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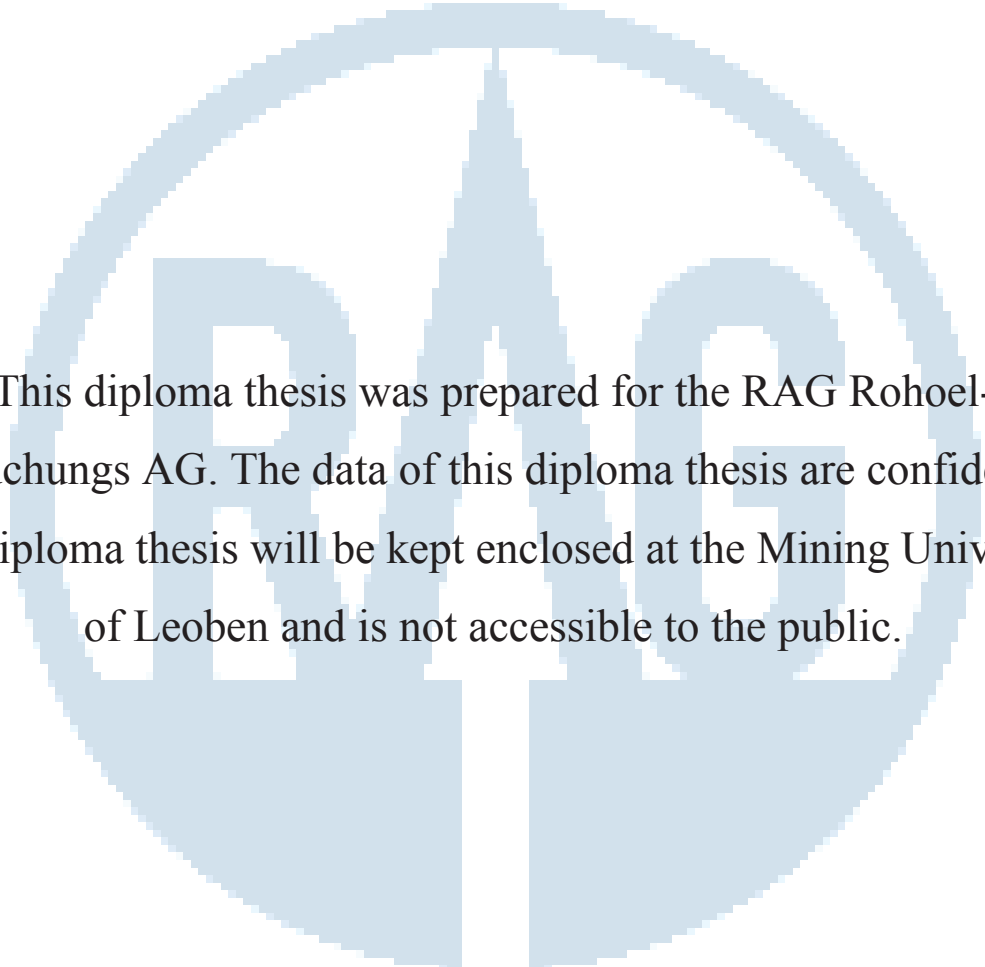
RADIAL DRILLING

DIPLOMA THESIS

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Mining and Metallurgical Machinery

Leoben, December 2009



This diploma thesis was prepared for the RAG Rohoel-
Aufsuchungs AG. The data of this diploma thesis are confidential.
The diploma thesis will be kept enclosed at the Mining University
of Leoben and is not accessible to the public.



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Diplomarbeit

Sehr geehrter Herr Bürßner!

Das von der Firma RAG Rohöl-Aufsuchungs AG zur Verfügung gestellte
Diplomarbeitsthema mit dem Titel

RADIAL DRILLING

wurde Ihnen zur Ausarbeitung übertragen. Die Arbeiten werden von Ihnen zur Gänze bei der
Rohöl-Aufsuchungs AG unter der Betreuung von Herrn DI Markus Seywald durchgeführt.
Die Betreuung am Lehrstuhl für Fördertechnik und Konstruktionslehre übernimmt
Univ.-Prof.Dipl.-Ing.Dr.mont. Franz Kessler.

Die Richtlinien „Guidelines“ des Lehrstuhls für Fördertechnik und Konstruktionslehre sind zu
beachten.

Dieses Schreiben wird nach Abschluss der Arbeit mit eingebunden.

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Univ.-Prof.Dipl.-Ing.Dr.mont. Franz Kessler

DI Markus Seywald

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Last but not least I would like to thank the companies which provided me with essential information concerning the Radial Drilling Technology.

Affidavit

Herewith I declare in lieu of oath, that this diploma thesis with the theme

„Radial Drilling“

is entirely of my own work. I have consulted only references cited at the end of
this volume.

Patrick Christian Bürßner

Leoben, December 2009

Abstract

It has been for years that the Rohoel-Aufsuchungs AG is searching for new production and stimulation methods which permit acceleration of production and reserve increase. One of these methods, albeit quite new in Europe, is the Radial Drilling Technology which has already been applied at three RAG wells since 2008. However, no significant sustainable increase in production of oil or gas occurred at any of the wells. This problem resulted in the topic of the diploma thesis at hand.

The major part of this thesis addresses the analysis of the functionality and the practical process of the Radial Drilling Technology as well as the necessary equipment for the operation of the method and the Hydro Jetting mechanism. Furthermore the advantages and disadvantages of this technology are discussed and a consideration of the patent law situation and the worldwide availability is given.

Moreover the obtainable substitution technologies are analysed and the method is examined from an economic point of view. Another aspect of this thesis comprises an extensive literature research as well as an evaluation of the possible field of application for this technology together with a depiction of the geological character of the reservoir as a prerequisite for a successful application of the technology.

By consideration of technologies that are based on respectively used in combination with the Radial Drilling Technology a short outlook into the future of enhanced oil recovery is given.

The results and technical expertise of the diploma thesis form a starting base for following steps concerning the application of the Radial Drilling Technology at RAG.

Key Words: Radial Drilling/Jetting, Hydro Drilling/Jetting, stimulation method, oil/gas exploration, reserve increase;

Zusammenfassung

Schon seit Jahren sucht die Rohöl-Aufsuchungs AG gezielt nach neuen Produktions- und Stimulationsmethoden, welche eine Produktions- bzw. eine Reservensteigerung ermöglichen sollen. Eine dieser in Europa noch relativ jungen Methoden ist die Radial Drilling Technologie, welche seit 2008 bei der RAG Rohöl-Aufsuchungs AG bereits bei drei Sonden angewendet wurde. Allerdings kam es bei keiner der drei Sonden zu einer nachhaltigen Produktionssteigerung von Öl oder Gas. Daraus ergab sich das Thema für die vorliegende Diplomarbeit.

Ein Großteil der Arbeit widmet sich der Analyse von Funktionsweise und praktischem Ablauf der Radial Drilling Technologie, sowie dem erforderlichen Equipment für die Durchführung der Methode und den Mechanismen des Hydro Jettings. Weiters werden die Vor- und Nachteile der Technologie erläutert und es wird sowohl auf die patentrechtliche Situation als auch auf die weltweite Verfügbarkeit eingegangen.

Darüber hinaus erfolgte eine Analyse von verfügbaren Substitutionstechnologien sowie eine wirtschaftliche Betrachtung der Methode. Ein weiterer Aspekt der Arbeit umfasst eine ausgiebige Literaturrecherche und eine Evaluierung der Einsatzmöglichkeiten für diese Technologie sowie der geologischen Beschaffenheit der Lagerstätten als Voraussetzung für den erfolgreichen Einsatz der Methode.

Mit der Betrachtung von Technologien die auf die Erkenntnisse der Radial Drilling Technologie aufbauen bzw. in Kombination verwendet werden, soll ein kurzer Ausblick in die Zukunft der Produktions- und Reservensteigernden Öl- und Gasförderung gegeben werden.

Die Ergebnisse und Erkenntnisse dieser Arbeit stellen eine Ausgangsbasis für weitere Schritte beim Einsatz der Radial Drilling Technologie in der Rohöl-Aufsuchungs AG dar.

Schlagwörter: Radial Drilling/Jetting, Hydro Drilling/Jetting, Stimulationsmethode, Öl/Gasförderung, Reservensteigerung;

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1 Introduction

The main subjects of this chapter are the current situation of the petrol industry as well as the set of problems and aims of this diploma thesis.

1.1 Problem

Nowadays as the world population has exceeded 6 bn and is heading for the 7 bn mark, the demand for fossil energy and renewable energies is evermore growing (see figure 1.). The security of energy supplies for mankind is for the most part guaranteed by fossil energy sources. Especially in emerging economies like China, India and Russia demand is much higher for low priced, conventional, fossil energy sources than for high priced, unconventional, renewable energies. As long as there are no legislative resolutions in the near future that are able to reduce demand for crude oil and gas the price for these resources will increase dramatically.

Just about 10 % of the oil production is disposed of for the fabrication of plastic materials or in the pharmaceutical industry, the rest is used for energy production and for means of locomotion. This in the future ever rising demand for oil will irrevocably cause a reduction of reserves and thus force the petrol industry to react by finding new ways of exploration and exploitation of both, old and new oil fields. Furthermore it will be necessary to increase production rates and develop new methods to optimise production.

Due to the high rate of exploration it becomes ever more challenging for operators to locate new reservoirs, that is to say that the number of oil or gas producing wells is decreasing. As a consequence every drilled metre becomes more costly and subsequently causes the oil price to rise which reached its peak in the middle of 2008 (see figure 2.). After the oil price slumped in autumn 2008 it has been rising again throughout the current year, heading for old marks again.

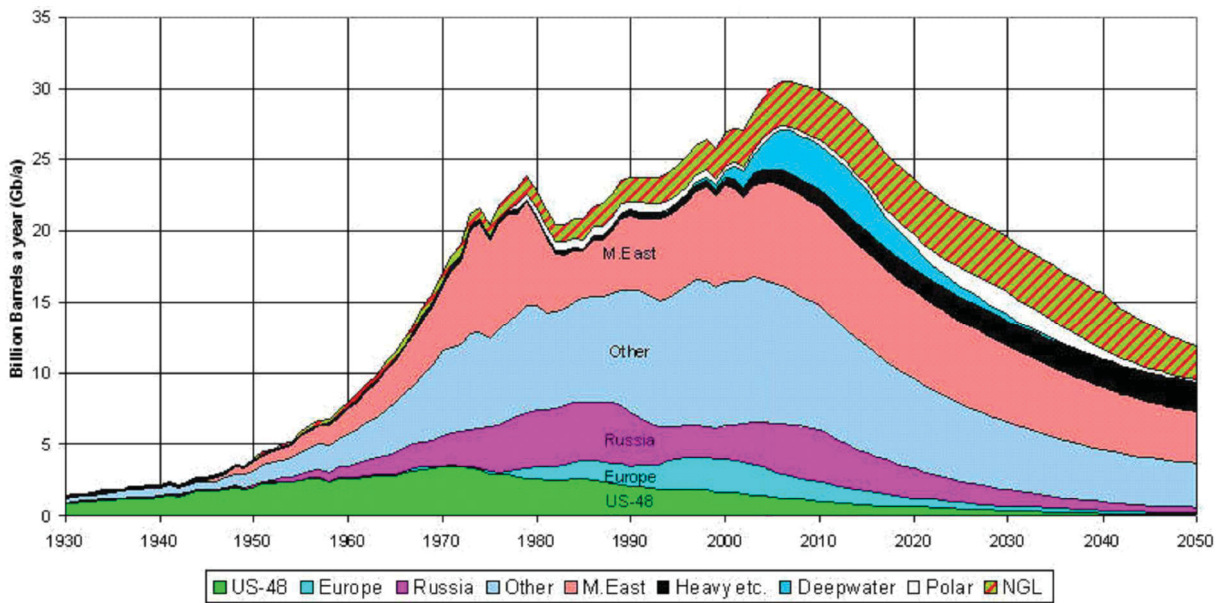


Figure 1: Oil production trend (barrel per year during the past few years) ^[1]

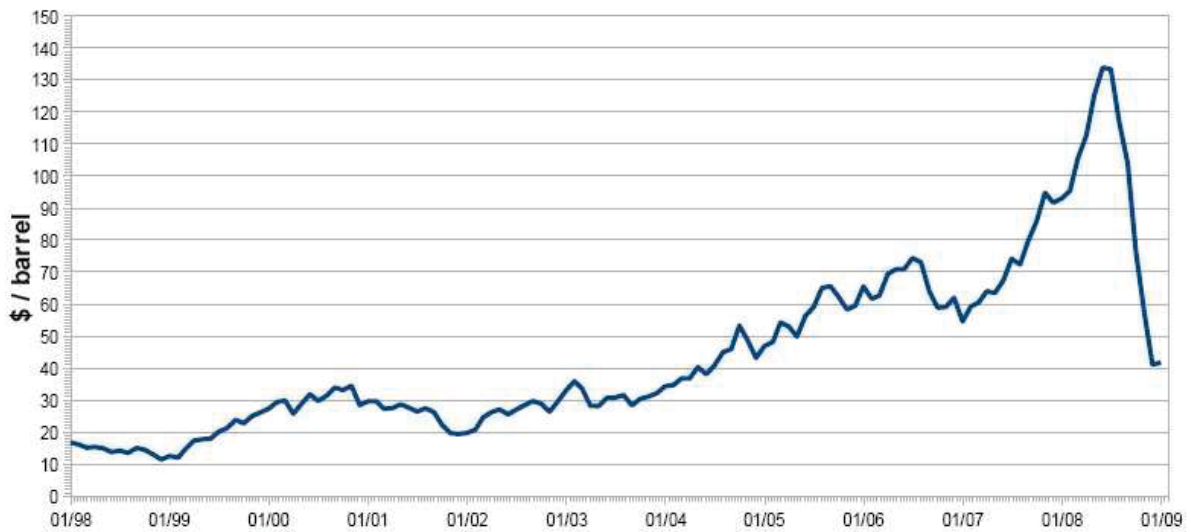


Figure 2: Crude Oil price (Dollar per barrel during the past few years) ^[2]

To reduce the costs of oil production and to satisfy both the company goals and the requirements of the stakeholders it is vital that the very conventional petrol industry really keeps to invest in research to develop new, innovative technologies.

In order to operate cost-effective in the petrol market it is essential to optimize the value-added process despite rising costs and significant pressure to be innovative.

The value-added process consists of:

- Geology
- Reservoir Engineering
- Drilling Engineering
- Production Engineering
- Separating
- Refining
- Transport

This diploma thesis deals with the Radial Drilling Technology (RDT) which turns out to be a new technology for the improvement of the production process in Europe.

The United States' petrol industry often acts as an outrider when it comes to new technologies. As soon as a technology proves successful in the American market they often spread and come to use in Europe as well. But in the near future it will become even more important for the European petrol industry to improve know how and knowledge concerning these new technologies in order to draw level with the Americans.

The Rohöl- Aufsuchungs AG (RAG) is one of these companies which are very committed to looking for innovative methods to increase production and reserves in order to strengthen respectively expand their position as operator in Middle Europe.

The Radial Drilling Technology is a stimulation method which enables the exploration of reservoirs without drilling new wells nearby. Additionally Radial Drilling is relatively cheap and needs less equipment as opposed to other competing methods like Fraccen for example.

The Rohöl- Aufsuchungs AG is one of the first companies in Europe that has applied the Radial Drilling Technology. Formerly this method has been applied only in the United States, Canada, Latin America and Russia.

Three contractors of the Rohöl- Aufsuchungs AG completed the first well, using the Radial Drilling Technology in 2008. One of the contractors tended the truck winch and carried out necessary workover tasks, one was in charge of the Coil Tubing (CT) and the third of the Radial Drilling equipment.

In 2009 two more well completions using the Radial Drilling Technology followed. Unfortunately none of them proved successful in terms of an enduring augmentation of the production rate. However, the reasons for the failed well completions remained unknown.

Given that there are plans for further well completions during the upcoming years the intention is not to become completely dependent on the knowledge provided by the contractors. Hence the demand for this diploma thesis.

For further well completions the findings from this thesis should enable the Rohöl-Aufsuchungs AG to be not a mere casual bystander but rather provide the necessary competence to have a say in the matter. The Production Engineering department under guidance of DI Markus Seywald wanted to build up consolidated knowledge concerning the Radial Drilling Technology and similar methods.

1.2 Aim of the diploma thesis

The primary objective of this diploma thesis is the collection of knowledge concerning the Radial Drilling Technology in order to provide for further well completions and minimise dependency on the contractors when it comes to technical decisions.

Furthermore the preselection of reservoirs should be facilitated and a better cost-benefit equation for the Radial Drilling Technology ensured.

It is decidedly not the objective of this diploma thesis to disclose the reasons for the three failed well completions as this undertaking would be far too complex apart from the fact that the causes are dependent on way too many factors to draw the right conclusions.

A further objective of this thesis is the search for alternative technologies which can be replaced by the Radial Drilling Technology, respectively are based on it.

Moreover the worldwide availability of the Radial Drilling Technology as well as the evaluation of company offering this service are subjects of this work.

One part of the diploma thesis is dedicated to the mechanism and equipment needed for Hydro Jetting. Another chapter describes the equipment which is required for Radial Drilling in order to facilitate the selection process of contractors.

Further aims are to evaluate the advantages and disadvantages of the Radial Drilling Technology, to comprise limiting factors of the technology, to determine the different fields

of application and to conduct a cost-benefit equation. For the purpose of the last mentioned aim the data of the contractor companies as well as of companies that offer Radial Drilling services are used.

An extensive literature research respectively an investigation of the state-of-the-art, including a patent and patent law research at the patent office in Vienna, round up the work.

2 Rohöl-Aufsuchungs AG

This chapter deals with the history, general principle and departments of the company that commissioned this diploma thesis.

2.1 History ^[3]

The Rohöl- Aufsuchungs AG was founded in 1935 as Rohöl-Gewinnungs AG by Exxon Mobile and Royal Dutch/Shell. This makes Rohöl- Aufsuchungs AG the oldest oil exploring and producing company in Austria and a pioneer when it comes to geology and drilling.

It was in 1937 that for the first time oil was explored in Zistersdorf in Lower Austria. An important event for the future of the Rohöl- Aufsuchungs AG was the nationalisation in 1946. Further areas were developed during the upcoming years in Upper Austria as well as in Salzburg. The signing of the treaty of Austria changed the ownership structure once more and made the Rohöl- Aufsuchungs AG a privately owned company again, the shares going back to the former stakeholders.

In 1968 the oil production peaked out, reaching 419.118 t. Nine years later the gas sales hit their peak at 879.726.000 m³.

The Rohöl- Aufsuchungs AG form of organisation was changed in 1992 from a private limited company to a public company. The stakeholders were the EVN Energie-Versorgung Niederösterreich AG with 50 %, the Mobile Oil Austria AG with 25 % and the Shell Austria AG with 25 %. Two years later E.ON Energie AG and Salzburg AG as well as Steirische Ferngas AG acquired together 60 % of the Rohöl- Aufsuchungs AG shares.

Another important step for the Rohöl- Aufsuchungs AG was the acquisition of concessions in Bavaria in 1997. The exploration of the major gas field in Haidach in the Austrian Molassezone took place in the same year. Several years later Mobile Oil Austria sold all their Rohöl- Aufsuchungs AG shares and 2003 Rohöl- Aufsuchungs AG contracted an international Joint Venture with Wintershall in Chiemgau in Bavaria. Around 2005

Shell Austria AG quit their role as the operator of the Rohöl- Aufsuchungs AG, which made the company independent in this respect and it has been ever since.

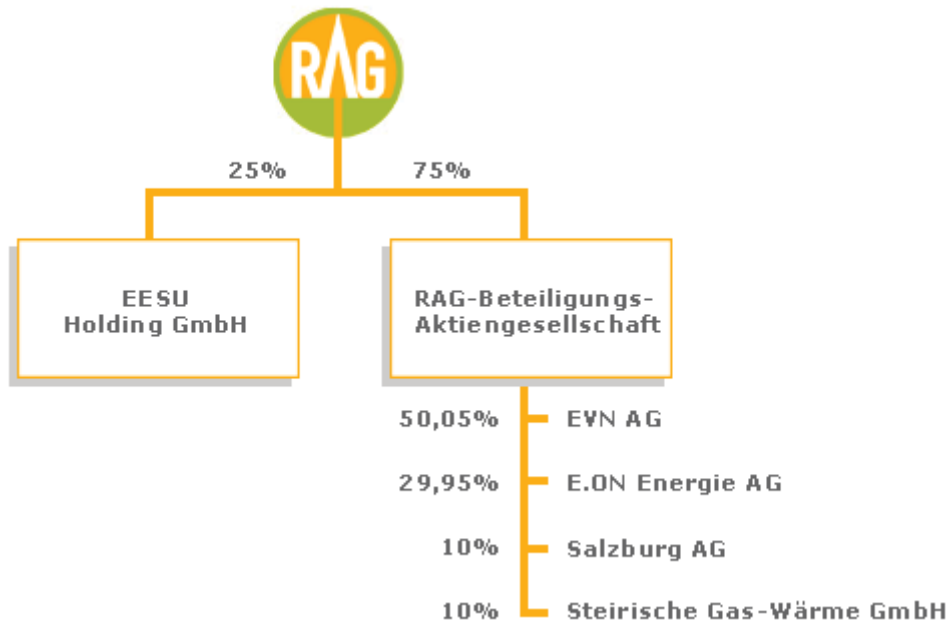


Figure 3: Ownership structure Rohöl- Aufsuchungs AG present ^[3]

The current headquarter of the Rohöl- Aufsuchungs AG is located in Vienna, including the Geoscience and Reservoir Engineering departments whereas the Production and Drilling Engineers are based at Gampern, Upper Austria.

2.2 General Principle of Rohöl- Aufsuchungs AG ^[3]

The General Principle of Rohöl- Aufsuchungs AG reads as follows:

“Social responsibility, integrity and respect for human beings are the basic values of our corporate identity and determine the way we conduct our business activities.” ^[3]

These principles are reflected in the three chief activities of the Rohöl- Aufsuchungs AG:

- Exploration of oil and gas
- Oil and gas production
- Gas storage

Gas storage is the most important one of these three chief activities (see figure 4.). A secure energy supply for Austria and Europe is a major goal of Rohöl- Aufsuchungs AG thus it is planned to enlarge the gas storages to reach the fulfilment of this goal in the future as well.

Health, safety and environment are the three catchwords that affect all actions that are undertaken in the three chief activities. Furthermore they are intended to guarantee the sustainability of the company in both Austria and countries abroad.



Figure 4: *The three chief activities of Rohöl- Aufsuchungs AG* ^[3]

Additionally to the chief activities the Rohöl- Aufsuchungs AG is also fostering renewable energies like geothermal energy sources and new technologies in order to satisfy current customer needs.

2.3 Departments, Facts and Figures ^[3]

The main departments of Rohöl- Aufsuchungs AG are:

- Geoscience
- Reservoir Engineering
- Drilling
- Production Engineering

The Rohöl- Aufsuchungs AG is an operating company with own concessions as opposed to its contractor companies like Schlumberger, Halliburton, Weatherford, ITAG or Baker Hughes which assist the above mentioned departments.

2.3.1 Geoscience

In order to locate fossil energy sources it is first of all crucial to explore the geological structure of the concession areas. It is done so by means of seismic exploration methods.

If the geological prerequisites for an oil or gas reservoir are given the assessment of the reservoir is the next step.

2.3.2 Reservoir Engineering

The Reservoir Engineers determine the size and probability of resources and reserves. Optimizing the yield of the reservoirs is another important task of the Reservoir Engineers as well as ascertaining the economics of the reservoirs. If a reservoir proves to be favourable the Reservoir Engineers have to plan the production and the field development.

2.3.3 Drilling

In the event of a reservoir being worth exploration a well has to be planned, measured, drilled and stabilised for which the Drilling Engineers are responsible.

In the past one and a half year the Drilling Department were provided with two new drilling rigs, the E200 and the E202.



