WELLHEAD PROTECTION CONCEPTS FOR SUBSEA MARGINAL DEVELOPMENTS - GRAND BANKS OF NEWFOUNDLAND

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WELLHEAD PROTECTION CONCEPTS FOR SUBSEA MARGINAL DEVELOPMENTS – GRAND BANKS OF NEWFOUNDLAND

by

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ABSTRACT

As the offshore industry matures on the Grand Banks, the desire to tap into more marginal oil and gas reserves will be realized and efficient exploitation will be required. A study has been undertaken to enable evaluation of wellhead protection concepts for subsea marginal developments located on the Grand Banks of Newfoundland. The study has focused mainly on concepts that maintain probability of well blowout as a result of freely floating and scouring icebergs below accepted levels of risk. The investigation provides a framework from which intelligent decisions can be made regarding the relative benefits and costs of different protection concepts.

In order to represent both ends of the spectrum in terms of size and architecture, two subsea marginal field development scenarios, considered typical for the area, were selected. These include (1) single well and (2) clustered multi-well developments tied back to an existing production facility.

A thorough overview of existing wellhead protection technical solutions such as Open Glory Holes, Cased Glory Holes, Caisson Wellhead Systems and Protective External Barriers were presented. Existing failsafe systems such as surface controlled-subsurface safety valves (SCSSV's) were also investigated in detail to determine their reliability and potential effectiveness for protection against uncontrolled well blowout in the case of catastrophic wellhead damage due to an iceberg encounter.

A minimum risk acceptance criterion associated with wellhead protection in the region was established to be less than 1×10^{-5} per annum. Utilizing existing methodologies developed from simple geometric models along with the appropriate iceberg data, an analysis was performed in order to determine the encounter and contact probabilities to wellhead facilities as they relate to the various protection concepts.

To support the selection and decision making process, a cost analysis was performed. The methodology used in the analysis involved a full comparison of capital expenditure (CAPEX) incorporating the risks associated with iceberg contact. Consequences resulting from an iceberg contact such as lost production, environmental cleanup and replacement / repair costs are factored by the probability of that event occurring.

Results of the study indicate that SCSSV's and other fail-safe systems offer an obvious solution for reduction in overall risk and up-front development costs. The cost analysis indicates the "Modified Cased Hole" protection concept to be most attractive protection solution from a combined cost & risk approach. A conventional "unprotected" subsea well installation for the Grand Banks may prove to be a feasible development scenario given further research.

Additional work is recommended addressing issues such as well downhole response mechanisms, SCSSV reliability and refinement to the inherent conservatisms & limitations in well blowout probability calculations.

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η	Total annual probability of iceberg contact
η_d	Annual probability of contact with freely floating icebergs
η_s	Annual probability of contact with scouring icebergs
K	Conversion factor (3.7 x 10^{-3} m^{-2} s)
d_w	Water depth
h	Structure height
ρ	Iceberg areal density
ρ_d	Areal density of icebergs with drafts between d_w and d_w-h
L_d	Effective width of iceberg keels in the d_w to d_w-h depth range
D_d	Effective diameter of the structure
v	Mean iceberg drift speed
p	Proportion of the iceberg population with drafts deep enough to strike the subsea structure
D	Iceberg draft
L	Iceberg waterline length
w	Iceberg width at a given z
w^*	Normalized iceberg width
z	Distance measure upward from iceberg keel tip
z^*	Normalized height above iceberg keel
f_s	Annual scour frequency (#/unit area/year)
L_s	Mean scour length
μ	Mean scour depth
$P(z)_S$	Probability of exceedance for the iceberg keel penetrating a depth z into a small diameter hole
$P(z)_L$	Probability of exceedance for the iceberg keel penetrating a depth z into a large open hole
P_{impact}	Proportion of icebergs reaching an installation

$P_{\det}$	Probability of detection success
P_{tow}	Probability of success for physical management operations
N	Net incremental system cost
C	Incremental CAPEX
C_R	Cost of risk
p_f	Annual probability of an iceberg event
R	Repair / Replacement cost
E	Environmental and equipment and cleanup cost
L_p	Cost of lost production
T	Life of field
^{o}C	Degrees Celsius
^{o}N	Degrees North
%	Percent

1.0 INTRODUCTION

The Grand Banks are located off the east coast of Newfoundland, covering an area of approximately 270,000 km^2 that is centered at 46° N latitude and 51° W longitude. General water depths across much of the banks range between 60 to 150m. Exploration of hydrocarbons in the region has been ongoing since 1966 and major oil fields have been discovered on the North Eastern Grand Banks at several locations such as Hibernia, Terra Nova, White Rose and Hebron/Ben Nevis (see Figure 1). The Grand Banks region has estimated recoverable oil and gas reserves and resources equalling 2.1 billion barrels of oil, 5.4 trillion cubic feet of gas and 313 million barrels of natural gas liquids (C-NOPB, 2005).

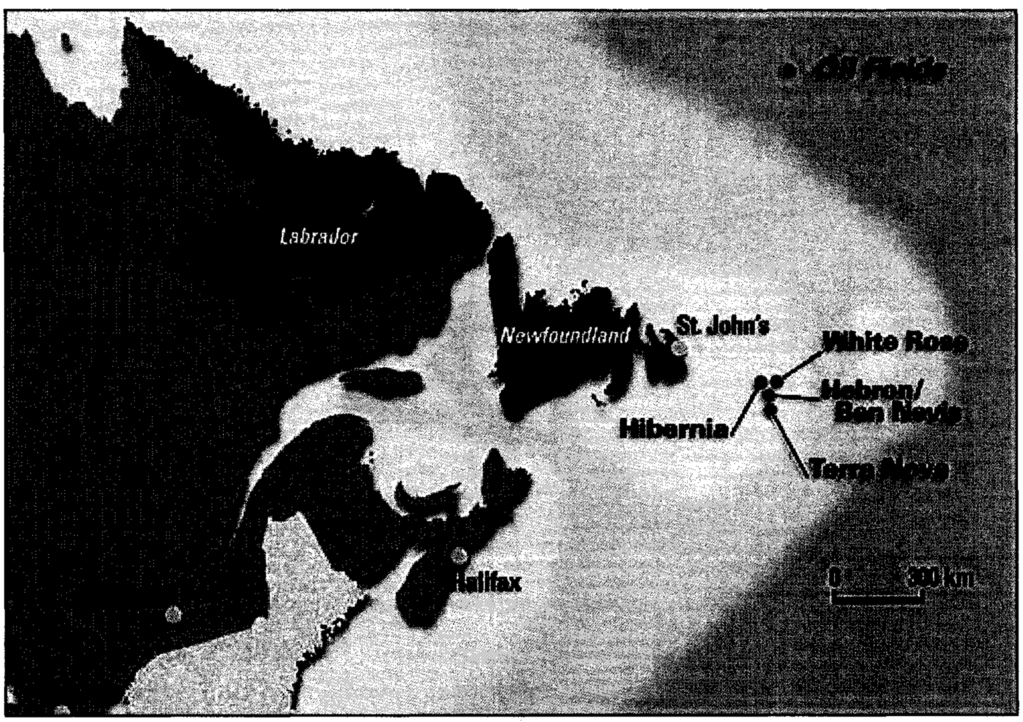

Figure 1 Major Oil Field Discoveries on Grand Banks (Compliments of Terra Nova Project Website)

From an environmental perspective, the Grand Banks are recognized as one of the most hostile offshore operating environments in the world, since it is influenced by a range of adverse conditions. The seasonal invasion of icebergs in the area is well known as the most formidable environmental influence because of their size, mass and energy. The waters offshore Labrador and Newfoundland are often referred to as "Iceberg Alley" as high numbers of icebergs move through the area each year. Historically, more than 480 icebergs cross the 48^{th} parallel annually, but there is considerable variability around this mean number from year to year (IIP, 2005). The icebergs are highly variable in terms of their size, keel depth and shape. Iceberg sizes range from a few metres to hundreds of metres and masses varying from hundreds to millions of tonnes.

Icebergs that are carried southward mainly from Western Greenland by Baffin and Labrador currents are known to float freely at deep drafts and occasionally ground and disrupt the seabed. Such events create iceberg scours and pits that could potentially damage structures installed on or near the surface of the seabed. Studies have shown icebergs scour at an average depth of 0.50 m and drift at a speed of 0.34 m/s in the Grand Banks region (Croasdale et al., 2000; MEDS, 1997).

Current developments of oil and gas on the Grand Banks have all incorporated some form of subsea infrastructure such as wellheads, trees, manifolds and flowlines. Seabed facilities such as these have been used more and more in other hydrocarbon producing areas such as the North Sea and Gulf of Mexico, and will also become an integral part of future developments on the Grand Banks. As the offshore industry matures on the Grand

Banks, the desire to tap into more marginal oil and gas reserves will be realized and play a key role in the regions exploitation of resources. In cases such as marginal field economics, subsea developments can bring significant reductions in development costs and tip the balance in favour of development. Such developments will most likely involve the use of a subsea satellite well or well cluster(s) tied back to an existing production facility via a subsea flowline. Existing developments such as Hibernia, Terra Nova and soon White Rose have all incorporated future expansion capabilities to accommodate tie-in of marginal fields.

One of the most crucial components of any subsea development is the wellhead, which provides pressure integrity for the well against an uncontrollable discharge of downhole fluid. Contrary to other subsea components such as manifolds, templates and flowlines, any damage to a wellhead could have major environmental consequences. In the unfortunate event of an uncontrolled subsea well blow-out caused by an iceberg collision, high potential for pollution and damage to the environment resulting from a major oil spill could occur.

Safe and economic utilization of subsea technologies requires that the risk of damage be reduced to an acceptable level. In terms of design, a key consideration relates to the risk of iceberg damage, and whether to protect subsea facilities from potential impacts of free floating and scouring icebergs. In order to ensure that the design and layout of subsea wellheads meets predetermined acceptable risk criteria, a requirement for some form of protection is necessary. Possible solutions include placing the equipment deep enough below the seabed to avoid contact or by means of a protective structure. The decision can also be made to accept occasional damage with repairs and/or replacement where the systems can be designed to be failsafe to avoid environmental damage.

To date, a number of alternative protection methods have been proposed and implemented on various offshore projects throughout the world. Such protection concepts include:

- Open Glory Holes
- Cased Glory Holes (or Submarine Silos)
- Caisson Wellhead Systems
- Protective External Barriers

Thus far on the Grand Banks, two forms of wellhead protection methods have been successfully implemented to protect wellheads from iceberg scour damage. These include excavated open glory holes for both the Terra Nova and White Rose development projects and a total of seven caisson wellhead systems installed on exploration wells drilled by Mobil and Petro-Canada.

1.1 Objectives

The present study aims to evaluate various wellhead protection concepts for subsea marginal developments located on the Grand Banks. The investigation seeks to provide the framework from which intelligent decisions can be made regarding the relative benefits and costs of different protection concepts while maintaining an acceptable level of risk. In order to achieve this goal, the following objectives will be addressed:

- Provide an overview of the Grand Banks iceberg environment including scour density, frequencies and scour characteristics for the region;
- Establish representative development scenarios for typical subsea marginal field developments on the Grand Banks;
- Present a thorough overview of existing technical solutions for wellhead protection and identify potential novel concepts;
- Establish minimum risk acceptance criteria associated with wellhead protection concepts for the Grand Banks region;
- Present methodology and conduct an analysis to determine the appropriate encounter and contact probabilities to seabed facilities located on the Grand Banks;
- Perform a cost of risk analysis in order to identify the most optimum wellhead protection solution for representative marginal subsea developments on the Grand Banks.

2.0 GRAND BANKS ICEBERG ENVIRONMENT

2.1 General

Icebergs that migrate to the Grand Banks are primarily calved off glaciers from Greenland and Baffin Island. The calved icebergs enter the waters of Baffin Bay and Davis Straight and drift south, following the powerful Labrador Current until they reach the Northwest Newfoundland shelf. At this point the current divides the iceberg population into two streams as illustrated in Figure 2. The majority of the icebergs flow either through the Avalon Channel along the coast of Newfoundland or through the Flemish Pass along the eastern edge of the Banks. A small number of icebergs also traverse directly across the banks (Cammaert & Muggeridge, 1988). It is estimated that it takes approximately three years for an iceberg to drift from its source glacier to the grand Banks (Kollmeyer, 1977).

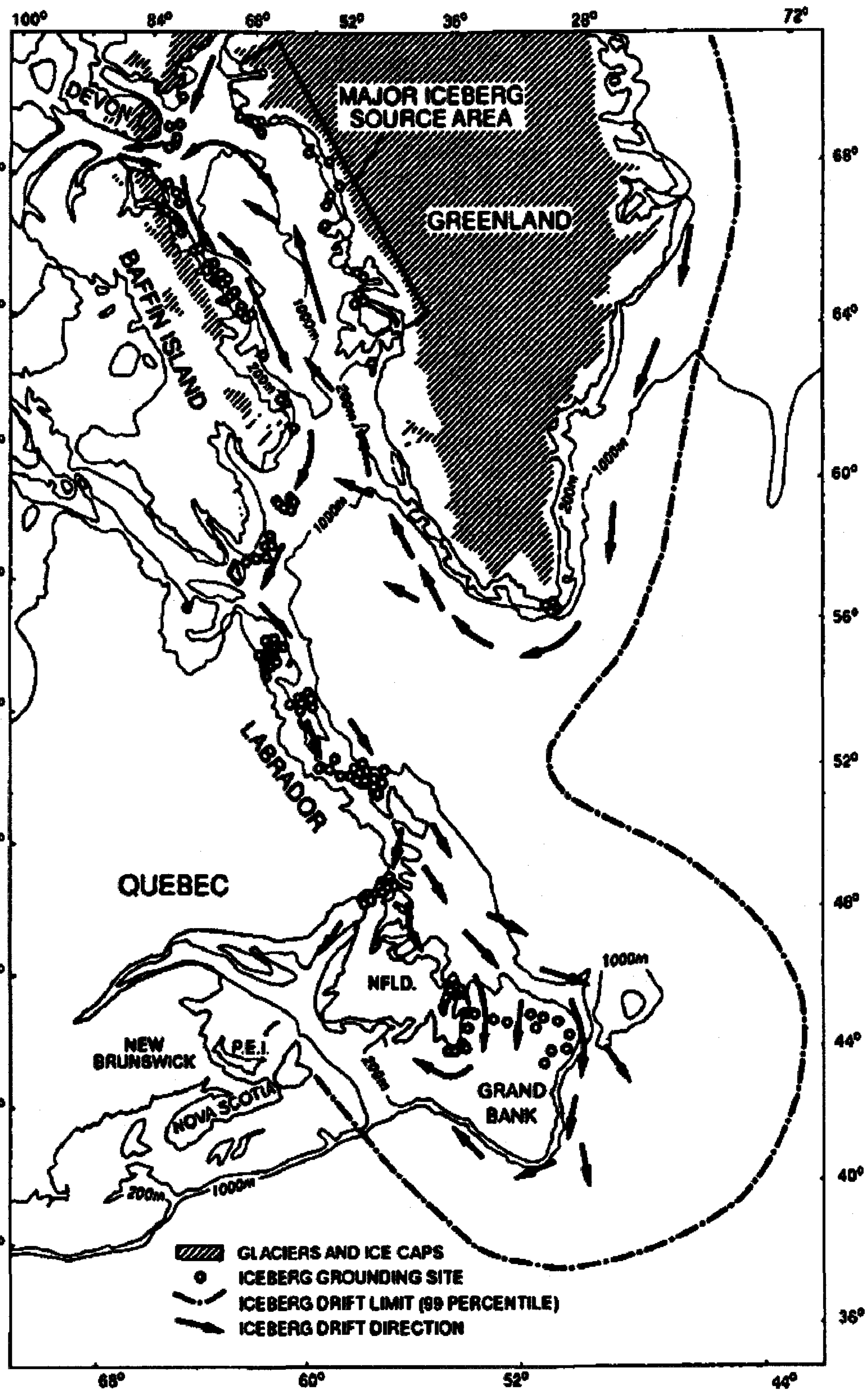

Figure 2 **Iceberg Paths on the Canadian East Coast (Lewis and Blasco, 1990)**

We are fortunate in having relatively good historical data on the number and locations of icebergs on the Grand Banks. The main sources of data have been accumulated by the International Ice Patrol (IIP), the oil and gas industry, and research institutes. As a part of the initiative of the Canadian Government through its Program on Energy Research and Development (PERD), a database was initiated in 1998 to assimilate all of the information on the annual iceberg population on the East Coast. The database is updated each year and improvements made to existing data.

The data collected in the PERD Iceberg Database goes back to 1810 as presented in Hill (1999). Hill presents an impressive compilation of 14,270 iceberg sightings from historical records such as shipping journals, gazettes, log books and diaries, and more recently the IIP between the years 1810 and 1958. Singh et al. (1998, 1999), Verbit et al. (2000, 2001 & 2002) and Comfort & Verbit (2003 & 2005) has added to this database to total 209,182 iceberg sightings on the Grand Banks between 1810 and 2004. Approximately 86% of the data contained in the PERD Iceberg Database has been collected by the IIP. The database includes general sighting information such as location, date, the shape and size of icebergs, and specific information such as waterline length, width, height, draft, and mass of icebergs. Figure 3 below shows the IIP iceberg sightings obtained during aerial surveys, which provides a good illustration of the iceberg extent encompassing the Grand Banks region (PERD, 2001).

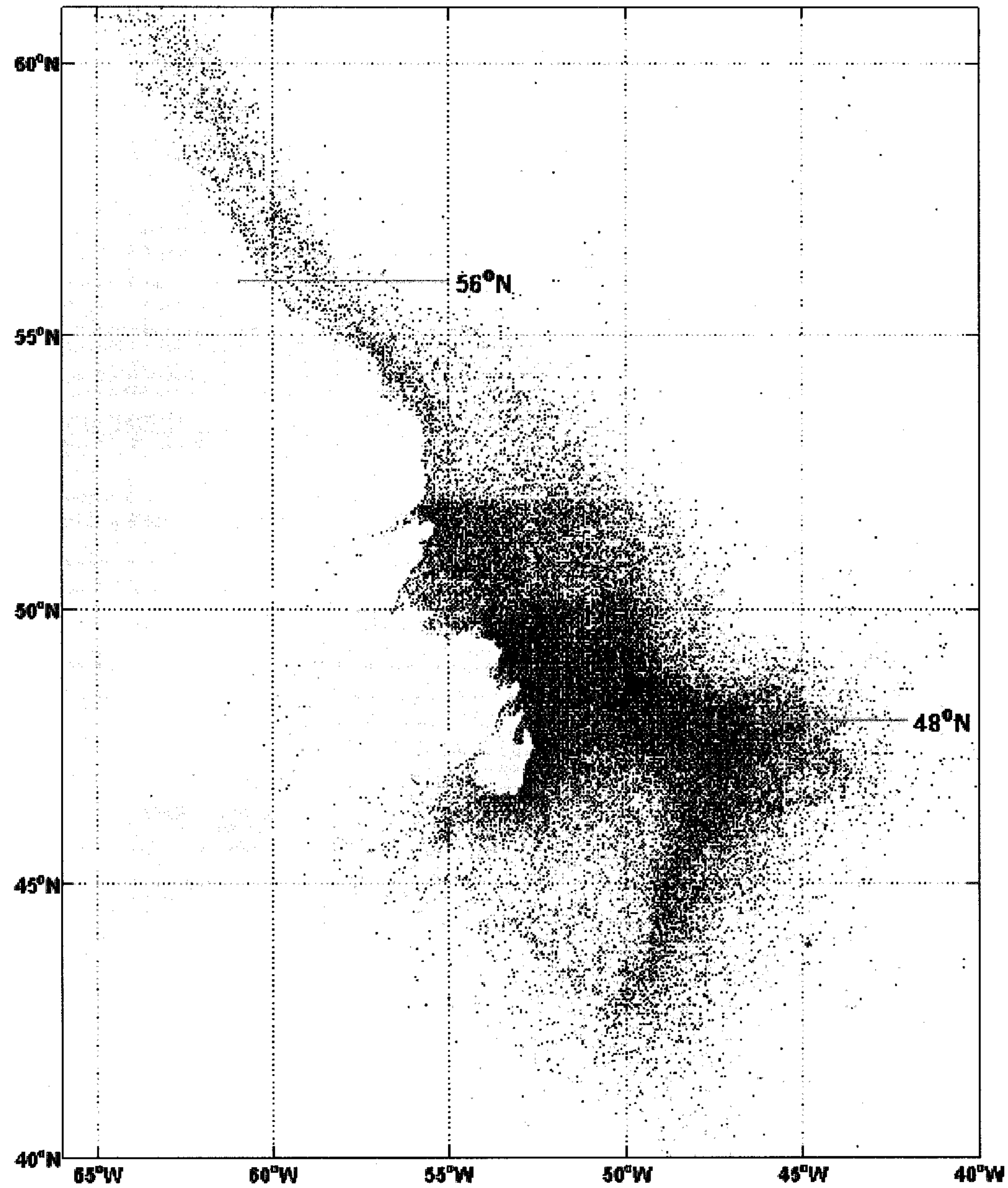

Figure 3 Distribution of IIP Iceberg Sightings Obtained During Aerial Surveys (PERD, 2001)

The occurrence of icebergs on the Grand Banks is highly variable. Marko et al. (1991) concluded that sea ice extent was one of the key parameters explaining variability in the number of icebergs crossing south of 48°N. The effectiveness of sea ice, in this respect, is dependant upon its abilities to prevent iceberg grounding and subsequent melting on shallow continental shelves together with its capacity for reducing free-drifting iceberg mass losses by suppressing elevated sea surface temperatures and wave heights (Marko et al., 1991). The number of icebergs reaching the Grand Banks is significantly higher in years when sea ice off Labrador extends out over the main part of the Labrador Current. In addition, ocean currents, variable climatic factors and local temperatures have a large influence with respect to the number of icebergs that make the journey to the Grand Banks.

A number of factors have been identified as effecting iceberg motion, including size, shape, mass, wind, water currents, waves, sea ice movement, ocean surface slope and coriolis force. It has been found that iceberg drift off the Grand Banks is directed primarily by the ocean currents (Cammaert, 1988).

One way to describe icebergs is by their above-water shape. One of five (5) different shapes is commonly assigned to icebergs for reporting purposes. These are shown in Figure 4 below.

PINNACLED (P)
Large central spire or pyramid of one or more spires dominating shape.

SPHERICAL (S)
A smooth and solid iceberg that has been rounded from rolling or bobbing in the water

DRYDOCKED (DD)
Eroded such that a large U-shaped slot is formed, with twin columns or pinnacles. The slot extends into the water line or close to it.

WEDGED (W)
Tilted iceberg with distinct cliff on one edge.

TABULAR (T)
Horizontal or flat-topped iceberg formed by calving from an ice shelf.

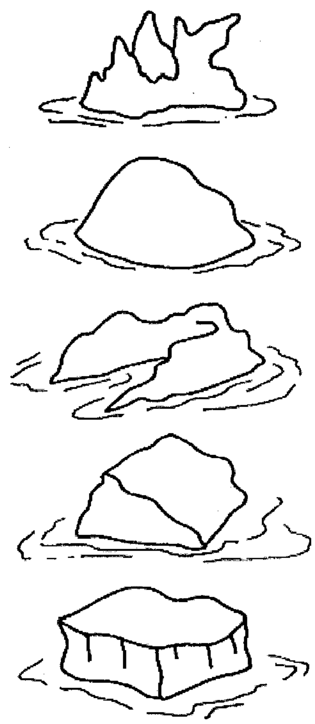

Figure 4 Iceberg Shapes (CANATEC et al., 1999)

Icebergs off the coast of Newfoundland and Labrador range in size from massive tabular and blocky icebergs in excess of several million tonnes to small bergs weighing 1% of this. Categories of iceberg sizes which are used for recording iceberg statistics range from very large (greater than 10 million tonnes and hundreds of meters long) to large, medium and small icebergs and on to bergy bits then growlers, which are grand piano size pieces. The average iceberg mass for the Grand Banks area is one to two hundred thousand tonnes, which is about the size of a cubic 15 storey building. See Table 1 for Iceberg size definitions.

Table 1 Iceberg Size Definitions (CANATEC et al., 1999)

Iceberg Size	Iceberg Heights (m)	Length (m)	Approximate Weight (tonnes)
Growler	Under 1	Under 5	1,000
Bergy Bit	1 to 5	5 to 15	10,000
Small	5 to 15	16 to 60	100,000
Medium	16 to 50	61 to 120	2,000,000
Large	51 to 75	121 to 220	10,000,000
Very Large	Over 75	Over 220	Over 10,000,000

On average, approximately 3000 icebergs drift annually into the Labrador Shelf area from Baffin Bay (Lever et al., 1989). The overall variation of icebergs numbers crossing south of 48°N latitude spans three orders of magnitude. For example, based on annual reports from the IIP between 1900 and 2004, the number of icebergs has varied from zero to over 2200 per year as illustrated in Figure 5. The mean number of icebergs passing south of 48°N is 478 icebergs with a standard deviation of 492 (IIP, 2005).

