SHETLAND ISLANDS COUNCIL

Tunnel links Yell Sound and Bluemull Sound
Technical evaluation and cost estimate

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TUNNEL LINKS YELL SOUND AND BLUEMULL SOUND
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1 SUMMARY

The Shetland Islands Council is considering establishing fixed links between the Mainland and the island of Yell across the Yell Sound, and also between the islands of Yell and Unst, across the Bluemull Sound. One option that is considered is sub sea rock tunnels.

The company O. T. Blindheim AS has been assigned by the Shetland Islands Council to provide a detailed appraisal of the proposed Bluemull Sound route, depth, cross section, the bill of quantities and the specifications and also provide a second opinion of the feasibility work conducted and a "ball park" cost of a tunnel to UK standard and specification BD78/99 cross-section. Based on the Bluemull Sound a similar analysis was to be done for the Yell Sound crossing.

The fixed link projects currently under planning will be the first of such kind in the Shetlands, and even the first road tunnels ever built in the islands. Thus, it is required that the tunnelling solution represents a sufficient level of confidence with regards to the responsible authorities, and also amongst funding institutions and the general public that shall be the users. Information is a key word in this context, and on the technical side, documented and tested solutions must be used. However, the solutions must be designated to the actual traffic volume constituting a cost-effective solution with a favourable cost-benefit ratio

For the feasibility studies of these tunnel projects and also for this report existing material that are accessible from such sources as the British Geological Survey, [Ref. 6] has been used as no site specific geological or geotechnical surface mapping are available at this stage.

The most dominant geological feature in the area is Walls Boundary Fault, striking in a NNE direction as a continuation of the Great Glen Fault in Scotland. The Nesting Fault, which is actually striking right through the Yell Sound in a NNW direction is one of its splays and it short-cuts across a major bend in the Walls Boundary Fault. Another prevailing fault zone associated with the Nesting Fault is the Bluemull Sound Fault. This fault strikes in NNE direction and is one of the splays off the Nesting Fault.

Geological classification of the bedrock indicates that at toft (mainland) the igneous intrusive rocks as granite and granodiorite are present. Rock exposures and samples from the core holes for the ferry terminal are mainly granodiorite, with some occurrence of alkali granite. At the other side of the Yell sound, at Ulsta the bedrock consists of mica-plagioclase gneiss, and gneissic metagranite, metamorphic rocks belonging to the gneisses of Yell.

A traffic volume in the range of 2000 to 2500 vehicles 20 years after opening could be a realistic assessment for these projects. The following design criteria were used for the evaluation and determination of tunnel standard and alignment: annual daily traffic ($AADT_{20}$) is assessed to 2500 vehicles with signed traffic speed of 80 km/hour and the heavy vehicles portion 10 to 15 %. A 50 m cover has been used at the location of the maximum water depth according to the bathymetric map with practically no soil deposits on the rock head, and 8% gradients at the steepest inclination.

The construction of these projects is expected to be completed within a construction time frame ranging from 19 to 30 months for the Bluemull Sound and 31 to 42 months for the Yell Sound. An average tunnelling advance of 35 to 45 per face per week has been used and with excavation going on simultaneously at 2 tunnelling faces for each tunnel.

In the Shetland Islands no road tunnels for public transportation purpose have been excavated in rock. The basis for the cost analysis is therefore the experiences gained from the construction of more than 20 sub sea road tunnels in Norway over the last 20 years. Also the successful construction of two sub sea tunnels in Iceland and the Faroe Islands over the last 5 years have been included in the "price reference bank" applied for this cost estimate.

The construction cost for these tunnel projects in the islands have bee estimated to approximately 14 mill. £ and 25 mill £ for the Bluemull Sound and Yell Sound respectively. In addition costs for investigations, planning, project management and access roads must be included. These amounts to some 4 to 6 mill. £ per tunnel project. Financial costs must be added.

The total annual cost reinvestment, operation & maintenance is assessed to 320.000 £ and 165.000 £ for the Yell Sound and Bluemull Sound respectively. Based on this an average cost per meter tunnel has been calculated to 63 £ (equivalent to 820 NOK) for both tunnels.

An essential element for the construction and the operation period is appropriate water control. Water inflow may cause severe problems for the project and probe-drilling ahead of the tunnel face is recommended to be executed on a continuous basis. Pre-grouting will be done according to the results from the probing. The rock support during construction shall be carried out in such a way that rock fall imposes no hazard to the workmen and that the tunnel, under no circumstances, shall be at the risk of collapse. For the permanent stability no rock fall shall be allowed that may land on or end up on the road lanes, or the pavement.

Further geotechnical investigations are needed, in general, there are two main aspects that call for such investigations;

- the rock surface is not accurately defined, and
- the location and condition of weakness zone(s), if any, are not known.

In addition, information on the rock mass quality at the tunnel level must be obtained.

To cope with this situation two different geophysical investigation methods are suitable:

1) Reflection seismic (including echo sounding)
2) Refraction seismic

To obtain geological information it also needed to include such investigations as a geological desk study of the areas, including aerial photo (vertical, stereo view) interpretations and literature search. Further detailed geological surface mapping for both Bluemull Sound and Yell Sound crossings including joint mapping and joint characterisation together with a survey of the quarries and rock cuttings close to the actual tunnel sites. Core drilling at each shore side should also be performed to obtain geological and hydrogeological information.

2 BACKGROUND AND PURPOSE

2.1 General

The Shetland Islands Council is considering establishing fixed links projects connecting the Mainland with the island of Yell across the Yell Sound, and also connecting the islands of Yell and Unst, across the Bluemull Sound, see Figure 1. At present, ferries are operating the crossing of these sounds. One optional solution for fixed links is sub sea rock tunnels.

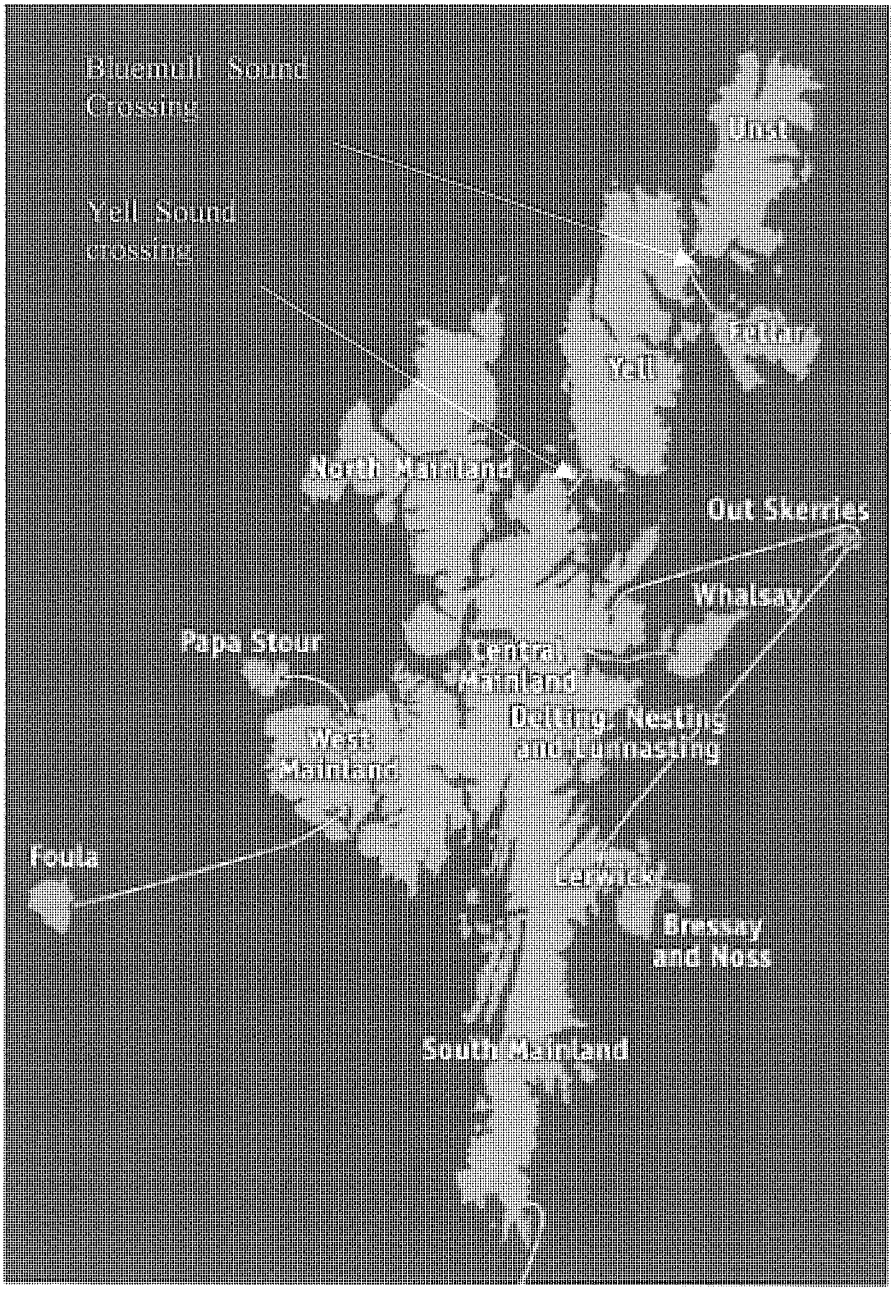

Figure 1. Overview map of Yell Sound and Bluemull Sound crossings

The company Halcrow Crouch prepared preliminary studies of alternative crossings of the Yell and Bluemull sounds, both concepts and tunnel routes. Their findings were reported in two documents; an initial outline feasibility study presented in April 2000 for the fixed links to Yell, Unst and Whalsay [Ref. 1]; and also the Yell/Unst fixed link-tunnel option presented in October 2000 [Ref. 2]. Halcrow concludes the feasibility of such tunnel options for the two crossings.

During the last two decades, a total of 23 sub sea road tunnels have been constructed in rock in Norway. Further, a sub sea road tunnel was completed in 1998 in Iceland, the Hvalfjördur tunnel, based on Norwegian guidelines. At present a sub sea road tunnel also designed and constructed in accordance with Norwegian guidelines, is due to be completed in the Faroe Islands in late 2002, whilst a second sub sea tunnel crossing in the Faroes is under planning. The company O. T. Blindheim AS, has been involved in the project in Iceland as well as those in the Faroe Islands.

O. T. Blindheim AS has been assigned by the Shetland Islands Council, and the objects of our assignment are as quoted in the following:

"Provide a detailed appraisal of the proposed Bluemull Sound route, depth, cross section, the bill of quantities and the specifications. From the seismic and geological data and information available, provide a second opinion of the feasibility work conducted and a "ball park" cost of a tunnel to UK standard and specification BD78/99 cross-section. The "ball park" cost should over all aspects of design, construction and equipping, including the provision of all services to required UK standards. Included in this process would be a direct liaison with Halcrow Group."

Further:

"Based on the analysis conducted for Bluemull Sound, and the specific information available for Yell Sound, provide a second opinion of the technical feasibility of such a crossing and a "ball park" costing for a Yell Sound tunnel to UK standard and specification BD78/99 cross section. The cost should cover all aspects of design, construction and equipping, including the provision of all services to required UK standards. Again a direct liaison with Halcrow Group would be appropriate."

At present a limited number of pre-investigations have been performed, and for the later development and detailing of both tunnelling projects a dedicated pre-investigation program is needed.

The findings and conclusions from our study are presented in this report, together with cost estimates and time schedules appropriate for the current stage of project planning.

2.2 Determination of tunnel category

According to British Standard (BD 78/99) the determination of tunnel categories is based on both traffic volume in terms of the annual average daily traffic (AADT) and the length of the tunnel. However, for tunnels beyond a length of 3000 m there is no differentiation on traffic volume between AADT 1000 and 10.000 vehicles, [Ref. 9], see Figure 2. Thus, the tunnels included in the fixed link program for the Shetland Islands are categorised according to the most strict safety provisions, which in simple terms means that irrespective of traffic volume the tunnel category would be the same.

The Norwegian guidelines, Handbook 021 issued by the Norwegian Public Roads Administration (NPRA) have a differentiation of tunnel classes which also is based on tunnel length and traffic volume. However, for low traffic tunnels, i.e. AADT less than 5000 vehicles, the same tunnel category applies irrespective of the tunnel length, [Ref. 10], see Figure 3. Handbook 021 has been subject to a recent revision, the new issue is planned to be implemented in May 2002. Although it has not yet been published in an English version, it forms the basis for this evaluation. In practical terms, this means that according to British standard the tunnel class will be the highest (Class AA) for the Yell Sound tunnel, due to its length, whilst according to Norwegian guidelines, the tunnel class will be the second lowest (Class B) for both the Yell Sound and Bluemull Sound crossings due to their low traffic volume. The Bluemull Sound tunnel will be classified as Class B according to BD 78/99.

It is not the purpose of this report to judge which one of these standards is the best one. The determination of tunnel categories are established in accordance with the best of experience taking into consideration the actual traffic situations that prevails in the two countries. Britain is a country with a rather large traffic volume in general, and tunnels are normally used in situations to get rid of "bottle necks" in areas of high traffic congestion. In Norway on the other hand, most of the road tunnels have been built for the low traffic segment, and particularly for the sub sea tunnels the majority falls within this category.

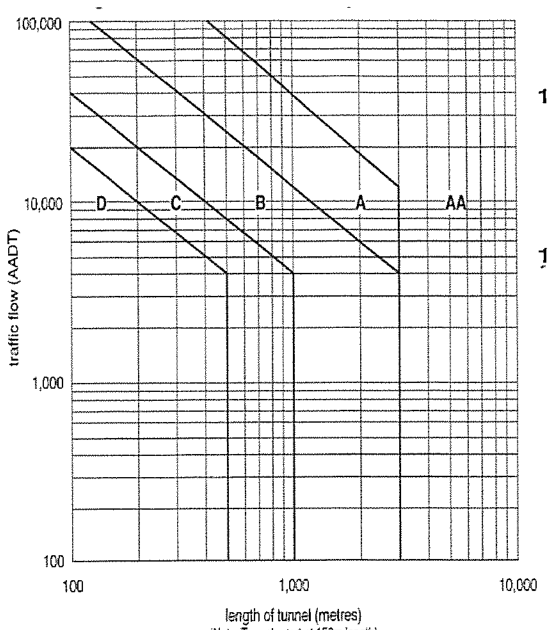

Figure 2. Tunnel categories according to British standard BD 78/99 [ref. 9]

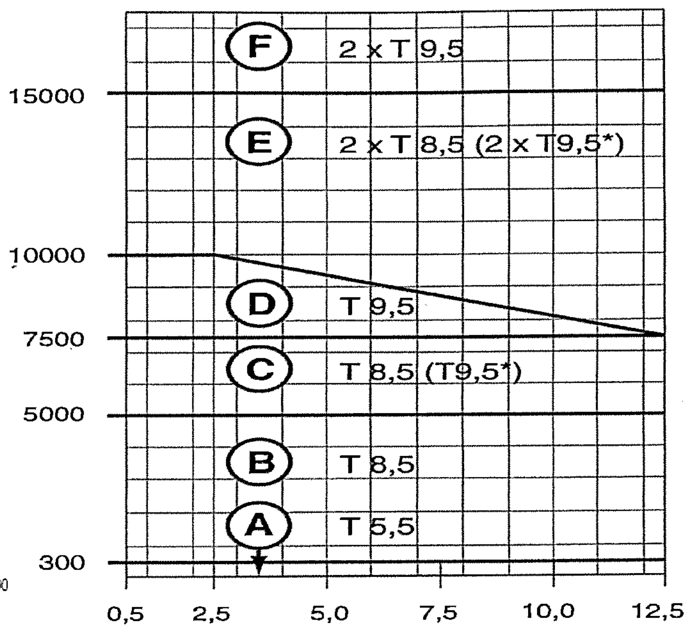

Figure 3. Tunnel categories according to NPRA [ref. 4]

The axis's for both graphs above are: traffic volume (AADT) vertically and tunnel length horizontally, with the tunnel length in m and km for Figure 2 and Figure 3 respectively.

