Foreword

This document describes well stimulation by hydraulic fracturing in conventional reservoir rocks. The corresponding guidelines are also presented. Hydraulic fracturing – also known as fracking – is a technique that has been used in Germany for over fifty years. The experience gained has been taken as the basis for the discussion, and the associated developments are also taken into account. The practices considered here represent the current state of the art.

This document is intended to serve as a reference for planning and execution of hydraulic fracturing projects and to provide a basis for communication with those concerned, either directly or indirectly. By virtue of the transparent presentation, the procedures are described in a manner which is clearly understandable for everyone, from the beginning of the initial planning operations all the way to completion of a well stimulation. The documentation also includes a discussion of measures for estimating, evaluating, and minimising possible risks on the basis of factual information.

1. Introduction

Since the initial application in the 1940s, well treatment by hydraulic fracturing has developed into a key technology for boosting production under the increasingly difficult conditions in oil and gas reservoirs. Over this period this technology has been applied to about two million wells worldwide. In the United States alone, an additional 35 000 wells are annually treated using these methods. In view of the world-wide decline in production from conventional reservoirs as well as the increasing exploitation of unconventional resources, the importance of this technology is steadily increasing. In this context, the term 'production from conventional reservoirs' is defined as production from reservoir rocks such as sandstone and limestone (including ‚*tight gas*'). Unconventional resources are defined as those which are present in source rocks such as shale and coal.

Hydraulic-fracturing technology has been employed in Germany since the 1960s for stimulating low-permeability conventional reservoirs, in order to increase productivity and profitability. Since that time, more than 300[1] hydraulic fracturing operations have been performed on natural gas wells in the area for which the *Landesamt für Bergbau, Energie und Geologie* (LBEG) is responsible.

The purpose of this document is to describe and explain the procedures currently applied in Germany for stimulating oil and gas wells by hydraulic fracturing in conventional reservoirs. The guidelines presented correspond to the current state of the art and apply to the

- selection, approval, and construction of a drill site
- planning, approval, and drilling of a well
- planning, approval, and execution of a hydraulic-fracturing operations

The document provides a reference for the planning and execution of hydraulic-fracturing projects, as well as for communication with those who are either directly or indirectly affected.

Special emphasis is placed on best-practice techniques for drilling and hydraulic fracturing in conventional reservoirs. The guidelines apply equally well to vertical or deviated drilling, including boreholes which are horizontal, and to both single and multiple treatments. Decades of experience has been gained for operations of this kind in Germany. The term "conventional reservoirs" also includes tight-gas or tight-oil reservoirs. In practice, the objectives of the procedures described are to effectively deal with the geological and technical challenges presented by the aforementioned activities, to avoid detrimental effects of such activities on the environment, and to minimise adverse effects on the surrounding area. These requirements apply especially to the protection of useful groundwater resources. Since hydraulic-fracturing operations are performed from boreholes, careful consideration of these boreholes themselves is decisive for the

[1] 325 hydraulic fracturing operations in 141 natural gas wells, including 69 wells in which multiple treatments have been performed, some of these also as repeated treatments; source: LBEG, dated 08th October 2013

appraisal of the environmental compatibility of such operations. As described in sections 4 (drilling) and 5 (completion), it is sometimes necessary for wells to be re-drilled before subsequent hydraulic fracturing operations can be performed after completion.

Wells that have been drilled and completed as per the standards prescribed in section 4 are deemed to be fit for hydraulic-fracking operations. This is, however, not the case for existing wells where compliance with these standards cannot be demonstrated. Additional proof that such wells possess the necessary stability with regard to the stresses that prevail during the fracking process must be provided in these cases. If necessary, additional safety measures must also be implemented.

The structure of the sections which begin with "Exploration of the geological basement" (3) is essentially identical. The descriptions of the various practices are preceded by specific explanations as an aid to understanding. The objectives are stated, and the corresponding best practice is explained in the appropriate context. Lists of pertinent German legal regulations, ordinances, and specifications, as well as important technical recommendations, are then presented.

2. Fundamental principles

During oil and gas exploration and production, reliable methods for avoiding risks to human health as well as minimising adverse effects on the environment and minimising the impact on the surrounding area are of paramount importance for the execution of all activities and operations. Furthermore, contamination of soil as well as pollution of groundwater in general, especially of groundwater resources currently or potentially in use, must be avoided. For this reason, numerous laws, ordinances, and requirements are in place to regulate industrial activities. Moreover, company-internal management systems have been established for ensuring compliance with these legal requirements, for implementing the necessary preventive measures, and for providing further defined solutions. Important examples include the following:

Bundesbergesetz (BBergG), Bundes-Bodenschutzgesetz (BBodSchG), Wasserhaushaltsgesetz (WHG), Bergverordnung für Tiefbohrungen (BVOT), Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV), Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen und über Fachbetriebe (VAwS), and the LBEG Rundverfügung: „Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen in Erdöl- und Erdgaslagerstätten in Niedersachsen".

The implementation of appropriate measures for avoiding hazards to human health as well as adverse effects on the environment, as prescribed by law, implies the following for fracking operations: Contamination of ground water by the entrainment of pollutants from the surface shall be avoided. The integrity of the wells and the presence of adequate sealing cap-rock strata shall be ensured. The propagation of hydraulic fracture systems shall be reliably predicted and controlled. Appropriate measures shall be implemented for ensuring safe disposalof the fluids from the initial flow-back phase and for avoiding any perceptible seismic tremors which may result from the operation. Reference wells are of special importance for this purpose. In the hydrocarbon-well data base (KW-DB) of the Landesamt für Bergbau, Energie und Geologie (LBEG), 2012 status, extensive data-sets provide coverage for the relevant regions. More than 16 000 entries exist for wells which have been drilled in Lower Saxony alone (including about 8 400 wells with depth greater than 800 m), Tran Viet (2013). From these entries, comprehensive, relevant information is available as a basis for performing the evaluations.

Having well fluids isolated from the environment and the population at large by two independant technical barriers (double barrier principle) at all times as proved to be a highly effective method in the industry (see Norsok 2013). The primary barrier (e.g., the production casing, production-string cement, casing, packers, completion string, subsurface safety valve etc.) prevents uncontrolled escape of fluids from the well. The operation of the secondary barrier (e.g., the anchor-pipe cement, anchor-pipe string, well-head) is independent from that of the primary barrier. Thus, the secondary barrier serves as a back-up system. Both mechanical and fluid systems can be employed as barriers. Application of the double-barrier principle has also proved to be a highly effective safety measure for hydraulic-fracturing operations as well as for the production phase.

3. Exploration of the geological basement

3.1. Ground water

Objective: Establish a data base with pertinent information on ground-water resources in the area surrounding the wells to be treated by hydraulic fracturing, the actual or potential uses of these ground-water resources, as well as the extent to which these resources require protection

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Bundesgesetz (1980): „Bundesberggesetz (BBergG)"
- Bundesgesetz (2009): „Wasserhaushaltsgesetz (WHG)"
- Bundesgesetz (1998): „Bundes-Bodenschutzgesetz (BBodSchG)"
- Bundesrechtsverordnung (2010): „Verordnung zum Schutz des Grundwassers (Grundwasserverordnung - GrwV)"
- Bundesrechtsverordnung (1999): „Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV)"
- Ländergesetz (2010): „Niedersächsisches Wassergesetz (NWG)"
- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)"
- Länderverordnung (2009): „Verordnung über Schutzbestimmungen in Wasserschutzgebieten (SchuVO)"
- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

Ground water is the most important fresh-water resource and in particular the primary source of potable water in Germany. For this reason, the natural purity of ground water must be maintained. Contamination by the infiltration of discharged or escaping pollutants must therefore be prevented. Ground water originates from the percolation of rain water or melting snow into the ground, and also from the seepage of water from bodies of water at the surface as well as from drainage ditches. This water is subject to contamination by air pollutants as well as by pollutants which result from land use, such as settlements and built-up areas, industry, traffic, raw-materials exploitation, and agriculture. Purification and retention processes occur during seepage of the water that results from percolation through layers of soil or rock. During these processes, the various strata function as natural filters and thus provide effective protection against contamination of the ground water. In order to maintain this natural protective potential, adverse effects on the soil and the hazard of contamination in the unsaturated zone must be minimised.

Because of the lithological structure of the formations present in North Germany, the useful, non-saline ground water resources usually extend to a depth of 200 m (neutral expert committee, 2012). In deeper zones, the ground water comes into contact with ascending Zechstein rocks, especially near salt stocks and salt ridges. As a result, the ground water may be highly saline. In the North German basin, the useful ground water resources are usually isolated from the brine or "saline" water in the deeper geological basement by practically impermeable rock strata. This natural geological barrier prevents mixing of the "fresh" ground water resources near the surface with the brine located in deeper aquifers. If this is not the case, local mixing of saline water with ground water may occur in some areas. Saline springs may originate in this manner and are sometimes utilised as medicinal springs in spas. The brine contained in deeper aquifers is often completely saturated with salts; that is, the salt content may amount to 250 g/l or even more (RWE, 2013).

For the hydrogeological characterisation of the areas under investigation and for the determination of potential environmental hazards, especially with respect to ground water, the following measures are usually implemented in practice:

BEST PRACTICE: CHARACTERISATION OF USEFUL WATER HORIZONS

- Investigation of relevant drainage ditches, bodies of water at the surface, ground water resources, and watersheds
- Literature surveys, data acquisition, measurements at specified times (such as critical dates) for plotting the gauge-tube levels of ground water or hydroisohypsometric curves in a contour chart (hydroisohypsometric diagram)
- Determination of the ground-water level curve and position of the surface element which extends between the hydroisohypsometric curves, the thickness of the ground water reservoir or aquifer, as well as the direction of ground-water flow
- Determination of the geometry of the ground water reservoir or aquifer (faults, channels, flow barriers)

- Determination of the hydraulic parameters for the ground water aquifer (rock permeability, flow velocity of the ground water, etc.)
- Determination of the thickness and extent of existing flow barriers for ground water, as well as hydrogeological windows between existing ground-water levels
- Determination of the protective effect of the overlying cap-rock strata or of the unsaturated zone, as well as thickness and composition
- Determination of the ground water quality (see also section 6.4.1.: Reference-state determination) with due consideration of existing anthropogenic paths of infiltration
- Determination of conservation areas (drinking water, medicinal springs, mineral water resources, etc.) as well as current utilisation of ground water

An example of the documentation for the characterisation of ground-water aquifers near the surface is presented in figure 1.

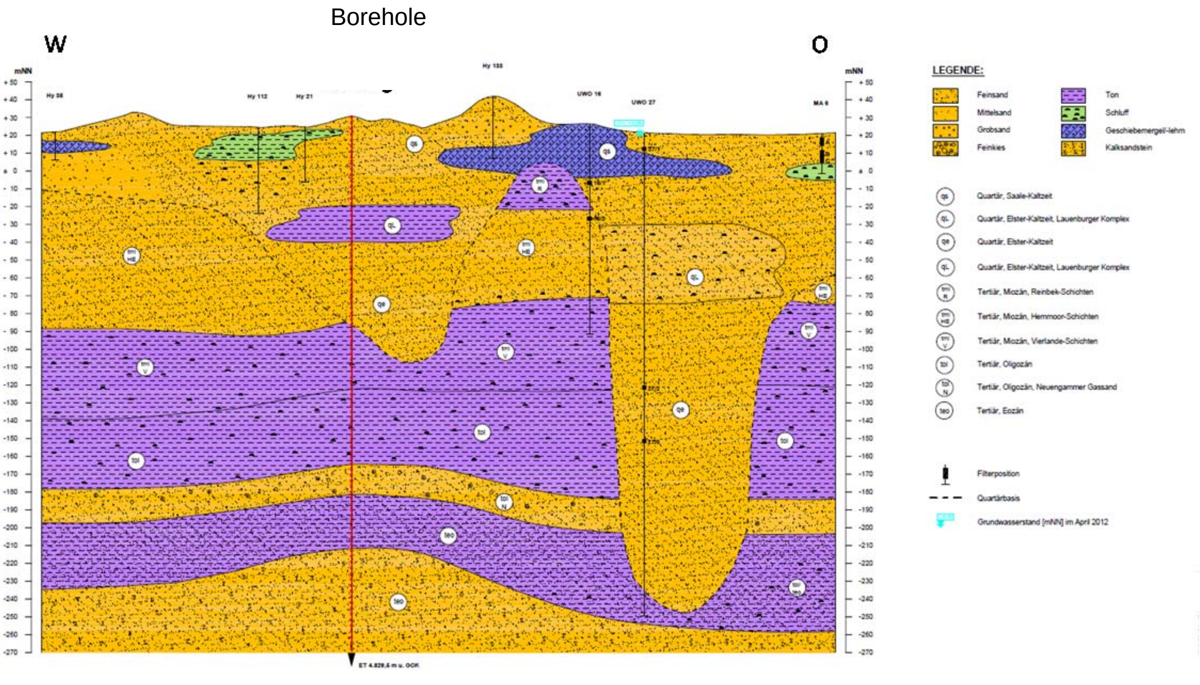

Figure 1: Characterisation of the upper ground water aquifers
For the characterisation, especially the geometry of the ground-water aquifer, the associated hydraulic properties, the ground-water level contour for the ground-water surface, and the direction of ground-water flow, as well as the ground-water quality, must be determined.

