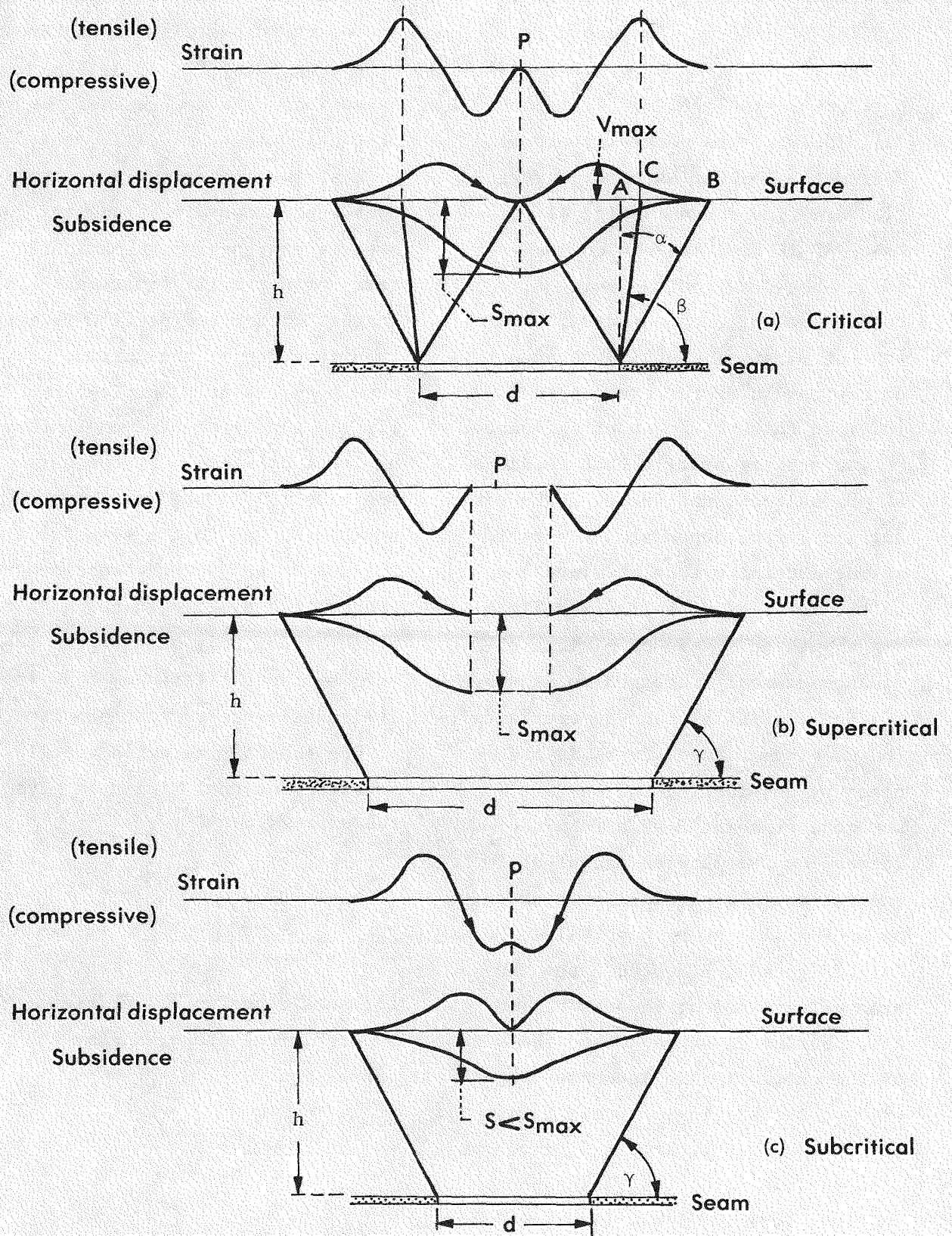


Fig. 1. Extraction areas and surface movements.⁵

for subsidence in the subcritical stage, where d is the full width of the mined area. Although a number of different profile functions have been reported, most of them are similar to those described by Eqs. (1) and (2). However, the mathematical form of these profile functions varies considerably. It is well known that the full subsidence (S_{\max}) is proportional to the seam thickness and the proportionality constant is between approximately 0.70 and 0.90.⁵

From numerous coal mining field observations, it was found that the horizontal displacement is directly proportional to the slope of the subsidence profile function, that is

$$y(x) = \frac{k \partial S(x)}{\partial x}. \quad (3)$$

Therefore, $y(x)$ for horizontal displacement can be obtained by direct differentiation of Eqs. (1) and (2) where $k = V_{\max}/(S_{\max}/h \tan \alpha)$. V_{\max} can be related to S_{\max} assuming that the horizontal displacement above the edge of the extraction area is a linear function of depth and has limiting values of zero at the seam and V_{\max} at the surface. Unfortunately, this has not been experimentally verified and thus represents the weakest point in calculating horizontal displacements.⁵ Assuming this, V_{\max} is given as

$$V_{\max} = \frac{\tan \alpha (\ln 2)}{2} S_{\max} \quad (4)$$

for critical and supercritical extraction, and given approximately as

$$V_{\max} = \frac{S_{\max}}{2} (\tan \alpha) \times \left[\frac{2d}{h \tan \alpha} - \ln \left(\cosh \frac{2d}{h \tan \alpha} \right) \right] \quad (5)$$

for subcritical extraction.⁵ Angle β is called the angle of break with typical values in the range 60° - 80° .¹⁴

Three important interpretations of how this type of subsidence might affect an underground coal gasification process are:

1) In the central region of an underground cavern, the roof subsides in a manner that plugs gas flow to this region. The plugged region might not be totally impermeable to gas flow, but the permeability would certainly be very much less than if bulking subsidence had occurred.

2) Gas leakage or water intrusion through this central region is not likely to be great since it is not under tension and is sometimes under compression.

3) Gas leakage and water intrusion should be maximized along the lines of maximum tensile strain at the edges of the cavern. Such a line is represented in Fig. 1(a) by OC. In regions

of calculated tensile strain we can expect cracks to open up, creating highly permeable paths.

As the mined seam deviates from horizontal, the subsidence becomes asymmetrical.⁵ See Fig. 2 for expected changes such as:

- a) maximum subsidence does not occur over the middle of the mined area,
- b) angles of draw at the top and bottom of the mined area are not the same,
- c) horizontal displacements are no longer symmetrical.