3 INVESTIGATIONS CARRIED OUT

3.1 Geological mapping

For the feasibility studies of these tunnel projects existing material that are accessible from such sources as the British Geological Survey, [Ref. 6] has so far been used. There has not been done any specific geological or geotechnical surface mapping for the sole purpose of evaluating the suitability of the rock mass for sub sea tunnelling.

During the first visit made to the site areas by our senior advisor Mr. Eivind Grøv, the geological and geotechnical conditions were briefly inspected. The geological conditions in the site area were also examined during site visits done by the Halcrow personnel during the preparation of their reports.

A number of articles and papers on the aspect of Shetland Islands geology are available. Some of these are particularly focusing the Walls Boundary Fault, and associated fault zones. These constitute geological and tectonic features that are expected to influence on the tunnelling conditions in both the Yell and Bluemull Sounds.

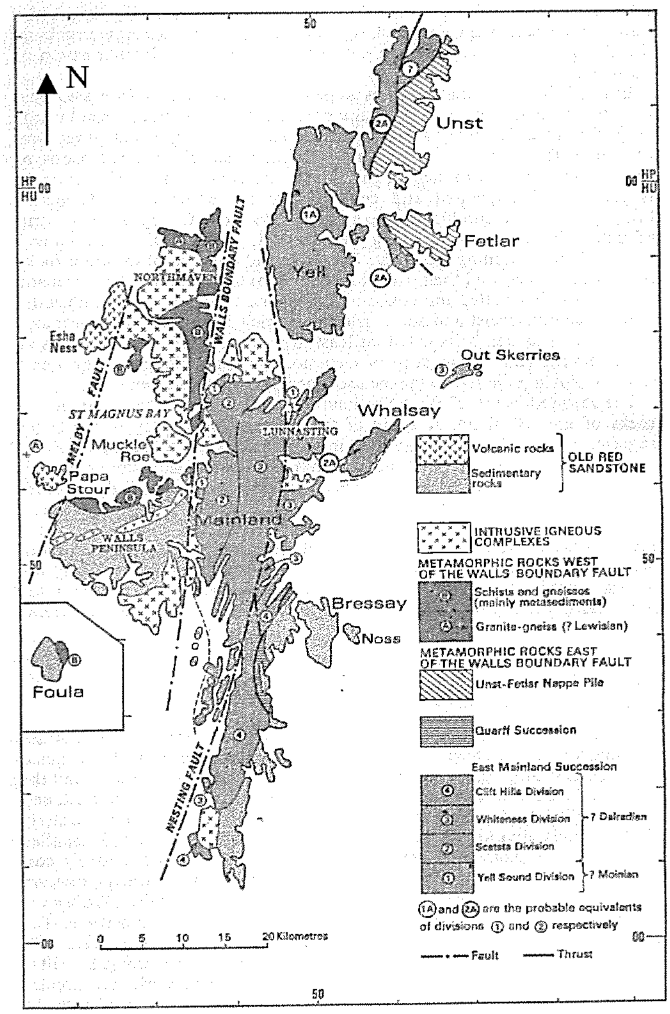

Figure 4. Bedrock geological map

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For the Yell Sound, geological information is also available from a few, shallow core holes, which were drilled for the investigations for the ferry and terminal replacement, see [Ref. 5]. These investigations were performed on-shore and off-shore close to the current ferry terminals, thus they are not located within or in the near vicinity of the tunnel corridor.

For the Bluemull Sound crossing, a geological report prepared for the industrial quarry located at Gutcher is a relevant reference with detailed geological descriptions that can be used for the tunnel project, see [Ref. 11].

The geological and geotechnical information available through these references is considered sufficient at this stage of the project, however, as will be further elaborated in chapter 9 below, detailed geological mapping at the different sites will be needed in later stages.

3.1.1 A brief geological and structural description of the areas in concern

Based on the current level of investigations the following main aspects of the geological and structural conditions can be summarised.

The Walls Boundary Fault, striking in a NNE direction is a continuation of the Great Glen Fault in Scotland and constitutes a governing structural feature in the Shetlands. The Walls Boundary Fault is a complex structure, and the Nesting Fault, which is actually striking right through the Yell Sound in a NNW direction is one of its splays and it short-cuts across a major bend in the Walls Boundary Fault. Another prevailing fault zone associated with the Nesting Fault is the Bluemull Sound Fault. This fault strikes in NNE direction and is one of the splays off the Nesting Fault. Both the latter fault zones have been interpreted as moving rocks on the west side of the fault to the north, 16 km and 5 km for the Nesting Fault and Bluemull Sound Fault respectively. The literature suggests that both fault zones have been the focus for movement between different blocks from the Devonian to the Jurassic age. The island of Yell has been shuffled along this fault zone to its current position between the Mainland and Unst. Figure 5 below shows structural boundaries and main tectonic structures in relation to the tunnelling projects.

Typically, the adjacent rock mass to such distinct zones are characterised by a gradual transition from competent bedrock to a central zone of crushed, fragmented and decomposed material, often associated with finer materials and clay minerals. Such transition zones are typically showing an increased number of joints towards the central zone. The tunnel crossings have to negotiate both the Nesting Fault from Mainland to Yell and the Bluemull Sound Fault, from Yell to Unst, thus it is required to obtain further information about the characteristics of these zones in relation to tunnelling feasibility. These weakness zones could be of different types of origin and the presence of fault zones or potential tensional joint systems along the orientation of the sounds must also be checked.

A brief mapping of joints was conducted during our site visit. Typically, at Mossbank at the Mainland side of the Yell Sound the dominating joint direction is N30°E, more or less parallel to the Bluemull Sound Fault. Further west, at the shore at the Fugla Ness, the major joint direction is typically N40-50°E with a sub-vertical to vertical dip. Other joint sets strike in north-westerly direction, which is parallel to the sound and the Nesting Fault.

At Ulsta, rock exposures close to the sea indicate a rather tectonised bedrock. The most dominant joint system is along the foliation, with a N30° E orientation, and vertical dip. Another joint set strikes N50-60° E, also vertical.

At the Yell side of the Bluemull Sound, the most dominating joint set strikes E-W, whilst another is N40°W. On the other side of the Bluemull Sound, at Unst, the most dominating features seem to be orientated N50°E.

The joint observations indicate a wide scattering of joint directions and there is no correspondence between the observations on one side of the sound to the other.

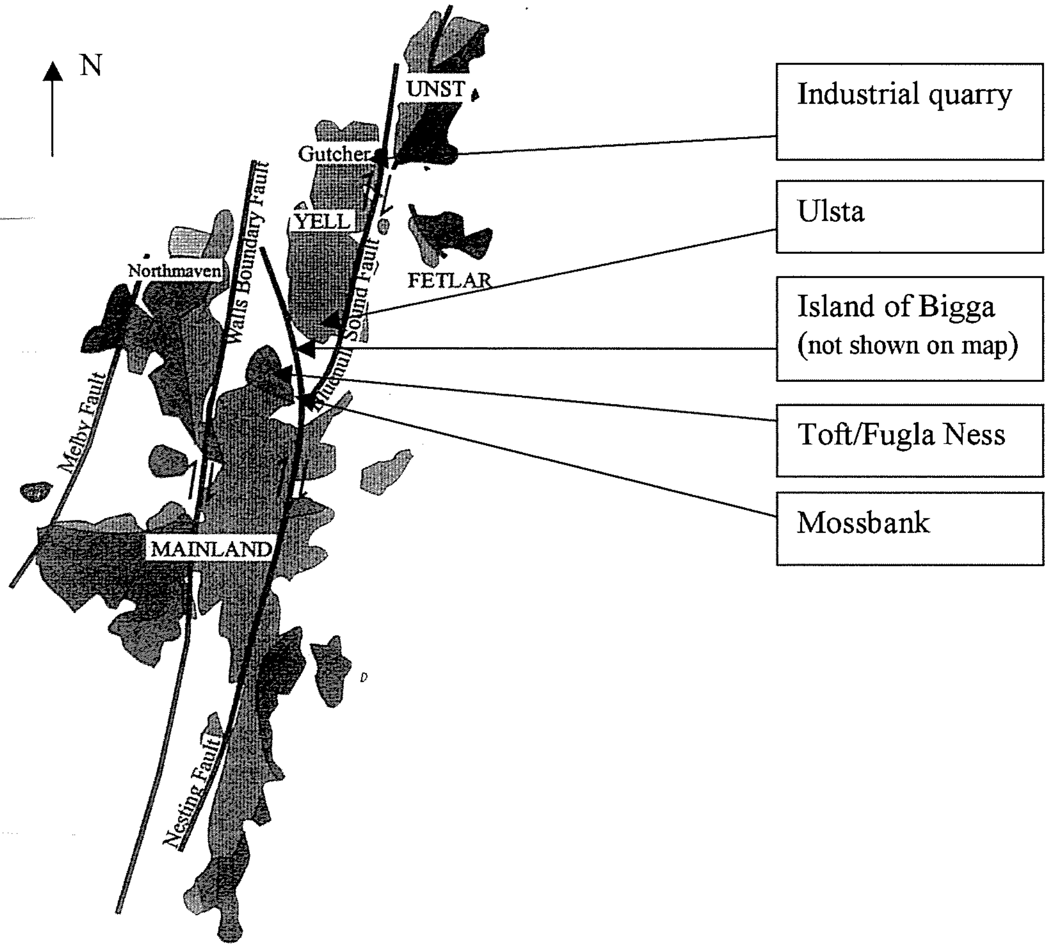


Figure 5. Tectonic structural map Shetland Islands

Geological classification of the bedrock indicates that at Toft (Mainland) the igneous intrusive rocks as granite and granodiorite are present. Rock exposures, and samples from the core holes for the ferry terminal are mainly granodiorite, with some occurrence of alkali granite. At the other side of the Yell Sound, at Ulsta the bedrock consists of mica plagioclase gneiss, and gneissic metagranite, metamorphic rocks belonging to the gneisses of Yell. The boundary between the gneisses of Yell and the igneous intrusive rocks has been interpreted to be found running in North-West direction through the island of Bigga, in the middle of the Yell Sound.

Further north to the Bluemull Sound, the bedrock at the Yell side of the sound is predominantly the same as described above, namely gneisses belonging to the gneisses of Yell. A detailed description of the geology of the Gutcher is provided in [Ref. 11], which is defining the rocks at the Gutcher, along the tunnel alignment at Yell, as psammites (metamorphosed sandstones). The psammites are intensely folded, and lie in a N-S orientated stripe.

Entering the sub sea section the tunnel will pass the Valayre gneiss, with augen "eyes" of microcline, also orientated in a N-S direction. Crossing the sound implies that the tunnel will encounter another rock sequence at Unst, consisting of schists and gneisses, which at the tunnel site are mainly mica-schist and hornblende gneiss.

3.2 Sea bed mapping

The Yell Sound and the Bluemull Sound, are both covered by bathymetrical maps, the Admiralty series of charts and publications, see [Ref. 7]. These are, however, not adequately detailed or accurate enough for the purpose of designing a sub sea rock tunnel, which is mainly due to the fact that seabed contours are missing in the central parts of the sounds. The Admiralty series of maps should be supplemented by surveys dedicated for this purpose. For the current stage in the planning process these maps can be used, however, on the condition that sufficient margins are included in the design to cope with the inaccuracy of the maps.

Based on the sea-bed mapping [Ref. 7] the maximum water depth in the Yell Sound, where the tunnel is planned to cross the sound between Toft and Bigga, is between 44 and 41 m. Along the tunnel alignment between Bigga and Yell, the water depth is at maximum 44 m. For the Bluemull Sound the maximum water depth according to the bathymetric map is 37 m.

3.3 Geophysical investigations

For the Bluemull Sound a reflection seismic survey has been undertaken in the area for the planned tunnel. The company, Caledonian Geotech performed the survey in 2000, see [Ref. 8]. The survey included hydrographic survey (echo-sounder), sidescan sonar and sub-bottom surveys using two separate seismic systems (Sparker and Pinger), both based on reflection seismic technique. A number of lines were surveyed, mainly perpendicular to the sound (along the tunnel route), but also lines parallel to the sound.

The results coincides well with the existing bathymetric map of the area, with a maximum water depth of 38 m, referring to the Ordnance Datum (OD is 1.37 m below Admiralty level). The results from this survey indicate a sedimentary overburden varying in thickness between 0 and 8 m, but mostly around 3 m thick. The seismic penetration in the bedrock is poor, and the results are not reliable at the tunnel level. However, according to the reference [Ref. 8] it indicates that the rock is hard and fresh, except in weaker, weathered gullies, which are indicated on the cross-sections and can be potential weak zones.

For the Yell Sound there is no similar geophysical survey conducted so far.

The need of further geophysical investigations is described in later chapters of this report.

3.4 Core drillings

As far as the material provided us is concerned, there is only shallow core drilling available for the Yell Sound crossing. These were conducted for the ferry terminals, a couple of km South East of the tunnel corridor. Also some 2 km north of the Bluemull shallow core drilling has been done, according to the Halcrow report, [Ref. 1] but this latter investigation has not been available for our review.

Consequently, there is no dedicated, deep core drilling available at this stage of the planning for any of the two tunnel projects. In the next planning stage of these projects, it is deemed necessary to do core drilling and testing associated with such drillings. In later chapters the content of core drilling will be described in further detail.

4 GEOMETRY OF THE TUNNEL

4.1 Design basis

The design basis for road tunnels is mainly based on the annual average daily traffic (AADT). In Norway the forecasted prognosis for year 20 after opening of the tunnel is normally applied for geometrical design, and 10 years after opening for the technical installations.

Recent recordings yielded a traffic volume equivalent to 560 vehicles in average per day including an approximate 15 % portion of heavy vehicles. In traffic prognosis it is common to apply an increased traffic the first year after opening, a typical one-time traffic increment due to the fixed link itself. Then onwards an annual, even traffic increase can be expected, based on the growth in traffic density locally. A traffic volume in the range of 2000 to 2500 vehicles could be a realistic expectation for these projects. This gives the following design criteria:

- Annual Daily Traffic : $AADT_{20}$ is assessed to 2500 vehicles
- Signed traffic speed : 80 km/hour
- Heavy vehicles portion : 10 to 15 %

Commonly in Norway, the AADT after 20 years represents the traffic increment after toll collection is removed. However, toll stations are not in the picture for these projects therefore an AADT of 2500 vehicles will be used in this report. This figure is probably more a best guess of the traffic load than a concrete, documented figure, but could be used in the early stage of the projects development. A traffic analysis is required to obtain a more accurate figure on expected traffic growth.