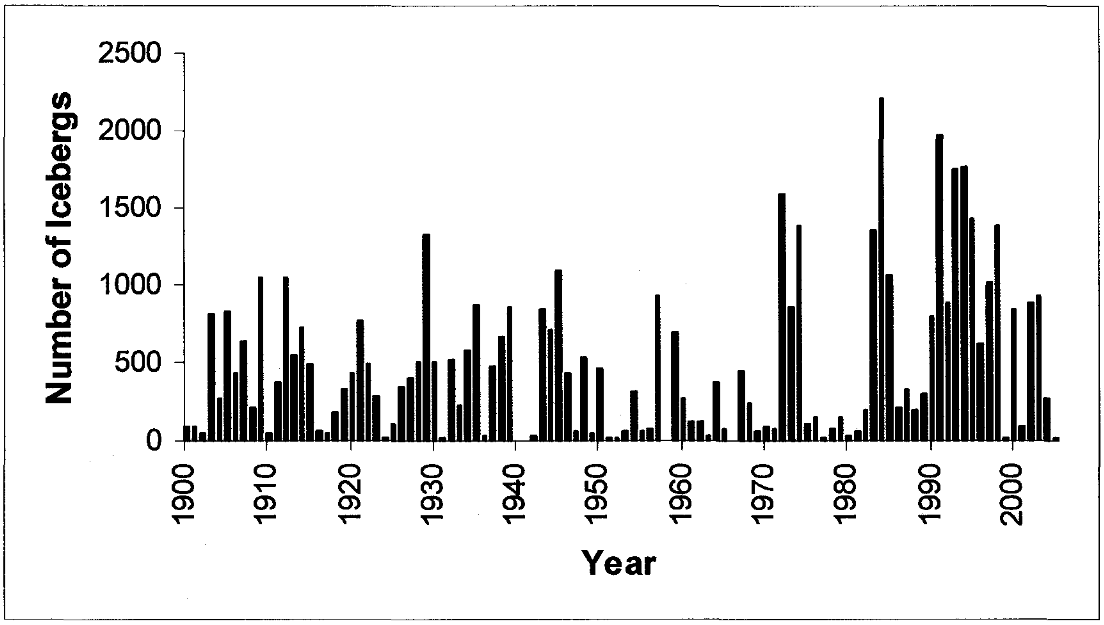

Figure 5 **Total Number of Icebergs Crossing South of 48°N Latitude Annually (IIP, 2005)**

Generally, high annual iceberg numbers occur in groups of 3 or 4 consecutive years, with local minimum counts tending to occur at intervals of 4 to 9 years (Marko et al., 1994). The iceberg flux is seasonal, extending from February until July, with April and May being the most prominent months (see Figure 6).

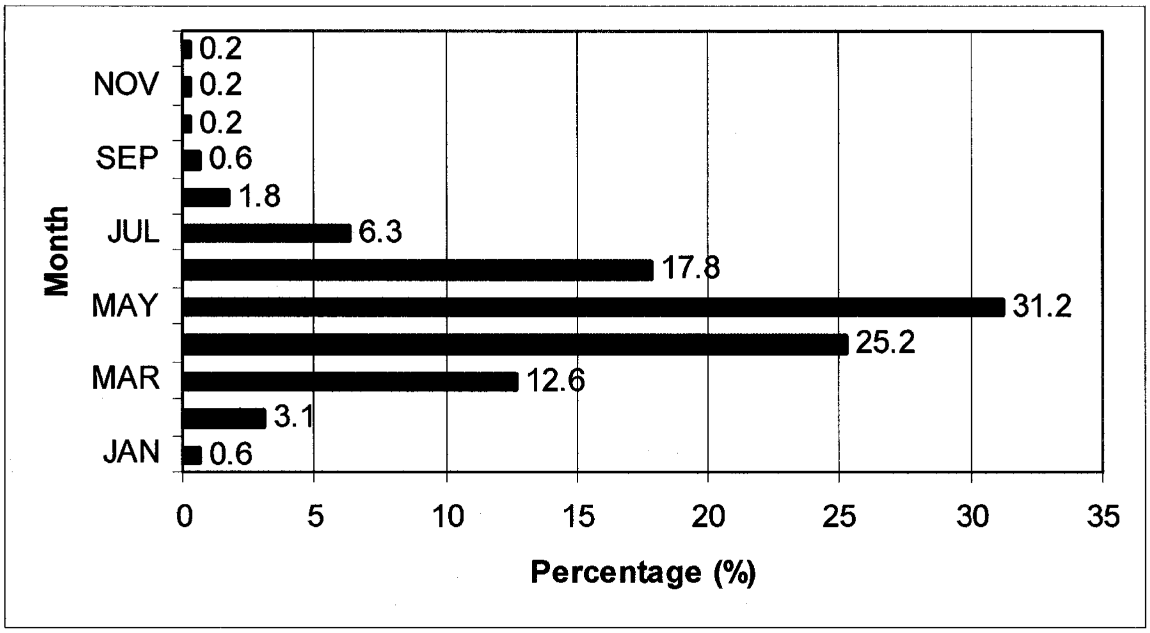

Figure 6 Monthly Variation of Icebergs Crossing South of 48°N Latitude (IIP, 2005)

The issue of global warming and climate change and its effects on iceberg severity on the Grand Banks has captured increased attention from the oil and gas industry in recent years. Brown (1993) concluded that ice and iceberg severities were considered unlikely to undergo major changes in the immediate future. However, over the next 50-100 years, if increasing concentrations of greenhouse gases result in consistent regional warming of 2 to 4°C, sea-ice retreat and lower Grand Banks iceberg severity are considered not unlikely long-term outcomes. However, the response of the east coast region to a gradual increase in greenhouse gas concentrations could well include short periods that favor higher sea-ice and iceberg severities (Brown, 1993). Further to this, Marko et al. (1994) concludes that no amelioration of ice and iceberg severity off eastern North America has, as yet, been identified in roughly a century of globally rising temperatures. Moreover, because of the inferred dominant influence of sea ice, it is extremely unlikely that postulated future increases in iceberg calving and simultaneous sea ice retreats could increase iceberg numbers south of 48°N without significant changes in the regional ocean and atmospheric circulations.

It is clear that future developments on the Grand Banks will be exposed to different iceberg populations, depending upon where they are located in the relative area. Oil and gas prospects that lie in deeper water areas towards the north and east sides of the Banks will experience more frequent and larger icebergs than in shallower central and southern portions.

Iceberg frequency is generally expressed in terms of areal density. Iceberg areal density is defined as the average number of icebergs that would be expected in a specified region (typically a degree square) expected at a given point in time as determined from historical iceberg sightings. The most reliable source of iceberg sightings on the Grand Banks in terms of frequency and coverage of surveys is the IIP, who regularly issue bulletins throughout the iceberg season showing the number of icebergs sighted per degree square (King et al., 2003). Areal density charts such as the one presented in Figure 7 by Jordaan et al. (1999) are derived from data collected over the years by the IIP.

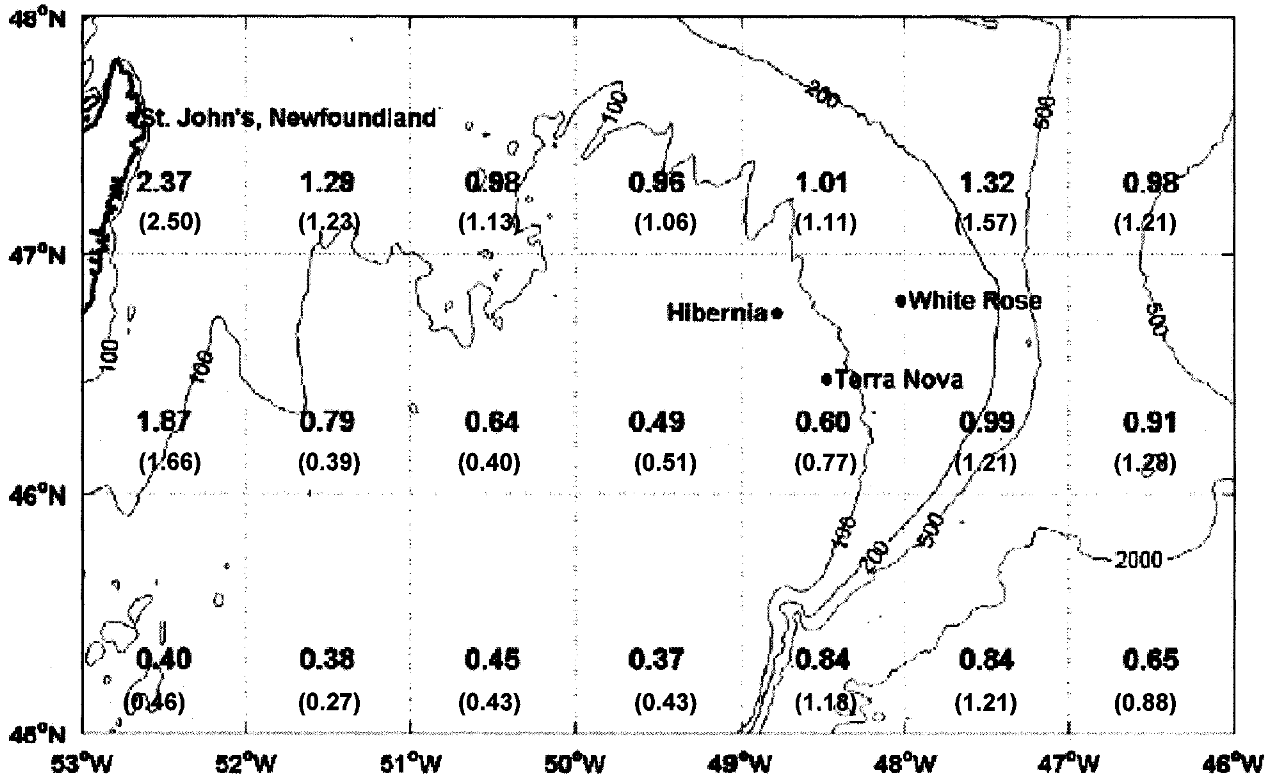

Figure 7 **Areal Density of Icebergs on the Northern Grand Banks (Top Values Based on Data from 1960-2000 & Bottom Values Based on Data from 1981-2000) (Jordaan et al., 1999)**

In this example, Jordaan has analyzed iceberg sightings with waterline lengths ≥ 16m and calculated the mean annual areal density per degree square for the Grand Banks and the adjacent regions based on data from the last 20 years (1981-2000) and the entire 1960-2000 period. A difference has been noted in areal densities for each time period, which could be attributed to either improved detection techniques or long-term iceberg frequency fluctuations (King, 2002).

2.2 Iceberg Scour on the Grand Banks

A fraction of the icebergs that penetrate onto the Grand Banks into water with depths less than their draft will make direct contact with the seabed in the form of a scour or pit. Iceberg scours commonly take the form of relatively long furrows and circular to elliptical pits in the surficial sediments. The furrows are formed by icebergs moving in contact with the seabed. Pits are possibly formed by the bearing capacity failure of the seabed for loads of icebergs at rest or catastrophically when icebergs split and roll into the seabed. Icebergs can oscillate vertically, repeatedly impacting the seabed while drifting to produce crater chains – a series of pits along their drift track (Lewis et al., 1987). An artistic impression of an iceberg scour is presented in Figure 8 below.

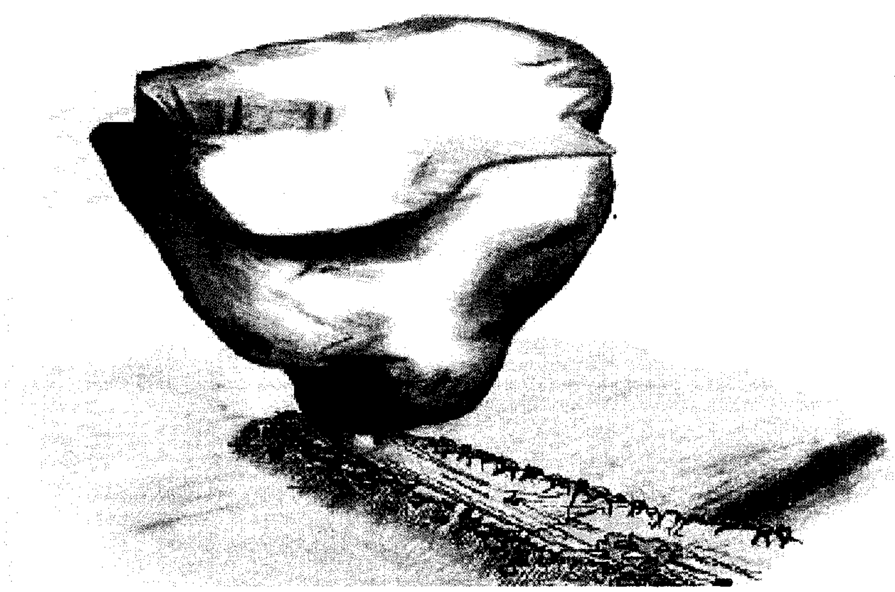

Figure 8 Artistic Impression of Iceberg Scour (Compliments of C-CORE)

The fact that large, deep draft icebergs may contact the seabed raises a number of concerns in the design of subsea facilities. Reliable information is required regarding the likelihood of iceberg contact, the probable depth of disturbance and the interaction forces generated to effectively design a safe and economical subsea installation. In order to estimate the probability of collision between icebergs and seabed structures, it is necessary to determine how frequently the icebergs scour and pit the seabed. Although there has been a substantial amount of work in recent years in an attempt to establish scour density and frequency estimates, the intent here is to a give a brief overview of some of those findings.

2.2.1 Scour Density

Iceberg scours are distributed throughout the Grand Banks. The distribution is uneven due to the variations in iceberg drift patterns, water depth and seabed soil type and slope. The Grand Banks Scour Catalogue (GBSC) represents the most up-to-date compilation of all ice scour data collected in the region since 1979. It was compiled by Canadian Seabed Research Ltd. for the Geological Survey of Canada, Atlantic between 1992 and 1995 (Myers et al., 1996) and updated again in 1999 (Canadian Seabed Research Ltd., 2000). The GBSC is an evolving database of information that is updated on a regular basis to include new scour information as it becomes available.

As of the 1999 update, the catalog contained records of 5720 scour features including 3887 individual scours (furrows or linear features) and 1773 iceberg created pits (craters or areal features). The catalog includes information on the feature type (i.e. scour or crater/pit), location, and physical dimensions. The study area as shown in Figure 9 was selected as it includes the most active area of offshore petroleum exploration, significant discoveries and production licenses within the Jeanne d'Arc sub-basin in water depths from 80-150m. The area includes Northeast Grand Banks, Flemish Pass and western portion of the Flemish Cap (Crosadale et al., 2000). The study region represents an area of approximately 100,000 km^2.

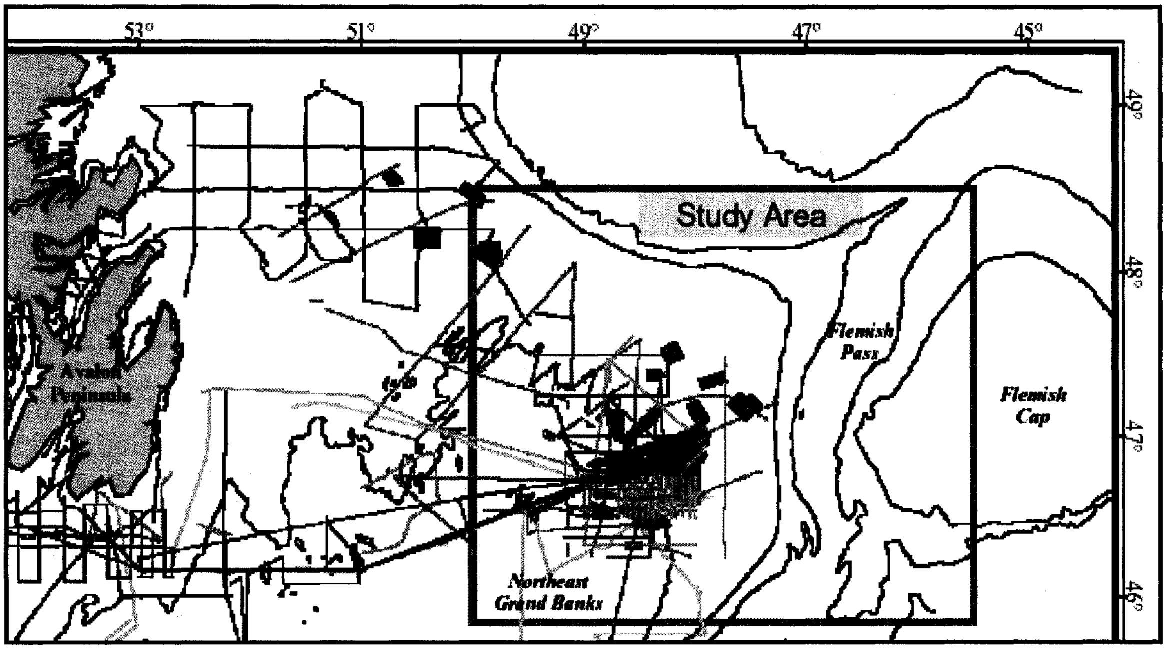

Figure 9 **GBSC Study Area Showing Survey Lines (Croasdale et al., 2000)**

For the most part, regional mapping of iceberg scours recorded in the GBSC have been identified and measured from various geophysical data sets from site surveys conducted since the late 1970's. A variety of detection techniques were used including: sidescan sonars, sub-bottom profilers, single beam and more recently, multibeam echo sounders.

It was concluded by Croasdale et al. (2000) that interpreter variability could lead to a minimum of 30% variation in scour density estimates. Scour depth data suffer from limitations of instrument resolution, degradation and infill, which all lead to underestimation of shallow scours and statistics biased to deeper scours. In addition, longer scours are often under represented in the database as they extend beyond the survey area.

The GBSC has been an important tool in assessing scour density (number of scours/km^2) for the Grand Banks region despite the inherent shortfalls. Scour density values for individual 1 km^2 grid cells range from 0 – 30 scours/km^2 within the study. The highest scour densities are those associated with most recent surveys using modern higher resolution equipment, suggesting scour events were either not visible on the lower resolution data or not interpreted on these earlier surveys (Croasdale et al., 2000).

Mean scour density values within selected bathymetric (depth) intervals were determined by Croasdale et al. (2000) based on the 1999 update of the GBSC. The mean scour density is 0.56 scours/km^2 for the total survey coverage in water depths less than 110 meters, and 0.86 scours/km^2 for the total coverage in water depths greater than 110 meters. The highest mean density, at 1.2-1.3 scours/km^2, occurs between 100-150 meters water depth. Lower density in deeper water may be related to a lower number of deep ice keels. The progressively lower mean density values in shallower water are probably due, in large part, to the reworking of scoured sediments by increased levels of hydrodynamic activity which has led to the obliteration of some scours over time, particularly those formed in sands. The GBSC includes relatively few scours for water depths greater than 150m on the Northeast Grand Banks, and no scours from the Flemish Pass region (Croasdale et al., 2000).

As a result of work conducted by C-CORE (2001a), further additions have been made to the GBSC to include more recent sidescan and multibeam seabed surveys conducted in the region surrounding the White Rose Development. The recent surveys in the area were analyzed and the data incorporated into the catalog. A total of 1455 iceberg scour records for the represented area (approximately 150 km^2) around White Rose were extracted. Scour density within the White Rose area ranged from 0 to 6 scours/0.25 km^2, with a mean scour density of 2.64 scours/km^2. Represented by Region 1, the study area used to determine scour Characteristics at White Rose is presented in Figure 10, overleaf.

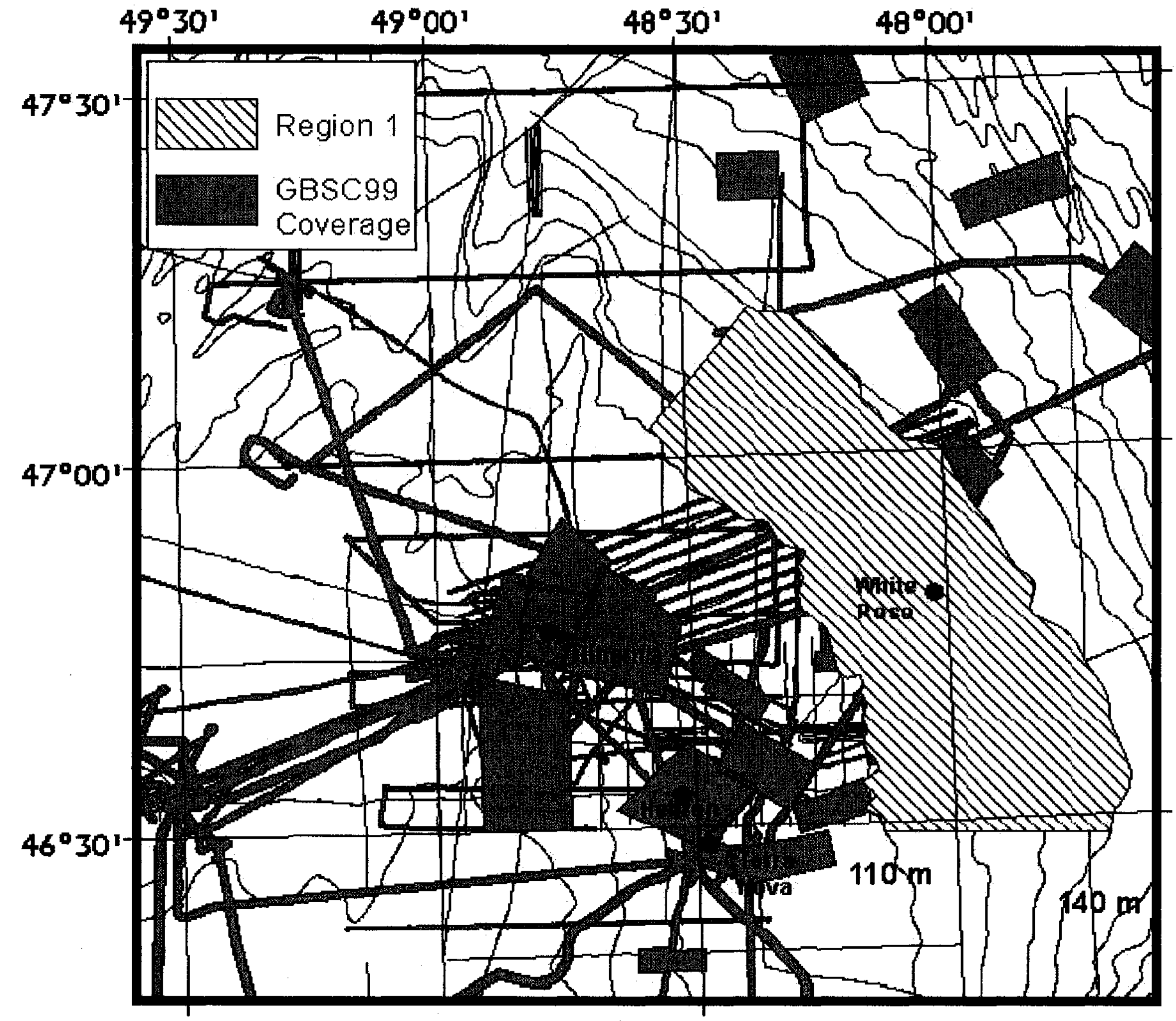

Figure 10 White Rose Study Area (C-CORE, 2001a)

A summary of scour density estimates from various sources is presented in Table 2, overleaf.

Table 2 Summary of Scour Density Estimates from Various Sources for the North-East Grand Banks

Reference	Water Depth (m)	Scour Density (scours/km^2)
Croasdale et al. (2000)[1]	≤ 110	0.56
	> 110	0.86
	100-150	1.2-1.3
C-CORE (2001a)[2]	110-140	2.64

Notes:

1. Representative for GBSC overall coverage area.
2. Specific to representative study area surrounding White Rose development location. Includes addition of recent survey data of the study area to the GBSC.

2.2.2 Scour Frequency

The issue of determining reliable scour frequencies is a major component for undertaking an accurate risk assessment. The scour density information described above shows interesting spatial trends, but is not directly applicable in establishing risk to subsea facilities. To assess the probability of a point, area, or linear feature on the seabed being contacted by a scouring iceberg, scour frequency information is necessary. Lewis et al. (1987) proposed four types of analyses that have been developed to determine the rates of scour on the Grand Banks. The following techniques were presented and explored in the paper:

- Geological Inference
- Grounding Model
- Repetitive Mapping
- Scour Degradation

2.2.2.1 Geological Inference

Utilizing the method of geological inference, average, apparent, long-term scouring rates for the Grand Banks region can be obtained from the ratio of seabed scour densities (scours/km^2) to the inferred age of the scour population. Lewis et al. (1987) suggested that the relatively young, low-density iceberg scour population on the Grand Banks began appearing approximately 2500 years ago. They used this as a basis for calculating a scour rate 4.0×10^{-4}/km^2/year for the Hibernia site. The same approach was used by C-CORE (2001a) based on the observed scour densities from the GBSC for the White Rose region to arrive at a scour rate of 1.0×10^{-3} /km^2/year.

