# Gas and Dolomite Outbursts in Ore Mines—Analysis of the Phenomenon and the Energy Balance

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**Abstract:** In this paper, we present the problem of gas and dolomite outbursts in copper mines. The energy balance of the phenomenon is analyzed. An examination of the porosity of the dolomites is performed; in addition, the content and pressure of the gas accumulated in the pore structure of the rock are determined. The gas energy accumulated in the pore space of rocks is determined depending on the transformation occurring during gas decompression. The work needed to crush the rock for the grain distribution characteristic of post-outburst masses is examined. The gas energy needed to transport rocks is analyzed. The purpose of the research is to determine the limit values of parameters describing the gas and rock system for which there is a risk of dolomite and rock explosions. For the characteristic porosity of dolomites of −5%, gas and rock outbursts at 5 MPa pressure in isothermal transformation can be expected, and if the transformation is closer to adiabatic transformation, outbursts can be expected at 10 MPa pressure.

**Keywords:** gas and dolomite outbursts; energy balance; gas in a porous structure

## 1. Outbursts of Gas and Rocks

Gas-induced geodynamic hazards occur in mining when gas, at a significant pressure, is present in the pores and crevices of the solid rock. Sudden discharges of gas may then occur, possibly with the ejection of rocks, or outbursts of gas and rocks. An outburst is a dynamic phenomenon in which the original structure of the rock is destroyed, with the products of the destruction being ejected into the working space.

To give a picture of a gas and rock outburst, it is necessary to examine the course of the process. As a result of an impulse caused by mining work (whether mechanical or using explosives), a rock surface is uncovered, and due to the potential energy of the gas and stresses in the rock mass, this surface crumbles and is forced out into the working space. A gas and rock outburst can be stopped if the ejected material fills the working space in a way that prevents the further transport of the material, or the energy (primarily the potential energy of the gas) accumulated in the rock is insufficient to break and transport the rock.

Because of the vast complexity of the causes of outbursts and the variety of conditions in which they occur, there are many hypotheses and theories that attempt to explain these phenomena. In general, each of these theories may be assigned to one of three groups, distinguished by the factor hypothesized to play the leading role in the process:

- The primary role of gas and its transformations;

- The destructive action of stresses in the rock mass;
- Energy phase transformations of a multi-parameter system including both the seam gas and the rock matrix.

The authors adhere to the theory that the chief role in the initiation and course of an outburst of gas and rock is played by gas at a significant pressure contained in the pores and crevices of the rock. Gas accumulates large quantities of potential energy, and in case of rapid decompression, that energy is given up with great power. The energy balance of the phenomenon is presented as the total work that gas contained under a certain pressure in a porous of rock is able to "produce" by expanding; on the other hand, the phenomena that absorb this work—rock fragmentation and its transport deep into the excavation site—must also be considered. The conditions for which the balance will be balanced will be determined. After exceeding one of the parameters (porosity or gas pressure), it will be possible for a burst to occur, because the work that the gas performs will be greater than that necessary to crush and transport the rock.

### 1.1. Outbursts of Gas and Coal

The problem of gas and rock outbursts has been an issue of concern in mining for over 150 years. Outbursts of coal and gases occur or have occurred in most of the world's mining regions [1–3]. At present, the problem is of greatest concern in China's mining industry, where one in three of the world's outbursts occurs. High levels of risk of outbursts are also present in Ukraine and Australia.

The most common gases present in coal beds are methane and carbon dioxide. Gas is present in coal in both adsorbed and free forms; the equilibrium of these components is defined by a sorption isotherm. Given the significant adsorptive capacity and low porosity of coal, the ratio of adsorbed to free gas is large. Although it accounts for only a small proportion of the gas contained in the rock, it is free gas that plays the key role in the initiation of an outburst [4], as it provides the energy needed to do the work of disintegrating the rocky material and, partially, to supply kinetic energy to the disintegrated rock [5], which initiates the transport of the ejected material [6,7]. As a result of the outburst, the coal is heavily disintegrated, and the gas pressure surrounding the newly formed grains falls rapidly from a value equivalent to the original pore pressure of the gas to the atmospheric pressure of the mine. This sudden change in pressure initiates the transport of the gas from the coal grains. The kinetic rate of diffusion of the gas from the coal grains is proportional to the square of the equivalent radius of the grains, and hence the emission of gas leads to the significant disintegration of the rock. Gas is dynamically released due to the combined processes of desorption and transport in the pore system of the grains produced by disintegration. It provides an additional portion of energy needed to do the work in the further transport of ejected material along the working space [8]. The transport of ejected material in the second phase of the outburst represents the fluid flow of gas and solid particles [9–11] with high density.

### 1.2. Outbursts of Gas and other Rocks

To date, the danger of outbursts in operations other than coal mining has mainly concerned potassium and salt mines [12,13]. Outbursts from sandstone forms lying above coal strata are relatively frequent [14]. Gas–sandstone outbursts are among the most significant hazards in subterranean engineering [15]. In copper ore mines, outbursts of sandstone and gas and of salt and gas have occurred [16]. Fundamental differences between coal and sandstone, dolomite or anhydrite, which may influence the occurrence of gas-induced geodynamic phenomena, result mainly from the sorption properties, chemical composition and mechanical parameters of those rocks [17,18].

## 2. Outbursts of Gases and Dolomite in Copper Ore Mines

In recent years, in mined deposits of copper ores in Poland, the presence of gases enclosed in the pores of copper-bearing rocks, particularly in carbonate rocks, has been detected with increasing

frequency [19]. Carbonate rock formations consist mainly of the mineral dolomite ($CaMg(CO_3)_2$), which very rarely occurs in nature in its pure form; it is most commonly found with impurities in the form of calcite ($CaCO_3$) and other minerals, such as compounds of iron ($FeS_2$), magnesium ($MgCO_3$) and silicon ($SiO_2$). Dolomite is a rock with a uniform, massive, compact structure. Due to the specific formation of dolomite deposits, it includes both open and closed pores [20]. According to the IUPAC classification [21], the pores in dolomite consist chiefly of mesopores, with diameters in the range of 0.002–0.050 μm, and macropores larger than 0.050 μm. The pores are of varying dimensions and shapes; they may perform a transport function in the migration of gases in the rock mass and may also constitute empty spaces with no contact with the surroundings. Our own microscopic observations of pore distributions in dolomite rocks indicate the presence of open and closed pores with a range of dimensions (from several micrometres to as large as 0.5 mm) and irregular shapes [22,23].

