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Jan MACUDA[1*] and Monika KONIECZYŃSKA[2]

ENVIRONMENTAL IMPACT OF EXPLORATION FROM UNCONVENTIONAL GAS DEPOSITS IN POLAND

WPŁYW PRAC POSZUKIWAWCZYCH NA ŚRODOWISKO W EKSPLORACJI NIEKONWENCJONALNYCH ZŁÓŻ GAZOWYCH W POLSCE

Abstract: Shale formations have been recently treated only as source rocks and sealing packages mainly of conventional deposits. At present shales, which have a considerable concentration of highly mature organic matter appearing in complexes of over 30 m thick are used as unconventional sources for natural gas production with the use of advanced drilling technologies. Natural gas production in such rock formations necessitates performing a horizontal section in the borehole and a big number of hydraulic fracturing jobs. The unconventional shale gas deposits have been prospected also in Poland for a couple of years. Exploration works mainly concentrate on a vast area passing from Pomerania through Mazowsze to the Lublin region in Poland. The analysis of the geologic analyses reveals that the most perspective are shales in the Lower Paleozoic at a depth of 2500 m in the eastern part to about 4000 m in the western part of the area. The paper is focused on the quantitative and qualitative evaluation of environmental impact of natural gas exploration works from unconventional deposits. Special attention was paid to the hydraulic fracturing jobs in shales, which create particular hazard for water and soil environment. These hazards already appear at the stage of preliminary works, when big quantities of chemicals and water for frac jobs are stored in the rig area, and then, during realization of works, when the spent hydraulic fracturing fluid may penetrate the water-bearing horizons in the caprock. The composition of fracturing fluid used in Gapowo B-1A well are given along with the results of chemical analyses of a few parts of spent fracturing fluid samples pumped out from the borehole. The fluid turned out to be high in salt (high specific electrolyte conductance (SEC) and total dissolved substances (TDS) and a high toxicity for most of the living organisms). For this reason the spent fracturing fluid should not enter the environment without control.

Keywords: natural gas, unconventional deposits, shale gas, exploration boreholes, environment, noise, drilling waste, hydraulic fracturing, fracturing fluid, spent fracturing fluid

Introduction

Classic gas and oil deposits are mainly connected with the process of hydrocarbon migration from source rocks (where hydrocarbons were generated) or reservoir rocks, which have very good hydromechanical properties (high permeability and considerable porosity). These deposits are located in structural, lithofacial or tectonic 'traps' and they

[1] Faculty of Drilling, Oil and Gas, AGH University of Science and Technology in Kraków, al. A. Mickiewicza 30, 30-059 Kraków, Poland, phone +48 12 617 22 26, fax +48 12 634 00 52

[2] Polish Geological Institute - National Research Institute, ul. Rakowiecka 4, 00-975 Warszawa, Poland, phone +48 22 459 20 25, fax +48 22 459 20 01, email: mkon@pgi.gov.pl

[*] Corresponding author: macuda@agh.edu.pl

considerably differ in their properties from the unconventional ones. The latter usually have low or ultra low permeability (usually below 0.1 milidarcy [mD] (10^{-16} m^2) [1, 2]. Four major kinds of unconventional gas deposits are usually distinguished [3, 4].

- Low permeability gas (0.1 to 0.001 mD), present in pores of limited contact among them (tight gas).
- Gas (methane) in coal seams, both free and adsorbed (Coal Bed Methane - CBM).
- Gas in clay and mudstones (shale gas, gas in clayey shales).
- Bounded gas in the form of hydrates - no efficient recovery technology.

Shale formations have been recently only treated as source rocks and sealing packages of conventional deposits. At present shales, which have a considerable concentration of organic matter (total organic carbon (TOC) above 1.5-2%), high thermal maturity index (vitrinite reflectance coefficient (Ro) above 1.3%) and which occur in complexes of thickness exceeding 30 m are used as unconventional deposits for advanced production of natural gas [5-7]. Unconventional gas deposits may also cover gas-condensate or purely gaseous deposits [8, 9]. Determining two-phase zones is vital for gas-condensate deposits [3, 10].

A dense grid of directional boreholes with long horizontal sections, where ten or so fracturing jobs are performed, should be performed. These jobs open fractures and a dense network of cracks around them, connecting the biggest possible number of rock pores and forming pathways for the migration of gas to the borehole, both the free and desorbed from organic matter and clayey minerals [11, 12].

Characteristic of „shale" deposits

Unconventional "shale" deposits are connected with natural gas occurrence in shale formations. In most cases these rocks are thick and they regionally extend with no structural traps or distinct gas/water contour. Additional property, which distinguishes them from classic hydrocarbon deposits is the necessity to use multilateral directional boreholes with long horizontal sections to carry on the production of natural gas [13, 14]. Multigrade hydraulic fracturing jobs are performed in horizontal sections to obtain commercial gas production [15-17].