Croasdale et al. (2000) suggests that the probable minimum and maximum estimates of scour age differ by almost an order of magnitude. They attempt to quantify this discrepancy by calculating an upper and lower bound based on scours estimated to have occurred over different geological time periods. They state that the recent geological record for the Grand Banks region indicates that 12,000 to 15,000 years ago, the water depth was 110m lower than it is today suggesting that current regions of the Grand Banks were above sea level. If all the scours still exist since 12,000 years ago for example, the lower bound frequency would correspond to 8.3×10^{-5}/km^2/year. On the other hand, in-filling and reworking rates for the shallow water regions (less than 110m) suggest that on average, scours created in the past 2500 years are still detectable. Thus, this case corresponds to the upper bound scour frequency equal to 4.0×10^{-4}/km^2/year.

2.2.2.2 Grounding Model

Lewis et al. (1987) presents a numerical grounding model as a means of calculating scour frequency. The model calculates the spatial distribution and mean frequency of iceberg groundings for 9.3 x 9.3 km cells based on input of long-term iceberg drift, iceberg draft distribution and the interaction of these parameters with bathymetry. Using this method, Lewis modeled the scour rate for the Hibernia region and calculated a scour rate of about 3.5×10^{-3}/km^2/year.

Additional propriety works in this area has been conducted to predict iceberg grounding rates for the Grand Banks region. Petro-Canada has developed an in-house iceberg collision simulation model called BERGSIM in order to determine iceberg collision risks relating to offshore facilities. Grounding models have also been developed and refined over the years by a number of sources to aid in predictions and provide useful risk assessments to local oil and gas companies.

Croasdale et al. (2000) applied a simple analytical based approach to predict scour frequency based on input of long-term mean iceberg flux and iceberg draft distribution. Using the degree square containing the Hibernia field as an example, they calculated a scour rate of 4.0×10^{-4}/km^2/year.

Perhaps the most recent and comprehensive work was performed by King et al. (2003) who developed a model to allow the grounding rate of iceberg keels to be estimated. The model uses data on iceberg frequency, draft distribution, mean drift speed, distribution of drift direction, water depth, and seabed slope and orientation. King used this approach to conduct a sample calculation for the White Rose region and computed a grounding rate equal to $6.2 \times 10^{-4}/km^2/year$.

2.2.2.3 Repetitive Mapping

Repetitive mapping surveys allow the scour frequency to be calculated by identifying any new scours features that have occurred at a given area over a given time interval between surveys. A number of repetitive surveys have been conducted on the Grand Banks with few new scours identified. Lewis et al. (1987) presented results of a survey area 120 km Northwest of Hibernia that was compared using sidescan sonograms over a six year period with surveys taken in both 1980 and 1986. There were no new scour features identified. Results presented by Geonautics Ltd. (1991) show one (1) new scour feature in a 490 km^2 area over a period of 11 years, which corresponds to a scour frequency of $1.9 \times 10^{-4}/km^2/year$.

Further work by Myers et al. (1996) identified two (2) new scours from resurveyed lines between Hibernia and White Rose, over an area of 273 km^2 based on an elapsed time of 11 years corresponding to a scour frequency of $6.7 \times 10^{-4}/km^2/year$.

Unlike regions such as the Beaufort Sea where scours are more prevalent, the usefulness of this method for estimating scour rates on the Grand Banks is limited due to the relatively low scour rates. In addition, the survey coverage and instrument resolution are all considerations when using this method.

2.2.2.4 Scour Degradation

Ice scours are degraded and eroded over time. Lewis et al. (1987) describes a method to estimate scouring rates from information on scour degradation and infilling rates for the Grand Banks. The approach assumes that the present scour population reflects an equilibrium between the rates of scour obliteration and scour formation. Thus by determining the rate of obliteration, the rate of replenishment or formation can be predicted. Based on this approach, Lewis et al. (1987) estimate that the present scour conditions at the Hibernia area would equal to a scour rate of about 1.0×10^{-3}. The effects of water depth and soil type need to be better understood before this approach can be used with any degree of confidence.

2.2.2.5 Summary

There is a level of uncertainty associated with each of the techniques presented above that must be taken into consideration when determining iceberg scour frequencies. For example, when utilizing the method of geological inference, estimating the age of the accumulated scours has potential for error. Croasdale et al. (2000) computes a factor of about 5 between the upper and lower bound scour frequency. This approach demonstrates the potential level of uncertainty involved when using such methods. A summary of scour frequency estimates utilizing the techniques outlined above from various sources is presented in Table 3.

Table 3 Summary of Scour Frequency Estimates for the North-East Grand Banks from Various Sources

Reference	Method	Frequency Estimate (scours/km²/year)
King et al. (2003)	Grounding Model	6.2×10^{-4}
C-CORE (2001a)	Geological Inference	1.0×10^{-3}
Croasdale et al. (2000)	Geological Inference - Upper Bound	4.0×10^{-4}
	Geological Inference - Lower Bound	8.3×10^{-5}
	Grounding Model	4.0×10^{-4}
Meyers et al. (1996)	Repetitive Mapping	6.7×10^{-4}
Geonautics Limited (1991)	Repetitive Mapping	1.9×10^{-4}
Lewis et al. (1987)	Geological Inference	4.0×10^{-4}
	Grounding Model	3.5×10^{-3}
	Repetitive Mapping	1.0×10^{-3}
	Scour Degradation	1.0×10^{-3}

2.2.3 Scour Characteristics

Scour characteristics have been determined from various geophysical data sets conducted on the Grand Banks using a variety of detection techniques. The GBSC has been an important tool in bringing this information together and determining spatial distribution and statistical properties of scour depth, width, length, orientation and iceberg pits.

2.2.3.1 Scour Depth

Sour depth distribution is often regarded as the most important issue for risk to subsea facilities as it is required to determine the proportion of scours that penetrate deep enough into the seabed to damage an installation located on or beneath the mudline. It is also one of the most difficult to characterize because the resolution of the seabed surveys results in the under-sampling of shallow depths, influencing the overall depth distribution. When measured scour depths are below the survey resolution they are sometimes assigned a value equal to the resolution (McKenna et al., 2003). Scour infilling is another factor to consider with respect to scour depth measurement distribution, especially in non-cohesive sediment as some level of scour infilling occurs during, or immediately following the scouring process. In addition, variations in depth across the width and differences in elevation between the start and endpoint of the scour (rise-up) result in difficulties evaluating traditional survey data to determine precise scour depths.

Croasdale et al. (2000) presents a maximum scour depth reported in the GBSC of 7m occurring in the 150-170m water depth range. For the 90-110m water depth range, the maximum depth is 3m with a mean of 0.48m. Mean and standard deviations of scour depth reported by Terra Nova (1997) are in close agreement with those of Croasdale et al. (2000). For the reported range of water depths of 80- 120m, the mean depth was 0.6m. Mean scour depth calculated for the White Rose region is considerably lower at 0.34m. This difference is due, in part, to the analysis technique used in the study to account for sub-resolution scour depth measurements. In addition, pits or craters may have been included to derive the Terra Nova result (C-CORE, 2001a).

2.2.3.2 Scour Width

Scour width is required for the calculation of scour crossing frequency over subsea structures. Scour width is perhaps the most defined of all scour characteristics and is relatively insensitive to location and water depth (Croasdale et al., 2000). Scour width is traditionally measured from crest to crest of the berms formed on the edges of the scour.

The mean width of iceberg scour marks on the Grand Banks is approximately 25m. For the 90 -110m water depth range, Croasdale et al. (2000) reports mean and maximum widths of 26m and 200m respectively. Similarly, mean scour depths reported by Terra Nova (1997) and C-CORE (2001a) are 25m and 24.9m for water depth ranges of 80-120m and 110-140m, respectively.

2.2.3.3 Scour Length

The mean scour length is required to calculate the frequency at which scours cross over subsea structures. Determining accurate scour lengths is sometimes difficult to achieve depending on the survey data available and methods employed. In many cases, only one or neither end of the scour is actually surveyed, resulting in mean scour lengths to be consistently underestimated.

For the northeastern Grand Banks, mean scour lengths are between 500m and 1000m, and have a coefficient of variation of about 1.5 (Croasdale et al., 2000; C-CORE, 2001a). For the 90 -110m water depth range, Croasdale et al. (2000) reports mean and maximum lengths of 650m and 9,400m respectively. Mean scour lengths reported by Terra Nova (1997) and C-CORE (2001a) are 565m and 588m for water depth ranges of 80- 120m and 110-140m, respectively. No significant relationship is noted between scour length and water depth.

2.2.3.4 Scour Orientation

For the most part it is very difficult to determine the actual direction of scouring icebergs unless there is clear definition of a scour initiation and a terminal pit. Scour orientation measurements in the GBSC range from 0^{o}-179^{o} by convention and do not indicate the actual scouring direction. Croasdale et al. (2000) reported that the majority of the scours in both directions are orientated N-S to NE-SW, with an inferred south to southwest scouring direction, consistent with the flow of the Labrador current across the region. In addition, it was recognized that preferred iceberg scour orientation was actually perpendicular to the bathymetric contours. Results presented by C-CORE (2001a) had a similar trend but they went a little further and determined the orientation of scours relative to the seabed slope. The results show that there is a tendency for icebergs to scour in a direction about -35^{o} relative to the down-slope direction, which corresponds to NNE for the study region.

2.2.3.5 Iceberg Pits

Pit features are not included with scours because they are best treated independently in risk analysis. Approximately 30% of the GBSC records are iceberg-created pits and have an average depth of 3.0m (Croasdale et al., 2000). In contrast, the mean depth of pits reported by C-CORE (2001a) for the White Rose study area is 1.1m with a mean linear dimension equal to 57m. Within the 1455 scours identified, there were 263 pit or crater events contributing only 6% to the area of disturbed seabed study area around White Rose. Pits as deep as 10m have been documented on the Grand Banks. Lewis (1987) presents details of a pit detected by sidescan sonar in 87 m of water, 11km east-southeast of Hibernia P-15 well having a depth of approximately 10m and diameter of about 150m. Work by C-CORE (2001a) corroborates this evidence.

2.2.3.6 Summary

In general, scour depth, width and length reported by Croasdale et al. (2000), Terra Nova (1997) and C-CORE (2001a) are in close agreement. Mean scour depth calculated for the White Rose region is considerably lower, however, this is attributed to the analysis technique utilized to account for sub-resolution scour depth measurements.

The work conducted by Croasdale et al. (2000) indicates that there are weak correlations between scour characteristics such as depth, width, water depth, sediment type and orientation.

A summary of statistical properties for scour depth, width and length according to water depth as outlined above are presented in Table 4.

Table 4 Comparison of Scour Characteristics from Various Sources

Reference	Water Depth (m)	Length (m)		Width (m)		Depth (m)	
		Mean	Std.	Mean	Std.	Mean	Std.
C-CORE (2001a)	110-140	588	784	24.9	14.4	0.34	0.30
Croasdale et al. (2000)	All depths	542	743	26	17	0.72	0.70
Croasdale et al. (2000)	≤ 110m	560	714	24	17	0.50	0.40
Croasdale et al. (2000)	> 110m	523	775	28	18	0.88	0.82
Terra Nova (1997)	80-120	565	618	25	14	0.60	0.30

3.0 MARGINAL SUBSEA DEVELOPMENTS

3.1 General

To date, four major oil fields (Hibernia, Terra Nova, White Rose and Hebron) have been discovered on the Grand Banks. Three of which, Hibernia, Terra Nova and White Rose have been brought on stream with permission from the Canada-Newfoundland Offshore Petroleum Board (C-NOPB) to produce on average 220,000 bopd, 150,000 bopd and 100,000 bopd, respectively. The Hebron development is still under commercial and technical evaluation. In addition to the four major oil fields, more than ten smaller oil and gas discoveries have also been made on the Grand Banks (see Figure 11).

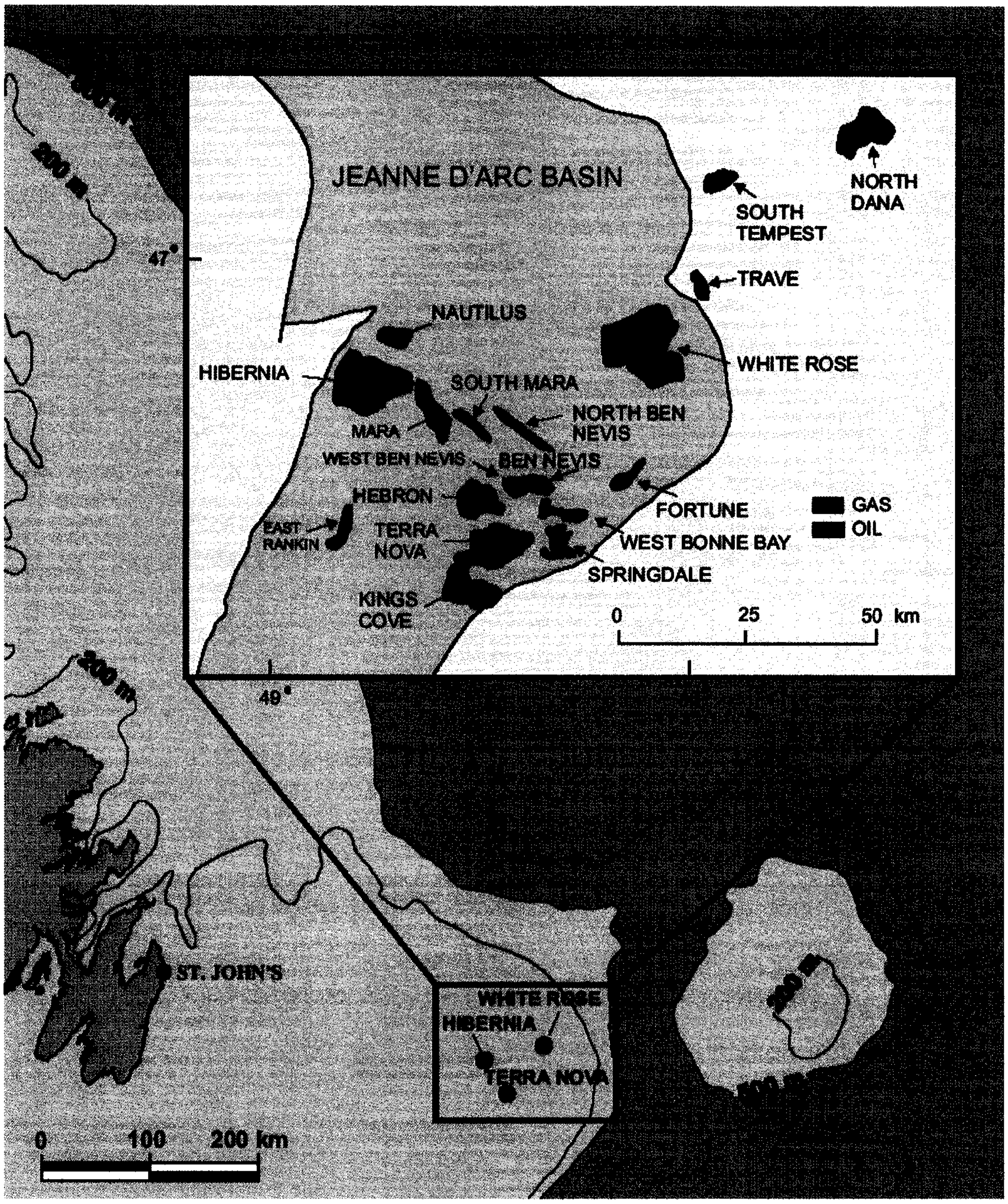

Figure 11 **Significant Discoveries Offshore Newfoundland (Compliments of Department of Mines & Energy)**

These minor fields, which include discoveries such as West Ben Nevis, Mara and Springdale, collectively have estimated in-situ oil reserves of approximately 290 million barrels and gas reserves of about 1.3 trillion cubic feet (C-NOPB, 2006). Typical oil reserve estimates for smaller fields are in the order of 10 to 30 million barrel range, with well productivities expected to be quite low. Since most of these smaller fields are the result of one discovery well, there is some uncertainty relating to their current oil reserve estimates and they could change considerably, should further delineation drilling be carried out. A summary of the petroleum reserves and resources for the Grand Banks as compiled by the C-NOPB is presented in Table 5.

Table 5 Petroleum Reserves(1) and Resources(2) Grand Banks (C-NOPB, 2005)

Field Name	**Oil**		**Gas**		**NGL's(3)**	
	$m^3 \times 10^6$	million bbl	$m^3 \times 10^6$	billion cu. ft.	$m^3 \times 10^6$	million bbl
Hibernia	197.8	1244	50.6	179	32.2	202
Terra Nova	56.3	354	1.3	45	0.5	3
Hebron	92.4	581	–	–	–	–
White Rose	45.0	283	76.7	2722	15.3	96
West Ben Nevis	5.7	36	–	–	–	–
Mara	3.6	23	–	–	–	–
Ben Nevis	18.1	114	12.1	429	4.7	30
North Ben	2.9	18	3.3	116	0.7	4
Nevis	2.2	14	6.7	238	–	–
Springdale	2.1	13	–	–	–	–
Nautilus	1.6	10	–	–	–	–
King's Cove	1.3	8	–	–	–	–
South Tempest	1.1	7	–	–	–	–
East Rankin	0.9	6	–	–	–	–
Fortune	0.6	4	4.1	144	1.2	8
South Mara	5.7	36	–	–	–	–
West Bonne	–	–	13.3	472	1.8	11
Bay	–	–	0.8	30	0.2	1
North Dana						
Trave	**437.3**	**2751**	**168.9**	**5990**	**56.6**	**355**
Sub–Total						

Notes:

(1) "Reserves" are volumes of hydrocarbons proven by drilling, testing and interpretation of geological ,geophysical and engineering data, that are considered to be recoverable using current

technology and under present and anticipated economic conditions. Hibernia, Terra Nova, and are classified as reserves.

(2) "Resources" are volumes of hydrocarbons, expressed at 50% probability of occurrence, recoverable that have not been delineated and have unknown economic viability.

(3) Natural Gas Liquids

(4) Produced oil reserves also include a small quantity of natural gas liquids. Produced volumes as of December 31 2005

Although these smaller fields do not appear to contain sufficient oil reserves to justify stand-alone development, they may be quite attractive as individual satellite field(s) tied back to an existing production facility, or in combination, when considered as candidates for simultaneous or sequential development (Wright et al., 1997).

Further exploitation of small and marginal fields will be essential for development of a mature oil and gas industry offshore Newfoundland. Existing infrastructure in the region such as Hibernia and Terra Nova can be utilized to make fields economic which otherwise may not be profitable. Innovative development solutions for the short life span of small/marginal fields are required particularly in harsh environments. Stimulating fiscal regimes for small field development is as important as state-of-the art technology, which reduces development costs and reaches pockets of oil/gas reserves, which a few years ago would have been left in the ground as un-producible. The technology to produce satellite fields has developed rapidly, and is routinely being used in many mature oil and gas provinces to develop small field reserves (10 to 50 million barrels) that are present around either fixed or floating production facilities.

The most likely development approach for marginal field development involves the use of a subsea system of wells tied back to an existing production facility via a flowline, commonly referred to as a tieback or step-out. The stimulus for this type of development approach has sprung almost entirely from demand in the North Sea, where operators are constantly trying to find new ways of making use of processing capacity on their platforms. Small reservoirs that are located around producing fields have been accessed by subsea wells, with their oil being piped back to existing platforms over distances up to 10 km, for processing and subsequent export to market (Wright et al., 1997).

Although there have not been any subsea marginal developments undertaken on the Grand Banks to date, local oil and gas operators have already started to evaluate these marginal fields as means to boost their production in the region. For example, tapping into marginal satellite fields and linking them to the Hibernia facility has been under consideration for quite some time. Hibernia Management and Development Company (HMDC) has been undertaking exploratory opportunities such as appraisal drilling in the Avalon portion of the Hibernia field in order to extend the life of the project and such development opportunities are currently being evaluated. In addition, Petro-Canada, Husky and Norsk Hydro have all been investigating the feasibility of tieback opportunities to the existing Terra Nova & White Rose FPSO's.

At present on the Grand Banks, all produced fluids from subsea wells are transported as a multi-phase fluid to the host production facility. The current industry record for the longest subsea tieback is 99.2 km, a wellhead to host platform step-out for Shell's Mensa subsea development in the Gulf of Mexico. Plans to set a new world record are already in progress with the development of the Statoil's Snow White (Snøhvit) project in the Barents Sea off northern Norway, due onstream late 2007. The project involves a tieback distance of 160 km from the field location via a single 27 inch multiphase pipeline to shore (Statoil Snøhvit Website, 2006). The maximum step-out distance for any subsea development is a function of a number of elements including the reservoir temperature, pressure, extent of natural drive available, water temperature, water depth and the constituents of the fluid itself. If for example, the distances over which produced fluids can be transported are increased, the profitability of marginal wells may become greater and reduce the need for large production facilities such as the Hibernia GBS and the Terra Nova & White Rose FPSO's.

Flow assurance issues such as hydrate and wax management need close attention as a result of very cold on-bottom water temperatures in the area. Secondary flow assurance concerns include management of scale and sand. In comparison to the North Sea and Gulf of Mexico, offshore Newfoundland has the most onerous requirements for wax management from an insulation standpoint (Offshore Magazine, 2004).

Recent technological advances in multi-phase pumping, metering and separation systems for boosting production from individual production wells to production facilities have made great strides in recent years. Marginal fields that were uneconomical just a few years ago have been brought on stream as a result. Multi-phase pumping systems boost dramatically the distance fluids can be transferred while flow meters provide data on well performance and in some cases eliminate the need for a separate production test line. Separation systems offer a number advantages such as reducing the risk of hydrate formation, reduce backpressure and thus increase tieback length and offers re-injection opportunities for separated gas and water in to the reservoir to sustain or increase oil production. Other advanced flow assurance technologies such as advanced passive flowline insulation and actively-heated flowlines offer some potential solution for the harsh Grand Banks environment where colder sea temperatures exacerbate common problems.

Even with the recent technological advances for development of subsea marginal developments, there will still be challenges in this area as a result of the harsh environmental conditions that exist on the Grand Banks. Obviously, iceberg scour is a key consideration for this subsea development approach, particularly as flowline tieback lengths increase. The costs and more marginal economics that are normally associated with small reserve developments will magnify the importance of the iceberg scour consideration for this development scenario.

3.2 Subsea Production Systems

One of the forces driving increased use of subsea production systems is the dramatic reduction in costs when compared with conventional methods. In many cases, the use of a subsea tieback is the only viable option to develop these resources (Devegowda & Scott, 2003).

Subsea production systems are made up of a number of components that work together as an integrated system to provide a means of distributing downhole fluids to a desired production facility. The main components of any subsea production system susceptible to threats from icebergs include the following:

- Wellhead
- Tree
- Manifold
- Template
- Flowline
- Control System
- Control Umbilical

Depending on the type of marginal development, single or multi-well, a number of the above components (i.e. manifold and template) may not be required or incorporated into the design. A brief description of each of these components is summarized below.

3.2.1 Wellhead

Most commonly located at the seafloor, the subsea wellhead provides pressure integrity for the well and acts as a structural foundation for a subsea drilling completion. The general function of a subsea wellhead system is to support and seal well casing strings, as well as supporting the blowout preventer (BOP) stack during drilling and control equipment (i.e. subsea tree) after completion. It must be designed as such to transmit applied loads to the casing strings and into the surrounding soil (API RP 17A, 2002). See Figure 12 for illustrations of typical subsea wellheads.

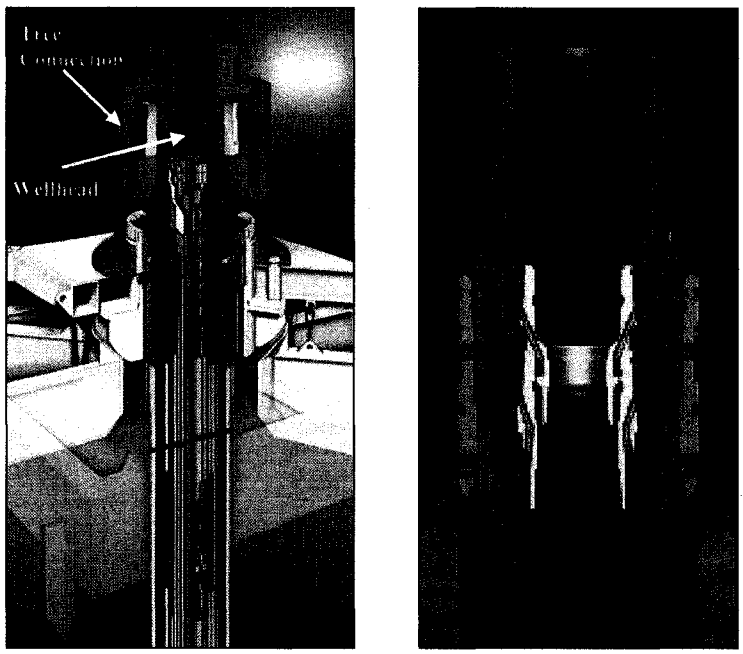

Figure 12 Typical Subsea Wellheads (Compliments of Dril-Quip)

3.2.2 Tree

Connecting to the top of the wellhead, the subsea tree (or Xmas tree) is the primary well control device. It consists of an assembly of components whose purpose is to contain reservoir pressure and permit access to the reservoir for maintenance and measurement. Trees normally consist of an arrangement of remotely controlled valves and piping to control the flow of oil and gas to and from the wells (see Figure 13).