## 2.1. Analysis of Historical Events

The risk of outbursts in copper ore mining was signaled by an outburst of gas and rock that occurred at the Rudna mine in Poland on 6 September 2009 [24]. This was an occurrence of not just national but worldwide significance, as such events had not previously been recorded in rocks of dolomite type. In 2018, there was a further incident classified as an outburst of gases and rock. In both cases, the volume of the outburst cavern was similar; they were measured at 250 $m^3$ and 219 $m^3$.

The first, unprecedented incident was subjected to detailed analysis. Studies showed that the main cause of the gas and rock outburst at the Rudna mine was the presence of gas in the dolomite [25,26]. Rocky material was ejected into the working space over a length of approximately 70 m, and the outburst cavern had a volume of 250 $m^3$. The quantity of released gas—chiefly nitrogen—was estimated at 12,000 $m^3$, and the mass of ejected dolomite was found to be 4000 tons [24]. The analysis of the ejected material showed, among other things, that the dolomite in the region of the outburst had different properties than in other parts of the deposit. Its structural and textural features differed from those of the surrounding carbonate rocks; among other things, it had larger than average porosity. The mean porosity determined for grains taken from the ejected material was approximately 20%, of which half consisted of closed pores capable of storing gas under high pressure for a long period. Laboratory tests of grains measuring approximately 10 mm showed that the pressure of residual gas in the pores remained at a level of at least 4 MPa for many months. It is estimated that the pressure of the seam gas may have been as high as 10 MPa. Measurements of pressure in a test hole excavated from a heading in the region in which the outburst occurred gave a value of approximately 6.5 MPa [27]. It is believed that dolomites exhibit such atypical structural and textural features in limited areas. Outside the area in question, the porosity of the rock can be expected to be much smaller [24].

## 2.2. Parameters of the Rock–Gas System for Dolomites from Copper Ore Mines

In the authors' studies of the rock–gas system, structural and gas-related parameters were determined for more than 30 samples of dolomites [17]. Minimum, mean and maximum values among the results obtained are given in Table 1.

**Table 1.** Results of analysis of gas-bearing properties of dolomite samples.

|  | Helium Density [g/cm$^3$] | Total Porosity [%] | Open Porosity [%] | Closed Porosity [%] | Content of Gas [cm$^3$/kg] | Seam Gas Pressure [MPa] |
|---|---|---|---|---|---|---|
| Min | 2.742 | 2.32 | 0.00 | 0.46 | 0.13 | 0.001 |
| Max | 2.935 | 23.05 | 17.89 | 19.13 | 144.82 | 0.998 |
| Avg | 2.871 | 9.51 | 3.84 | 5.67 | 36.73 | 0.255 |

The porosity of the analyzed samples was determined on the basis of a pointwise quantitative microscopic analysis. The total porosity of the samples ranged from 2.32% to 23.05%. The mean

porosity was 9.51%. Studies of outburst material from the Rudna mine, carried out at the Strata Mechanics Research Institute of the Polish Academy of Sciences, showed that the high porosities of the dolomite, ranging from 16.2% to 20.2%, were among the causes of the outburst of dolomite and gas that occurred in 2009 [24]. From the point of view of gas-related hazards, including geodynamic hazards, increased porosity implies the presence in the rock of space that may contain gas, and usually also means that the tensile strength of the rock is lower than that of rocks with similar structure but lower porosity.

A necessary condition for the initiation of an outburst is the presence of gas in the rock with sufficient energy to do the work of disintegrating and transporting the rock. The gas pressure was measured using the authors' self-developed analytical apparatus. The lowest values indicate the absence of gas in the porous structure of the analyzed rocks, while the highest values approach 1.0 MPa. Compared with the pressure measured in the outburst material from the Rudna mine (4 MPa), these values are relatively low and do not indicate any abnormality of the rock–gas system.

*2.3. Factors Determining the Possibility of Outbursts*

A sufficient condition for the initiation of an outburst is to guarantee that the work needed to disintegrate the rocky material is less than the potential energy of the gas. If these parameters have similar values, an outburst may be initiated, but its progress will be stopped. For an outburst to develop, it is necessary for the ejected material to be transported away, which in turn requires the supply of a further portion of energy. A full outburst thus requires that the gas accumulated in the pores and crevices of the rock has sufficient energy to disintegrate the rocky material and to transport it along the mine working space. In the case of coal, the transport of the outburst material can be largely caused by gas intensively desorbing from the heavily disintegrated grains. The entirety of the energy balance in the case of non-sorbent dolomites is based exclusively on free gas. The potential energy of the gas accumulated in the pores must do work resulting in the disintegration of the original structure of the rock and the supply of kinetic energy to it, enabling it to be transported along the working space.

Gas accumulated in dolomite is contained in the porous space of the rock, and therefore the presence in the rock of a highly porous structure is a necessary condition for the initiation of an outburst. The porous structure is also significant in view of the dependence of the potential energy of the gas on the volume of the porous space. The correlation of the porosity of a rock with its strength parameters is also extremely important. A rock with higher porosity will certainly have lower tensile strength, and thus less work will be required to break it down into grains of a given size.

## 3. Theoretical Analysis of Gas and Dolomite Outbursts

Based on the several decades of experience of the Strata Mechanics Research Institute of the Polish Academy of Sciences in relation to the analysis and prevention of outbursts, and the results obtained by multiple research groups, the following main postulates may be adopted concerning gas and rock outbursts in copper ore mines:

- A gas and rock outburst requires the presence of gas accumulated in the rock at high pressure—this is a sufficient condition for an outburst;
- The potential energy of the gas is required to do work in disintegrating the rock and supplying it with kinetic energy;
- The distribution of gas in the porous space of rock subject to outburst is quasi-uniform in the region of the rock affected by the outburst;
- In the course of the outburst, rock fragments become detached in a cascading manner and are transported along the working space;
- The transport of material represents a flow of gas and solid particles with high density;
- The ejected material consists predominantly of small rock grains;

–　The gas contained in the rock, which has only marginal sorption properties, is located in its porous structure as free gas;

–　The presence of a developed porous structure in the rock is a necessary condition for the presence of gas within it;

–　The outburst results in the formation of a cavern, often with its central point distant from the center of the ejected material.

