Subsea Tunnelling for Oil: the Petromine Concept

Kjell Holestol and Arild Palmstrom

Abstract—*Small-scale tunnelling for oil has been performed onshore since the turn of the century. In the late 1970s and in the 1980s, several proposals were set forth for using subsea tunnels in the exploitation of offshore oil and gas fields. A prefeasibility study carried out for the Troll oil and gas field in the North Sea has yielded interesting results for the subsea oil tunnel concept. This article describes how existing geological knowledge combined with geophysical measurements and exploratory oil well data have given a surprisingly large amount of information regarding ground conditions where the "geology" is hidden by deep water. The expected ground conditions have been used to work out specifications for development of a tunnel boring machine and equipment to tackle the prevailing ground conditions, which include squeezing rocks and, possibly, running ground and shallow gas. A tunnelling progress of 5 km/yr in hard crystalline rocks and up to 10 km/yr in the soft sedimentary rocks offshore is regarded as possible, given active development of the equipment to be used. Many future offshore oil and gas fields—especially those in arctic areas exposed to icebergs and extreme weather conditions—can be exploited advantageously by using subsea tunnels.*

Résumé—*Des petits projets de tunnels pétroliers sur terre ferme ont été réalisés depuis le début du siècle. A la fin des années 70 et au début des années 80, plusieurs projets sous la mer ont été imaginés pour exploiter les champs de gaz et de pétrole sous-marins. Une étude d'avant-projet faite pour les champs de gaz et de pétrole de Troll dans la mer du Nord a produit des résultats intéressants en ce qui concerne la notion de tunnel pétrolier sous la mer. Cet article décrit comment la géologie déjà connue combinée avec des mesures géophysiques et avec des données de puits d'exploration de pétrole ont produit une quantité surprenante d'information concernant les conditions du sous-sol où la "géologie" reste cachée par des eaux profondes. Les conditions du sous-sol attendues ont été utilisées pour préparer des spécifications concernant le développement d'un tunnelier et d'un équipement adaptés aux conditions existantes du sous-sol. Ce sous-sol contient des roches sous compression et peut-être aussi des sols coulants ainsi que des poches de gaz peu profondes. Une avancée du tunnel de 5 km/année dans les roches dures crystallines et jusqu'à 10 km/année dans les roches tendres sédimentaires sous la mer est possible si on développe entièrement l'équipement requis. Beaucoup des champs de gaz et de pétrole sous-marins futurs, en particulier ceux de l'arctique exposés aux icebergs et à des conditions climatiques extrêmes, peuvent être exploités plus facilement en utilisant des tunnels sous la mer.*

Around the turn of the twentieth century, oil was produced from a tunnel on Whisky Creek, Colorado. Between World Wars I and II, oil was produced in Europe from mines at the Pechelbronn and Wietze fields in France.

At the 1976 Rapid Excavation and Tunnelling Conference, McCusker and Tarkoy presented a paper on the feasibility of developing Arctic oil and gas reserves by tunnelling. In the following years a number of papers were presented—in both the U.S. and Europe—on tunnelling to offshore fields.

In 1978, initial studies were started in Norway by a group of consultants and contractors. The group selected the Troms II area, offshore of northern Norway, as the basis for a concept study. Because it is a rich fishing ground, the Troms II area was, and still is, the most controversial area in Norway for oil and gas exploitation.

In 1984 and 1985, prefeasibility studies were performed for Statoil by The Petromine Company[1] on the use of tunnels to the Troll field some 48 km offshore. The Troll field, the world's largest offshore gas field, once was estimated to contain more than 1.500 billion Sm³ recoverable reserves. During 1986, The Petromine Company further developed the technology necessary to drill and produce oil and gas from tunnels.

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North Sea Geology

The North Sea Basin is approximately 60 million years old. In spite of its relative youth, it is considered a typical deep sea ocean basin. The formation of the North Sea Basin has its origin in the geological processes that have been going on in the North Atlantic since the Jurassic age 180 million years ago (see Fig. 1). During that period, North America became separated from Europe and Africa along faults running along the continents. Later, in the Tertiary age (60 million years ago), Greenland and Scandinavia started to separate, and a shallow sedimentation basin gradually was formed.

These movements are caused by the effects of the continental drift, which still creates an annual 20-mm increase in the distance between Greenland and Norway.