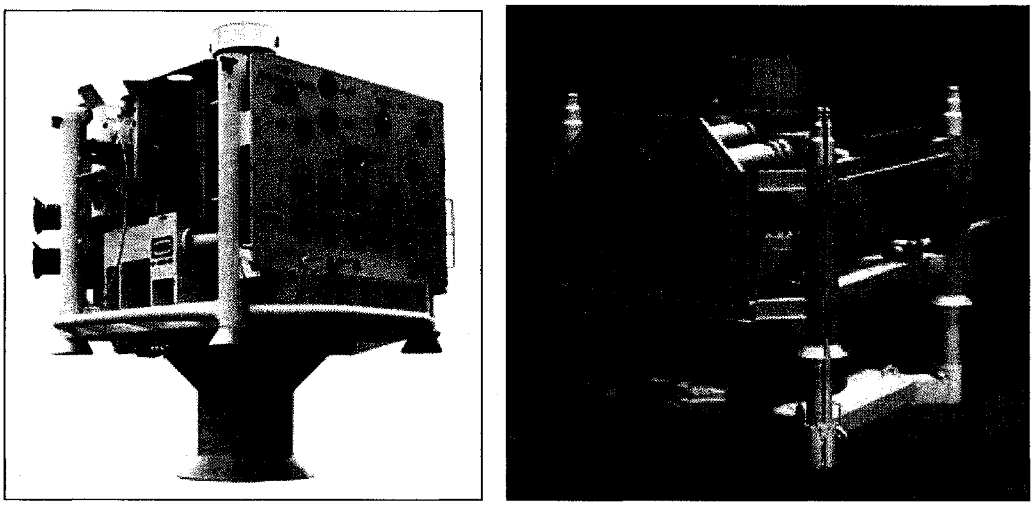

Figure 13 Typical Subsea Xmas Trees (Compliments of Offshore-Technology)

Subsea trees are used to control gas and/or oil production from a well, or water or gas injection into a well. Once in place, routine visual inspection and minor maintenance is generally carried out by the use of remotely operated vehicles (ROV's). The ROV's are outfitted with the necessary tooling systems to interface with the tree. The interventions can be either mechanical such as turning valve stems or hydraulic for direct actuator control (i.e. hot stab). In order for the ROV's to gain clear access to the trees at all times, an ROV access corridor of approximately 3m to 5m (will vary depending on the ROV type) must be specified around outer the extremity of tree footprint.

Subsea trees are available in a wide range of sizes and configurations. They include conventional versus insert or caisson trees, vertical versus horizontal and single versus multiple completion capacity. Plan dimensions of conventional vertical subsea trees are generally less than 5m x 5m and have heights above seabed level of about 5m to 8m.

For iceberg prone areas and in heavily traveled shipping lanes and fishing areas, trees can be situated below the seabed in order to provide protection. These concepts will be explored in more detail in Section 4.0.

3.2.3 Manifold

A subsea manifold is a system of piping and associated equipment used to collect production fluids from multiple wells or distribute injection fluids (see Figure 14 below).

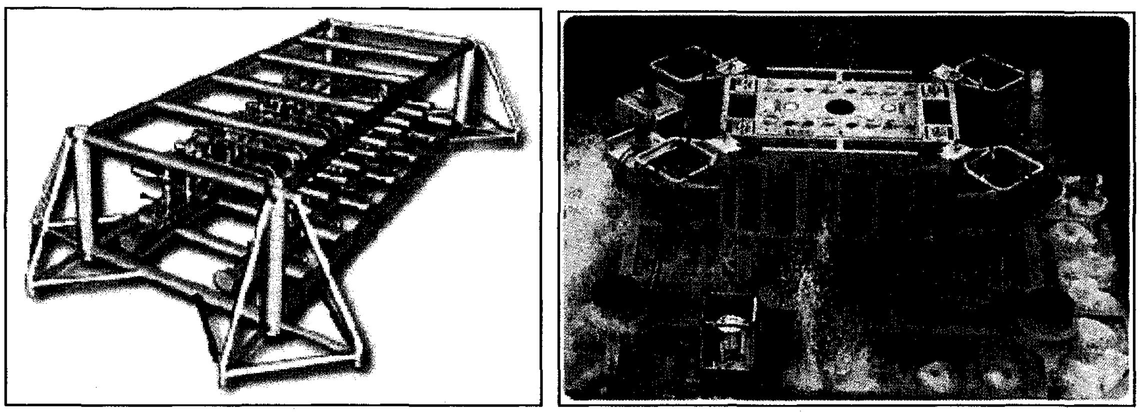

Figure 14 Typical Subsea Manifolds (Compliments of Offshore-Technology)

Production fluids are generally directed into flowlines sent back to the production facility while the injection fluids (water or gas) travel in the opposite direction and are directed into the wellbore and reservoir. In addition, gas lift and chemical injection fluids are also commonly distributed through manifolds. The associated equipment may include valves, connectors for flowline and tree interfaces and chokes for flow control. The manifold system may incorporate a control system and is sometimes an integral part of a template, or as in most cases, installed as a separate unit on its own. As with subsea trees, clear

ROV access is required around the perimeter of the manifold structure for inspection, maintenance and required operations. Dimensions of manifolds vary greatly in size and depend on the particular application and the number of wells it has been designed to accommodate.

3.2.4 Template

Development wells can be completed as individual stand-alone satellite wells or as template wells. Templates are basically steel structures, incorporating a variety of equipment guides, designed to provide structural support for a number of wellheads, Xmas trees and in some cases provisions for manifolds into a single subsea component assembly (see Figure 15 below).

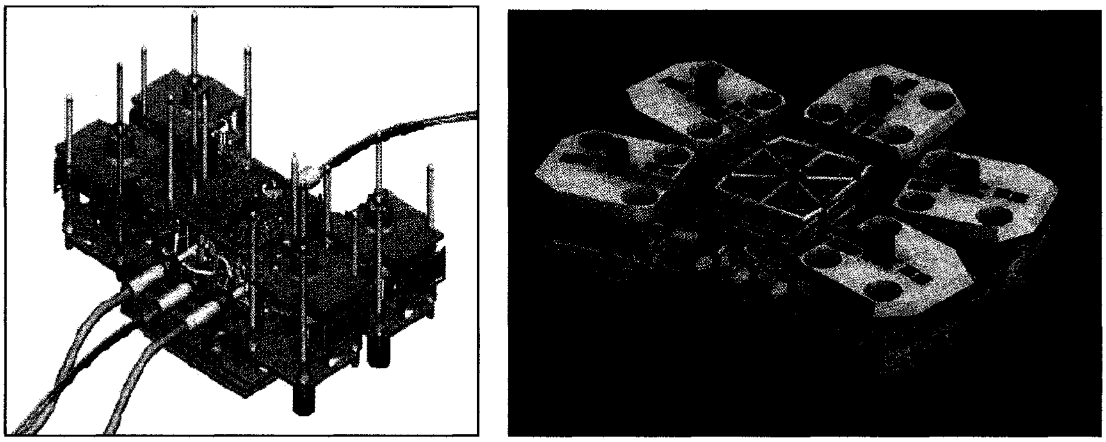

Figure 15 Typical Subsea Templates (Compliments of FMC Kongsberg)

After the wells have been drilled, the template serves as a mounting base and provides structural support for wellhead equipment and manifold. Template production trees can be connected directly to a production facility via flowlines and risers. As with manifolds, templates require clear ROV access and vary greatly in size. Templates used on the Terra Nova subsea development have varying number of wells (2-5) with plan dimensions of approximately 12m by 14m and stand approximately 8m in height.

3.2.5 Flowlines

Subsea flowlines provide a means of transporting fluid throughout a subsea production system. Flowlines function as production lines where fluid is routed to the production facility and injection lines, to bring chemicals, water and gas to the well bore and reservoir. Flowlines required for subsea production systems can be divided into three different categories:

- Inter-field flowlines: connecting the production facility to single field satellite well(s) or manifold / template structure(s) consisting of a number of wells;
- Intra-field flowlines: connecting field manifold / template structures to one another;
- Satellite well flowlines: connecting each satellite well to a field manifold / template.

Figure 16 illustrates a typical subsea flowline layout whereby inter-field flowlines are utilized to tie-back a number of subsea manifolds to a central floating production system.

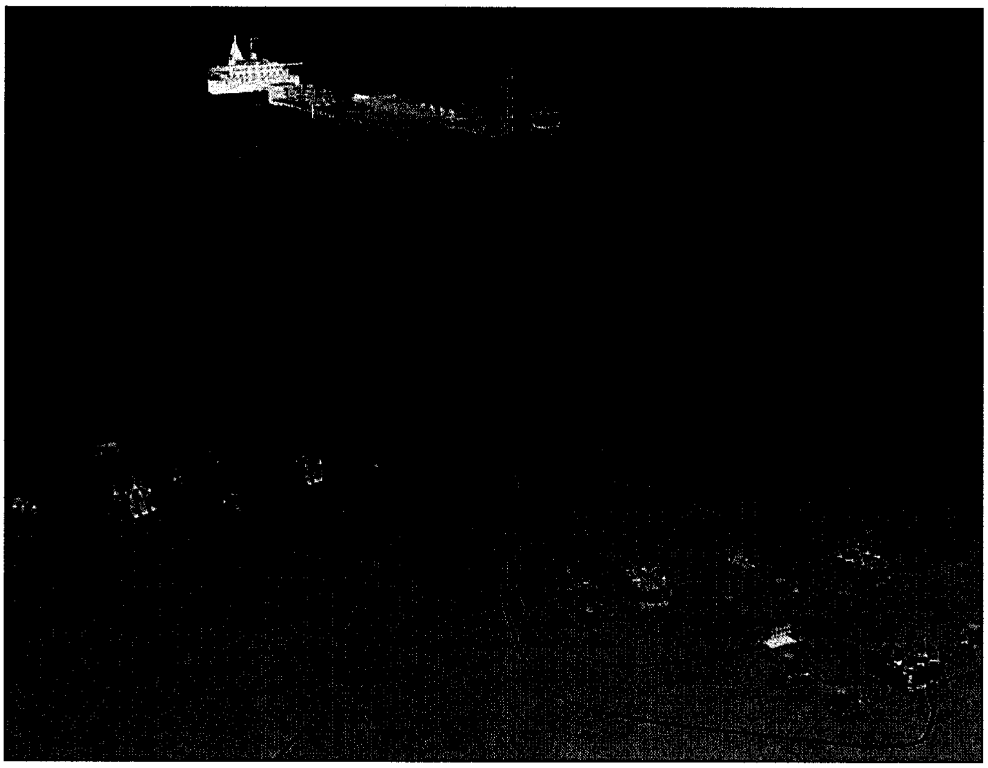

Figure 16 Typical Subsea Flowline Layout (Compliments of Offshore-Technology)

The length and size of flowlines depend on the final field layout and subsea architecture. Flowlines may be buried in trenches or left on the surface depending on flow assurance, stability and protection requirements. The flowlines can be of either rigid steel or flexible construction. Breakaway connectors are sometimes provided at the connections to the trees and/or manifolds to minimize damage in the event of iceberg impact or fishing gear interaction. Depending on the subsea architecture, flowline ends are sometimes terminated into structures such as pipeline end terminations or manifolds commonly referred to PLET's and PLEM's, respectively. For some subsea developments, enhanced subsea flowline systems in the form of bundles are used. Flowline bundles are generally made up of a number of rigid flowlines and hydraulic control lines which are all contained inside an external carrier pipe. Flowline bundles often incorporate manifold systems in the form of towheads and have active heating systems for improved flow assurance. See Figure 17 below which shows a typical flexible flowline and flowline bundle.

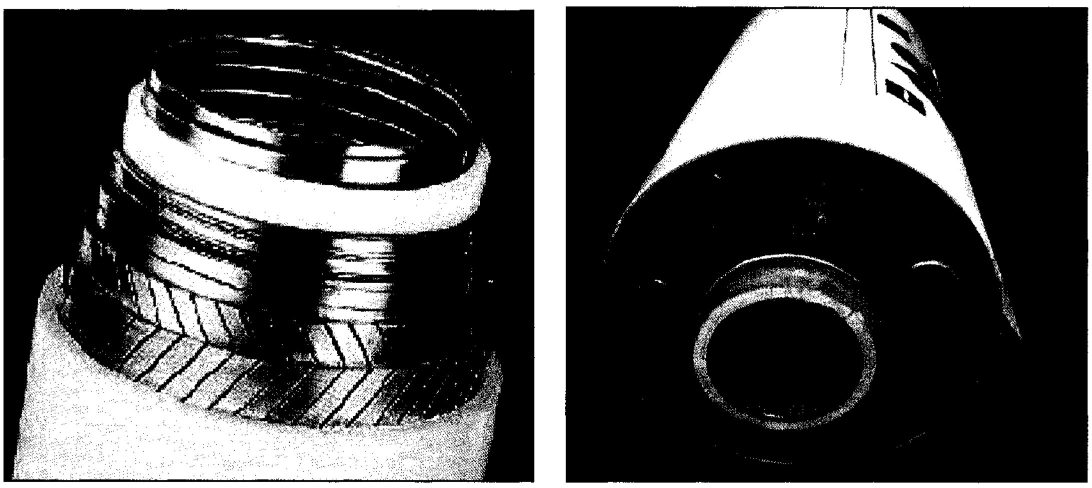

Figure 17 Typical Flexible Flowline and Bundle (Compliments of Technip and Subsea 7)

3.2.6 Control System

The subsea control system provides a communication control link between the production facility and the subsea system. Currently, the preferred industry control method involves the use of multiplex electro-hydraulic systems. Control modules are generally mounted on the individual trees or manifold components and signals are fed to the modules from the surface. The control system includes monitoring of well pressure and temperature, valve positioning, voltage, electric current, hydraulic pressure and electronic system condition monitoring.

3.2.7 Control Umbilical

As an integral component of the subsea control system, the subsea control umbilical provides the direct hard communication link between the production facility and the subsea system. Umbilicals can be made up of a number of services including hydraulic supply, chemical injection lines, electrical and power communication cables (see Figure 18). The umbilical hoses, lines and cables are generally bundled together in a single line and wrapped in an armor layer type construction. Services provided by the umbilical are distributed to the wells and manifolds as required. Distribution to multiple satellite wells, for example, can be provided by means of short control umbilicals in the form of jumpers or flying leads originating from a subsea distribution unit (SDU) for which the main control umbilical is terminated.

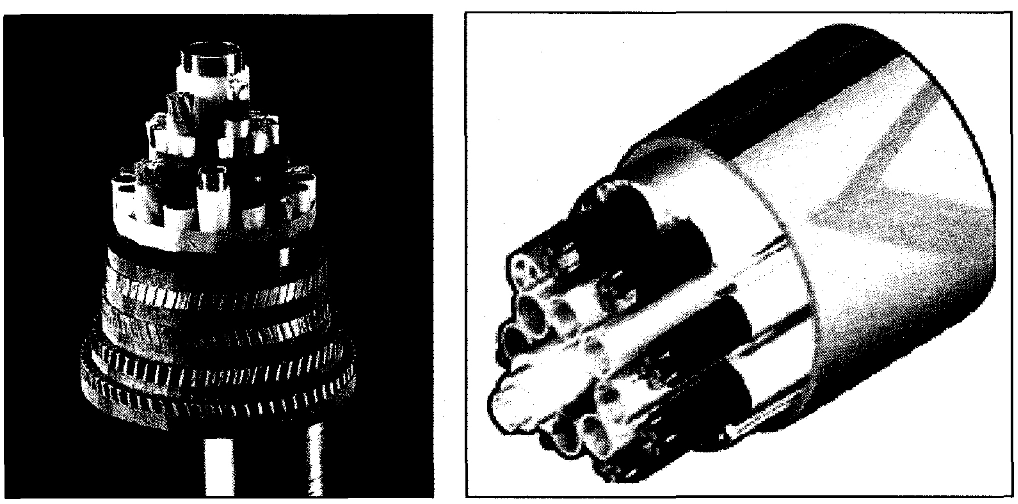

Figure 18 Typical Subsea Control Umbilicals (Compliments of DUCO)

3.3 Subsea System Layout

The layout and architecture of any subsea production system will depend on number of inter-related factors including:

- Oil and gas reserves;
- Field development strategy;
- Well design and construction limitations;
- Well testing requirements;
- Flow assurance considerations;
- Wellhead protection philosophy;
- Drilling, workover and offloading limitations;
- Subsea hardware selection;
- Seabed conditions;
- Subsea equipment installation logistics and cost.

Figure 19 shows a schematic of a typical subsea development system with all components located at seabed level.

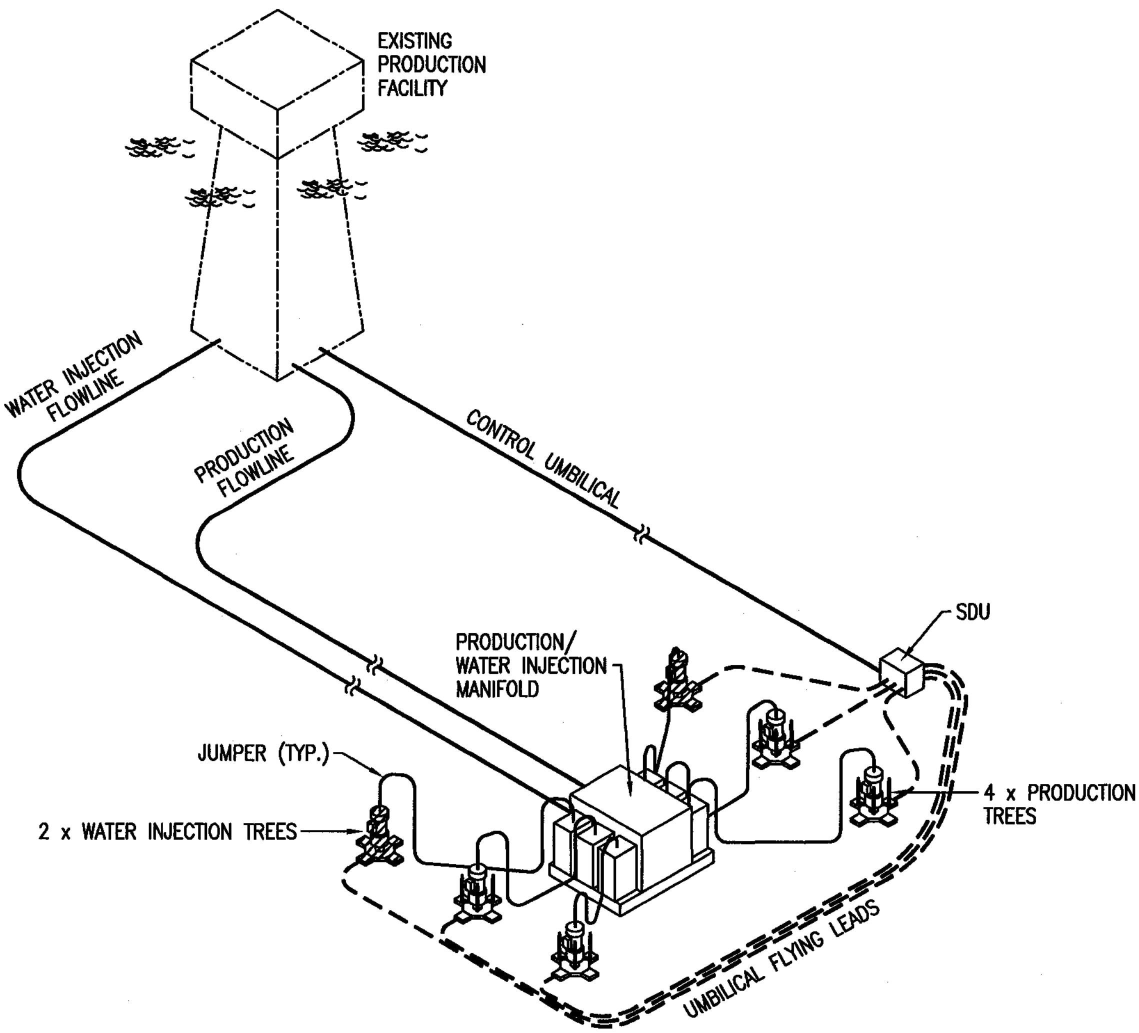

Figure 19 Typical Subsea Development System

Depending on the development scenario, marginal subsea developments can vary greatly in architecture and layout. Subsea technology in this area includes both single-well and multi-well completions incorporating various combinations of subsea components as summarized above. A marginal development can consist of one single satellite well or a number of wells including one or more production, lift or injector wells. Subsea layout options for marginal fields are generally grouped into two categories; satellite or clustered developments.

Subsea wells that are developed as isolated single satellites can be broken into two groups:

- A single satellite well, tied back to an existing production facility via a flowline or;
- Two or more wells that are drilled as satellites and tied back to a manifold/template structure located central to the wells via short flowline sections and in-turn tied back to an existing production facility via a flowline.

Similarly, a cluster development also consist of two forms:

- Two or more wells that are drilled through a template/manifold structure that is tied back to an existing production facility via a flowline or;
- Two or more wells that are drilled and tied into an adjacent manifold structure via flowline jumpers and in-turn tied back to an existing production facility via a flowline.

Functionally, both the satellite and cluster well systems work the same, however, components are arranged differently. A hybrid of these two arrangements can exist but they will not be explored as a part of this investigation.

Multi-well developments are typically faced with the compromise of locating wellheads to minimize flowine length and also to minimize drilling deviation angles. Generally, shortening the flowline lengths will be at the expense of higher deviation angles. In most cases, the minimization of flowline lengths will prevail over the minimization of deviation angles (CanOcean, 1990). There are a number of other reasons why clustered well arrangements are generally more attractive than satellites for multi-well developments on the Grand Banks. These include:

1. Avoids anchor interference problems from drilling vessels and thereby reduces risk of equipment damage.
2. Clustering close to manifold reduces or eliminates well-to-manifold flowlines, thereby reducing cost and eliminating the need for pigging and thermal insulation between the wellhead and manifold.
3. Eliminates any additional requirements of flowline trenching for protection against fishing and iceberg scour.
4. Offers advantages during drilling operations by the ability to access several well locations without the need to re-moor the drill rig.

Where well templates are not used for multi-well developments, subsea wells are generally spaced at a minimum of 25m away from any other permanent equipment to protect the wellhead from falling drilling and workover equipment. In the early days, it was very common that many wells would be drilled from a single subsea template, but this has been largely replaced by the use of wells that are completed individually. In comparison with manifolds, the geographical spread of template installations is much smaller. Manifolds are favored in cluster developments as they allow greater flexibility in terms of further tie-ins and daisy-chaining of future developments. In addition, single well completions are generally less complex than integrated templates, and offer flexibility in terms drilling because the wells can be completed before installing the template / manifold system.

3.4 Representative Marginal Developments

For the purpose of this study, two representative development systems relating to a subsea marginal development on the Grand Banks have been identified. They have been selected based on feedback from local oil and gas operating companies in the area and represent realistic development approaches. In addition, they are based on the use of conventional development equipment with no significant departures from current technology. Accordingly, the chosen systems represent both ends of the spectrum in terms of size and architecture and represent a realistic development approach for a range of cases. They are as follows:

Case 1: This system is representative of a small field requiring only a single well tied back to an existing production facility.

Case 2: This system is representative of a larger multi-well development, which is tied back to an existing production facility. The six wells are laid out as a cluster development with a manifold central to the wells that are grouped in two rows of 3 on either side of the manifold.

Development details of both systems are presented in Table 6.

Table 6 Representative Subsea Marginal Developments for the Grand Banks

Description	Case 1	Case 2
Recoverable Oil Reserves (mmbbls)[1]	20	50
Step-out Distance (km)	5	10
Water Depth (m)	80-150	80-150
Number of Wells (total) - Production - Injector	1 1 -	6 3 3
Well Productivity (bopd)	15,000	20,000
Peak Production (bopd)	15,000	40,000
Field Life (years)	6	8
Number of Flowlines - Production - Injector - Lift	2 2 - -	4 2 1 1
Number of Control Umbilicals	1	1
Number of Manifolds/Templates	-	1 x 6 slot

Notes:

1. Only oil reserves have been considered as they represent the most probable development scenario at this time for the regions marginal fields.

Figures 20 and 21 below present a schematic of each of the chosen subsea marginal developments as detailed in Table 3.2.