The spatial distribution of gas in the porous structure should be quasi-uniform, as this enables the disintegration of the rock into grains of small dimensions. The local accumulation of gas in an extensive crevice may lead to the detachment of a fragment of rock and the supply of additional energy to it, but it can hardly be expected that the rock would be strongly disintegrated as a result of this. If heavy disintegration of the rock occurs as a result of the event, this will enable the advective, fluidal or pneumatic transport of rocky material along the working space.

From an analytical standpoint, an outburst of gas and dolomite is an extremely complex phenomenon. The number of physical phenomena taking place in the course of an outburst, as well as their degree of complexity and interconnectedness, is enormous. To consider the potential possibilities of predicting such events based on selected parameters, it is necessary to determine the full energy balance of an outburst. The results of an energy balance indicate, in qualitative terms, the significance of particular parameters describing the rock-gas system, while quantitative analysis may be useful in determining critical values of those parameters. The determination of an energy balance is therefore key to evaluating outburst risk.

*3.1. Potential Energy of the Deformed Rock Mass*

Copper ore mining takes place in Poland at a depth of approximately 1300 m. Because of this large depth, the overburden exerts significant stresses on the deposited dolomite, causing deformations of its matrix. It is possible to estimate the potential energy of the deformed rock mass using the basic laws of physics.

$$E_p = \int_0^\varepsilon \sigma \cdot d\varepsilon = \frac{\sigma \cdot \varepsilon}{2} \tag{1}$$

where

$E_p$ is the elastic strain energy (MJ/m$^3$);
$\sigma$ is the stress (MPa);
$\varepsilon$ is the normal (linear) strain (-).

The elastic strain energy in a triaxial stress state is equal to

$$E_p = \frac{\sigma_1 \cdot \varepsilon_1 + \sigma_2 \cdot \varepsilon_2 + \sigma_3 \cdot \varepsilon_3}{2} \tag{2}$$

where

$\sigma_1, \sigma_2, \sigma_3$ are the principal stresses (MPa);
$\varepsilon_1, \varepsilon_2, \varepsilon_3$ are the normal strains (-).

The vertical stress $\sigma_1$ is calculated from the following formula:

$$\sigma_1 = \rho \cdot g \cdot H \tag{3}$$

where

$\rho$ is the rock density (kg/m$^3$);
$g$ is the acceleration due to gravity (m/s$^2$);

*H* is the depth of the deposit (m).

The horizontal stresses $\sigma_2$ and $\sigma_3$ are calculated from the following formula

$$\sigma_2 = \sigma_3 = \frac{v}{1-v} \cdot \sigma_1 \tag{4}$$

where

*v* is Poisson's ratio (for dolomite from the Legnica–Głogów Copper Region, *v* = 0.225).

Using Hooke's law, for a general triaxial stress state, the normal strains are given by

$$\varepsilon_1 = \frac{1}{E} \cdot [\sigma_1 - v(\sigma_2 + \sigma_3)] \tag{5}$$

$$\varepsilon_2 = \frac{1}{E} \cdot [\sigma_2 - v(\sigma_1 + \sigma_3)] \tag{6}$$

$$\varepsilon_3 = \frac{1}{E} \cdot [\sigma_3 - v(\sigma_1 + \sigma_2)] \tag{7}$$

where

*E* is Young's modulus (MPa) (for dolomite from the Legnica–Głogów Copper Region, *E* = 46,500 MPa).

Thus, the quantity of stored elastic strain energy can be estimated using the following equation:

$$E_p = \frac{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2v(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)}{2E} \tag{8}$$

The ore is mined at a depth of approximately 1300 m; thus, the value of $\sigma_1$ is

$$\sigma_1 = 2700 \text{ kg/m}^3 \times 9.81 \text{m/s}^2 \times 1300 \text{ m} = 35.7 \text{ MPa}$$

The horizontal stresses $\sigma_2$ and $\sigma_3$ are equal to

$$\sigma_2 = \sigma_3 = \frac{0.225}{1 - 0.225} \times 34.4 = 10.4 \text{ MPa}$$

Thus, the stored elastic strain energy is approximately $E_p = 0.012 \text{ MJ/m}^3$.

### 3.2. Energy of Gas Accumulated in the Porous Structure

The source of energy in the case of gas-induced geodynamic events is compressed gas filling the pores and crevices in the dolomite. The compressed gas does work in the course of decompression, with the transformation being intermediate between isothermal and adiabatic. Depending on the rate of flow of the gas, the dolomite gives up its heat with a certain power, which can be expressed with the following equation:

$$P = \rho_p \cdot c_p \cdot \dot{v} \cdot \Delta T \tag{9}$$

where

*P* is the power of heat transfer (J/s);
$\rho_p$ is the density of air at room temperature (g/L);
$c_p$ is the specific heat of air at room temperature (J/kg·K);
$\dot{v}$ is the air flow rate (L/s);
$\Delta T$ is the difference in temperature between the rock and the gas (K).

Depending on the duration of the outburst and the rate of heat exchange between the stream of gas and the rock, in the course of the decompression of the gas during the outburst, a thermodynamic

transformation will occur with an intermediate character between isothermal and adiabatic. In the first hypothetical case, the gas during decompression should maintain a constant temperature while taking heat from the rock; in the second case, there should be no exchange of heat between the gas and the rock.

To determine the work done by nitrogen during isothermal decompression, the following equation is used:

$$W = \int_{V_0}^{V_1} p(V)dV \tag{10}$$

Nitrogen, as the main component of the mixture filling the pores, is treated as an ideal gas. During isothermal decompression, the temperature *T* is constant, and hence the work done by the gas can be written as

$$W_i = nRT \int_{V_0}^{V_1} \frac{1}{V}dV = nRT\ [ln|V|]_{V_0}^{V_1} = nRT\ (ln|V_1| - ln|V_0|) = nRT\ ln\left(\frac{V_1}{V_0}\right) \tag{11}$$