Organic matter which generates hydrocarbons in shale rocks is kerogen. Its ability to generate hydrocarbons depends on the oxygen to carbon ratio and hydrogen to carbon ratio. The most favorable conditions for hydrocarbons generation was observed for kerogen type-III and partly kerogen type-II as far as gases and gas-condensates are concerned [18, 19].

When evaluating potential resources of natural gas, attention is also paid to TOC and Ro, which is the main component of kerogen [20]. The analysis of literature [3, 12] reveals that shales containing above 1-2% TOC have sufficient (commercial) amounts of gas, which can be produced. The best shales may reach even 12% TOC in various places all over the world. Apart from these properties, other reservoir parameters are taken into account: porosity > 4%, permeability > 100 nanodarcy ($>10^{-19}$ m^2), Ro > 1.3-1.5%. Such deposits have a natural system of fractures, though the matrix has a very low permeability 30 to 100 nD [13]. In coal-bed methane deposits the density of natural fractures is a significant parameter [21, 22]. Natural gas production from such rock formations cannot be performed without additional operations, *eg* hydraulic fracturing.

Drilling of exploration boreholes

Natural gas prospecting and opening unconventional gas deposits is realized through normal-diameter, multilateral drilling boreholes to a depth of a few thousand meters. Such constructions with long horizontal sections are practically the only way in which natural gas can be produced from shales. The exploration boreholes are drilled in the Horizontal Directional Drilling (HDD) technology. The first part is vertical and then at a certain depth it kicks off over the package of productive rocks in such a way that the trajectory is vertical in the moment it reaches the shales level. At present the horizontal sections are mostly 1.5 to 3.5 km long [13].

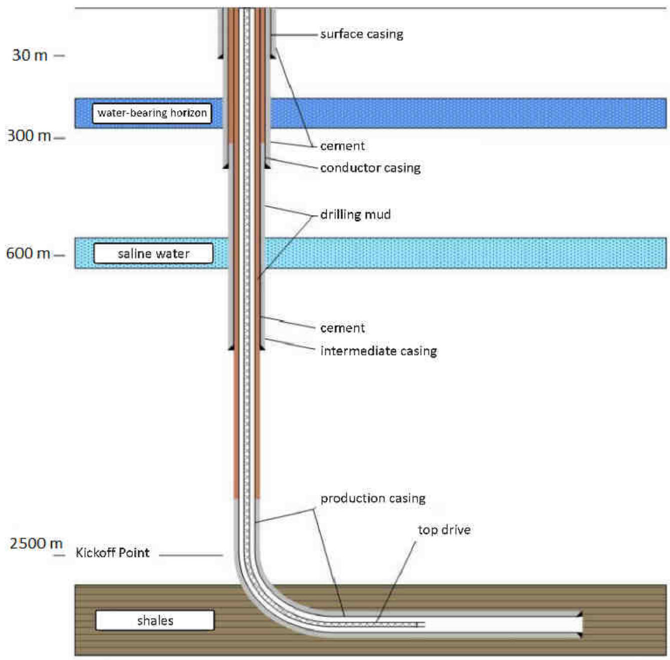

Fig. 1. Schematic of a shale gas exploration borehole [13]

The shale gas boreholes generally resemble exploration boreholes drilled for conventional gas and oil deposits. A typical schematic of an exploration borehole for unconventional deposits is presented in Figure 1. It consists of the following casing sections [14]:

- surface casing - 20” or 18 5/8” - to ca. 50 m of depth
- conductor casing - 13 3/8” - to ca. 500-900 m of depth (depending on the geological conditions in the given region),
- intermediate casing - 9 5/8” - to ca. 1500-2500 m of depth, depending on the geological conditions in the given region,
- production casing - 5” or 5 ½” 4000-6000 m long with a horizontal section 1000-2500 m long.

For the sake of providing stability of the drilled rock mass and tightness of the borehole construction all the casing sections are cemented to the surface.

Modern drilling tools are used for the realization of such boreholes. They are frequently set on a mobile base; their lifting capacity on hook is of 350-450 Mg and they are equipped with a Top Drive, 3 mud pumps of hydraulic power ca. (1200 kW) and submersible engine for horizontal drilling. The total capacity of driving motors supplying the rig subassemblies is 3000 to 4000 kW. The transport of the cuttings from the horizontal sections and their geomechanical stability are one of the most important issues while performing exploration boreholes [23].

Environmental impact of drilling on ground and water

When drilling exploration boreholes on unconventional shale deposits at a depth of 3000 to 4000 m an area of ca 2.0 to 4.0 ha has to be temporarily occupied and excluded from agricultural or forest production. In either case the size of the occupied area is significantly conditioned by the length of the access road, magnitude of rig subassemblies, depth and number of planned boreholes and capacity of pit where the fracturing fluid will be prepared.