Figure 5: *Drilling Rig E200* ^[3]

2.3.4 Production Engineering

The Production Department is in charge of the oil and gas production and the gas storage, both subsurface and on surface. They are applying existing and looking for new technologies to produce oil and gas in ever more effective and cost efficient ways as well as to develop new resources. The Radial Drilling Technology is one of these new technologies.

If a well is not producing respectively storing anymore it is the task of the Production Engineers to plane the abandonment of this specific well.

2.3.5 Concession Areas

The Rohöl- Aufsuchungs AG has concession areas in Austria (Upper and Lower Austria, Salzburg) and abroad in Bavaria (Chiemgau, Salzach-Inn). The Austrian concession areas are 5.147 km² large and the Bavarian concession areas measure 3.068 km².



Figure 6: RAG Concession Areas in Austria, Hungary and Bavaria ^[3]

In addition to the Rohöl- Aufsuchungs AG as oil and gas producing company, the OMV AG possesses concession areas in Austria. However, they are located mainly Lower Austria and the Burgenland.

On 1st October 2009 the Rohöl- Aufsuchungs AG acquired the Toreador Hungary Company which is a subsidiary of Toreador Resources and will be named RAG Hungary in future. In Hungary the intention is mainly to explore and produce oil and gas. The acquisition of the Hungarian Company means another step forward in the internationalisation strategy of the Rohöl- Aufsuchungs AG.

2.3.6 Facts and Figures

In the following itemisation some facts and figures about the RAG are listed:

- 22 to 25 wells (40.000 m) are drilled by RAG and its contractors per year
- Around 360 people are employed at the Rohöl- Aufsuchungs AG
- In 2008, 27 deep wells were drilled which equals 48,3 km. 6 of these wells are gas wells, 3 oil wells, 1 gas and oil well, 5 storage wells, 2 injector wells. The remaining wells are still to be tested, not rich or not yet completed.
- 104.070 tons crude oil were produced in 2008
- Natural gas production amounted to 308,4 million m³ in 2008
- Capital expenditure in 2008 added up to 89,3 million €
- Gas storage volume 2 bn m³ (forecast 5,7 bn m³ in 2017), annual consumption in Austria 8 bn m³
- 86 producing oil wells
- 117 producing gas wells of which 17 are gas storage wells

3 Radial Drilling Technology

This chapter deals with the Radial Drilling Technology in detail, including a contemplation of the state-of-the-art, research on the method, a discussion of the advantages and disadvantages as well as an evaluation of the availability and the limits of this technology.

3.1 Preface ^[4]

The Radial Drilling Technology is a stimulation technology for oil or gas wells which is intended to effect an increase of the production rate, respectively the well inflow performance if applied accurately. It is also possible to use the Radial Drilling Technology for injection drillings in conjunction with hot steam, hot water or acid in order to augment the oil discharge. The Radial Drilling Technology was used for the first time during the 1980s in the United States and the former Soviet Union. The Radial Drilling Technology turned out to be a very cost efficient and time-saving method (drilling four lateral wells takes only 2 to 4 days) and additionally no overly expensive or complex equipment is needed. Its purpose is the enlargement of the inflow range, radius as well as the inflow surface area.

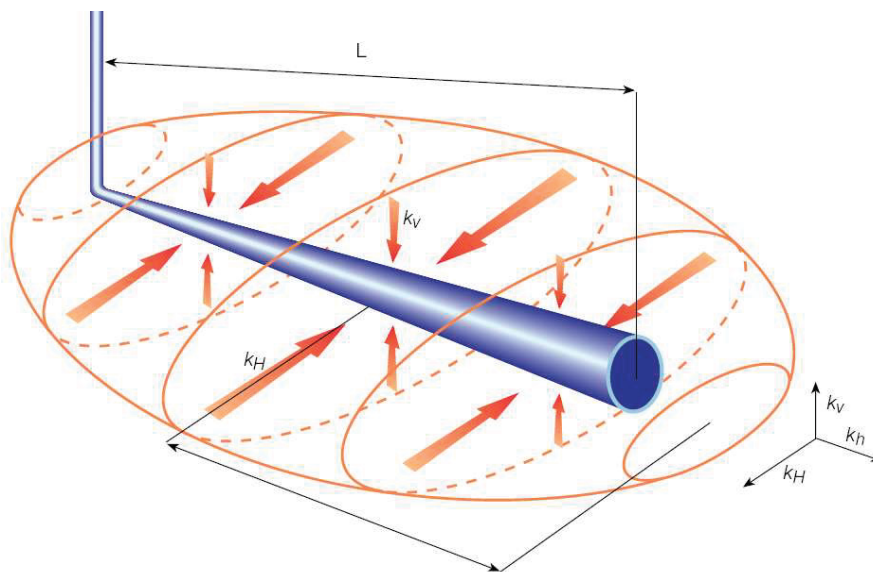


Figure 7: Radial drilled lateral well with inflow performance ^[5]

By usage of the Radial Drilling Technology it is possible to jet radial side tracks with a diameter of around 5 cm and about 100 m deep. Form and dimensions of these side tracks, also known as laterals, are heavily dependent on the formation and their geological characteristics and resistance respectively cementation.

The Radial Drilling Technology is usually applied to older wells which show lower inflow after some production time. However, the technology is seldom used for unperforated wells. This is just the case if compartments are radial located around the well which can not be reached by means of a conventional perforation (reach of a 1 m radius) respectively if a parallel well would be too expensive (see figure 8.).

The Radial Drilling Technology is predominantly applied to quasi vertical wells as it is impossible to drill the casing in horizontal wells. It proved very effective to drill the laterals at an angle of 90° and optionally, for not horizontal wells, provide for a height offset. The positioning of the desired azimuth is effected by usage of a gyroscope.

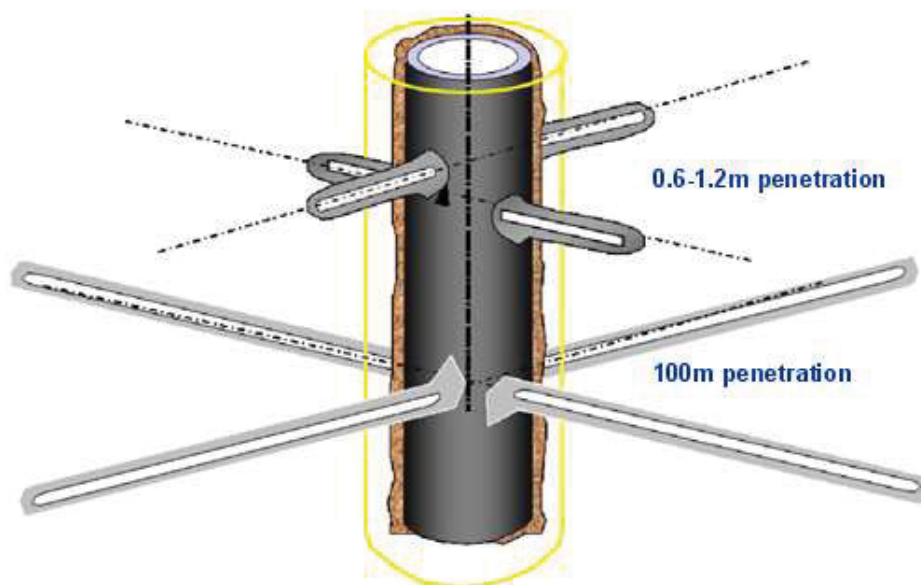


Figure 8: *Top laterals: conventional perforation; Bottom lateral: Radial Drilling Side Tracks* ^[5]

In order to apply the technology it is necessary to dispose of an easily controllable Coil Tubing construction. The Coil Tubings have been continuously improved over the past years so that they can be handled very precisely, thus fostering the development and facilitating the usage of the Radial Drilling Technology. This led at the beginning of the 21. Century to the

creation of a number of small Companies offering the Radial Drilling and advisory services to their clientele.

Using a Coil Tubing it is possible to drill radial wells even in depths of up to 3000 m. The minimum diameter for the casing is around 4 ½ inches with no upper limit. In contrast to conventional wells the laterals are left open hole and are not completed.

3.1.1 Operating mode off the Radial Drilling Technology

The Radial Drilling Technology generally comprises two operations:

- Milling
- Jetting

Before it is possible to jet into the formation respectively to jet a radial well, it is necessary to drill the casing. This happens during the first operation (see figure 9.). The casing is drilled with a milling cutter which is inserted via a flexible shaft into a deflector shoe and propelled by a Downhole motor (DHM).

The deflector shoe is located in the correct well depth and azimuth. Via the tubing line, the centralizer and anchor it is virtually connected firmly to the casing in order to keep the milling cutter constantly in the same position.

The Downhole motor is powered hydraulically by means of a special fluid. The motor together with the flexible shaft and the milling cutter are inserted into the well and the deflector shoe by means of a Coil Tubing and the motor is provided with the fluid (fluid pressure and flow rate).

On the other end of the Coil Tubing the fluid is compressed before it is pumped into the Coil Tubing. As soon as the milling cutter has drilled a hole into the casing the Coil Tubing together with the equipment can be extracted and the next operation can be begun.

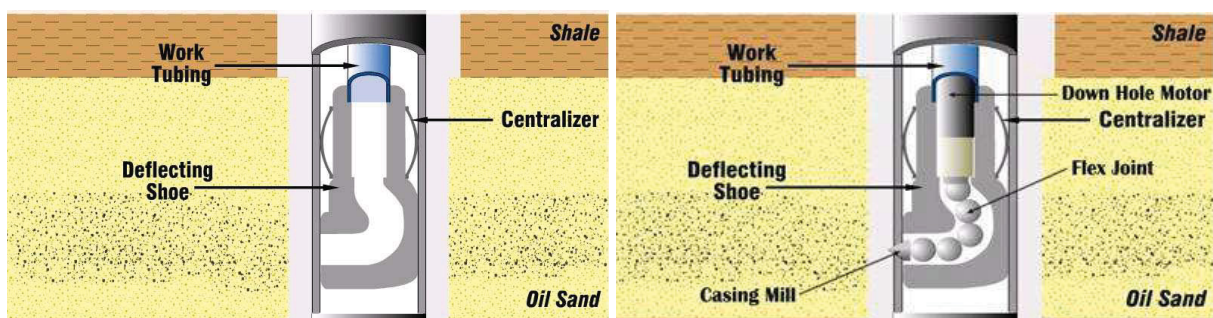


Figure 9: Left: Deflector shoe placed in Casing; Right: Casing Mill mills the Casing^[6]

The jetting comprises of two procedures, the jetting-in and the jetting-out. For the jetting the equipment attached to the Coil Tubing is replaced with a long hose and a nozzle. The Coil Tubing is inserted with the hose and the nozzle and by means of a high-pressure pump a different fluid is pumped through the nozzle. The nozzle is fitted with orifices for the fluid on both the front and the back. This is where the jetting-procedure begins.

With the aid of the Coil Tubing the nozzle drags itself through the deflector shoe and starts to jet a hole into the formation with its front orifices. The back orifices provide the necessary feed rate while the forward orifices cater for the required cutting effect allowing the nozzle to penetrate the sandstone further and further. As soon as the nozzle has reached its maximum drilling depth the procedure of jetting-out begins and the nozzle is slowly extracted by means of the Coil Tubing. The pressure at the nozzle is increased even further via a higher flow rate in order to enlarge the diameter of the hole with the rear jets as much as possible.

After the jetting-out (see figure 10.) is done the Coil Tubing together with the flexible hose and the nozzle is extracted and a side track has been completed.

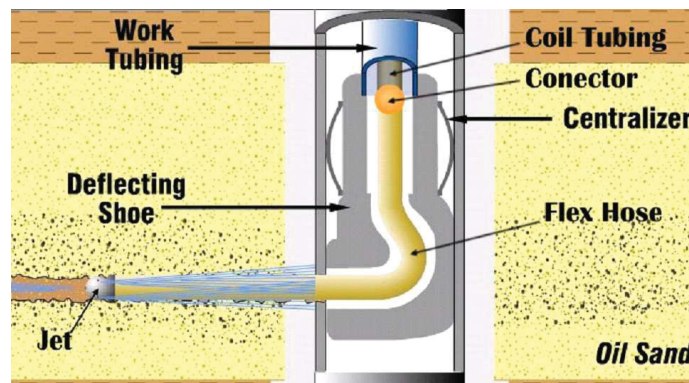


Figure 10: *Jetting-out of the formation* ^[6]

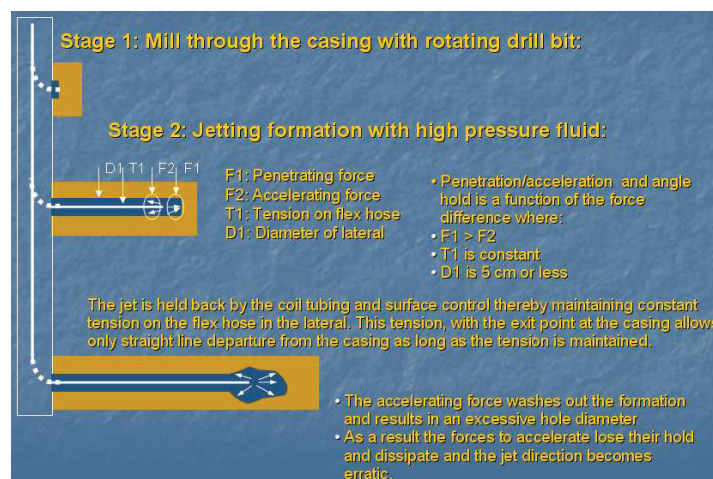


Figure 11: *Radial Drilling operation overview* ^[7]

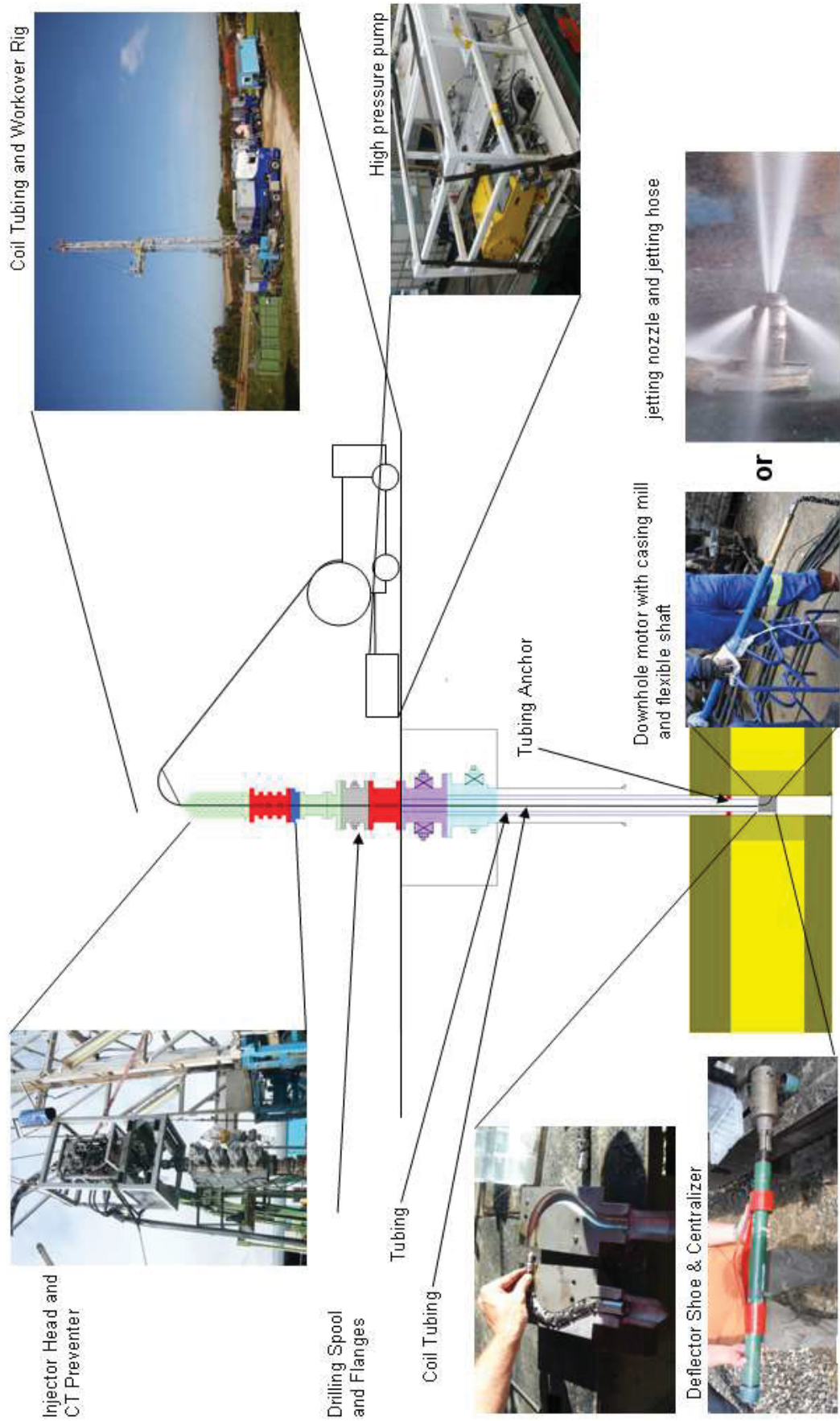


Figure 12: Radial Drilling operation overview and Equipment ^[8]

3.2 State of the Art

In order to investigate the state of the art a patent research at the patent office in Vienna was carried out and additionally a literature research by means of the SPE software was conducted in order to find relevant papers.

3.2.1 Literature Research

The literature research produced three SPE papers which are affine with the Radial Drilling Technology. The papers are as follows:

- (1) *Jet Drilling Tool: Cost effective lateral Drilling Technology for enhanced oil recovery*, SPE 68504 ^[9]
- (2) *Radial Drilling in Argentina*, SPE 107382 ^[10]
- (3) *First Experience in the Application of Radial Perforation Technology in Deep Wells*, SPE 107182 ^[6]

Concerning (1): The paper contains information about hydro jetting and its nozzle mechanisms. However it demonstrates the functioning of the Radial Drilling on the basis of a slightly modified Radial Drilling equipment compared to how it is described in this diploma thesis. Furthermore tests are described which took place on surface and are meant to explain the hydro jetting mechanisms in more detail. By means of a simulation it is pointed up how the different permeability's, skin damages and oil viscosities affect the production increase through Radial Drilling.

Concerning (2): The basis of the paper were research tests for Radial Drilling in Argentina. First the functioning of the Radial Drilling construction and its equipment are explained and advantages and disadvantages of the method are discussed. Then follows a depiction of subsurface Radial Drilling tests as well as a publication of measurement results before and after the Radial Drilling job. Furthermore the selection of potential wells is discussed. Therefore tests were conducted at wells which were fractured before the Radial Drilling and

were low permeable, not perforated and showed no production before the Radial Drilling. Additionally the wells were injected with water after the Radial Drilling, lead oils of high viscosity and featured a high water cut. The tests covered 22 wells.

Concerning (3): The basis of this paper were research tests for Radial Drilling in Bolivia. First the paper deals with the characteristics of reservoirs that are qualified for Radial Drilling. Then the potential wells are explained in more detail, stating their most important parameters. Additionally the geometric and mechanic characteristics of the wells are discussed as well as the production increase after the Radial Drilling job. At the end the function and the equipment of the Radial Drilling construction are explained as well as the main problems and the operative limits of the Radial Drilling Technology.

The findings and additional information of these three papers were analysed and included in several chapters of this diploma thesis.

3.2.2 Patent Research

The patent research produced three patents which are affin to the Radial Drilling Technology. To be counted among these patents (which are also valid in Austria) are:

- (1) Apparatus, System, and Method for Casing Hole Formation in Radial Drilling Operation, Brunet Charles [US], Bouchard Michel [CA], WO2008063267 (A1), 2008-05-29 ^[11]
- (2) Method of and Apparatus for Horizontal Well Drilling, Landers Carl W. [US], WO0058599 (A1), 2000-10-05 ^[12]
- (3) Nozzle for Jet Drilling, Buckman Jet Drilling INC [US], Buckman William G. SR. [US], Dotson Thomas L. [US], Mc Daniels Michael D. [US], Bell Wendell S. [US], WO03087522, 2003-10-23 ^[13]

Concerning (1): The first patent describes a new deflector shoe which consists of two parts: the deflector assembly and the drive assembly. The drive assembly is fixly connected to the deflector shoe during the installation process and is flanged off after the milling job.

The shoe can be turned on surface and on the lower end it features an anchor and a rotating device which allows for predetermined azimuths to be regulated. This deflector shoe enables to first drill the casing in several azimuths and to jet into all azimuths after the milling job. The arising economy of time for the Radial Drilling job is enormous.

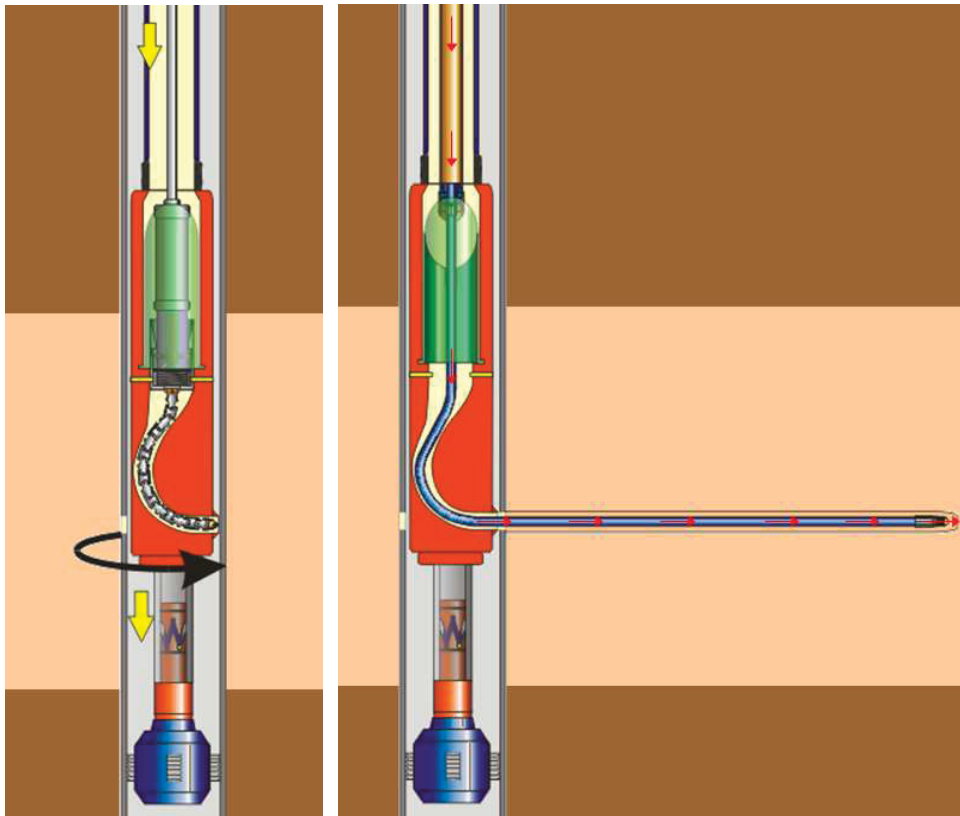


Figure 13: *Left: The two milling jobs ^[14]; Right: After the two milling jobs, starts the first jetting job ^[14]*

Concerning (2): The patent protects the whole Radial Drilling method itself. The patent is kept quite general and describes the whole Radial Drilling method, from the milling job over the jetting-in to the jetting-out. Also the acidizing at the jetting-out is explained and the fluids used for the job are discussed in more detail. Furthermore the Downhole motor, the call cutter, the jetting hose, the nozzle and the high pressure pump are explained.

Concerning (3): This patent protects the constructive execution of a special jetting nozzle. This nozzle features a disc mechanism. The disc is positioned inside the nozzle and is pivot-mounted. As soon as a fluid streams through the nozzle the disc starts turning and the nozzle is put into a swirling motion.

The aim is to enlarge the cross sectional area of the lateral and to hone the outline brims. The findings and additional information of these three patents were analysed and included in several chapters of this diploma thesis.