With a signed traffic speed of 80 km/hours, the design speed is normally 90 km/h.

4.2 Review of the current geometry of the tunnel alignments

According to Norwegian guidelines the minimum rock cover for a sub sea tunnel shall be 50 m as a basis for planning, but may be reduced to 40 m if the conditions are thoroughly documented and confirm good rock mass conditions. At this stage in the planning process it is recommended that a 50 m rock cover is used. By the time further information is available on the rock mass conditions and the actual depth of the bed rock in the sounds is well documented, a reduction of the rock cover can be implemented if the conditions turn out favourable.

The Norwegian guidelines recommend a gradient (inclination) of max. 7 % when the AADT is greater than 1500 vehicles (out of which a component of 10-15 % is heavy vehicles). When an overtaking lane is built, the gradient can be increased to 8 %. The vertical radius in the low-point shall not be less than 2090 m according to the Norwegian guidelines. The minimum horizontal radius to be applied is calculated using the stop length in a gradient of 8 % going downwards.

Based on the traffic density used the required tunnel profile, or cross section will be a T 8.5, which has a tunnel width of 8.5 m (2 lanes each 3,25 wide and 1 m pavement on each side). This produces an approximately 6.5 m high tunnel and with an min. excavated cross-section of 62 m^2.

Table 1. Minimum requirement according to Norwegian standards

Norwegian standard	Rock cover	Gradient (two lane)	Vertical radius	Cross section*	Horizontal radius
Minimum requirement	≥ 50 m	< 7 %	>2090 m	T 8.5 (62 m^2)	> 1030 m

Note. * indicates the theoretical excavation cross section acc. to Handbook 021

A comparison with the British standard, BD78/99 yields the following:

- Rock cover; there is no requirement found in British standard BD 78/99 on the minimum rock cover for sub sea tunnels.
- Gradient; the BD 78/99 is rather vague on this point, it states as follows: "Trunk road tunnels with gradients exceeding 6 % are unlikely to be practical".
- Vertical and horizontal curvature; the standard specifications on these aspects are not provided in BD 78/99. It is assumed that Halcrow design is based on the current regulations on the minimum requirements of vertical and horizontal radius.

4.2.1 Geometry of Bluemull Sound crossing proposed by Halcrow

The maximum water depth along the tunnel alignment in the Bluemull Sound is 36 m. The interpreted geological profiles prepared by Caledonian Geotech [Ref. 3], based on shallow reflection seismic survey, indicate that there is a sedimentary cap of approximately 5 m thickness on top of the bedrock, thus the bedrock is found at approximately – 40 m. The interpreted geological profiles also show a local depression which could be a weakness zone, reaching – 45 m. The current proposal has a roof level at this particular point at approximately – 85 m, thus the rock cover is somewhere between 40 and 45 m, and subsequently at this stage of planning the design is not fully in accordance with the Norwegian guidelines. A further detailed refraction seismic investigation is required to verify the depth of the bedrock and the quality of the rock mass along the preferred tunnel route.

The profiles from Caledonian show that there are indications of internal rock fabrics, which is understood to be jointed zones, or even weak zones of faulted character. These must be identified by use of further geophysical investigations, that is a refraction seismic survey.

The proposal by Halcrow is based on a maximum gradient of 8%, and a two lane solution throughout the entire length. Recent experience from the 7.2 km long Oslofjord-tunnel, which has a maximum of 7 % with an overtaking lane and AADT of 4000 vehicles, indicates that the heavy vehicles tend to slow the traffic flow going both upwards and downwards. As a comparison, the 2 tunnels in the Faroe Islands are both based on a 7 % maximum inclination, but in Iceland a maximum 8 % inclination was chosen with a third overtaking lane, both in accordance with the NPRA guidelines. Waivers can be accepted based on such grounds as; the actual mix of traffic with a small amount of heavy vehicles; or short length of inclined tunnel (less than 1 km); or city tunnels with typical rush-hours and reduced design speed limits. Even as steep a gradient as 10% has been used in tunnels in remote areas with small traffic volumes. However, steep gradients will result in reduced traffic speed, for heavy vehicles and underpowered cars, which could impose dangerous traffic situations and uncomfortable driving.

For the Bluemull crossing there is a potential for later adjustment of the profile (reducing the rock cover). At this stage of planning it is recommended that the existing alignment is maintained. This recommendation must also be seen in conjunction with the design traffic volume AADT (20 years), assessed to 2500 vehicles.

As far as the vertical radius is concerned, a radius of 2506 m has been chosen for the low-point in the tunnel, which is sufficient to provide comfortable driving conditions when passing the low point. The Halcrow solution has a horizontal radius of 940 m, which is slightly less than the Norwegian guidelines.

Halcrow has proposed a tunnel profile that produces a cross section of approximately 70 m^2. The main reason behind the differences of the Norwegian guidelines and the Halcrow design is related to the requirement that is forwarded by BD 78/99 to allow room for a 5.3 m free height versus a minimum of 4.6 m in the Norwegians guidelines.

It would be a possibility to provide a third, overtaking lane for a steep, inclined tunnel. To be able to accommodate a third line the Norwegian guidelines would require a cross-section fulfilling a T11.5 tunnel. The T11.5 cross-section produces a tunnel width of 11.5 m that provides room for 3 lanes with a carriageway of totally 9.5 m and 1 m pavement on each side.

The guidelines from NPRA do not recommend traffic by bicycles and pedestrians in tunnels longer than 4 km, and it must also be considered that the tunnels will have long, steep parts. Even with the proposed cross-section another 1 m must be added if a two lane road plus bicycle lane shall be included. Moreover, the time it will take for a bicyclist to pass the tunnel, may require additional ventilation installation to cope with the CO- and NO-values. It is probably more realistic to have a shuttle service to handle this type of traffic. According to BD 78/99 pedestrians, pedal cycles and motor cycles with engines below 50 cc are not permitted to enter road tunnels.

4.2.2 Geometry Yell Sound crossing proposed by O. T. Blindheim AS

A proposal for a sub sea tunnel alignment crossing the Yell Sound has been prepared by O. T. Blindheim AS and is included in this report. The proposal has been prepared basically in accordance with the requirements outlined above, and the Halcrow proposal where appropriate. This will produce a tunnel with a length of approximately 5.1 km.

The following main geometrical elements have been used to develop the proposal for the Yell Sound crossing:

- 50 m cover at the location of the maximum water depth according to the bathymetric map to the tunnel roof, with practically no soil deposits on the rock head.
- 8% gradients at the steepest inclination (towards Yell), with an intermediate inclination of 0.3 % towards the low point west of Bigga, before ascending towards the Mainland with a 6 % gradient.
- The vertical and horizontal curvatures have been chosen according to the proposal by Halcrow for the Bluemull Sound proposal.
- A vertical shaft, or drill-hole at the Mainland side to provide for the pumping line of discharged water.

- A cross-section corresponding to Halcrow proposal of 70 m^2.

There are, however, many uncertainties related to the alignment since no particular investigations have been undertaken. These uncertainties are as follows:

1) Due to that there is no particular investigations done in the Yell Sound as regards thickness of sediments at the sea floor and depth to the bedrock, there is inevitably some uncertainties related to the low point of the tunnel. The proposed location is motivated by the insignificant thickness of such sediments generally found in the sounds between the Shetland Islands.

2) The assumed water depths are based on the bathymetric maps made for ships and boat traffic, the Admiralty series of maps and charts, and do not cover the entire tunnel corridor. Deeper locations might occur in the area without being covered by the Admiralty chart.

3) Land acquisition. The portal at the Mainland side is located in an area consisting of private land, and also the connection road to the tunnel is planned at private land. It is required to further investigate this matter.

4.2.3 Proposed changes on the Bluemull Sound tunnel design

The tunnel alignment as received from Halcrow [Ref. 2] is not an optimised one. Based on the discussion above it is recommended that the tunnel alignment for the Bluemull Sound is modified according to the following:

1) The vertical curvature of 8% can be maintained, however, it is assumed that it would be an advantage for the comfort and the safety of the traffic if a third lane is included to provide space for overtaking traffic. Alternatively, the tunnel length could be increased with approximately 200 m at each side to provide a 7% gradient in the inclined parts of the tunnel.

2) The tunnel alignment could be modified to allow a shifting of the sub sea crossing slightly southwards. This will mainly improve the geometry of the portal area at the Yell side. The portal can be moved towards south where a lower terrain is found and thus the approach cutting can be reduced. A modified alignment would also provide a better intersection with an interpreted weakness zone (rock type boundary) that strikes in N-S direction between the Loch of Gutcher and the Wick of North Garth.

3) It is common in Norwegian sub sea road tunnels that there is only one drainage pipe, with cross-overs in locations with concentrated water leakage. The proposal from Halcrow shows a cross-section of the tunnel with two-sided gradients and drainage pipes on both sides and pipes embedded in concrete. It is our recommendation to change to one-sided gradient in the tunnel floor and install only one drain pipe, dimensioned with adequate capacity to handle the water inflow. Cross-overs are used in areas with significant water inflow to the tunnel. The pipes should be embedded in gravel and the tunnel profile should include a blasted ditch for the drain pipe.

5 CHALLENGES FOR THE SUB SEA TUNNEL PROJECT

In Norway, a country with a typical mountainous landscape, tunnels as a traffic element have been integrated in the public road network for several decades and with a total number of some 800 tunnels currently in use. The Norwegian construction industry is experienced in this kind of tunnelling and the public users are very much accustomed with tunnels.

The fixed link projects currently under planning will be the first of such kind in the Shetlands, and even the first road tunnels ever built in the islands. Thus, it is required that the tunnelling solution represents a sufficient level of confidence with regards to the responsible authorities, and also amongst funding institutions and the general public that shall be the users. Information is a key word in this context, and on the technical side, documented and tested solutions must be used. However, the solutions must be designated to the actual traffic volume constituting a cost-effective solution with a favourable cost-benefit ratio.

In the following, some aspects of the technical challenges and uncertainties that according to Norwegian experience are associated with the tunnel alternatives are listed.

- Tunnel entrances located in a flat landscape (Unst entrance is almost at sea level) with expected high (close to surface) ground water level within a jointed rock mass including also the aesthetic aspect of blending the portal with the surrounding landscape,
- Handling of water ingress from conductive geological features,
- Potential sub-glacial trenches filled with alluvium.
- Undocumented extension, location and condition of fault zones in both sounds,
- Safe environment for the tunnelling crews and personnel involved in the construction work,
- Provide a tunnel comfort and safety that encourages the public to use the tunnel, and
- Level and location of lowest rock surface in the sounds.

In the chapters below these aspects are dealt with, both from a technical point of view with regard to methods and ways to handle these challenges, and also with regards to the associated cost impacts.

Experience from other similar tunnelling projects that have been introduced as new technical advances suggests that information to the public is important, before the tunnelling work commences and also during the construction period. Particularly during construction the public opinion appreciates information such as related to the progress of the tunnelling work, how well the work proceeds etc. Regular news bulletins in radio/TV and updated homepages are effective ways to reach the majority of the public.

As was experienced for the Hvalfjördur tunnel in Iceland, a general negative public attitude beforehand of the construction was gradually turned positive during the progress of the work, as a result of frequent updating in the media. Today, the traffic volume in the Hvalfjördur tunnel is twice as much as the most optimistic prognosis on the planning stage was.

6 DESCRIPTION OF MAIN TUNNELLING AND COST ELEMENTS

6.1 Tunnel excavation method

The open cuts would under no circumstances be excavated by other methods than digging the soil and weathered rock and drilling and blasting the sound rock. For the excavation of the tunnel itself, the drill and blast technique is recommended for both the Yell Sound and Bluemull Sound tunnel crossings. In Norway, a total of almost 25 sub sea road tunnels have been completed, all constructed according to the drill and blast technique, in rock mass conditions similar to those found for the projects in the Shetland Islands. The tunnelling concept which has been applied in Norwegian sub sea road tunnels, is based on constituting a drained concept, thus water control is strictly required.

A TBM (Tunnel Boring Machine), which is a full face mechanical excavation method, could be applicable too, however, such excavation does not provide the same possibilities for probing and pre-grouting ahead of the tunnel face, to gain the necessary water control. TBM tunnelling has been performed in a number of large tunnelling projects, such as the Channel Tunnel, Øresund-connection etc., however, these were constructed as tunnels with water tight linings. Further, the tunnel alignments, both the vertical gradient and horizontal curvature may impose particular arrangements as far as muck transport is concerned. Another significant aspect that is in disfavour for a TBM is the length of the tunnels, considered as being too short for an economical viable TBM alternative. The circular cross-section produced by a TBM would either request a later enlargement by Drill & Blast, or a dimension that is far larger than actually needed.

Road header, as proposed by Halcrow may not constitute a feasible excavation method for the kind of rock types prevailing in these areas. The road header excavation method suits rock types with much lower strength than the gneiss, granodiorite etc. found in the actual site areas.

6.2 Water control and rock mass grouting

As mentioned above, an essential element for both the successful construction and the operation period is appropriate water control. In general, most of the tunnelling work will be carried out below the ground water level, and without special precautions, water inflow may cause severe problems for the project. Due to the jointed signature of the rock mass, probe-drilling ahead of the tunnel face is recommended to be executed on a continuous basis. This could include for example 2 to 8 holes, each with a length of 20 to 35 m, all drilled from the tunnel face and into the virgin rock mass ahead of the tunnel. Based on the observations and measurements made in these holes, pre-excavation grouting of the rock mass will be decided.

Such probing will provide an early warning if the rock mass quality ahead of the tunnel face is of poor quality due to weakness zones, water bearing joints and cracks, low rock cover and unexpected adverse situations. Depending on the nature of the rock mass in these holes, pre-defined grouting schemes are triggered. Without sufficient treatment of the rock mass by pre-grouting it is not seen feasible that pumping can be performed using reasonably sized pumping equipment. A systematic pre-grouting schedule must be incorporated in the tunnelling procedure.

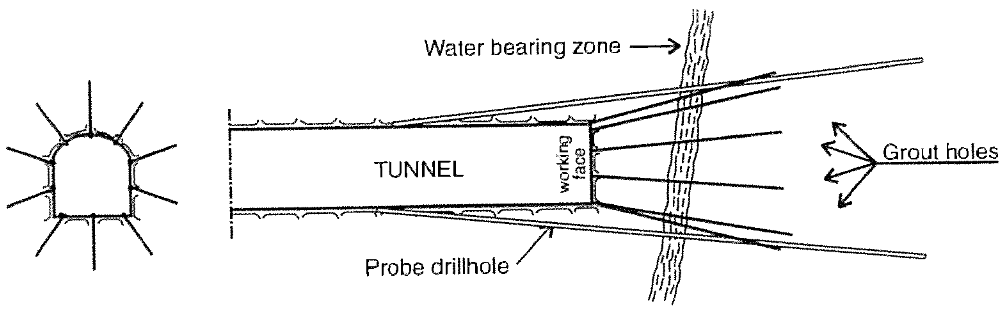


Figure 6. A typical scheme for pre-grouting ahead of the tunnel face

Rock types, such as typically hard and stiff sandstones, granites and gneisses etc. are associated with higher permeability through conductive zones and thus higher water inflow to the tunnel than metamorphic rock types such as schists. Metamorphic rock types, such as schists, are typically displaying a more impervious character. Typically, the ground water flow in granites and gneisses is associated with conductive zones such as open joints and cracks, whilst the influence from tectonic loading, folding and physical characteristics such as stiffness, and metamorphose all contribute in the natural impermeabilisation of metamorphic rocks.