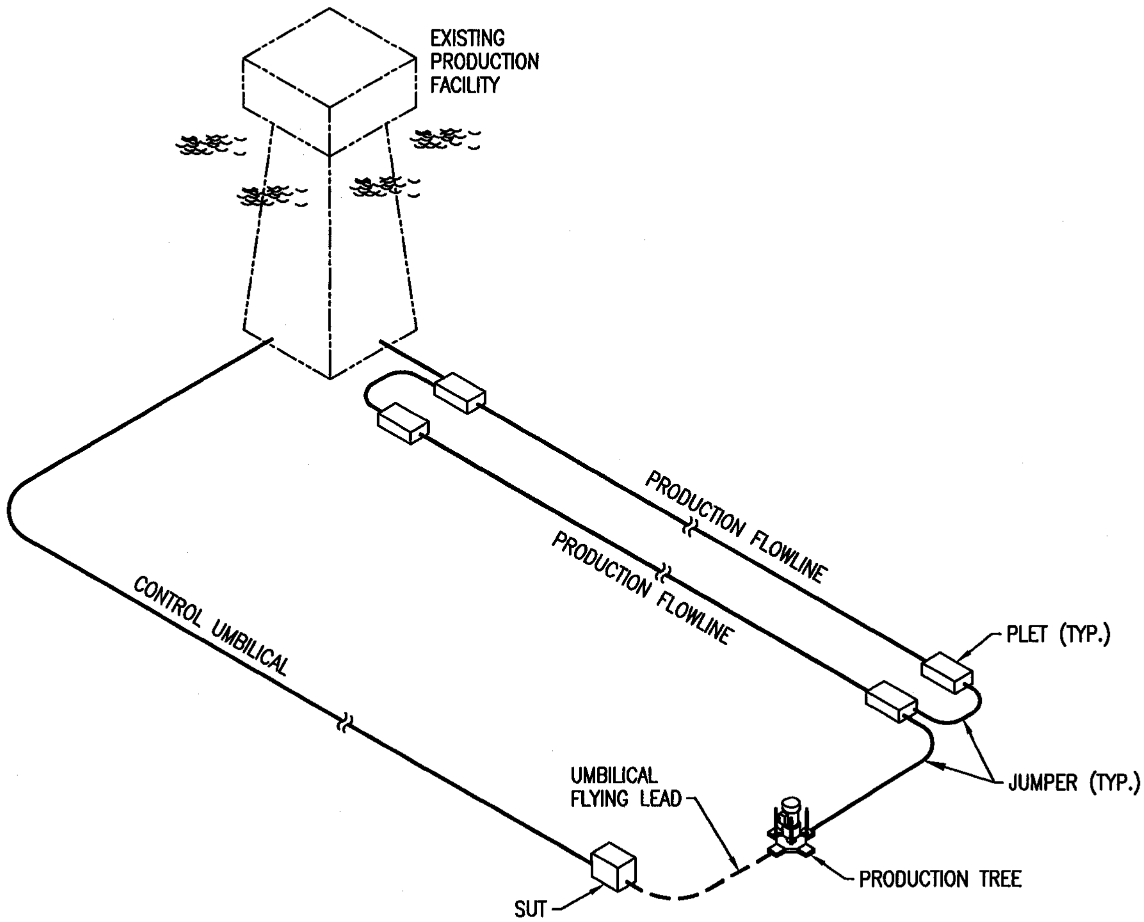

Figure 20 Representative Subsea Marginal Development – Case 1

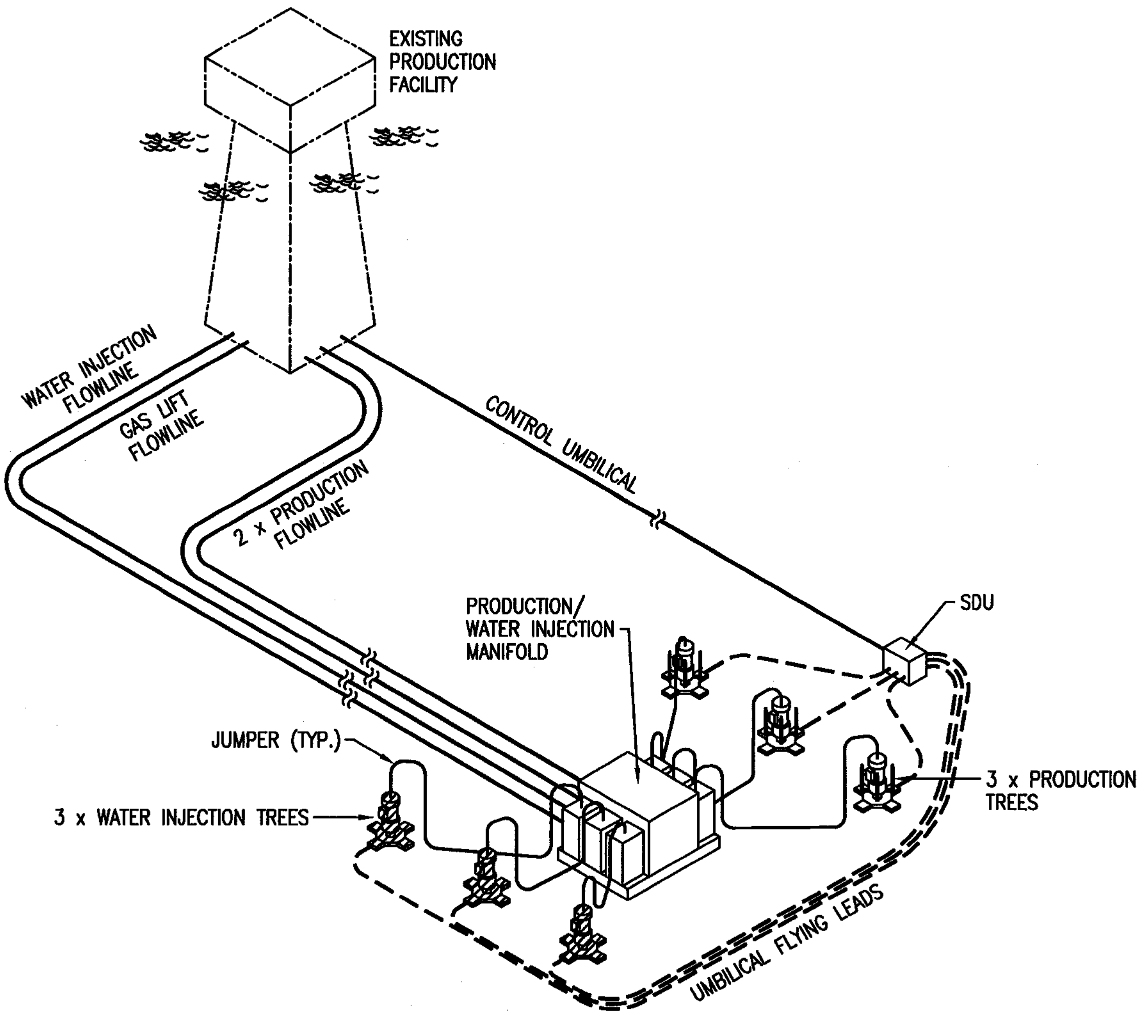

Figure 21 Representative Subsea Marginal Development – Case 2

4.0 WELLHEAD PROTECTION CONCEPTS

4.1 General

The threat of icebergs on the Grand Banks has led to the requirement for protection of wellheads and has thus become an integral part of subsea developments in the region. Regulatory requirements stipulate that appropriate measures in the design of subsea protection system components (i.e. wellheads) are taken to minimize the risk of damage to the environment from threats such as icebergs. Although the probability of scouring icebergs is relatively low on the Grand Banks, the associated risks are high, thus some form of protection has been generally accepted in the local Oil & Gas industry in order to ensure security of subsea wells.

The selection of a particular wellhead protection system for a given field should not be a stand alone decision but depends on a number of inter-related factors such as field size, number of wells in the development, the subsea architecture and hardware, and field development flexibility required. In addition, aspects such as safety, environment, economics, operability and reliability will undoubtedly play a large role in decision-making processes.

Various conceptual methods to protect wellheads from iceberg scour damage exist and have been evaluated over the years. Some of which have been successfully implemented in areas such as the Beaufort Sea and on the Grand Banks of Newfoundland. This section describes the wellhead protection options currently available. In addition, a number of novel concepts have been presented, some of which are variations or hybrids/extensions to existing concepts.

4.2 Existing Failsafe Systems

Currently, failsafe systems are adopted as a part of the design on every well drilled and perform an important safety function, especially for offshore installations. These safety systems are required to prevent injury to persons, damage to equipment, and serious pollution.

Subsea completions, which include integral wellhead components, should be designed to withstand a catastrophic failure in which the subsea tree is removed forcibly from the well, sometimes causing substantial damage to the upper wellbore. In the case of the Grand Banks region, this could occur when an anchor chain or fishing net is dragged over a subsea tree or from a more cataclysmic event such as an iceberg contact/scour event.

The most common type of failsafe systems adopted for well installations is the subsurface safety valve (SSV). Safety valves are vitally essential in offshore wells with harsh environments such as on the Grand Banks. These components are installed in wells with the hope that they will never be needed and offer significant safety margins by incorporating automatic shut-off valves in the wellbore. In the event of a major incident, however, this critical safety devise is subject to high demands. They provide the ultimate protection against uncontrolled flow between a producing formation and the surface in case of a catastrophic damage to wellhead equipment.

Two types of subsurface safety valves are available: surface controlled and subsurface controlled. Given the difficulties in testing or confirming the efficiency of these valves, surface-controlled safety valves are much more common. Set in the upper wellbore below the mudline, a surfaced controlled-subsurface safety valve (SCSSV) is installed to provide emergency closure of the producing conduits in the event of an emergency such as a wellhead failure. The safety-valve system is designed to be fail-safe, so that the wellbore is isolated in the event of any system failure or damage to the surface production-control facilities. There are two basic operating mechanisms: valves operated by an increase in fluid flow and valves operated by a decrease in ambient pressure. Figure 22 provides a typical illustration of the valves inner workings. The valves are hydraulically operated and fail-safe, that is, if the control signal or power is lost the valves will fail in the closed position.

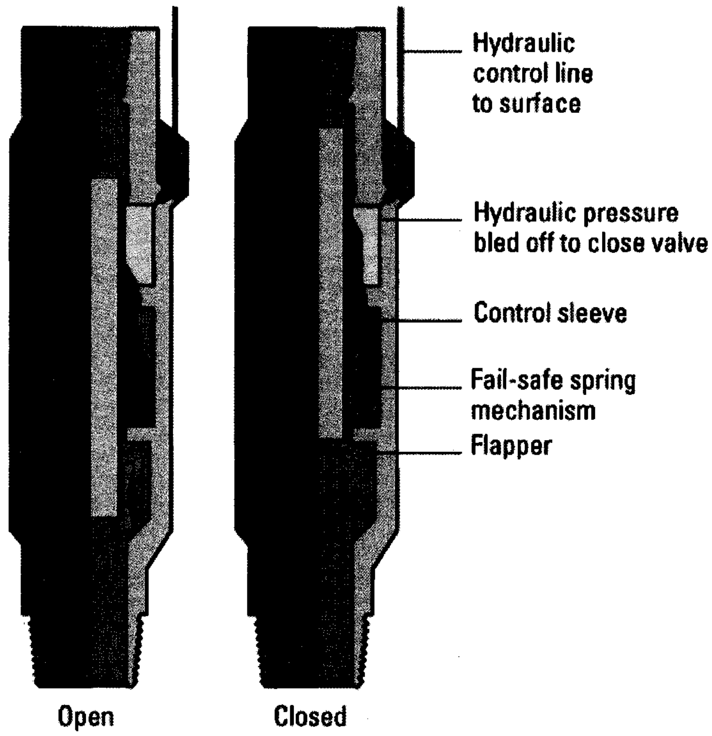

Figure 22 Schematic of Typical SCSSV (Complements of Schlumberger)

Two general failure modes can be identified in subsea completions: mechanical failure above and below the tubing hanger. In failure below the tubing hanger, which is the more serious of the two, the SCSSV's must be located at a position in the tubing that is below the calculated point of failure or area of influence (Nuttall, 1991). The SCSSV is run as an integral part of the completion string, normally positioned a minimum of 30m below the mudline. Recently, SCSSV's have been set at depths greater than 1000m below mean seabed level in the Gulf of Mexico, setting an industry record (Schlumberger Website).

Perhaps the most regulated component of an oil and gas well, the SCSSV must satisfy stringent technical, quality and operational requirements. The industry has made huge technical advances over the past few decades with great improvements in product reliability and Mean Time to Failure (MTTF), which is a measure of how long a particular component or even the whole network is expected stay working. A significant improvement in SCSSV performance has resulted, from an initial MTTF of 14.2 years (1983) to the most recent result of 36.7 years (1999). This represents a tremendous boost in well production availability and availability of the SCSSV as a safety barrier (Molnes & Strand, 2000).

The first safety devise to control subsurface flow was used in US inland waters during the mid 1940's. This Otis Engineering valve was dropped into the wellbore when a storm was imminent and acted as a check valve to shut off flow if the rate exceeded a predetermined value. A 1969 blowout in a well in the Santa Barbara Channel off California, USA, led to 1974 regulations that required the use of subsurface safety systems on all offshore platforms and installations in US federal waters (Garner et al., 2003). Many of the worlds other countries exploring for and developing oil and gas reserves have since followed suit.

Regulations for requirements of these safety valves vary between oil and gas provinces throughout the world. For all wells drilled in Canada, there is a specific requirement for the inclusion of a SCSSV. As stipulated by the C-NOPB under the Newfoundland Offshore Area Petroleum Production and Conservation Regulations, under Section 25 (1) to (4), require that:

"(1) Subject to subsection (2), an operator shall ensure that a development well is equipped with a SCSSV that is installed

(a) in the tubing at least 30 m below the sea floor; and

(b) in the annulus of the well at least 30 m below the sea floor where gas lift is used and where the wellhead is located above sea level.

(2) Where a development well is located in a zone where permafrost is present in unconsolidated sediments, the operator shall install an SCSSV in the tubing at least 30 m below the base of the permafrost.

(3) An operator shall not operate a development well unless the specifications, design, installation, operation and testing of each SCSSV installed on the well are in accordance with API Spec 14A Specification for Subsurface Safety Valve Equipment, and the API RP 14B Recommended Practice for Design, Installation, Repair and Operation of Subsurface Safety Valve Systems.

(4) An operator shall ensure that every SCSSV installed in a development well is

(a) pressure tested forthwith after installation; and

(b) function tested at least once every six months after the test referred to in paragraph (a)."

In addition to the legislative requirement of SCSSV's, operators generally specify a requirement for a double barrier in wells that can sustain natural flow. Additional downhole safety barriers such as production packers, annulus, gas-lift and inflow control / safety valves are sometimes installed on wells and provide extra protection to SCSSV's in case of an emergency. These are, however, adopted as secondary failsafe system to SCSSV's for well completions and are not specified for all well completion systems. As a part of the Terra Nova Development Plan, it was specified that each well would have two barriers in the wellbore. These barriers will consist of a packer and a surface-controlled subsurface safety valve (SCSSV) in the tubing string of all wells. In addition, each well would have a master and an annulus valve in the subsea or insert tree. All valves were specified as being of a fail-closed design.

Prior to the development of Terra Nova, Petro Canada looked at the reliability of a single SCSSV during concept evaluation stages and decided to install two such valves on all production wells located at a depth of approximately 200m from mean seabed. Although the valves are highly reliable, a decision was made not to rely on these valves because in a situation where an iceberg makes contact with a wellhead, there would be concerns of the tubing being pulled/yanked and unable to maintain integrity of the well (S. O'Brien, personal communications, 2003).

4.3 Open Glory Hole

The open or uncased glory hole protection concept consists of a large depression excavated in the ocean floor (See Figure 23). The hole allows standard equipment such as wellheads and satellite Xmas trees or multi-well templates to be placed in the bottom of the glory hole below the potential scour depth of a large iceberg. Structures in these open holes are only affected by scouring icebergs, since the structures would not extend above the mudline. For this reason, icebergs should not impact the production equipment and remedial work should not be required.

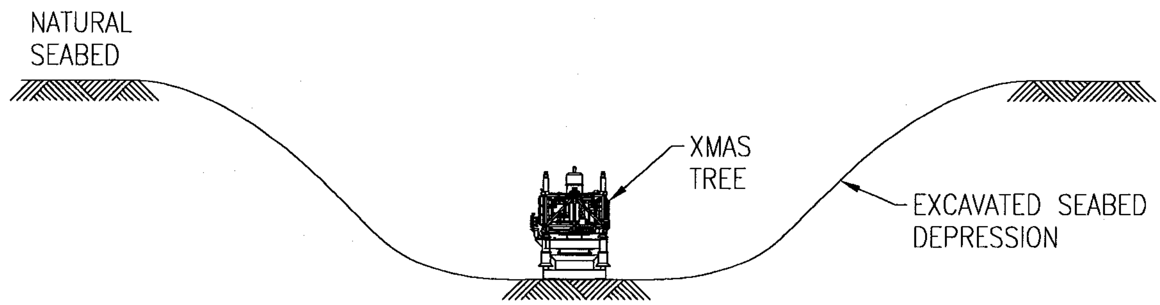

Figure 23 Open Glory Hole

The excavated depression is generally made large enough to allow for stable side slopes to insure stability of the soil. The glory hole should be sufficient to accommodate equipment requirements while at the same time provide adequate freeboard above the top of the equipment to allow for iceberg mechanisms such as scour, heave, pitch and rotation as it enters the hole.

Open glory hole excavation requires an extensive and costly construction period prior to commencement of drilling operations. A variety of factors such as soil conditions, water depth, environmental conditions and the remoteness of the work influence the overall cost of such excavations. A number of methods have been proposed and used over the years to excavate these holes; most of which have been developed for dredging of harbors, shipping channels and offshore diamond mining.

The history of open glory holes date back to early exploratory drilling in the Beaufort Sea during the late 1970's. The first 3.7m diameter bit was designed built and tested by Dome Petroleum Ltd. in 1978 as a glory hole excavation tool but met with limited success, however, the basic concept proved effective for excavating glory holes (Shields, 1994). Prior to 1982, glory holes excavated for the purpose of protecting subsea wellhead facilities from ice keel scour in the Beaufort Sea were completed entirely using large diameter bits deployed from drill ships. Since then, glory holes have been completed using a variety of dredging technology such as cutter suction, trailer and hydraulic grab dredging techniques (Stewart & Goldby, 1984). Three such excavation methods have been utilized to date on the on the Grand Banks of Newfoundland in order to successfully excavate a total of eight glory holes for both the Terra Nova and White Rose subsea development projects. Using an offshore construction vessel as its platform, large diameter reverse circulation drilling, trailing suction hopper dredging and clamshell grab systems have each been employed for the excavation of these glory holes with varying results.

The size of a glory hole depends on the equipment that is to be installed and this, in turn, depends on the number of wells that are to be completed within the glory hole. Base dimensions, for example, of the largest glory hole excavated for Terra Nova that consists of a 10 well multi-template system was 65m by 25m, roughly equivalent in size to a tennis stadium while the mudline dimensions reached up to 120m (Allen, 2000). Glory hole dimensions must be such to allow for sufficient space to install equipment and make flowline connections etc. In addition, a minimum clearance of approximately 3.5m around all equipment is required at the operational level to allow standard subsea completions and accommodate ROV access for routine visual inspection, operations and maintenance once the equipment is in place. These minimum dimensions will vary slightly depending on the type of equipment, subsea layout/architecture and ROV specification.

Glory hole depths depend on the height of the structure placed in the glory hole, since the clearance above the structure is the main consideration. The required depth of a glory hole for the Grand Banks region is in the order of 9m to 10m, which is the necessary depth to allow minimum height of the conventional wellheads above the seabed with a margin of several meters to allow for iceberg scour and other iceberg movement mechanisms such as heave as it enters the glory hole.

Excavation of side slopes is dependant on both practical requirements and soil stability. Glory holes excavated in the dense soil conditions of the Grand Banks have been excavated with side slopes of 3:1 (horizontal:vertical) and steeper. To facilitate the installation of flowlines and umbilicals, one of the four sides can be constructed with a more gradual slope of 5:1, commonly called a “Ramp”.

C-CORE (1997) conducted a study into the behavior of icebergs entering an open glory hole. A force equilibrium model of icebergs during steady state scouring of the seabed was combined with a model of transient motion to estimate the maximum penetrations of iceberg keels below the mudline for icebergs encountering deep open glory holes. The model results indicate that significant reductions in the probability of a scouring iceberg keel contacting seabed facilities can be achieved by placing those facilities in deep open glory holes.

Although a variety of research has been undertaken relating to the adequacy of glory holes, the value of these depressions in the seabed are questionable because of the potential for rubble to be pushed ahead of the large ice structures as it scours the seafloor. Equipment is still potentially susceptible to damage by scour debris and penetration by an unstable iceberg, which can heave, pitch and roll into it. In addition to the uncertainties relating to iceberg scour, these depressions do not provide protection from anchors or fishing net damage.

4.4 Cased Glory Holes (or Submarine Silo)

Cased glory holes and submarine silos are similar in concept to open glory holes but allow a much reduced excavation volume by use of a reinforced casing or cylindrical structure (steel or concrete) around the hole perimeter (See Figure 24).

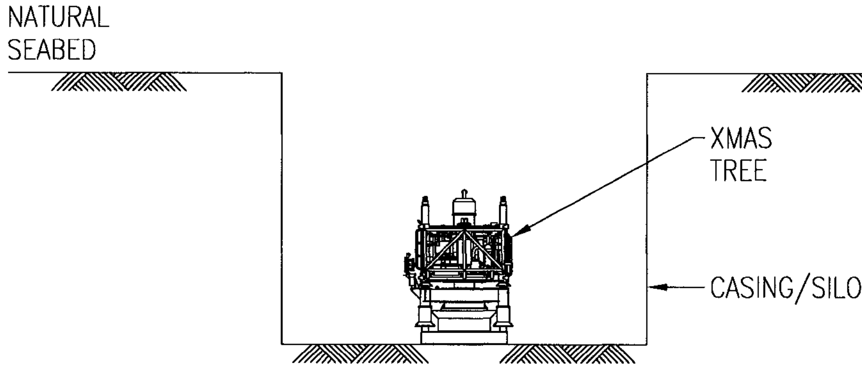

Figure 24 Cased Glory Holes (or Submarine Silo)

Cased glory holes and submarine silos integrate a casing or cylindrical structure set at a depth that provides protection and adequate clearance below the seafloor for the wellhead and Xmas tree that will be placed inside. The casing structures for some concepts extend slightly above the mudline, exposing it to contact from scouring, as well as freely floating icebergs with drafts between the water depth and the top of the structure. The upper section of the casing has been traditionally isolated by a weak shear joint located at a pre-determined elevation below seabed level. In the case of iceberg impact, the casing is sheared at the weak joint and the upper section of the casing is sacrificed, leaving the lower section of the casing, wellhead and Xmas tree intact. An iceberg impact would break the glory hole casing at the shear point, leaving the bottom part intact and the production tree and wellhead undamaged. The cased glory hole or silo is expected to be reusable after impact. Remedial work could consist of cleaning up the debris in the cased glory hole, installing a new top section of glory hole casing, and reconnecting flowlines and umbilicals. In addition, a roof can be provided to protect the conventional trees against dropped objects, dragging anchors, fishing gear and natural silting.

The cased holes or silos are large diameter cylindrical structures, typically 6m to 10m in diameter and up to 20m in depth. The purpose of the casing is to make the hole less vulnerable to sloughing, ravelling and sand deposition. The internal diameter of the cased hole will be large enough to accommodate the tree as well as provide necessary ROV access.

Installation can be carried out from a drilling rig or other construction vessel types. The cased holes can be installed prior to or during drilling operations. Systems developed to excavate cased glory holes and submarine silos include reverse circulation drilling that makes use of large diameter drilling technology borrowed from the mining and tunneling industries. Other installation techniques such as jetting and suction anchor technology can be adopted for areas where the soils are relatively soft and homogeneous; however, these systems are not practical for general conditions encountered on the Grand Banks.

The first commercial well drilled from a floating drilling platform using a cased glory hole system that was developed by Tornado Drill® and Gulf Canada. The 7.3m diameter cased glory hole for Gulf's Amauligak 0-86 well was drilled from the Kulluk during June of 1988 to a depth of 13.6m and took 12.5 hours to complete (Gilbert et al., 1989).

The silo concept for the Grand Banks was first investigated by Mobil for their use on the Avalon development at Hibernia to house subsea wellheads. A silo was drilled by the drilling contractor Sedco on one of the Hibernia appraisal wells (Ames et al., 1987). During the summer of 1990 a field trial to assess the feasibility of using the Tornado Drill® technology on the Grand Banks demonstrated that a cased glory hole system could potentially be used for the Terra Nova Field development. During this campaign, two attempts were made to excavate a cased glory hole from the Sedco 710 semi-submersible drilling unit at the Terra Nova O-90 location. The system called for installing a 7.3 m diameter steel casing by mounting a large-diameter drill bit in the bottom of it and drilling the bit and casing into the seafloor to a depth of 10 to 12m. A combination of time constraints, procedural and mechanical problems halted the program at a depth of 9.4m before the planned drilling depth was reached and the full casing was installed (Gilbert and Hampton, 1990).