In the course of drilling soil, ground and groundwater may be contaminated with fuel, oils, substances used for making drilling muds, cement slurry, technological fluids and fracturing fluid. Therefore, prior to the construction works within the rig area the state of the ground and water environment has to be analyzed to be able to establish a reference "background", on the basis of which potential changes can be assessed. These are analyses of CH_4 concentration in soil air, physicochemical and organic indices of soil, ground, surface water and groundwater. The scope of analyses of soil and ground most frequently covers: specific electrolyte conductance (SEC), AS - anionic surfactants, TDS - total dissolved substances, total organic carbon (TOC), Fe, Mn, B, Ba, Na, Ca, K, Br, Cl, NO_3, NH_4, phenols (phenol index) as well as petroleum hydrocarbons C_6-C_{12} and mineral oils C_{12}-C_{35} [24].

A considerably broader scope of analyses is planned for groundwater samples. Each time, after measuring the depth of the water level and pumping out 3 borehole volumes the following measurements are made: pH, specific electrolyte conductance (SEC), temperature and oxygen dissolved in water. Then groundwater samples are collected for laboratory analyses, *ie* [24]:

- general indices: pH, conductivity, turbidity, color, total dissolved solids, general total hardness, chemical oxygen demand ChOD, HCO_3 concentration,
- cations: Na, K, Li, NH_4, Be, Ca, Mg, B, Ba, Sr, Fe, Mn, Ag, Zn, Cu, Ni, Co, Pb, Hg, Cd, Se, Al, Cr, As, Mo, V, Sn, Sb, Ti, U,
- anions: F, Cl, Br, I, SO_4, CO_3, NO_2, NO_3, HPO_4,
- undissociated substances: phenol index, chlorophenols, glycols (ethylene glycol and propylene glycol), sum of aliphatic and aromatic hydrocarbons, organic matter, benzene, toluene, ethylbenzene, and xylens (BTEX), polycyclic aromatic hydrocarbons (PAHs), anionic and non-ionic detergents.

The preparation works on the rig lie in sealing the places where potentially dangerous substances are used (machine room, mud room, mud storages, fuel and lubricant storages, waste bins) with geomembrane, above which concrete plates or aggregate are disposed. Chemical substances used in the technological processes as well as the generated waste and cuttings are stored in tight tanks or containers. A collector trench is performed around the rig area for the rain waters. These solutions additionally protect the ground and groundwater against migration of contaminations inside the profile when a failure situation takes place. A view of a rig area during realization of the first in Poland exploration shale gas borehole with the use of MASSARENTI rig MAS 5000 E is presented in Figure 2.

Fig. 2. View of the rig while drilling an exploration borehole with a MASSARENTI rig MAS 5000 E [25]

Noise emission to the environment

Noise emissions accompanying drilling of deep shale gas exploration boreholes may be also an important environmental issue. When the rig is localized in highly urbanized areas or requires special protection, acoustic screens have to be applied.

Among the major sources of noise in the rig area are: power generators, engines driving rig devices, mud pumps and vibrating sieves. Presently the power aggregates are placed in closed rooms with unprotected walls (poor sound proof), whereas motors and mud pumps are completely or partly protected with a canopy (or partly housed). Vibration sieve shakers are generally unprotected. The distribution of noise level in the surrounding of the MASSARENTI rig MAS 5000 E when drilling a shale gas exploration borehole at 3700 m is presented in Figure 3. The rig was equipped with a hoist drive in the form of two DC motors 5GE 752 AR of constant power 1100 kW, mud pump drive in the form of 2 electrical engines 5GE 752 AR each and 4 combustion engines Caterpillar 3512 C4 powering electricity generators (1030 kW). The analysis of the results of acoustic measurements of noise A presented in [25], reveals that depending on the location of subassemblies, particular drilling rigs may affect the environment differently. This can be proved by the distinct directional acoustic plots. Considerable discrepancies in the noise level on the boundary of particular rigs show to the possibility of lowering their environmental impact by proper localization of the noisiest subassemblies to protected buildings and by using screening of other subassemblies and machines in the rig area [24]. This refers to a small distance from the rig, *ie* to about 200 m. Further from that place, the distribution of the noise level around the drilling devices assumes a circular form. In Table 1 we have average ranges of acoustic noxiousness of particular rig elements.