Additional to the independently conducted patent research a university request for a patent research (No. 93298/2009) was made at the patent office of Vienna. As the treatment of a patent research request takes quite some time it was not possible to include the results in this diploma thesis.

It was mainly the different companies which enabled a compilation of the state of the art. Most information and findings were extracted from presentations and Radial Drilling programs of companies which offer the Radial Drilling Technology.

3.3 Advantages and Disadvantages of the Technology ^{[2],[9],[10],[15]}

The following advantages can be drawn from the Radial Drilling Technology:

- An increase of the drainage radius and the flow profile of the well; achievement of a diminution of the pressure drop close to the well.
- Development of new compartments radial to the well and increase of the well productivity.
- Full lateral and vertical treatment control via gyroscope measurement and short Tubing's.
- No insertion of skin damage into the laterals.
- Small footprint and very cost effective and simple equipment needed for the job.
- Fewer time needed for the Radial Drilling job compared to other stimulation methods.
- The narrow laterals are able to overcome areas with high skin damage or bad facies and thus reach more productive areas and link them with the borehole.
- By means of the Radial Drilling Technology it is possible to jet very small horizons.
- The Radial Drilling Technology does not cause any fractures in the formation and thus limits the risk of encountering water leading horizons.

- The Radial Drilling Technology can be used in combination with several other technologies like acidizing, swabbing, Fraccen, steam injection, chemical treatment, water or CO₂ injection or other secondary or tertiary oil recovering methods.
- By use of the Radial Drilling Technology it is possible to predetermine perforation or Fracing directions.
- Weak environmental impact and few risks.
- The deflection radius needed for the horizontal drilling is quite small.
- If desired the horizontal depth of the lateral can be reduced to 2 to 5 m which is just enough in order to overcome the skin damage.
- Laterals can be jetted in single or multiple wells.
- Fewer wells are needed in order to make the same size of exploration field accessible by means of the Radial Drilling method compared to conventional methods. This entails fewer surface equipment, fewer lifting equipment, less lifting costs and less environmental impact.
- The Radial Drilling Technology can be applied for gas, oil, storage, explorations as well as injection wells.
- Via the horizontal well a bigger contact area of the reservoir is achieved.

Disadvantages of the Radial Technology can be named as follows:

- Completion of the lateral is not possible. Therefore the laterals are at risk of collapsing. The laterals remain open hole completed.
- It is not possible to influence the borehole pattern during the jetting of the side tracks.
- No data well logging is possible after the Radial Drilling.
- The Radial Drilling Technology is not suitable for hard and highly cemented or conglomerate containing reservoirs.
- The Radial Drilling Technology can be applied only for vertical boreholes.
- The size of the casing is downwards limited with 5 1/2" and its resistance must not be too high.
- The covering layer or a beneath located layer of the oil or gas leading horizon might be damaged in the course of the Radial Drilling job.

- It is not advisable to use the Radial Drilling Technology for horizons featuring a high water production.

3.4 Availability of Radial Drilling Technologies

The Radial Drilling Technology is available worldwide. There is a great number of contractors offering Radial Drilling. Most contractors are located in the Northern American area. This is a consequence of the fact that the Radial Drilling Technology was invented and patented as well as applied several times in the United States. Hereupon several small contractors emerged which obtained licences for the Radial Drilling Technology and started practicing it. After the Radial Drilling Technology had proved its status as a cost-efficient stimulation method in the United States, first tests were undertaken in Russia and Southern America. The Rohöl- Aufsuchungs AG is one of the first companies in Europe which applied the Radial Drilling Technology by means of a contractor.

The following companies offer services connected to the Radial Drilling Technology:

- Platinum Petroleum International Limited [USA] (holds Radial Drilling Technology licences for the Middle East, partner for work-over jobs is the company Radial Drilling Services, Inc. [USA])
- Jet Drill Well Services, LLC [USA] (executes work-over jobs)
- Well Enhancement Services, LLC [USA] (executes work-over jobs, has the sister company Energy Capital Group, LLC [USA])
- KOS Energy Services, LLC [USA] (executes work-over jobs, licensee of Buckman Jet Drilling, Inc. [USA])
- Jet Flow Energy [USA] (licensee of Buckman Jet Drilling, Inc. [USA])
- Berry Resources [USA] (licensee of Buckman Jet Drilling, Inc. [USA])
- Buckman Applied Research [USA] (licensee of Buckman Jet Drilling, Inc. [USA])
- Radcan Energy Services, Inc. [USA] (executes work-over jobs)
- KSAM RadFLO™ [Indonesia] (executes work-over jobs)
- Prodo Energy Inc. [Canada] (executes work-over jobs)
- RadJet, Inc. [USA] (executes work-over jobs)

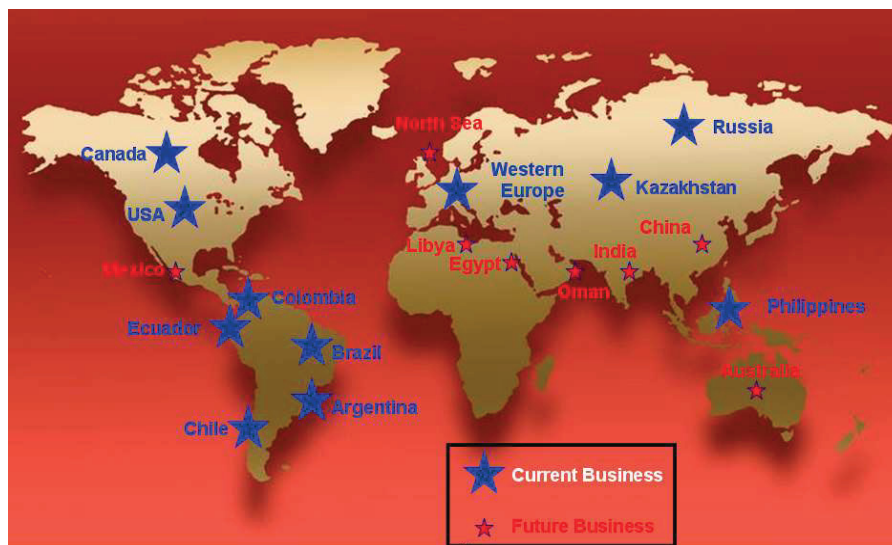


Figure 14: Radial Drilling Activities around the World ^[16]

3.5 Constitutive Technologies ^{[16],[8],[17]}

The broad variety of its constitutive technologies proves the Radial Drilling Technology to be very good combinable. Especially post drilling activities are most suitable in this account. The following methods lend themselves to constitutive technologies.

1. Local Acidizing
2. Steam injection
3. Water or CO₂ injection
4. Crack direction initiation
5. Swabbing

Concerning (1): Depending on the formation, a chemical treatment can take place, an acid wash can be applied after drilling each lateral by using the Radial Drilling system (with a modified nozzle head) to convey the chemicals into the laterals or by using a dual packer system to isolate the radials and inject chemicals under pressure. The main task of the acidizing is to bring the reactive fluid to the formation in order to ablate material from the formation. Acid is pumped into the borehole to allow for the removal of close formation or skin damage. Thus the drainage radius as well as the permeability of the well are increased. The following acids are used as fluids for different rock materials:

- Hydrochloric acid (HCL) in carbonate reservoirs
- Hydrochloric acid (HCL) in carbonate-cemented sandstone
- A mixture of Hydrofluoric acid (HF) and HCL in low-carbonate sandstones

Concerning (2): The injection of hot steam into the formation is counted as tertiary oil recovery respectively enhanced oil recovery and is used mainly in the case of highly viscous oils. The heat input reduces the viscosity of the oil which allows for it to diffuse more easily through the pores of the formation. By means of this technology it is possible to produce heavy crude oil in wells. The technology is also often implicated with the synonym HOSS (Heavy Oil Steam System). There are several ways of applying the HOSS technology. One method is to alternate hot steam injection and oil production in the same well. Another method is to drill two vertically shifted laterals and to inject hot steam into the upper one while the lower one is used for production. The last method requires two wells drilled side by side which interlock and both possess laterals. Hot steam is injected in one of the two wells while the other produces oil.

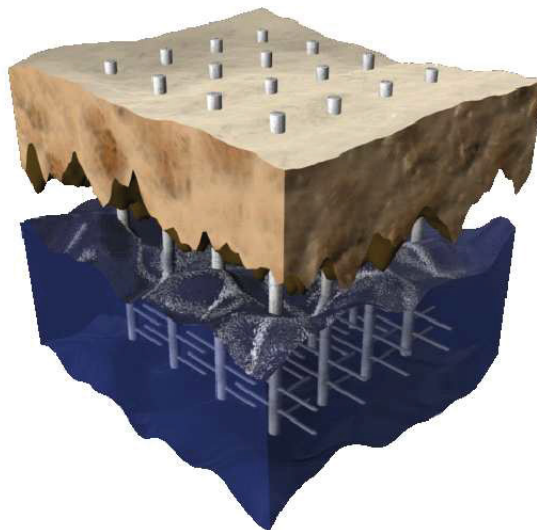


Figure 15: *Steam injection after Radial Drilling*^[17]

Concerning (3): The injection of water into a well can be counted among the oil recovery methods. Usually a water leading layer resides below an oil or gas horizon. As the reservoir is a self-contained system and oil is less heavy than water and thus floats on it, it is possible to maintain the pressure of the reservoir by flooding it with water even if at the same time oil is

extracted from the reservoir. Of course the water cut increases significantly during this procedure. The injection of CO₂ into the reservoir aims at the same result, however it has to be counted among the tertiary oil recovery methods.

Concerning (4): By means of the Radial Drilling Technology and the created laterals it is possible to initiate a crack direction for a subsequent Fracturing. Therefore it is possible to predetermine the direction or the depth of a frac as the lateral or laterals in itself mark a pre initiated crack and the frac forms where the resistance is lowest.

Concerning (5): When swabbing the pressure working inside the laterals is produced by means of a swabbing tool, a moving pipe, a wire line tool or a rubber-cupped seals up the wellbore. When the pressure inside the lateral is successfully reduced, it is easier to extract the oil or gas from the reservoir. Cleaning of the used drilling fluids by means of swabbing is recommended to avoid damaging reactions with the formation. This activity will also provoke the formation fluids to start flowing after stagnation during the Radial Drilling operations. During the swabbing it is crucial to be careful as kicks or wellbore stability problems are likely to occur.

3.6 Substitution Technologies

That the Radial Drilling Technology is versatilely applicable is demonstrated by the vast variety of its substitutional technologies. The following technologies can be counted as such:

1. Side Tracking
2. Post perforation
3. Hydraulic Fracturing
4. MaxPerf® Drilling Tool
5. Matrix Acidizing

Concerning (1): Side tracking is a method where a drilling tool is installed at the tip of a Coil Tubing which is then inserted into a already existing borehole. The coil is deflected inside the casing by means of a whip stock thus enabling the drilling of horizontal side tracks.

Side tracking allows for significantly narrower radiuses than conventional directional drilling by means of a drilling rig and a Downhole motor. The drilling tool on the Coil Tubing can either be a jetting nozzle which jets forward and sideways or a Downhole motor with direction indicating equipment. The advantages of the Radial Drilling Technology concern the working time and the lower effort needed for a job in comparison to side tracking. However the main advantage of the side tracking is that the borehole pattern can be exactly determined by means of logging.

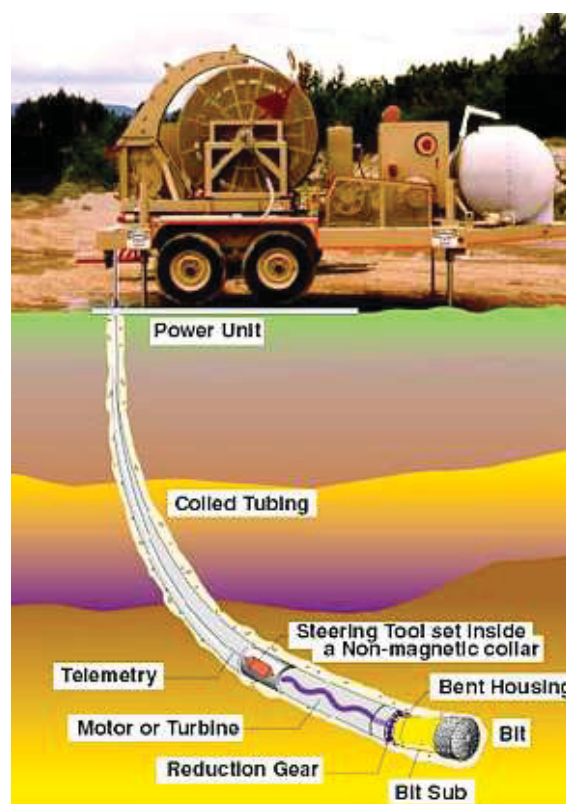


Figure 16: Side Tracking with Coil Tubing and Downhole motor ^[18]

Concerning (2): For the post perforation a jet gun is inserted into the casing and ignited at the pre-perforated position. The horizontal depth of the post perforation usually exceeds the depth of the first perforation significantly. The depth can come up to 1 m. Post perforations are often used in order to overcome skin damage areas in ultimate proximity to the borehole and in order to increase the permeability of the formation. With the Radial Drilling Technology it is not possible to create that many short laterals in massive formations. On the other hand it is possible to create several long side tracks in formations of moderate thickness which allow for a greater drainage radius than the short perforated tracks.

Concerning (3): Hydraulic Fracturing is a technology suitable for both oil and gas production. The technology is known as a stimulation method which allows for the increase of permeability of the rock by creating fractures. The basic idea of this technology is to connect many pre-existent little fracs in the reservoir via a big fracture emerging from the casing. The length of this fracture can come up to 500 m. The big frac is created by long-term injection of fluid (e.g. water with some high viscosity fluid additives) into the reservoir. In order to keep the frac open after the stimulation, propping agents like sand or gravel are added to the high pressure fluid which prevents a closing of the fractures.

An advantage of the Radial Drilling Technology is that significantly fewer equipment and time is needed and that it is more cost-efficient than a hydraulic Fracturing job. Another disadvantage of the Fracturing is that especially at wells with dangerously high water cut a frac could end right in a watercourse. The frac direction can be only to some extent predetermined as the frac forms usually where the resistance of the rock is lowest. The Radial Drilling Technology allows the predetermination of the direction but it is not possible that the borehole pattern deviates significantly from the horizontal or the azimuth as this would cause major friction and prevent the jetting hose from further penetrating the formation.

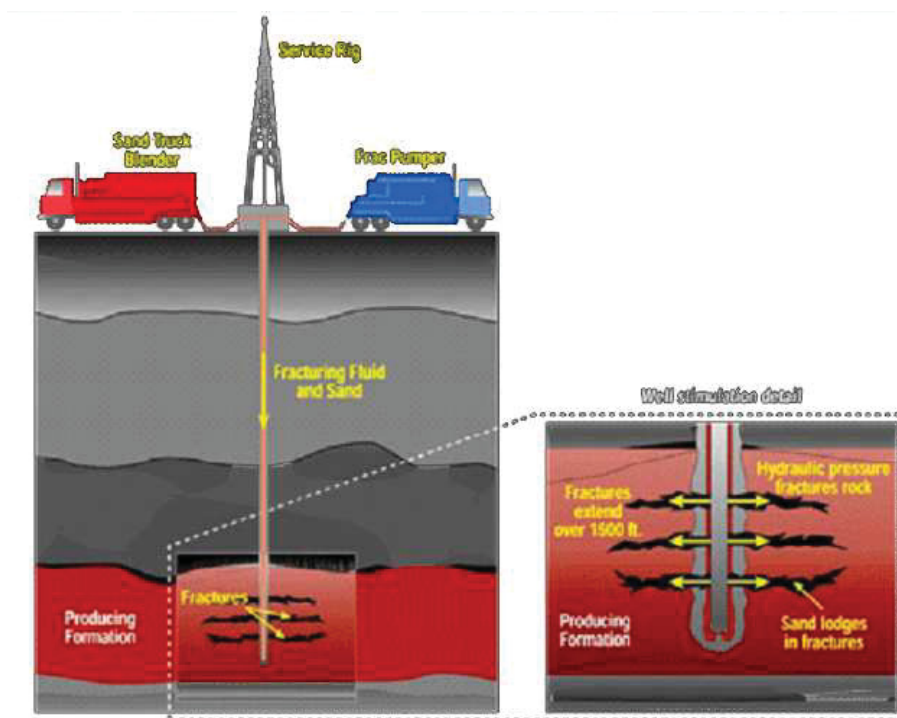


Figure 17: Hydraulic Fracturing ^[19]

Concerning (4): The MaxPerf® Drilling Tool Technology is the one most similar to the Radial Drilling Technology. Instead of a deflector shoe a complete string with equipment like milling section, drill section, motor section, control section, filter, anchor and circulation valve with tubing is inserted. The milling section features a casing mill which drills the casing. After the drilling the equipment is lowered and it is drilled around 1,8 m further down into the formation by means of the drill section. 1,8 m are sufficient in order to overcome the skin damage in direct proximity to the borehole and increase the permeability. The Radial Drilling Technology is fit to replace the MaxPerf® Technology as it also allows for the jetting of shorter laterals into the rock formation. The main advantage of the MaxPerf® Technology is that rock of any hardness and cementation is possible. Additionally the MaxPerf® Technology has been highly automated which entails less time consuming work processes in comparison to the Radial Drilling Technology.

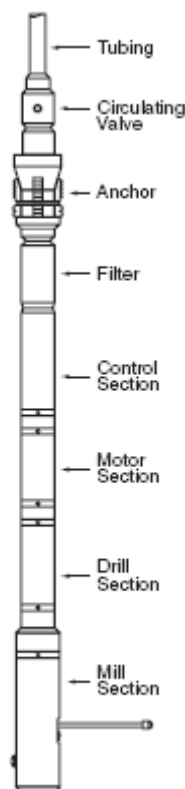


Figure 18: *MaxPerf® Drilling Tool* ^[20]

Concerning (5): Acidizing means that an acid solution is injected into an existing well at a pre-perforated section.

The acid solution undergoes a reaction with the rock formation and thus removes the skin damage in ultimate borehole proximity to a large extent and by doing so enhances the permeability for oil and gas. The Radial Drilling Technology allows for a more precise and intense injection of the acid solution into the rock formation during the jetting-out.

3.7 Technical Limits of the Radial Drilling Technology ^[8]

The application of the Radial Drilling Technology is limited by technical and physical boundaries. Following a list of the limiting factors, each with a short statement:

- Minimum Casing 5 1/2" (maybe in future 4 1/2")
The smaller the casing the smaller the space for the Radial Drilling equipment viz. the deflector shoe and its canal radius. A small radius causes problems first when it comes to the jetting, especially with the nozzle and the armature, and second when it comes to the milling, especially with the inclination and diameter of the flexible shaft.
- Maximum well inclination of 30°
If the well inclination is too high it is almost impossible to insert the flexible shaft and the hose into the deflector shoe.
- The well depth is limited by the length and the wall thickness of the Coil Tubing as well as its resistance.
- Resistance of the casing
If the casing is too resistant it is not possible for the miller to cut the casing.
- The depth of the side tracks is limited by the length of the hose and the tension respectively the stiffness of the hose. Another limitation is implied by the friction circumstances of the hose inside the side track respectively its hole pattern through the formation.
- Cementation and geological condition of the reservoir
Too compact reservoirs can not be jetted, furthermore sandstone with parts of conglomerates are very difficult to jet or can not be jetted at all. In the event of bigger caverns, cracks, fractures and hollows it is very likely that the feed rate decreases and the nozzle stops.

- The sump has to be of a sufficient depth in order to discharge the cuttings. If the cuttings (2 litre cuttings per 1 m drilled lateral) can not be discharged an afflux can occur. This can be avoided by interim circulation, therefore it is necessary to scan the borehole floor during the Radial Drilling Job.
- Inner diameter of the tubing line
The diameter must not be too small in order to insert the Downhole motor.
- The torque of the Downhole motor is limiting the cutting force which the bit is imposing on the casing. If the torque is too high the flexible shaft is likely break off, especially if the bit blocks and abruptly comes to a standstill.
- The diameter of the Coil Tubing is downwardly bounded by the increasing fall of pressure as well as by the required depth and resistance. Furthermore it is upwardly bounded by the inertia of the controllability of the Coil Tubing equipment as well as its complexity and ponderosity.
- A Radial Drilling operation can not be repeated as often as desired as the hose is likely to be broken after three operations and after one to two drillings the bit is worn out.
- Maximal four deflections are possible at one horizontal level (7 inch casing), otherwise the drilling of the side tracks would wash out the cement or formation close to the casing which would lead to a loss of feeding rate for the jetting.
- The diameter of the jetted holes (approximately 5 cm) is limited by the size of the nozzle and the intensity of the jet.
- A measurement or control of the side tracks (azimuth or inclination) is not possible.
- If the tubing line is not fixed during the operation it is not possible to insert the nozzle exactly into the hole in the casing. The reason is that the line might contract in the event of a circulation of warmer or colder fluids.
- The maximal pressure of the high pressure pump limits the length of the Coil Tubing (the loss of pressure increases proportional to the length of the Coil Tubing) and the pressure impacting on the nozzle.
- The pressure inside the jetting hose during the jetting works limits the flexibility of the hose and thus causes a significant increase of the friction losses (Newtonian friction by contact and a kind of Euler's rope friction during deflections).

- The weight on the bit is limited by the stiffness of the hose above the motor. If there is too much weight on the bit a standstill can occur respectively the bit can get stuck. If there is too little weight on the bit the casing mill can not penetrate the casing.
- It is not possible to mill the Casing couplings. Thus a GR-CCL correlation has to be carried out before the milling job in order to detect the casing couplings.
- The thickness respectively the height of the formation to be jetted has to be greater than or equal 1 m in order to successively apply the Radial Drilling Technology.
- The Radial Drilling Technology is not to be used for formations with a high portion of clay (limit at 50 %). Especially in combination with high water production it is not advisable to use the Radial Drilling Technology.

4 Hydro-Jetting

This chapter deals with the two major effects of the hydro jetting, the penetration effect and the pull effect. The configuration of the button nose nozzle which ought to jet into the formation by means of water jet energy is also mentioned in this chapter. The above mentioned effects are explained whereas the nozzle configuration is illustrated by means of figures. Furthermore the pressure losses inside the Coil Tubing are discussed.

4.1 Mechanism of Hydro jetting ^[9]

The mechanism of hydro jetting consists of two effects:

- Penetration Effect
- Pull Effect

The penetration effect is responsible for the rock and granules being torn and washed out of the formation and thus allowing for the nozzle to be able to drive further into the formation. The pull effect on the other hand is meant to ensure that the nozzle possesses enough shear force in order to move forward towards the heading face.

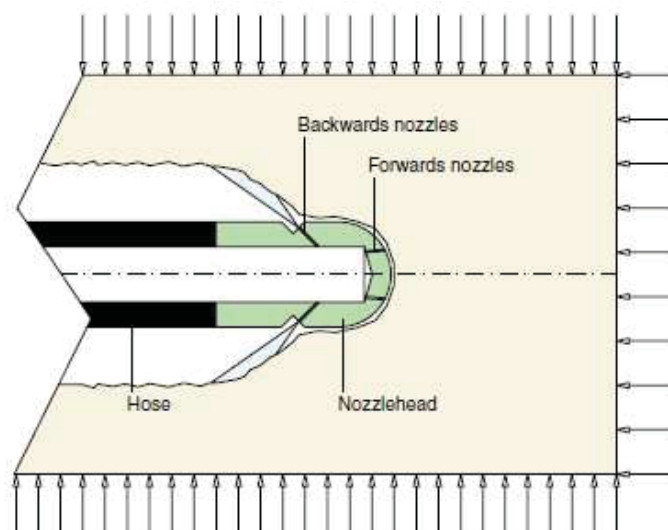


Figure 19: Sketch of the nozzle ^[9]

4.1.1 Penetration Effect

First the penetration effect, which consists of the following four mechanisms, should be dealt with:

- Surface Erosion
- Hydraulic Fracturing
- Poroelastic tensile failure
- Cavitation

Surface Erosion:

Surface Erosion is a mechanism where rock fragments are removed from the surface of the rock due to the shear and compression forces exerted on the rock surface due to the jetting flow, the jetting hose and the nozzle. It is indeed proved that this mechanism exists, yet its effectiveness is quite low.