Since the volume of the gas after transformation is a value that is hard to estimate, the Boyle–Mariotte Law is used:

$$pV = \text{const} \tag{12}$$

$$p_0V_0 = p_1V_1 \tag{13}$$

The work done by the gas under isothermal transformation is obtained as

$$W_i = nRT\ ln\left(\frac{p_0}{p_1}\right) \tag{14}$$

$$pV = nRT \tag{15}$$

$$W_i = p_0V_0ln\left(\frac{p_0}{p_1}\right) \tag{16}$$

For the computations in the case of adiabatic transformation, the First Law of Thermodynamics is applied:

$$\Delta U = \Delta Q - W \tag{17}$$

In an adiabatic process, there is no exchange of heat, and therefore

$$\Delta Q = 0 \tag{18}$$

$$\Delta U = -W \tag{19}$$

$$W_a = nc_v\Delta T \tag{20}$$

$$c_v = \frac{R}{k-1} \tag{21}$$

$$W_a = \frac{nR}{k-1}(T_0 - T_1) = \frac{nRT_0}{k-1}\left(1 - \frac{T_1}{T_0}\right) \tag{22}$$

By Poisson's Law:

$$p_0V_0^k = p_1V_1^k \tag{23}$$

$$pV = nRT \tag{24}$$

$$\frac{T_1}{T_0} = \left(\frac{p_1}{p_0}\right)^{\frac{k-1}{k}} \tag{25}$$

$$W_a = \frac{p_0 v_0}{\kappa - 1}\left(1 - \left(\frac{p_1}{p_0}\right)^{\frac{\kappa - 1}{\kappa}}\right) \tag{26}$$

where

$p_0$ is the pore pressure in the rock deposit;
$p_1$ is the pressure in the mine working space (0.11 MPa);
$v_0$ is the volume of the gas at pressure $p_0$;
$\kappa = 1.4$ is the adiabatic index.

The graph (Figure 1) shows the work done in the adiabatic and isothermal cases as a function of the gas pressure in the porous structure, for rocks of different porosity. Assuming parameters for a rock-gas system at risk of outburst ($\varepsilon = 20\%$, $p_0 = 10$ MPa), the work done in an adiabatic transformation is $W_a = 3.6$ MJ/m$^3$, while the work done in an isothermal transformation is $W_i = 9.0$ MJ/m$^3$; i.e., almost three times as high.
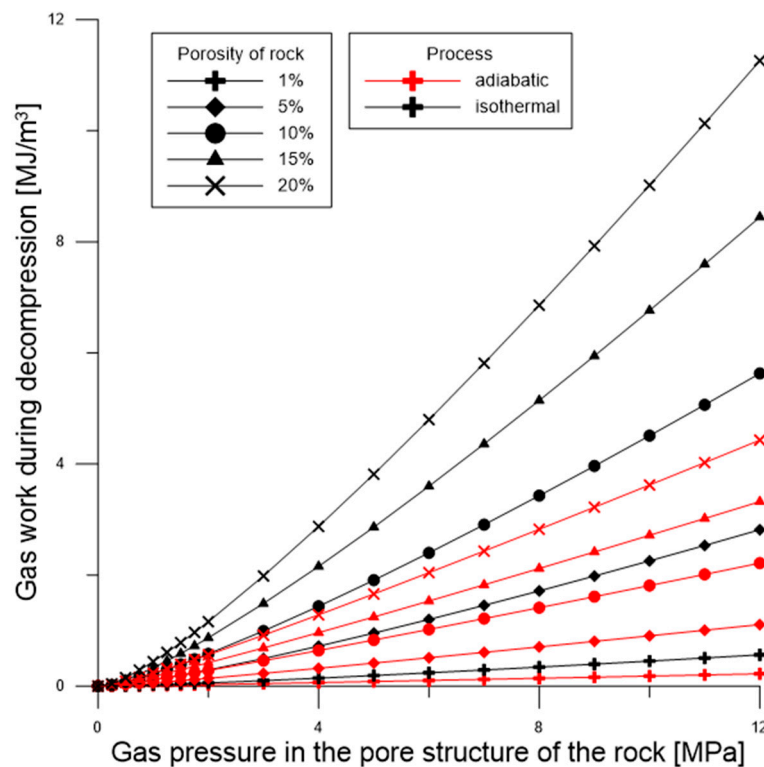


**Figure 1.** Work released during the decompression of gas from the porous structure of rock as a function of pressure.

Comparing the energy obtained as a result of elastic strain with the energy stored in the compressed gas in the porous structure of the rock, doing work in the course of decompression of gas during adiabatic transformation, assuming the parameters $\varepsilon = 20\%$ and $p_0 = 10$ MPa, the energy of the deformed rock mass is found to be less than one-hundredth of the energy of the gas. This amounts to 0.3% of the total energy needed to disintegrate and transport the rock.

### 3.3. Work Required to Disintegrate the Rock

The estimation of the work necessary to disintegrate rock is an exceptionally complex problem. Existing theories on the expenditure of energy on the disintegration process are based principally on attempts to link the degree of disintegration to the energy consumed. Rittinger's theory states that the energy of disintegration consumed in overcoming the forces of intermolecular cohesion in solid

materials is directly proportional to the newly formed surface area [28]. In turn, according to Kick's theory, the energy of disintegration is consumed in creating a deformation where the critical stress is exceeded, and the work done is proportional to the volume of the disintegrated material [29]. Bond's theory combines both of the above theories and divides the process of disintegration into two phases: in the first phase, deformation occurs, leading to a critical stress; and in the second, a suitable addition of energy causes the destruction of the cohesive intermolecular forces [30]. Among these theories, the interpretation given by Bond displays the best agreement with experiment [31,32]. According to Bond's theory, the work needed to disintegrate rock can be determined from the following equation:

$$
W_{p \to n} = W_u \left( \frac{\sqrt{d_{80}^n} - \sqrt{d_{80}^p}}{\sqrt{d_{80}^n}} \right) \sqrt{\frac{100}{d_{80}^p}} \tag{27}
$$

where

$W_{p \to n}$ is the work of disintegration (kWh/Mg);
$W_u$ is a unit of work (Bond's work index, kWh/Mg);
$d_{80}^p$ is the grain size representing 80% of the population in the product;
$d_{80}^n$ is the grain size representing 80% of the population in the initial material.

According to previous work [33,34], the value of $W_u$ for dolomites from the Polkowice-Sieroszowice mine is approximately 40 MJ/Mg, equivalent to 11.1 kWh/Mg. If we assume that the analysis concerns the process of disintegration of a cube of rock with 1 m edges into cubic grains with 1 cm edges, the work that must be done by the gas is approximately 10.1 MJ/m$^3$.

