Technical note

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GEOLOGICAL CO_2 STORAGE AND OTHER EMERGING SUBSURFACE ACTIVITIES:

D 3.2

COUNTERMEASURES AGAINST RISKS ARISING FROM SHALE GAS EXPLORATION

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Un grand merci & thank you!

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1 Context

Based on the review of best practices of monitoring for emerging subsurface activities (ESA) within deliverable D3.1 this technical note focuses on the risks, impacts and potential countermeasures mitigating these for shale gas extraction (SGE).

SGE involves hydraulic fracturing (fracking), which itself can be considered a standard technology in oil and natural gas abstraction for conventional resources, deep geothermal energy and tight gas. However, in contrast to geothermal projects and tight gas exploitation, SGE requires multiple drillings and fracking operations and involves large volumes of water and chemicals. Potential negative impacts on shallow groundwater resources, land use, waste disposal, atmospheric emissions and the toxicity of involved chemicals pose questions to authorities, water suppliers and the concerned public, and some of the above-ground activities related to SGE projects have been identified as major hazards.

Based on the prioritization of relevant risks (presented at the COSMA-TC of 13th Dec. 2013), D3.2 briefly summarizes the current European and German legislative framework, state of technology for SGE projects and reported incidents. Subsequently, mitigation measures to prevent damage to water resources are specified taking the water supplier's perspective.

Recent impact assessment studies and approaches to identify potential risks for the environment and human health for the whole SGE life cycle (AEA 2012; Bergmann et al. 2013; Ministry for the Environment 2013; NYCDEP 2009; USEPA 2004; USEPA 2013) were considered to determine existing SGE operators monitoring programs. Further reports are expected in the course of 2014 i.e. from the German and US federal environmental protection agencies specifically on impacts of hydraulic fracturing on water resources.

1.1 European versus the North American context

In conventional and tight gas exploration, stimulation by hydraulic fracturing has been used since 1949 in the U.S. and e.g. since 1961 in Germany. While these technologies require the use of comparatively small volumes of water, injected from vertically drilled boreholes, the technology of horizontal directional drilling enabled a rapid development of unconventional gas exploitation (AEA 2012) involving a high number of drillings, large volumes of water and the use of certain additives. Since media reports from the U.S. raised concerns about the environmental risks, the technology has been banned by some European states, while others started exploration projects. The framework and constraints in Europe are however different from the U.S., in particular regarding the

- depth of the target formations,
- population density in the areas concerned,
- existing legislative framework,
- "ownership" of mineral rights
- environmental, health & safety standards and
- recognized standards of good practice.

1.2 Legislative framework

In the U.S., since 2005 fracking is excluded from the Safe Drinking Water Act and regulation is under the responsibility of the federal states and thus heterogeneous. Regulatory approaches however increase and almost half of the states have enacted or pending legislation. Four components of SGE operations are generally addressed in states' regulations. These are i) Pre-drilling, ii) Groundwater and surface water impact, iii) Liquid wastes and fluids, and iv) Solid wastes.

In addition, the U.S. EPA is developing guidelines and standards, including waste water discharges, and the Dept. of Interior proposed a rule to publicly disclose used chemicals. The application of US EPA guidelines in federal regulation is however not mandatory. With regard to SGE, the EPA "Underground Injection Control (UIC) Program" covers drilling and injection as well as induced seismicity, and recommends monitoring of injection pressures and volumes.

On the level of the federal states, New York (state) is currently discussing buffer zones of 1.3 km to drinking water reservoirs, containment of waste water (produced water) and the mandatory disclosure of used chemicals. Pennsylvania authorities are working on new standards for well cementation, pressure monitoring and gas migration (Neutraler Expertenkreis 2012).

On European level, two issues are widely discussed: i) the regulation of the use of fracking chemicals within REACH and ii) mandatory Environmental Impact Assessment (EIA). Further aspects are dealt with within the Integrated Pollution Prevention and Control (IPPC) Directive (2008/1/EC), and in the Mining Waste Directive (2006/21/EC) requesting certain permission processes and monitoring specifications.