Based on innovations developed for the Beaufort Sea exploratory wells, the first submarine silo structure in the North Sea for the protection of wellhead and Xmas tree equipment was successfully installed in 200m of water during the summer of 1993. The structure was developed by Saga Petroleum a.s for protection of one water injection well on the Tordis Field from heavy trawl and fishing activity in the region. The silo consists of a 9m diameter, 7.7m high steel cylinder and it was penetrated 6.5m into the seabed. The 1.2m section which remained above the seabed were chamfered to make the unit overtrawlable (Guttormsen & Wikdal, 1994).

NAOEA (1996) conducted a study relating to the technical design aspects of a subsea silo type structure for wellhead protection and the findings indicated that interaction loads of massive icebergs were found to be in the order of 10-30 MN with significant downward components as well as horizontal. Another significant result of the numerical modeling is that the load on the keel of the iceberg may cause it to become unstable and if the berg were to capsize on top of a silo it is very doubtful that any practical structure could withstand the impact. Controlled failure schemes, such as the weak shear joint concept, may be effective for cased holes mounted at the seabed level under horizontal loading. However, this study indicates that the possible rotation of marginally stable icebergs would seriously damage any object with which it comes in contact.

The cased glory hole or silo system can be adapted to any field size or configuration but is particularly suited to single satellite and clustered wellheads. Standard Xmas tree design can be used, thus making use of proven technology. The hole must also be large enough to accommodate a BOP during the drilling phase but small enough to be run through the moon pool of a designated semi-submersible drilling rig or construction vessel.

Concepts proposed by Ames et al. (1987) and Gilbert et al. (1989) have multi-well drilling and completion templates that can accommodate wellhead and tree assemblies positioned inside large silos or cased holes ranging from 6.1m to 15m in diameter respectively.

Potential refinements to existing concepts could include installing the structure such that the top of the casing / silo is below the maximum scour depth, which would essentially eliminate the shear joint and upper casing segments. To protect the equipment below from scour debris for systems that have a shear joint, an inner protective shield above the tree can be added to reduce damage and make the task of cleanup following a scour much easier.

4.5 Caisson Wellhead System

The caisson wellhead system avoids the need for large-scale excavation of the seabed as required for the open and cased glory hole concepts. The approach places those components essential to the integrity of the well inside a caisson, at a depth below the mudline as to provide permanent protection against environmental and reservoir damage from icebergs. It differs from the conventional subsea production tree in that the caisson tree is divided into a lower and upper tree assembly. The design provides for installation of an insert tree containing lower master control valves installed on the critical wellhead components inside a larger than normal casing beneath the seafloor and below expected scour depth. The large casing is used to provide access for the wellhead connector and the lower tree valves. It uses modified drilling equipment to establish a wellhead to a depth of up to 20m meters below the seabed (See Figure 25).

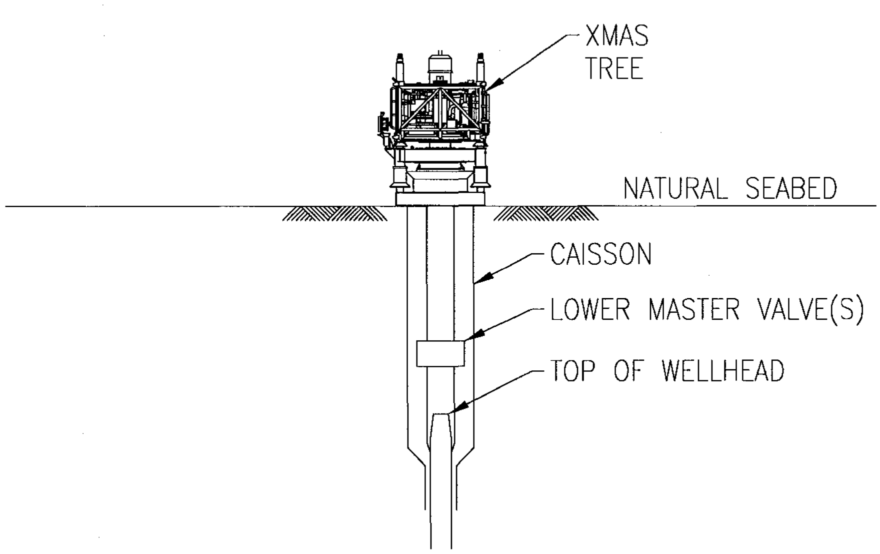

Figure 25 Caisson Wellhead System

Wellhead caissons will require the remaining tree functions to be exposed at seabed level but this surface equipment is limited to acceptable sacrificial components such as the drilling guide base and upper valve block and production tree. Because the upper tree portion stands proud of mean seabed level, the caisson wellhead system will be threatened by both freely floating and scouring icebergs. The seafloor tree portion of the caisson completion can be protected against dropped object protection, dragging anchors, fishing gear and natural silting by use of protective covering.

The caissons are designed to have a weak shear point in the well bore casing located at a pre-determined location below the seabed (typically equal to that of the maximum anticipated ice scour) to minimize damage to the insert tree. In addition, a breakaway flange above the master valve block can be incorporated to reduce the amount of damage during the shearing process. In the event of iceberg impact, the upper well bore casing and Xmas tree are sacrificed, while leaving intact the hydraulically operated failsafe lower production and annulus master valves and wellhead. If a caisson well were damaged from iceberg impact, remedial work would consist of removing the surface debris, dredging around the wellhead to gain access, and re-entry. If the well could not be re-entered, another well would have to be drilled to abandon the caisson well.

Installation of these systems is carried out from a conventional drilling rig as a part of the normal drilling program. However, special running tools and consumable caisson materials are required.

Caisson wellhead systems were originally conceived to protect against fishing gear damage. The first 0.762m (30 in.) diameter caisson completion system was installed in 1981 in the South China Sea. Two 0.914m (36 in.) diameter caisson drilling systems were also installed on the East Coast of Canada in 1983-84 (McIntosh et al., 1987). Since then five applications of this concept have been adopted on the Grand Banks to protect wellheads from iceberg scour protection. As a part of the Terra Nova Field exploration program, Petro-Canada used caisson wellhead systems on five suspended delineation wells drilled between 1985 and 1988. The high-pressure wellheads were placed in 1.067m (42 in.) diameter steel caissons, 21 m below the seafloor. The five existing caisson wells have been drilled and tested in a manner suitable for re-use and can potentially be completed as production wells, complete with gas lift capability when the appropriate time arises or when the field is proven to be commercial.

In comparison to the mudline profile of conventional Xmas trees, which stand approximately 7-8m in height, the seafloor tree portion of a Caisson completion maintains a low profile at 3-4m thus reducing the risk of impact with free floating icebergs.

CFER (1988) undertook a study for Petro-Canada Resources in order to investigate the collapse behavior of the existing 1.067m caisson completion systems and to assess the effectiveness of the system in protecting components essential to the integrity of the wellhead against damage that could result from various iceberg-caisson interaction scenarios. Using a relatively unsophisticated analytical approach, the findings indicated that if all of the variable parameters associated with caisson collapse strength and soil properties are favorable, the weak joint will act as intended and the wellhead will be protected in the event of collision with a translating iceberg. However, the potential variation in caisson strength and soil parameters is sufficient to suggest that, in some situations caisson collapse and subsequent wellhead damage could occur before load relief is achieved though weak joint separation. Load application in this study was restricted to an assumed maximum ice scour depth of 2.5m below the mudline.

Exploration wells that are located in iceberg-infested waters such as the Grand Banks have been traditionally abandoned after testing, mainly because the wellheads have no protection against iceberg impact. If a caisson wellhead is used and the well is successful, the well will initially be suspended and later re-entered for production. This is one key advantage to this type of system as it allows the exploration wells to be used for a later development. Obviously the use of a caisson wellhead system results in an incremental cost associated with additional rig time and equipments that must be borne at the time of drilling. The cost of drilling wells on the Grand Banks and the likelihood of future subsea development now justify retaining certain exploration wells for further testing and/or completion.

Because the production tree is located at mudline level, there is good ROV access for routine visual inspection, operations and maintenance. This however is a trade-off between the inaccessibility of the insert tree consisting of the lower master valves, which give rise to many service and maintenance concerns.

4.6 Protective External Barrier

External barriers can be developed by use of a number of materials including rock berms and rigid retaining structures made of steel and/or reinforced concrete. Protective barriers, located at the mudline, are essentially constructed or installed around the wellhead and Xmas tree to shield the equipment inside by either blocking or grounding the freely floating or scouring icebergs (See Figure 26).

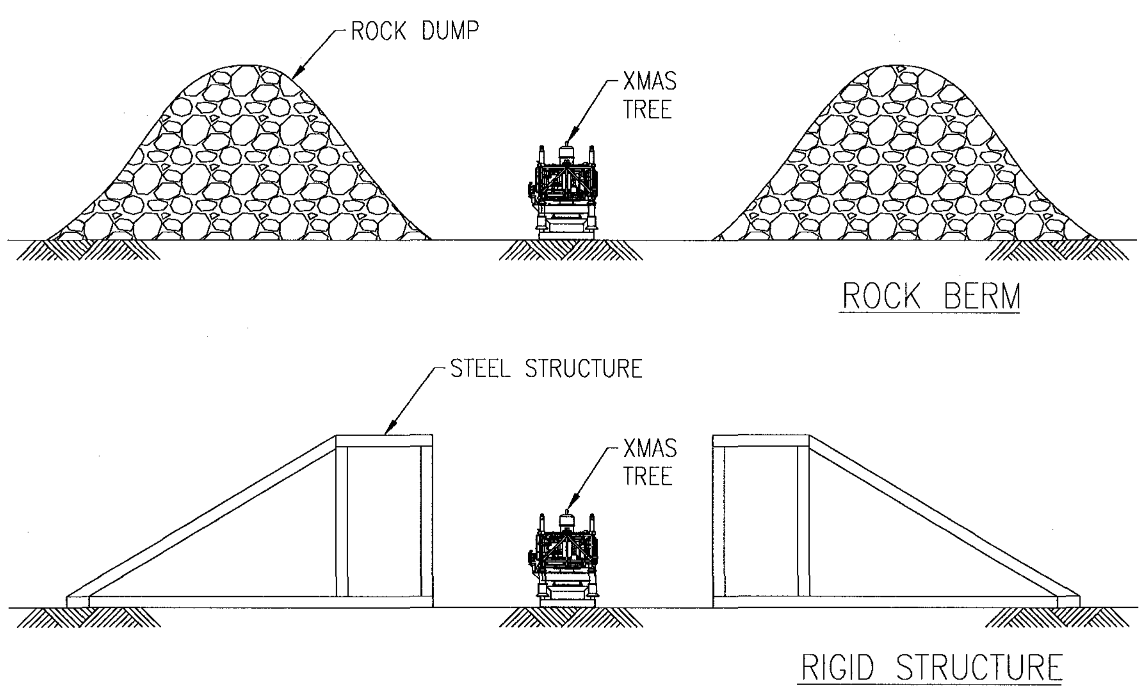

Figure 26 Protective External Barrier

Submerged rock berms are constructed walls on the seafloor formed by the dumping of rock material onto the seabed. The protection philosophy simply implies that by building rock barriers around an installation to be protected, the free floating or scouring iceberg is halted in its path and unable to penetrate the berm to cause damage to the installation. One of the main problems with this protection concept is that scouring icebergs always have to start moving again and has potential to work its way through the berm and enter the protected area.

Global forces developed due to the impact of very large icebergs on fixed subsea structures such as these are in the order of 100's of MN's. Whereas External Barriers are considered to be technically possible, the associated costs are considered prohibitive and are not feasible on economic grounds alone. Massive structures requiring extensive offshore installation campaigns are required. Further uncertainties such as the selection of ice load design criteria for such structures and the use of unproven technology make this option unattractive to local oil & gas operators. In addition, protective barriers offer a limited amount of protection from anchors or fishing activities and in general are susceptible to greater levels of risk in comparison to other protection concepts because they sit proud of the mudline and occupy large areas.

4.7 Novel Concepts

In addition to the existing wellhead protection concepts, a number of novel concepts are briefly presented below. Some of the concepts are variations or hybrids/extensions to existing concepts while others are novel in their own right.

4.7.1 Suction Anchor Technology or/ Large Diameter Driven Caisson

Using existing technology such as suction anchors or large diameter caissons could technically provide a practical solution for iceberg protection. The concept itself is essentially a deviation to the Cased Glory Hole / Silo concept (see Figure 27). However, due to the dense soil conditions and high presence of cobbles, boulders and hardpan, this concept is deemed not practical for Grand Banks region. In addition, installing this concept would prove to be expensive since it would require an extensive offshore campaign, involving a number of offshore equipment spreads (i.e. pile driving and soil excavation spreads).

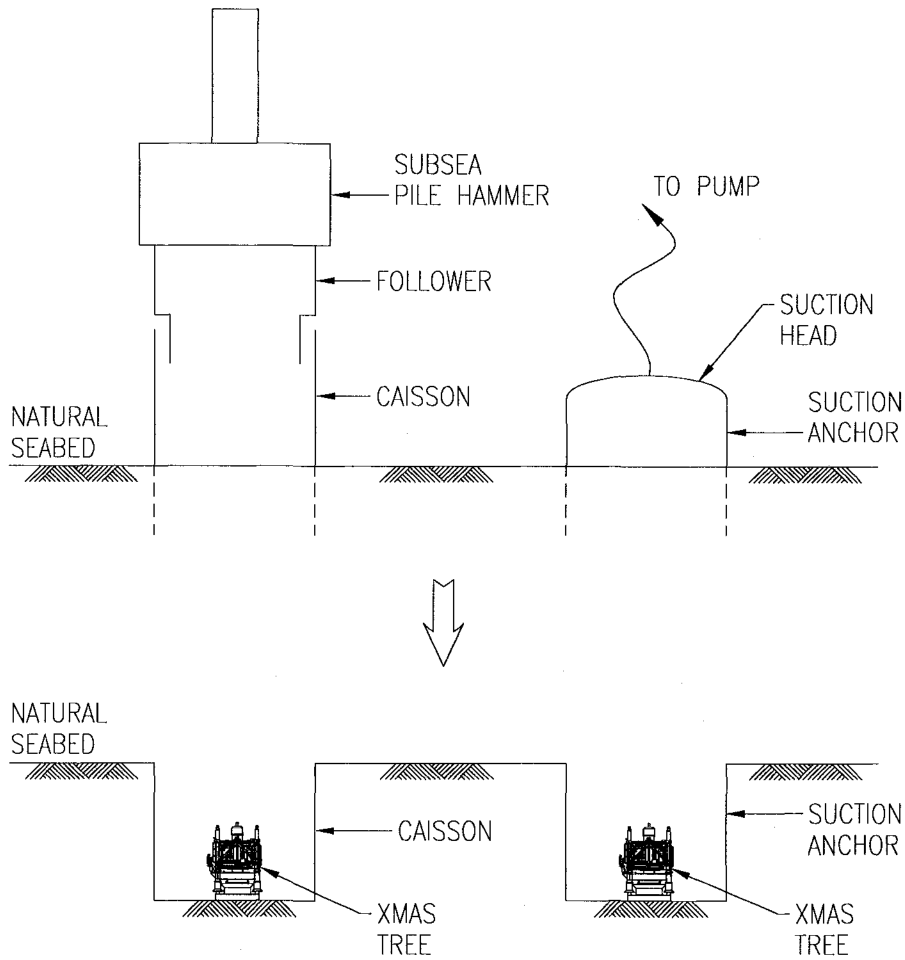

Figure 27 Suction Anchor Technology or/ Large Diameter Driven Caisson

4.7.2 Large Diameter Driven Pile Barrier

Utilizing large diameter driven piles to protect a wellhead situated at seabed level is essentially a deviation to Protective External Barrier concept (see Figure 28). Although this concept provides a practical solution to wellhead protection, there are a number of technical issues relating to its ability to resist against local and global iceberg impact forces. Due to the highly variable soil conditions and presence of boulders, there is also a moderate to high risk of encountering pile refusal during installation activities. As with the protective external barrier, this concept would require an extensive installation campaign requiring a large offshore construction vessel and associated equipment spread. In addition, materials costs for large diameter piles are relatively high.

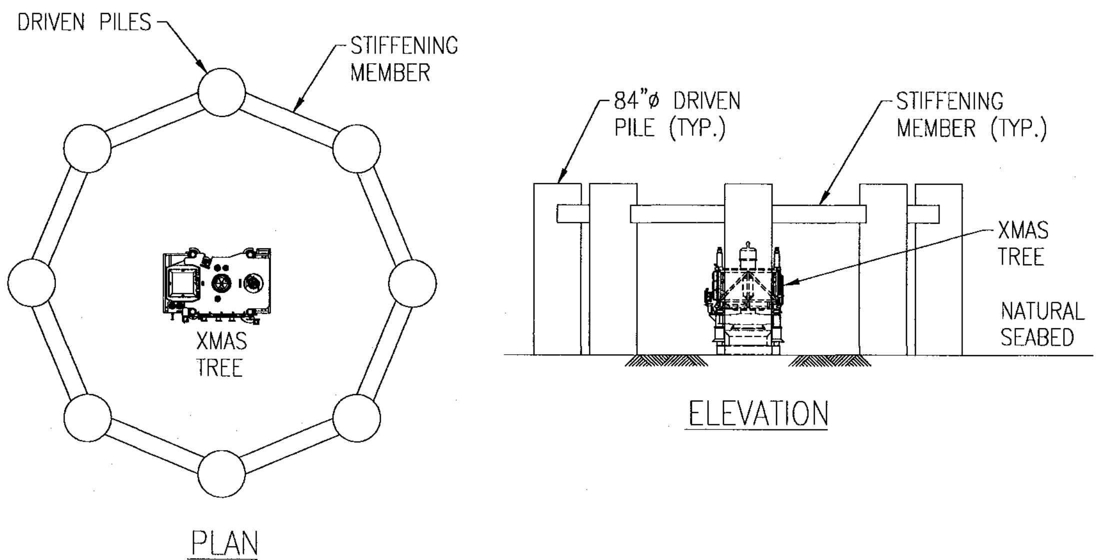

Figure 28 Large Diameter Driven Pile Barrier

4.7.3 Bowling Alley

The Bowling Alley concept is essentially a deviation from the traditional Open Glory Hole but allows for a minimized excavation volume by situating the manifold outside of the excavated hole (see Figure 29). The concept is most appropriate for multi-well developments and assumes that the manifold located at the mudline is sacrificial. Excavation of the seabed depression is ideally suited to trailer hopper suction dredging technology already proven in the area. One big drawback of this concept relates to the possibility of the trench becoming a routing guide for a scouring iceberg. Thus, in the case of a scouring iceberg there is an overall increase in risk of contact to multiple wells for any single iceberg event.

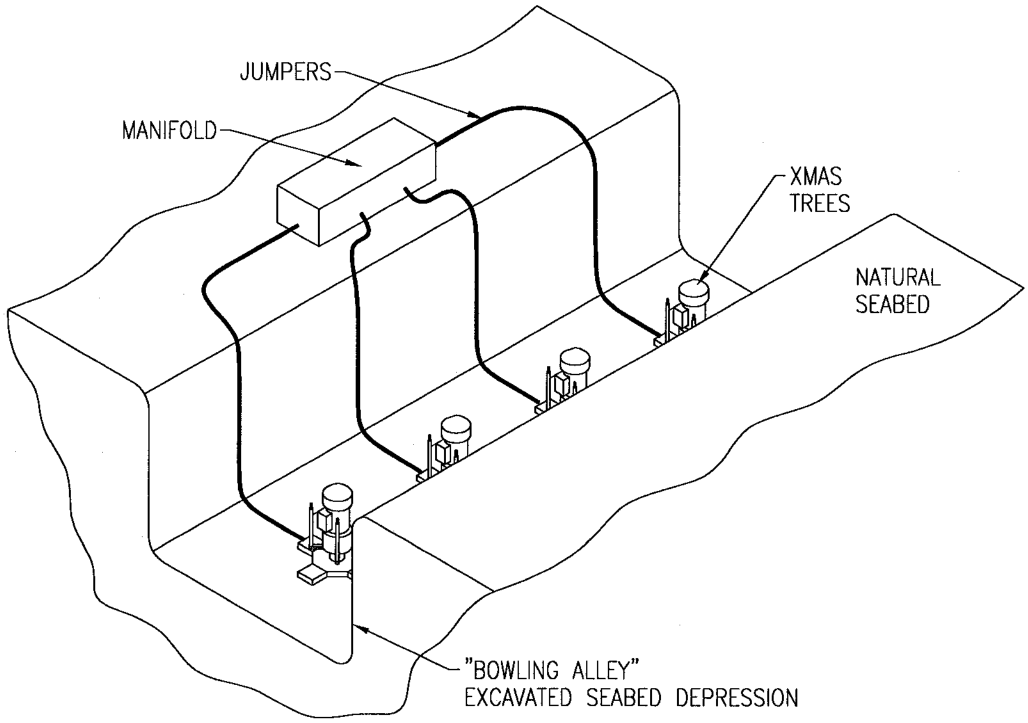

Figure 29 Bowling Alley

4.7.4 Bathymetric Shielding

The simplest of all novel concepts, bathymetric shielding eliminates any requirements for conventional wellhead protection as illustrated in Figure 30. This concept utilizes existing depressions / undulations in the seabed for protection against icebergs and takes into account predominate drift direction for icebergs in the general development region. Although this concept offers huge development cost savings, it is site specific and depends entirely on the seabed condition at the proposed development area. Decision-making relating to this concept relies heavily on iceberg data such as iceberg drift direction, drift speed and scour depth collected for the proposed region.

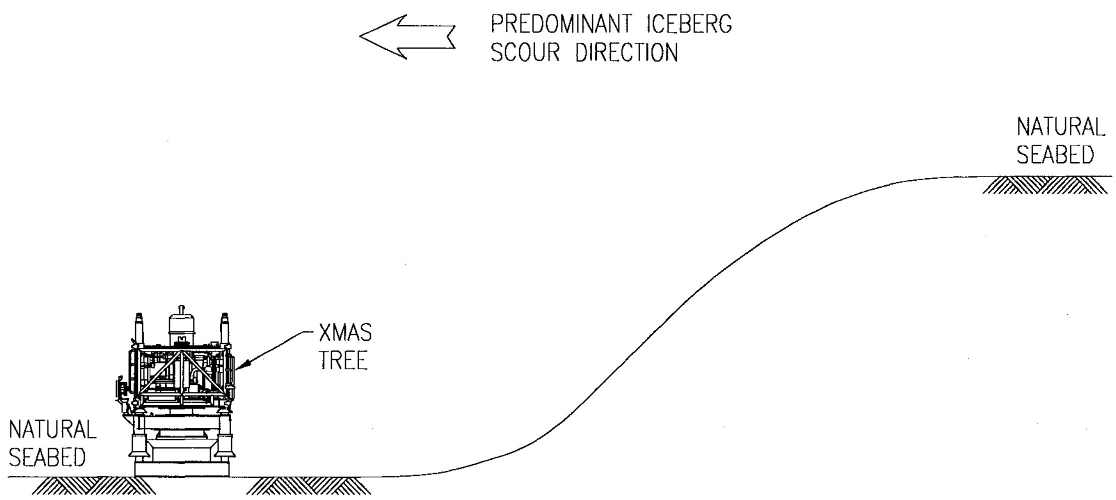

Figure 30 Bathymetric Shielding

4.7.5 Explosives

Considered as an alternative excavation method for the open glory hole, the use of explosives could potentially offer cost savings during the installation phase by allowing the hole to be created in a very short period of time (see Figure 31). However, the hole formed after detonation will require extensive remedial work to condition bottom of hole suitable for placement of subsea equipment such as manifolds and Xmas trees. Although considered as a technically feasible solution, this concept will however struggle to meet local environmental regulations and is thus considered not a viable alternative.