A more quantitative treatment of these effects is presented by Brauner.⁵

PLUG FAILURE

Plugs are caving processes that involve what appears to be a distinctly

different subsidence mechanism.¹⁴ They are characterized by a sudden lowering, en masse, of the cover overlying an unsupported opening, such as the opening created by a block-caving operation. The suddenness of the failure is usually evidenced underground by an air blast and on the surface by venting and a dust cloud. The intensity of the air blast varies from weak to strong, depending on the volume of the void that is closed and on whether or not the excavated zone is partially filled with broken rock. Because the body of rock subsides en masse, as opposed to the progressive type of subsidence, there is almost no volume expansion of the subsiding material. Thus, the volume of the surface void should be roughly equivalent to the volume of

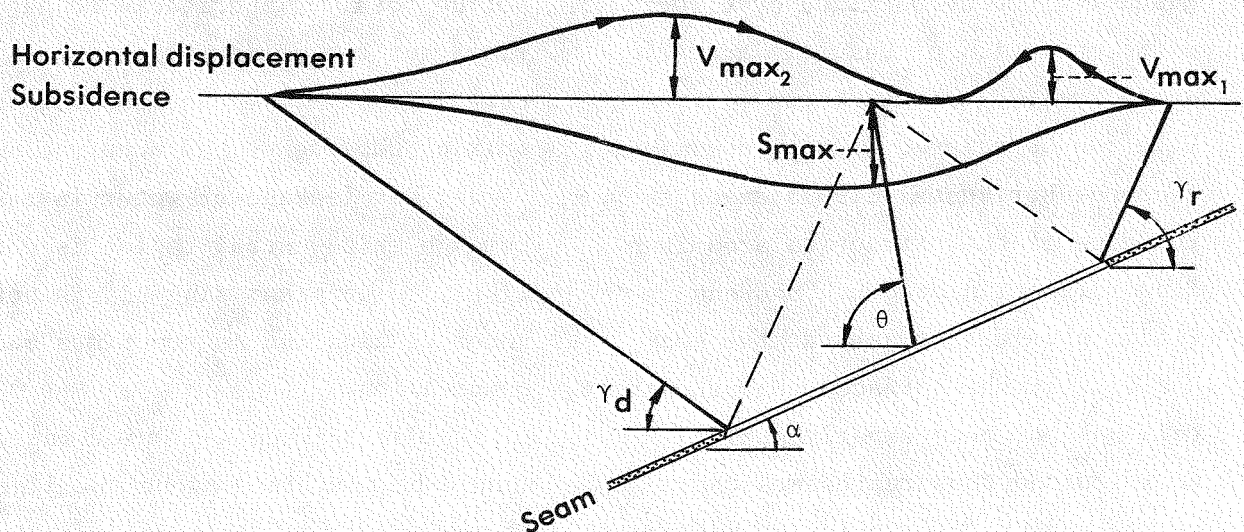


Fig. 2. Displacements over an inclined seam.⁵

unbroken ore removed from the operation, provided, of course, that the volume created by mining was not partially filled with broken rock or ore. Also, because the subsiding mass remains intact, the angle of break must be equal to or greater than 90°.

Plug subsidence generally occurs in weakly consolidated sediments or in closely jointed but weakly bonded rocks that in most instances show some weathering or decomposition products on the joint planes. This class of rock will not core and, as a general rule, the walls of exploration holes will collapse unless cased.

In some block-caving operations it appears that the subsidence process

starts with a succession of sloughs; after the cave has progressed part-way to the surface, the remaining cover fails as a unit. Usually, preceding failure, cracks or other signs of surface movement are not evident, at least to the unaided eye. Plug failures are more likely to occur in an area where the surface has already been broken by subsidence. Following the development of a plug, fractures, open cracks and terraces usually develop on the surface surrounding the resulting void. Ultimately these cracks and terraces obscure the original failure. No theory has been advanced to account for this type of failure mechanism.

Subsidence at the Podmoskovnaya and Schatskaya Underground Coal Gasification Stations in the Soviet Union

GEOLOGY

Podmoskovnaya and Schatskaya are located in the same general area, have the same type of deposit, and are thus discussed together.

Podmoskovnaya Station

A series of lignite and carboniferous boghead deposits extends over a 100,000-km² area, southwest of

Moscow.¹⁶ Because of the absence of tectonic and thermal influences, these beds have remained at a low stage of coalification.

The southern part of this basin extends around the city of Tula which is 200 km south of Moscow. The lignite beds are lenticular and are located between layers of clay, sand or very soft sandstone, at a depth varying from 50 to 200 meters. The thickness varies from 1 to 5 meters

and the deposit is full of water, making conventional mining of 35 million tons per year difficult.¹⁶

A relatively large metal industry was developed on the basis of this deposit and large gas-producing facilities—Lurgi system with enriched air—were built in Tula. These plants supplied part of Moscow's municipal gas requirements. The plants became less important when Moscow started receiving natural gas from the Northern Caucasus.

Underground gasification experiments were carried out in the Krustov region by various methods, even before the 1933 war. After 1940 all efforts were oriented towards methods not requiring underground labor but based on linking by countercurrent combustion. In 1940 a pilot plant was built by Podzemgaz, on the lignite bed of Novobass which is located 3 km southeast of Tula.

This station, called Podmoskovnaya, operated two beds of lignite. The first one, located at Novobass, had an irregular shape extending 2.5 km east to west and 2 km north to south. The coal seam thickness varied, and approximately only half of the 2.5-km² area contained coal that was more than 1 meter thick. The Soviets considered this to be the minimum seam thickness that could be gasified. The depth averaged 48 meters and varied between 34 and 60 meters; the thickness averaged 2.7 meters and

varied between 1.0 and 4.7 meters in the gasified zones. The coal seam was split into two to four subseams with different ash content, separated by layers of clay 0.2-0.5 m thick.¹⁷⁻¹⁹ A cross section of one portion of the area showing the coal seam and its overburden is presented in Fig. 3(c).^{20,21}

The bed contained 13 million tons of lignite with approximately 4.2 million tons recoverable.¹⁶ This reserve was exhausted around 1960 and a second bed was then operated at Gosteev, located 5 km southeast of the preceding bed. It had an elongated shape, stretching 2.5 km northwest to southeast and was 400 meters wide. The depth of the deposit was the same as that at Novobass; the thickness varied from 0.3 to 5.7 meters with an average of 3 to 4 meters. This bed contained 5 million tons of lignite of which approximately 2.6 million was recoverable, allowing the station to operate for an additional 5 years.¹⁴ The lignite had a calorific value of 2720 kcal/kg of whole coal with 25% ash and 25% moisture.

Schatskaya Station

The Schatskaya Station is located 100 km southeast of Tula, on top of a deposit very similar to the one at the Podmoskovnaya Station, consisting also of two lignite beds. The western bed,