3.2. Cap rock and barrier layers

Objective: Characterisation of the geological basement with respect to its barrier properties toward the ascent of fluids and toward the upward growth of artificially generated fractures

Pertinent German laws, regulations, ordinances, and specifications are the following:

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

The geological basement is usually an alternating stratification consisting of various geological layers with different hydraulic and mechanical properties. Many of these layers consist of materials with barrier properties. If these layers are sufficiently thick, they can be regarded as sealing cap-rock strata which are not permeable to ascending gases and liquids, provided that no open fracture networks are present, for instance, along fault lines and salt-stock flanks.

The existence of open fracture networks can be excluded in the presence of ductile, pliable materials. Self-healing effects are known to occur in such materials and have been described in publications, Williams et al. (2009), Reinicke et al. (2011), Hou et al. (2012). As a matter of principle, plastic behaviour can be assumed for unconsolidated Tertiary clays (such as Rupelton, Chatt) as well as for salt strata (for instance, in Muschelkalk, in Buntsandstein, and especially in Zechstein).

For the clay (shale) formations below the Tertiary system, the existence of fracture networks, especially along fault zones, depends on the tectonic situation at the particular location and therefore cannot be excluded. Exposed fissures present in surface outcrops are often completely healed in the underground system and are not relevant to migration. Furthermore, karstification may occur in carbonate facies. Appropriate investigations can be performed on location for clarifying the situation, for instance, by observing the loss-influx behaviour upon drilling through systems of fissures, by investigating the genesis of the fissures, by analysing the material concerned, and by examining possible post-genesis mineralisation processes.

The fluids present in the pores of the geological strata are subject to pressure, the so-called pore pressure. In the pore volume of an aquifer, hydrostatic conditions usually prevail. That is, the pore pressure at a specified depth corresponds approximately to the pressure caused by a column of water extending from this depth to the surface (as referred to the density) and is representative for this zone. In deeper, older formations, especially Triassic Northern and Northwestern Germany, on the other hand, hyperhydrostatic conditions are often observed. Conditions of this kind demonstrate that pressure gradients directed toward the biosphere may also occur in the case of aquifers in certain formations. However, they also demonstrate that the "charged" formations are sealed.

In order to prevent the ascent of fluids, the rock strata which are present between a hydrocarbon reservoir and the useful ground water horizons near the surface must be characterised and appraised with respect to their sealing properties, including the potential for the upward propagation of fissures. Hence, the presence of sufficiently tight cap rock strata must be demonstrated by means of a reliable lithological and hydraulic characterisation. That is, the existence of impermeable barrier layers as well as the absence of relevant migration paths through oth erwise tight barrier layers must be demonstrated with certainty (no open fissures and no pressure gradients directed toward the biosphere). The existence of effective barriers for limiting the vertical growth of fractures must be demonstrated by means of a geomechanical characterisation. In particular, this investigation must extend to the first cap-rock layer, and the minimal horizontal stresses in this layer must be determined.

For the Tertiary clays as well as the salt layers, such as Malm, Muschelkalk, Buntsandstein, and especially Zechstein, barrier characteristics can be assumed for the ascent of fluids and for the upward growth of fissures.

BEST PRACTICE: UNDERGROUND CHARACTERISATION

During the planning phase

- Description of the basement structure, for instance, with the aid of two- or three-dimensional seismic surveys, or both, in combination with borehole data
- Identification of potential barrier layers and evaluation of their permeability, as well as identification and appraisal of fissure networks and karstifications on the basis of information from reference wells, such as
    - Stratigraphic records and drilling reports
    - Lithological well logs
    - Drilling fluid samples
    - Lost-circulation and influx behaviour (over the entire distance drilled)
    - If appropriate, image logs as well as microresistivity logs, which provide information on fractures (usually available only for zones near reservoirs)
    - Utilisation of information on potentially fractured zones
- Identification and appraisal of geological faults, for instance, by means of
    - Results of two- or three-dimensional seismic surveys, or both, if available, borehole data or production data, or both, if available, which indicate the presence of dynamic flow barriers
    - Analysis of the influx-efflux behaviour during drilling through faults
    - Possible analysis of fault genesis (dilation or constriction processes)
    - Possible analysis of the material along the faults (for instance, water-saturated clays, salts)
    - Well logs (for instance, measurements for revealing microcracks in the borehole wall)
    - If appropriate, investigation of postgenetic processes (mineralisation)
- Geophysical measurements
- Identification and appraisal of abandoned and plugged wells (plugging reports and photographs)
- Possible quantification of the pore pressure over the entire distance drilled on the basis of information from reference wells for determining potential differences between geological strata (see section 4.3.)

- Possible description of the geochemical conditions in the target zone on the basis of information from reference wells

During the drilling operations (see section 4.3.)

- Monitoring of the drilling process, especially by observation of the influx-efflux behaviour and sampling
- If appropriate, performance of tests and measurements for determining the pore pressure, formation stress, and if appropriate, the direction of maximal horizontal stress
- Well logging for determining lithology and if appropriate, rock properties
- If appropriate, coring in the horizon to be treated and in the immediate barrier horizon for determining the rock properties
- Preparation of stratigraphic records for documentation of the geological profile and description of the penetrated geological strata, as well as drilling reports for recording of all relevant drilling events

An example of the documentation for the structural characterisation of the geological basement and the component strata is presented in figures 2 and 3.

3.3. Reservoirs

Objective: Characterisation of hydrocarbon reservoirs with respect to retention and flow properties

Pertinent German laws, regulations, ordinances, and specifications are the following:

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

From an economic standpoint, an essential prerequisite for the exploitation of reservoirs is the attainment of sufficiently high production rates and cumulative production volumes. In conventional reservoirs with higher permeability values, these conditions can usually be satisfied by means of vertical wells, from which production can begin without the need of more elaborate treatments after completion.

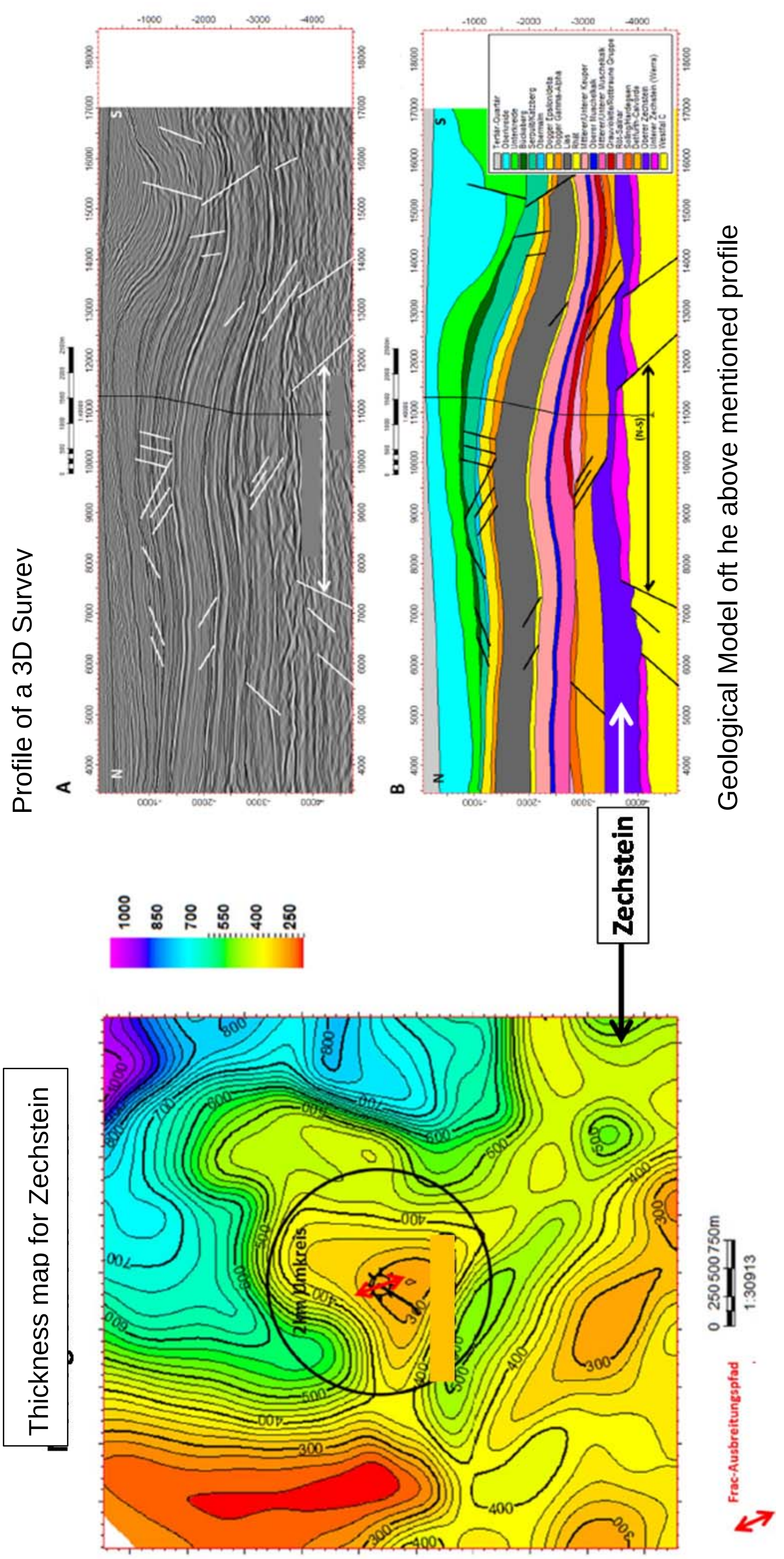

Figure 2: Characterisation of the geological basement in the area surrounding the projest area
The structure of the basement and the geological faults close to the project area are interpreted from 2D- and 3D seismic and nearby borehole data . These form the basis of the geological model and reservoir characterisation.

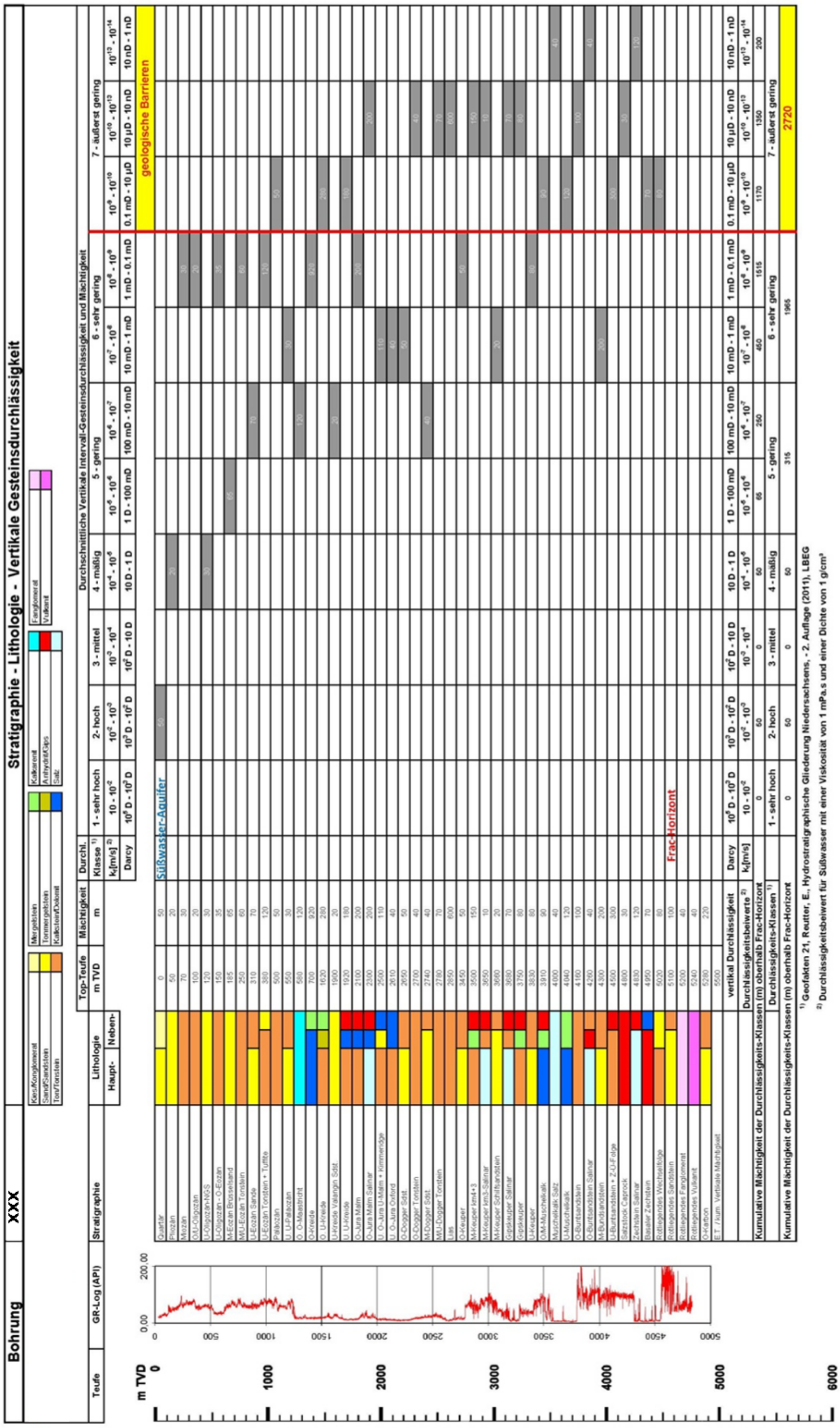

Figure 3: Characterisation of the geological basement at the drill site

The structure of the lithological and stratigraphic segences of the basement are interpreted and hydrogeological properties of the geological layers are evaluated

In reservoirs with permeability values less than about 1 milli-Darcy (tight reservoirs), the natural influx rate is usually not sufficient for profitable production. Wells have been stimulated by hydraulic fracturing since the 1940s in order to achieve economic production rates despite the unfavourable prevailing fluid flow properties. Up to and including the 1990s such operations were performed almost exclusively in conventional reservoirs of low permeability in sandstone and carbonate formations. Since the 1990's, however, hydraulic fracturing has also been performed to an increasing extent in unconventional source rock formations, particularly in the United States. Without treatment, the potential rate of production from gas wells in unconventional reservoirs is often far lower than 100 m^3/h (as referred to standard conditions), in comparison with several 10 000 m^3/h from conventional reservoirs of higher permeability.

