Extended Reach Drilling with the Shell Open hole Continuous Casing System for Horizontal Directional Drilling

Drilling Fluid Circulation and Technology Restart

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Most of all I would like to thank my parents and family for their unconditional love, support, wise advice and patience during my studies.

Rutger de Haij

Amsterdam, 11 February 2015.
ABSTRACT

As the global demand for energy increases and margins are under pressure, oil and gas companies are required to innovate. Over the last few years, the Wells R&D department at Shell Global Solutions International has been developing an alternative drilling methodology aiming at minimizing costs and environmental disruptions associated to conventional drilling activities.

The conventional drilling process of a well is based on a start and stop process due to the alternating operations of drilling and casing of the formation. Moreover, the telescopic profile of the well forces to adopt large casing diameters in the first section of the well, which leads to higher costs and a relevant environmental footprint of the drilling process.

The new casing technology is based on the concept of casing the hole while drilling. This is achieved by inside-out inversion of a steel pipe inside the borehole directly behind the bit. This introduces numerous advantages, one is that the hole is stabilised directly and risk of collapse is minimised.

The method can also be applied in Horizontal Directional Drilling (HDD) for the trenchless installation of service pipelines and enables extended reach drilling. With the conventional HDD method the drilling reach is limited to approximately 2 kilometres, with the Shell Open hole Continous Casing System (SOCCS) the reach is increased to 10 kilometres. Shell has licensed A. Hak Drillcon to further develop and commercialise SOCCS for this application.
EXECUTIVE SUMMARY

HDD
Horizontal Directional Drilling (HDD) has its origin in the Oil and Gas industry, but from the ‘70s the technology has been used and developed for trenchless installation of cables and pipelines. Nowadays the technology is standard in Europe and The Unites States for installing underground infrastructure. The maximum reach for a single side HDD drill is typically 2 kilometres and can be doubled by using a technique where the hole is drilled from two sides. The main limiting factors of the reach are the stability of the hole and the pullback capacity of the rig.

SOCCS
The Shell Open-hole Continuous Casing System (SOCCS) is a mono-diameter casing method based on the continuous inside-out inversion of a steel pipe. The technology is developed for the oil and gas industry to drill wells more cost-effective and environmental-friendly. The method can also be applied in HDD for the trenchless installation of service pipelines. It introduces several advantages compared to the conventional HDD method, such as extended reach up to 10 kilometres.

Mainly specialised in vertical drilling for hydrocarbon production, Shell has licensed A. Hak Drillcon to further develop and commercialize SOCCS for HDD. The first target for A. Hak Drillcon will be to successfully drill short crossings. In the long term distances from 5 to 10 kilometres are foreseen.
CHAPTER 1

1 HDD & SOCCS

This chapter represents a brief overview on horizontal directional drilling and the Shell Open-hole Continuous Casing System (SOCCS) and serves as an introduction to both technologies. For HDD the area of application, method of operation, used equipment and limitations are described. For SOCCS a brief general introduction of the conventional well drilling method for the oil and gas sector is given, followed by a description of the SOCCS method. Furthermore its advantages and the application in horizontal directional drilling are discussed.

1.1 HDD

1.1.1 AREA OF APPLICATION

Horizontal Directional Drilling has its origin in the Oil and Gas industry, but from the ‘70s the technology has been used and developed for trenchless installation of cables and pipelines. Nowadays the technology is standard in Europe and The Unites States for installing underground infrastructure like:

- Gas pipes;
- Water pipes;
- District heating pipes;
- Sewer pipes;
- Telecommunication;
- Power cables;
- Casing and host pipes.

According to the North American Society for Trenchless Technology (NASTT) the definition of (horizontal) directional drilling is:

“A steerable system for the installation of pipes, conduits and cables in a shallow arc using a surface launched drilling rig. Traditionally the term applies to large scale crossings in which a fluid-filled pilot bore is drilled using a fluid-driven motor at the end of a bend-sub, and is then enlarged by a washover pipe and back reamer to the size required for the product pipe. The required deviation during pilot boring is provided by the positioning of a bent sub. Tracking of the drill string is achieved by the use of a downhole survey tool.” (North American Society for Trenchless Technology)
1.1.2 **Method of Operation**
The method applied in horizontal directional drilling is divided in 3 steps:

- **Pilot bore;**

The first step after determination of the bore path is drilling the pilot bore. This is done with a drill head slightly larger than the used drill string. At the entry point the horizontal drilling rig is starting the bore at an angle between 5° and 35°. The drill head will be steered over its designated path (this process is elaborated later on) to the exit point, also known as the target pit. During the bore, the head can be driven either via the drilling rod string by the drill rig or via a rotation mechanism located in the borehole, a downhole mud motor. Drilling fluids drive the mud motor. Drilling fluids also have several other functions like disposing the spoil, stabilizing the hole and cooling the bore head. The drilling fluids are fed in via the hollow drill rod string and flow back to the entry point via the annulus between the drill string and the formation, Figure 1-1.

![FIGURE 1-1: HDD PILOT BORE (NATIONAL ENERGY BOARD, 2014)](image)

- **Reaming(s);**

After the pilot bore the diameter of the hole must be expanded to fit the product pipe. This process is called reaming and is done by attaching a so called reamer at the exit point, which is being pulled back with a rotating movement through the pilot hole to the entry point. Again drilling fluid is used and has the same functions as with the pilot bore. Sometimes one reaming is not enough. In this case drill string is attached to the (back of the) reamer and another reamer can eventually be connected and pulled through, Figure 1-2.
- Pulling-in;

The last phase is to pull-in the production pipe. With the (last) reaming, the (prefabricated) production pipe is connected to the reamer and pulled into the borehole from the exit point back to the entry point, Figure 1-3.

### 1.1.3 Equipment

At the locations of the entry point and target point, different types of equipment are installed to drill the hole. The drill rig is located at the entry site and this is called the rig site, see Figure 1-4. The target point is called the pipe site, here the production pipe is pulled into the borehole, see Figure 1-5.
FIGURE 1-4: LAYOUT OF RIG SITE (LMR DRILLING UK LTD)

FIGURE 1-5: LAYOUT OF PIPESITE (LMR DRILLING UK LTD)
A short description of the main equipment at the rig – and pipe site is given below.

- **Drill rig**

The drill rig is used to drill the borehole and pull-in the production pipe-line. For HDD applications generally the drill rig is mounted on a base frame, trailer, truck or tracked vehicle. This ensures the drill rig is easy to transport. The main parts of the drill rig are the drilling frame, the rotary power head and the thrust drive. Some rigs are equipped with over 600 tonnes of thrust/pullback power (Vermeer)

- **Drill rod string**

The drill rod string transfers loads from the rig to the drilling tools and consists of hollow drill rods screwed together. Loads acting on the string are:

- Axial tensile loads;
- Axial compression loads;
- Torsion loads;
- Bending loads.

The hollow drill rod string also transports the drilling fluids towards the drilling tools.

- **Drilling tools**

To excavate the soil different tools are used. A brief overview is given in Table 1-1.

**TABLE 1-1: DRILLING TOOLS BRIEF OVERVIEW**

<table>
<thead>
<tr>
<th>Tool</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Bit</td>
<td>&quot;A tool which cuts the ground at the head of a Drill String, usually by mechanical means but may include Fluid Jet Cutting.&quot; (North American Society for Trenchless Technology)</td>
</tr>
<tr>
<td>Downhole Mud Motor</td>
<td>&quot;A positive displacement drilling motor that uses hydraulic horsepower of the drilling fluid to drive the drill bit.&quot; (Schlumberger, 2014)</td>
</tr>
<tr>
<td>Reamer</td>
<td>A tool to expand the hole</td>
</tr>
</tbody>
</table>

- **Drilling fluids**

Drilling fluids are an important factor in HDD drilling and have the following functions:

- Excavate/loosen soil or rock;
- Clean the borehole;
- Prevent bed forming (sedimentation);
- Stabilize the borehole;
- Lower pipe friction at pull-in;
- Seal the wall of the borehole;

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- Cool, lubricate and clean the drilling tool/ drill rod string;
- Drive downhole mud motor.

Drilling fluids occur in different forms, liquid and gas. In trenchless applications usually liquid drilling fluids are used. They can be water, oil and synthetic based. A commonly used drilling fluid is a mixture of water and bentonite.

1.1.4 Limiting Factors

Today HDD is a standard method for installing underground infrastructure in Europe and The United States. It has many benefits above other methods, like:

- Safer for the environment;
- Less traffic disruption;
- Lower cost;
- Deeper installation possible;
- Longer installation possible;
- No access pit required;
- Shorter completion times;
- Directional capabilities.

(Direction Boring Advantage)

But the distance HDD drilling can cover in a single drill is limited. Currently this is around 2 kilometres. To double the reach the drill can be done from two sites where both drills meet in the middle. This is a difficult and expensive job. The factors that limit the HDD distance are:

- Buckling drill pipe in borehole;
- Torque and thrust on the drill rod string and the tooling;
- Hole stability;
- Effective hole cleaning;
- Down hole survey accuracy;
- Accuracy of the locating and steering system;
- Subsoil conditions;
- Pullback and hydraulic capacity of the drilling rig.

(Stein & Stein, 2010)

1.2 SOCCS

The Shell Open-hole Continuous Casing System is a mono-diameter method based on the continuous inversion of a steel pipe. The technology is developed for the oil and gas industry to drill wells more cost-effective.
1.2.1 Conventional Oil & Gas Wells
Conventional drilling methods make use of different sizes of casings. Starting at a large diameter at the surface and followed by smaller diameters towards the reservoir (tapered). The casings are used to isolate the different zones in the soil and to stabilize the hole. After a segment is drilled, the drill head is retracted, the casing is run (placed) and cemented. The drill head is lowered again to drill the next segment.

1.2.2 The SOCCS Method
Inversion is not new. It is used as a standard trenchless rehabilitation technology for water, sewer, gas and chemical pipelines and is called cured-in-place pipe (CIPP). This method uses polyester, fibreglass cloth or other materials that are suitable for resin impregnation.