Hydraulic Fracturing:

At its stagnation point the water jet builds up a very high pressure which diffuses into the formation and the sandstone granules. If the pressure is higher than the resistance which holds the rock together, it tears out granules from the formation. This mechanism lasts only as long as the permeability is high. The cracks that are created with this method are not very large as the diffusion surface does not exceed the surface of the water jet section.

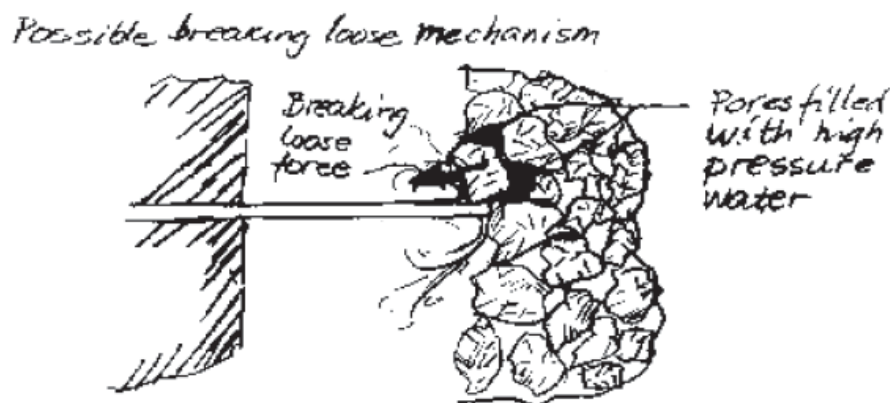


Figure 20: The hydraulic Fracturing mechanism ^[9]

Poroelastic tensile failure:

Due to a rapid decrease in pressure, caused by the high speed of the jet, a vacuum in contrast to the ambient pressure develops at the heading face. This causes proportional tensile stress at the heading face which – given that the differential pressure is higher than the bonding strength of the rock – tears granules out of the formation. The tensile stress is the reason for the compressibility of the rock granules and the pore fluid being not equal. Because of the shift of the equilibration the fluid flows through the pore space. This effect is very important for low permeable (1 mD) formations.

Cavitation:

As the nozzle outlet speed is enormously high Cavitation is likely to occur at certain spots in the water jet. This means that the pressure decreases below the vapour pressure and vapour bubbles build up which move together with the water jet. In the event of the water jet reaching areas of higher pressure the bubbles implode and shock waves build up which affect the formation by means of shock waves and additional tensile stresses.

4.1.2 Pull Effect

The pull effect which is meant to create the net forward thrust of the nozzle consists of three main mechanisms:

- The under pressure force
- The jetting force
- The ejector force

The under pressure force:

The under pressure force mechanism means that the nozzle is driven forward by means of a vacuum which is created at the tip of the nozzle. The vacuum – which equals the difference of the surrounding pressure p_o and the static pressure p_{stat} – is created by the high speed v_r of the fluid between the gap h . The smaller the gap h (distance between the nozzle and the heading face) the higher gets the fluid velocity v_r and the lower the static pressure p_{stat} . This means the

vacuum increases, thus the nozzle is sucked towards the heading face and the pulling force rises. The next figure is intended to explain this mechanism in more detail. Furthermore it is worth mentioning that this mechanism occurs only at the forward jets but not at the rear jets. In order to activate the mechanism the gap h has to be already very small ($h < 0,5 \text{ mm}$) which is provided by the jetting force.

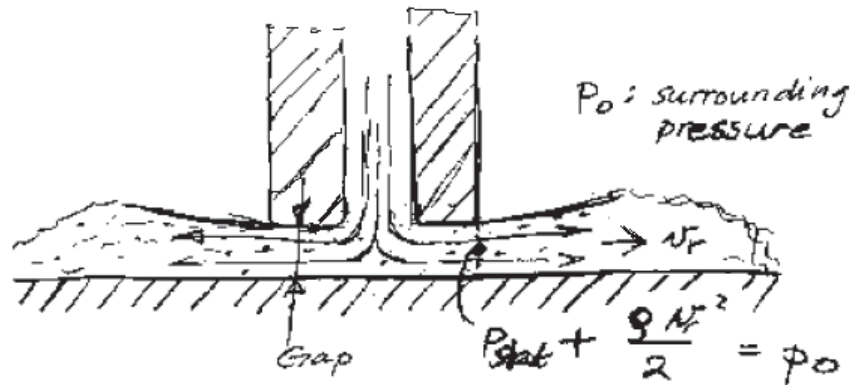


Figure 21: The under pressure force mechanism ^[9]

The under pressure mechanism is all the stronger the higher the surrounding pressure or back pressure. This means that for jetting tests which are carried out on surface (back pressure 1 atm) the under pressure force is significantly lower than subsurface (the back pressure is equal to or higher than the reservoir pressure).

The jetting force:

The jetting force is the result of the impelling forces of the rear jets which work on the lateral heading face. The impelling force that a rear nozzle creates equals the product of the mass flow (flowing through the orifices) and the exit velocity. It must be pointed out that the mass flow is proportional to the circulated volume flow rate of a nozzle and that the exit velocity decreases significantly according to the distance of the nozzle exit when exposed to air or in the ambient medium. If the nozzle is jetting a round shaped track it can be said that the jetting force is all the higher the narrower the track.

The ejector force:

The ejector force is based on an ejector effect which is created by the rear nozzles and sucks away the water from the front part of the nozzle. This effect causes low pressure in front of the nozzle head and thus supports the forward thrust and the under pressure force.

4.2 Nozzle configuration ^[21]

The button nose nozzle proved to be suited best for the hydro drilling. It possesses a nozzle jacket and an internal screw thread at the back. The most popular nozzle for Radial Drilling jobs with 5 cm lateral diameter are the 1/8 NPT button nose nozzles. The nozzle is screwed onto a port connection which is fixedly connected with the jetting hose. The nozzle possesses both forward and rear orifices. The task of the forward orifices is the ablation of the heading face whereas the rear orifices provide the drive of the nozzle.

The literature research produced the best ratio of forward and rear thrust to be 2/1. For this purpose 3 or 5 rear orifices (angle 35° to 45° to the horizontal) and 3 to 4 forward orifices (one or no orifice with an angle of 0° and 3 or several orifices with an angle of 15° to 25° to the horizontal) should be drilled into the nozzle. The larger the angle of the orifices the fewer thrust (rear or forward) the nozzle possesses and the more easily it washes out inside the lateral well. If the rear angle is too small there is a risk of the rear jet meeting the rear groove and thus energy is lost. On the other hand if the forward jets have a too small angle it is likely that the nozzle isn't cutting free enough at the tip and thus might be hindered by the remaining heading face.

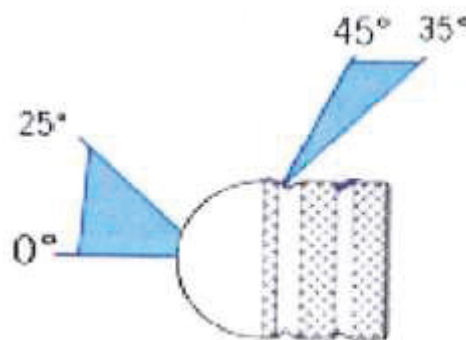


Figure 22: Spray pattern for a typical Hydro Drilling Button Nose Nozzle ^[21].



Figure 23: Left: Button Nose Nozzle for Hydro Drilling ^[8]; Right: Nozzle in action ^[8]

The rear orifices can be drilled in one of two grooves. It is better to use the forward groove for the rear orifices (see figure 23.) as the rear jets are thus placed farther from the armature.

Concerning the design of the nozzle it has to be kept in mind that it is configured for a flow rate of 12 to 15 lpm at pressures of 250 bar. The nozzles feature orifices of different sizes in order to fulfil the flow rate and pressure. Furthermore it is important to make sure that the jet speed at the exit of the orifice does not reach sonic velocity (1.519 m/s for water).

Table 1: Example for Nozzle configurations of Radial Drilling jobs.

Type	rear			forward			forward		
	number of orifice	angle degree	orifice size inch	number of orifice	angle degree	orifice size inch	number of orifice	angle degree	orifice size inch
BN12C(FR)-1/3(15°Ø16)-3028	3	35	0,028	3	15	0,016	1	0	0,016
BN12C(FR)-1/3(15°Ø16)-5022	5	35	0,022	3	15	0,016	1	0	0,016
BN12C(FR)-1/3(15°Ø16)-4025	4	35	0,025	3	15	0,016	1	0	0,016
BN12C(FR)-0/3(15°Ø18)-5022	5	35	0,022	3	15	0,018	0		
BN12C(FR)-0/3(15°Ø18)-3028	3	35	0,028	3	15	0,018	0		
BN12C(FR)-0/3(15°Ø18)-4024	4	35	0,024	3	15	0,018	0		
BN12C-1/3(15°)-5	5	35	0,023	3	15	0,017	1	0	0,017

A rough layout of the jetting force for a nozzle can be seen in figure 24. The calculation of the jetting force is based on the principle of linear momentum. The jetting force is the product of the mass flow and the jet velocity.

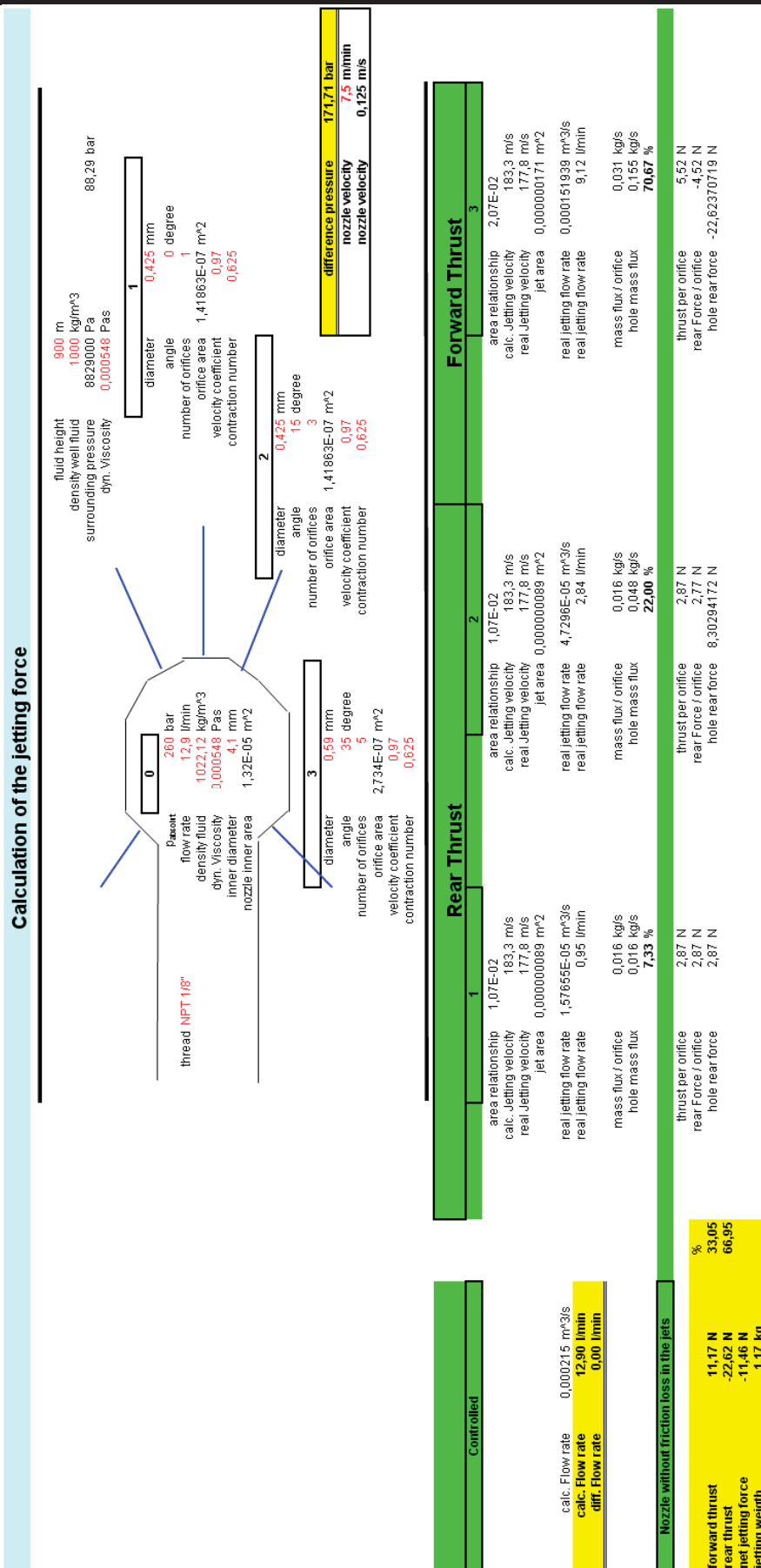


Figure 24: Calculation of the jetting force of a Radial Drilling nozzle.

The nozzle has to produce enough pulling force in order to pull the jetting hose into the formation. Figure 25. shows the three main weights that accrue during the jetting. The lifting weight is the only one to reduce the overall weight and thus lowers the pulling force.

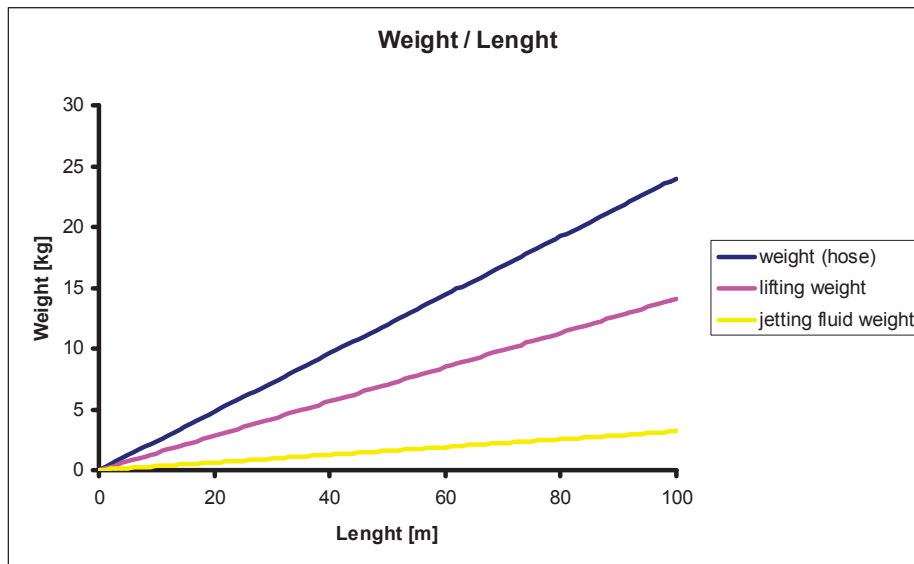


Figure 25: Diagram for hose, lifting and jetting fluid weight.

Figure 26. depicts the ration of the overall weight, working on the hose, and the pulling force which is alleviated by the frictional coefficient. The nozzle ought to have a net pulling force under full load of equalling 2 kg or 20 N.

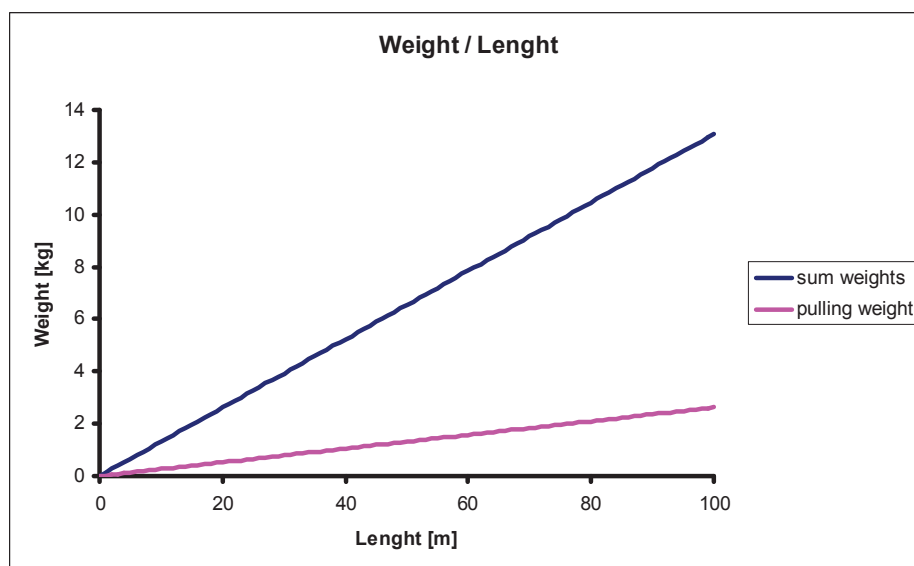


Figure 26: Diagram for pulling weight and sum of weights.

5 Radial Drilling Program

This chapter deals with the data and parameter analysis of the Rohöl- Aufsuchungs AG Radial Drilling jobs. The jobs were carried out by the companies ITAG, Coil Services and Radial Drilling Services. Furthermore the chapter contains an exemplar program of a Radial Drilling job.

In order to analyse the Radial Drilling Technology and write the Radial Drilling Program the following data sources have been used:

- Work-over reports of all three wells
- Radial Drilling work-over program of all three wells
- Analysis Report from Coil Services for the well Sonde 1 (10 diagrams of the runs for 4 laterals)
- Notes from Thomas Wöhrer for the job at the well Sonde 1
- Radial Drilling program of the company Radial Drilling Services
- Coil Services Radial Drilling Program for Sonde 1 and Sonde 3

5.1 Data Analysis of the wells Sonde 1, Sonde 2, Sonde 3

For reasons of space saving not all data and analysis are quoted here. Merely an excerpt from the data analysis of the well Sonde 1 and the final results will be given.

Figure 27. depicts the milling job of the fourth lateral which was the last one. During the insertion of the Coil Tubing into the well the coil had to be decelerated two times in order to avoid running it in too fast. During the whole insertion process no fluid was circulated into the coil. When the Radial Drilling depth was reached, the insertion process in the deflector shoe began, which was carried out successfully. The milling works begin and the pressure rises. It is crucial that the weight on bit is higher at the beginning of the milling job.

If the WOB is augmented automatically the pressure rises as the required milling torsional moment increase. During the exertion of the milling bit it got stuck once, pressure fell for a moment just to rise again. Additionally the pulling weight of the injector head increased significantly. After the exertion of the milling bit, the pump was shut off and the Coil Tubing was exerted.

Explanation of diagram (see figure 27.):

Corrected Depth [m]: Is the length which is inserted from the Coil Tubing.

Weight [kg]: Is the weight which has to be held by the injector head in order to prevent the Coil Tubing from running further into the well. If the WOB is increased the weight that is displayed here decreases.

Circulating Pressure [bar]: Is the pressure created by the high pressure pump on surface which pumps the fluid into the Coil Tubing. The working pressure of the nozzle, or the Downhole screw motor is substantially lower as the pressure loss in the coil (function of velocity, Coil Tubing length, pipe roughness, Coil Tubing diameter, fluid viscosity and density). The pressure loss of the Coil Tubing uses up a great deal of the created pressure of the pump.

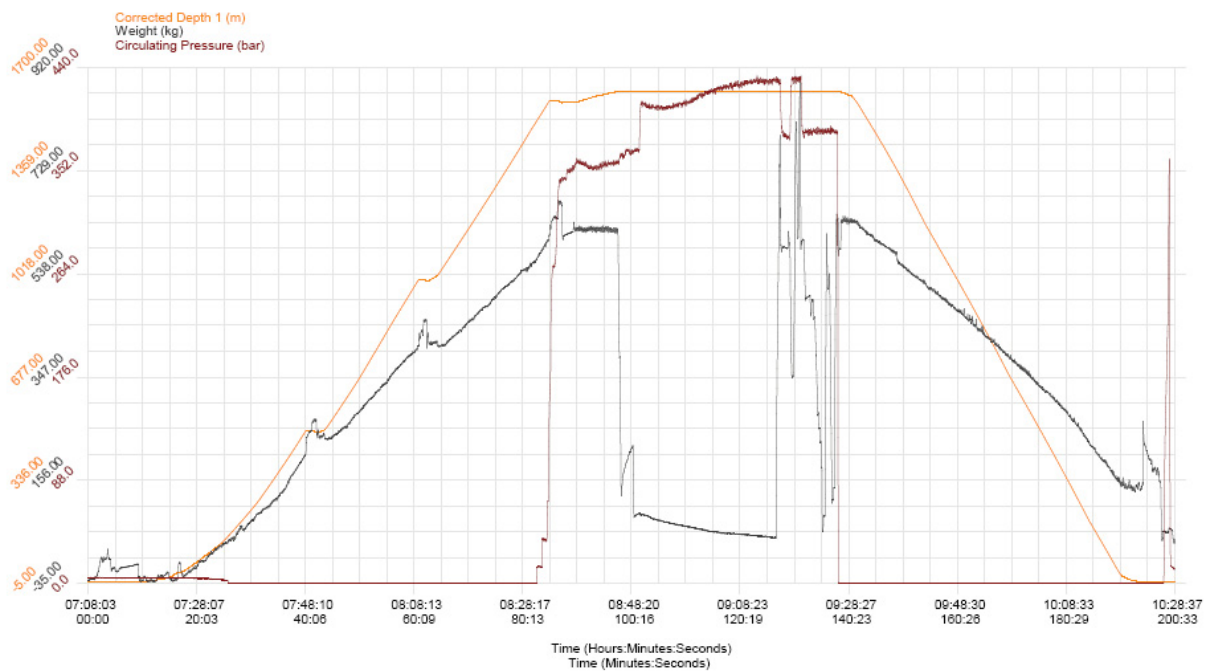


Figure 27: Diagram Sonde 1, Run 9, Milling.

Figure 28. shows the jetting job of the second lateral. Before the insertion of the Coil Tubing the nozzle was tested for functioning on surface. During the run-in process fluid was constantly pumped into the coil in order to avoid a vacuum inside the coil. Again the Coil Tubing had to be decelerated several times in order to avoid running it in too fast. After a successful insertion process in the deflector shoe the pressure respectively the flow rate is increased and the jet-in begins. During the jet-in process the weight on nozzle slightly decreases as the Coil Tubing is inserted further and further. As soon as the maximum lateral depth is reached the flow rate and thus the pressure have to be increased and the hose pulled out. By pulling the nozzle out a significantly higher tensile load on the injector head accrues. This is when the jet-out begins. During the exertion the tensile load for the coil is lower. After the jet-out the circulation of the fluid is terminated and the Coil Tubing together with the hose and the nozzle is exerted.