In this process, erosion products were transported out into the sea and sedimented. As the two continents continued to separate, heavy faulting caused the sea to become gradually deeper. During this time the thickness of the sediments became substantial—more than 5000 m in the deeper parts. Large movements along regional faults at the end of Tertiary age caused the formation of the present edge of the continental shelf.

The prefeasibility study on building tunnels to the Troll field triggered a more intense study of the geology of this area. The Troll field lies on a part of the continental shelf some 40–60 km offshore west of the town of Bergen. The sediments, which in this area are more than 3000 m thick, lie to the west of the crystalline basement rocks of the Fenoscandian shield. A tunnel to the Troll field, therefore, will involve driving in two markedly different rock formations, with hard, basement rocks close to the coast and soft sedimentary rocks along the remainder and the major part of the field. Figure 2 provides a geological profile of the area.

The geology has been evaluated from

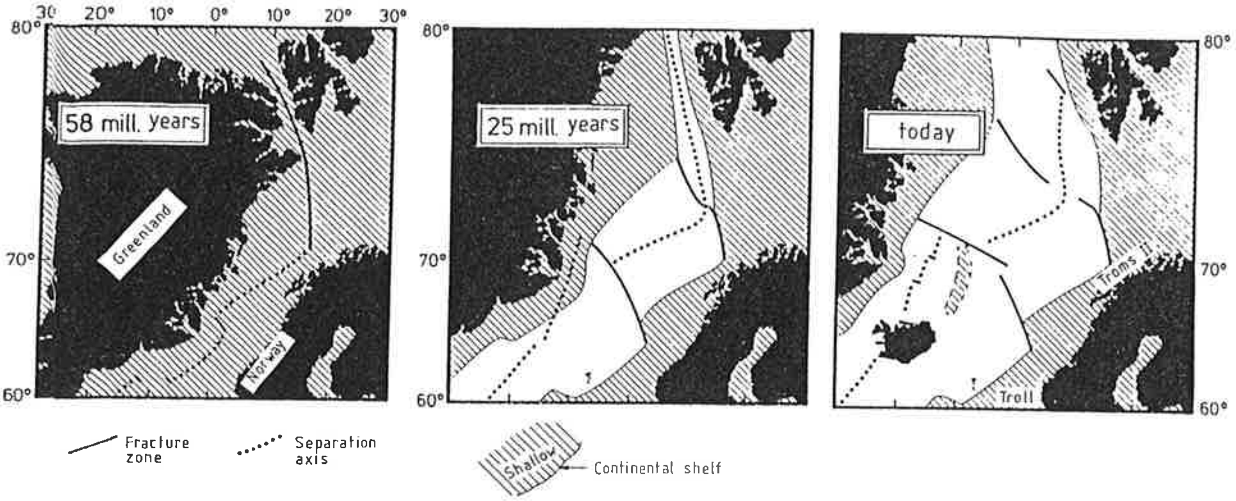

Figure 1. The formation of the North Sea basin.

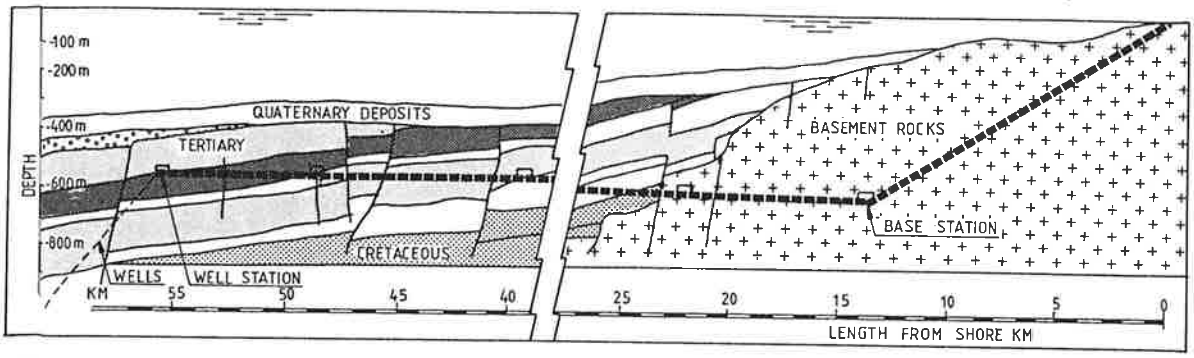

Figure 2. Geological profile of the North Sea.