Experiments with steel pipe inversion were first done in the Soviet Union during the 50’s. Further testing continued until the 90’s, resulting in several papers from Guist (’66), Al-Hassani (’72) and Reddy (’78, ’89, ’92). One of their results was that the knuckle radius for a certain pipe is more or less fixed. Hence, the dimensions of the outer pipe are fixed. See equation (1-1).
\[ r_k = \sqrt{\frac{d_{CDW} \times t_0}{8}} \]  

(Al-HASSANI, 1972)

With:

- \( r_k \) the knuckle radius [m]
- \( d_{CDW} \) the average of the pipe’s outer- and inner diameter [m]
- \( t_0 \) the initial wall thickness [m].

Based on that knowledge, development of SOCCS first started in 2005 with an inversion of a 100mm outer diameter (OD), 2mm wall thickness St-37 pipe. After determination of the right start-up procedure the inversion was a success. Testing went on and building a prototype rig started in 2009, which was finished in 2011. Several field tests have been done, with a test in 2013 resulting in a 444 metre of total inverted pipe.

### 1.2.2.1 Starting the inversion

As mentioned, SOCCS is based on the inversion of a steel pipe. To create a start point, the end of the pipe is inverted in four steps:

1. **Flaring**: the pipe is placed on a cone and compressive force is applied to flare the pipes end.
2. **Flattening**: the flattened end of the pipe is placed on/against a flat surface and a pipe with a slightly larger diameter is placed upon the SOCCS pipe to press the pipe towards the surface.
3. **Pre-version**: the flattened end of the pipe is welded onto a support ring and compressive force is applied on the pipe.
4. Inversion/eversion; the pipe is ready to be fully inverted/everted.

1.2.2.2 Continuous process
After the start of the inversion, drilling can begin. The force required to invert the SOCCS pipe is delivered by the pipe-pusher. This machine is located at the rig site. The support ring is held at the surface and the pipe-pusher pushes the SOCCS pipe through the hole behind the bottom hole assembly (BHA). For a continuous process two options for extending the pipe are available: welding another pipe on the existing pipe or in situ pipe forming.

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1.2.3 Advantages of SOCCS
SOCCS is a mono-diameter drilling method. Compared to conventional drilling methods, drilling with SOCCS:

- Is more time- and cost-effective; tripping the drill string to run a casing is not required. The decreased volume of the total mono-diameter drill results in less soil excavation.
- Has a reduced (environmental) footprint; the surface piercing area of the well is much smaller. Because of the mono-diameter concept, for example a conductor casing with an outer diameter of 600 mm can be reduced to 110 millimetres.
- Is safer (lower risk); the hole is cased just behind de BHA; the length of unsupported formation is kept at a minimum.
- Enables to drill deeper. Conventional methods restrict depth, due to the tapered casing construction. This is not the case with SOCCS.

1.2.4 Horizontal Directional Drilling Application
SOCCS was originally developed for drilling of wells for the oil and gas industry, but the method can be used for other applications as well. Trenchless installation of underground infrastructure for larger distances is one of them. The conventional HDD method is limited at approximately 2.5 kilometres; calculations show a distance of 25 kilometres for SOCCS in the distant future. Compared to conventional HDD, SOCCS supports/protects the formation during drilling and this ensures hole integrity. Also the wall friction of the pipe with the formation is absent; there is no relative movement between the outer pipe and the formation. With SOCCS the outer pipe is fixed, where in conventional HDD the entire pipe is pulled-in.

In 2013 Shell licensed SOCCS to A.Hak Drillcon. A. Hak commited to further develop SOCCS for application in HDD.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>area</td>
<td>m²</td>
</tr>
<tr>
<td>Aₘₘₙ</td>
<td>area of the annulus</td>
<td>m²</td>
</tr>
<tr>
<td>Aₘₘₙ₅OCCC</td>
<td>annular area SOCCS pipe</td>
<td>m²</td>
</tr>
<tr>
<td>Aₚ</td>
<td>discharge area</td>
<td>m²</td>
</tr>
<tr>
<td>Aᵢ</td>
<td>area of the inlet to the nozzle</td>
<td>m²</td>
</tr>
<tr>
<td>Aₙ</td>
<td>nozzle area</td>
<td>m²</td>
</tr>
<tr>
<td>Aₜ</td>
<td>throat area</td>
<td>m²</td>
</tr>
<tr>
<td>Aₙₗ</td>
<td>wall area</td>
<td>m²</td>
</tr>
<tr>
<td>αₜ</td>
<td>geometry factor</td>
<td>-</td>
</tr>
<tr>
<td>Bₚ</td>
<td>conduit geometry correction factor</td>
<td>-</td>
</tr>
<tr>
<td>Bₙ</td>
<td>viscometer geometry correction factor</td>
<td>-</td>
</tr>
<tr>
<td>b</td>
<td>jet pump area ratio</td>
<td>-</td>
</tr>
<tr>
<td>Cₙ</td>
<td>constant depending on the soil type</td>
<td>-</td>
</tr>
<tr>
<td>Cₙₖ</td>
<td>the angle of inclination correction factor</td>
<td>-</td>
</tr>
<tr>
<td>Cₘ</td>
<td>connection correction factor</td>
<td>-</td>
</tr>
<tr>
<td>Cₙₖₙₚ</td>
<td>fractional cutting concentration</td>
<td>-</td>
</tr>
<tr>
<td>Cₙₖₖₙₚ</td>
<td>cuttings concentration</td>
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<td>cutting size correction factor</td>
<td>-</td>
</tr>
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<td>c</td>
<td>cohesion</td>
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<tr>
<td>d₅ₜₜₙ</td>
<td>the mean cutting size</td>
<td>m</td>
</tr>
<tr>
<td>dₙₜₙ</td>
<td>blowout depth</td>
<td>m</td>
</tr>
<tr>
<td>dₙₘₙ</td>
<td>borehole diameter</td>
<td>m</td>
</tr>
<tr>
<td>dₙₚ</td>
<td>depth decrease curved section</td>
<td>m</td>
</tr>
<tr>
<td>dₚₚ</td>
<td>pipe diameter in centre line of the wall</td>
<td>m</td>
</tr>
<tr>
<td>dₙₚ</td>
<td>diameter of the diffuser</td>
<td>m</td>
</tr>
<tr>
<td>dₙₘ</td>
<td>hydraulic diameter</td>
<td>m</td>
</tr>
<tr>
<td>dₙ</td>
<td>internal diameter</td>
<td>m</td>
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<td>inner diameter old outer inverted SOCCS pipe</td>
<td>m</td>
</tr>
<tr>
<td>dₐₙₘ</td>
<td>reduced inner diameter of the original pipe</td>
<td>m</td>
</tr>
<tr>
<td>dₙₘₘₙₜ</td>
<td>minimum inner diameter ring</td>
<td>m</td>
</tr>
<tr>
<td>dₙₘ</td>
<td>inner diameter inverted reduced pipe</td>
<td>m</td>
</tr>
<tr>
<td>dₙ</td>
<td>diameter of the nozzle</td>
<td>m</td>
</tr>
<tr>
<td>dₙ</td>
<td>outside diameter</td>
<td>m</td>
</tr>
<tr>
<td>dₙₗₘ</td>
<td>outer diameter inverted section restart piece</td>
<td>m</td>
</tr>
<tr>
<td>dₙₗₘ</td>
<td>outer diameter original SOCCS pipe</td>
<td>m</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>SI Units</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>dp</td>
<td>drill string diameter</td>
<td>m</td>
</tr>
<tr>
<td>d_sp</td>
<td>true vertical depth end straight pipe</td>
<td>m</td>
</tr>
<tr>
<td>d_tvd</td>
<td>true vertical depth of the horizontal section</td>
<td>m</td>
</tr>
<tr>
<td>d_t</td>
<td>diameter throat</td>
<td>m</td>
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<tr>
<td>E</td>
<td>elastic modulus</td>
<td>N/m²</td>
</tr>
<tr>
<td>e</td>
<td>eccentricity</td>
<td>-</td>
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<tr>
<td>F</td>
<td>force</td>
<td>N</td>
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<td>F⁻¹</td>
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<td>Fanning friction factor</td>
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<td>f_trans</td>
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<td>h</td>
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<td>h_tvd</td>
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<td>m</td>
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<tr>
<td>K</td>
<td>minimum stain value</td>
<td>N/m²</td>
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<tr>
<td>K_di</td>
<td>diffuser friction-loss coefficient</td>
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<tr>
<td>K_en</td>
<td>throat entry friction-loss coefficient</td>
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<tr>
<td>K_n</td>
<td>nozzle friction-loss coefficient</td>
<td>-</td>
</tr>
<tr>
<td>K_td</td>
<td>throat-diffuser friction-loss coefficient</td>
<td>-</td>
</tr>
<tr>
<td>k</td>
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<td>Pa.s</td>
</tr>
<tr>
<td>k_p</td>
<td>Power law consistency index</td>
<td>Pa.s</td>
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<tr>
<td>L</td>
<td>length</td>
<td>m</td>
</tr>
<tr>
<td>L_bo</td>
<td>distance between the exit point and blowout</td>
<td>m</td>
</tr>
<tr>
<td>L_d</td>
<td>diffuser length</td>
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</tr>
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<td>L_tsp</td>
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<td>L_cp</td>
<td>length curved pipe section</td>
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<td>L_t</td>
<td>throat length</td>
<td>m</td>
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<tr>
<td>M</td>
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<tr>
<td>M_gd</td>
<td>cutting mass produced by the drill bit</td>
<td>kg</td>
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<td>M_tm</td>
<td>mass transported by mud</td>
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<td>mass flow rate</td>
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<td>m₁</td>
<td>mass flow rate of the liquid primary flow</td>
<td>kg/s</td>
</tr>
<tr>
<td>m₂</td>
<td>mass flow rate of the liquid secondary flow</td>
<td>kg/s</td>
</tr>
<tr>
<td>m₃</td>
<td>mass flow rate of the gas secondary flow</td>
<td>kg/s</td>
</tr>
<tr>
<td>N</td>
<td>pressure ratio</td>
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<td>N_reg</td>
<td>generalised Reynolds number</td>
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<tr>
<td>n</td>
<td>Herschel-Bulkley flow index</td>
<td>-</td>
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<td>Symbol</td>
<td>Definition</td>
<td>SI Units</td>
</tr>
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<td>--------</td>
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</tr>
<tr>
<td>(n_p)</td>
<td>Power law flow index</td>
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</tr>
<tr>
<td>(n_{pipes})</td>
<td>number of nozzle inlet pipes</td>
<td>-</td>
</tr>
<tr>
<td>(P_a)</td>
<td>annular drilling fluid pressure</td>
<td>N/m²</td>
</tr>
<tr>
<td>(P_b)</td>
<td>bursting pressure</td>
<td>N/m²</td>
</tr>
<tr>
<td>(P_{bh})</td>
<td>minimum fluid pressure in the borehole at BHA</td>
<td>N/m²</td>
</tr>
<tr>
<td>(P_d)</td>
<td>discharge pressure</td>
<td>N/m²</td>
</tr>
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APPENDIX A: CAVITY EXPANSION METHOD

The method described in this appendix is more or less the same text as published in NEN3651 (Dutch norms) and the report 'Maximum allowable pressures' (Keulen, 2001).