The differences between conventional and unconventional reservoirs in Germany are illustrated by the following examples:

	Conventional reservoirs (including tight reservoirs)	Unconventional reservoirs (shale gas and coal-seam gas)
Pay rock	Reservoir rock (sandstone, carbonate)	Source rock (shale, coal)
Typical formation	Triassic, Zechstein, Rotliegendes, Carboniferous	Cretaceous, Jurassic, Carboniferous
Permeability	Micro-Darcy range and larger	Nano-Darcy range
Depth	Deeper than about 2 000 m	Deeper than about 1 000 m
Cap rock	As a rule, clay, marl, and salt strata	As a rule, clay and marl strata, isolated salt strata
Type of well	Vertical and horizontal wells	Horizontal wells and multilateral horizontal wells
Experience with hydraulic fracturing operations in Germany	Since the 1960's, more than 300 hydraulic fracturing operations [2]	Only the Damme 3 well
Type of treatment	Simple treatments, a few multiple treatments, as well as repeated treatments	As a rule, multiple treatments
Typical volume of fluid per treatment	Up to 500 m^3 per treatment	Planned values for future treatments: up to 3 000 m^3 per treatment [3]

[2] In the area supervised by LBEG

[3] In the Damme 3 well: maximal injected hydraulic-fracturing volume: 4 352 m^3 during treatment 3

For the ascent of fluids from reservoirs toward the biosphere, relevant migration paths are necessary. For instance, a pressure gradient may be directed toward the biosphere, if open faults or fissures are present in the cap rock, and if hyperhydrostatic conditions prevail in the reservoir.

If hydrocarbons are present in a certain zone of a geological formation and if production from such a reservoir is economically feasible, relevant migration paths, such as naturally conductive faults or fissures, cannot be present. Conversely, if such migration paths were present, the existence of a reservoir would not be possible in the first place. If any hydrocarbons had originally been present, they would have escaped through these migration paths a long time ago, since the density of hydrocarbons is lower than that of water.

In the aquifer zone of geological formations, the presence of relevant migration paths cannot be excluded. However, such a migration path is really relevant only if a pressure gradient exists and is directed toward the biosphere. If hydrostatic conditions prevail in the aquifers, no pressure gradient acts in the direction toward the biosphere or toward "fresh" ground water in use. On the other hand, if hyperhydrostatic conditions prevail, the overlying cap rock must be "tight", and the presence of potential migration paths can be excluded.

Because of the differences in the density of gas, oil, and water, the initial pressure in zones which contain hydrocarbons becomes increasingly hyperhydrostatic with increasing height above the fluid contact. For long hydrocarbon columns, the pore pressure can attain values which are markedly higher than the hydrostatic pressure. Under these conditions hydrocarbons can mirgrate upwards but only if effective migration paths are created. Once production begins, the hyperhydrostatic pressure decreases, and the relevance of potential, artificially created migration paths decreases correspondingly.

BEST PRACTICE: RESERVOIR CHARACTERISATION

During the planning phase

- Characterisation of the reservoir and its content on the basis of seismic information, as well as information from reference wells with respect to reservoir, rock, and fluid properties, as well as pressure and temperature

During the drilling operations

- Determination of the reservoir properties, for instance, thickness, mineralogy, porosity, density, saturation, and permeability, as well as the dynamic Young's modulus, Poisson's ratio, Biot coefficient, horizontal and vertical stress states, as well as the direction of stress, based upon well logs, analysis of drilling-fluid samples, core material, and test results, if appropriate
- Determination of the reservoir fluid content, for instance, the gas, oil, and water composition as well as the properties based upon fluid samples, if available
- Determination of the reservoir pressure and reservoir temperature based on well logs and test results
- Determination of the productivity and free-flow potential for the well based upon measurements, tests, and calculations

4. Drilling

Drilling and completion of an oil or gas well comprises of several consecutive activities or operations:

- Preparation of the drill site
- Assembly of the drilling rig and associated equipment
- Drilling of the successive borehole sections and checking of their integrity
- Performance of well logs and tests, if appropriate
- Installation of the surface and sub-surface equipment
- Possible treatment, stimulation
- Disassembly of the drilling rig and associated equipment
- Start of production from the well
- Operation of the well and monitoring of its integrity
- Plugging of the well, removal of facilities, abandonment, and recultivation

4.1. Planning of a well

Objective: Planning to enable the flow of fluids only within the well thus protecting the ground water against contamination, to prevent the exchange of fluids between different rock strata, and to allow hydraulic fracturing operations to be performed safely.

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Bundesgesetz (1934): „Lagerstättengesetz (LagerstG)“
- Bundesgesetz (1980): „Bundesberggesetz (BBergG)“
- Bundesgesetz (2009): „Wasserhaushaltsgesetz (WHG)“
- Bundesgesetz (1998): „Bundes-Bodenschutzgesetz (BBodSchG)“
- Bundesrechtsverordnung (1990): „Verordnung über die Umweltverträglichkeitsprüfung bergbaulicher Vorhaben (UVP-V Bergbau)“
- Bundesrechtsverordnung (1995): „Bergverordnung für alle bergbaulichen Bereiche (ABBergV)“
- Bundesrechtsverordnung (1999): „Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV)“
- Ländergesetz (2010): „Niedersächsisches Wassergesetz (NWG)“
- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)“

Important technical recommendations:

- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations - Well Construction and Integrity Guidelines"
- API (2010): "Isolating Potential Flow Zones During Well Construction"
- NORSOK (2013): "NORSOK Standard D-010, Well integrity in drilling and well operations"

BEST PRACTICE: PLANNING OF A WELL

- Performance of an environmental-impact analysis (EIA) in conformance with UVP-V Bergbau, if necessary
- Design of a self-contained well with at least a double barrier toward ground water near the surface and toward the atmosphere by:
  - Designing and dimensioning of an appropriate casing and cementing program
  - Adequate borehole preparation for casing and cementing
  - Adjustment of the drilling fluid to match the requirements
  - Adequate centralising of the casing string during installation and cementing
  - Correct pumping and placement of the cement in the annulus
- Appropriate selection of a drilling path for avoiding recognisable risks
- Consideration of the safety-relevant aspects associated with the drilling operation in the course of the following activities:
  - Designing of the preliminary programme for the drilling operation
  - Designing and dimensioning of casing strings in compliance with the applicable engineering rules
  - Safe handling of hazardous substances
  - Installation of reliable devices for influx detection
  - Installation of an appropriate preventer system in correspondence with the requirements

The aforementioned operations shall be documented in an operational plan which shall be submitted to the responsible mining authority in the course of the request for the approval of the operational plan.

4.2. Well-site planning

Objectives: Ensure protection of the environment, especially of ground water and bodies of water, as well as minimising adverse effects on the surrounding area

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Bundesgesetz (1980): „Bundesberggesetz (BBergG)“
- Bundesgesetz (2009): „Wasserhaushaltsgesetz (WHG)“
- Ländergesetz (2010): „Niedersächsisches Wassergesetz (NWG)“
- Länderverordnung (1997): „VAwS - Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen und über Fachbetriebe“
- Länderverordnung (2009): „Verordnung über Schutzbestimmungen in Wasserschutzgebieten (SchuVO)“

Important technical recommendations:

- DWA(2005): „Technische Regel wassergefährdender Stoffe (TRwS), Ausführung von Dichtflächen"
- WEG (2006): „Leitfaden Gestaltung des Bohrplatzes"
- API (2010): "Guidance Document HF2: Water Management Associated with Hydraulic Fracturing"
- API (2011): "Guidance Document HF3: Practices for Mitigating Surface Impacts Associated with Hydraulic Fracturing"

Drilling operations are performed on and from a drill site. From this location (point at which the drilling operation begins), the geological target with the presumed or already proved hydrocarbon reservoir (target point of the borehole) must be attained in a technically safe manner. Since the target point is not necessarily situated vertically below the starting point, certain restrictions at the surface can be taken into account.

BEST PRACTICE: FINDING A LOCATION

- Identification of possible drilling locations within an area which is determined on the basis of geological and seismic results
- Identification of existing conservation areas (such as water conservation areas, nature-reserves, protected landscapes, biotopes, archeological excavation sites)
- Identification of surface water resources and inundated areas
- Identification of built-up areas and existing infrastructure
- Identification of underground pipelines, cables, radio communication channels, obstacles to air traffic, etc.
- Inspection of terrain for possible drill-site locations
- Preselection of a starting point which satisfies the requirements of environmental protection and land-use zoning, that is,
    - Ensuring a sufficient distance from protected areas
    - Ensuring sufficient distances from inhabited and built-up areas
    - Consideration of existing uses in the surrounding area
    - Consideration of the hydrogeological situation, for instance, in the case of water conservation areas
    - Minimising hindrances to traffic
- Documentation
- Contacting of local authorities and landowners for clarifying details of installation on the site

The aforementioned operations shall be documented in an operational plan, which shall be submitted to the responsible mining authority in the course of the request for the approval of the operational plan. The participation by local authorities and landowners shall be defined on the basis of this operational plan.

The drilling rig as well as all equipment facilities, materials, and personnel necessary for operation of the rig, shall be accommodated on the drill site. In order to ensure adequate protection of the ground water and surface water resources. The drill site shall be designed in such a way that no pollutants can penetrate into the ground or be discharged into bodies of water. If the planned distances to the nearest inhabited and built-up areas are not sufficient, appropriate measures, such as sound-proofing and prevention of disturbing glare from lighting facilities at night, shall be implemented to ensure that the limiting values for emissions and immissions are not exceeded.

BEST PRACTICE: DRILL-SITE PLANNING

- Investigation, analysis, and comprehensive description of all aspects of environmental protection and nature conservation which are relevant to the design and construction of the drill site. In particular, these aspects include:
  - Effects on flora, fauna, and surrounding biotopes, including protected zones underground
  - Impairment of natural landscapes, historical sites, archeological excavation sites, and living conditions for residents in the area (especially with respect to air quality, noise nuisance, increased road traffic)
  - Description of all construction materials as well as any auxiliary or process materials employed
- Subdivision of the drill site into functional sections in accordance with the WEG Guideline, "Designing of the Drill Site"
- Designing and dimensioning of the sections in correspondence with the associated water-hazard class (WHC sections) in such a way that no pollutants can penetrate into the ground. (Critical areas and components are the substructure of the drilling rig, including drilling cellar, floor space for installation of machines, Diesel-fuel storage tanks and, if appropriate, drilling-fluid tanks, equipment for the control of solids, and containers for cuttings.)
- Separation of the WHC sections from the other areas by appropriate constructional measures, with due consideration of additional volumes caused by heavy rainfall; prevention of overflow by suitable infrastructural measures (for instance, construction of drainage systems, installation of suction systems with adequate capacity)
- Designing of the drill site in such a way that emergency exits are accessible from every point on the site at all times
- Planning of suitable measures for assuring that cuttings, drilling-fluid residues, produced liquids, waste materials, and precipitation which occur on the drill site can be collected - separately if at all possible – and stored for proper disposal.
- Description of the drill-site design and structure, as well as the plans for measures to be implemented, with special emphasis on the technical installations (sealed surfaces, sewage and drainage systems, etc.)

- Description of the drilling operations themselves (technical processes, drilling and completion of the well)

The minimum requirements for drill sites in Germany are documented in the WEG Guideline, "Designing of the Drill Site". (The diagrammatic representation of a drill site documented in the guideline is illustrated in figure 4). The fundamental principles which are documented for a single-well drill site in the guideline also apply with the appropriate modifications to drill sites with multiple boreholes (cluster sites).