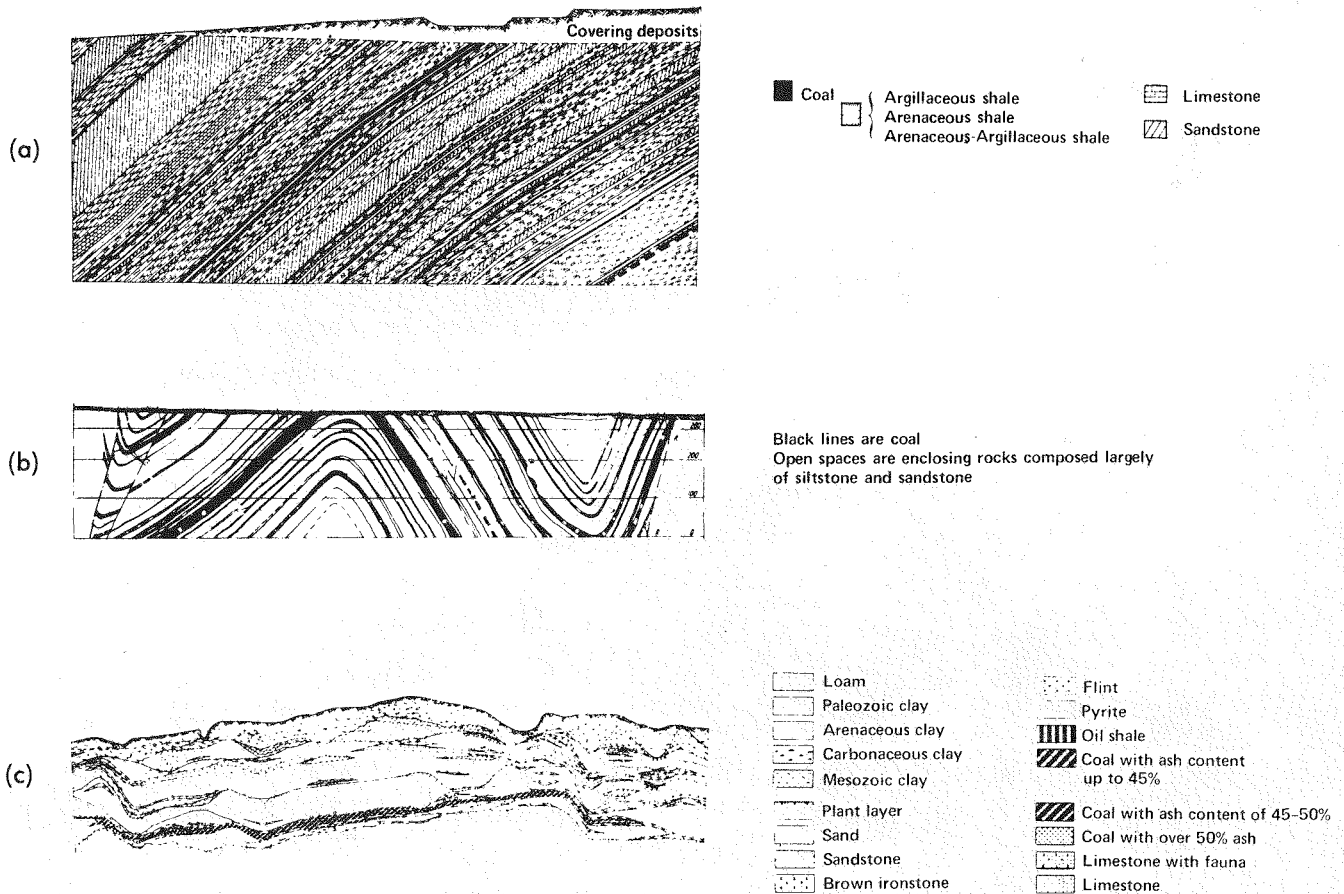


Fig. 3. Geological cross sections of the coal fields at (a) Lisichansk, (b) Yuzhno-Abinsk, and (c) Podmoskovnaya. We were unable to locate such a cross section for Angren. However, the figure does illustrate the variation in geological conditions addressed by the Soviets.¹⁰

located 2 km from the station, covers 10 km² and contains 19 million tons of recoverable fuel. The eastern bed, located 5 km from the station, covers 5 km² and contains 8 million tons of recoverable fuel. The entire bed is 40 meters below the surface with a varying thickness averaging 1.9 meters.

Overburden is the same as that at Tula with a roof that is partly sand and partly clay. The lignite contains 25% to 44% moisture and 37% ash, having a calorific value of 2600 kcal/kg.

The first tests at Schatskaya were carried out in 1956-1957. Schatskaya was planned as a replacement for

Podmoskovnaya which had almost exhausted its deposits at that time. At present, Schatskaya is still operating, whereas operations at Podmoskovnaya have been discontinued.

UNDERGROUND GASIFICATION PATTERN FOR HORIZONTAL SEAMS AND EXPECTED TYPES AND AREAS OF SUBSIDENCE

The Soviets gasified the Podmoskovnaya and Schatskaya coal seams by using a pattern of vertical wells, shown typically in Figs. 4(a) and 4(b). The vertical wells intersecting the coal seam were linked by countercurrent combustion.¹ Gasification was then carried out in either of two different ways. [See Figs. 4(a) and 4(b).] The decision depended on tradeoffs between gas leakage, flow resistance, flow control, gas quality, and resource recovery. The first method, illustrated in Fig. 4(a), involved injecting air into row 1 while removing the product gases from row 3. As the coal was removed, air injection was shifted to row 2 and product gas removal to row 4, thereby progressing along the coal seam.

The dotted lines from row 3 through row 5 outline the gas channel formed at the bottom of the coal seam by an earlier operation such as countercurrent combustion. The dotted lines from row 3 to line AB depict an expected location of the coal face at

some time during gasification. The shape of the cones of removed coal, between line AB and row 3, can vary significantly from one coal seam to another as well as in the same gasification pattern. Figure 4(a) shows symmetrical and regular cone shapes, to illustrate some typical features that are expected to affect subsidence.

One distinct area lies between line AB and the line through row 1. In this region, almost all the coal has been removed through gasification. As this region grows very large, through the propagation of the reaction zone along many rows of access pipes, it cannot arch. It will thus appear as a zone supported only on one side by coal, with the division being somewhere around line AB. It also has the feature that when the coal pillars between the gasification channels are gasified, they gradually become thin and eventually compress, thus setting the roof down gradually. This is in contrast to a long-wall mining operation where the roof is set down very abruptly behind the wall. We can thus expect primarily bending subsidence to take place when making the transition from coal to no coal, in the vicinity of line AB. Some bulking subsidence will probably also occur, but bending subsidence should predominate and should be evident in subsidence of the surface.