In the drilling process, drilling fluid is circulated to transport the cuttings from the bit to the surface. If the pressure in the uncased hole exceeds the pressure needed for plastic yielding or hydrofracture, a blowout occurs. Small paths grow where the drilling fluids can seep through. (Nederlands Normalisatie-instituut, 2012) At distance from the bore wall pressures decrease rapidly (Staheli, 1998).

Vesic first introduced the expansion theory for cavities in soil mass in 1972 (Vesic, 1972). Luger and Hergarden adjusted the theory further in 1988 to use it in HDD applications.

Vesic developed his method to determine the size of the plastic zone that is assumed to originate from increased fluid pressure in a borehole. The following assumptions were made:

- The medium is homogenous, isotropic and has infinite dimensions.
- In the cavity there is a uniformly distributed internal pressure.
- The soil behaves in the plastic zone as a compressible plastic solid, defined by Coulomb-Mohr shear strength parameters \( c, \phi \), as well as an average volumetric strain \( \Delta \).
- Beyond the plastic zone the soil is assumed to behave as a linearly, deformable, isotropic solid defined by a modulus of deformation \( E \) and a Poisson's ratio \( \nu \).
- Prior to the application of the load the entire soil mass has an isotropic effective stress \( q \).
- The body forces within the plastic zone are negligible when compared with existing and newly applied stresses.

Figure A - 1 represents the cavity and considers a cylindrical symmetrical problem of a gravity free medium. As shown in the figure, the shear stresses acting on an element vanish. This result in an equilibrium equation reduced to:

\[
\frac{\delta \sigma_r}{\delta r} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \quad (A-1)
\]

With:
- \( \sigma_r \) the radial stress \([N/m^2]\)
- \( r \) the distance to the centre of the cavity \([m]\)
- \( \sigma_\theta \) the circumferential stress \([N/m^2]\)

Luger and Hergarden assumed the mud in the soil to exert pressure on the soil. If this pressure is larger than a certain value, plastic deformation will occur. When the pressure increases the plastic zone will grow. To prevent a blowout, the pressure has to be determined which results in a plastic zone where the radius of the plastic zone is smaller than the safe radius around the hole. This safe radius is based on the distance from the centre of the hole to the surface (cover depth).
A hole is drilled as in Figure A - 1. The initial radius of the hole, $R_0$, increases under the influence of the drilling mud as shown in Figure A - 2. When a maximal allowable radius, $R_{p,max}$, of the hole is chosen, the radial stress, $\sigma_r$, can be derived as a function of the distance to the hole, $r$ (line B). At the boundary of the hole and the soil the mud pressure and the radial stress are equal. The maximum allowable pressure is given by the intersection between line A and B.

**FIGURE A - 1: REPRESENTATION OF CAVITY**

**FIGURE A - 2: BOREHOLE MUD PRESSURE VERSUS BOREHOLE RADIUS (LINE A) AND RADIAL TOTAL STRESS VERSUS R-COORDINATE.**
The highest pressure that can be sustained by the cavity is called the limit pressure $P_{\text{lim}}$. To prevent blowouts the upper boundary of the mud pressure, the maximum allowable pressure is set to 90 percent of the limit pressure.

Luger and Hergarden's theory resulted in a set of equations to calculate the maximum allowable mud pressure in a borehole.

These equations are based on the assumption of axial symmetry around the borehole and the following conditions:

- Equilibrium (A-1).
- Hooke's law for increments of elastic deformation.
- Mohr-Coulomb’s failure criterion.
- Absence of isotropic deformations in the plastic zone.

Material (soil) failure can be described by the Mohr-Coulomb Failure Criteria. This theory states soil failure occurs by a critical combination of normal stress and shear stress. Soil derives its shear strength from cohesion and frictional resistance, see Figure A - 3.

![Figure A - 3: Shear Strength Soil](image)

Mohr developed a representation of both two- and three-dimensional stresses and described a failure criterion based on the stress circle, see Figure A - 4.
Cohesion $(C')$

$$\Phi = \Phi'$$

Shear Strength $(S)$

$$\text{Normal Stress } (\sigma_n = \sigma' = \gamma^* h)$$

$$\sigma_3 \quad \sigma_1$$

$$\frac{(\sigma_1 + \sigma_3)}{2}$$

$$\frac{(\sigma_1 - \sigma_3)}{2}$$

With:
- $\sigma_1$ and $\sigma_3$ are the principal normal stresses [N/m$^2$]
- $c$ the cohesion [N/m$^2$]
- $\phi$ the internal friction angle [$^\circ$]
- $\sigma'_0$ the initial effective stress [N/m$^2$] given by:

$$\sigma'_0 = \gamma_s * h - u \quad (A-4)$$

With:
- $\gamma_s$, average unit soil weight [N/m$^3$]
- $h$, the cover depth [m]
The radius of Mohr’s circle describes the effective pressure where the soil starts to fail. To translate this to a downhole situation and to calculate, at which mud pressure the formation will fail, the weight of the soil and the pore pressures (vertical stress in the formation) have to be added to equation (A-3). This results in:

\[ P_f = (c \cdot \cot \varphi + \sigma'_{o}) \cdot \sin \varphi + \sigma'_{o} + u \]  

(A-5)

Rewritten:

\[ P_f = \sigma'_{o} \cdot (1 + \sin \varphi) + c \cdot \cos \varphi + u \]  

(A-6)

With:
- \( P_f \) the drilling fluid pressure [N/m²]
- \( \sigma'_{o} \) the effective pressure [N/m²]
- \( c \) the weight of the soil [N/m²]
- \( \varphi \) the angle of friction [-]
- \( u \) the pore pressure (water column) [N/m²]

To calculate the effectivemud pressures equations (A-7) and (A-8) can be used:

\[ P' = P - u \]  

(A-7)

\[ P'_f = P_f - u \]  

(A-8)

With:
- \( P' \) the effective pressure [N/m²]
- \( P \) the pressure [N/m²]
- \( P'_f \) the effective drilling fluid pressure [N/m²]

For mud pressures not reaching \( P'_f \) the radius of the borehole is described by equation (A-9):

\[ R_g = R_0 \cdot \left( 1 \cdot \left( \frac{P' - \sigma'_{o}}{G} \right) \right)^{0.5} \]  

(A-9)

With:
- \( R_g \) the radius of the borehole [m]
- \( R_0 \) the initial radius of the borehole [m]
- \( G \) the shear modulus [N/m²] given by:

\[ G = \frac{E}{2(1 + \nu)} \]  

(A-10)

With:
- \( E \) the elastic modulus of the soil [N/m²]
- \( \nu \) the Poisson ratio [-]

Equation (A-9) describes line A in Figure A - 2 not exceeding \( P_f \) and is the result of the application of Hook’s law on the increments of stresses and strains.

To construct line B of Figure A - 2 a particle is considered at the transition between the elastic and plastic zone. Using equation (A-6) and (A-9) the original position can be determined. This results in equation (A-11)
\[
\begin{align*}
s_0 &= s \left( 1 - \left( \frac{(\sigma'_0 \sin\varphi + c \cos\varphi)}{G} \right) \right)^{0.5} \\
\end{align*}
\] (A-11)

With:
- \(s_0\) the particle's initial position [m]
- \(s\) the particle's actual position [m]

The assumption is made that volume change doesn't occur in the plastic zone. The volume between \(r=s_0\) and \(r=s (=R_p)\) is equal to the volume \(r=R_0\) and \(r = R_g\). The current radius of the borehole can be expressed as a function of the initial radius and the radius of the plastic zone, see equation (A-12):

\[
R^2_g = R^2_0 + R^2_p \times \left( \frac{(\sigma'_0 \sin\varphi + c \cos\varphi)}{G} \right) \\
\] (A-12)

With:
- \(R_p\) the radius of the plastic zone [m]

Equation (A-12) describes the geometry of the hole and the plastic zone. Using the equilibrium condition (A-1), the value of radial stress at the transition from elastic and plastic behaviour and the Mohr-Coulomb failure criterion the radial stress as a function of the \(r\)-co-ordinate can be determined:

\[
\sigma'_r = \left( P'_f + c \cot\varphi \right) \times \left( \frac{R_p}{R} \right)^{2\sin\varphi} - c \cot\varphi \\
\] (A-13)

With:
- \(\sigma'_r\) the radial effective stress [N/m²]

Equation (A-13) describes line B from Figure A - 2 when \(R_p\) is substituted by \(R_{p,\text{max}}\).

Combining equation (A-12) and (A-13) the relation between the effective pressure in the hole and the actual radius of the hole is described.

\[
P' = \left( P'_f + c \cot\varphi \right) \times \left( \frac{1 - \left( \frac{R_0}{R_p} \right)^{2\sin\varphi}}{Q_p} \right) - c \cot\varphi \\
\] (A-14)

With Q:

\[
Q_p = \frac{(\sigma'_0 \sin\varphi + c \cos\varphi)}{G} \\
\] (A-15)

Equation (A-14) described line A in Figure A - 2 for pressures exceeding \(P_f\).