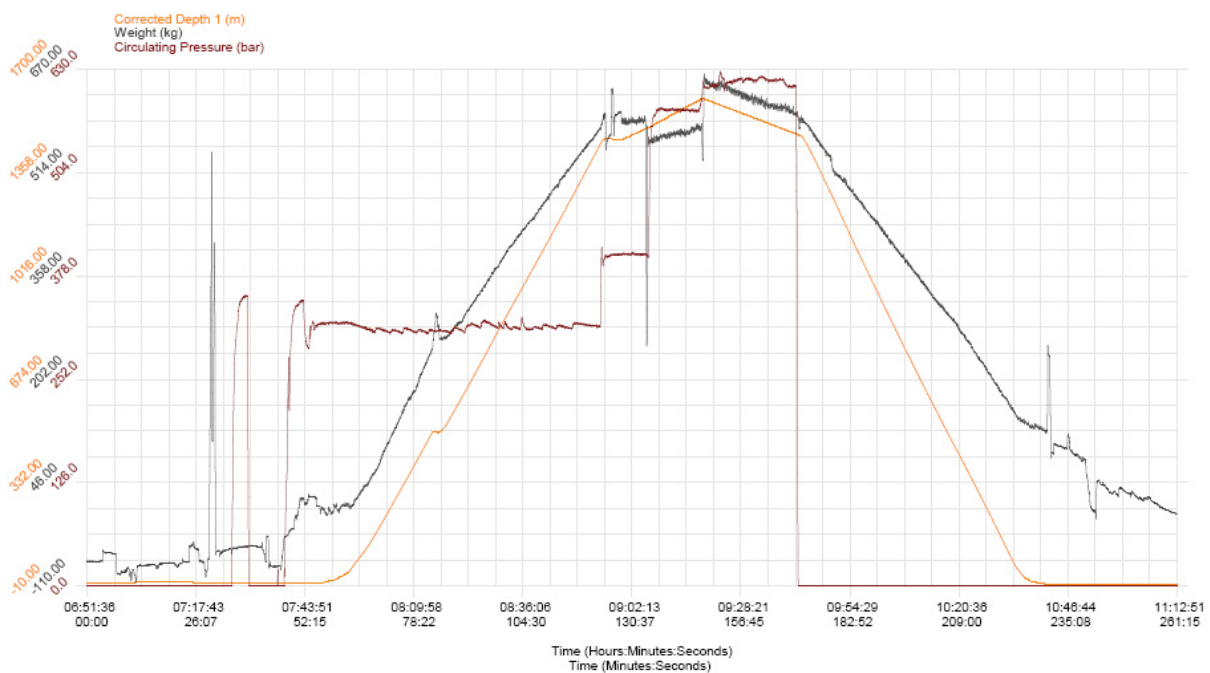


Figure 28: Diagram Sonde 1, Run 5, Jetting-in and -out.

The following three tables (see Table 2. & 3.) show a recapitulation of all important parameters and results of the jetting and milling runs of the well Sonde 1.

Radial Drilling Program

Table 2: Parameter analysis of runs 1 to 10 with 4 laterals of the well Sonde 1.

Lateral	Run	Operation	Note	Depth [m]	min (milling) in (jetting)		max (milling) out (jetting)		before (milling) before (jetting)		time			jet depth m	progress of jetting in		total volume	
					Pressure bar absolut	bar absolut	Pressure bar absolut	bar absolut	Pressure bar absolut	bar absolut	min in [sec]	jet in [sec]	jet out [sec]		m/min	jetting in	jetting out	l
	1	drill	Shoe is not in pos., POOH	1591,8	337						78							
1	2	drill		1591,8	407	547					22	20		94	4,27		1250	
1	3	jet	depth sensor defect	1595	316	385					59							
2	4	drill		1595	580	614					23	21		98	4,26		1610	
2	5	jet		1603,8	233	462												
	6	drill	flexible shaft broken	1602,5	408	347					52							990
3	7 a&b	drill	seperated data	1602,5	341	379						16	21	100	6,25		1250	
3	8	jet		1604,1	369	418					53							1050
4	9	drill		1604,1	549	606						18	23	99	5,50		1720	
4	10	jet																

Lateral	Run	Operation	Note	jetting in flow rate l/min	jetting out flow rate l/min	milling flow rate l/min
	1	drill	Shoe is not in pos., POOH			
1	2	drill		15,8	15,6	0,0
1	3	jet	depth sensor defect	0,0	0,0	21,3
2	4	drill		0,0	0,0	0,0
2	5	jet		11,4	10,2	0,0
	6	drill	flexible shaft broken	0,0	0,0	18,9
3	7 a&b	drill	seperated data	16,3	0,0	0,0
3	8	jet				
4	9	drill				
4	10	jet				

Radial Drilling Program

Table 3: Summary of the Data and Parameter Analyse of Sonde 1.

Data and Parameter Analysis:					
Drillen	flow rate range	5 to 5,8	gal/min	18,9 to 22	l/min
	flow rate average	5,5	gal/min	20,9	l/min
	pressure range	4588 to 6066,8	psi	316 to 418	bar
	pressure average	5453	psi	376	bar
	drill time range	52 to 78	min		
	drill time average	60,5	min		
Jetten in	flow rate range	3 to 4,3	gal/min	11,4 to 16,3	l/min
	flow rate average	3,8	gal/min	14,5	l/min
	pressure range	4949 to 8540	psi	341 to 588	bar
	pressure average	6810	psi	469	bar
	jet time range	16 to 23	min		
	jet time average	19,75	min		
	velocity local	7 to 8	m/min		
	velocity job average	5,1	m/min		
Jetten out	flow rate range	2,7 to 4,12	gal/min	10,2 to 15,6	l/min
	flow rate average	3,41	gal/min	12,9	l/min
	pressure range	4500 to 9130	psi	310 to 629	bar
	pressure average	7786	psi	536	bar
	jet time range	20 to 23	min		
	jet time average	21,25	min		
	velocity local	5 to 6	m/min		

Table 4. shows a well completion of a stimulated well of the Rohöl- Aufsuchungs AG. The aim was to jet four laterals, each at different depths and angles, into an already perforated area of the well. Concerning was a gas producing well with an inclination of 32°. For such heavy inclinations it is necessary to measure the azimuth of the deflector shoe beforehand by means of a gyroscope in order to avoid loosing direction (up vs. down) and thus jetting the wrong formation.

Table 4: Well completion for the Radial Drilling job for well Sonde 2.

<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>E-Kreuz: 3 1/8" 5M Flansch: 7 1/16" x 3 1/8" 5M</p> <p>Neigung: KOP: 610 m Aufbau auf 32° bis 980m dann konstant 32° bis Endteufe</p> <p>9 5/8" Csg 40 lbs/ft, J-55 bis ca. 595,9 m MD (595,9m TVD)</p> <p>Perforationen: 1161.5 – 1164.0m (2.5 m) 1166.0 – 1169.5m (3.5 m) 1170.5 – 1174.0m (3.5 m) 1177.0 – 1179.5m (2.5 m)</p> <p>7" Csg 23 lbs/ft, L-80 bis ca. 1760 m MD</p> </div> <div style="width: 45%;"> <p>Zementkopf: 350 m It. Bohrbericht</p> <p>geplante Radial Drilling per wartet = 125 bar</p> <p>1168,0 m MD (= 1108,4 m TVD) 1172,0 m MD (= 1111,8 m TVD) 1177,5 m MD (= 1116,4 m TVD) 1178,0 m MD (= 1116,8 m TVD)</p> </div> </div>		<div style="display: flex; align-items: center;"> <div> <p>Einbaudaten</p> <p>Länge: eingebaut (bzw. Teufe) bis (m)</p> </div> </div>	
		6" x 10" x 2 7/8" EU Tbg Hänger geteilt (rechts Gewinde)	0,17
2 7/8" EU Doppelnippel	0,19	0,36	
2 7/8" EU Kurzstücke (0,52 m)	0,52	0,88	
2 7/8" EU Kurzstücke (0,78 - 1,93 - 2,92 m)	5,63	6,51	
2 7/8" EU Kurzstücke (1,48 - 1,48 - 1,48 - 2,92 m)	7,36	13,87	
121 Single 2 7/8" EU Tubing, 6.5 lbs	1150,43	1164,30	
1. Loch => 93 m => bei 1169 m, AZI 312°			
2. Loch => 97 m => bei 1172 m, AZI 120°			
3. Loch => 96 m => bei 1177,5 m, AZI 316°			
4. Loch => 88 m => bei 1178 m, AZI 132°			
7" Tubinganker (neutral als Abstützung) 2792/102	0,71	1165,01	
2 7/8" EU Kurzstück	1,33	1166,94	
UBHO (2 7/8" EU M x 2 3/8" EU Z)	0,56	1167,50	
1 Single 2 3/8" EU Tubing	9,29	1176,79	
Deflector shoe	1,28	1178,07	

RDT at the well Sonde 3 (Oct. 2008):

The well Sonde 3 is an oil producing well which was drilled in 2002. The well shows after threefold perforation merely little productivity. The function of the technology should be demonstrated with this well. As the portion of asphalt's and paraffin's is very high, an efficient production is not possible. The borehole shows an inclination of 24° in the area where the Radial Drilling job is meant to be conducted. The height respectively the thickness of the layer which is to be jetted is about 20 m. A positioning by means of a gyroscope is not intended as there are no requirements concerning the azimuth of the laterals and there is no risk of damaging the layers above or beneath. Four laterals were jetted in different depths (depth 1.860,5 to 1.864,5 m), each shifted by 90°. The well is completed with a 7" casing in this depths. The upper perforation possesses the best reservoir qualities. Before the Radial Drilling job the fluid level was at 178 m, the tubing pressure amounted to 10 bar and the casing pressure to 1 bar. The expected reservoir pressure came up to 154 bar.

Well data:

Fluid level:	178 m
Tubing pressure	10 bar
Casing pressure	1 bar
Expected reservoir pressure	154 bar
Borehole inclination	24°
Layer thickness	20 m
Casing	7 inch
Depth	1.860,5 to 1.864,5 m

RDT at the well Sonde 1 (Mar. 2009):

The well Sonde 1 is an oil producing well of around 30 years of age which shows both a low permeability (high skin presumed) and productivity. The portion of paraffin's of this well is very high. The Radial Drilling Technology is meant to enlarge the drainage radius. With the help of Radial Drilling Technology the productivity should be increased by drilling through the damaged zone. The well is drilled vertically and a positioning via gyroscope is not necessary as there are no requirements concerning the direction of the laterals. Four laterals were jetted at this well (depth of 1.591,8 to 1.604,3 m) in different depths and each shifted at 90°.

The well is completed with a 7" casing at this depth. The dynamic fluid level was at 1.516 m before the Radial Drilling job; the tubing pressure amounted to 5 bar and the casing pressure to 4 bar. The expected reservoir pressure came up to 67 bar.

Well data:

Fluid level:	1.516 m
Tubing pressure	5 bar
Casing pressure	4 bar
Expected reservoir pressure	67 bar
Casing	7 inch
Depth	1.591,8 to 1.604,3 m

RDT at the well Sonde 2 (Apr. 2009):

The well Sonde 2 is a gas producing well which was drilled in 2008. The Radial Drilling Technology was intended to enlarge the drainage radius respectively the drainage area and thus detect additional reservoirs respectively compartments. The permeability amounts to 2 mD in the Radial Drilling area. The borehole features an inclination of 32° and therefore a positioning by means of a gyroscope is necessary in order to meet the requirements concerning the direction of the laterals. At this well four laterals (depth of 1.169 to 1.178 m) were jetted in different depths according to the predetermined azimuth. Again a perforated 7" casing is already positioned in this depth. The expected reservoir pressure came up to 125 bar.

Well data:

Borehole inclination	32°
Expected reservoir pressure	125 bar
Casing	7 inch
Depth	1.169 to 1.178 m
Permeability	2 mD

5.2 Radial Drilling Program including parameters

The following Radial Drilling program has been developed for the Rohöl- Aufsuchungs AG in future for Radial Drilling jobs. Therefore it is written in German to use it in future as an exemplar program.

Langfristige Vorbereitungsarbeiten:

- XXXX m neue XX“ EU XX lb/ft Tubinge antransportieren.
- Coil Service und notwendiges Equipment organisieren.
- Hochdruckpumpe mit Zulaufpumpe und Transferpumpe zwischen den Tanks bereitstellen.
- 800 L (für vier Löcher) Butylglykol organisieren und antransportieren (dem 2 % igen KCl Wasser werden 5 % Butylglykol beigemischt). Dieses Fluid wird nur für das Jetten verwendet.
- Für 4 Löcher werden cirka 3 m³ für Drucktests und cirka 10 m³ Flüssigkeiten fürs Milling (4.000 L) und Jetting (6.000 L) benötigt.
- Kontrolle ob GR-CCL vorhanden ist. Wenn keine Messung vorhanden ist. Messung einplanen und Position der Casing Muffen feststellen.

Unmittelbare Vorkehrungen:

- Entsprechende Anzahl bzw. notwendige Längen an Tubing Kurzstücken bereithalten für die einzelnen Runs.
- Generator zur Stromversorgung bereitstellen.
- Arbeits-Tank bereitstellen.
- 2 weitere Tanks für die Fluids bereitstellen: einen mit 2 % KCl- Wasser Lösung fürs Millen und einen mit Butyl Glykol fürs Jetten.
- Milling und Jetting Equipment antransportieren.
- CNG bereitstellen.

Zu Beachten:

- Den Deflector shoe (vor allem den Kanal), das Milling Equipment (Bohrer, Momentenstütze und Kardanwelle) und das Jetting Equipment (Düse und den Schlauch) vor dem Gebrauch Schmierfett auftragen.
- Tank der Behandlungspumpe säubern.
- Bevor die Flüssigkeit aus einem Arbeits-Tank von der Hochdruckpumpe angesaugt wird, muss sie gefiltert werden.
- Im Arbeits-Tank wird das Butyl Glykol dem KCl- Wasser vorm Jetten beigemischt.
- Notwendige Abnahmen laut WEG (Coil Tubing Zug und Drucktest durchführen).
- Spiegelmessgerät bei den Arbeiten ständig bereit halten (mit Stickstoffflasche, da die Sonde keinen Druck hat).

Radial Drilling Arbeiten:

1. Drücke kontrollieren und notieren. Spiegel schießen.
2. Anlage aufbauen.
3. Gegebenfalls Druck ablassen.
4. Produktionseinrichtung, E-Kreuz demontieren, eventuell Perdekopf abbauen und Pumpe freiziehen.
5. Pump-Gestänge ausbauen und ablegen.
6. Sonde auffüllen und mit 2 % iger KCl –Wasser Lösung sauber zirkulieren. Gegebenfalls Pille verwenden.
7. Restliche Obertageeinrichtung und Tubing Head Adapter demontieren, Preventer montieren (Funktionstüchtigkeit überprüfen).
8. Sohle mit Tubing abtasten (Teufe notieren) und versuchen mindestens bis XXXX m (Radial Drilling Teufe & erforderlicher Sumpf => 2 L Austrag pro 1 m gejetteten Loch) zu zirkulieren. Tubinge ausbauen und zugweise in den Turm stellen. (Falls tiefer zirkulieren nicht möglich ist – muss ein eigener Trip mit einem XX“ Rollenmeißel vor der Scraperfahrt eingeplant werden).

9. Mit X“ Scraper (inklusive XX“ Rollenmeißel) am XX“ Tubing einbauen. Tiefe der Sohle notieren.
10. Sohle bis genau XXXX m (Radial Drilling Teufe + erforderlicher Sumpf) sauber zirkulieren. (ca. 2 Umläufe zirkulieren).
11. Sonde mit CNG bis ca. XXX m ausliften, sodass ungefähr Druckausgleich (ca. +20 bar Overbalanced) zwischen Lagerstätte und Behandlungsflüssigkeit herrscht.
12. Strang ausbauen und zugweise in den Turm stellen.
13. GR-CCL Messung durchführen wenn keine vorhanden ist.
14. Deflector shoe mit Tubing Kurzstück und Centralizer aufnehmen und am neuen XX“ Tubing bis XXXX m einbauen (knapp unterhalb der Radial Drilling Teufen). Zirka 9,3 m (ein Single Tubing) oberhalb des Deflector shoes soll ein XX“ Anker in den Strang eingebaut werden. Um Drehmomente welche durchs Einfahren des Tubings entstanden sind zu vermeiden, sollte man den Strang vor dem fixieren des Ankers ein paar Mal anheben und absenken.
15. Schlumberger aufbauen und GR-CCL Korrelation durchführen, Schlumberger abbauen. Es ist darauf zu achten, dass das Loch nicht in der Höhe einer Casing Muffe gebohrt wird.
16. Tubing Strang so ausgleichen, dass das oberste Loch bei XXXX m gebohrt werden kann. Anker setzen, Drehung des Deflector shoes (nach Gefühl oder wenn vorgegeben mittels Gyro Messung positionieren) in den Azimut. Tubing Strang am Tubing Hanger absetzen.
17. Preventer demontieren, Drilling Spool mit seitlichem Anschluss auf Tubing Head montieren, Übergang, Schieber und Preventer von Coil Service montieren. (Im Tubing Hanger wird ein bereits eigens angefertigtes Kurzstück eingeschraubt, damit bei einem eventuellen Festsitzen des Jetting Schlauchs und des Coil Tubings der Elevator dort eingehängt werden kann).
18. Capillary Unit (mit ½“ Coil) mit notwendigen Sicherheitseinrichtungen (Preventer, Injector Head, Goosneck etc.) aufbauen, Drucktests (675 bar, 10.000 psi) und Zugtest (3.000 lb, 1.360 kg) mit dem Coil Tubing machen.

19. Schieber schließen und Preventer mit Wasser auffüllen und mit 50 bar abdrücken (Protokoll führen).
20. Milling und Jetting Equipment auf Funktion prüfen. (Jetting Schlauch 5 min lange mit 6 L/min durchzirkulieren, Downhole Motor muss sich bei 11 L/min drehen, Bohrtiefe des Bohrers kontrollieren und wenn notwendig so einstellen, dass der Bohrer das Casing durchbohrt).
21. Equipment für Casing Mill (Bending hose, Downhole Motor, Momentenstütze, Kardanwelle und Bohrer) am ½“ Coil montieren und mit 20 m/min in das Tubing einfahren. Während des Einfahrens regelmäßig Flüssigkeit in das Coil Tubing einpumpen. Zirka 100 m über dem Deflector shoe die Einfahrtgeschwindigkeit auf 10 m/min drosseln.
22. Für den Milling job wird die 2 % ige KCL Wasser Lösung verwendet (circa 1.000 L pro horizontalem Loch).
23. Wenn das gemessene Zuggewicht des Injectors abfällt, Coil stoppen (Tiefe des Deflector shoes erreicht). Coil Tubing leicht ausfahren bis Zuggewicht steigt (Gewicht und Tiefe aufzeichnen).
24. Pumpendruck aufzeichnen, kontrollieren ob Bohrer auch wirklich am Casing anliegt und nicht am Deflector shoe Eingang zu Stillstand gekommen ist, (während das Zuggewicht sinkt, sollte der Pumpendruck steigen).
25. Anfangs mit einem Volumenstrom von 9,5 L/min bis 11,4 L/min den Downhole Motor antreiben; später auf 18,9 L/min bis 22 L/min erhöhen (Mittelwert Milling Volumenstrom 20,9 L/min) und das Casing anfräsen. Downhole Motor Drehzahl 200 bis 225 U/min.
26. Die Bohrdauer kann variieren zwischen 30 und 90 Minuten je nach Zustand des Casings. WOB 27 kg bis 81 kg, Pumpendruck Obertags 316 bar bis 418 bar, Mittelwert 376 bar.
27. Falls der Bohrer in einem Perforationsloch festsitzt, Milling Equipment ziehen, Deflector shoe 15 cm höher oder tiefer setzen und fortfahren.

28. Wenn der Pumpendruck abfällt, Zirkulation einstellen, Coil markieren, Tiefe notieren und Casing Mill ausfahren.
29. Flansch zwischen Injector Head und Preventer lösen und Injector abheben. Milling Equipment ablegen, auf Funktion testen und Jetting Equipment (Düse und Schlauch) verschrauben. Jetting Equipment vorsichtig in den Preventer einführen und Injector Head wieder am Preventer befestigen.
30. Für den Jetting job wird die Butyl Glykol- KCL Wasser Lösung verwendet (1.500 L pro horizontalem Loch).
31. Jetting Equipment am Coil mit ca. 20 m/min einfahren, Spiegel schießen, während des Einfahrens 7,5 L/min Flüssigkeit mit 200 bar Pumpendruck in das Coil Tubing einpumpen (verpumptes Volumen festhalten). Zirka 100 m über dem Deflector shoe die Einfahrtgeschwindigkeit auf 10 m/min drosseln.
32. Schlauch in den Deflector shoe einfädeln (muss die Milling Tiefe vorher erreichen, Achtung Milling und Jetting Equipment haben unterschiedliche Längen).
33. Wenn der Einfädelvorgang erfolgreich war, Zuggewicht aufzeichnen, Coil markieren und Pumpendruck aufzeichnen.
34. Um den Widerstand am Beginn der Jetting Arbeiten zu überwinden der Druck vorzeitig gemindert werden.
35. Mit Jetting Arbeiten beginnen und Volumenstrom auf 14,5 L/min erhöhen. (Volumenstrom von 11 L/min bis 15,6 L/min). Pumpendruck auf 469 bar einstellen (von 341 bar bis 588 bar).
36. Falls es zu einem Druckabfall während des Jettens kommt, den Bohrfortschritt bzw. Vorschubgeschwindigkeit reduzieren.
37. Die Düse soll beim Jetten einen konstanten Schub (einstellbar über die Vorschubgeschwindigkeit) aufweisen, welchen man am Zuggewicht des Coil Tubing messen kann.
38. Falls es zu einem plötzlichen sehr hohen Druckanstieg kommt und kein Vortrieb zustande kommt, ist wahrscheinlich eine Düse verstopft. Einpumpen beenden, Equipment ausfahren und Schaden beheben.

39. Der Jetting-in Vorgang kann 10 bis 25 min dauern und ist abhängig von der Festigkeit der Formation.
40. Vorschub des Coils stoppen, wenn der Schlauch die maximale Radial Drilling Tiefe erreicht hat oder von selbst stoppt (z.B. in eine Kaverne gejettet).
41. Beim Herausziehen der Düse, den Volumenstrom erhöhen auf 12,9 bis 15,6 L/min um das Loch im Durchmesser zu vergrößern. Ausfahrgeschwindigkeit 2 bis 5 m/min. Pumpendruck auf 536 bar einstellen (von 379 bar bis 629 bar).
42. Der Jetting-out Vorgang kann 20 bis 50 min dauern. Die Dauer ist abhängig von der Festigkeit der Formation.
43. Wenn die Düse den Deflector shoe passiert hat, Pumpe abstellen, Coil Tubing und Jetting Equipment ausfahren.
44. Verpumpte Flüssigkeitsmenge festhalten.
45. Falls nach dem Jetten eines Side Tracks die Sonde auszirkuliert werden muss, so sollte man die Laterals bzw. deren Casing Löcher mit einem Tool verschließen um nicht Schmutz in die Side Tracks einzuzirkulieren und sie dadurch zu verschließen.
46. Flansch zwischen Injector Head und Preventer lösen und Injector abheben. Jetting Equipment abnehmen.
47. Nach den Jetarbeiten erneut Spiegel schießen. (Abschätzung von ev. zugeflossenen Volumina / verpumpten Volumina) – Stabilität der Sonde beobachten. Dieser Vorgang wird für alle X Löcher wiederholt.
48. Nach Fertigstellung des ersten Loches wird die Position (je nach Plan) in Richtung und Tiefe verändert. Dazu Obertage Equipment demontieren und ablegen.
49. Flansch zwischen Tubing Head (XX“) und Drilling Spool lösen und Tubing XX cm tiefer setzen.
50. Drehung des Stranges (nach Gefühl oder wenn vorgegeben mittels Gyro Messung positionieren) um XX° und den Tubing Strang auf neue Fräs-Teufe abhängen.
51. Nach dem Jetten des 2. Loches, Sohle tasten und gegebenenfalls auf nachfolgende Löcher umrüsten bzw. Strang ausbauen und mit glatten Strang und XX“ Rollenmeißel sauber zirkulieren.

52. Nach Fertigstellung des letzten Radial Drilling Lochs die Capillary Unit abbauen.
53. Sind alle X Löcher gebohrt wird der Produktionsstrang wieder eingebaut.
54. Die Bewertung einer eventuellen Produktionssteigerung erfolgt durch einen Wellchecker - Test nach der Wiederinbetriebnahme.
55. Anlage abbauen und Sondenplatz aufräumen.
56. Radial Drilling Equipment vor Korrosion und Gefrierschäden schützen (besondere Vorsicht ist beim Downhole Motor gegeben).