Sub sea tunnels in Norway have been constructed in the same types of rock that prevail in the area of the Bluemull Sound and Yell Sound crossings. The process of probe drilling and pre-grouting has proved to be an efficient way for artificial impermeabilisation, however, the extent of the grout work is normally more comprehensive in granites and gneisses than in metamorphic rock types.

6.3 Crossing of weakness zones

Based on the information from the regional geological mapping of the Shetland Islands [Ref. 6], it is expected that a number of fault zones might occur when crossing the Yell Sound as well as the Bluemull Sound. The character of these zones cannot be predicted precisely on the current geological basis, however, decomposed and fragmented rock, probably with clay minerals in fillings can be expected.

Extensive probe drilling must be planned for tunnel sections where such zones are expected with subsequent pre-grouting of the rock mass. In addition, other precautionary methods must be at hand during the tunnelling phase. Such methods should include short blasting round (reduced tunnelling advance per blast round) or split round blasting (dividing the full tunnelling cross section into 2 or more separate blastings), spiling bolts ahead of the tunnel face and immediate rock support.

A typical rock support measure in very poor rock mass conditions is cast-in-place concrete lining, which could include concrete cast invert too. An ultimate construction method in extremely poor rock mass is ground freezing. Ground freezing is a construction method that is only used for temporary stability of the tunnel. Cast-in place concrete lining is normally needed for permanent rock support where ground freezing has been applied. At this stage in the project the need for such a measure cannot be ruled out.

6.4 Rock support

As a functional requirement for the tunnel stability the rock support during construction shall be carried out in such a way that rock fall imposes no hazard to the workmen and that the tunnel, under no circumstances, shall be at the risk of collapse. For the permanent stability no rock fall shall be allowed that may land on or end up on the road lanes, or the pavement.

It is assumed that the main part of the rock support in the tunnels can be carried out with rock bolts and sprayed concrete, which is also proposed by Halcrow [Ref. 2]. However, the current geological information obtained does not provide a confident basis for support estimates. It is needed, particularly in the sub sea section of the tunnels to perform further investigations to build up a solid basis for support predictions.

During the tunnelling phase the rock mass is normally classified continuously to form basis for the rock support design. It is possible to choose between various classification systems. The most used ones are the Q-system, developed by the Norwegian Geotechnical Institute (NGI) and the RMR-system developed by Bienawski. Both systems are recognised on a worldwide basis in the tunnelling industry. Based on this quantitative classification the rock support will be determined. The Q-system includes recommendations on the permanent rock support relevant for the various classes of rock mass.

A typical combination of rock bolts and sprayed concrete for permanent rock support of a 9 m wide tunnel is given in table 2 below. This table is based on the recommendations forwarded by the Q-system, and could be used as a basis for the permanent rock support design.

Table 2. Typical rock support matrix based on the Q-system

Rock mass class	Very poor	Poor & fair	Good	Very good and better
Q-value	0.1 < Q < 1	1 < Q < 10	10 < Q < 40	Q > 40
Sprayed concrete thickness (mm)	90 – 150	40 - 90	0 - 40	No systematic sprayed concrete
Bolt pattern (m)	1.3x1.3 - 1.7x1.7	1.7x1.7 - 2.3x2.3	2.3x2.3 - spot bolting	Spot bolting

For rock mass conditions with Q-values below 0.1, that is extremely poor rock and worse, cast-in-place concrete lining is an applicable solution according to the Q-system, or combinations of reinforced ribs of sprayed concrete and bolting.

The quality of rock support, as described in the reports by Halcrow [Ref. 2] are typically rock bolts of steel rebars with a double corrosion protection by means of galvanizing and epoxy coating. The internal environment in a sub sea tunnel is quite harsh as the installations are exposed to both exhaust fumes and saline water, which require appropriate corrosion protection. The sprayed concrete support must also be designed taking the aspects of both corrosion protection and the durability of the final product into account, and a quality beyond the specified quality in [Ref. 2] would be needed, such as fulfilling the requirement of 45 MPa strength.

6.5 Water and frost protection

Neither the Norwegian nor the British standards specify particular functional requirements on the water protection of tunnels. However, based on recent experience from tunnels in Iceland, the Faroe Islands and Norway we would propose that the following functional requirements are applied:

1) *Running water (free flowing and dripping water) shall be shielded.* This requirement implies that no water is allowed to run or drip from the rock surface and onto the road surface. Buildings and installations in niches and recesses shall be protected from running and dripping water too. Even in tunnels with low total ingress of water (< 100 l/min · km), sporadically spot areas of running or dripping water may occur and these shall also be shielded.

2) *Dry and moist areas of the tunnel can be left without water protection.* Only dry and moist areas can be left without water protection.

3) *If registrations during the construction time indicate that running water occur seasonally these shall be shielded too.* Spot areas with running inflow water may occur with seasonal changes, particular along the on-shore part of the tunnels. This requirement takes care of seasonal changes.

4) *The above requirements are applicable for both walls and roof.* This requirement implies that the walls and the roof along the tunnel shall be treated in the same manner, without any differentiation between tunnel roof and tunnel walls.

The functional requirements as described above have been included on the cost calculation.

The need for frost protection is based on the annual frost amount (F) in the area, presented as h°C (hours x degrees Celsius). The temperature (< 0°C) is multiplied with the duration of each such occurrence of frost, that is the actual number of hours with temperatures below zero.

Information obtained for the Shetland Islands, provided by the Meteorological Office, indicates that the annual, average frost amount (F) during the last 14 years (from 010188 to 311201) has been less than 1000 h°C. The design basis should be the frost amount that statistically occurs once every 10 years (F10). Compared with geographical areas in Norway with a similar annual average frost amount (F<1000 h°C), the F(10) in the Shetland Islands is assessed to be in the range of 3000 to 5000 h°C.

The frost is expected to penetrate a few hundred meters into the tunnel due to natural ventilation, which is draught through the tunnel. The so-called "chimney effect" will be limited since both openings are at the same level for the Bluemull Sound. The proposed Yell Sound tunnel route has an approximately 20 m height difference, thus the natural draught will be towards the higher elevation, in Yell. The forced ventilation, though, will take the frost some additional 2-3 hundred meters into the tunnel. With the expected frost amount, it can be used as a preliminary assumption that the frost may occur some 500-1000 m in to the tunnels on each side. This leaves significant lengths in both tunnels where frost insulation of the water protection is not needed.

Frost and water protection of the tunnel can be done with a number of different types of construction. The cost estimates include a system consisting of concrete elements in the wall combined with an arch of polyethylene foam covered with sprayed concrete, see Figure 7 below.

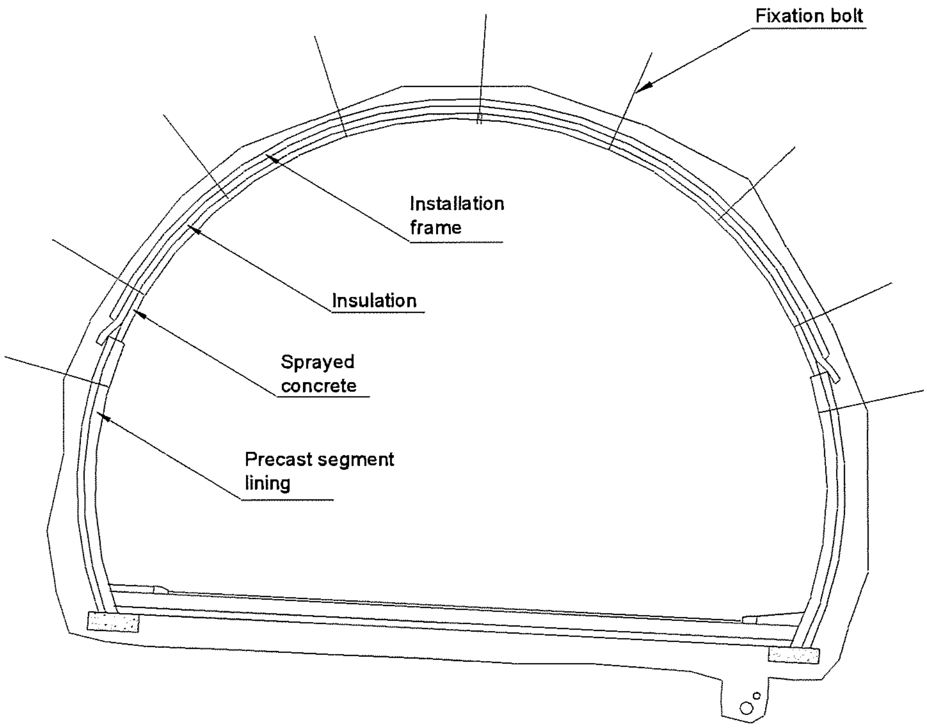


Figure 7. Water and frost protection with concrete wall elements and PE-foam/sprayed concrete

Figure 2 above shows one typical solution of water and frost protection system that has been widely applied in Norwegian road tunnels recently. This system has been approved by the NPRA to be used for all tunnel classes (see Figure 3) covering a wide range of traffic volumes corresponding to less than 5000 vehicles to above 15.000. See also Figure 8 on approved inner lining systems for water and frost protection in Norway. The proposed system consists of pre-fabricated concrete wall elements and PE-foam, the latter supported by steel beams and fixation bolts. For fire protection a layer of sprayed concrete is applied.

6.5.1 <u>The application of an inner lining</u>

The system described above has, due to its cost efficiency, been widely applied for water protection and an inner lining in areas also where frost is not considered a great problem. Some tunnels, particularly those with a high traffic volume are equipped with an inner lining, irrespective of water leakage. Such inner linings provide an improved aesthetical impression for the users and also an improved driving comfort. For the low traffic volume tunnels in Norway a variety of inner linings can be applied covering also the aspect of water protection.

According to [Ref. 14], Table 3 lists the different water and frost protection systems approved by the Norwegian Public Roads Administration for use in Norwegian road tunnels as of March 2002.

Table 3. Approved water and frost protection systems

Method of Water and Frost Protection Systems	**Tunnel class (AADT)**				
	A (< 2500)	**B** (2500-5000)	**C** (5000-10000)	**D** (10000-15000)	**E** (>15000, 2 tubes)
WG-Tunnel fabric, not insulated	○¹				
"Miljøhvelv", insulated (metal sheet W&FPS)	●	●	○²		
PE- foam w/ 60 mm sprayed concrete, steel fibers	●	●			
PE- foam w/ 70 mm sprayed concrete, mesh	●	●	●*	●*	●*
Concrete elements	●	●	●	●	●
Cast concrete with membrane	●	●	●	●	●

○¹ = may be used up to AADT 1000 (Annual Average Daily Traffic)and below a given frost limit (F_{10T}< 20000 h°C).
○² = concept is modified for tunnel class C.
●* = concrete wall elements must normally be used.

The WG-tunnel fabric lining satisfies stringent requirements regarding coverings for lorries as well as storage halls. The tunnel fabric consists of high quality PVC coated polyester fabric with a weight of 700 g/m^2. The WG-tunnel fabric is erected by clamping it between backing pipes, bolted to the tunnel periphery and pipe bands. All bolts pass through at fabric junctures.

The "Miljøhvelv" metal sheet system consists of a single sheet/cassette of aluminium, mineral wool mat with an overlay of high quality PVC foil. The cassettes are installed by means of profiles anchored to the surrounding rock. Initial W&FPS were of varying quality and this resulted in stricter specifications.

The Norwegian Public Roads Administration is continuously working to improve existing water and frost protection systems and develop new methods. The results of the last five years of development will be included in the revision of Design Guide 163. The Norwegian Public Roads Administration has recently finished a large research programme called "Tunnels for the citizen", where a sub-project "Water and frost protection" has highlighted the fire-, durability- and maintenance aspects of such systems. New systems have been developed and will go through an approval procedure during 2002.

7 DESCRIPTION OF MAIN TECHNICAL INSTALLATIONS

Installations and safety measures should be carried out in accordance with tunnel category B of the guidelines from the Norwegian Public Roads Administration (NPRA). This category has been used as comparison to the design prepared by Halcrow [Ref. 2].

7.1 Emergency lay-bys and turning niches

The maximum distance between neighbouring lay-bys should not exceed 500 m according to the Norwegian guidelines. The emergency lay-bys allow vehicles, which have faced a breakdown to be set aside to avoid disturbance of the traffic flow through the tunnel, and they should be large enough to accommodate large vehicles too. The length of lay-bys is 24 m according to Handbook 021, with 10 m at each side to provide a gradual extension of the tunnel cross-section. BD 78/99 does not provide any particular directive on the distance between each emergency lay-by, whilst Halcrow [Ref. 2] has indicated 250 m spacing to compensate for the steep inclinations (8 %) without a climbing lane.

These emergency lay-bys are also functioning as turning niches for cars.

Additional turning niches for large vehicles are required. The maximum distance between turning for large vehicles is 2000 m. Such requirement was neither found in the BD 78/99 nor in the Halcrow report [Ref. 2].

It is our recommendation that the spacing between the above mentioned emergency lay-bys and turning niches are adjusted to the actual geometry and traffic volumes of the tunnels, thus a maximum distance of 500 m as indicated by the Norwegian guidelines would be appropriate. More frequent niches are not adequately replacing the need of a climbing lane, or less steep gradient.

7.2 Safety measures

Safety measures in the tunnel are required according to the following.

- Fire extinguisher every 100 m (250 m).
- Emergency telephone every 100 m (500 m).

The BD 78/99 requirement is shown above with the Norwegian guidelines in brackets, indicating that the British standard is stricter than the similar Norwegian for these two specific elements.

In the table below, safety measures to be included are shown, with a comparison between Norwegian guidelines and Halcrow report [Ref. 2].

Table 4. Safety and fire preventive measures

Safety and Fire prevention equipment	Halcrow report [Ref. 2], Yell Sound tunnel Cat. B acc. BD 78/99	Norwegian guidelines
Emergency telephones	Required	Required
Radio Rebroadcasting	Not required	See note *
Traffic loops	Not required	Not required
CCTV	Not required	Not required **
Hand held extinguishers (see above)	Required	Required
Pressurised fire hydrants	Required	Not required ***
Fire hose reels	Not required	Not required
Emergency exit signs	Required	Not required ****
Emergency walk way	Required	Not required *****
Escape doors	Not required	Not required
Turning bays	Not required	Required, see above
Height limitation barrier	Not shown	Required
Red stoplight at tunnel portals	Not shown	Required
Automatic barriers at portals	Not shown	Option
Mobile telephone	Not shown	Option
Variable signs	Not shown	Option
Automatic barriers at the portals	Not shown	Option
Emergency power supply (UPS)	Not shown	See illumination

Notes:

* Broadcasting with the possibility for the tunnel operator to interrupt the ordinary broadcasting for local messages to the people inside the tunnel. Broadcasting of the 2 most common radio stations.

** CCTV, or a detection system shall be installed at the tunnel openings if automatic barriers are used.

*** The possibility of providing water for fire extinguishing shall be provided by water reservoirs inside the tunnel, e.g. from the water reservoir in the bottom of the tunnel, or in dedicated tanks outside.