To find the maximum effective mud pressure, the intersection between line A and B in Figure A - 2 is given by:

Confidential
\[ P'_{\text{max}} = (P'_f + c \cdot \cot \varphi) \times \left( \left( \frac{R_0}{R_{p,\text{max}}} \right)^2 + Q \right)^{-\frac{\sin \varphi}{1+\sin \varphi}} - c \cdot \cot \varphi \] (A-16)

With:

- \( R_{p,\text{max}} \) the maximum allowable radius of the plastic zone [m]

The value of \( R_{p,\text{max}} \) for a sand formation can be determined based on the maximum strain of the wall of the bore hole.

The strain of the borehole wall equals:

\[ \varepsilon_g = \frac{R_p}{R_0} - 1 \] (A-17)

With:

- \( \varepsilon_g \) the strain of the bore hole wall [%] as result of the mud pressure \( P \).

Substitution of equation (A-17) in equation (A-12) gives:

\[ R_o^2 \times (\varepsilon_g + 1)^2 = R_o^2 + R_p^2 \times Q \] (A-18)

Equation (A-18) can be written as:

\[ R_p^2 = \frac{R_o^2}{Q_p} \times 2 \times \varepsilon_g \] (A-19)

The maximum allowable radius of the plastic zone is then given by the following equation:

\[ R_{p,\text{max}} = \sqrt{\frac{R_o^2}{Q_p} \times 2 \times \varepsilon_{g,\text{max}}} \] (A-20)

For sand the value \( \varepsilon_{g,\text{max}} = 0.05 \).

For peat and clay a value of 0.5h for \( R_{p,\text{max}} \) is recommended.

As discussed the highest (effective) pressure the cavity can withstand is the limit pressure (\( P_{\text{lim}} \)). The limit pressure is calculated when \( R_{p,\text{max}} \) approaches infinity, resulting in:

\[ P'_{\text{lim}} = (P'_f + c \cdot \cot \varphi) \times Q_p^{-\frac{\sin \varphi}{1+\sin \varphi}} - c \cdot \cot \varphi \] (A-21)

If the calculated maximum allowable effective mud pressure is 90% or more of the effective limit pressure, than the effective limit pressure has to be taken as the maximum allowable effective mud pressure.

At shallower parts near the surface the soil is less firm and while drilling, a wedge can be pushed out. It is assumed this will occur at drilling depths less than 5 times the borehole diameter. The maximum allowable effective pressure then is:

Confidential
\[ P'_{\text{max}} = \sigma'_o \left( 1 + 0.3 \cdot \frac{h}{d_{bh}} \right) \]  

(A-22)

With:

- \( d_{bh} \) the borehole diameter [m]

The total maximum allowable pressure is a combination between the maximum allowable effective pressure and the groundwater pressure, resulting in:

\[ P_{\text{max}} = P'_{\text{max}} + u \]  

(A-23)
DRILLING FLUID RHEOLOGY

Drilling fluid rheology describes the deformation and flow of a drilling fluid mixture. This includes elastic, plastic and viscous behavior of a fluid mixture.

Viscosity is an important rheological parameter and is a measure of a fluid's resistance to flow. Two measures of viscosity can be distinguished: dynamic (or absolute) and kinematic viscosity.

The symbol used for dynamic viscosity is $\mu$ and it is measured in centipoise [cP]. One centipoise equals 0.001 N/s/m$^2$.

Dynamic viscosity is a measure of internal resistance and is defined as the ratio of viscous shear stress $\tau$ (N/m$^2$) to shear rate $\gamma$ (1/s). The shear stress is the force required per unit area to move the fluid at a given shear rate. The shear rate is the velocity gradient measured perpendicular to the flow. The formula that describes the relation for dynamic viscosity is given by:

$$\mu = \frac{\tau}{\gamma} = \frac{\tau}{\frac{dx}{dy}}$$  \hspace{1cm} (B-1)

With:
- $\mu$ the dynamic viscosity [cP]
- $\tau$ the viscous shear stress [N/m$^2$]
- $\gamma$ the shear rate [1/s]

Equation (B-1) shows a linear relation between the shear stress and the shear rate. Fluids with this property are called Newtonian fluids. Fluids that don’t have this property are called non-Newtonian fluids. Most drilling fluids are non-Newtonian fluids.

The relation between shear stress and shear rate is measured using a viscometer. In general the instrument consists of a cylindrical cup and a bob of which one is rotational and the other one is stationary. By rotating at different known speeds the torque required for these rotations can be measured. Often this is done at six speeds: 3, 6, 100, 200, 300 and 600 rpm.
If the measured relation between shear stress and shear rate is according to equation (B-1) and we thus have a Newtonian fluid, some parameters for pipe flow can be determined given a certain pressure loss.

The velocity distribution:

\[ V(r) = \left( \frac{\Delta P}{4 \mu L} \right) \times (R^2 - r^2) \]  (B-2)

With:
- \( V(r) \) the velocity [m/s]
- \( \Delta P \) the pressure loss [N/m²]
- \( L \) the length of the pipe [m]
- \( R \) the inner radius of the pipe [m]
- \( r \) the radial location [m]

The flow rate:

\[ Q = \frac{\pi R^4 \Delta P}{8 \mu L} \]  (B-3)

With:
- \( Q \) the flow rate [m³/s]

The viscous shear stress at radial distance \( r \):

\[ \tau = \frac{r \Delta P}{2L} \]  (B-4)

Equation (B-4) applies for steady laminar flow in circular pipes for both Newtonian- and non-Newtonian fluids.

Most drilling fluids are non-Newtonian fluids and their behavior can be characterized by different models.

One of the functions of drilling fluid is to transport cuttings to the surface. During pumping the fluid’s viscosity must be low enough to be pumped, but when pumping is stopped and the fluid comes to a standstill it must be able to keep the solids into suspension, form a gel structure. This can be achieved by using a shear thinning fluid. As shear rate decreases the fluids viscosity increases. A shear thickening fluid has opposite properties.

Three models commonly used to describe the shear behavior of a non-Newtonian fluid are (Figure B - 2):

- The Bingham Plastic Model
- The Power Law Model
- The Herschel-Bulkley Model
The Bingham Plastic model is often used to describe drilling fluids in HDD. The model assumes a certain force has to be applied to bring the fluid in motion; the fluid’s yield stress has to be overcome.

After this the fluid shows a linear relation between shear stress and shear rate. The model is described by:

$$\tau = \tau_y + \mu \gamma$$  \hspace{1cm} (B-5)

With:

- $\tau_y$ the yield stress [N/m$^2$]

Most drilling fluids are not fully Bingham plastic fluids. The Bingham Plastic model estimates its shear stresses based on parameters estimated with high shear rates. Therefore prediction of shear behaviour in the lower shear rate region where HDD acts is very poor (resulting in overestimating pressure losses).

The Power Law model doesn’t assume a yield stress but tries to characterize the shear thickening behaviour of a fluid with the following expression:

$$\tau = k_p \gamma^n$$  \hspace{1cm} (B-6)

With:

- $k_p$ the consistency index factor [Pas$^n$]
n_p the fluid flow index [-]

Where n_p:

\[ n_p = 3.32 \times \log_{10} \left( \frac{\theta_{600}}{\theta_{300}} \right) \] (B-7)

And k_p:

\[ k_p = 0.478803 \times \left( \frac{\theta_{300}}{511^{n_p}} \right) \] (B-8)

With:
- \( \theta_{300} \) the shear stress measured with the viscometer at 300 rpm
- \( \theta_{600} \) the shear stress measured with the viscometer at 600 rpm

While the Power Law model provides reasonable predictions at higher shear rates, it performs poor in the lower region (0-100 rpm). This is explained by the absence of a yield stress parameter in the model.

A combination between the Bingham Plastic model and Power Law model is the Herschel-Bulkley model, also referred to as the yield-power law model. The Herschel-Bulkley model is described by the following equation:

\[ \tau = \tau_y + k \times \gamma^n \] (B-9)

With:
- \( k \) the consistency index factor [Pa.s^n]
- \( n \) the fluid flow index [-]

Where \( \tau_y \):

\[ \tau_y = 0.478803 \times (2 \times \theta_3 - \theta_6) \] (B-10)

With:
- \( \theta_3 \) the shear stress measured with the viscometer at 3 rpm
- \( \theta_6 \) the shear stress measured with the viscometer at 6 rpm

The fluid flow index \( n \) is given by:

\[ n = 3.32 \times \log_{10} \left( \frac{\theta_{600} - (2 \times \theta_3 - \theta_6)}{\theta_{300} - (2 \times \theta_3 - \theta_6)} \right) \] (B-11)

And \( k \):

\[ k = 0.478803 \times \frac{\theta_{300} - (2 \times \theta_3 - \theta_6)}{511^n} \] (B-12)
The Herschel-Bulkley model more accurately represents fluid behavior of non-Newtonian drilling fluids in both low and high shear rate regions. A comparison of the treated models and actual measurements is given in Figure B - 3.

**FIGURE B - 3: RHEOLOGICAL MODELS VS. MEASUREMENTS**

To predict pressure losses in a pipe using the Herschel-Bulkley method requires a numerical approach. As this is complex, this report presents an analytical method mainly based on the Herschel-Bulkley method to predict pressure losses in a pipe and annulus (American Petroleum Institute, 2010).

Figure B - 4 shows advised drilling fluid mixtures and their properties for different soil types by Cebo Holland BV.
This table shows the properties of different drilling fluids from Cebo Holland B.V. For different shear rates of the deflection of the Fann viscometer is given. This is also done for the gel strength of the fluid after 10 seconds and 10 minutes. The Marsh Funnel (MF) readings give an impression of the viscosity of the drilling fluid. The fluid loss (FL) after 7.5 minutes represents the ability of the drilling fluid to seal the borehole and prevent fluid losses.
APPENDIX C: CRITICAL CUTTINGS TRANSPORT VELOCITY

Transportation of cuttings produced during the drilling process is done by drilling fluid. Given the rheological parameters of the drilling fluid (which define the carrying capacity), the fluid must have a certain flow velocity to keep the cutting particles in suspension. It is desired to determine the minimum velocity at which the particles stay in suspension, as this minimises pressure losses due to friction in the annulus. If the flow velocity is lower than the critical transport fluid velocity, particles will deposit and accumulate at the bottom of the pipe. A cutting bed is formed and the annular flow area decreases, resulting in an increase of flow velocity. The cuttings bed will stop growing once the velocity reaches the point where it equals the critical transport flow velocity, equilibrium is formed.