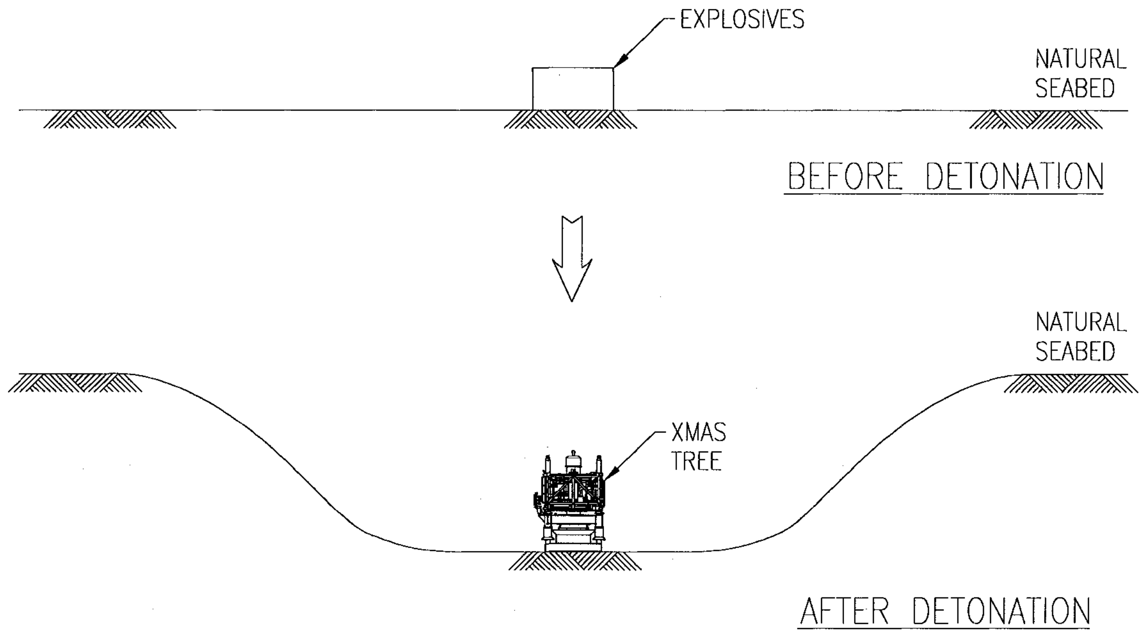

Figure 31 Explosives

4.7.6 Conventional Xmas Tree With Downhole Weak Shear Joint

This concept is a modification to conventional Xmas tree installed at seabed level whereby a downhole weak shear joint is incorporated into the well conductor pipe (see Figure 32). The incorporation of a weak shear joint essentially minimizes the downhole structural response in event of iceberg contact to Xmas tree/wellhead and thus increases the probability of proper SCSSV functionality. The concept eliminates the need for onerous wellhead protection requirements and assumes that the Xmas tree located at the mudline is sacrificial. Although there are some additional costs associated with installing a conductor with a weak shear joint, there are huge development cost savings when compared with other concepts. In addition, conductor weak shear joints have been successfully installed on appraisal wells previously drilled on the Grand Banks.

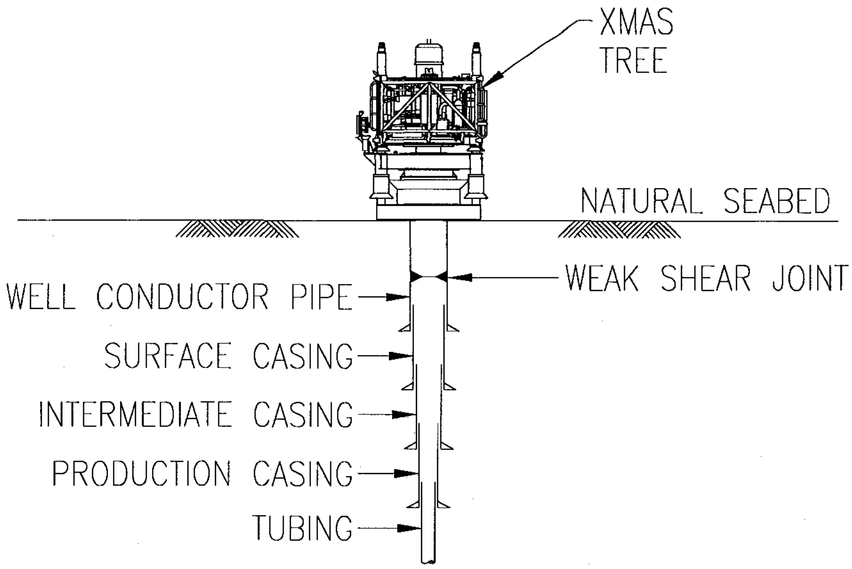

Figure 32 Conventional Xmas Tree With Downhole Weak Shear Joint

4.7.7 Modified Cased Hole

As presented in Figure 33, the modified cased hole incorporates features in order to improve the functionality of the overall concept. The modified concept eliminates the existing casing shear plane and upper casing segments by incorporating sloped excavated sidewalls for the upper portion of the casing under threat from iceberg scour. Depending on the soil conditions, soil reinforcement fabric may be required to stabilize the upper side slopes. The addition of an inner protective shield above the tree can also be incorporated to reduce damage in the event of a scour and make the task of cleanup following a scour event much easier. Installation and material costs for this modified version would be only slightly greater than the original design.

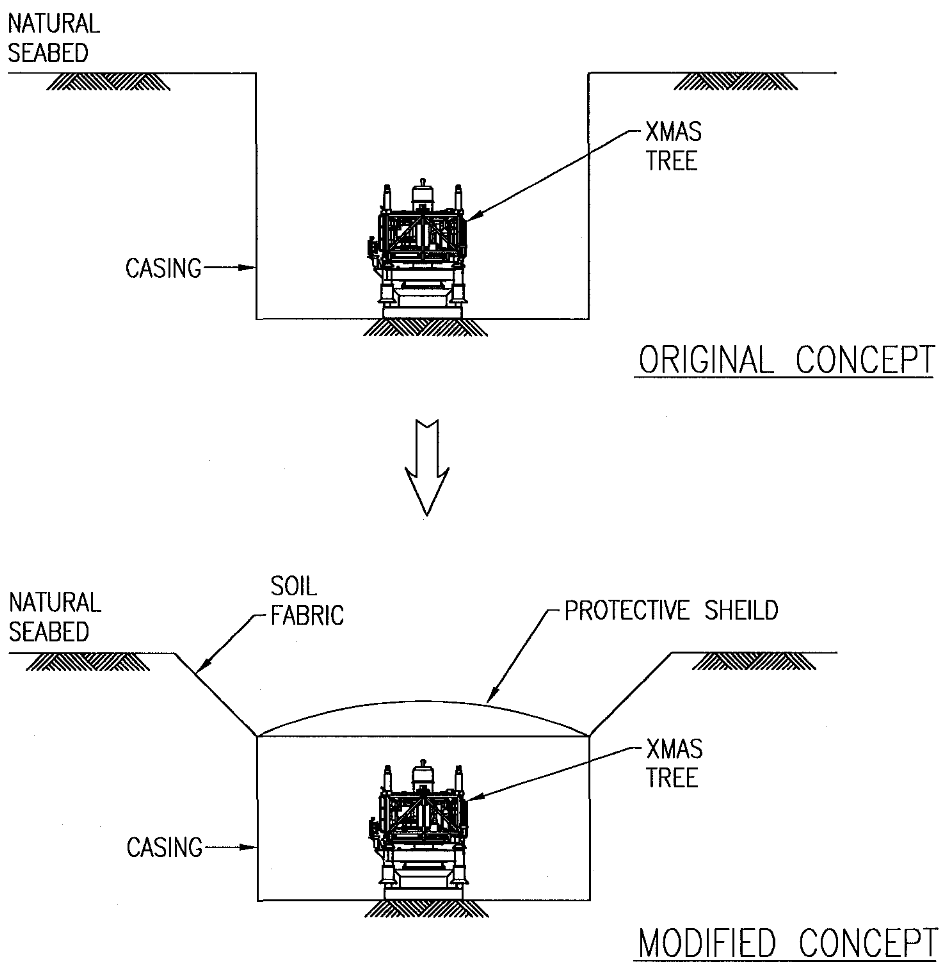

Figure 33 Modified Cased Hole

5.0 RISK ACCEPTANCE CRITERIA

5.1 General

Due to the fact that Grand Banks is situated in an area prone to icebergs, there is significant concern relating to interaction of icebergs with subsea equipment. In order to evaluate whether the inherent risks for various subsea wellhead protection concepts are tolerable, acceptance criteria must be established to serve as a baseline. Establishing acceptance criteria relating to levels of risk is not a straightforward process. Consideration must be given to both frequency and consequence of an event occurring.

In the case of subsea wellhead protection, the greatest concern lies with high potential for pollution and damage to the environment rather than loss of life. Major environmental consequences can result if a subsea blowout occurs, however, subsea wellhead failure does not usually lead to serious consequences with regard to human life.

Risk acceptance criteria (RAC) is generally used to express a risk level that is considered tolerable for a given activity. The RAC constitute a reference for the evaluation of the need for risk reducing measures and should be available prior to commencing any risk analysis (NORSOK, 2001). Before establishing an acceptable level of risk relating to wellhead protection for the Grand Banks region, some general background is necessary and an overview of the following relevant areas has been undertaken:

- General Levels of Risk
- Regulatory Requirements

- Existing Risk Criteria for the Grand Banks
- Codes and Standards

5.2 General Levels of Risk

Risk is composed of two elements, frequency and consequence and can be defined as the product of the frequency with which an event is anticipated to occur and the consequence of the event's outcome. Risk to personnel is often defined in terms of the annual probabilities of injury and fatality for an individual. In our everyday life we face many risks that are impossible to avoid and are a result of our everyday activities. As a common example, the individual risk (IR) of a personal causality while driving 10,000 miles per annum is in the order of 1 in 10,000 (1×10^{-4}) in any given year. This type of risk is applicable to the general public where the risks are "involuntary" and exist as a part of our society.

For a person working at a work site, a higher risk level is generally tolerable because they gain from being employed at the site – this is "voluntary risk". The risk to individual workers may easily be as high as 1×10^{-3} per year or more. Recent publications such as Wells (1996) as presented in Table 7, provide a summary of target risks that serve as a good guideline for the level of risk to the individual acceptable in a working environment.

Table 7 Risk Values Recommended by Wells (1996)

Description	Target Values of Maximum Risk Not to be Exceeded
Employee Individual Risk	
All Process Causes	10^{-4} per year
Specific Process Causes	10^{-5} per year
Public Individual Risk	
All Process Causes	10^{-5} per year
Specific Process Causes	10^{-6} per year
Risk of Major Incidents (societal risk)	
Near Miss from All Process Causes	10^{-4} per year
Accident from All Process Causes	10^{-5} per year
Catastrophic Accident from All Process Causes	10^{-6} per year
Accident from Specific Process Causes	10^{-6} per year
Catastrophic Accident, Specific Process Causes	10^{-7} per year

In the case of an offshore system, the total risk may include causes such as fire, ship collision, capsize, and wave loads in addition to ice loads. Statistics that relate to the offshore oil and gas industry provide a general indication as to the level of risk associated within that industry. Until recently, there have been no offshore production operations off the East Coast of Canada, so there is no track record that can be used to determine a suitable criterion for IR. However, other industries in Canada and North America, and offshore industry in other parts of the world have been examined to assist in setting realistic targets. Historical average IR's for the offshore industry based on data from the Norwegian and UK sectors of the North Sea (excluding the Piper Alpha data) are summarized in Table 8. It must be noted that the Piper Alpha disaster statistics has a significant affect on the historical IR levels. It has been neglected by industry because it is believed that this was a "once off event" and would lead to higher levels of risk for establishing risk criteria.

Table 8 Historical Average Individual Risk Data (Husky, 2000)

Occupation	Average IR (Excluding Piper Alpha)
Construction	1.05×10^{-3}
Drilling	8.76×10^{-4}
Production	8.76×10^{-4}
Maintenance	1.93×10^{-3}
Diving	2.19×10^{-3}
Cranes	2.72×10^{-3}
Domestic	1.75×10^{-4}
Average	$\mathbf{1.4 \times 10^{-3}}$
Source: Norwegian Petroleum Directorate (NPD) and the UK Department of Energy's annual Brown Book	

Similarly, upon review of the data presented by the Worldwide Offshore Accident Database (WOAD, 1998), risk levels to the individual are in the order of 10^{-3} per year. This data includes information on both mobile and fixed offshore units such as jackups, semi submersibles, jacket structures and tension leg platforms. Many of the accidents/incidents are associated with drilling operations, and greater than half of the fatalities were associated with this activity in the years 1980-1997.

In making design decisions relating to risk, it is important to consider both the probabilities and consequences of the events of importance. In the context of this thesis, major consequences can result if a subsea blowout occurs, which is of main concern when it comes to subsea wellhead protection. This type of risk is commonly termed environmental risk (ER) and can be measured in terms of the amount of oil spillage associated with various accident scenarios along with the likelihood of these scenarios.

Frequency data for accidental spill/release statistics for all units worldwide published by WOAD (1998) indicate that rates for large oil spills (1,000 to 10,000 tonnes) is less than of 10^{-3}. Spill frequency is best expressed in terms of a risk exposure factor based on the number of oil wells drilled or billion of barrels of oil produced. If a major spill is defined as 150,000 barrels or larger, five such spills have occurred in the history of worldwide offshore drilling. This represents a frequency of oil well blowout spills greater than 150,000 barrels of 9.4×10^{-5} per well drilled, or 1 such spill for every 10,600 wells drilled (Petro-Canada, 1998).

5.3 Regulatory Requirements

As a result of the accident on Piper Alpha on the 6th of July 1988 when 165 people died, a public enquiry was held under the chairmanship of Lord Cullen. The recommendations from the Cullen Report lead the UK offshore oil and gas industry into adopting a 'Safety Case' regime characterized by an acceptance that the direct responsibility for the ongoing management of safety is the responsibility of the operator and not the regulator. This risk-based approach stipulates that the operators be required to demonstrate to the regulator (make a 'case') that they are controlling their risks properly and doing everything 'reasonably practicable' for safe operation.

One of the objectives of a 'Safety Case' is to demonstrate that risk from potential major accident events has been reduced to a level "as low as reasonably practicable" (ALARP). ALARP expresses that the risk level is reduced (through a documented and systematic process) so far that no further cost effective measure is identified. The requirement to establish a cost effective solution implies that risk reduction is implemented until the cost of further risk reduction is grossly disproportional to the risk reducing effect (NORSOK, 2001). The ALARP principle (see Figure 34) used for risk acceptance is applicable to risk to personnel, environment and assets alike.

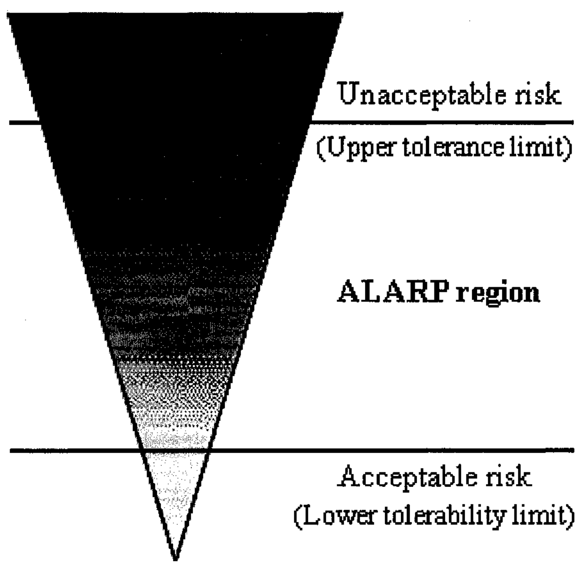

Figure 34 The ALARP Principle (NORSOK, 2001)

Like the UK offshore, regulatory bodies in Canada have adopted a similar approach. For oil and gas developments off the Grand Banks, all operators must fulfill the requirements as stipulated by the Canada-Newfoundland Offshore Petroleum Board (C-NOPB) under the Newfoundland Offshore Petroleum Installations Regulations. The Installation Regulations, under Section 43 (3) and (4), require that:

"(3) Target levels of safety for the risk to life and the risk of damage to the environment associated with all activities within each phase of the life of the production installation shall be defined and shall be submitted to the Chief at the time the operator applies for a development plan approval.

(4) The target levels of safety referred to in subsection (3) shall be based on assessments that are

(a) quantitative, where it can be demonstrated that input data are available in the quantity and of the quality necessary to demonstrate the reliability of the results; and

(b*) qualitative, where quantitative assessment methods are inappropriate or not suitable."*

In addition, the C-NOPB proposes guidelines that provide an outline as to what should be contained in a Safety Plan. A Safety Plan has to be submitted to the C-NOPB by the operator as a prerequisite to obtaining an authorization to conduct petroleum related work or activities in the Newfoundland Offshore Area. The Operators Safety Plan Guideline under Section 2.1, states that:

"One of the goals of the Safety Plan should be a demonstration that the "Target Levels of Safety" submitted as part of the Development Plan have been met and

that risks have been reduced to a level that is as low as reasonably practicable. However, as the targets referred to above apply to major hazards identified at the development concept phase, additional information should be included to demonstrate that all significant risks have been considered and are as low as reasonably practicable."

5.4 Existing Risk Acceptance Criteria for The Grand Banks

Petro-Canada's Target Levels of Safety for the Terra Nova project (Petro-Canada, 1998) describes the acceptable risk levels for incidents related to Terra Nova on an annual basis. Within the Target Levels of Safety requirements, Petro-Canada has essentially adopted the ALARP framework. This framework prescribes 10^{-4} as a minimum tolerability for safety level events with the goal that annual frequencies meet or exceed 10^{-5} annually. Risk for the Terra Nova project should therefore be mitigated at levels above 10^{-5} where practicable, and justification provided where not possible to do so. Table 9 illustrates the upper and lower bounds for risk within this ALARP framework.

Table 9 ALARP Requirements for Terra Nova (Petro-Canada, 1998)

	For any single incident	For all incidents
Intolerable	Greater than 1×10^{-4} per year	Greater than 1×10^{-3} per year
ALARP Region	From 1×10^{-4} to 1×10^{-5} per year	From 1×10^{-3} to 1×10^{-4} per year
Lower band of tolerability	Less than 1×10^{-5} per year	Less than 1×10^{-4} per year

Further to this risk base criteria, the relevant risk levels associated with this investigation relate to temporary ecological damage. Temporary Ecological Damage criteria are considered paramount in the analysis of iceberg impact risks described in this report because of the potential for hydrocarbon loss and blowout, should impact occur. Major hazard environmental risk is expressed in terms of the 'frequency of oil spills in excess of 50 barrels'. Petro-Canada's target levels of safety state that the frequency of release causing temporary damage to the ecological system in the exposed areas, shall be 1×10^{-4} per year for an individual incident and 1×10^{-3} for all incidents.

Similar to Terra Nova, Husky Oil has adopted the ALARP framework for its White Rose project but has imposed more stringent requirements. Target levels of safety for individual risk used for the White Rose project are summarized in Table 10.

Table 10 ALARP Requirements for White Rose (Husky, 2000)

Level	Individual Risk	Description
Intolerable	$IR > 10^{-3}$	Unacceptable, risk control measures must be taken
ALARP	$10^{-3} > IR > 10^{-6}$	It must be demonstrated that all practical means of risk reductions have been employed to ensure that the risk is as low as reasonably practicable
Negligible	$IR < 10^{-6}$	No need to consider further safety measures (For example an IR of 10^{-6} means that there is a 0.000001 probability of fatality per year for an individual on the installation)

For design purposes, a "trigger" value of 50 barrels has been defined by both Petro-Canada and Husky. For an ecological event(s) resulting in hydrocarbon loss to the environment in excess of this criterion, the scenario must be designed out. As for Terra Nova, scenarios for White Rose (of spills > 50 barrels) that cannot be designed against should be demonstrated to have an aggregate frequency of $< 1 \times 10^{-3}$ per year.

It should be noted that for ER, specific risk criteria cannot generally be quantitatively defined because of the very nature of possible routes to environmental impairment that are difficult to assess using subjectively generated probabilities (Husky, 2000). Where quantitative predictive methods allow, the expected oil spill frequency for actual operations, for example, iceberg scour collision damage to a subsea wellhead, can be compared with historical experience to determine whether the risk of oil spill is significantly different. These risks can be managed and reduced using practicable methods such as incorporating wellhead protection techniques into the design and adopting iceberg management systems.

5.5 Codes and Standards

Structures are generally designed to meet specified standards as set out in national codes. These codes are developed to insure adequate levels of safety to personnel and to the environment, and are developed in consensus by industry, government, and other interest groups.

As outlined above, the C-NOPB defines regulatory requirements for the Grand Banks. Their rules refer to Canadian and international offshore standards extensively. Unfortunately, there are no codes, standards or regulations that specifically deal with ice effects on sea floor facilities such as wellheads. Allyn (2000) undertook an extensive study relating the use of codes for ice loads and structures on the Grand Banks and concluded that the Canadian Standards Association (CSA) offshore codes provide the best design guidance relating to the Grand Banks ice issues.

The standard produced by CSA titled: *S471-04 General Requirements, Design Criteria, the Environment, and Loads*, was reviewed in detail. The standard sets forth requirements and guidance on design principles, safety levels, and loads to be used in connection with the design, construction, transportation, installation, and decommissioning of fixed offshore structures. Clause 4.13 states that:

> *"When scour, including ice scour, is expected to occur, the depth and lateral extent of scouring shall be evaluated on a site-specific basis and accounted for in the design".*

There is no further references to ice scour, but there is substantial guidance on safety issues. The standard states in clause 4.5.1 that one of the main objectives of the design shall be to ensure that:

> *"(a) the structure and foundation can sustain, during their life, all anticipated loads and deformations with an acceptable level of safety (see clause 4.5.2)."*

The standard then introduces an important aspect in clause 4.5.2 relating to risk levels in the form of two "Safety Classes". It defines two safety classes for the verification of the safety of the structure or any of its structural elements:

> *"Safety Class 1 - failure would result in great risk to life or a high potential for environmental damage, for the loading condition under consideration;*
>
> *Safety Class 2 - failure would result in small risk to life and a low potential for environmental damage, for the loading condition under consideration."*

Further guidance is provided in the notes provided at the end of the clause:

> *"(1) If loading hazards can be predicted sufficiently ahead of time to carry out a predefined emergency response plan that ensures personnel safety and environmental protection, then, for that particular loading condition, the structure may be Safety Class 2.*
>
> *(2) A safety class may be assigned to the structure as a whole or to its individual structural elements. For example, a structure designated Safety Class 1 as a whole may have certain of its structural elements designated Safety Class 2.*
>
> *(3) See Appendix A (of the Standard) for further information on the application of safety classes and on the associated reliability levels assumed in this Standard."*

As a part of formulating the CSA standard, exceedance probabilities and associated load factors were chosen in combination with factored resistances to result in a reliability level consistent with the target values for the appropriate safety classes. In the case of iceberg loads, which are rare events on the Grand Banks, it is recommended that the design loads be chosen based on an annual probability of exceedance between 10^{-3} and 10^{-4} (see Table 11).

Table 11 Annual Exceedence Probabilities For Specified Loads - CSA S471-04, Table A2 (CSA, 2004)

	Safety Class 1		**Safety Class 2**	
	Annual Exceedence Probability, p_E	**Load Factor**	**Annual Exceedence Probability, p_E**	**Load Factor**
Specified loads, E_f, Based on frequent environmental processes	10^{-2}	1.35	10^{-2}	0.9
Specified loads, E_r based on rare environmental events	10^{-4} to 10^{-3}	1.0	10^{-2}	1.0
Specified accidental load, *A*	10^{-4} to 10^{-3}	1.0	N/A	N/A
Note: Rare environmental events have an annual probability of occurrence of less than 0.5.				

Values of target reliability levels given in the standard were determined from calibrations made to existing design rules for offshore structures and basic considerations of safety of life and environment. For the calibration exercise, a range of conditions were considered with values of probability of failure falling in the range of 10^{-4} to 10^{-6} per annum for most conditions. The main reliability target of 10^{-5} per annum was chosen for Safety Class 1 and is illustrated in Figure 35.

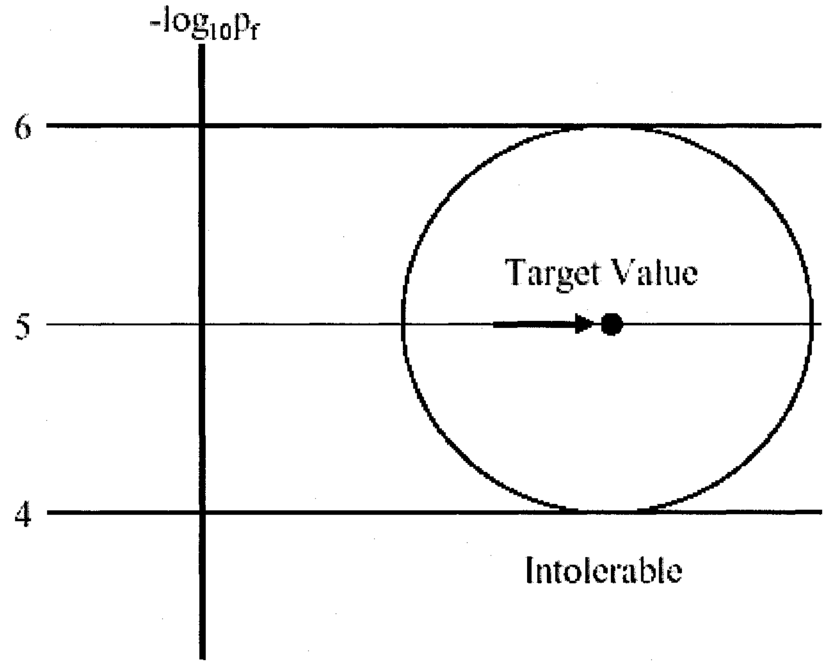

Figure 35 Illustration of Targets in the CSA Code for Safety Class 1 (Allyn, 2000)

Similarly, target safety levels for Safety Class 2 and for serviceability (Impaired function) were given as 10^{-3} and 10^{-1} per annum, respectively as summarized in Table 12.