However, the action of mill elements on a rock sample usually generates compressive or shear stresses within it. The situation is different when the cohesion of rock is lost during an outburst. Because the energy source is the gas accumulated in the porous space of the rock, the disintegration process is dominated by tensile stresses [35]. Because of these differences, the theory developed for the purposes of mineral processing technology cannot be directly adapted to the problem of gas and rock outburst. To determine what part of the energy released by the gas would be used for the disintegration of the rock into grains of a given size, it was necessary to carry out additional strength testing in the form of Brazilian tests [36,37]. A series of such tests was carried out on samples with a slenderness ratio of 1:1. The strength testing machine operated with a constant piston speed. By recording the force and displacement of the piston, it was possible to determine the tensile strength and work done by the machine in destroying the sample, as represented symbolically in Figure 2 and realistically in Figure 3.

A series of 10 Brazilian tests was carried out on dolomite samples. The tests were performed on a rigid press with a control system with a feedback loop, supplied by Instron-Wolpert Ltd. High Wycombe, Great Britain (Figure 4).

The computed values of the work done by the strength testing machine during the disintegration of the samples are given in Table 2.

Following the outburst in the Rudna mine, samples of rocky material were taken (Figure 5) from the vicinity of the cavern formed by the outburst and from the ejected material located furthest from the cavern. The material was sieved to determine the particle size distribution (Figure 6).

Based on the particle size distribution, four ranges were defined. The 2–20 mm range accounted for more than 56% of the total mass of rock (Table 3) involved in the outburst.
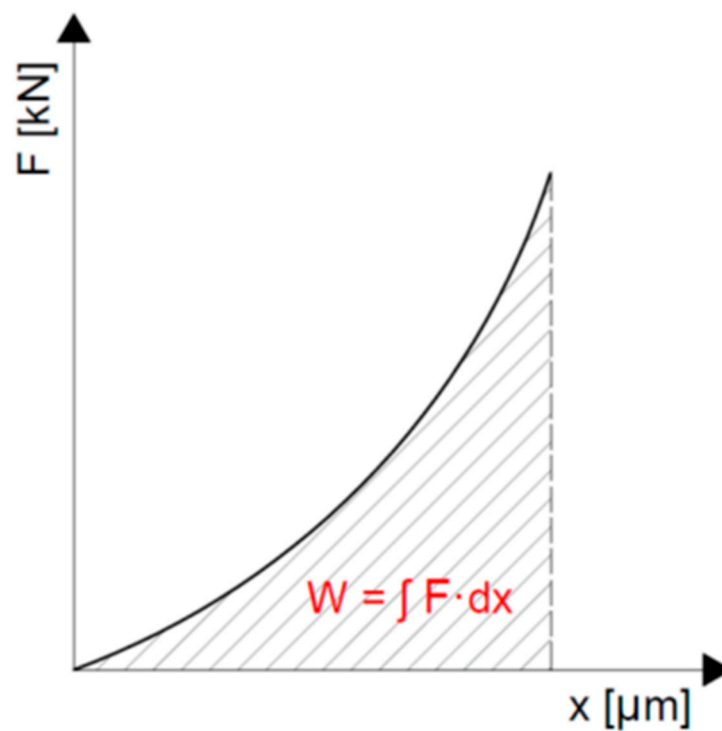
**Figure 2.** Theoretical graph illustrating determination of the work done by a strength testing machine in a Brazilian test.
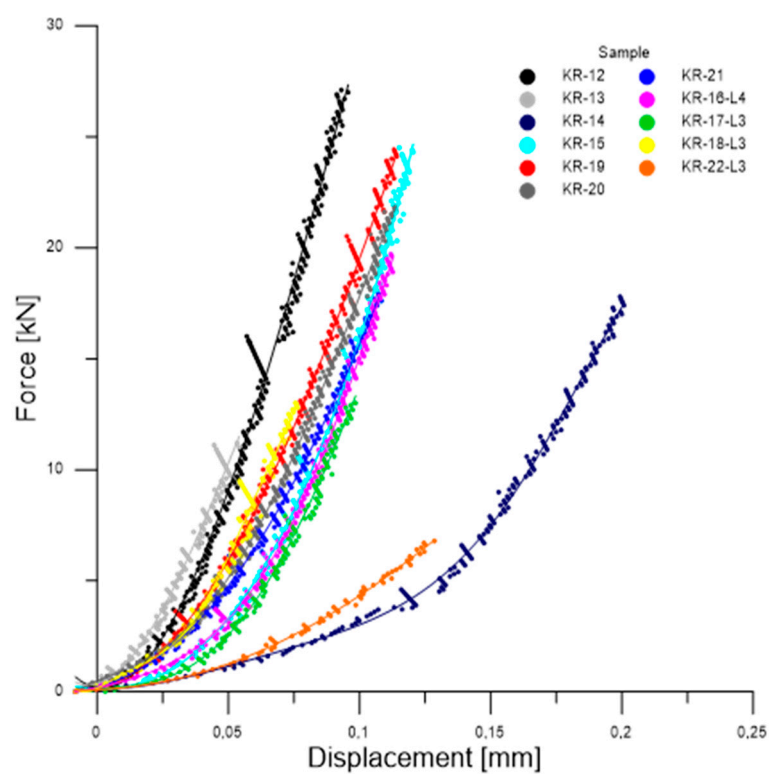


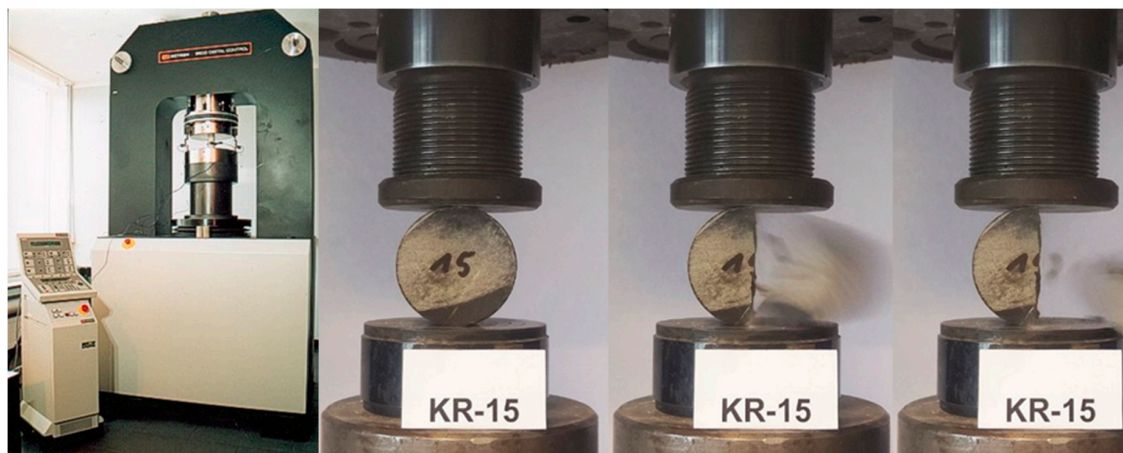**Figure 3.** Series of Brazilian tests for 10 dolomite samples.