**** Not a requirement, but often used.

***** The shoulders can be paved to provide a smooth surface to accommodate emergency walkway.

Automatic barriers at the tunnel portals are often used in combination with variable signs to prevent traffic entering the tunnel in any case of emergency. Alternatively, manual barriers can be installed, which actually means that a barrier of some sort need to be physically placed in front of the tunnel by tunnel operator.

It has become quite common to install antennas that will allow coverage by mobile telephones, within the GSM net.

Variable signs at the tunnel entrance, and also in some cases signs inside the tunnel that indicate to the traffic which way to go out of the tunnel in case of an emergency situation may also be an option.

Regardless of tunnel category, an emergency plan must be prepared before the tunnel enters operational status.

7.2.1 Fire protection

From statistics of car damage from insurance companies in Norway 1994 it was found that 256.989 claims were due to material damage in the traffic. 3031 were due to car fires. About 20 of these took place in tunnels. The rate of personal injury due to fires in vehicles is statistically 1 to 500. In other traffic accidents there are 1 personal injury out of 15-20 insurance damages. The numbers are confirmed by similar statistics from England and Germany.

The probability of fire in road tunnels depends mainly on the traffic amount and the tunnel length, but the probability of fire in trucks also increases when driving long steep slopes due to heating of the motor. These factors are included in the calculation program for estimation of tunnel fire hazard at NPRA. The frequency of fire in Norwegian sub sea road tunnels was in 1994 estimated to 0.02 fires per 1 mill. vehicle · km. For the new Oslofjord connection the estimated frequency of accidents is 1 every 7.5 years for a car fire and 1 every 20 year for a truck fire considering a tunnel length of 7500 m, max. gradient of 7%, and an AADT of 4200.

The above figures can be used as an indication of the probability of fires in a tunnel in general, and particular attention with respect to the actual traffic situation in Shetland should be carried out. Especially if the quality of the car park differs much from countries with which the statistics of car fires are compared.

7.3 Ventilation and illumination

7.3.1 Ventilation

The most common tunnel ventilation system applied in Norway is longitudinal ventilation using impulse ventilators. Such ventilators are commonly bi-directional, meaning that they are capable of blowing in both directions, with a primary direction of full effect and a secondary direction with approximately 60 to 80 % of the full effect. The ventilators will have pre-defined start and stop levels related to the concentration of CO, NOx and soot measured in the tunnel air. Running of the ventilation fans is controlled by the Programmable Logic Controller (PLC) system. The following are the maximum level acceptable for a road tunnel.

Table 5. Maximum acceptable concentrations of pollutants in tunnel air

Monitored elements (pollutants)	BD 78/99	Norwegian guidelines	Road tunnel with pedestrians/bicyclist length 1-4 km*
CO	200 ppm	200 ppm	25
Nox	15 ppm	35 ppm	2
Visibility	1,5 mg/m3	5 mg/m3	-

* No recommendations for tunnels beyond 4 km length.

Such measurements are done by use of CO/NOx indicators. For a tunnel that is 4-5 km long there are typically 3-5 such measuring stations distributed evenly along the tunnel length. Further, at each tunnel portal red, blinking lights can be installed to announce that the CO (NOx) level in the tunnel has reached an unacceptable level and the tunnel shall be temporarily closed until the air has been cleaned by the ventilators to an acceptable level. Optionally for this example, but often included in similar low traffic tunnels, is barrier at the portals with automatic closing.

In addition to the design criteria related to traffic intensity and air pollution, the ventilation system shall, according to Norwegian guidelines have sufficient capacity for smoke control to ensure a minimum air speed in any direction of 2 m/s, to cope with a smoke filled tunnel scenario where a private vehicle has caught fire (5 MW fire scenario). A total number of some 15 to 40 fans can be expected for each of these tunnels producing a total of 10.000 to 25.000 N thrust force.

7.3.2 Illumination

Road tunnels shall in general be illuminated. According to Norwegian practice the tunnels are divided into various zoning, such as entrance zone, transition zone and night light zone. The entrance zone and transition zone are established to allow the human eye to adapt from a daylight situation to tunnel illumination, or vice versa. Using a design speed of 90 km/h the length of the entrance and transition zones will be in the range of 100 to 300 m long and include adjustable illumination levels to take into account variations in the outdoor luminance. Normally 250 W and 100 W high pressure sodium lamps (Na-H) are used in these zones with varying spacing between the lamps. Handbook 021 provides guidelines for the determination of minimum illumination in the entrance and transition zones as a percentage of the outdoor luminance.

The general tunnel illumination (night light) consists normally of 35 W or 50 W low pressure sodium lamps (Na-L) with spacing 15 to 25 m. High pressure sodium lamps can also be used (Na-H). A maximum of 25 m spacing can be used to ensure visual guidance only through the tunnel, which has been proposed by Halcrow [Ref. 2], however, an even illumination is obtained with a smaller spacing, 15 to 18 m. According to Handbook 021 the illumination in the night light zone shall fulfil the requirement of 2 cd/m2.

In a two lane, bi-directional tunnel the lamps are commonly installed along the centre line for the tunnel. For a tunnel with 3-lanes there are several options where to install the lamps, using one or to rows of lamps. One such option is install two parallel rows of lamps, both rows shifted sideways from the centre line. Another option is to install one row along the centre line of the tunnel of the tunnel, as for a two lanes tunnel, but also one single row shifted aside from the centre line could be applicable.

Emergency power supply shall be included in every 4th or 5th lamp and shall lit for 1 hour after a power cut-off.

7.4 Water drainage and pumping

The BD78/99 does not provide any particular specifications for sub sea tunnels, thus, it is chosen to refer to the Norwegian guidelines on this aspect. The requirement for water inflow in Norwegian sub sea tunnels is normally set to a maximum of 300 l/min/km. For an example, the 4.6 km long Yell Sound tunnel would require a pumping capacity of almost 1500 l/min during the entire lifetime of the project. A major portion of the leakage water is saline.

According to BD 78/99 there is no concrete instruction on the quality of the pipework, other than specifying that plastic and related materials shall be avoided in tunnels. Experiences from Norwegian sub sea tunnels suggest that PVC/plastic pipes are used, or corrosion resistant steel qualities in both pipes and pumps due to the highly saline water. To reduce the pumping distance the low point of the tunnel is located close to the end of the western slope for the Yell Sound, whilst it is located more or less in the mid-point at the Bluemull Sound. It may also be an option to discharge the water through a vertically drilled hole close to the shore, rather than pump it to the closest portal, but this option can be evaluated in a later stage of the design process.

According to the Norwegian guidelines a water reservoir must be excavated in the low point of the tunnel to allow at least accumulation of 24 hours of steady ingress. Depending on the power back-up, the need of increasing the capacity to 48 hours capacity might be considered. This precaution is made to cope with a scenario involving a power cut-off or failure in the pumping system. This implies a reservoir of approximately 2200 m^3 (for 24 hours cut-off) with the assumed water inflow mentioned above for the Yell Sound, with a smaller reservoir needed for the Bluemull Sound (1150 m^3).

The drainage system must be designed to take the inflow of water. But there is also a need for a separate system for collecting flushing water since regular washing of tunnel walls and roof will be necessary. The system must also include sludge interceptors.

Both "dry" pumps and submerged pumps can be used for the discharge of inflow water, being connected to a separate discharge pipe.

Next to the water reservoir a pumping station needs to be placed. The pumping station is normally (according to Norwegian guidelines) equipped with pumps each having a capacity of 50 % of the actual leakage, and the total installation shall have a minimum of 50 % redundancy. The operation of the pumps shall be automatically controlled, by the PLC-system.

From the pumping station a pumping line shall lead the discharged water out of the tunnel, either to the portal itself or to a shaft for a controlled discharge of water at the surface. The pumping line must be designed for the actual pressure and should be resistant to corrosion (special steel or PVC pipes).

Typically, for the Yell Sound, 3-4 pumps would be needed, each with a capacity of 10-15 l/sec, lifting the water almost 100 m vertically. For the Bluemull Sound the maximum total allowable inflow is much less than for the Yell Sound, and consequently a smaller pump installation would be required.

7.5 Programmable Logic Controller (PLC) system

A Programmable Logic Controller (PLC) system is normally installed for the automatic running and operation of the tunnel installations.

The PLC typically operates the following installations in the tunnel, in an automatic mode. Below is provided an indicative list of typical operations dealt with by the PLC. However, it must mentioned that all these can be controlled manually from e.g. the switchgears.

- Ventilation fans; start & stop of fans, number of fans to operate at any time, which fans to run, air flow direction,
- Illumination lamps; illumination level in entrance areas,
- Discharge water pumps; start & stop of pumps, which pumps to run,
- Emergency equipment; indicator on fire extinguisher or emergency phone in use.
- Traffic barriers and warning signs; lowering of automatic road barrier, switching on/off warning signs.
- Power supply; switching to an emergency power supply mode.

7.6 Electrical supply and sub-stations/transformers inside the tunnel

Normally the sub sea tunnels are supplied with electricity from both sides. That implies that if there is fall out of electricity supply from one side there is adequate supply from the other side to continue normal operation mode of the tunnel. Thus the operation mode of the tunnel is not threatened.

However, situations might occur which cut the electricity supply from both sides. In such situations the typical mitigation is to install a diesel powered emergency power supply, which can either be a fixed station already in place or a mobile one that could also be located at the site. The fixed station is connected to the normal power distribution system in the tunnel. The mobile power supply is moved physically to a dedicated location in the tunnel where it is connected to the distribution lines.

Inside the tunnel, transformers and sub-station and also switchgears are located in conjunction with group of ventilators. Typically 4 to 8 ventilator fans are located within a distance of some hundred meters, and with a transformer next to these fans to make the cabling as short as possible.

The transformers are normally located in niches and situated in dedicated concrete buildings or steel containers to preserve undisturbed service. Thus there is no need of erecting permanent buildings outside the tunnel, as all service facilities needed, will be located in structures inside the tunnel. Further, it is not planned to establish a toll collection system or dedicated booth consequently all infrastructure needed to operate the tunnel will be located inside the tunnel.

8 TIME SCHEDULES

Based on a tunnelling concept as described in this report, time schedules for the Yell Sound and Bluemull Sound crossings can be established. As basis for these time schedules the recent experiences from Iceland and the Faroe Islands have been used, as they are considered relevant for the projects in the Shetlands.

The following are the most important milestones for the projects used in this comparison:

Table 6. Milestones for the Hvalfjördur tunnel and the Vágatunnilin

Milestones	The Hvalfjördur tunnel	The Vágatunnilin
Tunnel length (m)	5900	4900
Mobilization start	March 1996	September 2000
Tunnelling start	May 1996	October 2000
Tunnelling breakthrough	October 1997	January 2002
Tunnel opening	July 1998	March 2003 (planned)
Construction time	Appr. 30 months	Appr. 30 months (planned)

It is necessary to mention that the time used for installations work in the Hvalfjördur tunnel is considered as very tight, and should not be used for planning purposes. The planned duration of the construction work for the Hvalfjördur tunnel was 39 months including 3 months of testing of the operational status of the tunnel after opening. On the other hand, the planned duration of the installation work for the Vágatunnilin is probably a conservative approach. For the Yell Sound and the Bluemull Sound crossings the following estimates on time schedules can be given.

The duration of working shifts accumulated to almost a 120 hours for both the Hvalfjördur and Vágatunnilin projects, which is indeed above the Norwegian regulations as they allow approximately 105 working hours per week.

Table 7. Assessed duration of main construction activities Yell Sound and Bluemull Sound

Construction activity	Yell Sound	Bluemull Sound
Tunnel length (m)	~5100	~2600
Mobilisation/demobilisation	3-5 months	3-5 months
Tunnelling, 35-45 m * advance per week at each tunnel face	15-20 months	8-13 months
Installations and permanent rock support	13-17 months	8-12 months
Total construction time	31-42 months	19-30 months

* Note. Tunnelling in the Vágatunnilin averaged 45 m advance per face per week for a 10 m wide cross section, whilst for the Owners' planning purpose an average of 40 m per week per tunnel face was applied. For the Hvalfjördur tunnel an average of 37 m per week was achieved for the section of the tunnel that had a 11 m wide cross section, and 45 m per week for a 8.5 m wide tunnel cross section. These figures are quite in line with experiences from similar tunnelling projects in Norway.

The above activities and their indicative durations demonstrate that the two tunnelling projects could be completed within a realistic construction time frame ranging from 19 to 42 months. The above construction durations are based on the following assumptions:

- The contractor mobilises with one main site on either side of the sound, and a smaller satellite site on the opposite side.
- Excavation is ongoing at two tunnelling faces simultaneously starting at the same time and proceeding with merely the same advance rate.
- Various installations work is subsequently allowing the use of both portals.
- Main contractor is experienced in this type of tunnelling.
- Advance rate based on 30 and 50 m tunnel per week per face for 11 and 8.5 m wide cross sections respectively.

9 MAINTENANCE COSTS FOR A SUB SEA TUNNEL

For estimation of the maintenance costs the experience from Norwegian sub sea tunnels has been used as basis, see [Ref. 11], as a reliable data base exists. At the moment there are 17 tunnels which have been in operation more than 4 years with the oldest being in operation for 18 years. Most of them are comparable with the fixed links of Yell Sound and Bluemull Sound. The maximum gradient in these tunnels is between 8 and 10%, and 8 of the tunnels have current AADT between 1000 and 3000. One of the tunnels, the twin tube Tromsøysund crossing, has AADT around 7000.

The interior environment in a sub sea road tunnel is harsh, with saline water and exhaust fumes. The material quality, especially steel and concrete must be specified to meet strict requirements, in the sense of corrosion protection and corrosion resistance. This is equally important for installations and support measures. In Norwegian tunnels maintenance and replacement of such equipment has been a major cost factor during operation, particularly for the older tunnels that did not have the same quality requirements as those of today.

Further, in many tunnels the growth of algae in the drainage pipes has caused significant maintenance work.

For Norwegian sub sea tunnels the experience indicates that the annual cost for reinvestment, operation and maintenance varies in the range of 400 to almost 1000 NOK/m. Out of this, a substantial portion is related to the reinvestment costs, which could vary from 30 to 50 % of the annual total cost, that is in the range of 200 to 500 NOK/m. A further break down shows that the costs related to electricity represent a portion equivalent to 25 – 50 % of the annual total cost, and out of this portion, the electrical supply for ventilation purposes constitutes almost half the costs for electricity.

Calculating a rough figure of the assessed annual reinvestment, operation and maintenance cost for the fixed links in the Shetland Islands, the following assumptions have been used:

- Applying a rate of 0.75 NOK/kWh in the Shetlands that is 50% higher than the rate used in [Ref. 12].
- Using a reinvestment rate of 35 % of the operation and maintenance, indicating that a high quality standard is applied for these tunnels.
- Using an operation and maintenance cost of 600 NOK/m that is higher than the average in [Ref. 12], due to the costs of electrical supply.
- A design traffic of 2000 vehicles per day.
- A conversion rate of 13 NOK per pound sterling (£).
- No financial costs included.
- Assuming that the labour costs are comparable for Shetland and Norway.
- Uncertainties with regards to final cross-section, tunnel length etc. are not considered.

Table 8. Annual costs for reinvestment, operation and maintenance

Cost elements	Yell Sound	Bluemull Sound
Tunnel length	~ 5100 m *	~ 2634 m *
Operation and maintenance	235.000 £	120.000 £
Reinvestment	85.000 £	45.000 £
Total annual cost reinvestment, operation & maintenance	320.000 £	165.000 £

Note *. The length of portals have been included.