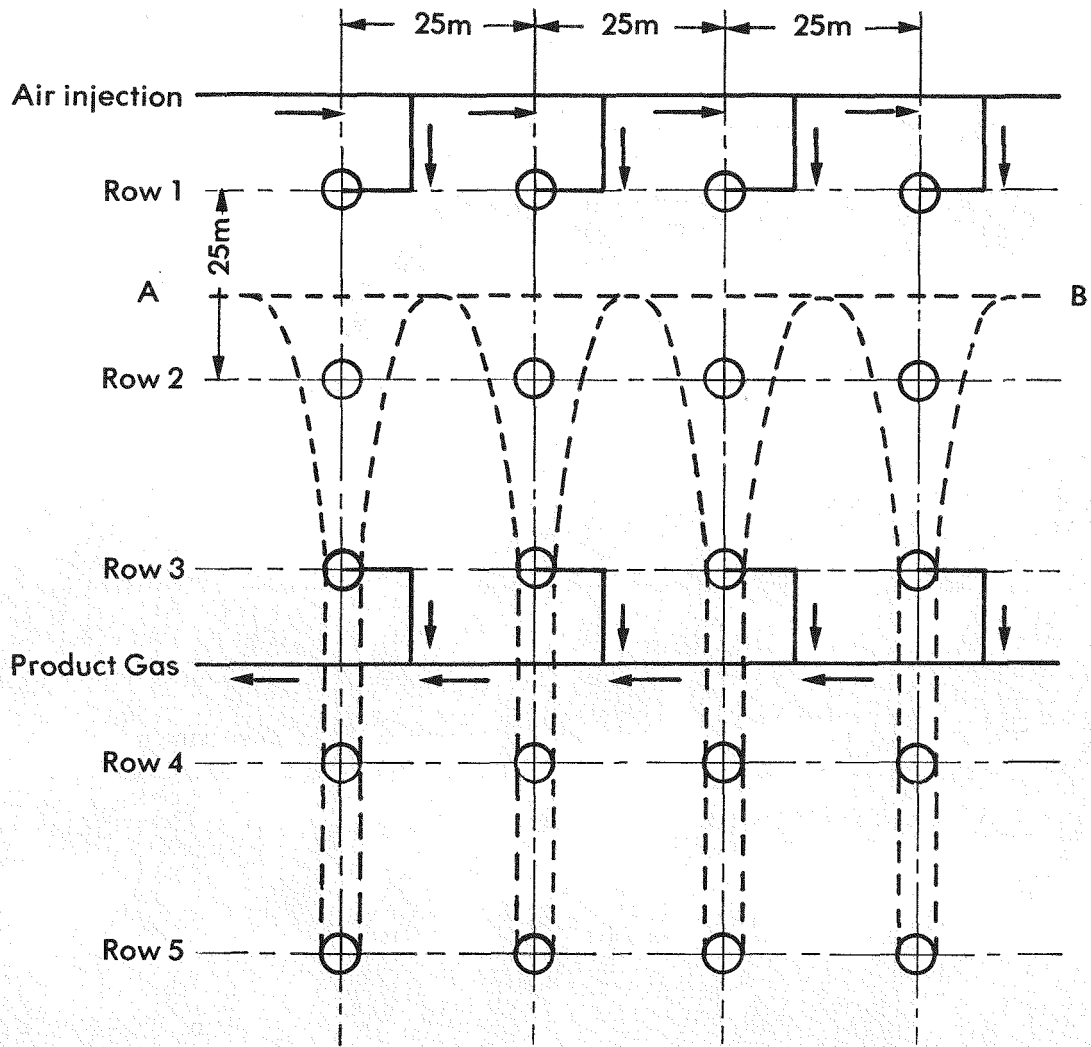


Fig. 4(a). Forward gasification in a typical pattern for horizontal coal seams.

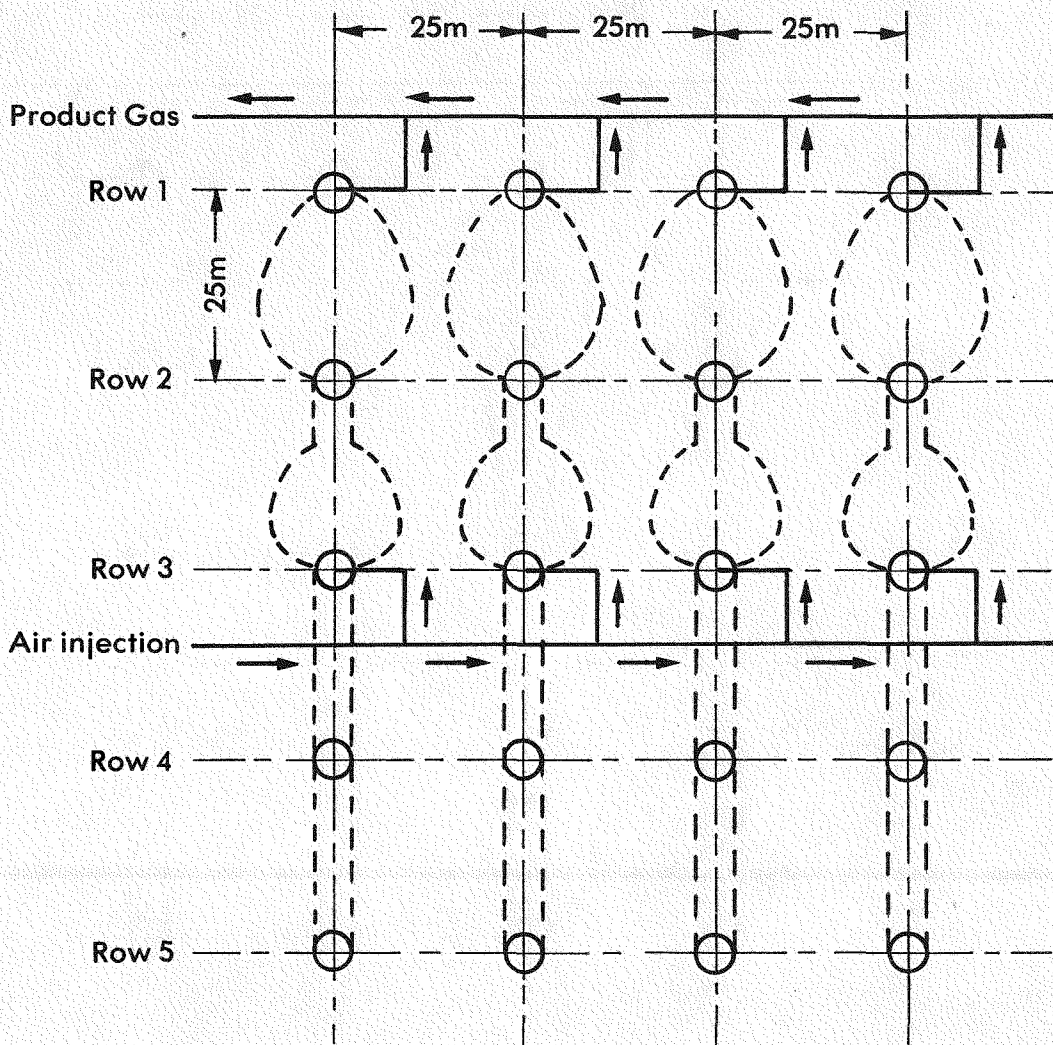


Fig. 4(b). Reverse gasification in a typical pattern for horizontal coal seams.

In the region from line AB to row 3, the linking channels are widened continuously. In this region the type of subsidence that will be observed is difficult, if not impossible, to predict in a quantitative way. It would be expected that initially the channel, while it is small, might form a self-supported hole with some coal rubble in it. As it grows, more coal will fall in until it reaches from the bottom to the top of the seam. At this point, the nature of the roof subsidence will depend critically on the physical nature of the roof. If the clay is soft and malleable, it will start to sag into the void. However, if it is more like a brittle rock or a sandy overburden, the result might be very different. In this region, we can therefore expect anything from stable caverns to any of the above-described types of subsidence, operating in an unpredictable manner.