Within REACH, hydraulic fracturing has not been addressed during the registration process, yet (Gottardo et al. 2013; Merenyi & Führ 2012). So far, fracking chemicals are neither catalogued nor - with regard to their introduction into groundwater bodies - addressed by existing directives such as the Water Framework Directive. What is not contained in annex VIII of the WFD is a priori no pollutant and/or is to be further regulated on member state level if necessary.

An EIA, on the other hand, is not mandatory, yet, as the given threshold of >500.000 m^3/day produced gas volume of annex I of the EIA Directive is typically not met by SGE. In 2013, the EU parliament has voted to amend the EIA Directive by requiring all private and public coal bed methane as well as shale gas exploration projects involving hydraulic fracturing in the EU to undertake an EIA (European Parliament Press release 09-10-2013).

In Germany, SGE is governed by the Federal Mining Act. Of relevance are further the Deep drilling ordinance and the Hazardous substances ordinance. Enforcement authorities are typically the Federal Ministries of Geology, Mining and the Environment. A stepped approval process includes overall and specific operation plans and public participation, if more than 300 people are affected. Fracking itself is a technology for well treatment and is permitted to be applied only under supervision of the competent authority. The use of groundwater in fracking requires permission according to the Federal Water Act.

Concerning monitoring and mitigation plans, all regulations so far demand monitoring concepts, list the target functions and assign reporting obligations, but do not contain specific measures.

2 Identification of risks

Based on deliverables D1.1 and D3.1, leakage of drilling fluids, fracking fluids and/or formation water were identified as main hazards to the environment and human health. While potential pathways are mainly faults and fractures, but may also be improperly sealed or abandoned wells, transport mechanisms include pressure increase in the subsurface or migration with the flowback. Risks in the technical system must be rated higher than in the geological system, and risks to shallow aquifers are so far mostly reported from above-ground handling of fluids and/ or flowback.

2.1 Risk inventory

Table 1 summarizes hazardous events and hazards from SGE from which subsurface migration and technical failure were identified to be of main concern (thus highlighted).

Table 1: Summary of risks associated with hydraulic fracturing [after Wright et al. 2010, COSMA-1 D1.1 and D3.1; as presented at the TC meeting of 13th Dec. 2013]

	Hazardous event	Hazard	"Fracking component"	Problematic contents
Above-ground handling	**Land disturbance**	Truck traffic Intensive industrial activities	Roads Pipe installations Compressor stations	Fuels Waste from fracking activities
	Chemical spills	On-site spills Vehicle-related spills	Fracking fluid[1] Flowback water[2] Produced water[3]	Additives Salts, heavy metals, radionuclides
	Waste disposal	Wastewater treatment and disposal activities	Flowback water Produced water	Additives Salts, heavy metals, radionuclides
Subsurface migration	**Structural compromise of geologic formation**	Disruption/ Change of groundwater flow paths	High number of drilled wells Casing or grouting failures	Hydraulic shortcut/ creation of preferential flow paths Connection of previously separated aquifers
	Impact to pre-existing fractures and faults	Major source of uncertainty is prediction of fracture dimensions and geology	Creation of continuous open faults	as above
	Upward migration of natural gas	as above	Mobilisation	Methane
Technical failure	**Drilling**	Leakage of drilling fluids		(Turbidity, Ca, Cl, TDS)
	Well construction failure	Leakage	Fracking fluid Flowback water Produced water	Additives Salts, heavy metals, radionuclides
Other	**Water consumption**	Aquifer depletion	Water withdrawal	Impact on aquatic and water level-dependent eco-systems Impact on shallow drinking water sources

1) "Fracking fluid" applies to injected fluids during the fracturing phase
2) "Flowback water" applies to fracking fluid returned during the production phase
3) "Produced water" applies to the rock formation water in the flowback

2.2 Known incidents

All major studies and reports concluded that drinking water contamination by fluid migration and methane leakage is mainly due to bad well integrity (e.g. Neutraler Expertenkreis 2012a; USEPA 2012). In USEPA (2012), one case study concerning the uncontrolled release of fracking fluids by a blowout during drilling was further detailed.