Based on the calculations in Table 7 above, an average cost per meter tunnel has been calculated to 63 £ (equivalent to 820 NOK) for both tunnels which is above the average for similar Norwegian tunnels.

Measures can be taken during the design phase of the tunnels to try to reduce the annual costs for reinvestment, operation and maintenance. A simple, but prime measure is to pay close attention to the chosen design solution bearing the operation costs in mind.

10 FURTHER GEOTECHNICAL INVESTIGATIONS

10.1 Geophysical investigations

The geophysical investigations that have been carried out so far give a good overview of the sea-bed conditions in the Bluemull Sound, but there is no similar information obtained for the Yell Sound crossing.

In general, there are two main aspects that call for further investigations;

- the rock surface is not accurately defined, and
- the location and condition of weakness zone(s), if any, are not known.

In addition, information on the rock mass quality along the tunnel route must be obtained.

To cope with this situation two different geophysical investigation methods are suitable:

1) Reflection seismic (including echo sounding)
2) Refraction seismic

For the Yell Sound a reflection seismic survey remains to be done for the purpose of defining the depth to the sea floor and also to provide information on the thickness of the sediments. Such a survey will bring the Yell Sound crossing to the same stage of the planning as the Bluemull Sound has reached, as per date.

Typically, the reflection seismic survey is performed in a grid to provide information of a larger area. The grid could consists of lines with a spacing of 50 to 100 m, and perpendicular lines with 200 m spacing. Increasing the number of lines to a fine grid will reduce the uncertainty related to the presence of topographical and geological unconformities and unevenness. For the Yell Sound crossing it is required to perform such a survey, as it will constitute the main basis for the identification of the tunnel corridor. Further, a reflection seismic survey would identify topographical depressions that could be potential weakness zones, and as such, these depressions would require more detailed investigations.

For the purpose of obtaining further details of potential weakness zones, it is necessary to conduct refraction seismic surveys. Spreads of refraction seismic lines will normally provide information on the rock surface and the location and condition of weakness zones. For the detection of vertical or sub vertical zones in the rock, i.e. zones where the rock is more crushed and fractured than normal, this geophysical method is highly recommended.

A typical refraction seismic survey consists of seismic lines each having a length of 235 m. The hydrophone cable is lowered to the sea floor. These lines shall be used particularly in the central parts of the sounds, in areas with low rock cover and where the reflection seismic has identified potential weak zones. Close to the shore lines a line or two shall be considered for the verification of the bedrock surface. Before concluding the final tunnel alignment in the sub sea part, it is recommended to fill in with refraction lines to provide a more or less full coverage, to establish a "describing profile". Altogether, the number of refraction seismic lines would probably be from 20 to 30 spreads for the Yell Sound crossing, and 10 to 20 for Bluemull

Sound. However, the final number will certainly depend on the findings underway in the pre-investigations.

Based on the findings from the seismic surveys, sea floor maps as well as rock head maps are normally produced for such tunnel projects.

For the on-shore sections of the two tunnels the use of refraction seismic should be considered in certain areas where great thickness of soil and sediments cover the tunnel alignment. For the Bluemull Sound, typical locations that could be investigated are such as: in the portal area at the Yell side, the first section of the tunnel with low rock cover at the Unst side and typical zones that can be seen at the shore line at the Unst side next to the sound.

For the Yell Sound, refraction seismic could typically be applied in both portal areas to obtain information on the depth to the bedrock and the quality of the bedrock.

10.2 Topographical and bathymetrical mapping

At present there are topographical maps available for the concerned areas in scale 1:10.000, which is an appropriate scale for the current stage of planning. However, for detailed design it is required to utilise more detailed maps. Typically topographical maps in scale 1:5000, with 5 m contour lines are used for the tunnel alignment drawings, whilst the portals for example require even more detailed maps, such as scale 1:1000 (or even 1:500) with 1 m contour lines.

For the sub sea section, bathymetrical maps with an accuracy of 1 m contour lines must be prepared based on the echo sounding. These maps are then confirmed, or adjusted according to the results gained by the refraction seismic survey.

10.3 Geological mapping and core-drilling

Currently a number of regional and general geological maps and reports are available. Further, geological details are available for the Bluemull Sound report prepared by Halcrow. On this basis it is proposed that the following geological pre-investigations and studies are conducted to build up a robust geological model of the actual areas. It is also indicated roughly the sequence for each of the elements in the pre-investigation schedule.

As a first step the following studies and field investigations are proposed:

- Geological desk study of the areas, including aerial photo (vertical, stereo view) interpretations and literature search.
- Detailed geological surface mapping for both Bluemull Sound and Yell Sound crossings including joint mapping and joint characterisation.
- A number of quarries and rock cuttings close to the actual tunnel sites could be used for the purpose of obtaining geological information, particularly including details of the rock mass jointing.
- Core drilling including for example 1 to 3 holes at each shore side to obtain general information about the geological strata. Water pressure testing to gain hydrogeological data

such as conductivity of the bedrock is also recommended. Rock mass classification of the cores. Finally, core samples for laboratory testing of physical properties of the various rock types.

Upon interpreting the results from the seismic surveys a further detailing of the pre-investigations would be required, which could include aspects such as:

- Dedicated core drilling, which might include both vertical (geological strata) and inclined (particular zones) holes and water pressure testing. This will provide further geological data, bedrock descriptions and identification of zones and joints, rock mass classification and also hydrogeological data.

When the tunnel alignment has been fixed:

- Detailed geological mapping of the portal areas.

It must be pointed out that the core drilling includes drilling from the shores on both sides of the actual sounds to be crossed. It is not included in this programme that coring shall be performed in the sounds themselves from ships, unless particular adverse conditions are indicated from other pre-investigations.

10.4 Shallow investigations at the portal areas

At the time the tunnel corridor has been established and whilst seeking the detailed locations of the portals it is necessary to do shallow investigations in the portal areas. These could include refraction seismic as described above, but also percussion (or core) drillings.

The main objective of these shallow investigations is to confirm the thickness of soil and sediments related to the excavation of the portals and the location of the top of the bedrock. The upper part of the bedrock is normally of rather poor quality, and extensive use of support measures may be required.

11 COST ESTIMATES

11.1 Basis for the cost analysis

In the Shetland Islands no road tunnels for public transportation purpose have been excavated in rock. The basis for the cost analysis is therefore the experiences gained from the construction of more than 20 sub sea road tunnels in Norway over the last 20 years. Also the successful construction of two sub sea tunnels in Iceland and the Faroe Islands over the last 5 years have been included in the "price reference bank" applied for this cost estimate.

The reference tunnels mentioned above have all been constructed according to the guidelines prepared by the Norwegian Public Road Authorities, NPRA. For the cost estimate of Shetland Islands tunnel links the British tunnel standard BD78/99 has been used, supplemented with NPRA guidelines where applicable and particularly on aspects related to sub sea tunnelling, which is not covered by BD78/99.

Construction of a sub sea tunnel in the Shetland Islands implies that both equipment and skilled workers are recruited from abroad for the tunnelling work. Work related to transport, road pavement, concrete etc. could possibly be performed using local contractors, or by the Shetland Islands Council itself, its construction division. Savings on the cost of tunnelling can be achieved on material such as concrete and reinforcement, but this has only marginal impact on the price, as the time for carrying out the work is the most important.

The labour cost in the Shetland Islands has been indicated as less expensive than in Scandinavia, thus savings can be obtained on the local supply as mentioned above. At this stage we have not included any such savings, as the cost estimate is based on Scandinavian prices.

In later design stages, a more detailed break-down can be done, diversifying local supplies from external/foreign.

The cost estimates have been prepared using NOK as the basis, converting to British Pounds. For the conversion an exchange rate 13 NOK = 1 £. The cost basis in the cost calculations is December 2001.

11.2 Calculation with uncertainty

In Appendices 1 and 2 a cost analysis of the tunnel is shown. The calculation method is according to Steen Lichtenberg, as described in Appendix 3.

11.3 Sub sea tunnel

11.3.1 Open cuts

The open cuts will be excavated partly by drill and blast of rock and partly by digging the soil. Since the open cut areas will be partly below the sea level too, preparation work is required. It is assumed that a concrete portal is needed, and pre-cautions have to be taken when the portal is located close to the sea, and below the sea level.

Included in the cost estimate are also the costs associated with the open cuts and portals in the tunnel approaches. For the two projects a length of 500 and 200 m approach cutting has been included for the Bluemull Sound and Yell Sound respectively.

11.3.2 Tunnel

The tunnel will be excavated by the use of drill and blast. Extensive use of probe drilling and pre-grouting will be necessary.

For the main part of the tunnel water inflow along joints and cracks in the rock mass can be expected, but the use of probe drilling and pre-grouting will reduce the amount of water inflow and prevent unwanted, adverse situations to occur during the tunnelling process. Grouting of joints may also constitute a stabilising effect on the rock mass.

Preparedness for negotiating severe weakness zone while tunnelling under the sounds must be done. This includes different construction methods as mentioned above, but also procedures for handling of critical rock fall or water inflow to the tunnel, so that loss of the tunnel shall be avoided.

11.4 Cost calculations

11.4.1 Tunnel construction costs

Appendices 1 and 2 provide full details on the cost calculations for the two tunnel projects. A summary of the cost calculations is provided in the table below. The probability that the cost will be lower or higher than the mean value is 50 %. The standard deviation is approximately 10 %, which means that with a probability of 67% the construction costs of the tunnels will be within the standard deviation. That is the mean value +/- 10 %.

Table 9. Construction costs

Activity	Yell Sound	Bluemull Sound
Construction cost (mean value), tunnel and open cut	24.7 mill £	14.1 mill £
Standard deviation	2.2 mill £	1.2 mill £
Cost per m tunnel and open cut	4875 £	5495 £

When the cost figures shall be evaluated, it is essential in the Steen Lichtenberg method to look at the variance to identify the elements with the largest uncertainty.

It can be seen from the cost calculations that the following elements need special attention in the planning process:
- concrete tunnel (culvert) in the open cuts (amount),

- cement grouting (amount),
- rock excavation (price),
- sprayed concrete for rock support (price and amount), and
- water and frost protection (price and standard).

These items are mainly related to water inflow and handling of water in the tunnel, and also to rock support. These are motivating the geotechnical investigation programme that focuses on possible weakness zones in the sounds and the possible need of grouting the rock mass.

In the cost estimate transport of blasted rock material up to a distance of 3 km from the tunnel portals to the final rock dump has been included. If an appropriate rock dump cannot be found within such a distance, additional costs must be included for transport of the blasted material.

There are no considerations done to the potential of selling the blasted rock material, or using it within the Shetland Islands Council itself. However, such aspects could be looked into at a later stage of the project.

In the cost estimate rock support with the systematic use of rock bolts (5.5 bolts per m tunnel) and sprayed concrete (1 m^3 per m tunnel) has been included, and with appr. 50 m of cast-in place concrete lining.

The costs for rock excavation also comes out with a high variance. This is mainly due to the large volume of rock where the total cost will be sensitive to the unit price for drill and blast.

The costs related to water and frost protection gives the same variance as for rock excavation. In the cost calculations it is assumed that 90% of the tunnel (walls and roof) will need protection. Here the preferred standard (and price) will influence the total price.

Although the installation and other completion work of the tunnel have substantial costs, these cost figures do not have the same uncertainty as the main items mentioned above.

Table 10. General deviation from the cost calculation

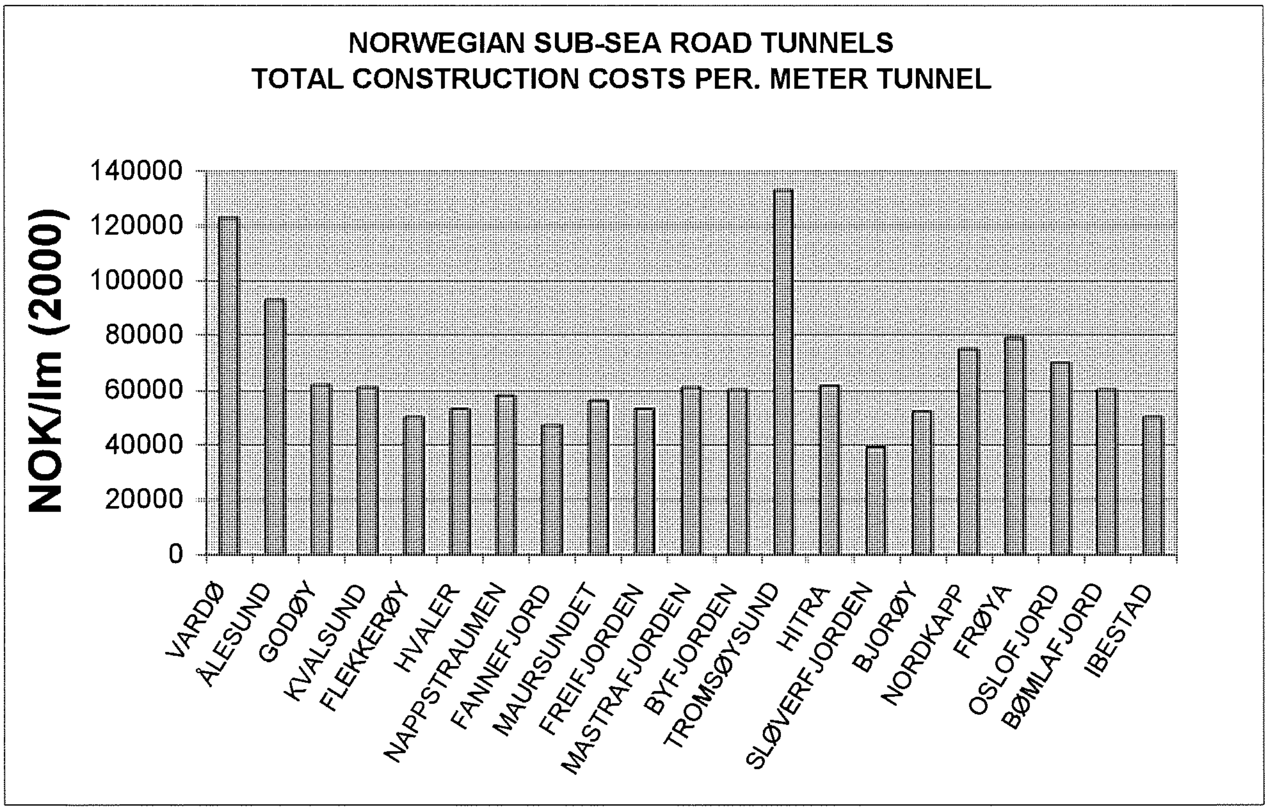
General deviation (from expected)	Min	Engineering value	Max
Complexity	-5	5	10
Geological investigations	-5	0	20
Government regulations	-5	0	15
Political decisions	-5	1	5
Environmental impacts	0	0	10
Smaller items not included	0	2	4
Competition/market situation	-2	0	4

The cost calculation takes into account a number of general deviations that may affect the cost of the project. Complexity of the tunnel is regarded as above the average, as this will be the first sub sea road tunnel in the Shetlands. Further the lack of geological information gives a great uncertainty regarding the amounts and costs. It is regarded that the impact on the environment will have to cope with stricter rules in the future, thus an assumed cost increase, and also the fact that the approaches are located in cultivated land areas. Competition/market, which will at least include the Scandinavian and British construction markets, are considered to have the possibility for both an increase and reduction in cost in comparison to the present situation.