![Figure C-1: Bed Forming](image)

FIGURE C-1: BED FORMING

To determine the critical transport fluid velocity the Cutting-Transport model from Larsen et al. is used (Larsen, Pilehvari, & Azar, 1997). The model is in field units.

The critical transport fluid velocity is the sum of the cuttings transport velocity and the equivalent slip velocity, see equation (C-1). The equivalent slip velocity is defined as the velocity difference between the cuttings and the drilling fluid.

\[
V_c = V_{cut} + V_{slip}
\] (C-1)

With:

- \(V_c\) the critical transport fluid velocity [m/sec]
- \(V_{cut}\) the cuttings transport velocity [m/sec]
- \(V_{slip}\) the equivalent slip velocity [m/sec]

The cuttings transport velocity can be expressed through a mass balance on the cuttings see equation (C-2).
\[ M_{gd} = M_{tm} \]  

With:
- \( M_{gd} \) cuttings mass produced by the drillbit [kg]
- \( M_{tm} \) the mass transported by the mud [kg]

Equation (C-2) can be written as:

\[ \gamma_{cut} \times Q_{prod} = V_{cut} \times A_{ann} \times C_{conc-fr} \times \gamma_{cut} \]  

With:
- \( \gamma_{cut} \) the density of the cuttings [kg/m\(^3\)]
- \( Q_{prod} \) the volumetric production rate of cuttings [m\(^3\)/sec]
- \( A_{ann} \) the area of the annulus [m\(^2\)]
- \( C_{conc-fr} \) the fractional cuttings concentration by volume at the cuttings transport velocity [-]

Equation (C-3) can be written as:

\[ V_{cut} = \frac{Q_{inj}}{A_{ann} \times C_{conc-fr}} \]  

The rate of penetration can be determined from the volumetric production rate of the cuttings by equation (C-5).  

\[ ROP = \frac{3600 \times Q_{prod}}{A_{h}} \]  

With:
- \( ROP \) the rate of penetration [m/hr]
- 3600 is the number of seconds per hour [sec/hr]
- \( A_{h} \) is the area of the drilled hole [m\(^2\)]

Combining equation (C-4) and (C-5) results in an expression for the cuttings transport velocity.

\[ V_{cut} = \frac{ROP}{3600 \times \left( \frac{A_{p}}{A_{h}} \right) \times C_{conc}} \]  

Or:

\[ V_{cut} = \frac{ROP}{3600 \times \left( \frac{d_{p}}{d_{bh}} \right)^2 \times C_{conc}} \]  

With:
- \( A_{p} \) the area of the drill string [m\(^2\)]
- \( C_{conc} \) the cuttings concentration by volume at the cuttings transport velocity [%]
- \( d_{p} \) the drill string diameter [m]
- \( d_{bh} \) the borehole diameter [m]
From experimental data it is found that the annular cuttings concentration, at the cuttings transport velocity can be expressed as a function of the rate of penetration see equation (C-8).

\[ C_{conc} = 0.005419344 \times ROP + 0.505 \]  

(C-8)

The equivalent slip velocity is predicted by calculating the apparent viscosity, given by equation (C-9).

\[ \mu_a = \mu_p + \frac{8 \times \tau_y \times (d_{bh} - d_p)}{V_c} \]  

(C-9)

With:
- \( \mu_a \) the apparent viscosity \([\text{Pa.s}]\)
- \( \mu_p \) the plastic viscosity \([\text{Pa.s}]\)
- \( \tau_y \) the yield point \([\text{N/m}^2]\)

The predicted equivalent slip velocity is given by equation (C-10) or (C-11).

For \( \mu_a < 0.053 \) Pa.s:

\[ \bar{V}_{slip} = 16.929 \times \mu_a + 9.862 \]  

(C-10)

For \( \mu_a > 0.053 \) Pa.s:

\[ \bar{V}_{slip} = 83.8 \times \mu_a + 6.32 \]  

(C-11)

With:
- \( \bar{V}_{slip} \) the predicted equivalent slip velocity \([\text{m/sec}]\)

To generalise the predicted equivalent slip velocity, correction factors for angle of inclination, cutting size and mud weight have been introduced.

For the angle of inclination (90° degrees for a horizontal pipe) the correction factor is given by equation (C-12).

\[ C_{ang} = 0.0342 \times \theta_{ang} - 0.000233 \times \theta_{ang}^2 - 0.213 \]  

(C-12)

With:
- \( C_{ang} \) the angle of inclination correction factor \([-]\)
- \( \theta_{ang} \) the angle of inclination from the vertical \( [^\circ] \)

The cutting size correction factor is given by equation (C-13).

\[ C_{size} = -40.945 \times d_{50 \text{cut}} + 1.286 \]  

(C-13)

With:
- \( C_{size} \) the cutting size correction factor \([-]\)
- \( d_{50 \text{cut}} \) the mean cutting size \([\text{m}]\)
The correction for the mud weight is given by equation (C-14) or (C-15).

For $\gamma_m < 1042.5$ kg/m$^3$:

$$C_{mwt} = 1 \quad (C-14)$$

For $\gamma_m > 1042.5$ kg/m$^3$:

$$C_{mwt} = 1.28971 - 0.0002779 \times \gamma_m \quad (C-15)$$

The generalised equivalent slip velocity is given by equation (C-16).

$$V_{slip} = \bar{V}_{slip} \times C_{ang} \times C_{size} \times C_{mwt} \quad (C-16)$$

As equation (C-9) needs the critical transport fluid velocity to determine the apparent viscosity, it is necessary to iterate equation (C-9) to (C-16) and (C-1) to approximate the critical transport fluid velocity. For the first iteration an estimation of the critical transport fluid velocity has to be made.

During drilling the SOCCS pipe will follow the BHA at a certain distance. As the annulus of the uncased hole is larger than the SOCCS pipe annulus and critical transport fluid velocities increase with diameter, the uncased hole is normative for the calculation. To determine the velocity in the SOCCS pipe the following equation can be used:

$$V_{c,SOCCS} = V_c \times \frac{A_{ann}}{A_{ann,SOCCS}} \quad (C-17)$$

With:
- $V_{c,SOCCS}$ the critical transport fluid velocity [m/sec]
- $A_{ann,SOCCS}$ the annular area in the SOCCS pipe [m$^2$]
APENDIX D: SOCCE REACH SENSITIVITY ANALYSIS AND MAXIMUM REACH SIMULATION

This appendix describes a method to determine the sensitivity of the inversion distance of the SOCCE technology to different factors followed by a method to determine the maximum inversion distance. These methods are applied on a model developed by R. Albert to calculate the maximum inversion distance (Albert R., SOCCE Distance Capabilities Model, 2014). The basis of this model is the ‘Von Mises Theorem’.

The ‘Von Mises Theorem’ predicts when a ductile solid will yield under multi-axial loading conditions. The following text of the derivation of the ‘Von Mises Theorem’ is based on the supplement provided with the course EAS 4200C Aerospace Structures of the University of Florida in Fall 2009 (University of Florida, 2009).

A solid deforms when a force is applied, in other words when work is done on a solid deformation takes place. The amount of deformation of the solid is proportional to the work done on the solid. This work is stored as energy in the solid as potential energy, which is called the strain energy. The distribution of the strain energy in the solid may not be uniformly. The strain energy per unit volume is given by:

\[ U = \iiint \sigma(x, y, z)dVol \]  

\[ (D-1) \]

With:
- \( U \) the strain energy per unit volume [J]
- \( U_0 \) the strain energy density [J/m³]
- \( Vol \) the volume [m³]

In the case of uniaxial stress state, the strain energy is equal to the area under the stress-strain curve, see Figure D - 1.

![Figure D - 1: Stress-Strain Curve and Strain Energy](image-url)
The area under the stress-strain curve is equal to:

\[ U_0 = \frac{1}{2} \sigma \varepsilon \]  

(D-2)

With:
- \( \sigma \) the stress [N/m\( ^2 \)]
- \( \varepsilon \) the strain [%]

For the general 3-D case the strain energy density is expressed as:

\[ U_0 = \frac{1}{2} \left( \sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \sigma_z \varepsilon_z + \tau_{yx} \gamma_{yx} + \tau_{zx} \gamma_{zx} + \tau_{xy} \gamma_{xy} \right) \]  

(D-3)

With:
- \( \tau \) the shear stress [N/m\( ^2 \)]
- \( \gamma \) the shear strain [%]

If the solid is loaded within the elastic zone, the strain energy can be completely recovered by unloading the solid. Equation (D-3) can be simplified by considering a coordinate system that is parallel to the principal stress directions. In this system shear components don’t exist. Equation (D-3) results in:

\[ U_0 = \frac{1}{2} \left( \sigma_1 \varepsilon_1 + \sigma_2 \varepsilon_2 + \sigma_3 \varepsilon_3 \right) \]  

(D-4)

The linear relationship for stresses and strains is given by:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3
\end{bmatrix} = \frac{1}{E} \begin{bmatrix}
1 & -\nu & -\nu \\
-\nu & 1 & -\nu \\
-\nu & -\nu & 1
\end{bmatrix} \begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3
\end{bmatrix}
\]  

(D-5)

With:
- \( E \) the elastic modulus [N/m\( ^2 \)]
- \( \nu \) the Poisson ratio [-]

Substituting (D-5) in (D-4) results in:

\[ U_0 = \frac{1}{2E} \left( \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu (\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1) \right) \]  

(D-6)

The strain energy density of a point in a solid can be thought of as consisting of two parts: the dilatational strain energy density \( U_h \), due to change in volume and distortional strain energy density, \( U_d \), responsible for change in shape. In order to determine these components, we divide the stress matrix into similar components: the dilatational stress matrix, \( \sigma_h \), and the deviatoric matrix, \( \sigma_d \).