Sicherheits- und Umwelttechnische Aspekte:

- Vor Übersiedlung der Behandlungswinde Zufahrt und Sondenplatz inspizieren.
- Potentialausgleich sämtlicher mit der Bohrung in Verbindung stehender Geräte herstellen (ITAG, Schlumberger, Coil Services, Kräne...)
- Anrainer in unmittelbarer Nähe des Sondenplatzes sollten vor Aufstellung der Behandlungswinde von den geplanten Arbeiten informiert werden und darauf hingewiesen werden, dass eventuelle Lärmbelastigungen nur kurzfristig auftreten werden.
- Nach Abschluss der Arbeiten muss der Sondenplatz unverzüglich von übergelaufener Spülung, Zement, etc. gereinigt werden. Auf Ordnung und Sauberkeit am Sondenplatz ist während und nach Abschluss sämtlicher Arbeiten besonders zu achten. Außerdem ist dafür zu sorgen, dass nicht mehr benötigtes Equipment umgehend nach Beendigung der Arbeiten abtransportiert wird.
- Vor Slickline- Arbeiten ist eine entsprechende Sicherheitsbelehrung zu machen.
- Sicherheitsunterweisung „Arbeit mit Coil Tubing“ durchführen. Abdrückarbeiten am Coil Tubing Unit laut WEG-Richtlinien durchführen.

6 Prerequisites of potential wells

This chapter deals with the prerequisites a reservoir and a borehole ought to possess as well as with the factors that have to be explored thoroughly in advance in order to carry out a Radial Drilling job respectively in order to evaluate potential candidates.

6.1 Prerequisites of reservoirs ^{[8],[22]}

Basically a reservoir should be chosen which features the possibilities of increasing reserves or increasing production. Therefore possible applications are as follows:

- Gas or oil wells with low permeability and high skin
- Gas or oil wells with new compartments in coaxial position to the well which present new reserves but would be not economic to be drilled from surface.
- Gas storage wells with low permeability
- Injector wells with low permeability or high skin

The reservoir which concerns geology, permeability, mediums and facies ought to feature the following prerequisites:

- The thickness of the oil or gas horizon must not be lower than one metre in order to apply the technology successfully.
- The horizon to be jetted through should not feature high portions of clay. The limit is 50 % and in combination with high water production the appliance of the technology is rendered impossible.
- There should be no water layers or water leading areas in ultimate proximity to the reservoir (check risk with distance to the water leading areas, oil or gas horizon thicknesses and inclination) which could be encountered during the Radial Drilling and thus destroy the well.

- The reservoir sealing layer of the oil or gas leading horizon, which is to be jetted must not allow for the jetting hose to jet through and thus destroy it.
- The horizon should be of sandstone without any conglomerates. Furthermore the sandstone should be little cemented and feature low hardness to enable the nozzle to penetrate into the formation. However the formation must not be too crumbly either in order to prevent the side tracks from collapsing after the job which would mean that increasingly sand would be produced together with the fluids and damage the pumps and valves.
- The whole reservoir should not feature high portions of paraffin's otherwise paraffin's creation is likely to occur after the jetting job or during the circulation of cold fluids which could lead to a blockage of the jetted side tracks with paraffin's. Reservoirs with high local (near by the borehole) portions of paraffin's are useable for the Radial Drilling Technology because the portions of paraffin's beyond the borehole can be very low.
- The oil or gas production should not be too low before the Radial Drilling job as the increase in production averages out at 132 % (world wide experience of a Radial Drilling contractor) and too low pre production would lengthen the pay back period for the Radial Drilling job enormously.
- Radial Drilling jobs in high depth are preferable. The depth of the reservoir must not be too low as the low reservoir pressure might lead to a collapse of the completed side tracks. The toughness of the reservoir is increasing with the depth of the reservoir. Of the toughness of the reservoir is not high enough, the side tracks might collapse.
- The reservoir must not feature a high tendency to creation of water blockage as this would require alternative mediums for the jetting (e.g. diesel, oils of low viscosity and Butyl Glycol).
- Basically it is preferable to dispose of several core samples of the formation to be jetted through in order to judge if it is possible to jet the formation by means of a nozzle.
- The horizon to be jetted through ought not to feature any caverns or fractures otherwise the jet would circulate free. Furthermore the geology respectively the rock has to be preferable homogenous.

The Radial Drilling Technology is suited best for reservoirs which feature the following properties:

- If the formation was reached by the drilling works just on the edge and features a bad facies there.
- If the permeability lies beneath 5 to 10 mD for gas production wells.
- If the drainage radius is to be enlarged and new reserves are expected in radial position near the borehole.
- If the reservoir is damaged in the area of the borehole (e.g. skin, water blockage, and closed pores) and the formation features significantly better permeability and facies outside this area.
- If a reduction of the shock pressures is desired whose origins lie close to the borehole and which are lessened by the Radial Drilling through a enlargement of the drainage.
- If the horizontal permeability K_h of a reservoir is significantly higher than the vertical permeability K_v (see figure 7.). The permeability is dependent on the geological strains. In direction of the maximum strain, the permeability is much higher than the vector of permeability, perpendicular to the maximum strain.
- If the fluid viscosity inside the reservoir is very high.
- If the facies (e.g. permeability and porosity) fluctuate heavily radially around the reservoir.

6.2 Prerequisites of boreholes ^{[22],[4]}

The borehole, containing casing, cementation and borehole form, should meet the following requirements:

- In order to guarantee that the Radial Drilling job is technically feasible the casing has, according to the state of the art, to be at least a 5 1/2" casing.
- The inclination of the well should not exceed 30° in the section of the Radial Drilling.

- Inclined wells (inclination $> 15^\circ$) require the azimuth to be chosen in a way the arrangement of the deflector shoe leads to a well direction of the radial drilled well that is horizontal or inclined to the horizontal $\pm 10^\circ$ at the most (depends on the thickness of the layer).
- When jetting several wells at the same depth it is not advisable to go below an angle of 90° as this could lead to washouts. However radial drilling in differing depths per well (30 cm minimum) is recommendable.
- The tensile strength toughness and hardness of the casing ought not to exceed that of a grade L80 otherwise it is not possible to drill the casing.
- The thickness of the casing must not exceed 11 mm and it has to be avoided to drill any couplings.
- Radial Drilling jobs can be carried out only in section of the borehole which does not feature a second overlapping casing. This means that only one casing is needed which is coated by cement and the formation.
- A dense cementation is required in the area of the Radial Drilling to prevent fluid from leaking between casing and formation. You also need the cementation near by the casing for drilling a little borehole with the milling bit in the cementation or the formation for starting jetting.
- In the area of the Radial Drilling the cementation must not be too dense and the cement not too thick, otherwise the jet is not able to penetrate the formation.
- The sump of the existing well has to be deep enough in order to gather all the cuttings from the jetting job. If the floor is not deep enough it is necessary to circulate the cuttings out during the jobs. For this purpose it is necessary to close the side tracks so that they do not fill up with cuttings.
- There must not be any scaling or paraffin accumulations on the tubing or the casing which could hinder the Radial Drilling job. If there are any accumulations the tubing has to be changed or a scrapper run has to be carried out in the casing.
- It has to be possible to reach the Radial Drilling section inside the borehole by means of the deflector shoe and a 2 3/8" tubing as the area which is to be jetted must not be blocked by formerly completed equipment.

7 The Radial Drilling Equipment

This chapter deals with the equipment that is needed for a Radial Drilling operation and the requirements it has to meet respectively all aspects that have to be considered.

7.1 Surface Equipment

It is very important that the equipment needed for the operations on surface is easy to transport (truck or trailer). Furthermore it ought to be weatherproof and meet the requirements of European Standards. It is also advisable to provide for an external energy supply and a workshop at the well, to allow for workings on the equipment. A generator is one possibility to provide for the energy supply. The different parts of the equipment are discussed in the following.

7.1.1 High pressure pump including drive

The high pressure pump resembles the core of the Radial Drilling Technology. It is creating the necessary flow rate and the pressure that is needed for the jetting and the milling downhole. Usually a piston pump with three pistons and self-controlling valves as well as an oil sump is used for the high pressure pump.

The pump station aspirates the liquids (water or potassium chloride-water dilution optionally with butyl-glycol) from tanks, compresses them and eventually injects them into the Coil Tubing. It might be necessary to install a fore pump (pressure 5 bar, flow rate view high pressure pump) before the high pressure pump in order to suspend Cavitation at the suction side.

The pump can be propelled in two ways:

- Electric motor: electric with an electric converter and a generator or a fix installed energy supply.
- Hydraulic motor: by means of a diesel aggregate and a hydraulic converter.

The electric motor is very quiet, does not take up much room, is very cost efficient, does not create any direct emissions and the flow rate can be controlled step less. In contrast the diesel engine is very loud and takes up much room due to the size of the converter. Furthermore the hydraulic converter is very expensive and fault-prone, creates emission and the parameters can not be controlled in the same efficient way as with the electric converter (more efficiency loss).

The converter for both ways of actuation is necessary as the pressure of the pump is proportional to the torsional moment of the motor and the flow rate of the pump is proportional to the rotation speed of the motor. This means that both the usage of a diesel motor and a electro motor is bound to the torque curve. Therefore it is necessary to install the frequency converter in order to provide pressure and flow rate of the pump independently.



Figure 29: *Left: High pressure pump with hydraulic drive ^[8]; Right: High pressure pump with electric drive.*

Concerning the regulation of the pump it is necessary mentioning that the flow rate is adjusted at the converter by means of the pump rotation speed and the pressure results from the load (Downhole screw motor or Button Nose Nozzle).

The pump has to be able to create the pressure and at the same time maintain the adjusted rotation speed and the flow rate.

It is important to provide for a separate lubrication of the pump in order to avoid lubrication insufficiencies or overheating at lower rotation speed of the pump. Furthermore the pump case should be manufactured from high-grade steel if acids, diesel or other aggressive fluids are to be injected. A filter ought to be installed before the fore pump in order to protect the pump from solid matters in the fluids. The pressure created by the pump can be measured with a manometer. If the pump is placed outside the danger area of the well it is not necessary to endue it with respectively the motor with a firedamp protection.

Manufacturers of such pump aggregates are the companies URACA and Hammelmann in Germany or the Woma and Kamat-Lewa in Austria.

Parameters:

60 kW capacity, flow rate can be regulated from 5 to 27,5 lpm, discharge pressure 1.000 bar, converter with 400 V, 81 A, 50 Hz feed, load pressures: Downhole screw motor 10 to 24 bar, button hole nozzle 200 to 300 bar.

A maximum pump pressure of 1.000 bar is necessary as the pressure loss inside the Coil Tubing is enormously high. The pressure loss is proportional to the length of the Coil Tubing and greatly dependent on its inner diameter.

7.1.2 Generator und electricity supply

The generator should be powered by a diesel motor which has to be used for the above mentioned alternative with the electric motor. A generator is not needed should the high pressure pump possess a diesel motor with hydraulic converter. It is advisable to place the generator as far away from the well as possible as it is quite loud, produces emissions and the danger areas like the explosion area of the well have to be respected according to the distance decree. Furthermore the generator should be easy to transport (by truck or trailer) and handle.

Parameters:

Capacity should exceed 60 kW, generator with 400 V, 81 A backup, 50 Hz frequency, powered via diesel motor.



Figure 30: Diesel driven generator with 400 V, 81 A and 50 Hz.

7.1.3 Fluids and tank ^{[23],[24],[25]}

Three fluids are needed for a Radial Drilling operation:

- Water
- Butyl glycol
- Potassium chloride

For the milling job a 2 % potassium chloride-water emulsion is blended. For the jetting job 5 % butyl glycol is added to the 2 % potassium chloride-water emulsion. Generally it is advisable to use two to three separate tanks, one tank for each fluid and one tank to be kept in reserve. The tanks ought to be cleaned thoroughly in advance.

In order to prevent the high pressure piston pump from damage the maximum particle size of the emulsion should be lowered to approx. 5 microns by filtering. For wells of significant depth it is recommendable to install a heat exchanger after the tanks. Its purpose is to warm the fluids until they reach the same temperature as the reservoir and thus minimise the expansion of the tubing line. Otherwise you can reduce the expansion by install a Tubing anchor.

The 2 % potassium chloride-water emulsion is often used for the stimulation of crude oil reservoirs. With its surface tension it prevents water from breaking into the hydrocarbon containing reservoir and destroying it blocking the oil or gas. An additional characteristic of the potassium chloride-water emulsion is that it does not affect the Downhole motor respectively its elastomer stator so that they do not macerate.

Butyl glycol is a sort of alcohol and in conjunction with the potassium chloride-water emulsion forms a mucilaginous lubrication which favours the jetting. Thus the frictional losses during the jetting are reduced which allows for the nozzle together with the hose to advance further into the reservoir. Furthermore the 5 % butyl glycol-2 % potassium chloride-water emulsion is meant to prevent water blockage by reducing the surface tension.

Often an acidification is carried out in combination with the Radial Drilling. The acidification takes place during the jetting-out leaving the actual jetting operation unaffected. For the acidification either a 5 to 20 % acetic acid-water intermixture or 3 to 15 % muriatic acid-water is used. When intending an acidification it is crucial to make sure that the tanks as well as all other parts of the equipment are acid-resistant. The main purpose of an acidification is to enlarge the diameter of the side track and open the pores of the reservoir, thus increase the permeability.

For a Radial Drilling job with four lateral holes approx. 13.000 litres of fluids are needed, whereof around 3.000 litres are required for the pressure tests and 10.000 litres for the actual operation itself. For the pressure tests either clear water or the 2 % potassium chloride-water emulsion is used. The milling job requires 4.000 litres of 2 % potassium chloride-98 % water emulsion (volume per lateral 1.000 L). For the jetting job around 6.000 litres of 5 % butyl glycol 1,9 % potassium chloride-93,1 % water emulsion are needed (volume per lateral +/- 1.500 L).

7.1.4 Christmas tree and Blow out Preventer

Prior to the Radial Drilling works the Xmas tree of the well has to be dismantled and reconverted for the Coil Tubing job.

The Radial Drilling Equipment

The Xmas tree together with all other super structural parts of the well e.g. a pump jack have to be dismantled completely except for the tubing head and components below. Afore the well has to be pumped full in order to work approximately 20 bar overbalanced (by oil wells you have to pump intermittently to stay overbalanced). The old tubing has to be extracted and replaced by a new one on the point of which the deflector shoe with centraliser and anchor are placed. The tubing line together with the tubing hanger is inserted into the fix installed tubing head.

According to findings of the RAG production engineers a short tubing has to be fixed above the tubing hanger. Its main purpose is to cut the jetting hose in case of an emergency and allow for the Coil Tubing to be extracted without being damaged. The short tubing should be long enough to clasp the tubing with the elevator and lift the tubing line with the winch in order to cut the hose between the casing and the deflector shoe. Otherwise it would be inevitable to cut the Coil Tubing should the hose get stuck inside a lateral and not break under tension. As the short tubing is quite high it is necessary to install several transitions and flanges (or one very high spool) on the tubing head to gain height.



Figure 31: *Left: Insertion of the deflector shoe into the tubing head; Right: Tubing head with flanges, drilling spools, gate valve and preventer.*

The preventer is set onto the flanges and drilling spools and is screwed on. On top of the preventer the injector head and the gooseneck is placed. The main purpose of the preventer is to prevent a blow out. In case of an emergency the preventer seals the Coil Tubing outwards, during the operation the preventer is always open. As a preventive measure the preventer disposes of four rams (from top to bottom: blind rams, shear rams, slip rams, pipe rams) ^[9]. The preventer is part of the Coil Tubing equipment.



Figure 32: 4 1/16" 10.000 psi VAN OIL Blow out preventer ^[26]

7.2 Coil Tubing, Casing and Tubing

The Coil Tubing equipment consists of the coil, a reel with or without drive, a gooseneck and the injector head. The Coil Tubing equipment is provided by the contractors. The Casing, often many years old, is firmly cemented into the ground and may feature slight to heavy corrosion. The tubing line used for the Radial Drilling operation should be in mint condition.

7.2.1 Casing ^[27]

The most frequent casing types in reservoir proximity of the RAG are:

- Casing 7" 23 Ib/ft, 8,1 mm wall thickness, grade J55 or L80, ID 161,7 mm.
- Casing 7" 29 Ib/ft, 10,4 mm wall thickness, grade J55 or L80, ID 157,1 mm.
- Casing 4 1/2" 11,6 Ib/ft, 6,3 mm wall thickness, grade J55 or L80, ID 101,6 mm.

- Casing 9 5/8“ 36 Ib/ft, 8,9 mm wall thickness, grade J55 or L80, ID 226,6 mm.
- Casing 9 5/8“ 43,5 Ib/ft, 11 mm wall thickness, grade J55 or L80, ID 222,4 mm.
- Casing 5 1/2“ 14 Ib/ft, 6,2 mm wall thickness, grade J55 or L80, ID 127,3 mm.
- Casing 5 1/2“ 15,5 Ib/ft, 7 mm wall thickness, grade J55 or L80, ID 125,7 mm.
- Casing 5 1/2“ 17 Ib/ft, 7,7 mm wall thickness, grade J55 or L80, ID 124,3 mm.
- Casing 6 5/8“ 20 Ib/ft, 7,3 mm wall thickness, grade J55 or L80, ID 153,6 mm.
- Casing 6 5/8“ 24 Ib/ft, 8,9 mm wall thickness, grade J55 or L80, ID 150,4 mm.

The inner diameter of the casing is a decisive factor for the deflector shoe's outer diameter (112 mm). According to research there are Radial Drilling constructions which can be operated in 4.5" casings. The casings are 12 m long and connected with couplings. Before the Radial Drilling job is starting the position of the couplings have to be checked with a GR-CCL. During the job it is very important to avoid milling into a coupling and to not exceed the drift diameter with the equipment during the insertion. Grade J55 is normalised rolled and hardened steel whereas L80 is tempered steel. The J55 features a greater toughness than the L80 and thus is more difficult to chip. Both sorts of steel are manufactured by VÖST Alpine Tubulars in Kindberg or other suppliers.

The resistance, alloying additions and hardness of the casings are crucial for the milling process. As the casings are exposed to very corrosive mediums over the years, they corrode which means that their wall thickness decreases. In some cases even pitting corrosion or intercrystalline decomposition occurs. Of course the corrosion of the casing favours the milling process. Prior to the actual milling job a scraper run should be carried out in order to remove incrustations from the casing.

Material properties of the Grade J55:

- Minimum yield strength 379 N/mm²
- Maximum yield strength 552 N/mm²
- Ultimate tensile strength 600 N/mm²
- Hardness 8 to 14 HRC
- Yield ratio 0,8

Material properties of the Grade L80:

- Minimum yield strength 552 N/mm²
- Maximum yield strength 655 N/mm²
- Ultimate tensile strength 760 N/mm²
- Hardness 23 HRC
- Yield ratio 0,85 to 0,9

7.2.2 Tubing ^[27]

The Tubing line should act as a receiver for the deflector shoe. The tubing lines are 9,1 to 9,4 m long and are held together by couplings. For the Radial Drilling jobs 2 3/8 “ EU 4,6 to 4,7 Ib/ft Tubings or 2 7/8 “ EU 6,4 to 6,5 Ib/ft Tubings are used at the Rohöl- Aufsuchungs AG. Both are made of Grade J55 or L80 steel. The inner diameter of the 2 3/8” Tubing is 50,7 mm and is thus smaller than the outer diameter (43 mm) of the Downhole screw motor. The tubing line is connected with the deflector shoe via a short tubing and a coupling. The centralizer is placed several centimetres above the deflector shoe whereas the anchor is installed approximately 9 metres above the deflector shoe in the tubing line. Without the anchor the tubing line would expand or contract due to the difference in temperature inside the well, the fluids and the long term tensile strain.

The Tubing line is adjusted after insertion by means of CCL measurement and levelled at the right depth before it is settled together with the tubing hanger into the tubing head. In the event of the tubing line getting stuck it is possible to circulate fluid via the Tubing line into the Casing in order to loose it. If the deflector shoe has to be turned around inside the bore hole it is necessary to remove the drilling spools and the flanges, lift the Tubing and turn it around by means of the elevator. It is important to bear in mind that the rotation angle on surface is not the same as subsurface as the tubing line gets twisted over the whole well depth due to the friction against the casing (exact position with Gyro tool).

7.2.3 Coil Tubing equipment ^{[26],[28]}

The Coil Tubing is used as a lifting accessory for the Downhole screw motor and the jetting hose. By means of the Coil Tubing these two can be inserted and supplied with the fluids. The Coil Tubing equipment is provided by the contractors like the company Coil Services.

For the Radial Drilling Job a ½” Coil Tubing of WEBCO Industries Inc. is used. The respective tubing has a wall thickness of 0,0049“ which consequently equals an ID of 0,402”. The coil is manufactured from grade Duplex Alloy 19D; beforehand it gets rolled and subsequently shaped to a pipe and welded lengthwise. The coil is of 3.500 m length and wound up on a reel which is affixed to a trailer. A small coil is used as bigger coils are considerably more expensive and require extensive equipment. A disadvantage of such small coils is the smaller inner diameter which leads to significant pressure losses at high flow rates. The collapse pressure for this Coil Tubing is 1.000 bar (15.000 psi), the maximum operating pressure for this Coil Tubing (CT) is 675 bar (dynamic) and the volume for this Coil Tubing is 286 litre / Length is 3.532m.

As the coil must not be kinked it has to be routed towards the preventer respectively the injector head via a gooseneck which allows for a soft bending. The gooseneck features a radius of around 1,8 m and is installed on the preventer or the injector head.

The Coil Tubing can be driven either by means of the reel or with an injector head. The drive via the injector head is to be preferred to the reel, especially for deeper bore holes, as a coil driven by a reel is more likely to deform due to the deflection caused by the gooseneck.

The injector head performs two tasks, first it has to straighten the coil to prevent it from bending and second it has to move the coil up and down inside the tubing. The injector head consists of hydraulically driven reels which can move the coil upwards and downwards at a speed of 125 ft/min (38,1 m/min). The injector head is equipped with sensors which measure the weight, the speed and the way of the coil.



Figure 33: Left: Coil Tubing injector head with gooseneck ^[26]; Right: Coil Tubing reel ^[26]

On the reel-side the coil is connected with a fluid distributor which is also connected to the high pressure pump. With a screw coupling on the loose end of the coil the jetting hose or the Downhole can be attached via the bending hose.

It is important for the coil to have a definitely smaller OD than the drift diameter of the tubing and that the pressure losses and the load pressures are not higher than the maximum pressure of the pump.

7.2.4 Deflector shoe

The deflector shoe (OD 112 mm) is the core piece of the Radial Drilling Technology. The deflector shoe has on the upper end a 2 3/8" EU or 2 7/8 EU external screw thread which can be screwed together with a coupling and the tubing. The deflector shoe is made of nitriding steel; it gets turned, milled and nitrated for a long time at the end of the manufacturing process. The long nitriding leads to a final hardness of around 70 HRC. Such hardness is required as the milling bit (hardness around 63 HRC) is rotating inside the conduit of the deflector shoe during the milling job. Of course it is undesirable that in the course of doing so the milling bit damages or abrades the deflector shoe. The conduit has an inner diameter of around 26 mm and a j-shaped run which allows for the milling bit to the exit of the deflector shoe at a 90° angle to the vertical and mill the casing. The shape of the conduit is of great importance for both the jetting and the milling process.

If the conduit is too narrow or is not of the correct shape it is impossible for the jetting hose to jet through it. If the conduit is too wide it is impossible to direct the cardan shaft (OD 22 mm) through and it is likely to kink.

The shoe is separated in the middle of the conduit and consists of two parts which are held together by two screws and are centred by two alignment pins. The conduit possesses of two recesses at the exit which fulfil two main tasks. First they are intended to discharge the cuttings which are produced from the milling and jetting and second it is possible to circulate fluids via these recesses. The circulation is carried out in the event of the deflector shoe together with the tubing is stuck inside the casing.