existing reflection seismic profiles between the field and the shore. Good seismic reflectors make tie-in to the exploration wells in the Troll field possible. Although the reflectors cross faults, including some with large displacement, there is little doubt about the age and stratigraphy of the rocks between the coast and the Troll field. Because of relatively constant sedimentation conditions in the North Sea, it is assumed that the rock distribution at the oil field is representative for the area between the oil field and the shore. The rocks at the level of the tunnel belong to the Cretaceous and Tertiary sequences. The strata have an even but slightly westerly dip, and progressively younger rocks will be encountered by the tunnel driven towards Troll.

The logs from the exploration wells at the fields include continuous records of geophysical parameters and visual descriptions of drillhole spoil. A combination of these well data has yielded valuable information on the rock types along the well hold. By following the seismic reflectors, it has been possible to develop a geological model along the tunnel alignment.

Rock Mass Classification

A system of classifying the rock mass conditions along the tunnel with respect to tunnelling conditions has been developed for the study (see Table 1). Based on the geological model, the main tunnelling parameters in this system are:

- Rock types and assumed strength.
- Assumed rock stresses compared to rock strength.
- Water leakage possibilities.
- Possible shallow gas occurrences.

Because rock cores of the actual sediments to be penetrated by the tunnel have not been taken, the assessment of their physical and mechanical properties has had to be based on comparisons, indirect methods and experience. Comparisons have been made with areas characterized by similar geological conditions in Denmark, where strength data exist from tests on core samples. In addition, studies have been made to determine empirically the strength of rock along a drilled well, using ordinary wellhole logs as a basis for study. Specially developed computerized processing has been carried out to produce rock strength data.

All methods of assessment used in the study have led to the conclusion that most of the sediments probably have a uniaxial compressive strength of 3–15 MPa; only small pockets or thin layers of sand/silt may have lower strength.

The mechanical behavior of the rock mass is dependent on the nature of the applied stresses. In this area, the stresses are high compared to the rock strength and the ground around the tunnel is assumed to give "squeezing" conditions. The lining of the tunnel has been designed to withstand these conditions.

Thus, the geological model along the tunnel profile has provided a basis for assessing the quantities of the different classes of tunnelling conditions.

Tunnelling

The basement rock mass extends up to 20 km from shore in the Troll area. Tunnelling in these rock qualities and with high water pressures is a well-known experience because of the many subsea tunnel projects undertaken in Norway. Hence, this tunnelling is not expected to pose any new and unsolved problems and, therefore, is considered technically feasible given modern technology.

Beyond the basement, tunnelling towards the field will have to be performed in increasingly weaker sedimentary rocks. Mixed face conditions, squeezing, running, and, occasionally, flowing ground will have to be overcome. Moreover, the tunnelling process has to tackle, with a high degree of safety, possible occurrences of shallow gas deposits (methane etc.) under hydrostatic pressure.

Table 1. Simplified ground classes in sediments with expected tunnelling problems.

Class	Rock mass conditions	Assumed compressive strength (MPa)	Assumed distribution along a tunnel (%)	Tunnelling problems
I	Weak marl, siltstone claystone	3–25	76	Squeezing behaviour, stability problems.
II	As class I, with thin layers of limestone		17	As for class I. Mixed face for TBM drilling.
III	Lenses/thin layers of sand	<1	0.5	Possibility of water/shallow gas. Great stability problems. Pre-grouting required.
IV	Thin silt/ siltstone layers	<1	4	Great stability problems. Possible swelling problems.
V	Thick layers of limestone	50–150	1.5	Possibility of water leakage. "Hard rock" for TBM drilling.
VI	Faults of importance		1	Possible stability problems. Pregrouting may be required.

The geological evaluations described above have been used to establish "outline specifications" for the tunnelling boring machines (TBMs) and equipment. Among the most important of these specifications was the requirement that the machines and equipment be capable of coping safely with the expected ground conditions while at the same time yielding a high rate of progress. Meeting these requirements seems possible provided there is appropriate development of existing technology over a three- to four-year period. The development of testing of a prototype TBM is considered essential to this process.