**Figure 4.** Strength testing machine "Instron" and dolomite sample "KR-15" in a Brazilian test.

**Table 2.** Results for work done in Brazilian tests and tensile strength.

| SAMPLE | $W$ [J] | $R_R$ [MPa] |
|---|---|---|
| KR-12 | 1.06 | 10.5 |
| KR-13 | 0.25 | 4.4 |
| KR-15 | 0.83 | 9.5 |
| KR-16-L4 | 0.68 | 7.1 |
| KR-17-L3 | 0.39 | 5.2 |
| KR-18-L3 | 0.35 | 6.8 |
| KR-19 | 1.01 | 9.4 |
| KR-20 | 3.85 | 8.7 |
| KR-21 | 0.71 | 6.6 |
| KR-22-L3 | 0.32 | 2.6 |



**Figure 5.** Outburst material from the Rudna mine [38].
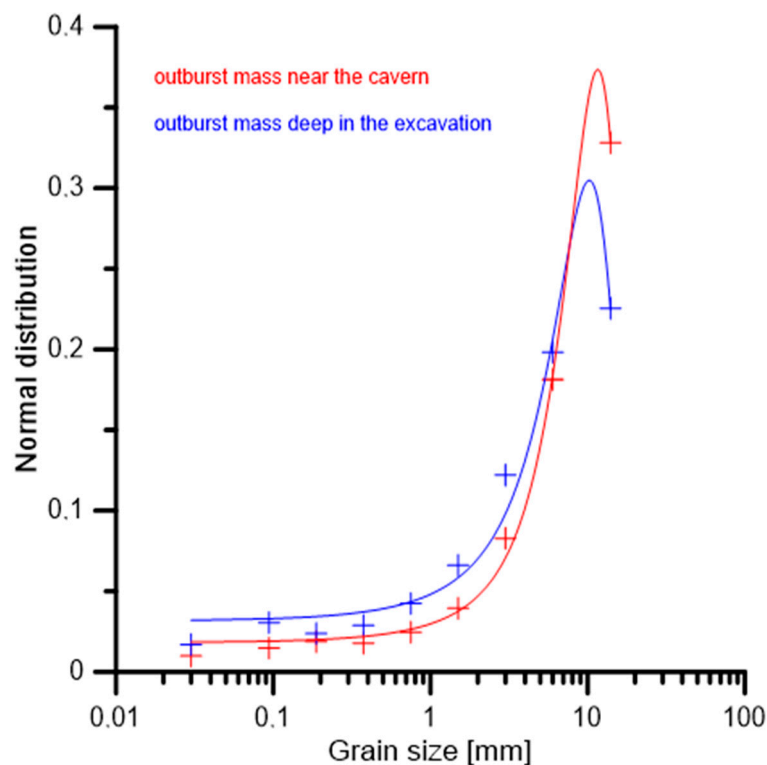
**Figure 6.** Particle size distributions from the furthest and nearest outburst material.

**Table 3.** Mean contribution of grain size classes to the mass of outburst material and the newly formed surface.

| Range (mm) | Mass Contribution (%) | Surface Area of Grains (m$^2$) |
|:---:|:---:|:---:|
| 0.0–0.2 | 5.1 | 30,3570 |
| 0.2–2.0 | 11.6 | 697 |
| 2.0–20 | 56.9 | 342 |
| 20–200 | 26.4 | 16 |
| **Total surface area (m$^2$)** | | **304,625** |

The work required to disintegrate 1 m$^3$ of rock into grains measuring approximately 1 cm$^3$ may be estimated based on the following formula:

$$\frac{W_r}{V_u} \cdot \frac{p_{n1}}{p_1} = \frac{W}{V} \cdot \frac{p_{np}}{p_p} \tag{28}$$

which gives

$$W_r = \frac{W \cdot p_{np} \cdot p_1}{V \cdot p_p \cdot p_{n1}} \tag{29}$$

where

$W_r$ is the work required to disintegrate a unit volume of rock during the outburst (J);

$W$ is the work done in destroying a sample in the Brazilian test (J);

$V_u$ is the unit volume (m$^3$);

$V$ is the sample volume (m$^3$);

$p_{n1}$ is the newly formed surface after disintegration of 1 m$^3$ (m$^2$);

$p_{np}$ is the newly formed surface after the Brazilian test (m$^2$);

$p_1$ is the surface area of a 1 m$^3$ cube ($p_1 = 6$ m$^2$);

$p_p$ is the surface area of the sample ($m^2$).

Knowing the surface areas formed as a result of the disintegration of 1 $m^3$ of rock, it is possible to determine the work that must be done by the gas in disintegrating a sample into grains of a given size. The results are given in the Table 4.

**Table 4.** Results for work done in disintegrating particular samples.

| SAMPLE | $W_r$ |
|---|---|
| | ($MJ/m^3$) |
| KR-12 | 0.18 |
| KR-13 | 0.04 |
| KR-15 | 0.14 |
| KR-16-L4 | 0.10 |
| KR-17-L3 | 0.06 |
| KR-18-L3 | 0.05 |
| KR-19 | 0.15 |
| KR-20 | 0.60 |
| KR-21 | 0.10 |
| KR-22-L3 | 0.05 |
| **mean** | **0.15** |

Comparing the values for the work that must be done by the gas in disintegrating the rock, it is observed that the work resulting from compression or shearing (Bond's theory) is more than 100 times greater than the work done in the case of tensile stress.