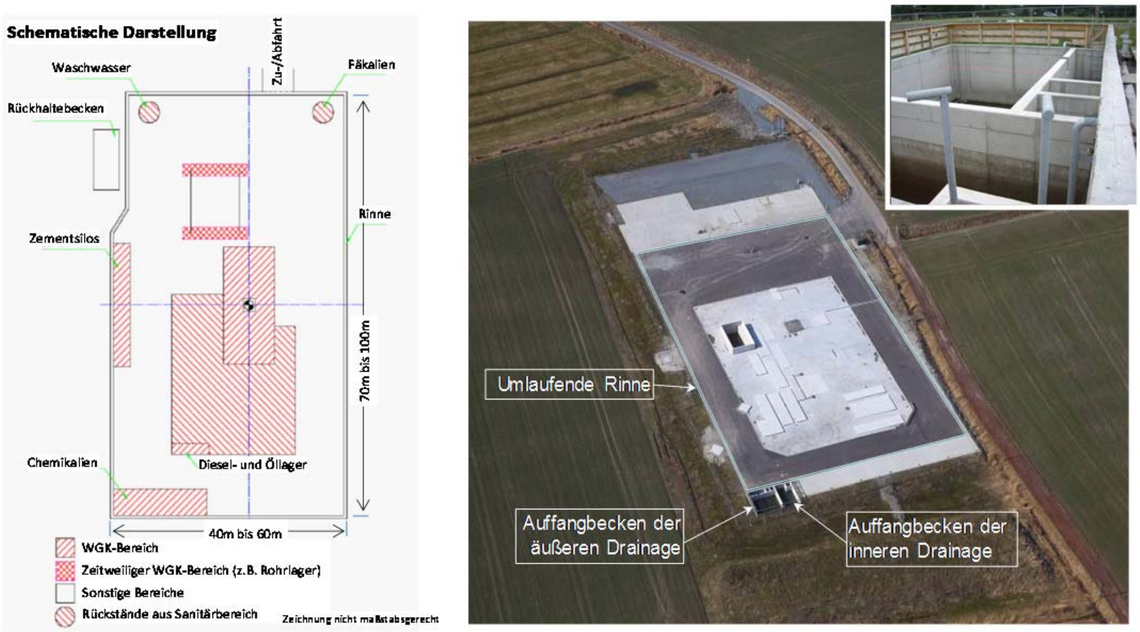

Figure 4: Drill site for a single gas well
The site for the drilling rig as well as the equipment, facilities, materials and personnel necessary for operation of the rig shall be constructed in conformance with WEG standards. The design of the drill site (sealed surfaces, sewage and drainage systems, etc.) and planning of measures for the collection and disposal of the cuttings, drilling-fluid residues, produced liquids, waste materials, and precipitation which occur on the drill site shall ensure that no pollutants can penetrate into the ground or contaminate bodies of water. The paved surface area of the drill site shall depend on the size and type of drilling rig to be installed. In the aerial view, additional areas for accommodating containers employed as living quarters or for use as parking space are shown at the upper edge. The unpaved areas for storing the top soil are also visible in the figure.

The aforementioned operations shall be documented in an operational plan, which shall be submitted to the responsible mining authority in the course of the request for the approval of the operational plan. If the operational plan has been approved, the drill site can be constructed in conformance with the approved plan and with due consideration of the relevant technical standards. For this purpose, the following basic principles shall be observed:

BEST PRACTICE: SITE CONSTRUCTION

- Restriction of activities to less critical times of the year for avoiding unnecessary disturbance of the fauna in especially sensitive areas
- Removal and storage of the top soil during preparation of the drill site for later restoration and care of the site, or for landscape-recultivation measures if no economically recoverable hydrocarbons are found

If economically recoverable hydrocarbons are found:

- After completion of the drilling activities, adaptation of the area occupied by the facility to match the requirements of the production operation (as a rule, a decrease in the area of the site), if appropriate
- Adaptation of the site for the construction of a gas-drying plant (GDP) as specified in the applicable ordinance relating to facilities for handling substances involving a risk of water pollution and to technical operations (VAwS)
- Compensation of the impact on the natural environment and landscape by appropriate counteractive and substitutional measures in agreement with the responsible governmental authorities (for instance, by adapting the site to match the landscape)

If no economically recoverable hydrocarbons are found:

- Plugging of the well, dismantling and removal of all drill-site equipment, and restoration of the site to its original condition
- Minimal requirements on plugging of wells documented in "Richtlinie über das Verfüllen auflässiger Bohrungen" des LBEG (1998), see also Tran Viet (2013)

BEST PRACTICE: PLUGGING AND DISMANTLING

Plugging of wells with due observance of the specifications given in „Richtlinie über das Verfüllen auflässiger Bohrungen" des LBEG

4.3. Drilling operations

Objectives: Environmentally compatible drilling operations, acquisition of information for characterising the geological basement or for the production of hydrocarbons, or both

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)"

Important technical recommendations:

- API (2010): "API 13A Specification for Drilling Fluids Materials"
- DVGW (1998): Technische Mitteilung Merkblatt W116 „Verwendung von Spülungszusätzen in Bohrspülungen bei Bohrarbeiten im Grundwasser"

Wells are usually drilled by the rotary method with continuous removal of cuttings by the circulating drilling fluid. Drilling of a well comprises several cycles which consist of drilling - casing – cementing of casing. The diameter of the borehole becomes smaller with each cycle, since the new section must be drilled and cased through the previously installed casing string. The final cycle of the operation is the completion of the well (installation of the underground equipment necessary for production).

Typical drilling fluids usually consist of water, clay, and various additives for controlling filtrate losses, density, and viscosity. The drilling fluid transports the cuttings to the surface, lubricates and cools the bit or other drilling tool, and stabilises the borehole wall. By virtue of its density, the drilling fluid prevents invasion of the borehole. To perform these functions, the composition and rheological properties of the drilling fluid must be specified appropriately.

BEST PRACTICE: DRILLING FLUID

- For drilling through ground-water horizons near the surface, fresh-water-and-clay-based drilling fluids with additives such as sodium carbonate, starch, and cellulose are employed.
- Drilling-fluid additives which are employed for drilling through ground-water horizons shall be limited to substances which have been certified to be safe, for instance, by the Hygiene Institute of the Ruhrgebiet in Gelsenkirchen.
- The necessary or allowable density range of the drilling fluid shall be determined with the use of information from reference wells or with the application of predictive methods for determining the pore pressure and fracture pressure, or both. If necessary, the density range shall be adapted during the drilling operation as required.
- For drilling below the anchor-pipe string, the properties of the drilling fluid shall be determined on the basis of the expected lithostratigraphy and on the information from reference wells. If necessary, these properties shall be adapted during the drilling operation as required.

The term "mud logging" or "sampling" designates the process of examining and evaluating the rock-cuttings transported to the surface and documentation of the results, together with relevant drilling parameters in the so-called "mud log" or "sampler log".

After completion of the drilling operations in a borehole section, well logging shall be performed in the open borehole prior to installation and cementing of the casing. These well logs are recorded for various purposes, including the identification and evaluation of formations which contain hydrocarbons.

BEST PRACTICE: SAMPLING AND LOGGING (see also 3.2.)

- Monitoring of the drilling process by sampling and continuous recording of the relevant drilling parameters, of gas or oil shows, and of the lithology derived from the examination of the cuttings, as well as
  - measurement of variations in the volume of drilling fluid,
  - recording of gas influx,
  - recording of variations in the density of the drilling fluid
- If necessary, coring operations to obtain representative rock samples
- Well logging to determine geophysical and petrophysical rock properties within the scope of the lithological determination, among other purposes
- Well logging to determine the trajectory of the borehole and of the borehole volume, if appropriate
- If appropriate, pressure testing to determine the pore pressure or other pressure values relevant to hydraulic fracturing, or both

4.4. Casing

Objectives: In combination with cementing, stabilisation of the borehole and prevention of fluid migration into adjacent geological strata behind the casing

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)"

Important technical recommendations:

- API (2006): "API SPEC 5CT/ISO 11960, Specification for Casing and Tubing"
- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations - Well Construction and Integrity Guidelines"
- API (2010): "API SPEC 5B, Specification for Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads"
- WEG (2006): „Technische Regel - Futterrohrberechnung"

At the planned depths, or at depths dictated by potential borehole problems, the borehole is cased with steel pipe – designated as casing – and cemented. The composite system consisting of steel casing and cement sheath stabilises the borehole and also protects the ground water horizons near the surface. Furthermore, a separation is provided between horizons with different pore pressure, and the borehole section in the next depth interval can thus be safely drilled with the necessary drilling-fluid properties.

Several casing strings are generally installed before reaching the target formation. The casing string for the first borehole section is designated as the conductor pipe. It is installed either by ramming or by drilling a borehole section of sufficient diameter to accommodate it. The purpose of the conductor pipe is to prevent the foundations under the drilling rig and drill site being compromised. It also isolates the borehole from the ground-water horizons near the surface. The next casing string is the anchor-pipe string. The purposes of this string is to form a barrier to protect deeper-lying ground-water aquifers intended for public use, to support the subsequent casing strings, and to accomodate the first preventer stack. If necessary, intermediate casing(s) string may be used for purely technical reasons associated with drilling operations. The production casing is the last casing string to be installed. The completion equipment is installed on this string for the subsequent production phase. This string is subjected to pressure during hydraulic fracturing.

The casing strings installed and cemented at greater depths may either extend all the way to the surface or terminate in the lower section of the preceding casing string, where they are anchored as so-called liners.

Thus, several concentric casing strings are present in the uppermost section of the well at the ground-water level. The outermost string is the conductor pipe, which directly faces the ground water horizons near the surface. Toward the centre, the conductor pipe is followed by the anchor-pipe string, which supports all further casing strings. The preventer stack, consisting of the so-called "blow-out preventers" (BOP), is also connected to the anchor-pipe string, either directly or by means of a double flange. The purpose of these safety devices is to ensure that a reliable barrier is present at all times. Thus, the well can be "shut-in" if the pore pressure encountered in a formation exceeds the hydrostatic pressure of the drilling-fluid column, and, if an invasion by formation fluids into the borehole is evident. The production casing is the innermost of the concentric casing/liner strings.

BEST PRACTICE: CASING SCHEME

- The design of a casing programme which ensures safety during the drilling operation, the possibility of performing treatments, and safe production under the geological and technical conditions which prevail at the site
- Installation of the conductor pipe in a massive and stable rock formation, or after attainment of a predetermined energy value for ramming
- Setting of the anchor-casing string below the useful ground water horizons near the surface in a stable, integral formation, and cementing all the way to the surface
- Selection of the setting depths for the subsequent casing strings with due consideration of the rock-mechanical strength and pore-pressure values to be expected, for avoiding fracture of the rock in the respective uncased section of the borehole, for instance, if an unexpected influx of formation fluids occurs and must be circulated out
- Checking and verification of the stratigraphic depth by sampling and analysis of cuttings at previously defined intervals over the entire distance drilled

Casing and casing connectors shall be designed and dimensioned to withstand the stresses to which the casing string will be subjected during its entire life cycle. These stresses are caused especially by external pressure exerted by borehole fluids, by drilling-fluid residues which remain behind the casing, or by plastic rocks (clays, salts), by internal pressure (caused, for instance, by pressure testing or stimulation measures), and by axial loads (due, for instance, to dead weight during installation), as well as bending stresses in the case of major variations in inclination and direction of the well, WEG (2006).

BEST PRACTICE: DESIGNING AND DIMENSIONING OF CASING

- Designing and dimensioning of the casing in conformance with WEG rules for the axial stresses as well as those due to external and internal pressure, in correspondence with the expected pressure during hydraulic fracturing, and stresses which occur during production, with due consideration of the mechanical strength values, calculated
- as specified in API Bul 5C3/ISO 10400 or as indicated by the casing manufacturer
- Quantitative checks on the dimensioning of casing with the application of accepted methods of calculation which are documented in series of technical rules
- Consideration of the ambient temperature underground for its effect on the yield limit (decreased value, so-called hot yield limit)
- For deflected and horizontal boreholes, consideration of bending stresses during installation
- Consideration of the possible occurrence of corrosive fluids in selecting the casing material

The installed casing strings consist of individual pipe lengths or sections which are mutually joined by threaded connections. The individual casing sections must be connected in accordance with the instructions given by the manufacturer and by the operator. Observance of these instructions is a prerequisite for attaining the required load-bearing capability in the connection and for ensuring an effective and reliable seal against fluids in the expected stress range.

Casing consists of high-grade heat-treated steel and has already been subjected to a technically elaborate testing process by the manufacturer. If production casing is involved, the tests must be supervised by an expert who has been appointed by the operator. The test programme includes an internal-pressure test with water at the nominal pressure.

The installed casing strings have their integrity verified during the process of internal-pressure testing or internal pressure-relief testing, see 4.6.

BEST PRACTICE: INSTALLATION OF CASING

- Conditioning of the borehole for installation of the casing string
- Connection of the casing sections during installation in accordance with the manufacturer's instructions
- In the case of gas-tight connectors with metal-to-metal seals (so-called premium connectors): testing of the connection and generation of a protocol by computer-aided recording and plotting of the make-up torque in a diagram for electronic and visual evaluation
- If necessary, centralising of the casing string with the use of centralisers for ensuring optimal placement of the cement

An example of well designing and dimensioning is presented in figure 5.