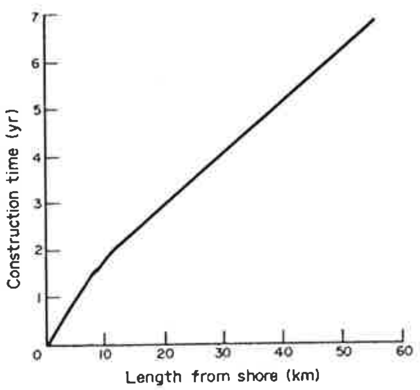

Figure 3. Construction time versus distance from shore.

Construction Time

The construction time for a tunnel to the Troll field has been estimated based on the lengths of the different rock mass classes and a critical path analysis (CPM) of the tunnelling progress within each class (see Fig. 3). The CPM analysis was based on the performance data established for the specified TBM system and included all work operations during tunnelling, including scheduled and unscheduled spots, as well as the construction time for the base station and the intermediate stations to be provided at 10-km intervals.

Shallow Gas

A great effort has been made to develop a probe drilling system for the safe detection of shallow gas pockets ahead of the tunnel. The probe drilling and grouting system was based on development of existing techniques and components.

The drilling system adopted is basically a diamond drilling equipment fortified with a "down-the-hole" motor with "measurement-while-drilling" equipment on board. A valve and stuffing box arrangement has been outlined for protection against uncontrolled entry of gas and/or water into the tunnels. The system is a combination of down-the-hole packer/nonreturn valve and a tunnel-located valve/stuffing boxes/shear ram arrangement.

Novel grouting techniques and materials were studied in great detail. Contrary to previous assumptions, it was found to be technically not feasible to seal the ground sufficiently against influx from shallow gas pockets. Therefore, gas pockets must be avoided as far as possible; if encountered during probe drilling from the tunnel, they must be drained.

Well Drilling: Process and Facilities

Drilling of wells from a level deep below the bottom of the sea causes problems different from those encountered in drilling from sea level. In the former case, it is necessary to create a pressure in the drilling mud that balances the pore pressure of the formation. This problem has been solved by choking the return mudline by means of special valves.

Furthermore, safety has been increased during all phases of operating, in comparison with conventional surface drilling, by means of an increased number of barriers in the blowout-preventer system. In the unlikely event that all barriers should fail, a pressure-relief system will divert the flow to shore in a controlled manner.

Due to the well-defined slope of the

pipelines (tunnels) from the well stations to the base station close to shore, multiphase flow is possible for almost any type of reservoir. This reduces dramatically the need for process equipment at the wellheads and, consequently, the space required at the well stations.

Figure 4 provides a profile of proposed well station for the Troll field.

Future Developments

Future exploration activities will take place in new geographical areas, many with hostile climates, deep water and sensitive environments. These activities, combined with developed tunnel technology—especially with regard to increased tunnelling rates—will make the oil mine concept an attractive solution.

The economy of the concept has been investigated through cost-sensitivity analysis. These analyses were based on difficult North Sea geological conditions and on a developed TBM technology.

Figure 5 indicates the influence of both the field reserves and distance from shore on the unit cost, given an internal rate of return of 15%.

One example of a promising area for a Petromine development is the Troms II area of northern Norway. Other examples in Norway are areas close to

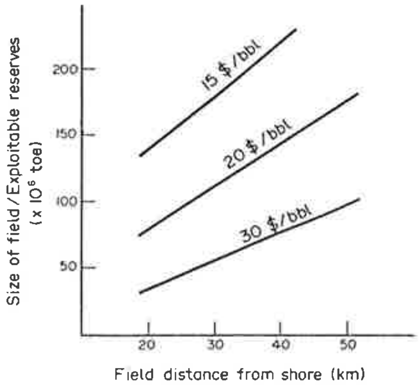

Figure 5. Costs vs field size and distance from shore for an oil mine in the North Sea.

the western coastline, characterized by water depths of more than 300 m; or the waters around the arctic islands of Spitsbergen, Hopen and Bear Island.

Worldwide there are many interesting areas where a Petromine development may prove feasible. Possible hydrocarbon deposits offshore of East Greenland today seem exploitable only by means of tunnels below the sea bottom due to the presence of icebergs. Petromine development of other arctic oil resources—for instance, offshore Alaska, northern Canada and Siberia—may be cheaper and less threatening to the environment than development by surface structures.