Figure 4(b) presents the alternate method for gasification used by the Soviets. In this case, gasification initially takes place by injecting air into row 2 and withdrawing the product gas from row 1. When the gas quality falls off due to coal exhaustion, the injection is then moved to row 3. The product gas removal may then remain at row 1 or be moved to row 2. Figure 4(b) illustrates where

gasification was completed between rows 1 and 2 and air injection was then moved to row 3, with product gas still being drawn off at row 1. The significance of this figure is to illustrate the very different development of the underground cavern in the coal. In this mode of operation there may never be a total coal removal zone as shown in Fig. 4(a). Thus, there is no well-defined equivalent to bending line AB in Fig. 4(a). We therefore expect the subsidence to be dominated by caving or by bending into the individual channels as the channels widen. Any type of subsidence might then operate, depending on the nature of the overburden. Subsidence in any particular area might become predictable either through experimentation or extensive operational experience.

SUBSIDENCE AT THE PODMOSKOVNAYA AND SCHATSKAYA STATIONS

The Soviet system of gasification at Podmoskovnaya and Schatskaya, described in the previous section, includes also a gasification rate of 2000-3000 Nm³/hr of air per channel (Nm³ is standard cubic meters). The rate at which the surface subsided, even over the areas where gasification was most intense, was comparatively small (30-60 mm/day).^{16,22} The subsidence also occurred in a regular,

continuous manner as the gasification was carried out.^{22,23} This is in contrast to a catastrophic subsidence one might expect from the sudden collapse of a large cavern. Semenenko²² also pointed out that the surface subsidence immediately followed the gasification. When the gasification rate was increased or decreased, the subsidence rate followed it correspondingly without any observable time delay. A very important result was that the spatial progress of the underground gasification zone was monitored continuously by monitoring the spatial and time dependency of the surface subsidence.^{22,26,27,29,30} The continuousness and immediateness of the subsidence was probably due to a combination of the overburden having a large clay and sand content of very low strength and to the very large area of coal being swept out by the gas generators (several hundred meters wide). This span was much too large for the self-forming arch to hold up the roof. Unfortunately, none of the Soviet papers describing subsidence reveal the direction of gasification, discussed in the previous section.

An excavation was carried out at Podmoskovnaya after gasification. No self-supporting caverns were above 1 meter in diameter.²¹ This further indicates that the immediacy of the subsidence was probably due mainly to the existence of the malleable clay

overburden which almost immediately folded into any void that was formed. It would also have been possible to use surface subsidence to monitor coal removal not only along line AB in Fig. 4(a), but also in the fingers between line AB and row 3, as well as in the unconnected gasified zones illustrated in Fig. 4(b).

The Soviets made some quantitative measurements of the subsidence at Podmoskovnaya, which are presented in Fig. 5.¹⁶

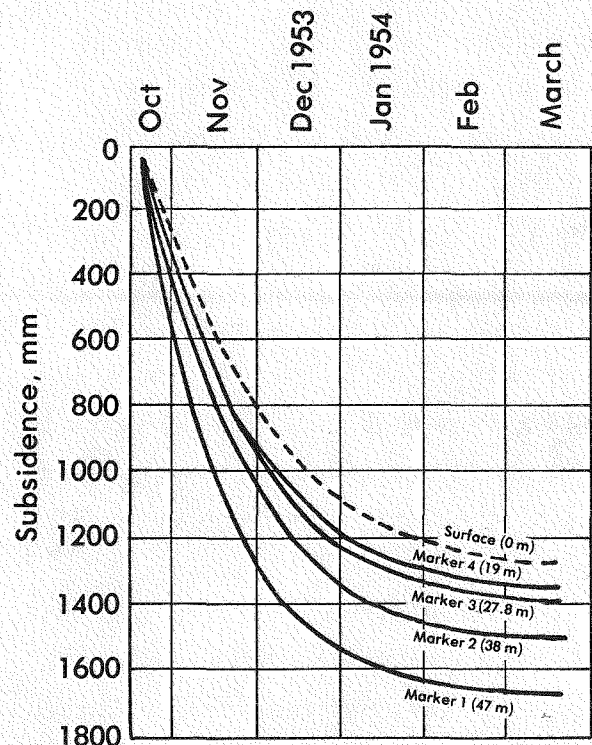


Fig. 5. Subsidence and its rate of progress for the surface and for markers anchored at various depths in a hole (marker 1 is at the roof of the bed) (Tula station).

This figure shows the time and depth dependency of subsidence, over

one of the channels, during gasification and illustrates three interesting features:

1) There appears to be no time lag between subsidence immediately above the coal seam and subsidence at the surface.

2) There is a slight amount of bulking whereby the surface subsidence is slightly less than the subsidence immediately above the seam.

3) The final subsidence was close to 2 meters for gasification of an approximately 3-meter-thick seam at a time later than shown in the figure. This accounts for almost all of the carbonaceous content of the seam since the coal was approximately one-third ash. On the basis of these data, we conclude that bending subsidence best describes the behavior at Podmoskovnaya, even though there

was a slight amount of bulking. This is also consistent with the observation of cracks that reached the surface from the gasification zone, as identified by gas leakage.²² Such cracks were not continuous over the entire surface above the gasified zone, but were localized to a relatively small area near the edge of the gasified space. As discussed earlier, this is consistent with what we expected from the model for bending subsidence and did not expect for the other types of subsidence. After a zone had been gasified, the final surface profile consisted of a slight ripple having the dimensions and shape of the gasification generator, with the spacing between the valleys being equal to the spacing between the channels. The exact magnitude of the ripple was not reported.

Subsidence at the Angren Underground Coal Gasification Station

GEOLOGY

Angren is situated in the Uzbekistan Republic (Turkestan) and is 120 km southeast of Tashkent.^{16,24} The Angren deposit of brown coal was discovered in 1933, and detailed prospecting of the deposit began in 1940.²⁵ This deposit is one of the largest in Central Asia. In the

northeastern part of this deposit the brown coal stratum is 60 meters thick. At the point where the underground gasification station was built, the coal seam thickness varied from 3 to 20 meters, having an average thickness of 9.2 meters. The depth varied from 110 to 195 meters, averaging 150 meters, and the slope varied from 5° to 15°. Gas permeability of brown Angren coal

is higher than that of Moscow coal. Mean moisture content of the crude coal is 31%, ash content of the dry fuel is 16%, and sulfur content is 1.5%. The calorific value of the coal is 3650 kcal/Nm³.

The floor of the bed consists of 10 to 15 meters of clay and alevrolite, covered by a layer of basalt. At the roof of the bed a coaly schist of 40 meters, containing 10% combustible matter, was partly gasified with the coal. Higher up exists a layer of kaolin 20 to 30 meters thick that helped minimize gas leakage. Several water-bearing strata also exist in the overburden.

Construction of the station began in 1952, and it is still operating at present. It was planned to be the

largest underground gasification station in the Soviet Union with the capacity of producing 2.3 billion Nm³ of gas per year, having a calorific value of 1000 kcal/Nm³.

SUBSIDENCE AT ANGREN

Underground gasification at Angren was carried out in the same basic pattern as at Podmoskovnaya. In general, the resulting subsidence at Angren was not studied in as much detail which evidently was due to lack of concern, since land is fallow as compared to Podmoskovnaya.¹⁸ There appears to be no quantitative subsidence data in the literature comparable to the data obtained at Podmoskovnaya.