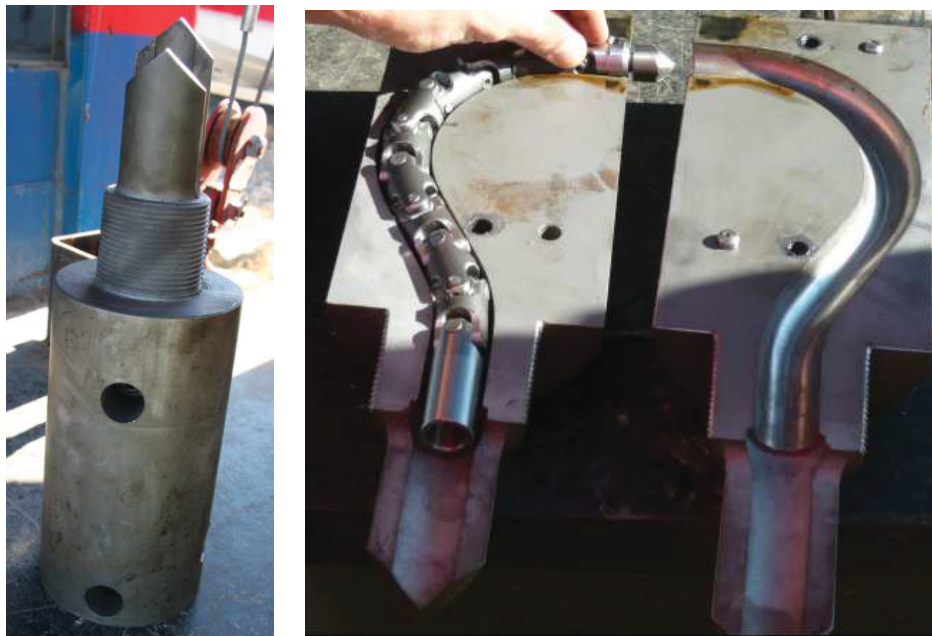


Figure 34: *Left: Radial Drilling Services deflector shoe; Right: Deflector shoe with Cardan shaft and milling bit.*

At the upper end the deflector shoe has two bevelled points of different length. If the deflector shoe is screwed together there are two grooves between the points in which the torque supply can engage. The torque supply is directed into the conduit during the milling process and by means of the T-piece it can rest on the grooves and thus transfer the moment to the shoe and in the broader sense to the tubing. The points are of different heights in order to allow for the T-piece to be placed on the grooves. Prior to use lubrication grease ought to be applied to the deflector shoe in order to minimise the friction losses during the milling and jetting process.



Figure 35: *Left: Torque supply moves in the deflector shoe; Right: Torque supply is fixed in the deflector shoe.*

By means of a gyro meter it is possible to turn the exit of the deflector shoe together with an installed gyro landing tool into the right direction. The gyro landing tool is installed, one Tubing piece, above the deflector shoe. Especially for inclined wells or heavily inclined reservoir layers the jetting direction is of great importance.

7.2.5 Anchor

The main purpose of the anchor is to fix the deflector shoe during both the milling and the jetting job and to prevent any movement caused by thermal or mechanical extension. Otherwise it would be likely to loose the side track and thus impossible to find it again. For the purpose of a Radial Drilling job an anchor without seal and which is to set mechanically is sufficient. The anchor is installed around 9 m above the deflector shoe in the tubing line and is set via eight rotations anti-clockwise and loosened with another eight rotations clockwise. During the setting claws dig into the casing which make any movement up- or downwards impossible. The setting process is mostly conducted under pretension or compressive load and via a rotation of the tubing by the elevator on surface. It is crucial to ensure that the anchor is capable of tolerating the respective load, fits the tubing and can be fixed inside the casing.

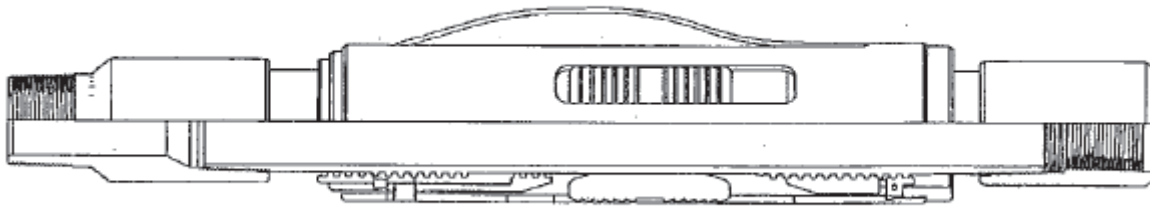


Figure 36: 7" Tubing anchor catcher ETI-B ^[29]

7.3 Milling Equipment

The milling equipment consists of the milling bit, the flexible shaft, the torque supply, the Downhole screw motor and the centraliser. All these instruments are needed in order to drill the casing and afterwards to jet with the button nose nozzle into the oil- and gas-bearing formation.

7.3.1 Milling Bit

The first task of the milling bit is to cut the casing and afterwards drill a hole (about 20 mm deep) into the surrounding cement, thus clearing the way for the nozzle. The wall thickness of the casing amounts to 6 to 11 mm. The milling bit is exposed to very high impact loads during the milling and can therefore not be made of hard metal. A power-metallurgical manufactured HSS which gets hardened to hardness of around 63 HRC after the turning and grinding lends itself to a material. Thereby the milling bit gains a substantial hardness on the cutting edges, which is good for avoiding abrasion and a high toughness in the core which is good against the impact loads. The milling bit has an OD of 22 mm and is manufactured as three cutting edge bit with surrounding chip breaker. Three cutting edges are better for centralising the milling bit than two. The milling bit is charged with very little weight on bit (12 to 40 kg at a rotation speed of 150 to 200 rpm). This leads to the fact that actually not a real cutting process takes place at the cutting edges but rather a grinding or rubbing process. The chippings look like very thin, short needles. The higher the WOB the larger become the chippings and the more cutting force and cutting torque is necessary. In order to not exceed the motor torque (approx. 50 Nm) the WOB must not be too high.

However it ought not to be too low either as otherwise the milling bit would not be able to penetrate the casing. The WOB is the result of the total sum of all single weights of the milling equipment, the deflector and friction losses inside the deflector shoe and the conferrable weight of the bending hose from the coil to the Downhole motor.



Figure 37: *Left: Milling bit with three cutting edges and round tool holder; Right: Chippings.*

The outline contour of the milling bit is exactly attuned to the chipping process. The milling bit performs a curve-like movement while penetrating the casing. Initially it rests against the deflector shoe with the outer cutting edge; hence the deflector shoe has to be of greater hardness than the milling bit in order to not abrade. To allow for the milling bit penetrating the casing more easily the front part of the cutting contour got pointed in order to increase the contact pressure and to concentrate it on a specific spot. Subsequently the inclination of the contour decreases to the back as the contact pressure is sufficient for the remaining chipping process. The milling bit features a conical undercut which is meant to make sure that the milling bit can be easily extracted from the bore hole.

The milling bit is connected to the flexible shaft via a shaft to collar connection. For this purpose a round tool holder with grub screw safety (prevents circular and axial movement) or a square tool holder with grub screw safety (prevents axial movement) can be used. However the square tool holder appears to be preferable as it does not lose its torque supply function in the event of a defective mounting.

7.3.2 Flexible shaft

The flexible shaft is a cardan shaft in the majority of cases as this is able to transmit higher moments with a narrower deflection (radius 70 mm) better than a bendable shaft made of spring steel. The cardan shaft is a standard part and is made of several links which are connected by cardan joints, embedded in slide bushes. The cardan shaft is intended to deflect the torsional moment of the moment and the WOB of the milling equipment inside the deflector shoe by 90° and transmit it to the milling bit. The cardan shaft possesses of two shaft to collar connections. One to the shaft of the torque supply carried out as a screwed fastening and another to the milling bit, carried out as inner square tool holder or inner round tool holder with grub screw safety. The cardan shaft is manufactured from machining steel and has an OD of around 22 mm. The links can be put at a maximum angle of 45° towards each other (inside the conduit OD 26 mm the angle is approx. 20° to 30°). The bigger the angle the lower the conferrable torsional moment of the cardan shaft gets.



Figure 38: Left: Cardan shaft in pendulous state; Right: Cardan shaft inside the deflector shoe.

7.3.3 Downhole screw motor ^{[27],[30]}

The main task of the Downhole motor is to provide the torsional moment which the milling job requires. The Downhole screw motor is a positive displacement motor which is manufactured after the Moineau concept working according to the displacement principle. As there exists no specific Downhole screw motor for the Radial Drilling Technology it is inevitable to resort to small drilling Downhole motors or to Downhole motors which are used for tubing cleaning works.

Furthermore it is necessary to slightly modify the Downhole screw motor in order to allow for the torque supply to be flanged on the stator. The Downhole motor is screwed together with the bending hose at the upper end, then the bending hose is flanged on the Coil Tubing. The bending hose is intended to reduce the demand of the Coil Tubing on the milling bit. The demand respectively the WOB on the motor is a function of the stiffness and the length of the hose. The Downhole screw motor is supplied with fluid via the hose. Inside the Downhole motor there is a spiral rotor and as a negative a stator made from elastomer. The fluid flows through the sub, drives the rotor and then after the power section leaks from the motor via boreholes in the casing. A certain portion of the fluid leaks from the bush of the torque supplies as the Downhole motor has to be cooled and lubricated in the front spindle section.

Parameters:

Length 1.630 mm, OD 43 mm, Power section lobe configuration Rotor / Stator 5/6, mud flow 12 to 30 lpm, rotating speed 120 to 294 rpm, pressure drop at no load 10 to 24 bar, torque at shaft 20 to 50 Nm, max. differential pressure drop available 18 to 27 bar, max. Power 0,3 to 1,4 kW, Downhole temperature max. 100°, weight 14 kg, max WOB 600 kg, max density of process water or mud 1.300 kg/m³.

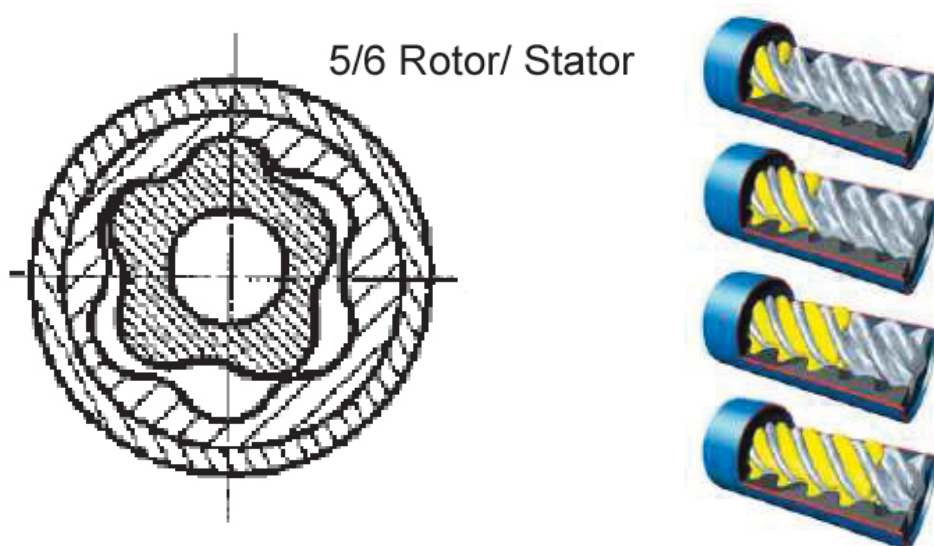


Figure 39: Left: Power section lobe configuration Rotor/Stator 5/6 ^[27]; Right: Power section in action ^[30]

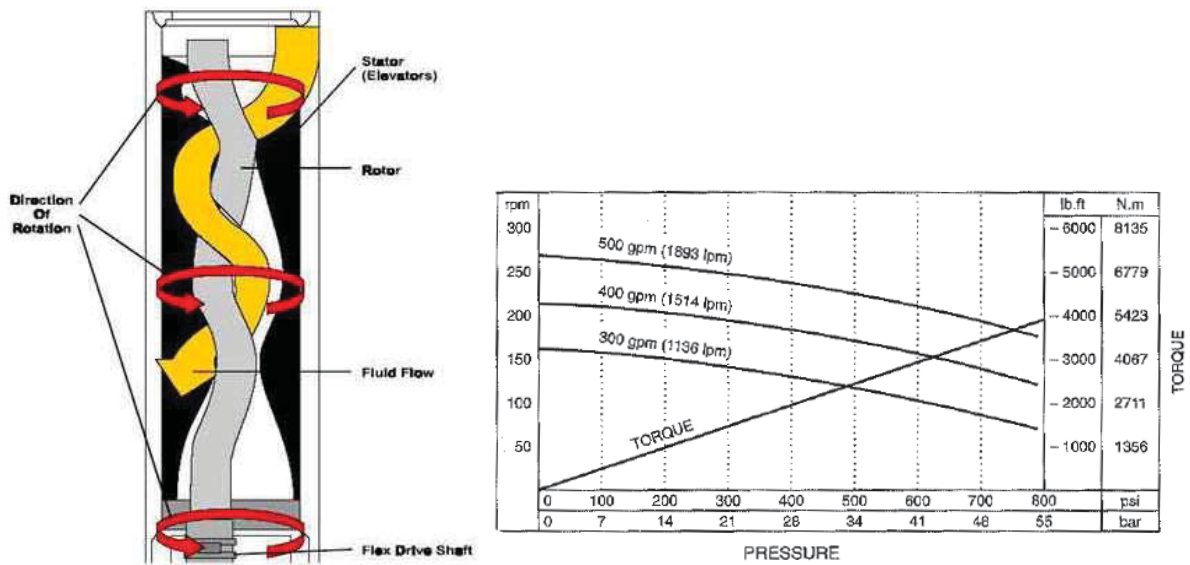


Figure 40: Left: Function of the Power section^[31]; Right: Curve for different flow rates and torque^[27]

The torque is directly proportional to the pressure drop across the motor. The rotary speed is directly proportional to the flow rate. The higher the number of shaft lobes, the lower the rotary speed. It varies only slightly with torque and pressure drop.



Figure 41: Downhole screw motor

7.3.4 Torque support

The torque support is meant to prevent the stator of the Downhole screw motor from beginning to rotate inside the tubing. The torque support transmits the required hogging moment to the deflector shoe and the Tubing. As the Downhole screw motor is fixed to the Coil Tubing only by means of a hose it is not possible to work without a torque support.

The torque support consists of four parts: the torque bush, the shaft, the plain bearing bush and the T-piece. The torque bush is flanged on the Downhole screw motor. The torque bush transmits the hogging moment and is intended to radially embed the shaft in a pressed-in plastic bearing bush. The T-piece is fixed to the torque bush by means of two grub screws. The T-piece reaches into the two notches of the deflector shoe and thus transmits the hogging moment. Inside the torque bush there is the shaft which on one end is flanged on the rotor of the Downhole screw motor and on the other end is connected to the cardan shaft. The torque bush, the shaft and the T-piece are milled and turned parts made from tempered steel. When assembling, first the shaft has to be flanged on the rotor before the torque bush with the bearing bush is put over the shaft and screwed with the stator of the Downhole motor. Finally the T-piece is pushed onto the torque bush and secured with grub screws. The torque bush features a round shaped outline contour which accurately glides into the deflector shoe and thus prevents the Downhole motor from overturning. The T-piece rides the notch during the milling process until it eventually reaches the semi-circular end of the notch and thus ensures that the milling bit does not protrude too far from the deflector conduit.

7.3.5 Centralizer

The centralizer is a welded construction, consisting of five parts: a ring and two interlocking half-shells (fixed together by means of two screws or straight pins) which are welded with two flat springs. The main task of the centralizer is to bring the deflector shoe which has a smaller diameter (OD 112 mm) out of the central position and to press the exit of the conduit against the casing (ID 7" casing 157,1 mm) in order to make sure that the milling bit does not rotate free. The centralizer is installed just above the deflector shoe. It is 600 mm high and is fixed to the tubing and the coupling by means of grub screws. In order to install it the centralizer has to be pulled over the coupling with a ring and the half-shells have to be screwed together before the grub screws can be fastened. The centralizer respectively its flat springs have to be adjusted according to the relevant ID of the casing in order to bring up the required excentricity. When assembling it is crucial to make sure that the flat springs are placed at the opposing side of the conduit exit.



Figure 42: *Left: Centralizer fixed on tubing*

7.4 Jetting Equipment

The jetting equipment consists of two parts: the jetting hose and the 1/8" NPT button nose nozzle. Both parts are screwed together via armatures and the hose is screwed to the Coil Tubing.

7.4.1 Jetting nozzle ^{[21],[32]}

The main purpose of the nozzle is to crush the rock subsurface and to jet a side track of 100 m length and with a diameter of 5 cm into the formation. For this purpose the nozzle has to have enough feed forward (created by the rear nozzles) and cutting force (created by the forward nozzles). The ideal ratio of rear thrust to forward thrust is 2/1. The remaining thrust (ca. 1,5 to 2 kg) has to be sufficient to drive the nozzle and the hose forward. As jetting nozzles 1/8" button nose nozzles from the company Aqua Mole Technologies are used. These nozzles are suited best for hydro jetting in sandstone formations. The company Aqua Mole manufactures the nozzles with any jet configurations according to specification. The nozzles are made by turning from alloyed steel. After turning the outer and inner contours the orifices are drilled. The nozzle is screwed to the screwed end of the jetting hose with a 1/8" NPT thread. It is advisable to use a Teflon tape for the screwing in order to better seal the thread. Furthermore it is crucial that the rear jets are drilled in the forward groove as otherwise the rear jets would spray on the armature and thus energy would be lost. The nozzle is charged with around 9 to 14 lpm fluid. In order to let the flow rate flow through the nozzle a pressure of around 150 to 300 bar is necessary. The jet velocity at the exit of the orifices is very high as there the lateral cut of the hose compared to the lateral cut of the nozzle (orifice) is very small.

Full particulars of the nozzle configuration like number of orifices, diameter, angle and position of the orifices are described in detail in chapter 4.2.



Figure 43: *Left: Button Nose nozzle in action; Right: 1/8" Button Nose nozzle for Hydro drilling.*

7.4.2 Jetting hose ^[33]

The jetting hose is meant to supply the nozzle with fluid (pressure and flow rate) and whilst doing so create as little pressure loss as possible. As jetting hose serves a hose of around 100 metres length and with an inner diameter of 6,3 mm and a outer diameter of 13 mm. The hose has a very thin and abrasion-resistant outer layer and tolerates dynamic pressures of up to 210 bar as well as static pressures of up to 800 bar. Furthermore it ought to be chemical-resistant to water-glycol, probably to diesel respectively acid-resistant. It is also important that the hose has a minimum bending radius of 50 mm or less as it stiffens automatically under high pressure which makes it difficult to run it through the conduit of the deflector shoe. The hose consists of an inner cover made from nitrile rubber, a pressure carrier made from high-tensile steel wire and finally a cover layer made from synthetic rubber. The hose features armatures on both ends which are screwed with the 1/8" NPT button nose nozzle on one side and the Coil Tubing on the other side. The jetting hose must not be too heavy in order to allow for the nozzle to pull the hose into the formation. The abrasion-resistant outer layer is intended to prevent the hose from being damaged by being dragged over the cragged surface of the side track.

The Radial Drilling Equipment



Figure 44: *Left: Jetting hose connected with nozzle; Between: Jetting hose; Right: Jetting hose connected with Coil Tubing.*

8 Economic point of view

This chapter deals with the economic viewpoint of the Radial Drilling Technology. The main target is to discuss how the Radial Drilling affects the production increase of a well and how long it takes until the Radial Drilling job amortizes.

8.1 Cost-Benefits Analysis

Unfortunately the three Radial Drilling jobs which were carried out at the wells Sonde 3, Sonde 1 and Sonde 2 were not sustainable successful. At the well Sonde 3 only the technical feasibility of the technology could be proved. The well Sonde 2 showed good production already before the appliance of the Radial Drilling Technology. Unfortunately the search for compartments radial of the well was not successful and thus the reserves could not be increased. As no tests for production rates by means of a well checker have been carried out before and after the Radial Drilling job, it is not possible to state significant production rates here in this chapter.

These tests have been carried out for the well Sonde 1 before and after the Radial Drilling job. The results are displayed in the following figures (see figure 45. to 47.). The production records span a period of 740 days whereby the Radial Drilling job was carried out during the days 521 to 540. After the Radial Drilling job the increase of the gross production respectively water production was significant. The reason was that first of all the technical water had to be pumped from the well. It took a few days until the oil production increased to 3,9 m³. However this increase did not last too long and today, after 740 days, the well shows a production of 2,1 m³/d (previously 2,0 m³/d). Thus no significant production increase could be noticed but it has to be mentioned that the water production decreased from 2,6 to 1,9 m³/d which means that the water cut was reduced from 56 % to 47 %. Currently it isn't possible to judge if the water cut reduction is sustainable or unsustainable.

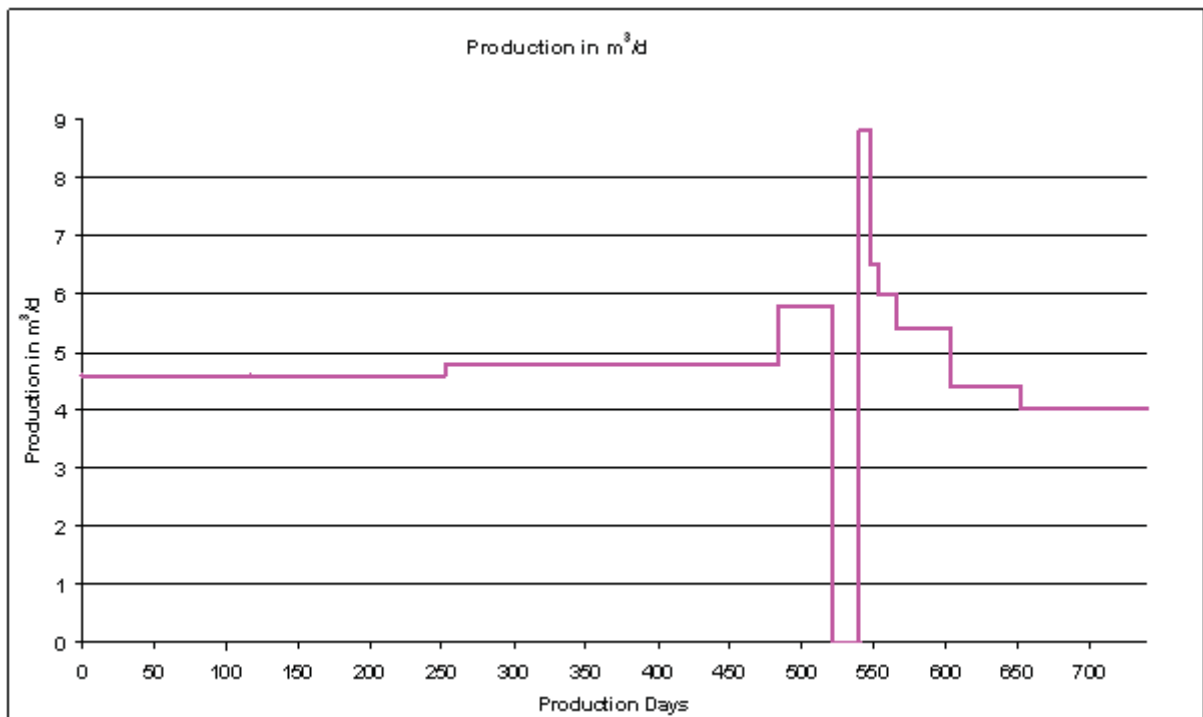


Figure 45: Gross Production of the well Sonde 1.