Government regulations and political decisions are also considered in the cost calculation. Typically, a delayed political decision might lead to an increased cost, as might also be the case if a political decision imposes regulations and requirements beyond the applied standards and those included in the cost calculation. Future requirements on the fixed link alignment and possible requirements on the safety in the tunnel (additional lane for cyclists, additional tunnel for one way traffic etc.) may have major impact on costs and selection of alternative between routes and type of crossing. Such changes are not included in the cost estimates.

The final aspects to be included in the cost calculation would be those related to pre-investigations, project planning and site supervision of the tunnel construction.

Table 11. Construction costs Norwegian sub sea road tunnels



As a comparison to the construction cost figures that have been developed for the Bluemull and Yell Sound crossings the statistical data from similar tunnels in Norway is included in Table 11 above. The following must be noted:

The construction cost for the tunnel projects referenced above (Table 11) is updated to 2000 level taking into account the inflation rates, cost escalation and increased standard requirements.

The Tromsøysund tunnel consists of two parallel tubes, thus the construction costs in Table 11 must be divided by 2. Further the high costs for the Nordkapp tunnel, The Oslofjord tunnel and the Frøya tunnel are related to the handling of adverse rock mass conditions.

The average cost per m tunnel based on the Norwegian tunnels is thus around 60.000 NOK, or 4600 £ (13 NOK = 1 £).

Worth mentioning is also the assessed construction costs for the two tunnels in the Faroe Islands which both are expected to be below 50.000 NOK, or 3850 £.

11.4.2 Pre-investigations, planning and site supervision of tunnel construction

For the projects, Yell Sound and Bluemull Sound, a total cost for the pre-investigations is assessed to be in the range of 1.000.000 £.

Assuming that the projects proceed in a similar way as typically prevails in Norway, an estimated cost of 500.000 £ to 750.000 £ per tunnel project can be assessed covering the design phase, starting with the pre-feasibility study throughout to detail design and tender documents. Running the two projects simultaneously is expected to reduce the design costs somewhat.

As far as project administration during the construction phase (site follow-up and supervision) is concerned, the costs associated with this aspect is very variable, from project to project and from country to country, and even the type of contract to be applied would influence on these costs. A rough estimate based on the following assumptions can be provided:

Assuming that the construction time is 2 and 3 years for the Bluemull Sound and Yell Sound respectively, with a clients crew of 6 persons at each project, and an annual cost of 70.000 – 120.000 £ per year per person including all site facilities and over-head costs such as: salary, social and security provisions, offices, cars etc.

The total project administration during construction will then be in the range of 0.9 - 1.5 and 1.3 - 2.2 mill. £ for Bluemull Sound and Yell Sound respectively.

11.4.3 Financial costs and taxes/VAT

The financial costs and costs related to taxes and VAT have not been included in the cost estimates.

11.5 Roads

The sub sea road tunnel will be linked to the existing national road network, with as short connection roads as practically possible. For calculation of the costs related to these connecting roads, it is more appropriate that detailed calculations are prepared by the relevant body within the Shetland Islands Council. This will provide more accurate costs on road construction, land acquisition etc. in the islands than is possible for O. T. Blindheim AS at this stage.

A rough cost estimate, however, is included as a basis to prepare total project costs. For the estimate the following assumptions on improving/upgrading existing roads or constructing new roads to connect the national road to the tunnel portals have been used:

- Bluemull Sound: a 500 m long connection is needed to tie up with the main road at the Unst side; whilst a 700 m long road is needed to connect to the Yell side.
- Yell Sound: a 1000 m connection is needed to tie up with the main road at the Yell side and a shorter, 500 m road is needed for connection at the Mainland side.
- A total cost of 1.300 £ per m road including also land acquisition, design etc.

This implies that the road costs of 1.6 mill. £ and 2 mill. £ will be added to form the project costs of the Bluemull Sound and Yell Sound projects respectively.

11.6 Total project costs

In Table 12 below the total project costs will be provided.

Table 12. Total project costs (exclusive financial and taxes/VAT)

Cost element	Bluemull Sound	Yell Sound
Tunnel construction, mill. £	14.1 ± 1.2	24.7 ± 2.2
Planning and pre-investigation tunnel, mill. £	0.9 – 1.2	1.1 – 1.4
Site supervision tunnel	0.9 – 1.5	1.3 – 2.2
Connection roads, mill £	1.6	2
Total project costs, mill £	**16.3 – 19.6**	**26.9 – 32.5**

As can be seen from the table the total project costs will be in the range of 16 to 20 mill. £ and 27 to 33 mill. £ for the Bluemull Sound crossing and Yell Sound crossing respectively.

The pre-investigations that have been proposed are needed to improve the correctness of these estimates and increase their confidence.

12 CONCLUSION

This report has reviewed the possibility and feasibility of crossing the Bluemull Sound and Yell Sound with sub sea rock tunnels. There are no infrastructure rock tunnels in the Shetland Islands at present, and these tunnel projects will be the first of their kind in the islands, and probably the first also within the entire UK.

A number of sub sea tunnels have been constructed in the Norway, and also in Nordic countries like Iceland and the Faroe Islands. The concept that these tunnels have been built according to has been the basis for these projects too, in addition to the standards of BD 78/99.

At present, the material available on geotechnical data is rather scarce and it is needed to perform additional geotechnical investigations to form the basis for a robust and confident cost estimate. On the current basis the cost estimate for the Bluemull Sound crossing is 14.1 mill £ +/- 1.2 mill £, and for the Yell Sound 24.7 mill £ +/- 2.2 mill £. These cost estimates are limited to the construction costs only, additional pre-investigations, project management, access roads and financial costs must be included to summarise the total project costs.

The project construction time has been assessed to 31 to 42 months for the Yell Sound crossing and 19 to 30 months for the Bluemull Sound. The most suitable construction method to be applied is found to be conventional drill and blast, with rock bolts and sprayed concrete as support and probe drilling and pre-grouting as an integral part of the excavation procedure.

Trondheim, 3rd of May 2002
for O. T. Blindheim AS

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Quality control:

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Senior advisor/geotechnical engineer

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Sub Sea Tunnel	**BLUEMULL SOUND**				
Client	**Shetland Islands Council**				
Contract No.	**2484**	**O. T. Blindheim AS**			
Tunnel length	**2564 m**	**BD 78/99**	**2414**	**T14:**	**150**
Concrete culverts in opening	**70 m**		**(niches and laybyes)**		
Total tunnel length	**2634 m**				
COST CALCULATION		**1 GBP =**	**13,00 NOK**		
Process code acc. to NPRA		**ALT. BD 78/99**			

Proces code	Text/resources	Unit	Amounts Min	Assumed	Max	Price Min	Assumed	Max	Expected value	Sum GBP 1000 Midd.v.	St.dev.	Var
0	**MAIN PROCESS No. 0 - Planning and investigations**											
1	**MAIN PROCESS No. 1 - Preparations and general costs**											
12	**Mobilisation, operation unit. Operational**	% of posts 1 - 7				18,0	35,0	45,0				
		LS, KGBP	1	1	1	**1679,7**	**3266,1**	**4199,3**		**3 135**	504	2,54E+05
2	**MAIN PROCESS No. 1 - Rock blasting and transport (outside tunnel)**											
22	**Open cuts (tunnel entrances)**											
22.1	Preparation work	LS, KGBP	1	1	1	19,2	38,5	76,9		**42**	12	1,33E+02
22.2	Open cut Unst	m3,GBP/m3	5000	15000	20000	1,5	6,2	13,5		**94**	40	1,62E+03
22.3	Open cut Yell	m3,GBP/m3	10000	20000	30000	1,5	6,2	13,5		**134**	54	2,88E+03
22.7	Rock support	LS, KGBP	2	2	2	1,5	4,6	23,1		**15**	9	7,42E+01

Proces code	Text/resources	Unit	Amounts Min	Assumed	Max	Price Min	Assume	Max	Expected value	Sum GBP 1000 Midd.v.	St.dev.	Var
3	**MAIN PROCESS No. 1 -Tunnelling work**											
31	**Work ahead of tunnel front**											
31.0	Grouting of open cut areas	LS, KGBP	0	0	0	38,5	384,6	769,2		**0**	0	0,00E+00
31.1	Probe drilling	m/m tunnel	1	4	8				**4,2**			
	Probe drilling, total	m,GBP/m	**2564**	**10256**	**20512**	3,1	5,4	13,5		**70**	29	8,27E+02
31.2	Core drilling	m/m tunnel	0	0	0,2				**0,04**			
	Core drilling, total	m,GBP/m	**0**	**0**	**512,8**	57,7	96,2	230,8		**12**	10	9,72E+01
31.3	Pregrouting											
	Drilling	lm/m	2	4	9				**4,6**			
	Drilling, total	m,GBP/m	**5128**	**10256**	**23076**	0,8	1,2	3,8		**19**	8	5,70E+01
	Cement	tons/m	0,2	0,275	0,8				**0,365**			
	Cement, total	tons, KGBP/t	**512,8**	**705,1**	**2051,2**	0,3	0,6	1,9		**763**	296	8,77E+04
	Chemical grouting	tons, KGBP/t	0	0	10	7,7	15,4	23,1	**2**	**31**	31	9,47E+02
32	**Tunnel excavation**											
32.1	Excavation by drill and blast											
	Length of tunnel BD 78/99	m	**2364**	**2414**	**2614**				**2444**			
	Cross section excavated	m^2	62	70	85				**71,4**			
	Rock excavation	m3,GBP/m3	**151528**	**171080**	**207740**	5,4	6,9	10,8		**1 289**	200	4,00E+04
	Length of tunnel T11,5	m	**100**	**150**	**200**				**150**			
	Turning niches, laybyes	m^2	75	85	100				**86**			
	Rock excavation	m3,GBP/m3	**11250**	**12750**	**15000**	5,4	6,9	10,8		**95**	15	2,15E+02
32.4	Niches, Pumping sump	m3,GBP/m3	**5000**	**7000**	**12000**	5,8	8,1	15,4		**69**	18	3,09E+02
32.7	Mucking and transport to rock dump											
	Excavated from Yell	m	1000	1500	2000				**1500**			
32.71	3 km from tunnel opening	m3,GBP/m3	**73900**	**110600**	**148800**	1,7	3,1	5,8		**371**	101	1,01E+04
32.72	3 km from tunnel opening	m3,GBP/m3	**93878**	**80230**	**85940**	1,7	3,1	5,8		**281**	65	4,22E+03
33	**Rock support**											
33.21	Spiling bolts	pcs/m	0	0,02	0,2				**0,052**			
	Spiling bolts, total	pcs, GBP/pcs	**0**	**51,88**	**518,8**	15,4	30,8	46,2		**4**	3	1,03E+01
	Basic rock support system											
33.22	Bolts	pcs/m	3	5	9				**5,4**			
	Bolts, total	pcs, GBP/pcs	**7782**	**12970**	**23346**	17,3	25,0	46,2		**388**	108	1,17E+04
33.4	Sprayed concrete	m^3/m	0,3	0,8	2				**0,94**			
	Sprayed concrete, total	m3,GBP/m3	**778,2**	**2075,2**	**5188**	138,5	215,4	288,5		**523**	200	4,00E+04

Proces code	Text/resources	Unit	Amounts Min	Assumed	Max	Price Min	Assume	Max	Expected value	Sum GBP 1000 Midd.v.	St.dev.	Var
33.5	**Cast in place concrete**											
33.51	Walls and roof	m, GBP/m	20	50	200	1730,8	3076,9	5000,0		**236**	115	1,33E+04
33.52	Invert	m, GBP/m	0	0	200	1153,8	1538,5	3076,9		**71**	62	3,79E+03
33.53	Full concr. lining w/membr	m, GBP/m	0	0	0	13461,5	#####	28846,2		**0**	0	0,00E+00
34	**Water and frost protection**											
34.2	Concrete walls, height 4 m	m/m	0,5	1	1				**0,9**			
	Concrete walls, height 4 m	m, GBP/m	**1047**	**2094**	**2344**	326,9	461,5	692,3		**930**	194	3,77E+04
34.3	PE- foam, fire protected	m/m	0,5	1	1				**0,9**			
	PE- foam, fire protected, t	m, GBP/m	**1047**	**2094**	**2344**	538,5	692,3	961,5		**1 384**	252	6,36E+04
34.3	Non-isolated freestanding	m/m	0,1	0,2	0,3				**0,2**			
	Non-isolated freestanding,	m, GBP/m	**250**	**500**	**750**	692,3	846,2	1346,2		**458**	107	1,14E+04
35	**Portals, pumping station, buildings**											
35.1	Portals and Concrete tunnel in open cut											
	Concrete tunnel	m, GBP/m	20	50	200	2692,3	3846,2	6153,8		**302**	143	2,04E+04
35.3	Pumping station											
	Civil work	LS, KGBP	1	1	1	23,1	30,8	50,0		**33**	5	2,90E+01
	Pumps etc.	LS, KGBP	1	1	1	38,5	53,8	115,4		**63**	15	2,37E+02
35.5	Buildings											
	Transformer-/electr. in tun	pcs., KGBP	1	3	5	7,7	15,4	23,1		**46**	15	2,37E+02
	Transformer-/electr. Above	pcs., KGBP	2	2	2	30,8	38,5	57,7		**82**	11	1,16E+02
36	**Lighting, ventilation, safety and environment**											
36.1	General	LS, KGBP	1	1	1	138,5	192,3	307,7		**205**	34	1,15E+03
36.2	Lighting	LS, KGBP	1	1	1	53,8	138,5	307,7		**155**	51	2,58E+03
36.3	Ventilation	LS, KGBP	1	1	1	50,0	96,2	192,3		**106**	28	8,10E+02
36.4	Safety equipment	LS, KGBP	1	1	1	61,5	192,3	384,6		**205**	65	4,18E+03
36.5	ATC (Automatic traffic cor	LS, KGBP	1	1	1	26,9	34,6	57,7		**38**	6	3,79E+01
36.7	Control centre	LS, KGBP	1	1	1	38,5	69,2	84,6		**66**	9	8,52E+01
4	**MAIN PROCESS No. 4 - Drainage**											
41	Drainage system	m, GBP/m	1564	3664	3764	13,5	19,2	28,8		**65**	14	1,99E+02
42	Permanent discharge pipe	m, GBP/m	1100	1500	2000	38,5	57,7	115,4		**99**	25	6,40E+02