Subsidence at the Lisichansk and Yuzhno-Abinsk Underground Coal Gasification Stations

GEOLOGY

The Lisichansk and Yuzhno-Abinsk underground coal gasification stations, although widely separated geographically, have the common feature of gasifying steeply dipping coal seams. The design of the underground portion of the system follows the same basic

approach. Lisichansk has thin seams (0.4-1.5 m) and Yuzhno-Abinsk has thick seams (0.8-9 m), making it useful to compare them both in this section.

Lisichansk Station

The Lisichansk underground coal

gasification station lies on the southwestern outskirts of Lisichansk and occupies part of the water-divide region between the Severnyi (North) Donets river and the right-hand tributary of the Belenka river. The Donets basin site is about 4.5 km long and 1.6 km wide, covering an area of 7.2 km². (See Ref. 20.) The ground surface inclines to the southwest and is dissected by deep narrow ravines, some with regularly flowing water (up to 15 m³/hr). Relative elevations in the area reach 100 meters.

The Donets basin proper, also called the Old Donbass, stretches 150 km from west to east.¹⁶ It occupies 23,000 km² in the eastern part of the Ukraine and extends into the territory of the Russian Republic (Rostov) to the east. New discoveries have doubled the Great Donbass area which is assumed to extend to Kiev in the west and to the Volga in the east. It is the oldest and most important producing basin, supplying 35% of the total USSR coal since 1955. In that year it produced 140 million tons out of the USSR total of 391 million tons. Its relative importance, however, is decreasing as new basins are being developed in Siberia. The size of the deposit was clearly a major stimulus for the Soviets in establishing an underground coal gasification station in this area. If

the problems associated with gasifying this coal could be resolved at one location, an almost generic solution for a very large energy supply would be at hand.

The Donets basin dates from the carboniferous age and has been strongly disturbed tectonically. It contains 120 workable beds with the quality varying from anthracite to steam coal and containing a large proportion of coking coal.

The underground gasification station at Lisichansk was located at the outcrop of a dense cluster of 13 thin seams that slope toward the south at a regular 30° to 45° angle. [See Fig. 3(a).] Ten of the seams were considered suitable for gasification since they are at least 0.4 meter thick. Except for one seam that is 1.5 meters thick, all other seams that are suitable for gasification vary in thickness from 0.4 to 0.8 meter.²⁴ Argillaceous and arenaceous shales largely exist in the seam roof and floor rocks. Limestone exists in the roof of some of the seams. The seam outcrops are covered by a thin layer of younger formations and the seams have been mined to the 40-meter level. The calorific value of the mined coal is 4500 kcal/kg, and the ash and volatile contents of the coal are about 15% and 40%, respectively. Water inflow is linked with sandstone and limestone. Coal reserves for

industrial purposes, at the 500-meter level, amount to 41 million tons.

This deposit is characterized by an abundant water inflow. Old mines are located close to the gasification sites and have permitted complete exploration of certain panels to be carried out, after gasification.

Some of the earliest work on underground coal gasification in the USSR was carried out at Lisichansk in 1933. Work continued up to World War II when the Germans destroyed the station. It was rebuilt after the war and operated for some time before operation was discontinued.

Yuzhno-Abinsk Station

The Yuzhno-Abinsk station is located in the Kuznetzk basin at the southeastern end of western Siberia, near the sources of the Tom river. This is a few hundred kilometers from the Chinese border.^{16,32}

This basin, of Permian age, extends over 26,700 km². It is the second-largest producing basin in the USSR (15.3% of the total production in 1958) and its importance is growing. Its reserves, which are five times those of the Donets basin, contain 30% coking coal.

Construction of the underground gasification station began in 1952 and the station first went into operation in 1955. It is located near

Kiselovsk, in the central section of the basin, above a cluster of 23 seams of coal. Average thickness of the seams is between 0.8 and 9 meters, with the exception of the Moshchnyi seam which has an average thickness of 20 meters. The average thickness of the seams, excluding the Moshchnyi seam, is 2.72 meters. The combined total thickness of all the seams is 79.8 meters, forming an acute syncline. The edge of the syncline is almost 200 meters deep for the main bed, and its sides have a 55°-70° slope. The coal has an average ash content of not more than 9% and a moisture content of not more than 8% in situ. The roof and floor of the seams show siltstone or sandstone, and sometimes argillite. [See Fig. 3(b).] At the time of this writing this station is still in operation.

UNDERGROUND GASIFICATION PATTERN FOR STEEPLY DIPPING SEAMS AND EXPECTED TYPES AND AREAS OF SUBSIDENCE

The types of subsidence that can be expected and their specific locations in the gasification pattern are illustrated in Fig. 6, which represents a diagram of a typical underground gas generator for steeply dipping coal seams. The figure shows in concept the spatial distribution of how the coal might be consumed after a significant amount of gasification has

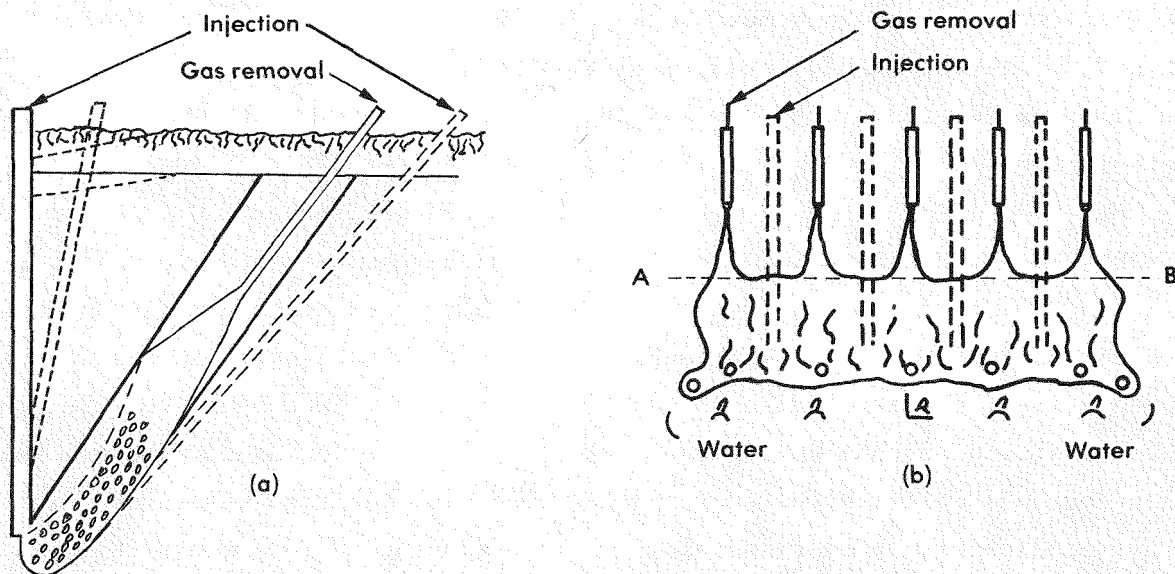


Fig. 6. Typical diagram of an underground gas generator for steeply dipping coal beds: (a) end view, (b) plan view.

taken place. It illustrates two distinctly different zones, separated by line AB [Fig. 6(b)], and very different subsidence characteristics can be expected above and below the line.