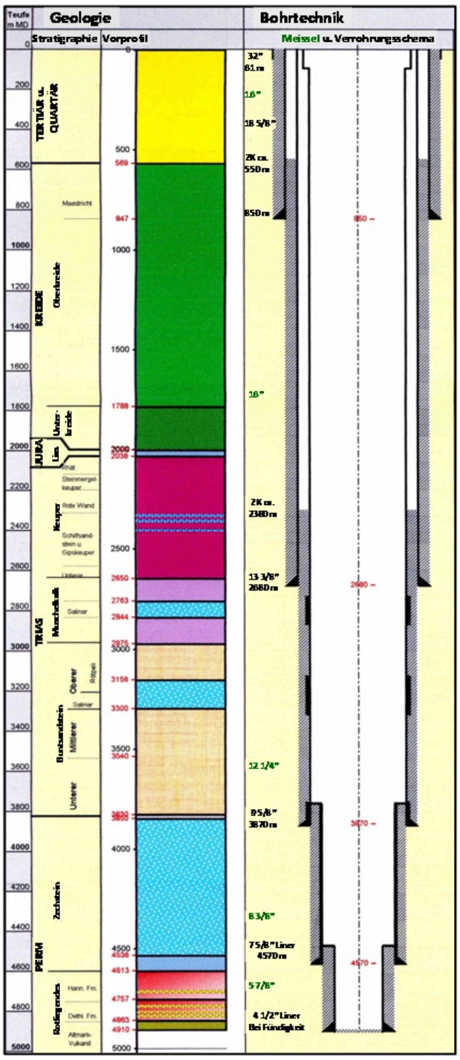

Figure 5: Well designing and dimensioning

Wells are drilled and cased to provide a closed conduit between the reservoir and the surface facilities. Sections of steel casing are installed in the borehole. The annulus between the steel casing and the rock formation is filled with cement. The setting depths for the casing strings are determined by the geological and hydrogeological conditions at the site. The casing strings and connections are designed and dimensioned as specified in the WEG series of technical rules. The integrity of the technical facility thus constructed is continuously monitored in the course of the drilling and casing operations as well as during the subsequent production operation.

4.5. Cementing

Objective: In combination with the casing, stabilisation of the borehole and prevention of fluid migration into adjacent geological strata

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (VOT)“

Important technical recommendations:

- API (2008): "API 10TR4, Selection of Centralizers for Primary Cementing Operations"
- API (2008): "API 10TR1, Cement Sheath Evaluation"
- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations - Well Construction and Integrity Guidelines"
- API (2010): "API RP 10D-2/ISO 10427-2, Centralizer Placement and Stop Collar Testing"
- API (2010): "API SPEC 10A/ISO 10426-1, Cements and Materials for Well Cementing"
- API (2013): "API RP 10B-2/ISO 10426-2, Testing Well Cements"

A cement slurry or suspension is pumped through the casing string into the borehole and around the casing shoe into the annulus. During this process the drilling fluid which is present in the annulus is displaced upward. The objective of this procedure is to provide a hydraulic seal by completely filling and lining the annulus with a cement sheath which surrounds the casing, and which extends all the way to the surface or to a previously defined level.

For planning and dimensioning a cementing operation, the necessary cement volume as well as the required density and height of the cement column must be known. These values are especially important for avoiding accidental fracturing of the formation.

BEST PRACTICE: PLANNING OF A CEMENTING OPERATION

- Examination of reference wells for cementing problems
- Determination of the borehole volume by means of caliper logs
- Planning of anchor-string cementing all the way to the surface
- Limitation of additives for cementing of the anchor string to substances which have been certified to be environmentally compatible
- Planning of the cementing operations for the intermediate casing strings and the production casing – in correspondence with technical and geological conditions – down to a planned and specified depth
- Installation of casing centralisers and optimisation of their placement, in order to ensure the highest possible "stand-off ratio" for the installed casing strings
- Planning of cement grades and density on the basis of pore-pressure and fracturing-pressure predictions (see section 3.2.); ensuring that the hydrostatic pressure of the cement column effectively counteracts the pore pressure of the formation without the risk of cement losses
- Matching of the density and rheological properties of the drilling fluid, of the cement slurry, and of the buffer fluid between the drilling fluid and cement slurry for ensuring maximal displacement of the drilling fluid by the buffer fluid and cement slurry
- For casing strings which are subjected to pressure during a hydraulic fracturing operation, appropriate adaptation of the cement properties to prevent crack initiation in the cement sheath during the treatment
- Planning and specification of the setting time (hardening time) for the cement slurry with due consideration of the real borehole temperature

Effective centralising of the casing string to be cemented and avoidance of appreciable mixing zones between the cement slurry and drilling fluid are prerequisites for ensuring high quality of a cementing operation.

BEST PRACTICE: CEMENTING OPERATION

- Laboratory analysis of the prepared cement slurry prior to pumping into the borehole for determining the properties (such as the rheology, stiffening and consolidation characteristics, free water content, compatibility with the buffer fluid and drilling fluid); furthermore, additional back-up sampling of dry material and cement slurry for more comprehensive analyses at a later time, if appropriate
- Checking to ensure that the wellbore is free of any obstacles which might hinder pumping of the cement slurry into the borehole
- Conditioning of the drilling fluid for ensuring maximal displacement by the buffer fluid and cement slurry

- If possible, motion of the casing string during the cementing operation, preferably by rotation
- Ensure an adequate period of time is allowed for setting (hardening) of the cement

The result of each completed cementing operation shall be controlled as described in section 4.6.

4.6. Integrity and control

The installed casing strings shall be tested for integrity after installation and cementing. This is done by means of an internal pressure test with drilling fluid before the start of drilling operations from the casing string concerned. The test pressure is determined from the highest value of the pressure to be expected at the casing shoe during the drilling, casing, and cementing operations for the next borehole section. The production casing or liner (the final casing string) shall be subjected to a test pressure which generates the same stresses as those which occur during a hydraulic fracturing operation, if this casing string is subjected to pressure during such a treatment.

The pressure test duration shall be at least 30 minutes. The casing string's integrity is considered proven if the pressure approaches a final, stable value. This value must be greater than 90 per cent of the initial value. The observed decrease in pressure is usually caused by the viscoelastic and viscoplastic behaviour of the complex composite system consisting of the well-head equipment, drilling fluid in the casing string, cement sheath (or residual drilling fluid behind the casing string), and rock formation. That is, it usually is not the result of fluid loss due to leakage.

The completed cementing operation shall be checked by well logging and testing. Cemented and uncemented intervals can be recognised from the interpretation of temperature logs and acoustic logs which have been recorded under the corresponding boundary conditions. The quality of the cementation can also be determined by various measuring methods under the appropriate boundary conditions. Cement top determinations can be performed by measuring the temperature, since the chemical reactions which occur during the cement-setting process generate heat and thus cause a brief increase in temperature in the cemented zone (duration: 12 to 24 h). During the passage from a transmitter through the system consisting of steel casing, cement, and rock formation to a receiver, an acoustic signal naturally loses energy. The determination of this energy loss constitutes the basis of the acoustic methods in their simplest form, since a relationship exists between this loss of energy and the portion of the casing circumference which is surrounded by cement.

The test programme includes pressure tests and possibly pressure-relief tests after drilling into the cement. In a formation-integrity test, the applied pressure is increased to the highest expected value at the casing shoe during the drilling, casing, and cementing operations for the next borehole section. In a leak-off test, the applied pressure is increased to the leak-off value (for determining the fracturing pressure). In an "extended leak-off test" both the fracture pressure and the minimal principal normal stress are determined. For well logging, pressure testing, as well as the continuation of the drilling operations, adequate setting time for the cement is a prerequisite. To avoid damage to the cement sheath during the setting process, the following general rule should be observed: Operations should not be continued until attainment of a previously specified strength value. The setting time which is necessary to reach this strength value depends on the type of cement, the temperature, the pressure, as well as setting accelerators which are used.

BEST PRACTICE: INTEGRITY AND CONTROL

- Well logging (for instance, temperature logs) for cement-top determination
- If necessary, and particularly for production casing , demonstration of cementation quality by acoustic well logging
- Before drilling into the cement, performance of a pressure test for checking the sealing integrity of the well casing at a pressure value relevant to the respective casing section; for liners, performance of an influx test as an alternative to check the integrity (pressure-relief test)
- After drilling into the cement, performance of a pressure test for verifying the integrity of the casing-shoe cementation, as well as the compressive strength of the rock formation below the casing shoe

5. Well completion

5.1 Underground equipment

Objectives: Protection of the cemented casing string; allow the flow of fluids from the desired production horizon; solution of production problems

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)"

Important technical recommendations:

- API (2005): "API standard 14B, Design, Installation, Repair and Operation of Subsurface Safety Valve System"
- API (2006): "API SPEC 5CT/ISO 11960, Specification for Casing and Tubing"
- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations - Well Construction and Integrity Guidelines
- API (2010): "API SPEC 5B, Specification for Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads"

Completion is the process of preparing a well for production after termination of the drilling operations. As a rule, the completion process comprises the following steps: (1) installation of the final casing string in the horizon from which production is to take place; (2) cementing of the annulus between the steel casing and borehole wall; (3) installation of the tubing in the borehole; (4) installation of the well-head with the necessary devices for opening and closing of the well; (5) in the case of cemented final casing strings, perforation of the casing section in the reservoir zone with the use of sand-blasting, bullet-charge, or shaped-charge perforators.

Should the proposed completion be unsuitable for fracking operations a casing string can be installed exclusively for hydraulic fracturing (as a substitute for the aforementioned tubing). For this purpose, a well-head which has been approved specifically for use in hydraulic fracturing operations is installed. After fracking operations have been completed the production completion may be installed.

As an alternative to a cemented final casing string, uncemented special-purpose liners can be employed, especially in horizontal wells. (Examples include liners equipped with sliding side doors and external packers, slotted liners, and predrilled liners.) Among other purposes, such liners have been specially developed for multiple hydraulic fracturing treatments.

Tubing is steel pipe of small diameter which is anchored in the cased well-bore zone of the well with the use of a packer (a hydraulic sealing element) at its lower end. As a rule, a tubing string consists of pipe lengths, each about 9 m long, which are joined with tight screw connections. As dictated by the requirements, a tubing string includes various special elements, such as a subsurface safety valve, sliding side door, nipple profile, etc.

The tubing constitutes a further barrier between the production or injection media and potentially useful water-bearing horizons (aquifers). The integrity of the tubing is monitored by observation of the pressure in the (first) annulus between the tubing and production casing, in combination with a production packer.

BEST PRACTICE: COMPLETION PLANNING

- Reliable description of the expected operating conditions and calculation of the triaxial stresses on the tubing (collapse, bursting, and axial loads) with the use of appropriate software
- Designing and dimensioning of the tubing, especially with respect to the material, geometry, and type of connector for the given reservoir fluids and for the prevailing borehole conditions, with due consideration of the normative specifications, as described in section 4.4 for API and non-API tubular goods and connectors
- Designing and dimensioning of the packers and of the installed special elements for the given reservoir fluids and for the prevailing borehole conditions
- Planning and installation of a subsurface safety valve for ensuring automatic shut-in upon failure of the surface equipment, at least to the extent specified in BVOT

- Designing and dimensioning of the well-head for the given conditions
- For wells to be treated, designing and dimensioning of the completion facilities for withstanding the expected hydraulic-fracturing pressure, or planning of a special string for the purpose
- documentation of the completion, including the preparation of all associated records and reports
- The aforementioned operations shall be documented in an operational plan, which shall be submitted to the responsible mining authority in the course of the request for the approval of the operational plan. If the operational plan has already been approved, the completion can begin.

BEST PRACTICE: COMPLETION

- Observance of the manufacturer's instructions and specifications for tubing connections
- Computer-aided inspection of the connections for verifying the make-up quality
- Appropriate pressure testing (well-head test, annular pressure test, tubing-pressure test) for verifying the tightness of the installation

6. Hydraulic fracturing

Hydraulic-fracturing operations are performed to improve the influx conditions in the formation which surrounds a well. The term hydraulic fracturing, also known as "fracking", designates the process of generation and propagation (or opening) of one or more cracks or fissures in a rock stratum. This treatment can be repeated several times on a well. The fractures constitute flow channels, which can extend over a distance up to a few hundred metres into the formation and thus improve the influx into the well. The operation is performed with the use of a liquid, which is pumped into a well under high pressure through the casing string and through the perforations in the casing into the target formation. As the fracturing pressure is exceeded, cracks are initiated in the target formation. If the pumping process continues, these incipient cracks grow and propagate farther into the formation. If pumping ceases, all of the fracturing liquid still present in the cracks flows back, and the artificial fissures begin to collapse and close under the prevailing formation pressure. In order to prevent complete closing and healing of the fissures, proppants such as sand are usually added to the fracturing liquid. These proppants then remain in the fissures for keeping them open.

The cracks propagate in the direction of least resistance, that is, in the direction perpendicular to the lowest principal stress. At depths greater than about 600 m, the vertical stress is the highest of the principal stresses. Below this depth, vertical fissures are usually generated. At depths less than about 600 m, the vertical stress is usually the lowest of the principal stresses. Consequently, the resulting fractures range from cracks with horizontal components all the way to completely horizontal fissures. As a matter of principle, the spatial extension of the fissures in the vertical direction is shorter than that in the horizontal direction, since the interbedding of the geological strata with different properties and horizontal stresses hinders the vertical growth of cracks. Furthermore, cap-rock strata over reservoirs also constitute barriers to the propagation of cracks. Lengths and heights (or widths in the case of horizontal fissures) depend on the volume of liquid which is injected into the formation, on the rheological properties of the injected liquid, and on the geology, Economides and Martin (2007).