Proces code	Text/resources	Unit	Amounts Min	Assumec	Max	Price Min	ıssume	Max	Expected value	Sum GBP 1000 Midd.v.	St.dev.	Var
5	**MAIN PROCESS No. 5 - Sub-base and pavement**											
55.1	Sub-base and pavement	m2,GBP/m2	26044	30640	35236	5,8	6,9	11,5		**233**	38	1,41E+03
6	**MAIN PROCESS No. 6 - Road surface**											
		tons/m		1,8								
65	Road surface	tons,GBP/ton	4688	5515	6342	38,5	46,2	57,7		**259**	26	6,83E+02
7	**MAIN PROCESS No. 7 - Environment, curbs and carriageway marking**											
74	Environment	LS, KGBP	1	1	1	7,7	11,5	28,8		**14**	4	1,79E+01
75	Curbs	m, GBP/m	6078	6178	6578	5,4	7,7	11,5		**50**	8	5,84E+01
77	Carriageways markings	LS, KGBP	1	1	1	23,1	30,8	38,5		**31**	3	9,47E+00
	Sum excl of mobilisation and operational costs									**9 332**	603	3,64E+05
	SUM									**12 467**	786	6,18E+05
	General deviation (from expected)											
	Complexity	%	-5	5	10					**499**	374	1,40E+05
	Geological investigations	%	-5	0	15					**249**	499	2,49E+05
	Government regulations	%	-5	0	15					**249**	499	2,49E+05
	Political decisions	%	-5	1	5					**75**	249	6,22E+04
	Environmental impact	%	0	0	10					**249**	249	6,22E+04
	Smaller items not includec	%	0	2	4					**249**	100	9,95E+03
	Competition/marked	%	-2	0	4					**50**	150	2,24E+04
	Sum General deviation	KGBP								**1 621**	891	7,94E+05
										14 088	**1 188**	1,41E+06
											Stand. Dev.	
	EXPECTED CONSTRUCTION COSTS (1000 GBP), tunnel + cut &					**2564**	**+**	**500**	**GBP**	**14 088**	**1 188**	1,41E+06
	COST PER M OF TUNNEL, INCL. TUNNEL ENTRANCES					**=**	**3064 m**		**GBP**	**5 495**		
						Uncertainty, %					**8,4**	

Sub Sea Tunnel	**YELL SOUND**				
Client	**Shetland Islands Council**				
Contract No.	**2484**	**O. T. Blindheim AS**			
Tunnel length	**5070 m**	**BD 78/99**	**4770**	**T14:**	**300**
Concrete culverts in openinç	**30 m**		**(niches and laybyes)**		
Total tunnel length	**5100 m**				
COST CALCULATION		**1 GBP =**	**13,00 NOK**		
Process code acc. to NPRA		**ALT. BD 78/99**			

Proces code	Text/resources	Unit	Amounts Min	Amounts Assumec	Amounts Max	Price Min	Price Assumec	Price Max	Expected value	Sum GBP 1000 Midd.v.	St.dev.	Var
0	**MAIN PROCESS No. 0 - Planning and investigations**											
1	**MAIN PROCESS No. 1 - Preparations and general costs**											
12	**Mobilisation, operation unit. Operationa**	% of posts 1 - 7				18,0	35,0	45,0				
		LS, KGBP	1	1	1	**2936,4**	**5709,6**	**7341,0**		**5 481**	881	7,76E+05
2	**MAIN PROCESS No. 1 - Rock blasting and transport (outside tunnel)**											
22	**Open cuts (tunnel entrances)**											
22.1	Preparation work	LS, KGBP	1	1	1	19,2	38,5	76,9		**42**	12	1,33E+02
22.2	Open cut Mainland	m3,GBP/m3	5000	10000	20000	1,5	6,2	13,5		**74**	30	9,09E+02
22.3	Open cut Yell	m3,GBP/m3	5000	10000	20000	1,5	6,2	13,5		**74**	30	9,09E+02
22.7	Rock support	LS, KGBP	2	2	2	1,5	4,6	23,1		**15**	9	7,42E+01

Proces code	Text/resources	Unit	Amounts			Price			Expected	Sum GBP 1000		
			Min	Assumed	Max	Min	Assumed	Max	value	Midd.v.	St.dev.	Var
3	**MAIN PROCESS No. 1 -Tunnelling work**											
31	**Work ahead of tunnel front**											
31.1	Probe drilling	m/m tunnel	1	4	8				**4,2**			
	Probe drilling, total	m,GBP/m	**5070**	**20280**	**40560**	3,1	5,4	13,5		**139**	57	3,23E+03
31.2	Core drilling	m/m tunnel	0	0	0,2				**0,04**			
	Core drilling, total	m,GBP/m	**0**	**0**	**1014**	57,7	96,2	230,8		**23**	20	3,80E+02
31.3	Pregrouting											
	Drilling	lm/m	2	4	9				**4,6**			
	Drilling, total	m,GBP/m	**10140**	**20280**	**45630**	0,8	1,2	3,8		**38**	15	2,23E+02
	Cement	tons/m	0,1	0,275	0,8				**0,345**			
	Cement, total	tons, KGBP/t	**507**	**1394,3**	**4056**	0,3	0,6	1,9		**1 426**	627	3,94E+05
	Chemical grouting	tons, KGBP/t	0	0	10	7,7	15,4	23,1	**2**	**31**	31	9,47E+02
32	**Tunnel excavation**											
32.1	Excavation by drill and blast											
	Length of tunnel BD 78/99	m	**4720**	**4770**	**4970**				**4800**			
	Cross section excavated	m^2	62	70	85				**71,4**			
	Rock excavation	m3,GBP/m3	**297600**	**336000**	**408000**	5,4	6,9	10,8		**2 531**	393	1,54E+05
	Length of tunnel T11,5	m	**250**	**300**	**350**				**300**			
	Turning niches, laybyes	m^2	75	85	100				**86**			
	Rock excavation	m3,GBP/m3	**22500**	**25500**	**30000**	5,4	6,9	10,8		**191**	29	8,62E+02
32.4	Niches, Pumping sump	m3,GBP/m3	**5000**	**7000**	**12000**	5,8	8,1	15,4		**69**	18	3,09E+02
32.7	Mucking and transport to rock dump											
	Excavated from Yell	m	1000	1500	2000				**1500**			
32.71	3 km from tunnel opening	m3,GBP/m3	**73900**	**110600**	**148800**	1,7	3,1	5,8		**371**	101	1,01E+04
32.72	3 km from tunnel opening	m3,GBP/m3	**251200**	**257900**	**301200**	1,7	3,1	5,8		**887**	211	4,43E+04
33	**Rock support**											
33.21	Spiling bolts	pcs/m	0	0,02	0,2				**0,052**			
	Spiling bolts, total	pcs, GBP/pcs	**0**	**102**	**1020**	15,4	30,8	46,2		**8**	6	3,98E+01
	Basic rock support system											
33.22	Bolts	pcs/m	3	5	9				**5,4**			
	Bolts, total	pcs, GBP/pcs	**15300**	**25500**	**45900**	17,3	25,0	46,2		**763**	212	4,51E+04
33.4	Sprayed concrete	m^3/m	0,3	0,8	2				**0,94**			
	Sprayed concrete, total	m3,GBP/m3	**1530**	**4080**	**10200**	138,5	215,4	288,5		**1 029**	393	1,54E+05

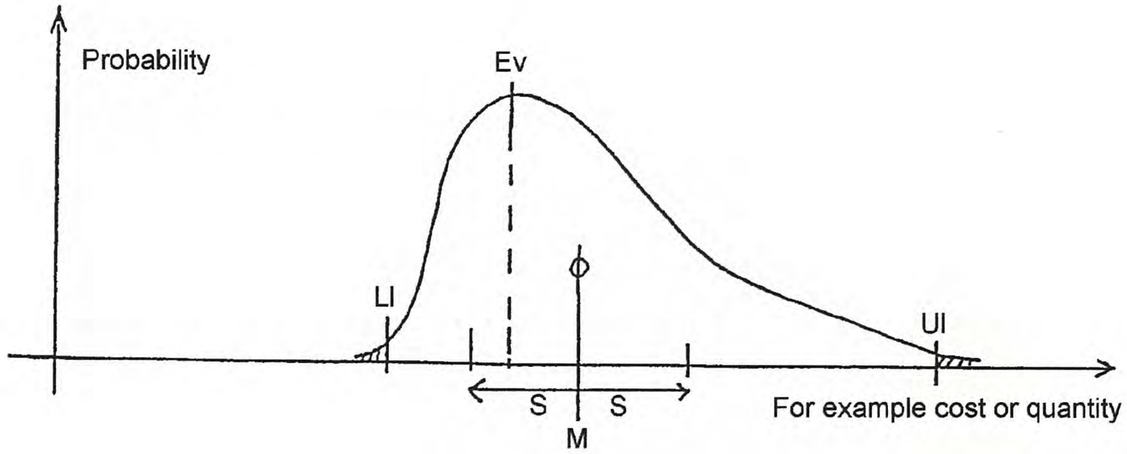
Proces	Text/resources	Unit	Amounts			Price			Expected	Sum GBP 1000		
code			Min	Assumed	Max	Min	Assumed	Max	value	Midd.v.	St.dev.	Var
33.5	**Cast in place concrete**											
33.51	Walls and roof	m, GBP/m	20	50	300	1730,8	3076,9	5000,0		**300**	175	3,08E+04
33.52	Invert	m, GBP/m	0	0	200	1153,8	1538,5	3076,9		**71**	62	3,79E+03
33.53	Full concr. lining w/membr	m, GBP/m	0	0	0	13461,5	17307,7	28846,2		**0**	0	0,00E+00
34	**Water and frost protection**											
34.2	Concrete walls, height 4 m	m/m	0,5	1	1				**0,9**			
	Concrete walls, height 4 m	m, GBP/m	**2300**	**4600**	**4850**	326,9	461,5	692,3		**2 014**	410	1,68E+05
34.3	PE- foam, fire protected	m/m	0,5	1	1				**0,9**			
	PE- foam, fire protected, t	m, GBP/m	**2300**	**4600**	**4850**	538,5	692,3	961,5		**2 997**	526	2,76E+05
34.3	Non-isolated freestanding	m/m	0,1	0,2	0,3				**0,2**			
	Non-isolated freestanding,	m, GBP/m	**250**	**500**	**750**	692,3	846,2	1346,2		**458**	107	1,14E+04
35	**Portals, pumping station, buildings**											
35.1	Portals and Concrete tunnel in open cut											
	Concrete tunnel	m, GBP/m	30	50	200	2692,3	3846,2	6153,8		**310**	135	1,83E+04
35.3	Pumping station											
	Civil work	LS, KGBP	1	1	1	23,1	30,8	50,0		**33**	5	2,90E+01
	Pumps etc.	LS, KGBP	1	1	1	53,8	76,9	115,4		**80**	12	1,51E+02
35.5	Buildings											
	Transformer-/electr. in tun	pcs., KGBP	3	4	5	7,7	15,4	23,1		**62**	14	1,89E+02
	Transformer-/electr. Above	pcs., KGBP	2	2	2	30,8	38,5	57,7		**82**	11	1,16E+02
36	**Lighting, ventilation, safety and environment**											
36.1	General	LS, KGBP	1	1	1	192,3	307,7	461,5		**315**	54	2,90E+03
36.2	Lighting	LS, KGBP	1	1	1	76,9	192,3	307,7		**192**	46	2,13E+03
36.3	Ventilation	LS, KGBP	1	1	1	100,0	134,6	192,3		**139**	18	3,41E+02
36.4	Safety equipment	LS, KGBP	1	1	1	173,1	269,2	384,6		**273**	42	1,79E+03
36.5	ATC (Automatic traffic cor	LS, KGBP	1	1	1	26,9	34,6	57,7		**38**	6	3,79E+01
36.7	Control centre	LS, KGBP	1	1	1	38,5	69,2	84,6		**66**	9	8,52E+01
4	**MAIN PROCESS No. 4 - Drainage**											
41	Drainage system	m, GBP/m	4070	6270	6570	13,5	19,2	28,8		**118**	22	4,65E+02
42	Permanent discharge pipe	m, GBP/m	1100	1500	2000	38,5	57,7	115,4		**99**	25	6,40E+02

Proces code	Text/resources	Unit	Amounts Min	Amounts Assumed	Amounts Max	Price Min	Price Assumed	Price Max	Expected value	Sum GBP 1000 Midd.v.	St.dev.	Var
5	**MAIN PROCESS No. 5 - Sub-base and pavement**											
55.1	Sub-base and pavement	m2,GBP/m2	43095	50700	58305	5,8	7,7	10,6		**400**	54	2,92E+03
6	**MAIN PROCESS No. 6 - Road surface**											
		tons/m		1,8								
65	Road surface	tons,GBP/ton	7757	9126	10495	38,5	46,2	57,7		**428**	43	1,87E+03
7	**MAIN PROCESS No. 7 - Environment, curbs and carriageway marking**											
74	Environment	LS, KGBP	1	1	1	7,7	11,5	28,8		**14**	4	1,79E+01
75	Curbs	m, GBP/m	10090	10190	10590	5,4	7,7	11,5		**82**	13	1,58E+02
77	Carriageways markings	LS, KGBP	1	1	1	23,1	30,8	38,5		**31**	3	9,47E+00
	Sum excl of mobilisation and operational costs									**16 313**	1 154	1,33E+06
	SUM									**21 794**	1 452	2,11E+06
	General deviation (from expected)											
	Complexity	%	-5	5	10					**872**	654	4,27E+05
	Geological investigations	%	-5	0	20					**654**	1 090	1,19E+06
	Government regulations	%	-5	0	15					**436**	872	7,60E+05
	Political decisions	%	-5	0	5					**0**	436	1,90E+05
	Environmental impact	%	0	0	10					**436**	436	1,90E+05
	Smaller items not included	%	0	2	4					**436**	174	3,04E+04
	Competition/marked	%	-2	0	4					**87**	262	6,84E+04
	Sum General deviation	KGBP								**2 920**	1 689	2,85E+06
										24 715	**2 228**	4,96E+06
											Stand. Dev.	
	EXPECTED CONSTRUCTION COSTS (1000 GBP), tunnel + cut &					**5070**	**+**	**200**	**GBP**	**24 715**	**2 228**	4,96E+06
	COST PER M OF TUNNEL, INCL. TUNNEL ENTRANCES					**=**	**5070 m**		**GBP**	**4 875**		
						Uncertainty, %					**9,0**	

STEEN LICHTENBERG CALCULATION METHOD
Successive calculation

SUCCESSIVE CALCULATIONS

In a process of decision making it is important to have tools at hand to produce reliable cost- and time-estimates. These estimates are often associated with a great deal of uncertainty. Professor Lichtenberg developed a method which is approaching a decision based on successive calculations.



The figure above shows **the basal elements** associated with professor **Lichtenbergs method**. Based on this method we take the advantage of a calculation programme which applies risk analysis.

The objective of this method is to identify and estimate individual cost elements (by price and quantity), and give each a lower limit (Ll), upper limit (Ul) in addition to expected value (Ev) or best guess. On this basis the arithmetical mean value (M) and standard deviation (S) can be calculated for each element.

This is an approximate **correctness** if Ll and Ul correspond to 1%- and 99%-values in the **calculation of probability**, see the figure above. The robustness of the calculation method depends on the stipulation of Ll and Ul.

S^2, is a term for variance, and the most uncertain elements have highest variance. When a first calculation approach is executed, it's important to study the variance. To reduce the uncertainty in a calculation the elements with highest variance shall be focused closely.

It is often possible **to reduce the uncertainty** by splitting of elements or by further investigations and a closer evaluation. Splitting and successive calculation often gives a good result.

The results from the calculations give a total mean value for the cost or time (for example). The probability that the total cost will be lower or higher than the mean value is 50%. Considering the standard deviation, the probability that the total costs will fall within (+/-) the standard deviation is 67%.

O. T. Blindheim AS applies the method succesive calculation as a standard routine in all cost estimates.

BLUEMULL SOUND DRAWINGS FROM HALCROW [Ref. 2]