Below line AB one can expect relatively well behaved bending subsidence with the surface subsidence being slightly shifted horizontally from the ground movement immediately over the seam. This shift has been discussed in this report and illustrated in Fig. 2.

The most catastrophic, uncontrollable, and unpredictable subsidence characteristics that have been observed when gasifying thick seams have been due to general growth and widening of the coal channels above line

AB. As the channels widen, they can form large diameter shafts that have a very significant vertical component. In the extreme case of a 90° dipping seam, they are vertical, open shafts that gradually grow from the bottom up and widen as they grow. As they approach the surface, there is a point where the surface will collapse into the cavern. This collapse can be visualized, in part, as a relatively thin surface layer collapsing into a very deep and wide, almost vertical shaft. This subsidence cannot be described correctly as bending subsidence, but rather as bulking or chimneying subsidence, which takes place in a very unpredictable and catastrophic manner. When this happens,

it opens up a large permeable hole in the gasification zone that must be plugged to prevent massive gas leakage. The plugging is accomplished by filling the hole with mud by using a bulldozer.

SUBSIDENCE AT THE LISICHANSK STATION

When the coal seams at Lisichansk were gasified, the exact distribution of the gasified regions vs regions where coal was left unaffected was not always predictable or reproducible. This could have been due to very thin seams which would result in small changes in thickness and have a great effect on the process. The distribution that was found in one gasification experiment is presented by Silin-Bekchurin et al.²⁰ In this experiment, one side of the panel being gasified was dominated by "fingering" (a general widening of the gasification channel drilled along the coal seam) with little removal of coal between the channels. This is illustrated by the zone above line AB in Fig. 6. The other side of the panel (gasified in the same experiment, at the same time) showed very little fingering with the coal between the channels being removed efficiently.

In either case, very little subsidence was observed at Lisichansk, due to the thinness of the seams and the thermally induced swelling and slagging of the roof rock.^{16,22}

The subsidence rate was very small (1 mm per day). In one typical case for the thickest seam gasified (2 meters), the total subsidence was 0.43 meter after 4½ years.

Since Lisichansk was located near existing mine operations, it was possible to excavate gasified regions and thus accurately determine the nature of the subsurface subsidence. One of the dominant features observed was the large amount of slag formed in the regions where the coal had been gasified.^{34,35} One would expect the amount of slag formation to be larger at Lisichansk than at any other station since oxygen-enriched air was used most of the time for the gasification. This would increase the burn temperature. The slag had a bulking effect in two ways:

- a) it was full of voids, causing it to swell to approximately twice its original volume, and
- b) it formed pillars which supported the roof in some regions. Some bulking collapse occurred in some regions between the pillars and extended approximately one seam thickness (2 meters) into the overburden. The remaining subsidence appeared to take place as bending subsidence.

SUBSIDENCE AT THE YUZHNO-ABINSK STATION

Reports on subsidence at Yuzhno-

Abinsk have the common theme that, as the burn front approached the surface, severe subsidence occurred with abrupt formation of deep craters, resulting in a dramatic increase in gas leakage from the system until the craters were filled with mud by bulldozers (Refs. 16, 21-23, 32, 33, 36).

Many quantitative measurements of subsidence rate vs time were made with level markers at the surface and at various levels below the surface. The distinguishing feature of the subsidence at this station was its magnitude and its catastrophic nature. Bending subsidence would occur at some relatively stable rate during the gasification, and then, rather unexpectedly, there would be a very abrupt increase in the subsidence rate around the production holes, forming craters. In one typical experiment reported at this station, the Soviets were gasifying a seam that averaged 7 meters in thickness (IV Vnutrennyi).³² As the flame front approached the surface, subsidence craters up to 20 meters in diameter and 15 meters deep were formed. The surface subsidence rate changed from approximately 500 mm/month to 1700 mm/20 min.³⁶ These craters generally occurred in the region of the production holes. (See Fig. 7.) However, the craters did not occur in the coal outcrop itself, but in the overburden. (See Fig. 8.) Because of this occurrence

the gas flow or pipe connections that went into the coal from the outcrop were not disrupted. Collapse of the overburden, however, temporarily disrupted the process by causing gas leakage to increase from 15% to 40%. This leakage was reduced to 25% by filling the hole with mud. A general view of subsidence development for this experiment is presented in Fig. 7.²¹ It can be seen that there are not only subsidence craters around the gas exhaust holes, but that there is also general subsidence of the gasified region. This would indicate that some general bending subsidence occurred over the entire gasified region, with chimneying subsidence possibly best describing the cratering.

The most likely explanation for the craters around the exhaust holes can be seen in Fig. 6. General widening of the drilled channels in the coal, illustrated by the fingering above line AB, can generate fairly wide shafts along the seam. These shafts are at the same dip as the seam. For steeply dipping seams, such shafts will correspondingly approach the vertical. As these shafts grow and approach the surface, the surface layer eventually becomes so thin that it collapses into the cavern. In this case, for steeply dipping seams, the effective cavern depth is not limited to the thickness of the seam, but can be many times the seam