6.1. Planning of hydraulic fracturing operations

Objectives: Optimal designing, dimensioning, and execution of the hydraulic-fracturing operation and limitation of the resulting crack propagation and spatial extension of the fissures to prevent fractures propagating into overlying barrier layer

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Bundesrechtsverordnung (1990): „Verordnung über die Umweltverträglichkeitsprüfung bergbaulicher Vorhaben (UVP-V Bergbau)"
- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)"
- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

Important technical recommendations:

- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations"
- API (2011): "Guidance Document HF3: Practices for Mitigating Surface Impacts Associated with Hydraulic Fracturing"

Hydraulic-fracturing operations are planned with the use of modelling software expressly developed for the purpose. The application of these software systems requires a good characterisation of the formation to be treated and of the overlying cap-rock strata, especially with respect to their geomechanical properties and stress distribution. The information necessary for this purpose is usually available with the desired quality from (preferably stimulated) reference wells, or from the well on which the hydraulic fracturing operation is to be performed.

In particular, the results of microseismic measurements are available for permitting reliable predictions with respect to the geometry of fissures. Logs of this kind have been recorded in several thousand wells in the United States. For unfaulted formations, these results exhibit relatively good agreement with the predictions, Fisher and Warpinski (2012). The previously described increase in the share of horizontal crack components with decreasing depth has also been confirmed by these results. This trend continues all the way to horizontal fissures in formations close to the surface.

In Germany, successful microseismic measurements have currently been performed only in the shale-gas well, Damme 3. These results have not yet been published, however. All other attempts to record seismicity which is induced by hydraulic fracturing have failed. The distance between the fissures thus generated and the recording instruments is too large, see also 6.4.3. Qualitative information on the dimensions of hydraulically generated fractures has been available from German tight-gas wells since the end of the 1970's. These results indicate that the crack growth is overestimated because of the simplification of the crack geometry taken as basis for modelling. In this model, the crack geometry is assumed to be limited to (only) two oppositely positioned fissures, Brinkmann et al. (1980), Reinicke et al. (1983). As demonstrated in various mine-back tests, real systems of fissures are more complex, Fisher and Warpinski (2012). If this complexity is neglected, the model may yield erroneous results.

If the quantity and quality of information available from reference wells are not sufficient for planning, various preliminary injections can be performed before the hydraulic fracturing operation itself, in order to obtain additional information. Tests of this kind include the following:

- Breakdown test: Injection of liquid for determining the fracturing pressure of the formation and the volume of liquid which the formation can accommodate
- Step-down test: Injection of fracturing fluid at different rates without proppant for determining pressure losses due to friction and for optimising the extent of the hydraulic fracturing operation
- Data frac: Injection of fracturing fluid without and with proppant for acquiring information for diagnostic studies, for quickly checking the characteristics of the hydraulic fracturing operation, as well as for the ultimate specification the parameters for the operation or, if appropriate, improvement of their accuracy; in the case of proppant use, determination of frictional losses and improvement of the proppant-accommodation capacity during the hydraulic fracturing operation itself

BEST PRACTICE: PLANNING OF A HYDRAULIC FRACTURING OPERATION

- Underground characterisation as described in sections 3.2 and 3.3
- If necessary, preliminary injections for acquiring additional information
- Planning of a hydraulic fracturing operation with the application of generally accepted methods
- As a matter of principle, application of commercially available simulators
- Prerequisite for designing a hydraulic-fracturing operation: avoidance of any significant vertical crack growth into the overlying barrier layer
- Design of the hydraulic fracturing operation with longitudinal crack growth, with appropriate measures for ensuring the observance of minimal distances from geological faults and neighboring wells in the target formation
- Checking of the methods and parameters by a recognised expert
- Planning of the hydraulic-fracturing operation itself

- For already existing, older wells, supplementary proof of suitability in the following manner, if necessary: (1) pressure testing by imposing the planned maximal hydraulic-fracturing pressure on the casing strings which are to be directly subjected to pressure during the operation; (2) repeated well logging and evaluation for determining the quality of the cementation
- As a precautionary measure: determination of possible incidents as well as their extent and severity (for instance, estimating the possible volume of escaping or spilled fluids), and the preparation of a hazard-prevention plan on the basis of this information, including the appropriate measures to be implemented for limiting the consequences of the respective incident (governmental authorities, companies, remedial action and methods, materials, etc.)
- Preparation of a monitoring concept for surveillance and control of the hydraulic-fracturing operation and the results of this operation
- Preparation of a waste-disposal or recycling concept for dealing with flow-back fluids
- Preparation of the necessary documentation as specified in the „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen", with the following information:
  - Extent and technical execution
  - Pressure which is applied during the hydraulic fracturing operation
  - Well schematic diagram
  - Production profile and predicted production
  - Conservation areas (nature-preservation areas, national parks, biospheric reservations, protected landscapes, nature reserves, natural-history monuments, protected landscape components, biotopes, fauna-flora habitats)
  - Water conservation
  - Settlements, built-up areas
  - Well site and hydrogeological characterisation of the site
  - Equipment required for the hydraulic fracturing operation
  - Hydraulic calculations
  - Stratigraphy / lithology
  - Stratigraphic sequence and rock permeability
  - Structural maps and sections
  - Thickness maps for barrier layers
  - Reservoir parameters
  - Additives for the hydraulic fracturing fluid
  - Alarm plan, etc.

As an example, the result of a simulated hydraulic fracturing operation is illustrated in figure 6.

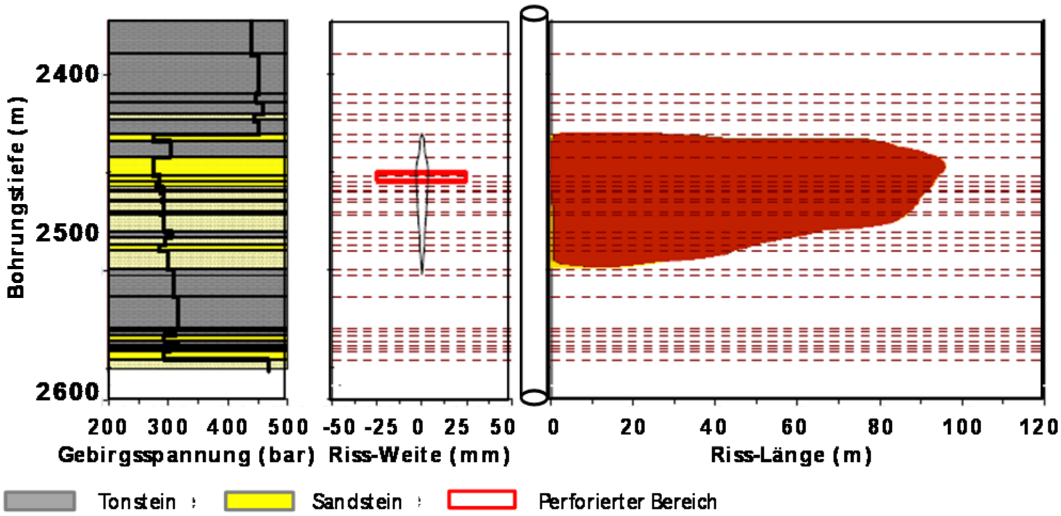

Figure 6: Result of a simulated hydraulic fracturing operation
Planning of hydraulic fracturing operations, and especially the prediction of the position and extent of the fissures to be generated, are performed with the application of recognised methods and with the use of commercially available simulators. The characterisation of the formation to be treated and of the associated cap-rock strata, especially of their geomechanical properties and stress distribution, constitute the basis for planning.

The aforementioned operations shall be documented in an operational plan, which shall be submitted to the responsible mining authority in the course of the request for the approval of the operational plan. The participation by local authorities shall be defined on the basis of this operational plan.

6.2. Fluids for hydraulic fracturing operations

Objective: Generation of the fissure systems necessary for economic as well as optimised production of hydrocarbons without any unacceptable alteration of the useful ground-water horizons

Pertinent German laws, regulations, ordinances, and specifications are the following:
- Bundesgesetz (2009): „Wasserhaushaltsgesetz (WHG)"
- Bundesgesetz (1998): „Bundes-Bodenschutzgesetz (BBodSchG)"
- Bundesrechtsverordnung (2010): „Gefahrstoffverordnung (GefStoffV)"
- Bundesrechtsverordnung (1999): „Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV)"
- EU-Verordnung (2006): „Registrierung, Bewertung, Zulassung und Beschränkung chemischer Stoffe (REACH)"

- EU-Verordnung (2012): „Verordnung über die Bereitstellung auf dem Markt und die Verwendung von Biozidprodukten"
- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)"
- Länderverordnung (1997): „VAwS - Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen und über Fachbetriebe"
- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

Important technical recommendations:
- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations"
- API (2010): "Guidance Document HF2: Water Management Associated with Hydraulic Fracturing"
- API (2011): "Guidance Document HF3: Practices for Mitigating Surface Impacts Associated with Hydraulic Fracturing"

For the initiation and propagation of hydraulically generated cracks, fluids are injected into the formation at a pressure higher than the fracturing pressure. The primary constituent of hydraulic-fracturing fluids is usually water. As indicated by Miskimins (2011), water usually accounts for 70 to 90 per cent of the injected fluid volume. The remainder consists of proppants (7 to 28 per cent) and additives (0.2 to 4 per cent); see figure 7.

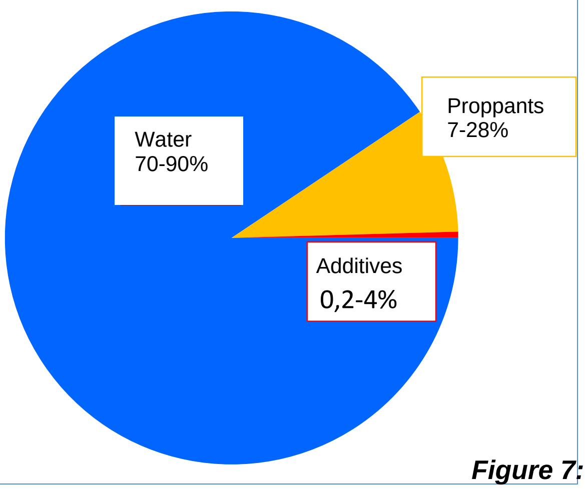

Figure 7: Hydraulic-fracturing fluid additives

During the main injection, the hydraulic-fracturing fluid is pumped into the well in three stages: (1) as a "pad" (as a rule, without proppant), in order to fracture the formation and widen the fissures thus generated for receiving the proppant, (2) as a "proppant slurry" or "carrier", in order to transport the proppant into the fissures, and (3) as a "flush" (without proppant), in order to displace the suspension with the proppant from the well into the fissures.

6.2.1. Water

The water requirement depends on the type of hydraulic-fracturing operation to be performed and ranges to a maximum of 500 m^3 per treatment for typical "gel" treatments in conventional reservoirs. In unconventional reservoirs, larger volumes are usually required for each operation. In conventional reservoirs, repetition of the treatment is usually not necessary over the lifetime of a well.

The water employed for hydraulic fracturing has, to date, been drawn from the municipal water-supply grid, from the operator's own wells, or from processing plants. Drinking-water quality is certainly not necessary for this purpose. Water has sometimes also been drawn from surface resources, such as bodies of water. The possibility of recycling flow-back fluids has also been investigated.

Water employed for hydraulic-fracturing operations is stored in tanks or water pits, or both.

BEST PRACTICE: WATER SUPPLY

- Supply of water for hydraulic fracturing in conventional reservoirs (up to 500 m^3 per treatment) from the municipal water supply grid or from the operator's own well
- Ongoing investigation of the possible treatment and re-use of flow-back fluids from previous operations for subsequent hydraulic fracturing operations

6.2.2. Basic ingredients and additives

For many reasons, various ingredients are added to hydraulic-fracturing fluids, for instance, in order to

- force the fissures thus generated to remain open (with proppants, such as sand)
- increase the capability of the fluid to transport proppants (for instance, with polymers)
- decrease the frictional loss during the injection process (agents for improving flow properties)
- improve the flow-back properties of the fluid, or permit flow-back in the first place (gel breaker)
- prevent the entrainment of biological substances (for instance, with ultraviolet radiation)
- if necessary, avoid swelling and precipitation of minerals (by addition of salts)
- correlate and identify the produced fluids (with the use of tracers)

The primary ingredient (water), the proppant, and the additives are mixed on the well site immediately before the hydraulic-fracturing operation and then injected into the well.

Additives for hydraulic-fracturing fluids are products which are manufactured by various service companies and are sold under various registered trademarks. These products usually consist of several chemical ingredients and are normally prepared by mixing of these materials. Unambiguous identification numbers (CAS and UN numbers) are assigned to the individual ingredients. As a rule, all pertinent toxicological data with respect to effects on human health and the environment are known for these substances. Information on potential water-pollution hazards is available, and the classification in conformance with the German Ordinance Relating to Hazardous Substances is also known. Appropriate analyses are performed on those substances for which no corresponding information is available. The analyses currently in progress are intended to provide fundamental information on the microbiological and chemical conversion processes of the substances which remain in the formation (degradation reactions as well as reactions of hydraulic-fracturing fluids with reservoir water and reservoir rock).