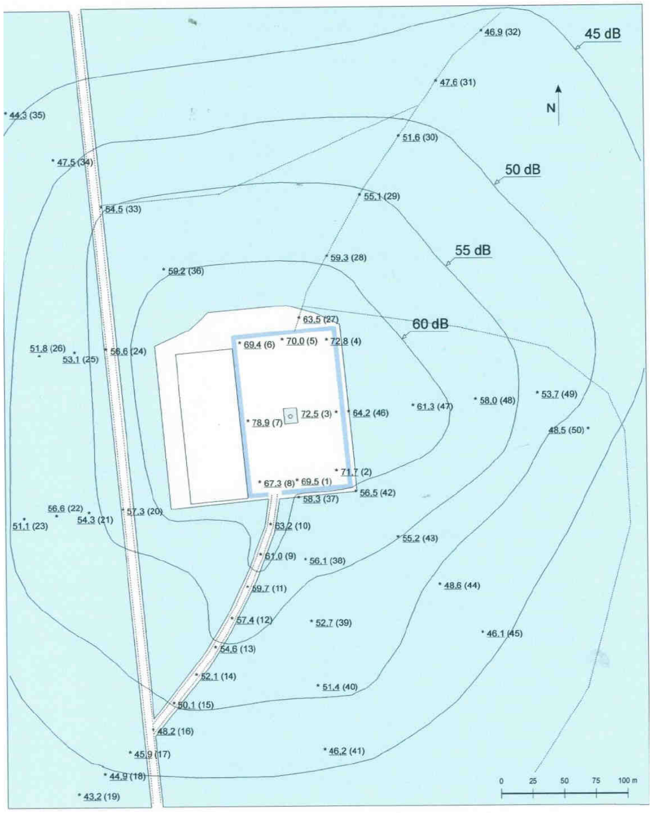

Fig. 3. Distribution of noise level in the neighborhood of the MASSARENTI rig MAS 5000 E [25]

Table 1

Average ranges of isolines 35, 40 and 45 dB for an open area [25]

No.	Rig	Range of isolines [m]		
		35 dB	40 dB	45 dB
1	Drillmec 2000 HP	635	472	312
2	MASSARENTI MAS 5000	672	502	323
3	Bentec EuroRig 450	627	487	309

Types and quantity of precipitations while drilling exploration boreholes

Drilling precipitations which have diversified chemical composition, mechanical properties and potential environmental toxicity appear in the process of drilling boreholes

[26]. Taking physicochemical properties as a criterion, the drilling waste can be divided into:

- cuttings coming from all drilled rocks in the borehole profile,
- drilling mud.

Among the main sources of waste present in the precipitations are: chemicals used for making and regulating technological parameters of muds, biocides, oil products, corrosion inhibitors, chemicals used for drilling up and enhancement of hydrocarbon production, reservoir fluids in the form of brine and oil [21].

Depending on the depth of drilling, a few types of mud are used for drilling shale gas exploration boreholes in Poland, *eg* bentonite, clay-free polymeric mud which reduces hydration of clayey rocks and for drilling up sales (drill in fluid), muds having inhibition qualities and protecting against damage to the permeability of the near-wellbore zone. The type of mud is selected individually on the basis of the geologic, reservoir and technical-technological conditions of drilling. Moreover additional quantities of other waste are produced while drilling a borehole, casing and cementing jobs *eg* cement slurry residue, waste produced during exploitation of mechanical devices, hydrated sediments from the treatment of industrial waste and communal waste.

Pursuant to the regulation of the Environment Minister of 27 September 2001 about the catalog of waste [27], the waste generated in the process of drilling exploration boreholes can be classified as:

- 01 05 05* - mud and drilling waste containing oil,
- 01 05 06* - mud and drilling waste containing dangerous substances,
- 01 05 07 - mud containing barite and other waste than listed in 01 05 05 and 01 05 06,
- 01 05 08 - mud containing chlorides and waste other than listed in 01 05 05 and 01 05 06,

(* - dangerous waste)

Part of the drilling waste are dangerous and while storing in the rig area they should be properly protected against penetrating the ground and water environment [26].

Apart from drilling waste it is also other waste which is generated in the rig area, which belongs to the following groups: 06, 07, 08, 12, 13, 15, 16, 17 and 20. The main types and average quantities of waste produced in the course of drilling exploration boreholes to the depth of 4000 m are listed in Table 2.

Table 2

Quantitative list of major types of waste produced while drilling an exploration borehole to a depth of 4000 m

No.	**Waste type**	**Amount of waste [Mg]**	**Share [%]**
1	Waste mud, cuttings	3904	99.874
2	Synthetic waste	0.518	0.013
3	Used oils	0.700	0.017
4	Oiled wipers	0.190	0.004
5	Fluorescence lamps and other waste containing mercury	0.047	0.001
6	Welding waste and used electrodes	0.086	0.002
7	Iron and steel waste	3.5	0.089
Total		3909.041	100.00

Opening shales with the hydraulic fracturing method

Hydraulic fracturing of shales is performed to liberate gas encapsulated in the rock micropores and adsorbed in the organic matter. After the drilling job is finished and the casing is perforated, large quantities of prepared fracturing water with sand (proppant) are injected into the rock medium to generate and support fractures in the selected interval of the horizontals borehole section (Fig. 4).