Possible oil discoveries in the interesting structures off the southern coast of England and in the British Channel also might be exploited only by means of oil mines. There are areas along the eastern and western coasts of the United States and Canada, and off the coasts of South America, New Zealand, and Antarctica, where tunnels certainly will be considered.

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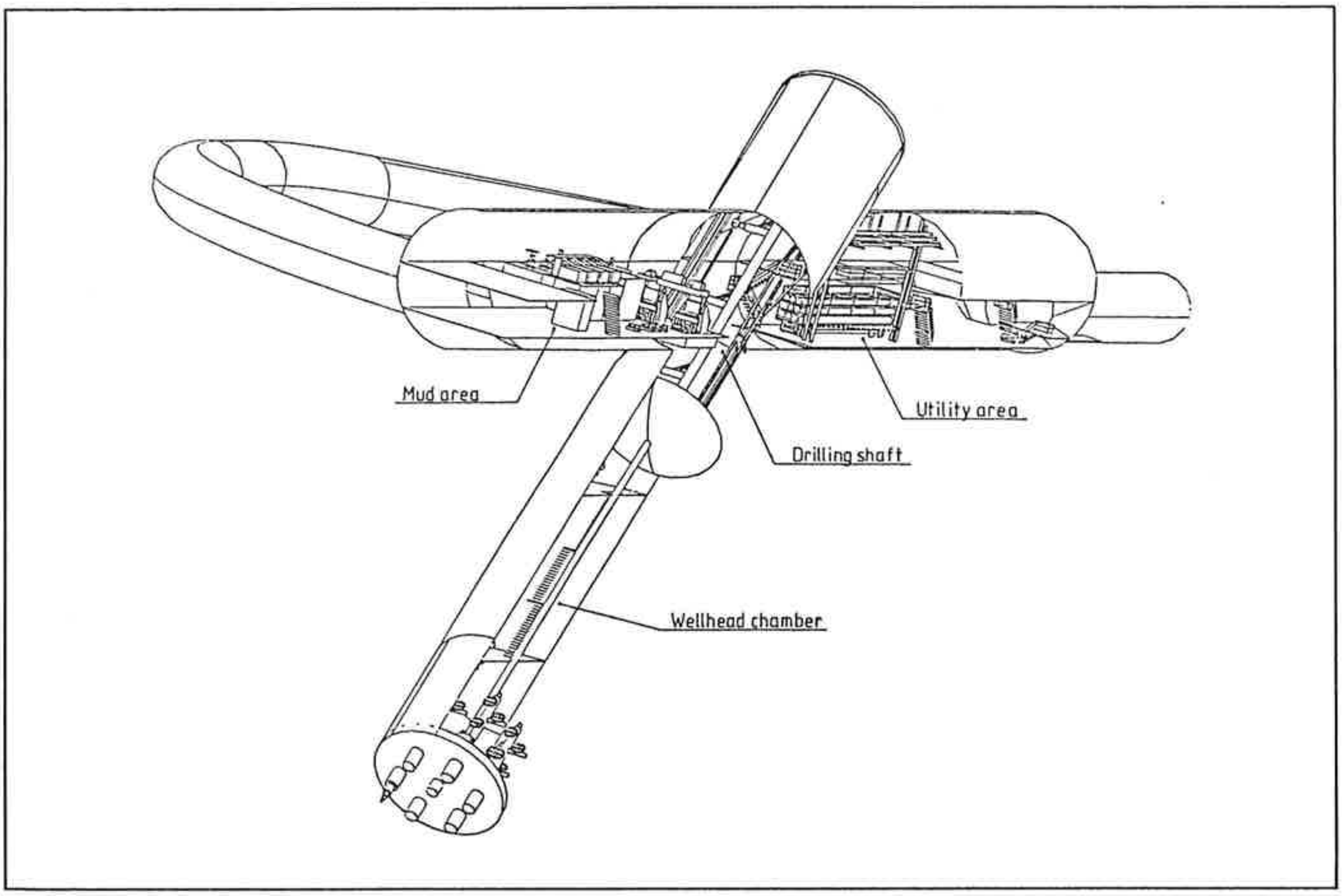

Figure 4. Drawing of a proposed well station for the Troll field.

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Note

[1]The participating partners of The Petromine Company are Selmer Furuholmen (Contractors), Berdal (Consultants), NRC (Drilling Engineers) and Norcem Cement (Cement Producers).