Proppants, such as sand, do not present any risk of ground-water contamination and are therefore not considered further in this context. The number of chemical ingredients employed for the preparation of hydraulic-fracturing fluids in Germany was less than 50 at the beginning of 2013. As a rule, 5 to 15 such ingredients are employed for preparing these fluids. Analyses have been performed on the ingredients listed in the world-wide portfolio of about 600 substances, which has been published during the interim. The results of these analyses indicate that a few of these substances possess one or more properties which are "a cause for alarm", Tyndall (2011). This concern is thoroughly justified even if one takes various mitigating circumstances into consideration in estimating the risk associated with hydraulic-fracturing fluids. Besides the properties of the undiluted substances themselves, such factors include the concentration of the substances, the extent to which they persist in the environment, and the essential paths along which they can be absorbed or ingested by humans or transported into the environment, UBA (2011).

Information from various sources is employed for estimating the risk of soil contamination and ground-water pollution, and especially the hazards to useful water resources, which result from the entrainment and transport of contaminants at the surface. Among other criteria, the hydraulic-fracturing fluids in question are classified with respect to the associated water-pollution hazards and in correspondence with the Ordinance Relating to Hazardous Substances. Furthermore, toxicological data which are pertinent to effects on human health and the environment are employed for the purpose. These data include the results of tests with algae, fish, daphnia, and bacteria, as well as tests for determining the biological degradability.

BEST PRACTICE: HYDRAULIC-FRACTURING FLUIDS - INGREDIENTS AND ADDITIVES

- Limitation to the use of ingredients and additives for which all toxicological data pertinent to effects on human health and the environment, as well as all necessary data concerning water-pollution hazards and classifications in conformance with the Ordinance Relating to Hazardous Substances are available
- Avoidance of any hydraulic-fracturing-fluid mixtures which are classified as hazardous in accordance with the European CLP Ordinance and higher as slight water-pollution hazards (WGK 1)
- Selection of the remaining ingredients with due consideration of their potential water-pollution and soil-contamination hazards
- Publication of complete information on all basic ingredients and additives employed for a hydraulic-fracturing operation, especially with respect to:
  - The purpose for which these materials are employed
  - Identification numbers (CAS, UN numbers) of the ingredients contained in these materials and the identification of all basic ingredients and additives, as well as the hydraulic-fracturing fluid as a whole, as specified the by the laws and ordinances relating to hazardous substances
  - Classification in WGK for basic ingredients, additives, and hydraulic-fracturing fluid as a whole
  - Total quantities of the respective ingredients
  - Effective content (mass content in %) of the respective ingredients in the hydraulic-fracturing fluid
  - Extent and severity of the possible adverse effects (for instance, possible leakage volumes)
- Continuous checking of the type, number, as well as concentration of basic ingredients and additives

6.3. Execution of hydraulic-fracturing operations

Objectives: Safe execution of hydraulic-fracturing operations as well as the avoidance of hazards to humans and to the environment

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Bundesrechtsverordnung (2002): „Betriebssicherheitsverordnung (BetrSichV)“
- Bundesrechtsverordnung (2013): „Gefahrgutverordnung Straße, Eisenbahn und Binnenschifffahrt (GGVSEB)“
- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)“
- Länderverordnung (1997): „VAwS - Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen und über Fachbetriebe“

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen“

Important technical recommendations:

- API (2009): “Guidance Document HF1: Hydraulic Fracturing Operations”
- API (2010): “Guidance Document HF2: Water Management Associated with Hydraulic Fracturing”
- API (2011): “Guidance Document HF3: Practices for Mitigating Surface Impacts Associated with Hydraulic Fracturing”.
- WEG (2006): „Technische Regel - Futterrohrberechnung“

During a hydraulic-fracturing operation, the casing strings are subjected to severe loads, and thus to high stresses. As a “buffer” to protect the casing strings against damage, the pressure in the successive annuli between the individual casing strings can be adjusted to intermediate values. Careful monitoring of the pressure in the different annuli allows corrective action to be taken before the attainment of previously calculated maximal permissible pressure values in the event of unexpected variations in pressure, for instance, upon stoppage of the injection pumps. Generally, reaction times in the order of seconds are possible should such incidents occur. Should this reaction time be too long, the annuli will be provided with safety valves for pressure relief and discharge. This measure ensures that the calculated maximal permissible pressure values are not exceeded.

BEST PRACTICE: EXECUTION OF A HYDRAULIC FRACTURING OPERATION

- As a “buffer” for protecting the casing against damage, adjustment of the pressure in the successive annuli between the concentric casing strings to intermediate values (annuli 1 and 2, as well as annulus 3, if appropriate); calculation of the load or stress on the casing during a hydraulic-fracturing operation, as specified by the WEG rule for casing calculations, but not higher than 80 per cent of the yield limit, as a maximum (DIN EN 10002), at the respective ambient temperature
- Continuous electronic monitoring of the annular pressure values (as a rule, in annuli 1 and 2) during the execution of a hydraulic-fracturing operation
- Automatic emergency shut-down of the injection pumps for stopping the hydraulic-fracturing operation upon attainment of the previously specified maximal permissible pressure values
- As a precautionary measure, limitation of the pressure in the annuli by means of safety valves (in conformance with the Ordinance Relating to Pressure Vessels) for pressure relief and discharge into receiving tanks, with triggering-pressure values which have been specified by an expert on the basis of the relief-valve characteristics.

Equipment and material, especially chemicals, shall be transported to and from the operations site in compliance with the specifications of the Ordinance Relating to Hazardous Substances in Highway Traffic (GGVSEB). Storage is subject to the Ordinance Relating to Installations for Handling Substances Involving a Water-Pollution Hazard and shall be performed and supervised by specialised companies (VAwS). The operator shall:

- Minimise of disturbances and impairments resulting from the transport of equipment and material in the surrounding area, for instance, by completely avoiding nighttime transports and by using appropriate transport routes, including the construction of access routes, if necessary
- Observe all the relevant GGVSEB and VAwS specifications for the transport of chemicals to the site and storage of these chemicals at the site
- The quantity and duration shall be kept to a minimum for the storage of chemical ingredients and additives with due consideration of the water-pollution hazard class

The execution of hydraulic-fracturing operations requires a large array of special installations, including tanks, mixing machines, proppant-transport equipment, pumping units, as well as hoses, pipes, control valves, manifolds, and similar components. This equipment is provided by the service companies which perform hydraulic-fracturing operations. Furthermore, these companies provide the monitoring and control systems which are necessary for a successful hydraulic-fracturing operation.

- Testing of equipment and installations for correct function and safety, as well as approval by a responsible person appointed in compliance with mining law
- Performance of pressure tests on high-pressure piping and other facilities at the surface (as a matter of principle, pressure testing by imposing at least 1.1 times the expected maximal pressure), as well as semi-annual pressure testing of the individual components at 1.5 times the nominal pressure
- Replacement of defective equipment
- If necessary, verification of the functionality test results by an independent expert
- If necessary, implementation of preparatory measures specified in the hazard-prevention plan for dealing with unexpected incidents
- Conducting a final preliminary conference with all persons involved, with special emphasis on the safety and operational sequence of the hydraulic-fracturing operation to be performed

After verification of the functional capability and safety of the installed facilities and equipment, the hydraulic-fracturing operation can begin, see figure 8. The time required for pumping depends on the volume of fluid to be injected and is usually of the order of hours. The pumping rate depends on the particular fluid which is injected. In the case of gel treatments, the pumping rate usually ranges between 4 and 6 m^3/min in Germany.

- Operation by specialised, experienced personnel only
- Execution of the hydraulic-fracturing operation as specified in the plan, preferably during daylight hours; prerequisite for nighttime operation: adequate lighting on site
- Electronic monitoring of the hydraulic-fracturing process and reaction to events for ensuring safe execution of the hydraulic-fracturing operation, see 6.4.2

Figure 8: Execution of a hydraulic-fracturing operation
The operation is conducted from the well site. Transport of equipment and material, especially of chemicals, to and from the site, as well as storage on site, must comply with the relevant legal regulations and specifications. Equipment and material shall be checked prior to operation; if necessary, the equipment shall be subjected to a pressure test for approval. The hydraulic-fracturing operation shall be executed as planned, preferably during daylight hours. The hydraulic-fracturing process shall be continuously monitored electronically, in order to allow an appropriate reaction to unplanned events. For the case that no appropriate reaction occurs in due time, safety devices such as relief valves shall ensure that the calculated maximal permissible pressure values are not exceeded.

6.4. Data acquisition, analysis, monitoring

Pertinent German laws, regulations, ordinances, and specifications are the following:

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"
- Wichtige technische Empfehlungen:
- API (2009): „Guidance Document HF1: Hydraulic Fracturing Operations"

Comprehensive monitoring shall be conducted before, during, and after a hydraulic-fracturing operation, in order to ensure that the operation has been performed safely, successfully, and without adverse effects on the environment. In particular, it shall be ensured that the water-supply aquifers near the surface have not been contaminated by the operation. In this monitoring process, the following activities can be distinguished:

- Determination of the reference state
- Monitoring during the hydraulic-fracturing operation
- Monitoring after the hydraulic-fracturing operation

6.4.1. Determination of the reference state

Objective: Creation of a basis for comparison with future measurements

Important technical recommendations:

- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations"
- API (2010): "Guidance Document HF2: Water Management Associated with Hydraulic Fracturing"

Samples shall be taken from ground-water aquifers near the surface as well as from bodies of water in the vicinity of the proposed fracking activities. The information gained from the analysis of such samples is especially important if the available data concerning the existing condition of the surface and ground water in the area are not sufficient. This consideration applies particularly to regions with known environmental-impact issues, for instance because of biogenetic gas, as in the Münster area, Melchers (2008). The determination of the reference state prior to the beginning of activities allows the detection of changes which occur later. Since the ingredients of the hydraulic-fracturing fluids are known, possible causes can be determined and classified if changes in the composition of ground water are observed.

BEST PRACTICE: DETERMINATION OF THE REFERENCE STATE

- Determination of the reference state in local bodies of water and in ground water near the surface, by sampling and sample analysis if necessary, especially in existing water-supply wells, before starting a hydraulic-fracturing operation
- Designing and planning of the sampling programme for monitoring purposes, during and after the hydraulic-fracturing operation, with due consideration of the prevailing flow of ground water

6.4.2. Process monitoring during the hydraulic fracturing operation

Objective: Ensuring the safety of the hydraulic-fracturing operation, as well as limitation of crack propagation, if vertical crack growth is restricted by an overlying barrier layer

Pertinent German laws, regulations, ordinances, and specifications are the following:

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

Important technical recommendations:

- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations"

During a hydraulic-fracturing operation, reliable process monitoring and effective quality control are decisive for successful execution of the operation without adverse effects on the environment. The extent of the monitoring measures depends on the respective prevailing conditions.

Hydraulic-fracturing operations are planned with the application of appropriate simulation models. These models are used to predict the propagation and geometry of fissure systems, especially on the basis of the pumping rate, injection pressure, injection rate, proppant concentration, fracture-fluid rheology, and relevant petrophysical parameters. If the actual values of these parameters are continuously monitored during the hydraulic-fracturing process, a real-time simulation allows real-time monitoring of the crack propagation as well as an effective reaction to unforeseen developments in due time.

An absolute prerequisite for a safe and reliable hydraulic-fracturing operation is continuous monitoring of the pressure values in the entire system at the surface. Measuring points are usually located on the mixer (blender), on the high-pressure pumps, in the high-pressure zone, and at the well-head. Continuous monitoring of the pressure values is necessary for allowing immediate recognition of deviations from the plan, as well as the appropriate corrective action, before proceeding to further activities. Minor corrections with respect to the original plan (for instance, small changes in the pumping rate and fracturing pressure, as well as concentration changes in the fluid composition and proppant concentration) are usually sufficient for continuing the hydraulic-fracturing operation.

Unexpected or unusual pressure variations may also indicate a problem. Pressure deviations which result from leakage, for instance, in the underground system, are easy to detect. If such deviations occur, the hydraulic-fracturing operation can be discontinued immediately.

BEST PRACTICE: PROCESS MONITORING DURING THE HYDRAULIC-FRACTURING OPERATION

- Monitoring of the parameters which are relevant to a simulation of the crack propagation
- Use of the planning software for real-time simulations during the hydraulic-fracturing operation, in order to monitor the progress of the operation and the development of the fissure geometry
- Monitoring of the pressure values in the high-pressure system, especially the injection pressure at the well-head and the pressure values in the annuli which have not been cemented all the way to the surface, and appropriate reaction to unforeseen events
- Monitoring of the injected volumes of hydraulic-fracturing fluid and all additives for comparison with later flow-back volumes
- Operation by experienced, specialised personnel without exception

6.4.3. Micro-seismic and micro-deformation monitoring

Objective: Measurement of the crack propagation during the hydraulic-fracturing process

Pertinent German laws, regulations, ordinances, and specifications are the following:

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

Important technical recommendations:

- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations"

The propagation of a fissure can be visualized by means of micro-seismic and micro-deformation monitoring provided that the distance between the fissure and the measuring and recording instruments is not too large. This technology is applied in the United States, especially in shale-gas wells which are not too deep, in order to evaluate new hydraulic-fracturing techniques. The efficacy of such techniques in new areas can thus be improved, and simulation programs for predicting crack propagation can be calibrated in this manner.