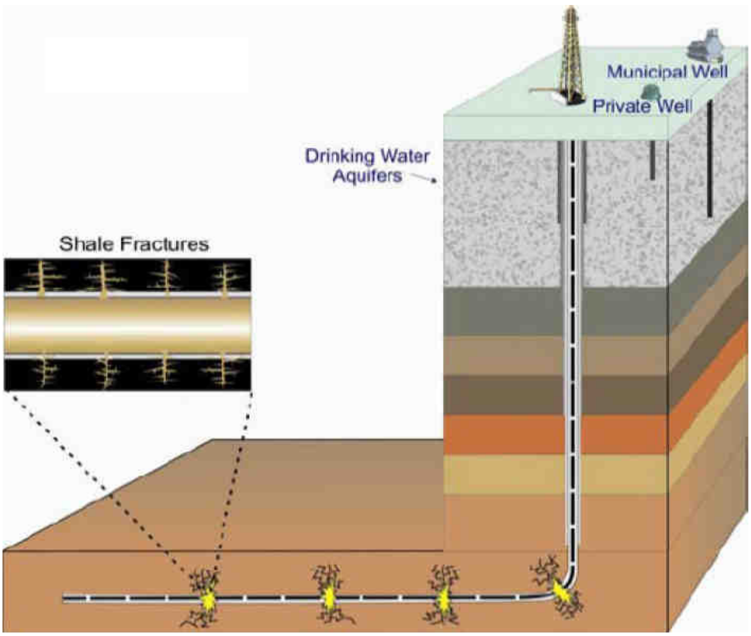

Fig. 4. Schematic of hydraulic fracturing in a horizontal borehole [28]

In industrial practice about 10 to 15 frac jobs are performed in a horizontal section ca. 1500-2000 m long. On average 8000 to 30000 m^3 of fracturing fluid and 500 Mg to 2500 Mg of proppant are used during one frac job [12]. The water and proppant injection efficiency is 6 to 20 m^3/min, at the pumping pressure of 100 MPa [17, 29]. The hydraulic fracturing job helps propagate the fracture at a distance of 200 to 300 m [22].

Facturing fluids

The fracturing fluid used in shale rock is mainly made of water, sand and a small amount of various chemicals. Their task is to lower friction when the fluid is pumped, lower surface tension, form gel, prevent scale formation and corrosion of production pipes, adjust pH, prevent development of bacteria and stabilization of clayey particles concentration in the fluid. Fracturing fluid consists of water in 90.5%, sand in 9% and chemicals in 0.5% (Fig. 5).

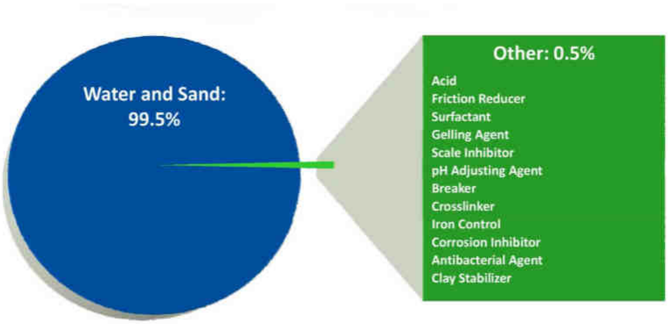

Fig. 5. Concentration of technological substances in fracturing fluid [14]

Table 3

Composition of fracturing fluid in Gapowo B-1A [30]

Hydraulic fracturing fluid composition: Chemical substance in fracturing fluid	**Chemical Abstract Service number (CAS)**	**Maximum ingredient concentration in hydraulic fracturing fluid [% by mass]**
Water	7732-18-5	97.26231769
Silica substrate	66402-68-4	0.96243748
Mullite	1302-93-8	0.91411425
Silicon dioxide	7631-86-9	0.26117550
Silica crystalline-cristobalite	14464-46-1	0.13058775
Choline chloride	67-48-1	0.12834003
Hydrochloric acid	7647-01-0	0.10916275
Sasol DHR 200	64742-48-9	0.07389841
Guar gum powder	Proprietary	0.06608919
Colemanite/ulexite distillates, (petroleum), hydrotreated light	Proprietary Blend 64742-47-8	0.03476695 0.01957735
Potassium carbonate	584-08-7	0.00847536
Gluteraldehyde	111-30-8	0.00816513
Potassium hydroxide	1310-58-3	0.00516431
Elementis Bentone® 150	14808-60-7 (Quartz), 629-11-8 (1,6-Hexanediol)	0.00361538
Tetrasodium EDTA	64-02-8	0.00210192
Alcohols, C_{12-15}, ethoxylated	68131-39-5	0.00189248
Propylene glycol	57-55-6	0.00187365
Ammonium persulfate	7727-54-0	0.00178336
Formic acid	64-18-6	0.00093683
Cinnamaldehyde	104-55-2	0.00093683
Propylene carbonate	108-32-7	0.00072308
Ethylene glycol	107-21-1	0.00047460
Oxyalkylated alcohol based polymer	34398-01-1	0.00031228
N-naphtha nicotinamide	770680-45-0	0.00031228
Lutensol TO-8 (1,6)hexanediol	629-11-8	0.00028923
Methanol	67-56-1	0.00016330
Crystalline silica (quartz)	14808-60-7	0.00013749
Trisodium nitrilotriacetate	5064-31-3	0.00010510
Sodium hydroxide	1310-73-2	0.00007006