### 3.4. Transport of Outburst Material

The gas contained in the pores of rock does work during the disintegration of the rock. An excess of gas must be available to perform additional work in transporting the outburst material into the mine working space. In the outburst that occurred at the Rudna mine in 2009, rocky material was transported approximately 60 m into the working space (Figure 7), and in the 2018 incident at the Polkowice-Sieroszowice mine, the outburst material travelled more than 25 m along the working space, as shown by a sketch taken from the scene of the outburst.
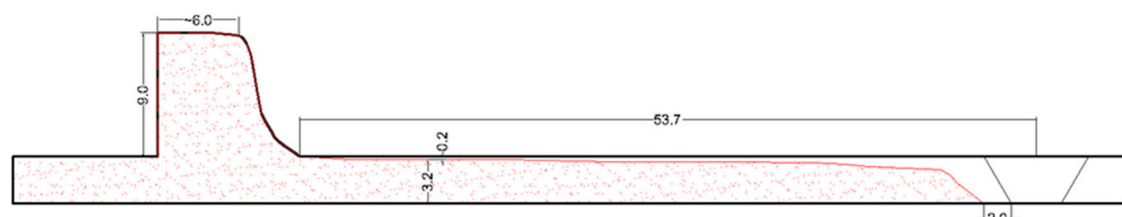


**Figure 7.** Sketch made at the site of the outburst at the Rudna mine in 2009 [39].

The disintegrated rock falling from the cavern settles on the floor of the working space and gradually fills its cross-section, while gas is constantly released from the disintegrating rocks. The reduction in the cross-section of the working space causes a local increase in the velocity of the gas to a value that enables the transport of rocky material along a further part of the working space. The following is the condition for a single grain to be set in motion by the stream of gas:

$$T_s < F_n \tag{30}$$

where

$T_s$ is the static friction between grains (N);
$F_n$ is the force exerted on the grain by the stream of gas (N).

The static friction force between grains is compared with the force exerted by the stream of gas on the surface of the considered grains. The majority of the rock found in the outburst material consisted of grains measuring approximately 10 mm. The friction and the force exerted are compared in Equation (31), which is used to give the velocity of the stream of gas above which material will be transported into the working space (Equation (32)).

$$T = F_n \;\rightarrow\; m_z \cdot g \cdot f = \frac{\rho_g \cdot V^2}{2} \cdot S \tag{31}$$

$$V = \sqrt{\frac{2 \cdot T}{\rho_g \cdot S}} = \sqrt{\frac{2 \cdot m_z \cdot g \cdot f}{\rho_g \cdot S}} \tag{32}$$

where

$m_g$ is the mass of a single grain of size $d = 10$ mm (kg);
$g$ is the acceleration due to gravity (m/s$^2$);
$f$ is the coefficient of static friction (-);
$\rho_g$ is the density of the gas (kg/m$^3$);
$S$ is the surface area of the grain on which the stream of gas is acting (m$^2$).

The coefficient of static friction was determined experimentally using an inclined plane, on which rock grains close to 10 mm in size were placed. The measuring apparatus is shown diagrammatically in Figure 8.
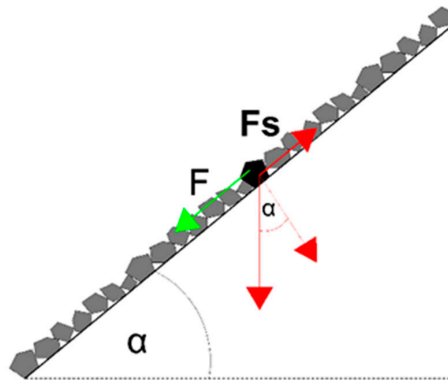


**Figure 8.** Inclined plane used for measurements of coefficient of static friction.

In the experiment, a randomly selected rock grain with a size close to 10 mm was placed at different points on the prepared inclined plane in a horizontal position. The angle of inclination of the plane, α, was then increased until the grain was set in motion. The directly measured results are given in Table 5.

**Table 5.** Angles of inclination of plane at which grains were set in motion.

| No. | Angle of Inclination α (°) | No. | Angle of Inclination α (°) |
|---|---|---|---|
| 1 | 68 | 6 | 65 |
| 2 | 69 | 7 | 68 |
| 3 | 67 | 8 | 72 |
| 4 | 69 | 9 | 70 |
| 5 | 70 | 10 | 69 |
| **Mean angle of inclination** | | | **69** |

Using the balance of forces on an inclined plane (Equations (33) and (34)), the mean coefficient of static friction was determined at approximately $f = 2.61$.

$$F = F_s \quad \rightarrow \quad mg \sin \alpha = mgf \cos \alpha \tag{33}$$

$$f = \frac{\sin \alpha}{\cos \alpha} = \tan \alpha \tag{34}$$

Returning to Equation (32), we may compute the velocity above which the transport of the grains takes place:

$$V = \sqrt{\frac{2 \times 0.003 \times 9.81 \times 2.61}{1.30 \times 0.0001}} = 33.1 \text{ m/s}$$

The work required to transport $1 \text{ m}^3$ of rock half of the distance occupied by the outburst material at the Rudna mine may be determined from the following formula:

$$W_t = \rho \cdot g \cdot f_k \cdot s \tag{35}$$

where

$\rho$ is the density of the rock (kg/m$^3$);
$g$ is the acceleration due to gravity (m/s$^2$);
$f_d$ is the coefficient of kinetic friction (-);
$s$ is the distance over which the outburst material was transported (m).

The coefficient of kinetic friction was determined experimentally in a friction cone experiment. The process and interpretation of the experiment are shown diagrammatically in Figure 9.
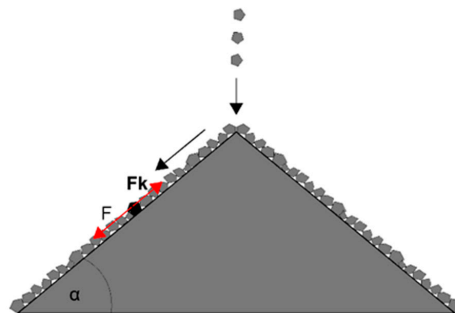


(a)



(b)

**Figure 9.** Cone experiment used to determine the coefficient of dynamic friction of dolomite grains: (**a**) theoretical, (**b**) practical.

For statistical purposes, the experiment was repeated 10 times. The results are given in Table 6.