During micro-seismic monitoring, the propagation of a fissure is observed by localisation, recording, and spatial representation of acoustic signals which are generated by crack-induced variations of the stress in the rock formation (opening of fissures) and of the fluid pressure (leak-off). On the basis of experience gained in the United States, these signals can be observed over distances up to a maximum of 1 500 m in shale reservoirs with the use of geophones, Fisher and Warpinski (2012). In many other reservoirs, the maximal distance over which such measurements are possible is decidedly shorter, and the applicability of this method to conventional reservoirs is thus limited.

In the case of micro-deformation monitoring, the propagation of a fissure is localised by the measurement of extremely small crack-induced displacements. The measurements are performed either at the surface or in a neighboring well with the use of highly sensitive "tiltmeters" (inclination sensors). The tiltmeters employed for the purpose are capable of detecting changes of inclination in the nano-radian range at the surface. From the surface, the direction of crack propagation can thus be determined down to a depth of about 3 000 m. For determining the dimensions of the fissures, underground measurements must be performed. For fissures with a height from 30 to 60 m, the maximal distances for the measurements are only 150 to 300 m, Warpinski (2013).

The results of single monitoring-field-test campaigns (for instance, Horstberg: fracturing depth about 3 600 m, GeneSys: fracturing depth about 3 700 m), as well as noise-level measurements (Joswig, 2005) in Lower Saxony have confirmed the observations of Fischer and Warpinski (2012): Because of the geology and depth of conventional reservoirs, it is almost impossible to determine the propagation of a fissure below the Zechstein salt by measurements at the surface, even with highly sensitive instruments. Conclusive micro-seismic eventshave hitherto been successfully recorded only for the shale-gas well Damme 3 by underground monitoring from Damme 2.

6.4.4. Seismic monitoring

Objective: Real-time determination of potential seismic tremors and especially of the magnitudes of these tremors, in order to allow appropriate action to be taken if the intensity of the tremors increases.

Pertinent German laws, regulations, ordinances, and specifications are the following:

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

Important technical recommendations:

- DIN-Norm 4150: DIN EN 1998-1/NA Nationaler Anhang – National festgelegte Parameter, Auslegung von Bauwerken gegen Erdbeben

From experience gained in areas where earthquake hazards exist, it is well known that perceptible tremors can occur as a result of a hydraulic-fracturing operation. Areas in Germany which are classified as earthquake zones in accordance with DIN 4150 are limited to the *Oberrheintalgraben*. Outside of the areas designated as earthquake zones, the occurrence of perceptible seismic tremors which are induced by hydraulic-fracturing operations is not probable (Richter, 2011). This conclusion applies especially to hydraulic-fracturing operations for the stimulation of gas production, since the injections are not performed in existing fault zones – as opposed to geothermal projects, for instance. In Lower Saxony, the same conclusion is confirmed by the hydraulic-fracturing operations performed in conventional reservoirs in the past. No perceptible seismic events occurred in the course of these projects, as demonstrated by the BGR German Regional Seismic Network and by the WEG *Bergschadenskundliche Beweis-Sicherungssystem*, see figure 9.

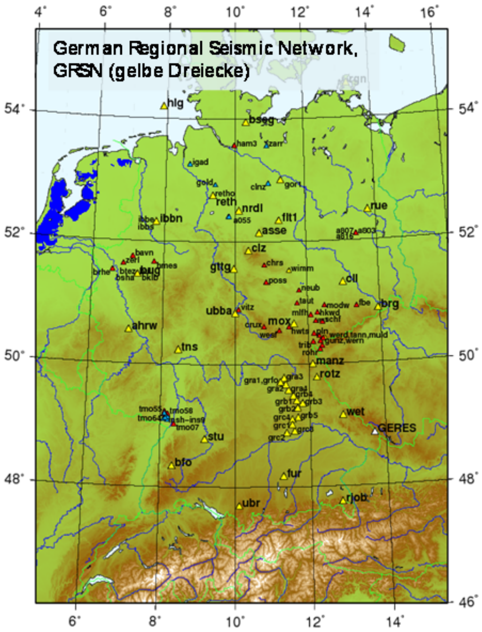

Figure 9: Seismicity induced by hydraulic fracturing operations
For estimating the risk of perceptible tremors at the earth's surface, the natural seismicity in areas where hydraulic-fracturing operations are performed is monitored by means of the GRSB and WEG verification systems. During the execution of hydraulic-fracturing projects, seismic monitoring with the aforementioned surveillance systems is supplemented with the use of mobile units outside of the area monitored by WEG, if necessary.

BEST PRACTICE: SEISMIC MONITORING

- Determination of the natural seismicity in the area where hydraulic-fracturing operations are in progress, by means of the BGR GRSN (German Regional Seismic Network), with supplementary information from the WEG *Bergschadenskundlichen Beweis-Sicherungssystem*, if necessary
- Monitoring of seismic activities during the execution of hydraulic-fracturing projects by means of the aforementioned surveillance systems, with the supplementary use of mobile units outside of the area monitored by WEG, if necessary

6.4.5. Posttreatment monitoring

Objective: Measurement for determining vertical crack growth in the near-wellbore zone

Pertinent German laws, regulations, ordinances, and specifications are the following:

- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen"

Important technical recommendations:

- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations"

The monitoring methods which are most frequently applied after hydraulic-fracturing operations in vertical wells are temperature logging and tracer measurements for determining the length and height of the fissures thus generated. However, the information which can be acquired by these methods is limited to the near-wellbore zone. The importance of such methods decreases as the development of computer-based modelling techniques progresses, since the entire system of fissures can be simulated by the latter. By means of these modelling methods, for instance, pressure-transient measurements can be simulated. In simplified form, such measurements had already been the object of investigations at the end of the 1970's and beginning of the 1980's, Brinkmann et al. (1980), Reinicke et al. (1983).

The temperature variation is determined over the fractured zone and beyond by means of temperature logging,. Deviations between the temperature variations before and after the hydraulic-fracturing operation result from cooling by the hydraulic-fracturing fluid, which is usually injected at the ambient temperature at the surface. This information is useful for determining which perforations have accepted hydraulic-fracturing fluid and, to a limited extent, the vertical crack growth which has occurred immediately behind the casing.

For the purpose of tracer measurements, a tracer is added either to the proppant or to the hydraulic-fracturing fluid. After a hydraulic-fracturing operation, appropriate well logs are recorded to detect the tracer. Thermal neutron absorbers as well as radioactive tracers, for instance, can be employed for these measurements. The purpose of the measurements is to demonstrate that vertical crack growth or correct placement of the proppant, or both, have in fact occurred as intended. As in the case of temperature logging, the range of detection by this method is very small, within a metre at best, and thus limited to the near-wellbore zone.

6.4.6. Postcompletion monitoring

Objective: Verification of the technical integrity of the well and associated equipment during normal production operations

Pertinent German laws, regulations, ordinances, and specifications are the following:
- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)"

Important technical recommendations:
- API (2009): "Guidance Document HF1: Hydraulic Fracturing Operations"

The purpose of production monitoring is to demonstrate the technical integrity of the well and of the associated equipment. During this phase, continuous monitoring, especially continuous pressure monitoring, is necessary.

During the drilling operation, the integrity of the casing and casing shoe is verified by pressure testing. During the hydraulic-fracturing operation, the integrity is demonstrated by means of pressure monitoring in the annuli for ensuring that no leakage occurs between the annuli, and especially for ensuring that no leakage occurs in the riser. Monitoring of the annular pressure values also continues after completion of the hydraulic-fracturing operation and extends over the entire lifetime of the well. For this purpose, possible fluctuations of the pressure values in the closed annuli must be taken into consideration. Such fluctuations can result from variations of the conditions in the riser, especially because of pressure and temperature effects, and can occur even if the necessary integrity has been demonstrated.

BEST PRACTICE: POSTCOMPLETION MONITORING

- Determination of the minimal and maximal annular pressure values to be expected under normal operating conditions
- Monitoring of the pressure in the annuli of a well until final abandonment and plugging
- Inspection of the well by field personnel at regular intervals for determining normal well and operating conditions, as well as any deviations from normal conditions, for instance, well-head, riser, and annular pressure values, leakage, etc.
- Analysis of the produced liquids for salts and corrosion products
- Inspection of the subsurface safety valves at regular intervals, if present
- Inspection of the sealing elements and maintenance of the flange connections in the well-head at regular intervals
- Upon removal of well-equipment components, visual inspection for documentation of the conditions and status after operation, for instance, inspection of the risers for corrosion and erosion
- In the course of work on the well, logging for determining the condition of the subsurface and surface equipment, for instance, multiarm-caliper log, if necessary

6.5. Initial flow-back phase

Objective: The maximal possible flow-back and recovery of injected hydraulic-fracturing fluid without proppant from the formation, and correct recycling or safe disposal of the flow-back media, in order to avoid hazards to humans and to the environment

Pertinent German laws, regulations, ordinances, and specifications are the following:

- Bundesgesetz (2009): „Wasserhaushaltsgesetz (WHG)“
- Bundesrechtsverordnung (2010): „Gefahrstoffverordnung (GefStoffV)“
- Bundesrechtsverordnung (2013): „Gefahrgutverordnung Straße, Eisenbahn und Binnenschifffahrt (GGVSEB)“
- EU-Verordnung (2006): „Registrierung, Bewertung, Zulassung und Beschränkung chemischer Stoffe (REACH)“
- Länderverordnung (2006): „Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen (BVOT)“
- Länderverordnung (1997): „VAwS - Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen und über Fachbetriebe“
- LBEG (2012): „Rundverfügung: Mindestanforderungen an Betriebspläne, Prüfkriterien und Genehmigungsablauf für hydraulische Bohrlochbehandlungen“
- Wichtige technische Empfehlungen:
- API (2010): “Guidance Document HF2: Water Management Associated with Hydraulic Fracturing”

After completing a hydraulic-fracturing operation the fissure will close onto the proppant fill under the pressure of the formation, the well is put into production. For the subsequent production, two phases must be distinguished: on the one hand, the flow-back phase (recovery of liquid with a significant concentration of hydraulic-fracturing fluid), and on the other hand, the production phase as such (production of reservoir fluids which are practically free of flow-back media). The term “practically flow-back-free production” implies that the flow-back liquid is essentially free of solids and of viscosity similar to that of water.

During the flow-back phase, 20 to 60 per cent of the injected hydraulic-fracturing fluid is recovered. Almost all of the injected proppant remains in the artificially generated fissures as planned. The liquid from the reservoir includes condensed water and in some cases hydrocarbon condensates. If the hydraulic-fracturing operation has been performed in a formation zone which contains hydrocarbons, the liquid also includes connate water which has been dislodged from the rock by shear forces. Saturated reservoir brine is not present in the recovered liquid until a much later stage of production - if it occurs at all.

The flow-back fluids which are recovered immediately after a hydraulic-fracturing operation provide information on the composition of injected liquids for which advective laws and relationships apply. Advective flow is controlled by pressure gradients, in contrast to diffusive transport, which follows concentration gradients and proceeds much more slowly. Diffusion is not significant for underground transport. Hardly any conclusive, detailed information is currently available on the composition of the liquids which are recovered during the initial flow-back phase.

The following options are available for recycling or disposal of the recovered flow-back fluids:

- Disposal by certified companies
- Injection into wells approved for the purpose by mining authorities
- Treatment and recycling for re-use in further hydraulic-fracturing operations

In considering these options, the choice depends on a number of factors, such as the availability of certified waste-disposal companies, the availability of appropriate injection wells and horizons as well as their eligibility for approval, the capacity of available treatment plants as well as their ability to ensure the observance of the specified threshhold values for possible discharge into bodies of water at the surface.

The usual practice at present is to employ the services of certified waste-disposal companies for eliminating the fluids recovered during the flow-back phase. However, the fluids which occur during the production phase are injected into wells approved for the purpose under mining law.[4]

BEST PRACTICE: FLUID MANAGEMENT

- During the flow-back phase (recovery of liquid with a significant concentration of hydraulic-fracturing fluid), treatment of flow-back fluids in a well-clean-out unit with a two-phase separator and flaring of the gas phase or combustion in an appropriate installation (such as an enclosed-burner system)
- During the production phase, treatment in a dehydration unit
- Sampling, analysis, and appraisal of the recovered flow-back fluids for determining the polymer or gel content
- Continuous long-term sampling, analysis, and appraisal of the flow-back fluids for determining the content of components which are relevant to drinking water purity
- Disposal of the fluids from the flow-back phase by certified waste-disposal companies
- Minimising of the volume and duration of intermediate back-flow-fluid storage in the area approved for the purpose on the drilling or well site

[4] An overall concept for handling of the aqueous flow-back fluids, including treatment and recycling in compliance with WHG, is in preparation.

- Injection of the liquids from the production phase into appropriate wells approved under mining law
- Loading and unloading as well as road transport of the flow-back fluids in conformance with GGVSEB
- Permanent proof of waste disposal as agreed

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