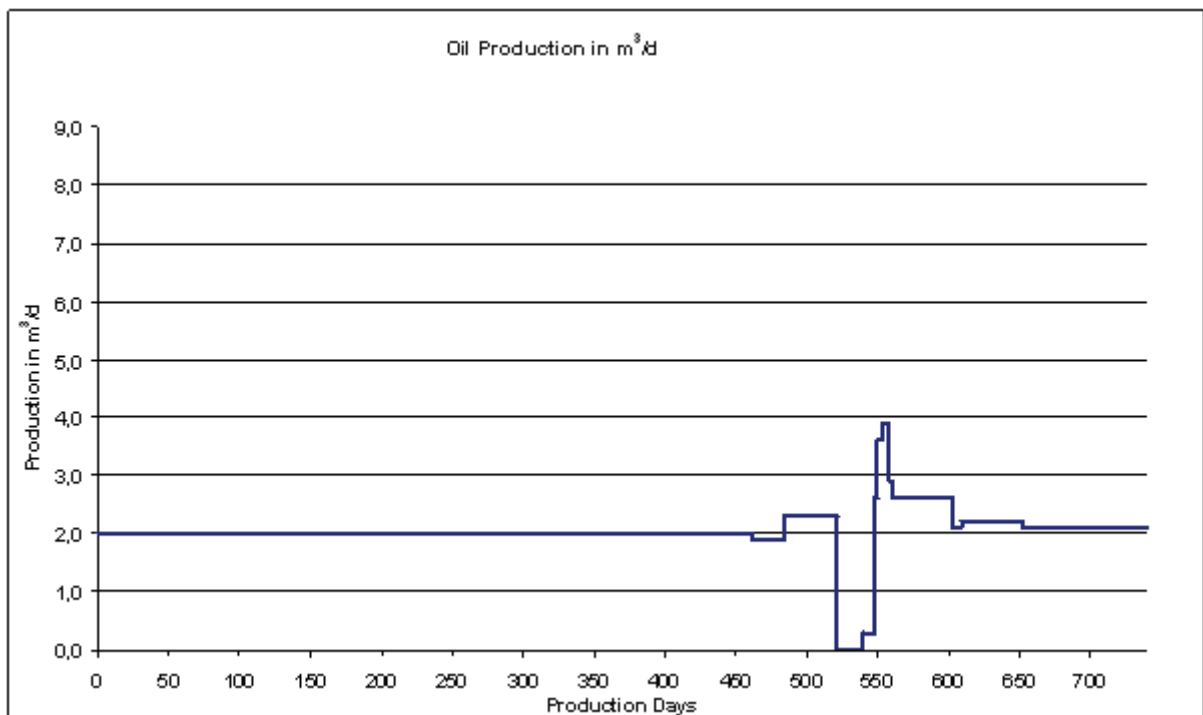


Figure 46: Oil Production of the well Sonde 1.

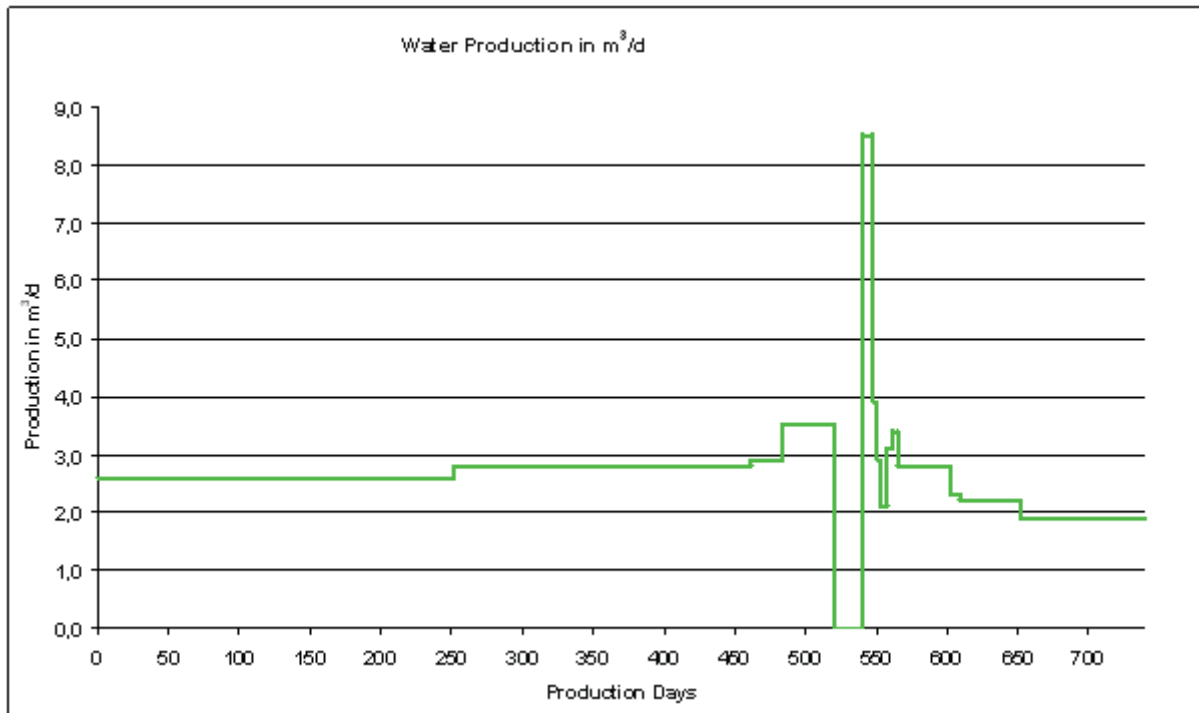


Figure 47: Water Production of the well Sonde 1.

The following figures (see figure 48. and table 5.) stem from Radial Drilling Services and show the sustainable increase in production arising from their Radial Drilling jobs (approx. 300 wells).

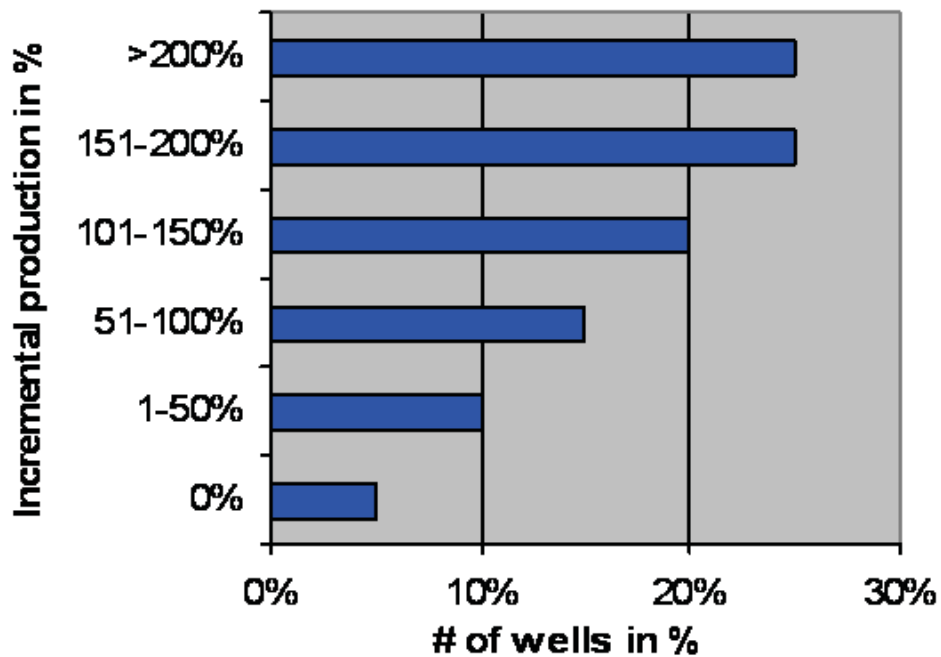


Figure 48: Overview of production increase for wells where Radial Drilling Technology jobs were applied. ^[16]

Economic point of view

Table 5: *Production Results of the company Radial Drilling Services* ^[5]

Formation	Geographic Area	# wells	Before Radial Drilling			After Radial Drilling				Remarks
			Oil bopd	Gas mcf/d	Water bwpd	Oil bopd	Gas mcf/d	Water bwpd	Oil/Gas % incr.	
Carbonates	Western Urals, Russia	10	327	0	64	715	0	67	119%	Rehabilitation project
Carbonates	Kansas USA	1	1.2	1.7	n/a	8	12	n/a	567%	Testing potential
Carbonates	Kansas USA	1	0	10	n/a	3	108	n/a	980%	Testing potential
Carbonates	Punta Arenas Chile	1	5.7	0	0	39	0	0	584%	Drainage improvement
Sands	Punta Arenas Chile	1	0	96	0	0	860	0	796%	Drainage improvement
Sands	Punta Arenas Chile	1	20	0	0	38	0	0	90%	Drainage improvement
Sands	Punta Arenas Chile	1	8.2	0	0	51	0	0	522%	Acid injection thru radials
Sands	Bolivia	1	34	0	0	84	0	0	147%	Deep well test (3251m)
Sands	Atyrau, Kazakhstan	20	410	0	0	1161	0	0	183%	Rehabilitation project
Carb/sands	Patagonia, Argentina	18	216	0	0	390	0	0	81%	Optimization project
Carbonates	Tatarstan, Russia	50	1277	0	0	3321	0	0	160%	Long term contract
Carbonates	Russia	3	124	0	0	297	0	0	140%	Rehab. test in Russia
Carbonates	Russia, Tatarstan	1	14	0	0	182	0	0	1200%	Radials with acid work
Sands	Punta Arenas Chile	1	0	0	144	0	0	611	324%	Injectivity testing (water)

From the figure (see figure 48.) one can calculate an average increase in production in sandstones with an expectation value of 132 %.

The following calculations (see table 6.) are based on the above mentioned rates of production increase and are intended to depict a connection between pay back period, production before Radial Drilling and the increase in production. For the calculation it was assumed that the oil price amounts to 80 \$/bbl, the exchange rate is 0,6658 € for a Dollar and the net earnings come up to 50 % of the oil price.

Economic point of view

Table 6: Relationship between pay back period, production before Radial Drilling job and increase in production, if the Radial Drilling job is carried out by the company Radial Drilling Services.

Costs of an RD job [RD Services]		201.200 €	
increase in production		132 %	
before RD Production m ³ /d	after RD Production m ³ /d	pay back period years	
0,1	0,23	24,91	
0,25	0,58	9,97	
0,5	1,16	4,98	
0,75	1,74	3,32	
1	2,32	2,49	
2	4,64	1,25	
3	6,96	0,83	
4	9,28	0,62	
5	11,60	0,50	
pay back period		1 years	
before RD Production m ³ /d	increase in production %	after RD Production m ³ /d	
0,1	3288,49	3,39	
0,25	1315,40	3,54	
0,5	657,70	3,79	
0,75	438,47	4,04	
1	328,85	4,29	
2	164,42	5,29	
3	109,62	6,29	
4	82,21	7,29	
5	65,77	8,29	
Production before RD		2 m³/d	
increase in production %	after RD Production m ³ /d	pay back period years	
10	2,20	16,44	
20	2,40	8,22	
30	2,60	5,48	
40	2,80	4,11	
50	3,00	3,29	
60	3,20	2,74	
70	3,40	2,35	
80	3,60	2,06	
90	3,80	1,83	
100	4,00	1,64	
125	4,50	1,32	
150	5,00	1,10	
175	5,50	0,94	
200	6,00	0,82	
250	7,00	0,66	
300	8,00	0,55	

It is remarkable that theoretical especially oil wells with a very low production rate need enormous increase in production in order to achieve an economic pay back period for the Radial Drilling job.

Unfortunately reserve increase effects or an enhancement of the life cycle of the well have not been considered in the economic calculation as there are no significant data available for this purpose because there was no experience in Radial Drilling so far.

9 Outlook and Appendix

The Radial Drilling Technology offers a new method for well production and injection enhancement. Compared to conventional technologies, the Radial Drilling Technology represents a safe, environmentally friendly and cost effective alternative as several laterals will be drilled in one Coil Tubing run. The Radial Drilling job will be performed in wells without a need for pulling tubing or handling big volumes of chemicals at high pressure.

With respect to the future it is important to further develop the Radial Drilling Technology, which stands but on the beginning of its development, and in the course of doing so amend the weaknesses and disadvantages of this technology. One of the first steps to come will be to make the Radial Drilling Technology applicable for small wells and casings of around 4 ½ “. Therefore a reconstruction of the deflector shoe, of the cardan shaft and the deflector radius is necessary.

Furthermore the hydro drilling nozzle technology has to be explored further in order to make the jetting of firmer cemented rocks possible and to create bigger and smoother side tracks. As soon as the durability of the milling (casing mill) and the jetting (hose and nozzle) equipment is increased and amended the next step will be to reduce the time needed for the ex- and insertion of the Coil Tubing. Therefore a rotation mechanism would be suitable which is connected to the casing by means of an anchor. The development of a rotation mechanism which enables the completion of all milling jobs on one horizontal level and then a change of the Coil Tubing to the jetting equipment to jet all the remaining laterals would significantly shorten the time needed for the completion of a job. This would also mean competition for technologies like the “MaxPerf® Drilling Tool” concerning short laterals (1 to 5 m).

Maybe it is also possible to develop a deflector shoe which can be shifted in vertical direction which would make the exertion and insertion during the short tubing installation unnecessary. Future research should also consider the milling job. There have to be other ways of opening up the casing in a certain section in order to jet out like e.g. a “Rohrwolf” instead of a casing mill, treating the casing with acid or to open up the whole casing area by means of a section mill.

It is crucial to thoroughly think about which wells or reservoirs enable the application of the Radial Drilling Technology. A careful preselection of potential candidates (see chapter 6) is the first step towards a successful Radial Drilling job. Especially the evaluation of the rock and formation which is to be jetted is important; by means of jetting tests on experimental rigs and with different nozzles it has to be determined if the rock features the right facies in order to allow for a successful application of the Radial Drilling Technology.

Another task that has to be completed in the near future is to determine how to combine the Radial Drilling Technology with secondary and tertiary production methods and how these combined technologies can successfully and economically applied at Austrian reservoirs.

The main disadvantages of the Radial Drilling Technology are the uncompleted laterals which run the risk of closing or collapsing. In order to solve this problem a lot of research work will be necessary. A supporting effect could be created – similar to the Fracking – by means of a gravel pack which is pumped into the laterals. The ends of the lateral exits towards the casing would have to be covered with a filter.

It is obvious that there is a great deal of research potential concerning the Radial Drilling Technology and other stimulation methods. With hindsight to the development of the oil price in the future it is essential for operator as well as for contractors to overcome the conventional production and stimulation methods and head towards new and innovative technologies such as the Radial Drilling Technology.

10 Reference List

- [1] Campbell, 2009. *Oil and Gas Liquids 2004 Scenario* [online]. ASPO.
Available at: <http://www.albany.edu/geosciences/04oilpeak.jpg>
[Accessed 6. Oct. 2009].
- [2] Städtler, 2009. *Crude Oil Price 1998-2009* [online].
Available at: <http://economatters.files.wordpress.com/2009/02/crude-oil-prices-1998-2009-what-matters-weblog.jpg> [Accessed 6. Oct. 2009].
- [3] 2009. *Rohöl-Aufsuchungs AG* [online]. RAG.
Available at: <http://www.rohoel.at/> [Accessed 30. Sep. 2009].
- [4] Seywald, Marschall, 2009. *Usage of Radial Drilling by RAG*. Oil Gas European Magazine. Volume 35 3/2009, page 114-116.
- [5] Radial Drilling, 2007. *Radial Drilling Technology Presentation* [online].
Available at: www.radialdrilling.com [Accessed 28. Sep. 2009].
- [6] Cirigliano, Blacutt, 2007. *First Experience in the Application of Radial Perforation Technology in Deep Wells*. SPE 107182.
- [7] 20. Feb. 2008. *Introduction to Radial Drilling Presentation*. Coil Services.
- [8] Seywald, 26. Apr. 2009. *Radial Drilling Presentation*. RAG.
- [9] Buset, Riiber, Eek, 2001. *Jet Drilling Tool: Cost effective lateral Drilling Technology for enhanced oil recovery*. SPE 68504.
- [10] Bruni, Biassotti, Salomone, 2007. *Radial Drilling in Argentina*. SPE 107382.
- [11] Brunet, Bouchard, 29. May 2008. *Apparatus, System, and Method for Casing Hole Formation in Radial Drilling Operation*. WO2008063267 (A1).
- [12] Landers, 5. Oct. 2000. *Method of and Apparatus for Horizontal Well Drilling*. WO0058599 (A1).
- [13] Buckman SR., Dotson, Mc Daniels, Bell, 23. Oct. 2003. *Nozzle for Jet Drilling*. Buckman Jet Drilling INC [US]. WO03087522.
- [14] RAD Jet, Jun. 2008. *Efficient Completions Presentation*. RAD Jet.

Reference List

- [15] Jelsma, *Production Enhancement through application of Radial Drilling*. Radial Drilling Services.
- [16] 19. Nov. 2007. *Radial Drilling Technology Presentation*. RADCAN Energy Services INC.
- [17] Radial Drilling, 8. May. 2007. *The HOSS Heavy Oil Steam System Presentation* [online]. Radtech International Inc. Available at: www.radialdrilling.com [Accessed 5. Nov. 2009].
- [18] Available at: <http://www.kingroyalty.com> [Accessed 5. Nov. 2009].
- [19] Available at: <http://www.irvineenergy.com> [Accessed 5. Nov. 2009].
- [20] Available at: <http://maxperf.ca> [Accessed 5. Nov. 2009].
- [21] Aquamole Technologies, May. 2009. *Aqua Mole Technologies High Performance, Custom Drilled, Pipe Cleaning Nozzles*. Aqua Mole Technologies.
- [22] Knoll, 9. Jul. 2009. *Evaluierung von Radial Drilling Kandidaten im Asset Gas*. RAG.
- [23] Jelsma, 2009. *Radial Drilling Program*. Radial Drilling Service.
- [24] Seywald, Gesterkamp, 30. Sep. 2008. *RAG Radial Drilling Sonde 1 Job Nr: 08-0215*. RAG.
- [25] Seywald, 16. Mar. 2009. *Behandlungsprogramm LFD.NR. 16/09 für Sonde 1*. RAG.
- [26] 2009. *Coil Services Brochure*. Coil Services.
- [27] Nguyen, Gabolde, 2006. *Drilling Data Handbook 8th Edition*. Editions TECHNIP.
- [28] 2009. *Webco Laser Line coiles Tubing* [online]. Available at: www.webcotube.com [Accessed 7. May 2009].
- [29] Heginger, 2009. *Tubing Anchor chatcher Model ETI-B*. Normec oilfield Products Sales and Services GmbH.
- [30] R&M Energy Systems, May 2009. *Moyno Power Sections, Excellence Through Innovation* [online]. R&M Energy Systems. Available at: www.rmenergy.com [Accessed 10. Jun. 2009].
- [31] Oct. 2009. *Mud motor* [online]. Available at: www.wellcollc.com/images/glossary/mud_motor.jpg [Accessed 27. Jun. 2009].
- [32] Aquamole Technologies, May. 2009. *Aqua Mole High Pressure Cleaning Button Nose Nozzles* [online]. Aqua Mole Technologies. Available at: www.aquamole.com [Accessed 27. Jun. 2009].
- [33] Mar. 2008. *Hydraulik-Schlauch, Armaturen und Zubehör Katalog*. Parker.

11 Bibliography

- 21. Jan. 2009. *RAG erweitert Gasspeicher massiv* [online]. ORF. Available at: <http://oesterreich.orf.at/stories/336743/> [Accessed 29. Sep. 2009].
- 2006. *Presentation Radtech Ago06*. Radtech International Inc.
- Radial Drilling, 28. Feb. 2007. *Radial Drilling System Components Presentation* [online]. Radtech International Inc. Available at: www.radialdrilling.com [Accessed 1. Sep. 2009].
- Seywald, Gesterkamp, 30. Sep. 2008. *RAG Radial Drilling Sonde 3 Job Nr: 08-0126*. RAG.
- Viertler, Jul. 2009. *Hochdruckreinigungs-Berechnung*, URACA Pumpenfabrik GmbH & CoKG Bad Urach.
- Municipal Supply Company, Jun. 2009. *High Pressure Cleaning Button Nose Nozzles* [online]. Municipal Supply Company. Available at: www.munisupply.com [Accessed 25. Jul. 2009].
- Economides, Hill, Ehlig, Economides, 1993. *Petroleum Production Systems*. Prentice Hall PTR, New Jersey, Flow throw chokes.
- Seywald, 2009. *Sondenbehandlungsbericht Sonde 1*. RAG.
- Seywald, 2009. *Sondenbehandlungsbericht Sonde 3*. RAG.
- Seywald, 2009. *Sondenbehandlungsbericht Sonde 2*. RAG.
- W.Dickinson, R.W. Dickinson, 1985. *Horizontal Radial Drilling System*. SPE 13949.
- Ursegov, Bazylev, Taraskin, 2008. *First results of Cyclic steam stimulation of vertical wells with radial horizontal bores in heavy oil carbonats*. SPE 115125.
- W.Dickinson, Dykstra, Nordlund, 1993. *Coild-Tubing radials placed by water jet drilling: Field results, theory, and practice*. SPE 26348.
- Rae, Lullo, 2001. *Chemically-Enhanced Drilling with coiled tubing in carbonate reservoirs*. SPE 67830.
- W.Dickinson, R.W. Dickinson, Herrera, Dykstra, Nees, 1992. *Slim hole multiple radials drilled with coiled tubing*. SPE 23639.

- Yonghe, Chunjie, Lianhai, Weiyi, 2000. *Application and Development of Drilling and Completion of the Ultrashort-radius radial well by high pressure jet flow techniques*. SPE 64756.
- Willi Bohl, Wolfgang Elmendorf, Aug. 2008. *Technische Strömungslehre*. Vogel Fachbuch.
- W.Dickinson, R.W. Dickinson, Pesavento, 1990. *Data Acquisition, analysis, and control while drilling with horizontal water jet drilling systems*. SPE 21602.
- Bürßner, 3. Aug. 2009. *Patentrecherchenantrag Radial Drilling Nr. 93298/2009*. RAG.
- Bharath, 10. May 1999. *Coiled Tubing Hydraulics Modeling*. CTES, L.C.
- Winter, Promitzer, Klasnic, Obernberger, May 2000. *Hydraulische Rohrrauigkeit von Stahlmediumrohren für Fernwärmenetze*. Institut für Grundlagen und Verfahrenstechnik und Anlagentechnik. TU Graz.

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14 List of Abbreviations

A	ampere
AG	Aktien Gesellschaft
approx.	approximately
atm	physical atmosphere
bn	billion
CA	Canada
cm	centimeter
CNG	Compressed Natural Gas
CO ₂	carbon dioxide
CT	Coil Tubing
DHM	Downhole motor
DI	Diplomingenieur
E200	electric 200 tons lifting force
E202	electric 202 tons lifting force
e.g.	for example
E-Kreuz	Eruptions- Kreuz
EVN	Energie Versorgung Niederösterreich
EU	External Upset
ft/min	feet per minute
gal	gallon
gal/min	gallon per minute
GmbH	Gesellschaft mit beschränkter Haftung
GR-CCL	Gamma Ray- Casing collar locator

List of Abbreviations

h	gab
HCL	Hydrochloric acid
HF	Hydrofluoric acid
HOSS	Heavy Oil Steam System
HRC	hardness acc. to Rockwell
Hz	hertz
lb/ft	pound per feet
ID	inner diameter
Inc.	Incorporated
KCl	potassium chloride
kg	kilogram
kg/m ³	kilogram per cubic metre
K _h	horizontal permeability
km	kilometre
km ²	square kilometre
K _v	vertical permeability
kW	kilo Watt
L	litre
LLC	Limited Liability Company
L/min	litre per minute
lpm	litre per minute
m	metre
m ³	cubic metre
m ³ /d	cubic metre per day
mD	milli Darcy
min	minute
mm	millimetre
m/min	metre per minute
m/s	metre per seconds

List of Abbreviations

N	Newton
Nm	Newton metre
No.	Number
N/mm ²	Newton per square metre
NPT	National Pipe Thread
OD	outer diameter
OMV	Österreichische Mineralöl Verwaltung
p _o	surrounding pressure
POOH	Pull out of hole
psi	pound per square inch
p _{stat}	static pressure
RAG	Rohöl- Aufsuchungs AG
RD	Radial Drilling
RDT	Radial Drilling Technology
Rpm	rotations per minute
Sec	seconds
SPE	Society of Petrol Engineers
t	tons
U/min	Umdrehungen pro Minute
US	United States of America
USA	United States of America
V	voltage
viz.	videliced
v _r	fluid velocity
WOB	Weight on bit
€	Euro
%	percent
“	inch
°	degree
\$/bbl	dollar per barrel