Nolen (2011) concluded from regulatory agency reports for the US that 0.7% of all active oil and gas wells in Texas, Kansas and New Mexico (conventional and unconventional resources, n = 219.546 wells) showed to have an impact on nearby groundwater resources, and 0.06% of wells in Texas and Kansas (n = 203.235) had an impact on surface water bodies. Impacts explicitly from SGE wells were however not reported, yet.

Bachu & Watson (2014) concluded from a case study in Alberta, Canada that, while subsurface migration is manageable by proper geological site characterization, defective wells would be more difficult to assess and manage. A data analysis of 315.000 oil and gas wells, which were tested at rig release and, if done after 1995, at abandonment showed that about 4.6% of the investigated wells had surface casing vent flows and/or gas leakage. They further related the number of wells drilled per year and percentage of leaky wells to different regulatory and standardization approaches and thus to variable materials and drilling and installation technologies. ExxonMobil, for example, stated too, that long-term experience with cementing covers 80 years, now and old cements were more prone to degradation, but pointed out that repair technologies would be available, too (Neutraler Expertenkreis 2012b).

Jackson et al. (2013) reported from an investigation of 141 wells in Pennsylvania, that stray gas methane was six times higher than average within a 1 km radius around a fracking site, ethane was 23 times higher, and propane was detected in 10 from 141 wells. Schwartz (2014) summed up that in Pennsylvania about 10% of new wells and 50% of old wells that had been fracked are affected by stray methane gas resulting from bad casing of the wells. Natural methane background concentrations are however also high.

According to a (unpublished) study by the Polish Geological survey (pers. communication Monika Konieczynska, 24-06-2014) methane showed to accumulate below protective liners sealing the bore pad and surrounding area. To which extent shallow aquifers could be affected by dissolving methane has to be further investigated.

3 State of technology

For most of the activities during shale gas exploration, the standards of conventional oil and gas drilling are applicable. Thus, technical standards to apply best practices of drilling and design and maintain the well's integrity are already high and multi-barrier systems are implemented in order to protect the environment, groundwater and human health (Schilling 2012).

Technical barriers include a system of four (cemented) casings at the well head and upper 300 m. Geologically, groundwater bearing formations used for drinking water supply (typically up to 200 m deep) and shale gas bearing formations (typically 1.000 to 4.000 m deep) are separated by multiple confining layers.

3.1 Bore-pad / Surface protection

The drilling pad itself and the whole working area is typically sealed with protective liners against soil and shallow groundwater contamination, with overflows into storage systems with oil separators.

Surface run-off is collected in channels surrounding the construction site (Neutraler Expertenkreis 2012b). Storage on site usually involves double-walled tanks while open ponds are becoming an exception.

3.2 Drilling and casing

Typically, the API standards (American Petroleum Institute 2009), in Germany supplemented by the DVGW rules (DVGW 1998; DVGW 2001), are applied and fracking is only approved after the borehole has been examined to prove proper construction (mandatory in the UK; RAENG (2012)).

Analogous to conventional oil and gas, methane may enter the borehole during drilling (leading to so-called "kicks" or blow-outs). Blow-out preventers (BOP) and the continuous assessment of the drilling progress, borehole pressure, cementing process and cement quality are thus standard technologies. The multi-barrier concept further includes a system of casings with cemented annular spaces with

1- a conductor casing (stabilization at the surface) bound to the first aquifer
2- a protective casing (surface casing) bound to the uppermost confining layer
3- intermediate casings (technical casing) to protect deeper groundwater layers and
4- the production casing, drilling to proceed each with a leak-off test

Casing materials and cements must be adapted to local conditions, e.g. with regards to tensile strength, temperatures, corrosion resistivity etc. Because of costs, different materials may be used with depth and conditions. Minimum compressive resistance after stimulation must be higher than 3 MPa and maximum permeability 0.1 mD along a "sufficient" length (Schilling 2012).