The composition of fracturing fluid depends on the properties of rocks to be fractured in a given place, technology and design of the borehole, and also the fracturing technology [15, 29]. In practice the fracturing fluid used for drilling exploration boreholes does not have any stable composition. These are mixtures sequentially added and their composition is adjusted during the job, depending on the indications of control devices. This stems from the fact that other components are needed for making fractures in shales, other are used to stop swelling of clayey minerals and still different to maintain the proppant in fluid, so that it can be injected to the fracture to support it and then 'break' the structure of the suspension to pump out the used frac fluid and hydrocarbons without removing proppant from the fracture. As a consequence it is practically impossible to take a representative frac fluid sample, and its characteristic is determined by giving an interval of concentrations or maximum concentrations of particular substances (Table 3).

According to the Polish and EU law all chemical substances used in the process of hydraulic fracturing should be admitted to use in Europe and have characteristics, which precisely determine their chemical and physical properties, toxicity, hazard and neutralization methods in case of uncontrollable contact with people or environment. The charts are used for elaborating emergency procedures in case of undesired events during transport and storage of particular substances and the hydraulic fracturing job. If the job is performed carefully, the fracturing fluid practically does not have contact with the environment before the depth of fracturing, which in Poland is at least 2500 m b.s.

The water demand is environmentally important for hydraulic fracturing. One frac job requires as much as a tens of cubic meters of water which is used in a few days' time. Very rarely such amounts are available from local sources on demand. Besides a momentary consumption of such a big amount of water could negatively influence the groundwater and surface water resources. Therefore accumulation of water for hydraulic fracturing jobs should be realized over a sufficiently long period of time so that the available resources are not exceeded. The sources frequently have to be diversified and in particular cases water has to be transported from more distant places. This is environmentally advantageous when not only fresh waters are used, but also brines, rain waters, treated sewage and treated used fracturing fluid. The use of such alternative sources of water is regulated by the respective legal acts. At present only some of these sources could be used in Poland.

Used fracturing fluids

After the frac job is completed, some quantity of fracturing fluid returns through the open head to the surface. This fluid differs from the injected fracturing fluid because it gains new properties after contacting the rock, reservoir fluids and chemical reactions between the original components in the high pressure and temperature conditions. Analogous to the fracturing fluid, the chemical composition of reservoir fluid is not constant, though by controlling the pressure on the outflow and collecting samples sufficiently frequently, one can make a characteristic of the successive parts.

Varying yields of spent fracturing fluid return to the surface but generally about 15-20% of the injected fluid returns to the surface after a few days. The boreholes are deep in Poland therefore spontaneous outflows vanish very quickly. For this reason either gaslift or specialist pumps have to be used to produce larger amounts of fluid.

Hydrocarbons are one of the most characteristic components of the spent fracturing fluid. Even in the lack of industrial inflows of reservoir fluids, certain amounts of natural gas and condensate can be expected (Table 4). These substances have to be separated from the return fluid before it is sent to the collectors, where it is finally stored. These are two- or three-phase separators which remove gas from it and allow for collecting liquid hydrocarbons to special tight containers. The collected condensate has an industrial application, whereas methane from the exploration boreholes is most frequently combusted on flares. The combustion (Fig. 6) causes that almost 100% of carbon dioxide and vapor reach the atmosphere instead of methane, which is more efficient as far as the greenhouse effect is concerned.

Table 4

Exemplary determining organic indices in the successive parts of past-fracture fluid [31]

Sample No.	Benzene	BTEX	Methane	Hydrocarbons $C_2 - C_{10}$
	[μg/dm^3]			
1	< 0.5	< 0.5	1 368	1 253
2	< 0.5	< 0.5	3 505	3 113
3	< 0.5	< 0.5	1 889	2 117
4 (behind separator)	< 0.5	< 0.5	144	358
5 (behind separator)	< 0.5	< 0.5	120	306

Fig. 6. Combustion of natural gas separated from spent fracturing fluid after the frac job

Table 5
Exemplary physicochemical characteristic of successive parts of fluids returning from the same frac job [31]