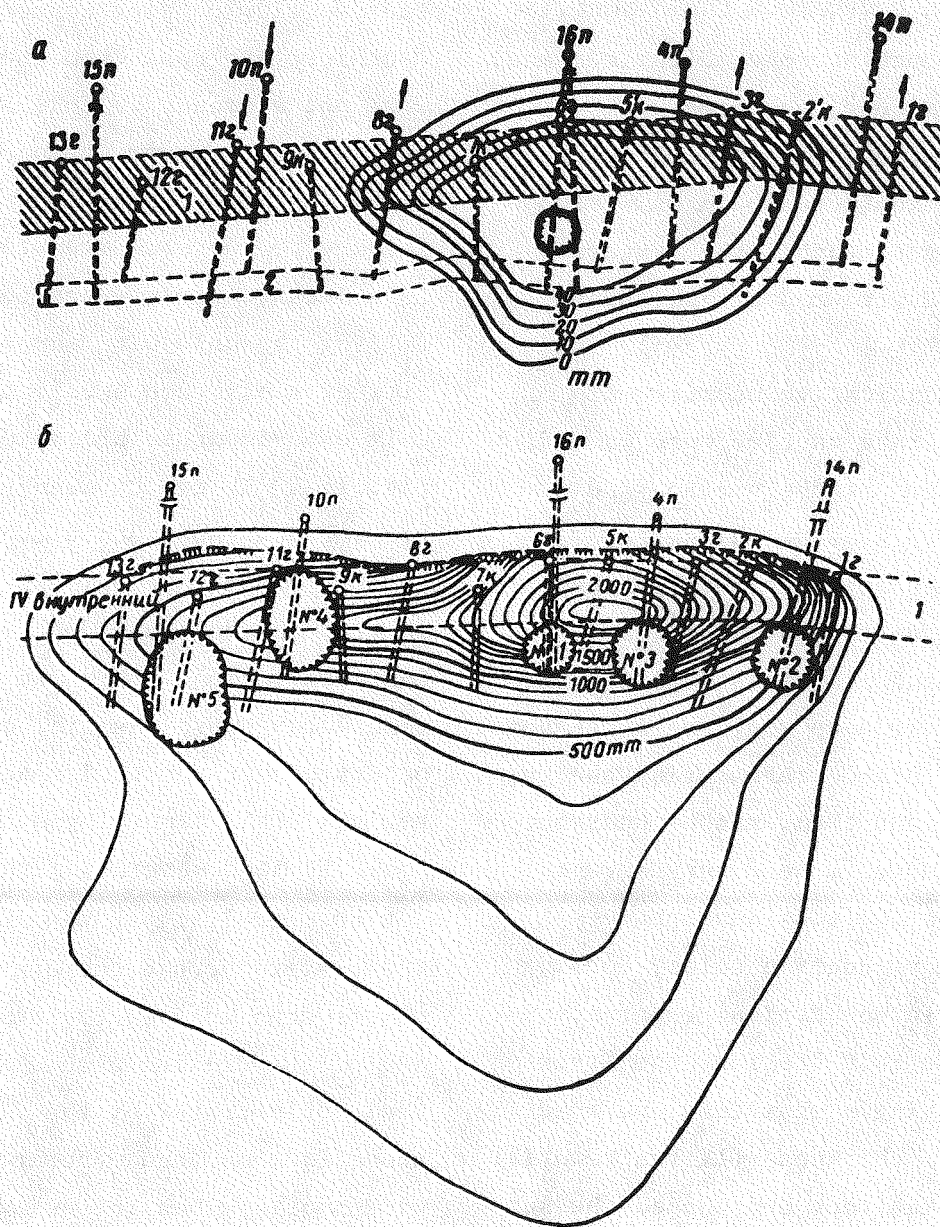


Fig.7. Development of the ground subsidence above the gasified space of underground gas generator No.1 of Yuzhno-Abinskaya station: (a) in the initial period of gasification; (b) in the last period of gasification; 1—outcrop of coal seam IV Vnutrennyi below covering rocks; 2—ignition crosscut of the generator; 1z, 3z, 6z, 8z, 11z, 12z, 13z—gas-removal holes; 4n, 10n, 14n, 15n, 16n—field opening-up holes for blast injection; 2k, 5k, 7k, 9k—holes for controlling the gasification process; 1,2,3,4,5—craters (troughs) formed above the gasified space. The crater numbers correspond to the sequence of their formation.

thickness. The collapsing surface layer can first fall into the top of the hole and then slide down the rest of the cavern. This presents a par-

ticularly hazardous problem of catastrophic subsidence, with the hazard being magnified by the dip of the seam.

Conclusion

Subsidence in gasification of thin seams of 1 to 3 meters is dominated by bending subsidence for both horizontal and steeply dipping beds. There is no measurable time delay between gasification of the coal and observation of the surface subsidence. Also, there is little bulking. However, slagging might produce some bulking.

Thick seams present more severe subsidence problems, as expected, with steeply dipping beds being the most hazardous for any given thickness. This is due to the formation of steeply dipping shafts which can cause major catastrophic subsidence, forming craters and resulting in massive gas leakage from the system.

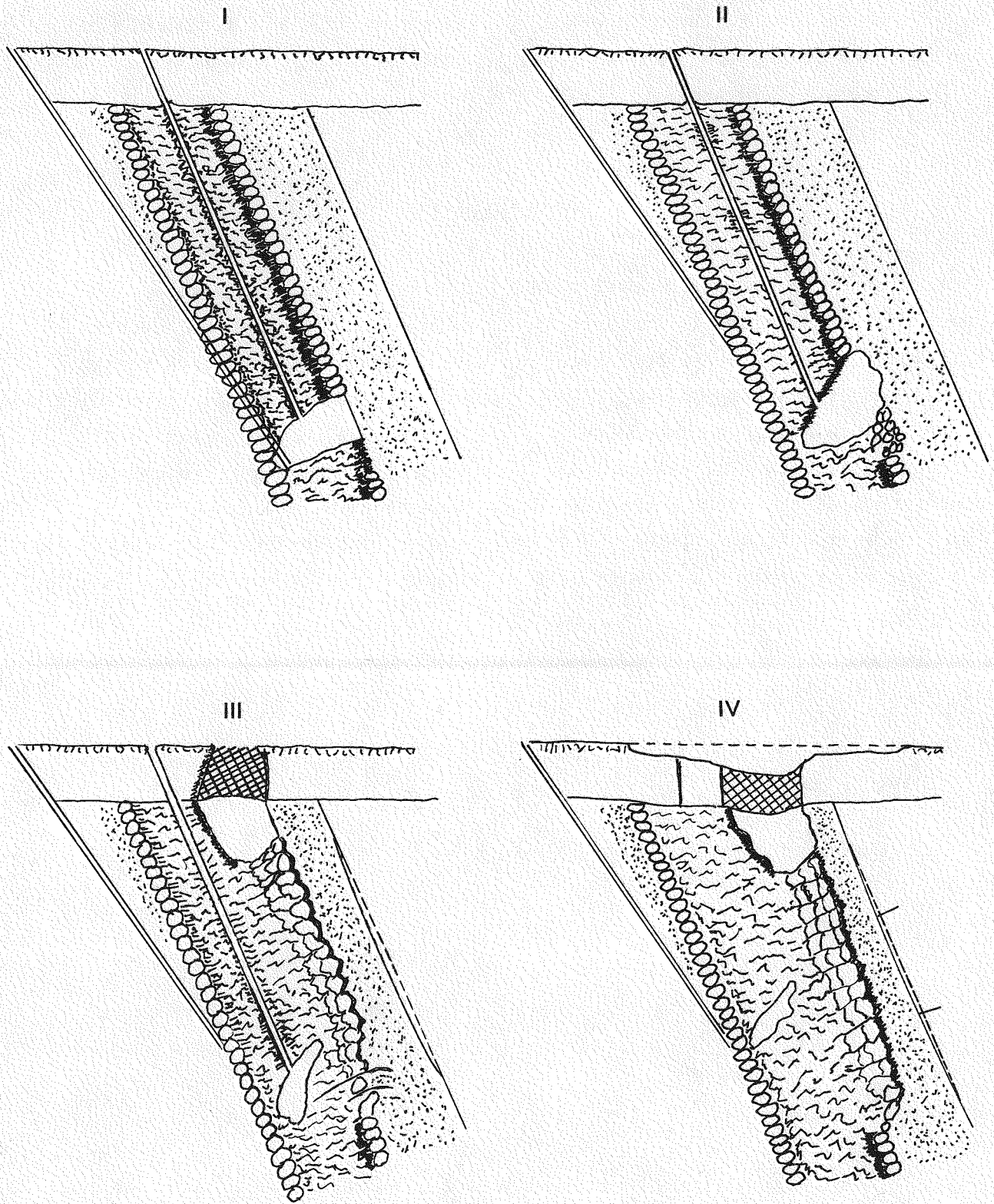


Fig. 8. Gasification of a thick sloping bed (Yuzhno-Abinskaya). Behavior of roof.

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