In Germany, drilling fluids and cements for the upper 500 m of the borehole must further fulfill the specifications of the Federal Water Act for use in groundwater (Uth 2012).

3.3 Fracking fluids

Extent and composition generally strongly depend on the geology of the reservoir and the shale gas properties. Following the intense public and scientific debate, nowadays their characteristics are partly published by the companies, which is however still not mandatory in most cases (Schilling 2012). Chemical analyses are usually carried out by operators and to a variable extent by the respective Dept. of Environmental Protection.

Because of cost and environmental impacts, efforts increase to recycle fluids from produced water and to substitute biocides and highly toxic ingredients. What is not recycled is typically disposed via injection boreholes, what may pose an additional risk to water resources or in conventional wastewater treatment plants.

Debate is ongoing concerning the underground dispersion and fluid-rock-interactions. BGR (2012) for example concluded that groundwater resources should be classified into usable and unusable resources and further stated that fracking fluids usually stay in deep, salty, unusable groundwater where they are diluted by a factor of 4 to 5. Exxon Mobil (2014) reports that currently only two hazardous substances according to the water pollution classification system are used. The substitution of biocides in water-sensitive areas is possible by UV-disinfection, but only, if turbidity is not too high (Uth 2012).

3.4 Monitoring

With special focus on groundwater resource protection, USEPA (2012) concluded that the minimum set of information must allow for the assessment of:

- pre-existing connection between the shale gas formation and groundwater resources used for drinking water supply
- groundwater and surface water quantity and quality before and after fracking
- location, dimension and connectivity of (created) fractures
- changes in flow between the target formation and shallow aquifers

Baseline monitoring must cover a "sufficient" time-span and natural flows of groundwater, methane, CO_2, background seismicity etc. and must include deep and shallow formations.

To assess the risks for the stimulation and production phase, during borehole completion, the following (operational) parameters are typically assessed by the operator (Schilling 2012):

- stratigraphy and lithology
- mechanical, thermal and chemical properties of fluids, target formation and overburden (measurement/ logging while drilling, see annex II in D3.1)
- depth profiles of stress, pore pressures, temperature, porosity, ...
- geomechanical rock analyses such as stability, friction angle and coefficients, ...

General test procedures by the operators after borehole completion, as partly required by the competent supervising authority, include micro-/ mini-fracs (so-called data-fracs to predict and model the geometry and orientation of induced fractures), leak off tests, pressure logging, caliper logs, cement bond logging and geochemical analyses of groundwater (Schilling 2012). They are used together with the data-fracs to calibrate and validate models.

Special monitoring requirements during operation and limits for chemicals are typically specified in the permissions. They are mainly depending on the design of the production site, their proximity to ground and surface water, and the toxicity of chemicals (DECC 2014). Operators focus on detecting undesired intakes and fluid movements behind the casing as wells as on maintaining well integrity. Tools and methods are recommended e.g. in the USEPA standard for mechanical integrity of injection wells (USEPA 2013a) and include temperature logs, noise logs, tracer logs and flowmeter measurements (production logs), and cement bond logs, gamma-ray logs and visual casing inspection (mechanical integrity tests). A good indicator for gas migration through the annular spaces is a sustained casing pressure (SCP), for which probability is typically increasing with well age (Schilling 2012). Well integrity (leak-off tests, annular pressures) should be monitored regularly and especially after fracking as the pressures involved in stimulation can potentially damage casing or cements (Dusseault 2001 cited in Schilling 2012).

4 Discussion

During shale gas exploration, the risk for failure is highest in the technical system and during the fracking procedure itself by which further geological pathways could be activated. This time-span however covers only weeks and any improper behavior of the borehole or formation is detectable, if monitored according to technical standards. Failure in the geological system on the other hand are more difficult to evaluate and could lead to long-term effects in operation and post operation and site closure (Bergmann & Meiners 2014). So far, no incidents have been reported, but it may be too early to conclude that fluid migration to shallow aquifers along pre-existing natural hydraulic connections is unlikely (IRGC 2013).