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3
\end{bmatrix} = \begin{bmatrix}
\sigma_h \\
\sigma_h \\
\sigma_h
\end{bmatrix} + \begin{bmatrix}
\sigma_{1d} \\
\sigma_{2d} \\
\sigma_{3d}
\end{bmatrix}
\]  

(D-7)
Where the dilatational component $\sigma_h$, also known as the volumetric stress, is defined as:

$$\sigma_h = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad (D-8)$$

The dilatational energy density can be obtained by substituting equation (D-8) into equation (D-6).

$$U_h = \frac{1}{2E} \left( \sigma_h^2 + \sigma_h^2 + \sigma_h^2 - 2 \cdot v \cdot (\sigma_h \cdot \sigma_h + \sigma_h \cdot \sigma_h + \sigma_h \cdot \sigma_h) \right) \quad (D-9)$$

This can be written as:

$$U_h = \frac{3 \cdot (1 - 2 \cdot v)}{2E} \cdot \sigma_h^2 \quad (D-10)$$

$$U_h = \frac{3 \cdot (1 - 2 \cdot v) \cdot \sigma_1 \cdot \sigma_2 + \sigma_3^2}{3} \quad (D-11)$$

$$U_h = \frac{(1 - 2 \cdot v)}{6E} \cdot (\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2 \cdot v \cdot (\sigma_1 \cdot \sigma_2 + \sigma_2 \cdot \sigma_3 + \sigma_3 \cdot \sigma_1)) \quad (D-12)$$

The distortion part of the strain energy is found by subtracting the dilatational component from the total strain energy density.

$$U_d = U_0 - U_h = \frac{(1 + v)}{3E} \cdot \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1 \cdot \sigma_2 + \sigma_2 \cdot \sigma_3 + \sigma_3 \cdot \sigma_1$$

$$\quad = \frac{(1+v)}{3E} \cdot \frac{\sigma_1 - \sigma_2^2 + \sigma_2 - \sigma_3^2 + \sigma_3 - \sigma_1^2}{2} \quad (D-13)$$

The last term of equation (D-13) can be written as an equivalent stress called the von Mises stress, $\sigma_{VM}$.

$$U_d = \frac{(1 + v)}{3E} \cdot \sigma_{VM}^2 \quad (D-14)$$

Where:

$$\sigma_{VM} = \sqrt{\frac{\sigma_1 - \sigma_2^2 + \sigma_2 - \sigma_3^2 + \sigma_3 - \sigma_1^2}{2}} \quad (D-15)$$

The von Mises theorem states that a ductile solid will yield when the distortion energy density reaches a critical value for that material. Since this should also be true for uniaxial stress states, the critical value of the distortion energy can be estimated from the uniaxial test. At the yielding point in a uniaxial test the state of stress in terms of principal stress is given by: $\sigma_1 = \sigma_Y$, and $\sigma_2 = \sigma_3 = 0$. The distortion energy density becomes:

$$U_d = \frac{(1 + v)}{3E} \cdot \sigma_Y^2 \quad (D-16)$$
The energy density calculated in equation (D-16) is the critical distortional energy density for the material. According to the von Mises theorem, the material will yield under multi-axial conditions when the distortional energy is equal or greater than the critical value for the material:

\[
\frac{1 + \nu}{3E} \sigma_{VM}^2 \geq \frac{1 + \nu}{3E} \sigma_y^2
\]  
\[(D-17)\]

\[
\sigma_{VM}^2 \geq \sigma_y^2
\]  
\[(D-18)\]

Equation (D-18) states that the material yields when the von Mises stress exceeds the yield stress of a material. The von Mises stress can be written in terms of stress components as:

\[
\sigma_{VM} = \sqrt{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} \]  
\[(D-19)\]

For a two-dimensional stress plane, \(\sigma_3 = 0\), the von Mises stress defined in terms of principal stresses becomes:

\[
\sigma_{VM} = \sqrt{\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2}
\]  
\[(D-20)\]

In terms of general stresses:

\[
\sigma_{VM} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 - \sigma_{xx} \sigma_{yy} + 3 \tau_{xy}^2}
\]  
\[(D-21)\]

Equation (D-21) describes an ellipse. In Figure D - 2 equation (D-21) is plotted on the \(\sigma_1 - \sigma_2\) plane. The interior of the ellipse describes the combined biaxial loading stresses where the material is safe against yielding under static loading.

---

FIGURE D - 2: FAILURE ENVELOPE OF THE DISTORTION ENERGY THEORY
APPENDIX E: BLOWOUT AREA

When the BHA returns to the surface often a blowout occurs because the maximum allowable soil pressure decreases with decreasing cover depth. From geometry this location can be calculated. At this location the minimum fluid pressure is higher than the maximum allowable soil pressure, see Figure E - 1.

![Blowout Location Diagram]

FIGURE E - 1: BLOWOUT LOCATION

In conventional HDD exit points are drilled at angles between 5° and 35°. The first 3-4 sections are straight, after that curvature can start. The chosen exit angle depends on the minimum bending radius, $R_{\text{min}}$, of the pipe. Ruhrgas AG has recommended a rule of thumb in 1996 which links the minimum bending radius with the pipe outer diameter, $d_o$, see equation (E-1) and (E-2).

For an outer diameter <0.7m:

$$R_{\text{min}} = 1000 \times d_o$$

(E-1)

For an outer diameter >0.7m:

$$R_{\text{min}} = 1400 \times \sqrt{d_o^3}$$

(E-2)

With:

- $R_{\text{min}}$ the minimum bending radius [m]
- $d_o$ the pipe outer diameter [m]

The Drilling Contractors Association developed a design guideline describing a method to determine the minimum design radius. The design radius is depending on the following factors:

- Outer diameter of the pipe
- Wall thickness of the pipe
- Physical properties of the soil

The design radius can be determined from equation (E-3).

$$R_{\text{design}} = C \times \sqrt{d_o \times t}$$

(E-3)
With:
- \( R_{\text{design}} \) the design radius [m]
- \( C \) a constant depending on the soil type (see Table E-1) [-]
- \( t \) the pipe wall thickness [m]

### TABLE E - 1: CONSTANT DEPENDING ON THE SOIL TYPE, \( C \)

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>Cone Penetration Test CPT</th>
<th>Standard Penetration Test SPT</th>
<th>Elastic Modulus ( E_s ) [MPa]</th>
<th>Soil Constant ( C ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( q_c ) [MPa]</td>
<td>( N30 ) [Stroke/30cm]</td>
<td>( [MPa] )</td>
<td>( [-] )</td>
</tr>
<tr>
<td>Dense sand</td>
<td>&gt; 20</td>
<td>&gt; 50</td>
<td>100 - 200</td>
<td>8500</td>
</tr>
<tr>
<td>Medium dense sand</td>
<td>10 - 20</td>
<td>25 - 50</td>
<td>50 - 100</td>
<td>9400</td>
</tr>
<tr>
<td>Loose sand</td>
<td>5 - 10</td>
<td>10 - 25</td>
<td>20 - 50</td>
<td>10200</td>
</tr>
<tr>
<td>Stiff clay</td>
<td>&gt; 2</td>
<td>&gt; 8</td>
<td>10 - 25</td>
<td>10500</td>
</tr>
<tr>
<td>Medium stiff clay</td>
<td>1 - 2</td>
<td>2 - 8</td>
<td>5 - 10</td>
<td>11500</td>
</tr>
<tr>
<td>Soft clay</td>
<td>&lt; 1</td>
<td>&lt; 2</td>
<td>0 - 5</td>
<td>12500</td>
</tr>
</tbody>
</table>

The minimum allowable curvature for steel pipes is determined by equation (E-4).

\[
R_{\text{min}} = E_s \times \frac{SF}{K} \times d_o
\]  

(E-4)

With:
- \( R_{\text{min}} \) the minimum allowable curvature [m]
- \( E \) the elasticity modulus [N/m²]
- \( SF \) a safety factor (1.3) [-]
- \( K \) the minimum stain value [N/m²]
- \( d_o \) the outer diameter of the pipe [m]

Given a certain depth, \( D_{bo} \), at which the drilling fluid pressure is larger than the maximum allowable soil pressure and the distance, \( L_{bo} \), of the blowout to the exit point (when BHA returns to the surface) can be determined by the geometry relations arising from Figure E - 2.
FIGURE E - 2: GEOMETRICAL ANALYSIS EXIT POINT

For $d_{tvd} < L_{tsp} \cdot \sin(\alpha)$ equation (E-5) can be used:

$$L_{bo} = \frac{d_{bo}}{\tan \alpha_e} \quad (E-5)$$

With:
- $d_{tvd}$ the true vertical depth of the horizontal section [m]
- $L_{tsp}$ the true length of the straight pipe section to the surface [m]
- $L_{bo}$ the distance between the exit point and the blowout [m]
- $d_{bo}$ the depth where the drilling fluid pressure exceeds the maximum allowable soil pressure [m]
- $\alpha_e$ the exit angle of the drill [°]

For $D_{tvd} > L_{tsp} \cdot \sin(\alpha)$ the following relations can be derived:

$$d_{sp} = L_{tsp} \cdot \sin \alpha_e \quad (E-6)$$

With:
- $D_{sp}$ the true vertical depth at the point where the straight pipe section towards the surface starts [m]

With relation (E-7) the depth decrease over the curved section can be calculated with:

$$d_{cp} = d_{tvd} - d_{sp} \quad (E-7)$$
With:

- \( D_{cp} \), the depth decrease of the curved section [m]

Equation (E-8) describes the bending radius of the curved section.

\[
R = \frac{d_{cp}}{1 - \cos \alpha_e} \tag{E-8}
\]

With:

- \( R \), the bending radius of the curved section [m]

Using \( R \), \( y \) can be calculated.

\[
y = R - d_{tvd} \tag{E-9}
\]

With:

- \( y \), the difference between the radius and the true vertical depth of the horizontal section [m]

Using equation (E-10) and (E-11), one can find an expression for \( \beta \), see equation (E-12).

\[
y + d_{bo} = R - d_{tvd} + d_{bo} \tag{E-10}
\]

\[
y + d_{bo} = R \cdot \cos \beta \tag{E-11}
\]

\[
\beta = \cos^{-1} \left( \frac{R - d_{tvd} + d_{bo}}{R} \right) \tag{E-12}
\]

With:

- \( \beta \), the angle between the normal and the point of the blowout lying on the circumference of the circle that can be described by the bending radius [°].