Sample No.	pH	SEC	Colour	Turbidity	ChOD	PhI	Cyanides	AS	TDS	General basicity	General hardness
	-	[µS/cm]	[mg Pt/ dm^3]	[NTU]	[mg/dm^3]					[mg $CaCO_3/dm^3$]	
1	6.67	90000	130	0.7	60	< 10	< 1	15	91006	168	12329
2	6.60	100000	20	0.4	46	< 10	< 1	29	68448	152	14103
3	6.55	101000	128	0.5	70	< 10	< 1	16	68472	156	14366
4	7.01	107000	90	2.7	92	< 10	< 1	13	73769	240	15971
5	7.03	109000	159	0.7	69	< 10	< 1	19	72148	210	16301

SEC - specific electrolyte conductance, ChOD - chemical oxygen demand, PhI - phenol index, AS - anionic surfactants, TDS - total dissolved solids

Table 6
Exemplary concentrations of anionic components in the successive parts of fluid returning from the same job [31]

Sample No.	F	Cl	NO_2	Br	NO_3	HPO_4	SO_4
	[mg/dm^3]						
1	5.40	37 000	5.88	473	4.72	< 30	< 50
2	< 10	42 000	6.23	526	4.91	< 30	< 50
3	< 10	42 000	6.05	531	6.38	< 30	< 50
4	< 10	45 000	7.20	605	5.0	< 30	< 50
5	< 10	43 000	6.86	565	5.63	< 30	< 50

Table 7
Exemplary concentrations of cationic components in the successive parts of fluid returning from the same job [31]

Sample No.	B	Ba	Ca	Cr	Fe	K	Mg	Mn	Na	P	SiO_2
	[mg/dm^3]										
1	38.0	53.6	4120.0	< 0.3	9.0	428.0	495.0	2.4	17598.0	< 5.0	64.0
2	39.0	60.9	4720.0	< 0.	11.0	467.0	563.0	2.4	19215.0	< 5.0	61.0
3	39.0	61.2	4804.0	< 0.3	11.0	462.0	576.0	2.4	19131.0	< 5.0	61.0
4	39.0	69.0	5351.0	< 0.3	11.0	489.0	634.0	2.5	20528.0	< 5.0	57.0
5	39.0	70.4	5461.0	< 0.3	12.0	499.0	647.0	2.6	20843.0	< 5.0	59.0
Sample No.	**Sr**	**Ti**	**Zn**	**Hg**	**Li**	**Be**	**Al**	**V**	**Co**	**Ni**	**Cu**
	[mg/dm^3]			[µg/dm^3]							
1	380.0	0.3	< 0.3	< 0.3	8800	< 50	< 500	< 1000	< 50	< 500	< 500
2	452.0	0.3	< 0.3	< 0.3	10000	< 50	< 500	< 1000	< 50	< 500	< 500
3	456.0	0.4	< 0.3	< 0.3	10300	< 50	< 500	< 1000	< 50	< 500	< 500
4	505.0	0.4	< 0.3	< 0.3	11600	< 50	< 500	< 1000	< 50	< 500	< 500
5	523.0	0.4	< 0.3	< 0.3	12000	< 50	< 500	< 1000	< 50	< 500	< 500
Sample No.	**As**	**Se**	**Mo**	**Ag**	**Cd**	**Sn**	**Sb**	**Tl**	**Pb**	**U**	
	[µg/dm^3]										
1	< 2000	< 2000	< 50	< 50	< 50	< 500	< 50	< 50	< 100	< 50	-
2	< 2000	< 2000	< 50	< 50	< 50	< 500	< 50	< 50	< 100	< 50	-
3	< 2000	< 2000	< 50	< 50	< 50	< 500	< 50	< 50	< 100	< 50	-
4	< 2000	< 2000	< 50	< 50	< 50	< 500	< 50	< 50	< 100	< 50	-
5	< 2000	< 2000	< 50	< 50	< 50	< 500	< 50	< 50	< 100	< 50	-

Apart from water, the remaining components of the used fracturing fluid are substances used for the preparation of the fracturing fluid, frequently after chemical reactions, and dissolved solids and liquids of rock formations undergoing the frac job. The basic physicochemical characteristic of the successive parts of the used fracturing fluid from the exploration borehole in the Lublin area is presented in Table 5. Very high salt content manifesting itself in high SEC and TDS causes that the fluid is toxic to most of the living organisms, therefore cannot be disposed to the natural environment without control.

What is characteristic here is a very high, up to tens of grams per liter concentration of chlorides (Table 6), sodium, calcium and potassium (Table 7). Exemplary changes in the concentrations of successive parts of the returning fluids during one frac job are listed in Tables 6 and 7.