While monitoring and maintenance plans concerning the technical system are usually well defined as part of the permissions (regular component testing and replacement), mitigation plans may be rather general and information is not publically available, yet. Thus, knowledge gaps and room for improvement exist.

Standards, such as e.g. OPG (2012) demand the proper management of risks, which is the definition of a course of action to correct the failure, based on the number of barriers, criticality of failure, prioritization etc. Such a well failure model would result in a corrective response matrix including:

1- a list of critical elements and typical modes of failure
2- an action plan stating required resources, responsibilities, response time, etc.
3- a prioritization of risks/ response times
4- the required well status for/ during repair (operate, close in, suspend)

Further, all potentially affected stakeholders need to be identified and access to data has to be provided to them.

4.1 Regulatory instruments

Shale gas exploration is legislated under the according mining laws, water issues and groundwater protection on the other side belong to the according water acts (German Federal Water Act, US Safe Drinking Water Act etc.). Thus, different competencies need to be disentangled and responsibilities to be clearly and consistently assigned.

The competent authorities need to develop further regulatory instruments (Esterhuyse 2013; IRGC 2013), such as:

- baseline monitoring protocols,
- setback rules (=safe distances),
- data dissemination rules (= e.g. establishment of a central management agency),
- long-term monitoring plans (and assignment of financial responsibility).

4.2 Monitoring techniques

Basic requirement is the understanding of the geological and hydrological systems and their interaction prior and during shale gas exploration. The operators are generally responsible for the according emission-based monitoring and risk management.

Responsibility for baseline surveys and monitoring of the formations separating the shales (operators) from shallow aquifers (water suppliers) is so far not regulated and thus a gap of knowledge and no mitigation concepts exist. Potential monitoring techniques, such as 4D seismics (Johann et al. 2006) or airborne monitoring (stereo-pair aerial photography to identify fractures or faults, remote magnetic sensing to find old wells, infrared and resistivity data to identify near-surface structural features and shallow gas occurrence; GWPC (2012)) exist, but their application is a matter of cost (and thus assignment of responsibilities). Table 2 summarizes the main concepts.

Table 2: General monitoring and mitigation concept for the previously identified relevant risks

	Key parameter	Monitoring	In charge*	Mitigation**	Gaps // Open questions
In-zone	**Pressure within formation**	micro-seismic fracture monitoring temperature logging	operator	lower reservoir pressure by abstraction	./.
	Pressure within well	annular pressure	operator	multi-barrier concept; repair/ remedial casing/cementing;	./.
	Fracture geometry	micro-seismic logging temperature logging	operator	creation of a hydraulic barrier upstream of the fault	models taken from conventional oil&gas drilling need further development
Above-zone	**Pressure within formation**	pressure transducers in deep monitoring wells situated between bore pad and drinking water source	competent authority and/or operator	sealing of the fracked reservoir with a very dense material	lack of monitoring wells in that depth
	Induced seismicity	micro-seismic logging (surface and/ or borehole)	operator	stop of operation; check of well integrity; repair if needed	cost of advanced technologies such as 4D logging
Freshwater system	**Hydrostatic pressure**		water supplier and/or authority	creation of hydraulic barriers/ pressure release by abstraction	./.
	Chemical composition of ground- & surface water	pH, temperature, TDS; turbidity, chloride	all parties	1- comparison against flowback fingerprint to verify source 2- comparison against groundwater protection limit values 3- remediation/ treatment	baseline surveys in different geological formations; dilution factors and fluid-rock interactions of fracking chemicals; ability of WWTP to cope with loads in produced water
	Gas detection	methane, ethane, propane	well owner / water supplier	1- isotopic composition to determine source 2- venting 3- water treatment 4- reconstruction of well	effort & cost of monitoring
Vadose zone	**Soil water composition**		authority	determination of source, followed by remedial treatment	lack of baseline data; effort & costs of monitoring
	Soil gas composition	methane, ethane	authority		effort & cost of monitoring
Technical system	**Well integrity (prior, during and after production)**		operator	repair or abandonment	handing over procedures of responsibility; financial responsibility for "orphaned" wells

** recommendation*
*** with the objective to protect (shallow) groundwater resources*

4.3 Conclusions

Specific measures apart from the repair of technical failure of well integrity could not be identified. This is due to i) the lack of reported incidents and ii) the lack of (undisclosed) precise mitigation plans, which are typically determined between the operators and competent authorities, which are mining rather than water authorities.