Equation (E-13) describes the contribution of the curved section to the total horizontal distance between the point of the blowout and the exit point.

\[
L_{cp} = \left( (y + d_{sp}) \cdot \tan \alpha_e \right) - \left( (y + d_{bo}) \cdot \tan \beta \right) \tag{E-13}
\]

With:

- \( L_{cp} \), the length of the curved pipe section [m]

The total horizontal distance between the point of the blowout and the exit point is then given by equation (E-14).

\[
L_{bo} = L_{cp} + L_{tsp} \cdot \cos \alpha_e \tag{E-14}
\]
APPENDIX F: JET PUMP THEORY

This appendix describes an approach to construct a preliminary design of a jet pump. The text is based on chapter four: Jet pumps of the Pump Handbook (3rd edition) from Charles C. Heald (Karassik, Messina, Cooper, & Heald, 2001). This chapter describes the jet pump theory developed by Richard G. Cunningham.

First the efficiency of a design is estimated and optimized, after which further dimensions are determined using rules of thumb from literature.

A jet pump transfers energy from one flow (primary flow) to another flow (secondary flow). This can be from a gas or a liquid flow to a variety of flows: a liquid, a gas, and a two phase flow of gas-liquid mixture or a mixture with solid particles.

A jet pump is also referred to as an ‘eductor’ or an ‘ejector’. The main advantage of the jet pump is that the pump doesn’t have moving parts. This causes the pump to be simple, reliable, and cost effective. The disadvantage of the pump is its low efficiency, due to friction and mixing losses. Cavitation is an important phenomenon that must be tried to be avoided by design.

![FIGURE F - 1: JET PUMP OVERVIEW](image)

The liquid jet pump model is based on conservation equations for energy, momentum and mass. Friction coefficients (K) describe real-fluid losses. The assumptions for the theory are as follows:

1. The primary and secondary streams enter the mixing throat with uniform velocity distributions, and the mixed flows leave the throat and the diffuser with a uniform velocity profile.
2. The gas phase, if present, undergoes isothermal compression in the throat and diffuser.
3. All two-phase flows at the throat entry and exit consist of homogeneous bubble mixtures of gas in a continuous liquid.
4. Heat transfer from the gas to the liquid is negligible; the liquid temperature remains constant.
5. Change in solubility of the gas in the liquid from pressure P_s to P_d is negligible.
6. Vapour evolution from and condensation to the liquid are negligibly small.

With reference to Figure F - 1, Bernoulli’s principle states:

\[ P_i + \rho_1 \frac{V_i^2}{2} = P_o + \rho_1 \frac{V_n^2}{2} + K_n \rho_1 \frac{V_n^2}{2} \]  
\[ (F-1) \]

With:
- \( P_i \) the pressure of the fluid at the inlet of the nozzle [N/m²]
- \( \rho_1 \) the density of the primary fluid [kg/m³]
- \( V_i \) the velocity of the primary fluid [m/s]
- \( P_o \) the pressure of the fluid at the inlet of the throat [N/m²]
- \( V_n \) the velocity of the fluid at the nozzle [m/s]
- \( K_n \) the nozzle friction coefficient [-]

For:

\[ P_i = \bar{P}_i \]  
\[ (F-2) \]

With:
- \( \bar{P}_i \) the average pressure of the fluid at the inlet of the nozzle [N/m²]

The nozzle equation is:

\[ P_i - P_o = Z (1 + K_n) \]  
\[ (F-3) \]

With:
- \( Z \) the jet dynamic pressure [N/m²]

The two-phase secondary flow is described by:

\[ \frac{dP}{\rho} = V \, dV + d \left( K_{en} \frac{V^2}{2} \right) = 0 \]  
\[ (F-4) \]

With:
- \( K_{en} \) the throat entry friction-loss coefficient [-]
- \( V \) the velocity of the fluid [m/s]

The density of the secondary fluid as a function of static pressure and flow ratios \( M \) and \( \phi \) is:

\[ \rho_{2G} = \frac{m_2 + m_G}{Q_2 + Q_G} = \frac{m_1 \left[ \frac{m_2 + m_G}{m_1} \right]}{Q_1 \left( M + \phi \right)} = \rho_1 \left[ \frac{S + M + \gamma \phi_s}{m + \phi} \right] \]  
\[ (F-5) \]

With:
- \( \rho_1 \) the density of the liquid primary flow [kg/m³]
- \( \rho_{2G} \) the density of the bubbly secondary flow [kg/m³]
- \( m \) the mass flow rate [kg/s]
- \( m_1 \) the mass flow rate of the liquid primary flow [kg/s]
m₂ the mass flow rate of the liquid secondary flow [kg/s]
m₈ the mass flow rate of the gas secondary flow [kg/s]
Q₁ the volumetric rate of the liquid primary flow [m³/s]
Q₂ the volumetric rate of the liquid secondary flow [m³/s]
Q₆ the volumetric rate of the gas secondary flow [m³/s]
S the density ratio, ρ₂/ρ₁ [-]
M the liquid/liquid flow ratio, Q₂/Q₁ [-]
φ the gas flow ratio, Q₆/Q₁ [-]
φₛ the gas flow ratio at s, Q₆ₛ/Q₁ [-]
γ gas density ratio at s, ρ₆ₛ/ρ₁ [-]

Integration of equation (F-4) using the density relation and continuity results in the throat-entry equation:

\[ M \left( P_a - P_o \right) + P_x \phi_x \ln \frac{P_x}{P_o} = Z \frac{s \cdot M + \gamma \cdot \phi_s}{c^2} \ast \left( 1 + K_{en} \right) \ast (M + \phi_O)^2 \]  \hspace{1cm} (F-6)

Where:

\[ c = \frac{A_{2G\alpha}}{A_n} = \frac{A_t - A_n}{A_n} = \frac{1 - b}{b} \]  \hspace{1cm} (F-7)

Where:

\[ b = \frac{A_n}{A_t} \]  \hspace{1cm} (F-8)

With:
c the ratio between the bubbly secondary flow area and the nozzle area [-]
b the jet pump area ratio [-]
Aₙ the area of the nozzle [m²]
Aᵣ the area of the throat [m²]

Equating control volume forces and fluid momentum changes:

\[ (P_o - P_a) \ast A_{th} - \tau \ast A_w = (m_1 + m_2 + m_G) \ast V_{3t} \ast m_1 \ast V_n = (m_2 + m_G) \ast V_{2G0} \]  \hspace{1cm} (F-9)

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Where:

\[
\frac{\tau A_w}{A_t} = K_{th} \rho_{at} V_{at}^2
\]  \hspace{1cm} (F-10)

With:
- \(A_t\) the area of the throat [m²]
- \(\tau\) the shear stress [N/m²]
- \(A_w\) the wall surface [m²]
- \(K_{th}\) the throat friction-loss coefficient [-]

The mixed primary and secondary fluids from \(t\) to \(d\):

\[
\rho_{3t} V_{3t}, \rho_{3d} V_{3d}
\]

**FIGURE G - 1: DIFFUSER**

The flow from point \(t\) to \(d\) is described by:

\[
\int_t^d \frac{dP}{\rho} + \int_t^d V dV + \int_t^d \frac{\Delta P_f}{\rho_{3t}} = 0
\]  \hspace{1cm} (F-11)

With:
- \(\Delta P_f\) the pressure loss due to friction [N/m²]
- \(\rho_{3t}\) the combined density of the fluids in the throat [kg/m³]

Integrating equation (F-11) and substituting the density and continuity relations, the diffuser equation becomes:

\[
(P_o - P_t) + \frac{P_o \phi_x}{1 + M} \ln \frac{P_d}{P_t} = Z b^2 \left[ \frac{1 + S M + \gamma \phi_x}{1 + M} \right] \times \left[ (1 + M + \phi_x)^2 - \alpha^2 (1 + M + \phi_d)^2 - K_{dl} (1 + M + \phi_t) (1 + M) \right]
\]  \hspace{1cm} (F-12)

With:
- \(K_{dl}\) the diffuser friction-loss coefficient [-]
- \(\alpha\) the diffuser area ratio, \(A_i/A_d\) [-]

The previous equations described the jet pump from nozzle to diffuser for liquid-jet liquid but also for liquid-jet gas-liquid and liquid-jet gas pumps. For a liquid-jet liquid pumps the equations can be...
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simplified by elimination of all gas flow ratio terms, \( \phi \). This reduces equations (F-1), (F-6), (F-9) and (F-12).