**Table 6.** Angles of inclination of friction cone.

| No. | Angle of Inclination $\alpha$ (°) | No. | Angle of Inclination $\alpha$ (°) |
|-----|-----|-----|-----|
| 1 | 35 | 6 | 37 |
| 2 | 37 | 7 | 37 |
| 3 | 36 | 8 | 37 |
| 4 | 38 | 9 | 38 |
| 5 | 36 | 10 | 36 |
| **Mean angle of inclination** | | | **37** |

Equation (35) can be used to estimate the work done by the gas in transporting 1 m³ of disintegrated rock:

$$W_t = 2700 \times 9.81 \times 0.75 \times 35 = 0.70 \, \text{MJ/m}^3.$$

## 4. Critical Conditions at Which Outbursts May Occur in Dolomite

By summing the work needed to disintegrate 1 m³ of rock into grains of similar size to those found in the outburst material, the kinetic energy of gas accelerated to more than 33.1 m/s and the work needed to transport 1 m³ of rock, we obtain

$$0.15 \, \text{MJ/m}^3 + 0.001 \, \text{MJ/m}^3 + 0.70 \, \text{MJ/m}^3 \approx 0.85 \, \text{MJ/m}^3$$

Figure 10 shows the work done during the decompression of the compressed gas contained in the porous structure of the rock, assuming an isothermal or adiabatic transformation, as a function of the pressure of the gas for different rock porosities. The red line marks the theoretical boundary above which it is possible for an outburst to occur in dolomite.
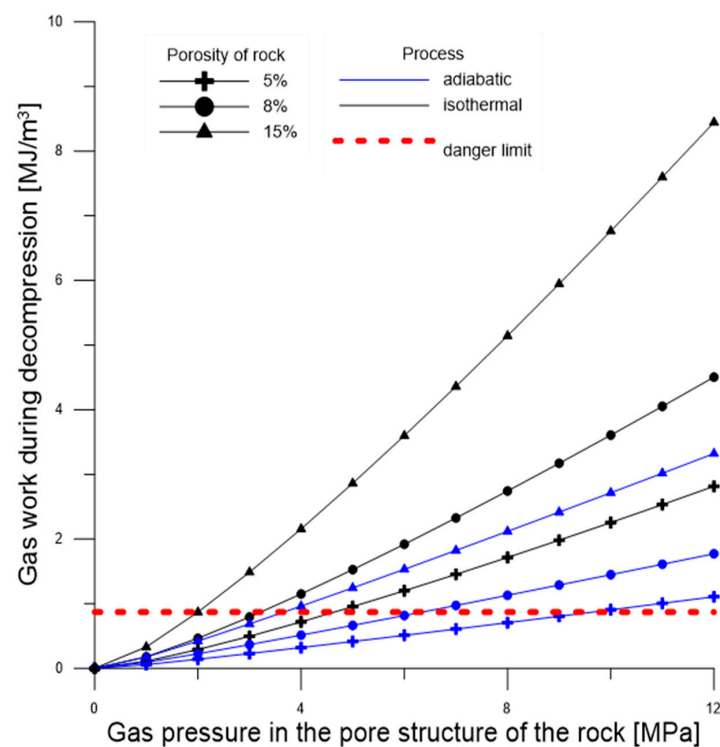


**Figure 10.** Work released during the decompression of gas from the porous structure of rock as a function of the pressure and porosity, shown with the theoretical minimum work required to disintegrate and transport the rock.

It remains difficult to determine the nature of the transformation of the gas during sudden decompression from the porous structure of the rock. It should be assumed that the actual transformation is intermediate between adiabatic and isothermal, and thus that the total energy accumulated in the gas determines a range in which the phenomenon may occur. The lower boundary of this range corresponds to an adiabatic transformation, which supplies less energy and thus requires a higher porosity and higher gas pressure. In this case, an outburst of gases and dolomite at high rock porosity (above 15%) requires the pressure of the gas in the porous structure to be above 3 MPa. If the rock has low porosity (below 5%), the pressure of the gas must exceed 12 MPa. In the case of an isothermal process, for rocks with a porosity above 15% the lowest pressure is 2 MPa, while for rock with extreme low porosities of around 2%, the required gas pressure is 10 MPa. It should be noted that each of the outbursts occurred following blasting work, and thus occurred in a situation where the structure of the roof rock was cracked or weakened. It may therefore be assumed that the outburst was initiated by the firing of explosive materials, but the rock was disintegrated and transported by the action of the gas contained in its pores and crevices.

## 5. Conclusions

The gas-bearing capacity of the analyzed dolomite samples is statistically around 100 times lower than that of hard coal. In the case of dolomites, however, sorption is only a marginal phenomenon, and the dominant gas in the porous structure is nitrogen. Thus, it may be assumed that the quantity of gas used in determining the balance is present in the form of free gas.

According to the classical theory of gas and rock outbursts, the energy of the gas accumulated in the rock pores must be sufficient for the gas to do work in destroying the rock and transporting it along the working space [40–43], and such events are initiated by blasting work which weakens and alters the system of pressures in the rock mass.

The work done by the gas during sudden decompression is of an intermediate character between isothermal and adiabatic. In the first stage, this work is used to disintegrate the rock. The methodology for measurement adopted here, based on Brazilian tests, led to an estimate of the mean work required to be done by the gas in disintegrating 1 m$^3$ of rock at approximately 0.15 MJ/m$^3$.

The remaining energy is used to transport the ejected material along the working space. Based on the product of the density of the transported rock, the acceleration due to gravity, the coefficient of kinetic friction, and the distance over which the rock is to be transported, the work required to be done by the gas in transporting the outburst material was estimated at approximately 0.70 MJ/m$^3$.

Comparing the estimated values of the energy of the compressed gas accumulated in the porous structure of the rock and the potential energy of the deformed rock mass with the work required to disintegrate the rock and transport it along the working space, it is concluded that theoretical analysis allows the possibility of outbursts in dolomite. The boundary conditions are determined based on the porosity of the rock and the pressure of the gas contained in its porous structure.

In summary, the total energy that can be generated as a result of decompression of gas contained under pressure to around 12 MPa in dolomites with a standard porosity of around 5% is in the range for adiabatic conversion of 0.05–1 MJ/m$^3$, while for isothermal conversion it is in the range of 0.1–3 MJ/m$^3$. The sum of work required for shredding and transporting the rock along the excavation is 0.85 MJ/m$^3$. This means that, for the characteristic porosity of dolomites, we should expect an ejection at a sufficiently high pressure—in the case of isothermal conversion, this is a pressure of 5 MPa, and for adiabatic conversion, this is about 10 MPa.

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