In general, the application of matured technical standards and exhaustive site characterization positively affect the risk of failure in the technical or geological systems. Site characterization must include the proper determination of

- Pathways
- Groundwater quality baseline for deep and shallow aquifers
- Inventory of chemicals disclosing identity and quantities
- Flowback characterisation and disposal management

Major issues and thus need for further research is seen in:

- the uncertainty in prediction of geological system behaviour
- fluid-rock interaction and fate of introduced chemicals

According to Bergmann & Meiners (2014), the probability of unintended fracture propagation cannot be assessed beforehand and Davies et al. (2012) reported fractures propagating up to 580m below ground surface. AEA (2012) thus concluded that at less than 600 m deep shale gas formations there is a moderate risk for fluid leakage via wellbore or induced fractures and gas migration through natural pathways. The deeper the fracking horizon is, the better protected are shallow aquifers because of more confining layers in between. On the other hand, deeper wells pose higher risks to well failure because of their longer casing and cementing and higher pressure gradients.

For public water suppliers near shale gas production sites it is strongly recommended to

- get involved and request transparency;
- question fluid and flowback composition;
- demand baseline sampling and access to data;
- determine thresholds and best "fingerprint" for contamination;
- request involvement in monitoring plan and risk management development.

Together with the site operator and the competent authority, the following questions should be discussed during the (mandatory) risk management approach:

- What is the minimum distance (both laterally and vertically) between the explored shale and deepest drinking water source?
- How is water management intended (source, volumes, disposal, …)?
- Which proppants, biocides and further additives are used for drilling/ hydraulic stimulation (volumes, hazard classes)?
- Which dilution factors are required / expected with regard to water protection guidelines?
- Are available treatment options for produced water sufficient or is there an upgrade or back-up needed?
- Who is responsible for which target zones in monitoring (in-zone, above-zone, freshwater aquifers, surface water, soil and atmosphere)?
- What are limit values for i) closer monitoring, ii) immediate stop of operation, iii) immediate remedial action?

Summary table

Table 3: Summary of conclusions for the previously identified relevant risks

	Hazardous event	Hazard	Risk assessment	Mitigation
Subsurface migration	**Structural compromise of geologic formation**	Disruption/ Change of groundwater flow paths	low / long-term effects unknown depending on depth and history of oil & gas drilling and/ or underground mining several hundreds meters of low permeable formations between frac horizon and drinking water aquifers shales have very low water content	Modelling and evaluation of real versus predicted behaviour Stop of operation Sampling from deep and shallow aquifers to assess contamination potential; dilution, movement, ... Creation of a hydraulic barrier
	Impact to pre-existing fractures and faults	Major source of uncertainty is prediction of fracture dimensions and geology	low - medium high level of uncertainty/ lack of data to constrain parameters issue of induced seismicity	Avoidance of fracturing near pre-existing faults
	Upward migration of natural gas	as above	low - medium naturally no gradient, thus induced by opening pathways see well failure	Regulation of gradient towards the fracs & borehole (hydraulic barrier, abstraction) Repair or abandonment of failed wells
Technical failure	**Drilling**	Leakage of drilling fluids	low- medium ("human factor") depending on maturity of technical standards	Logging-while-drilling with ongoing monitoring and adaptation of mud composition; multi-barrier concept (blow out preventers etc.)
	Well construction failure	Leakage	medium - high depending on maturity of technical standards, well age and number of abandoned wells	Repair or abandonment of failed wells Assignment of responsibilities for "orphaned" wells

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