In some regions increased concentrations of radioactive elements can be also expected in fracturing fluids which return to the surface after the job. This mainly refers to frac jobs in such formations which were enriched in natural radio nuclides. No higher than naturally occurring and safe for human being radioactive isotopes have been found in the used fracturing fluids in Poland [31], *ie*:

- for ^{40}K: 51 ± 11 to 347 ± 20 Bq/kg (in Pomeranian Basin) and 12 ± 7 to 492 ± 35 Bq/kg (in Lublin Basin);
- for ^{226}Ra: < 10 to 48 ± 4 Bq/kg (in Pomeranian Basin) and 19 ± 3 to 29 ± 3 Bq/kg (in Lublin Basin);
- for ^{228}Th: < 10 to 21 ± 3 Bq/kg (in Pomeranian Basin) and < 10 Bq/kg (in Lublin Basin).

Conclusions

The presented evaluation of environmental impact of exploration works for hydrocarbons from unconventional deposits reveals that both the drilling works and hydraulic jobs create a slightly bigger hazard than in the case of conventional deposits. In Poland shales appear at great depth therefore the exploration boreholes have to be deep. Moreover, the rigs have to have better technical parameters and installed capacity of driving motors. When drilling such boreholes more space is needed for the rig, more waste is generated and more noise is emitted to the environment than in the conventional deposits. This is particularly important when performing numerous and extensive hydraulic fracturing jobs on the shales. In such conditions the reuse of the fracturing fluid for the successive hydraulic fracturing jobs is a good solution. This however requires very efficient technologies of treating the fluid mainly from hydrocarbons, dissolved salts and chemicals used when preparing the fluid. In addition, special guidelines for the environmental and technological aspects of conducting drilling and hydraulic fracturing jobs in shales should be worked out to guarantee safe exploration and extraction of hydrocarbons from unconventional deposits.

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WPŁYW PRAC POSZUKIWAWCZYCH NA ŚRODOWISKO W EKSPLORACJI GAZOWYCH ZŁÓŻ NIEKONWENCJONALNYCH W POLSCE

[1] Wydział Wiertnictwa, Nafty i Gazu, Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie
[2] Państwowy Instytut Geologiczny Państwowy Instytut Badawczy, Warszawa

Abstrakt: Formacje łupków do niedawna traktowane były jedynie jako skały macierzyste i pakiety uszczelniające głównie dla złóż konwencjonalnych. Aktualnie w świecie skały łupkowe, które charakteryzują się znaczną koncentracją materii organicznej o wysokiej dojrzałości termicznej i występujące w kompleksach o miąższości powyżej 30 m, są wykorzystywane jako złoża niekonwencjonalne do eksploatacji z nich gazu ziemnego przy wykorzystaniu zaawansowanych technologii wiertniczych. Wydobycie gazu ziemnego z takich formacji skalnych wiąże się z wykonaniem w poziomym odcinku otworu dużej ilości zabiegów hydraulicznego szczelinowania skał. W Polsce od kilku lat prowadzone są również prace poszukiwawcze niekonwencjonalnych złóż gazu ziemnego w skałach łupkowych. Koncentrują się one głównie w szerokim pasie ich występowania, przebiegającym przez Polskę od Pomorza poprzez Mazowsze po Lubelszczyznę. Z analizy dotychczasowych badań geologicznych wynika, że najbardziej perspektywiczne jest występowanie tego typu złóż w skałach łupkowych dolnego paleozoiku, zalegających na głębokościach od 2500 m we wschodniej części tego pasa do około 4000 m w jego części zachodniej. W pracy skoncentrowano się głównie na ilościowej i jakościowej ocenie wpływu prac poszukiwawczych za gazem ziemnym w złożach niekonwencjonalnych na środowisko naturalne. Szczególną uwagę zwrócono na zabiegi hydraulicznego szczelinowania skał łupkowych, które stwarzają największe zagrożenia dla środowiska gruntowo-wodnego. Zagrożenia te występują już na etapie prac przygotowawczych, w wyniku magazynowania na wiertni dużych ilości środków chemicznych i wody do zabiegów szczelinowania oraz w trakcie ich realizacji w wyniku potencjalnej możliwości przedostania się płynu pozabiegowego do występujących w nadkładzie utworów wodonośnych. W pracy podano skład cieczy szczelinującej użytej do zabiegu w otworze Gapowo B-1A oraz wyniki analiz chemicznych kilku partii płynu pozabiegowego, odpompowanego z otworu. Stwierdzono jego wysokie zasolenie, przejawiające się wysokimi wartościami parametrów PEW i SSR oraz dużą toksyczność w stosunku do większości organizmów żywych. Z tego względu płyn pozabiegowy nie może dostawać się do środowiska w sposób niekontrolowany.

Słowa kluczowe: gaz ziemny, złoża niekonwencjonalne, gaz z łupków, otwory poszukiwawcze, środowisko, hałas, odpady wiertnicze, szczelinowanie hydrauliczne, płyn szczelinujący, ciecz pozabiegowa