For the nozzle:

\[
P_t - P_o = Z \cdot (1 + K_n) \tag{F-13}
\]

For the throat entry:

\[
P_s - P_o = Z \cdot S \cdot (1 + K_{en}) \cdot M^2/c^2 \tag{F-14}
\]

For the throat:

\[
P_t - P_o = Z \cdot \left[ \frac{2 \cdot b + 2 \cdot S \cdot M^2 \cdot b^2}{1 - b} - b^2 \cdot (2 + K_{th}) \cdot (1 + S \cdot M) \cdot (1 + M) \right] \tag{F-15}
\]

For the diffuser:

\[
P_d - P_t = Z \cdot b^2 \cdot (1 + S \cdot M) \cdot (1 + M) \cdot (1 - K_{di} - \alpha^2) \tag{F-16}
\]

The pump efficiency \( \eta \) is defined as the ratio of useful work rate on the secondary fluid to the energy extracted from the primary fluid:

\[
\eta = \frac{Q_2 \cdot (P_d - P_s)}{Q_1 \cdot (P_t - P_d)} = M \cdot N \tag{F-17}
\]

With:

\( N \) the pressure ratio [-]

By combining equation (F-13), (F-14), (F-15), (F-16) and (F-17), \( N \) can be written as:

\[
N = \frac{2b + \frac{2SM^2b^2}{1-b} - b^2(1 + K_{td} + \alpha^2)(1 + M)(1 + SM) - \left( \frac{SM^2}{c^2} \right)(1 + K_{en})}{1 + K_n - 2b + \frac{2SM^2b^2}{1-b} - b^2(1 + K_{td} + \alpha^2)(1 + M)(1 + SM) - (1 - j) \left( \frac{SM^2}{c^2} \right)(1 + K_{en})} \tag{F-18}
\]

With:

\( K_{td} \) the combined friction-loss coefficient for the throat and diffuser [-]

\( j=0 \) when jet loss occurs and \( j=1 \) when jet loss doesn’t occur [-]

In a normal case jet loss does occur, equation (F-18) becomes:

\[
N = \frac{2b + \frac{2SM^2b^2}{1-b} - b^2(1 + K_{td} + \alpha^2)(1 + M)(1 + SM) - \left( \frac{SM^2}{c^2} \right)(1 + K_{en})}{1 + K_n - 2b + \frac{2SM^2b^2}{1-b} - b^2(1 + K_{td} + \alpha^2)(1 + M)(1 + SM) - \left( \frac{SM^2}{c^2} \right)(1 + K_{en})} \tag{F-19}
\]

By varying parameters \( b \) and \( M \) and keeping all other parameters constant in equations (F-17) and (F-19) the efficiency can be optimized.

The density ratio is depending on the density of the primary and secondary flow. For the friction-loss coefficients literature recommends the following:
Choosing α small (0.224 (Karassik, Messina, Cooper, & Heald, 2001)), for ρ1=1035 kg/m3, ρ2=1100 kg/m3 and for the friction loss coefficients the recommended values from Table F - 1 the following efficiency table can be constructed:

Table F - 2 shows an optimal efficiency of 29.5% at M=1.2 and b=0.2.

Cavitation may occur in the jet pump's mixing throat. When the backpressure P_d reduces, the pump will produce a larger secondary flow Q2 and thereby a larger M. The efficiency will track along the curve as in figure Figure F - 3. But after the throat-inlet pressure (P_o) is reduced to the vapor pressure (P_v) of the secondary liquid. Any further drop in the backpressure has no effect on the flow ratio. The flow ratio will stabilize. The ratio is given by:

\[ M_L = c \cdot \frac{P_s - P_v}{\sigma_c \cdot Z} \]  \hspace{1cm} (F-20)

Where Z is:

\[ Z = \frac{N + 1}{N} \cdot \left( \frac{P_d - P_v}{1 + K_n} \right) \]  \hspace{1cm} (F-21)

### TABLE F - 1: RECOMMENDED VALUES FOR K FRICTION-LOSS COEFFICIENTS

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Recommended Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_n</td>
<td>0.04 - 1.0</td>
<td>0.05</td>
</tr>
<tr>
<td>K_{en}</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>K_{td}</td>
<td>.17 - .40</td>
<td>.20</td>
</tr>
</tbody>
</table>

With:

- \( M_L \) the cavitation-limit flow ratio [-]
- \( P_v \) the vapor pressure of the secondary fluid [N/m²]
- \( \sigma_c \) the cavitation coefficient with values 0.8 – 1.4 (Cunningham, Jet Pump Theory and Performance with Fluids of High Viscosity, 1957), recommended 1.35 (Cunningham, Hansen, & Na, Jet Pump Cavitation, 1970) [-]

\[
\begin{align*}
V_n &= \sqrt{\frac{2 \cdot Z}{P_1}} \\
A_n &= \frac{Q_1}{V_n} \\
d_n &= \sqrt{\frac{4 \cdot A_n}{\pi}}
\end{align*}
\]

FIGURE F - 3: EFFICIENCY CURVE WITH CAVITATION LIMIT (B=0.2, \( P_s=3 \) BARS, \( P_0=13 \) BARS, \( \Sigma=1.35 \))

To prevent cavitation, \( M \) has to be smaller than \( M_L \). By eliminating all entries from Table F - 2 where \( M>M_L \), an optimized \( M-b \) combination can be chosen that doesn’t cavitate. (\( M_L \) should be recalculated for every \( M \) and \( b \) combination).

After selecting the optimized \( M-b \) combination dimensions can be determined.

The area of the nozzle:

\[
V_n = \sqrt{\frac{2 \cdot Z}{P_1}}
\]

\[
A_n = \frac{Q_1}{V_n}
\]

The diameter of the nozzle:

\[
d_n = \sqrt{\frac{4 \cdot A_n}{\pi}}
\]
With:

\[ d_n \text{ the diameter of the nozzle [m]} \]

The nozzle design is recommended to be a short-entry internally-convex profile and long conical nozzles should be avoided. A literature study done by MTI Holland B.V. shows an angle of 30° at the entry of the nozzle (first part) and 14° for the second part of the nozzle. (Verichev, 2009)

![Figure F-4: Nozzle Design](image)

The distance between the nozzle and the entrance of the throat is important for the efficiency of the pump. Sanger and Vogel found that maximum efficiency was found when placing the nozzle at the entrance of the throat \( (sp/d_t=0) \) (Sanger, 1970) (Vogel, 1956), using nozzles with an external concave tapering, leading to a thin lip at the outlet. This design represents the theoretical model where the jet loss is eliminated, because the jet discharges to pressure \( P_0 \) at the throat inlet. Zero spacing promotes cavitation. From literature it’s found that a range of \( sp/d_t = 0.5 – 2 \) give good efficiencies (Bonnington & King, 1976). Sanger found that retracting the nozzles to 1 throat diameter provided good cavitation resistance and gave only a small loss in efficiency. A value of \( sp/d_t = 1 \) therefore is recommended.

The throat inlet contour is recommended to be short (large converge-angle) and well rounded. (Karassik, Messina, Cooper, & Heald, 2001)

The area of the throat:

\[ A_t = \frac{A_n}{b} \quad (F-25) \]

The diameter of the throat:

\[ d_t = \sqrt{\frac{4 \times A_t}{\pi}} \quad (F-26) \]

The length of the throat should be long enough to allow complete mixing, but as short as possible to minimize frictional losses. A throat length of \( L_t/d_t = 6 \) is recommended. (Karassik, Messina, Cooper, & Heald, 2001)

The diameter of the diffuser follows from:
\[ A_d = \frac{A_t}{\alpha} \quad (F-27) \]

With:
- \( A_d \) the area of the diffuser [m²]
- \( d_d = \sqrt{\frac{4 \times A_d}{\pi}} \) \quad (F-28)

With:
- \( d_d \) the diameter of the diffuser [m]

The length of the diffuser depends on the angle chosen for the cone. The length follows from:
\[ L_d = \frac{d_d}{2 \tan \beta} \quad (F-29) \]

With:
- \( L_d \) the length of the diffuser [m]
- \( \beta \) the angle of the diffuser [°]

A diffuser angle < 7° is recommended to prevent flow separation (Fried & Idelchik, 1989)
APPENDIX K: PROJECT PROPOSAL

Over the last few years, the Wells R&D department at Shell Global Solutions International (NL) has been developing alternative drilling methodologies aiming at minimizing costs and environmental disruptions associated to conventional drilling activities.

The conventional drilling process of a well is based on a start and stop process due to the alternating operations of drilling and casing of the formation. Moreover, the telescopic profile of the well forces to adopt large casing diameters in the first section of the well, which leads to higher costs and a relevant environmental footprint of the drilling process.

To improve the economic and environmental performance of the drilling operation, one of the proposed methods, relies on the inside-out inversion of steel pipes. In this process, the pipe is inverted inside a borehole to continuously case the formation while drilling. A number of benefits are clearly associated to this process which justifies its development. Some to mention are the possibility to:

- construct a mono diameter well from surface to the targeted depth
- significantly increase drilling distances thanks to the reduced friction coefficient that is established between the inverted and non-inverted pipe section
- minimize the open-hole section length, enabling operation in difficult soil conditions
- when the concept is applied to the pipeline, enabling a direct installation of the service pipe
- reduce the environmental footprint of the drilling operation.

This technology can be also successfully applied to Horizontal Directional Drilling (HDD) for the trenchless installation of service pipelines, introducing specific advantages, such as the capability of extending the reach above the typical limit of 2 km for conventional HDD installations; ensuring the hole stability (which is a typical limitation for HDD installations where the formation is characterized by gravel, cobbles, boulders and fractured rock). Furthermore, risk mitigation solutions have been developed in order to ensure the installation completion.

The technology has been proven to be reliable and effective on a laboratory scale and for this reason considered mature for the deployment in the field via means of HDD.

Being mainly specialized in vertical drilling for hydrocarbon production, Shell has decided to find a partner specialized in HDD technology, able to provide the necessary equipment and expertise for the project. For this reasons, a license agreement was issued by Shell to A-Hak Drillcon.

A-Hak Drillcon B.V. is a Dutch company specialized in the design, engineering and construction of controlled directional drillings and non-controlled directional drillings for underground infrastructures.

A strategy for the implementation has been developed and approved. The first target for 2014 is the execution in Q2 of a field trial project in the Netherlands. A second project is already in the scope for Q4, and other possible projects for this year are currently under consideration. The
first projects aim at proving the consistency of the technology in field conditions for short HDD crossings.

For the longer term, installations of 5 km and beyond are foreseen. The extended reach involves additional challenges, mainly in terms of drilling execution (e.g. mud circulation, retrievability of the BHA, friction reduction, steerability and communication to/from the drilling assembly), that need a thorough understanding and significant theoretical study.

Within this context, the Shell Wells R&D department is currently looking for a final year Master's student who will address the afore-mentioned challenges and give a sound contribution to the project. The first part of the work will consist of the identification of challenges and a selection of two challenges for further research in the second part. Furthermore, the successful candidate will acquire a broad hands-on experience, being involved also in the field trials, and be exposed to decision-making meetings and interaction with a large number of third parties, thus, having the opportunity to hone his/her communication, negotiation and strategic-thinking skills.

(C.Ibba, 2014)