Table 12 Safety Classes and Reliability Levels - CSA S471-04, Table A1 (CSA, 2004)

	Target Annual	
	Consequences of Failure	**Reliability Level**
Safety Class 1	Great risk to life or high potential for environmental pollution or damage	$1\text{-}10^{-5}$
Safety Class 2	Small risk to life and low potential for environmental pollution or damage	$1\text{-}10^{-3}$
Serviceability	Impaired function	$1\text{-}10^{-1}$

In addition to the CSA standards, a review of equivalent international codes has been undertaken with focus on information pertaining to risk and reliability levels, specification of distinct safety classes and guidance related to iceberg scour. In general, there was not a large amount of detail given to iceberg scour, however, ISO 19902, *Petroleum and Natural Gas Industries - Fixed Steel Offshore Structures (Draft International Standards 2003)* presents a strategy whereby "life safety classes" (representing manned and unmanned installations) and "consequence categories" (low, med & high) are used (ISO, 2003). The required reliability or annual probabilities of exceedance associated with design loads or actions depend on each of these.

ISO 19902 takes an approach whereby structures can be categorized by various levels of exposure to determine criteria that are appropriate for the intended service of the structure. This applies to the design of new structures and to the assessment of existing structures.

The life-safety category addresses personnel on the platform and the likelihood of successful evacuation before a design environmental event occurs. Clause 6.6.2 states that:

The category for life-safety shall be determined from:

a) S1 Manned non-evacuated

b) S2 Manned evacuated

c) S3 Unmanned

The consequence category considers the potential risk to life of personnel brought in to react to any incident, the potential risk of environmental damage and the potential risk of economic losses. Clause 6.6.3 states that:

Factors that should be considered in determining the consequence category include:

- *Life-safety of personnel on, or near to, the platform brought in to react to any consequence of failure, but not personnel that are part of the normal complement of the platform;*
- *Damage to the environment;*
- *Anticipated losses to the owner, to other installation owners, to industry and/or to other third parties as well as to society in general.*

The consequence category shall be determined from:

a) C1 High consequence category

b) C2 Medium consequence category

c) *C3 Low consequence category*

It is recognized that consequence category definitions include a degree of judgment. The category that applies to a structure shall be determined by the owner of the structure prior to the design of a new structure and shall be agreed by the regulator where applicable.

The 3 categories for each of life-safety and consequence can be combined into 9 exposure limits as presented below in Table 13.

Table 13 Determination of Exposure Level – ISO 19902, Table 6.6-1 (ISO, 2003)

Life-safety Category	Consequence Category		
	C1 High Consequence	**C2 Medium Consequence**	**C1 Low Consequence**
S1 Manned Non-evacuated	L1	L1	L1
S2 Manned Evacuated	L1	L2	L2
S3 Unmanned	L1	L2	L3

In 1999, the Canadian Standards Association (CSA) embarked on an initiative to revise the existing Offshore Standards including CSA S471. This revised CSA code has set the basis for harmonization with the ISO Offshore Structures Code (Frederking et al., 2004).

5.6 Application to Wellhead Protection

With all wellhead installations, there is potential threat to the environment by means of pollution. In order to minimize this risk, these systems are generally provided with barriers in the well bore, including a surface-controlled subsurface safety valve (SCSSV) and a fail-closed master valve in the subsea or insert tree. For wellheads that are susceptible to potential damage from scouring icebergs these threats are even greater. Under these conditions alternative protection techniques as discussed in Chapter 4 must be strongly considered along with employing iceberg management programs.

Major environmental consequences can result if a subsea blowout occurs as a result of iceberg impact, and is thus the main concern when considering wellheads. A subsea release of well fluid from oil producers would result in a pool forming on the sea surface. The location of the subsea wells would be such that they would be considerable distance from the main installation and risks to personnel are considered remote. In addition to the environmental ramifications, the business consequences of significant damage to an asset could also be very high, particularly if a wellhead was lost because of iceberg scour. Securing a well that has been damaged could conceivably take months and cost 10's of millions of dollars. Well productivities for typical producer wells on the Grand Banks reach as high as 30,000 bbl (4800 m^3) per day. If such of an event were to occur, it would potentially be catastrophic to the environment and oil and gas community alike.

With regard to the two levels of safety as presented in CSA S471-04, Safety Class 1 would result in great risk to life or a high potential for environmental damage. For the case of a subsea blowout, extreme consequences would result if a release of thousands of m^3 per day for several or more days occurred. This would correspond to the case where a wellhead that was damaged as a result of an extremely deep scour or damage to the valves causing loss of integrity to the well. In this case, blowout of a well on iceberg contact presumes that the downhole SCSSV fails to function correctly. Subsea system components such as wellheads and Xmas trees fall into Safety Class 1 because they offer high potential for environmental damage if impacted directly by an iceberg.

Safety Class 2, which would result in small risk to life and low potential for environmental damage, would only apply in this case if the reliability of the emergency response measures and/or backup control systems was clearly demonstrated to be adequate for any eventuality. Obviously, systems offering this level of reliability would be difficult to achieve for events such a subsea well blowouts that normally take days to even months to bring under control. Subsea system components such as flowlines, umbilicals and manifolds fall into Safety Class 2 because they offer small risk to human life and low potential for environmental damage if impacted directly by an iceberg. These subsea components are generally located at or above seabed level and are essentially considered sacrificial parts of the overall subsea system. Subsea facilities, such as these are designed with failsafe systems to minimize any adverse environmental effects in the event of failure or damage. Having the flowlines and manifolds on the seafloor will provide access for inspection, testing, repair, replacement or removal. In order to minimize spills caused by possible ice scour, the affected subsea facilities will be shut in and flushed with injection water. Emergency shutdown valves and weak links are installed to minimize environmental harm from accidental damage.

For the purpose of this study, it will be assumed that any contact between an iceberg and an Xmas tree or wellhead could result in a blowout, resulting in an uncontrolled oil flow from the well releasing large quantities of hydrocarbons into the environment. This is clearly a Safety Class 1 event. Other installations, such as flow lines, where the potential damage to the environment is small, should be treated using Safety Class 2 guidelines.

5.7 Recommendations

Allyn (2000) states that the safety class targets that are specified in the CSA fixed structure design code can be used to gauge the consistency in reliability targets for seafloor facilities such as wellheads. However, large uncertainties relating to the nature and risk of iceberg scour on the Grand Banks, along with the unknowns about the effectiveness of various protection schemes, make this type of assessment approach quite challenging.

In the absence of more specific methodology and guidelines to deal with protection of subsea facilities, it is recommended that the CSA target safety levels and design strategies be followed as summarized previously in Table 12. In terms of Safety Class, wellheads should be considered as Class 1, since failure or damage could lead to significant hydrocarbon release resulting in adverse environmental damage. For this case, the CSA standard recommends an annual target safety level of 10^{-5}. When considering the two cases proposed in this investigation, this would apply to the following facility arrangements:

- Case 1 - One isolated single well, or
- Case 2 - Several wells clustered around a single manifold.

The annual target level for a single well or a multi-well cluster installation incorporating each proposed protection concept is therefore 10^{-5}.

For particular developments systems such as Case 2 that consist of multi-wells, each well will have an associated probability of failure. Obviously the consequence of failure increases with the number of wells and it is advisable to increase the reliability level of the individual wells so as to maintain the probability of a serious (Safety Class 1) consequence at an acceptable level. Since more than one well may be contacted by a single iceberg, it may be prudent to design each well in the cluster for a target of less than 10^{-5} per year. This can be achieved, for example, by increasing the depth of the shear plane for caisson completion systems or increasing the burial depth of trees for cased and open glory holes. Reducing the overall footprint of a multi-well installation will also reduce the overall risk and increase the total reliability of the system. In addition, iceberg management programs will also serve to reduce overall risk to these subsea installations.

6.0 PROBABILITY OF ICEBERG CONTACT TO WELLHEAD FACILITIES

6.1 General

A considerable amount of work has been undertaken over the last two decades in an attempt to estimate the risks to subsea facilities from encroaching icebergs on the Grand Banks. One of the earliest studies to determine such risk to offshore platforms on the Grand Banks was carried out by Blenkarn & Knapp (1969). They estimated the number of icebergs passing through a one-half degree rectangle based on International Ice Patrol sightings from 1948 to 1956. Reddy et al. (1980) elaborated on this approach and showed how to use Monte Carlo simulation to determine confidence limits on the impact probabilities estimated using the method of Blenkarn and Knapp with empirical Bayesian techniques.

During the extensive oil exploration in the Arctic during the early 1980's, geometric solutions for determining the probabilities of impacts by ice floes onto fixed platforms were developed by the oil and gas industry. Around the same time, Petro-Canada (1984) undertook an extensive study to quantify the probability of damage to subsea installations due to iceberg collision or scouring on the eastern Grand Banks. The study investigated the probability of damage to individual subsea installations, such as satellite wells, manifolds, templates, and flowlines, as well as the overall probability of damage to the entire subsea system. The iceberg collision risk simulator BERGSIM was subsequently developed by Petro-Canada in 1984 as a part of the study to estimate the probabilities of icebergs on the Grand Banks colliding with fixed structures. During the last two decades, further work in this area has been undertaken by local oil and gas operators plus a variety of local and national institutes, universities, government bodies and engineering consultants (Reddy et al., 1980; Sanderson, 1988; Fuglem et al., 1996; C-CORE, 1998; Croasdale et al., 2000; King et al., 2003). As a result, a number of variations to these early approaches have been developed and published in a number of sources to estimate probability of iceberg contact.

Two basic kinds of data are generally adopted to express the density of icebergs for use in calculations for iceberg contact probability; iceberg flux and areal density. Iceberg flux analysis uses data relating to flux across a line (e.g. 48° latitude) in a time interval, at a given point in time. The use of flux data is rather difficult as the motion of icebergs includes a large random component, combined with a net directional component, and thus requires the estimation of meander coefficients.

In comparison, the use of areal density data as discussed in Chapter 2.1 corresponds to a ‘‘snapshot’’ of the area under consideration. The theory for this approach was first presented by Sanderson (1988), who developed an approach to determine the frequency of multi-year floe impacts (or iceberg impacts) with structures such as Molikpaq in the Beaufort Sea. The area used for this approach could be any area but generally a degree square is the unit used. A degree square varies in size with latitude but is a convenient measure in view of the IIP data collection practices. The areal density would be simply the number of icebergs in a degree square at a given point in time, and values would be available for the entire iceberg season, at various points in time.

Simulation methods such as BERGSIM can be based on both areal density as well as flux data; however, these methods are more complicated and are not necessary if collision probabilities are all that is needed in the calculation. For risk analysis calculations, the most reliable method of calculation is made using areal density data because they are simpler and less prone to measurement errors than methods requiring estimates of iceberg flux (Jordaan et al., 1999). For this reason, areal density data will be used in the analysis to determine probability of iceberg contact, presented herein.

Evaluating risk to wellhead and tree facilities essentially involves two separate issues - iceberg collision with wellhead facilities and the damage caused as a result. Calculating the probability of collision is relatively easy to determine by means of simple geometric models given the appropriate iceberg data. Assessing the level of damage, however, requires an assessment of structural response mechanisms, iceberg strength, and iceberg behavior following first contact (Croasdale et al., 2000). The later issue is outside of the scope of the present study and will not be addressed.

As outlined in Section 3.2, subsea production systems include components such as wellheads, trees, manifolds, templates and flowlines. For the purpose of this investigation, the emphasis will be focused primarily on subsea wellhead and tree components as they represent the most critical elements when considering protection from iceberg collision.

Subsea facilities located above seabed level and those located below are at risk from icebergs. Since scouring is relatively an infrequent occurrence, the probability of contact to structures located below seabed level is significantly lower than for structures projecting above the mudline. The intent of this chapter is to present a methodology in order to determine the appropriate interaction probabilities to wellhead facilities as they relate to the various protection scenarios (as outlined in Section 4.0). Figure 36 is a flowchart that illustrates the general approach used for determining annual iceberg contact probabilities for facilities located both above and below seabed level.

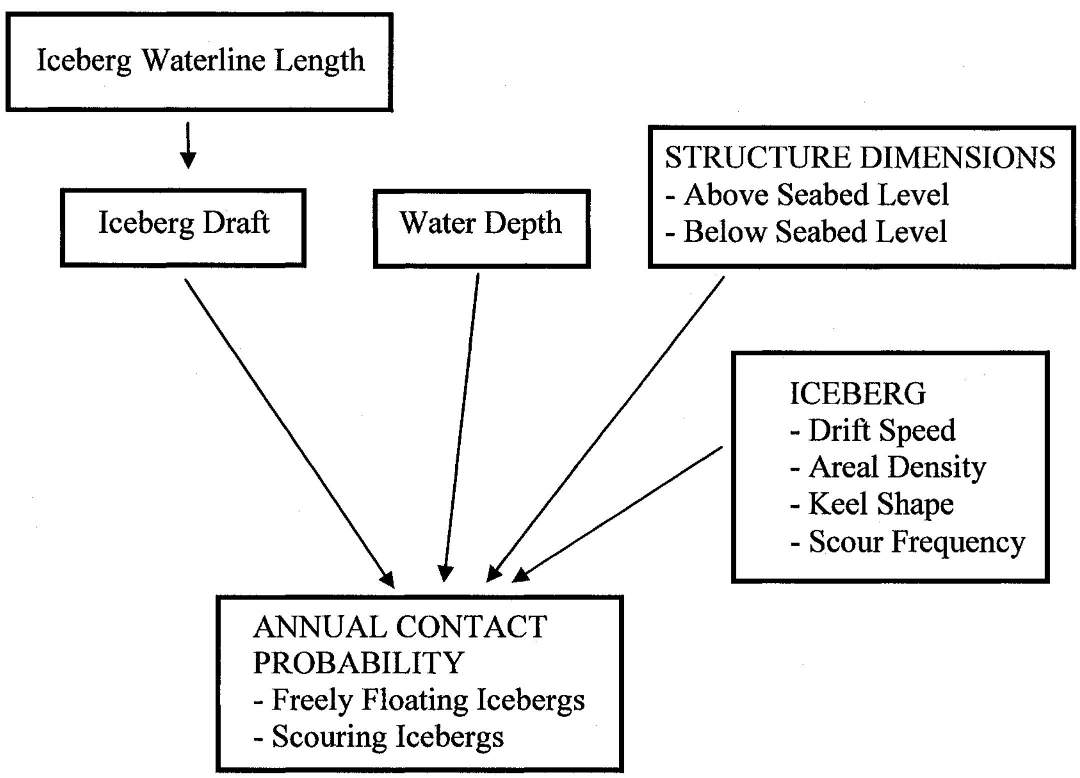

Figure 36 Flowchart Showing General Approach used to Determine Annual Contact Probabilities

The effect of iceberg management and its ability to reduce risk levels will also be discussed.

The estimates presented herein are determined for the general area of focus that encompasses the northeast Grand Banks, as it represents a region of significant oil and gas development opportunity. This area is defined by degree square 46^{o} to 47^{o} N and 48^{o} to 49^{o} W. In addition, a water depth of 100m will be used throughout this study as it is representative of water depths encountered on the northeast Grand Banks.

6.2 Facilities Above Seabed Level

Subsea facilities that are positioned completely or partially above the seabed level are at risk from freely floating and scouring icebergs. The total probability of iceberg contact can be given by the following expression:

$$\eta = \eta_d + \eta_s \qquad (6.1)$$

Where η is the total annual probability of iceberg contact, η_d is the annual probability of contact with freely floating icebergs and η_s is the annual probability of contact with scouring icebergs. The methodology for estimating the probability of contact for both freely floating and scouring icebergs for subsea facilities above mudline is described in subsequent Sections 6.2.1 & 6.2.2.

6.2.1 Contact Frequency with Freely Floating Icebergs

Iceberg collisions from freely floating icebergs to subsea facilities may occur from icebergs with drafts between the water depth and the depth of the top of the structure. The annual contact probability from freely floating icebergs can be estimated from the average iceberg population (per unit area), average drift speed, and the sum of iceberg keel and structure widths at the point of contact. C-CORE (2001b) presented the following relationship in order to calculate the annual frequency of contact for freely floating icebergs with a subsea structure:

$$\eta_d = \rho_d (L_d + D_d) v \cdot K \qquad (6.2)$$

Where η_d is the annual contact frequency of freely floating icebergs with a structure extending a distance 'h' above the mud line; ρ_d is the areal density of icebergs with drafts between d_w (the water depth) and d_w-h (the water depth less the height of the structure); L_d is the effective width of iceberg keels in the d_w to d_w-h depth range; D_d is the effective diameter of the structure; and v is the mean iceberg drift speed. If the areal density is given as an annual average number per degree square, and dimensions are in meters and speed is in m/s, a conversion factor K (3.7×10^{-3} m^{-2} s) is required to obtain η_d.

6.2.1.1 Iceberg Areal Density

As discussed in Section 2.2, areal density (ρ) refers to the average number of icebergs that would be expected to be seen in a particular region (typically a degree square) in a particular time frame (typically a year). Jordaan et al. (1999) have analyzed iceberg sightings from IIP data and calculated the mean annual areal density per degree square for the Grand Banks and adjacent regions, which are shown in Figure 7. Based on the more conservative areal density values calculated from data collected over last 20 years (1981-2000), a mean annual areal density of 0.77 icebergs / year / degree square has been selected, representing the area defined by degree square 46° to 47° N and 48° to 49° W.

The areal density of icebergs with drafts deep enough to make contact with a subsea structure is calculated from the total iceberg areal density (ρ) and the proportion (p) of the iceberg population with drafts deep enough to strike the subsea structure. The product of these two parameters yields ρ_d as given below:

$$\rho_d = \rho \cdot p\left(d_w > d > \left(d_w - h\right)\right) \tag{6.3}$$

6.2.1.2 Iceberg Draft Distribution

To determine the proportion of icebergs with sufficient draft to impact a wellhead structure, the distribution of iceberg drafts must be determined. The general approach most readily used in the industry is to define iceberg size in terms of waterline length and generate other iceberg parameters using relationships based on waterline length. Iceberg waterline length distribution is fairly well documented, thus, by utilizing the appropriate iceberg length/draft relationship, it is possible to generate the iceberg draft distribution (King, 2002).

The iceberg waterline length distribution on the northeast Grand Banks have been determined to have an exponential distribution with a mean of 59m (Jordaan et al., 1995). King (2002) analyzed 211 known iceberg draft measurements obtained off the coast of Newfoundland and determined that the mean iceberg waterline length for this data set was 115m with a mean draft of 80m. King presented the following relationship between iceberg waterline length (L) and draft (D):

$$D = 3.23L^{0.68} \tag{6.4}$$

Where the standard deviation of the residuals is 0.25. Since the mean waterline length for icebergs with measured drafts is 115 m, it is obvious that this dataset is biased towards larger icebergs and cannot be used directly to generate a draft distribution. Thus, to generate a sample of iceberg drafts, a large sample of waterline lengths, exponentially distributed with a mean of 59 m was generated and the corresponding drafts were calculated using the following equation derived by (King, 2002):

$$D_i = \exp(\ln(3.23) + 0.68\ln(L_i) + N(0,0.25)) \tag{6.5}$$

Where $N(0,0.25)$ is a random variable with a mean of 0 and a standard deviation of 0.25. Only icebergs with waterline lengths ≥ 16m were considered because the areal density value does not include icebergs smaller than this value.

Based on the above approach, the exceedence probability distribution of iceberg drafts is presented in Figure 37. Although this distribution can be modified to account for icebergs with drafts greater that the water depth in the study region that will ground and be filtered out of the keel population, King (2002) showed that the influence of bathymetric filtering was minimal for a water depth of 100m.

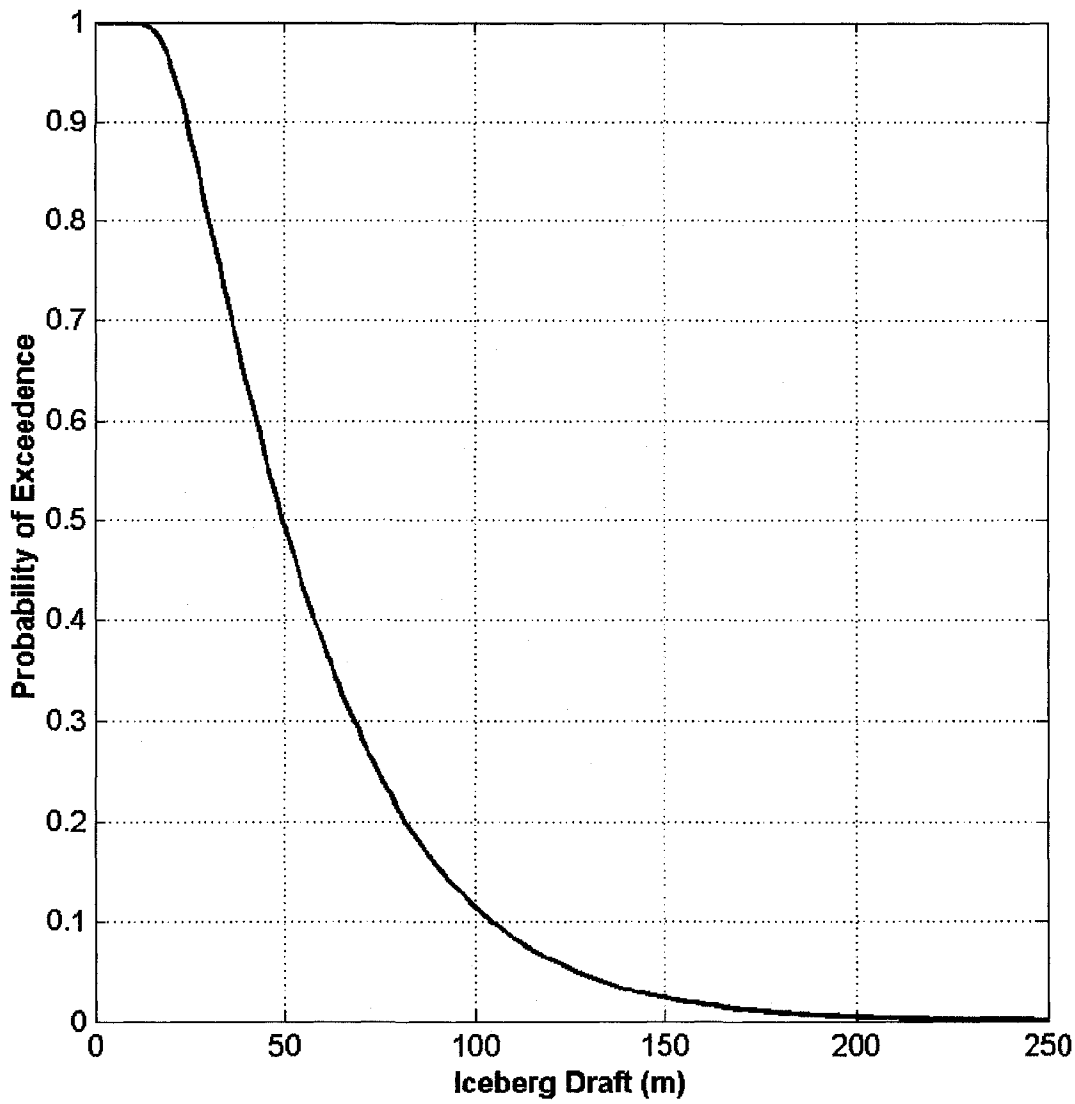

Figure 37 Probability of Exceedance for Iceberg Draft Based on Length/Draft Relationship (Waterline Lengths ≥ 16m) (C-CORE, 2002)

6.2.1.3 Effective Keel Width

The width of an iceberg keel at the level of a subsea structure also affects iceberg probability of contact, since a wider keel has a higher probability of impact. Field measurements of icebergs on the Grand Banks were documented in the Mobil Hibernia

Development Studies (Dobrocky, 1984). The data were obtained using sonar measurements of each iceberg at various positions around the iceberg's circumference and at various depths. Mean values of iceberg width were computed at each sonar depth for each iceberg in the data set. These widths were plotted against distance above the iceberg keel and then normalized with respect to iceberg draft allowing the profiles to be used to generate iceberg keel widths for a variety of iceberg drafts and elevations. Croasdale et al. (2000) derived a second-order least squares fit of normalized iceberg width (w^*) as a function of normalized height above the keel (z^*) for the bottom 30% of the iceberg data. This relationship was given as:

$$w^* = -9.31z^{*2} + 5.3z^* + 0.26 \quad (6.6)$$

Where $z^* = z / D_i$; $w^* = w / D_i$; z is the distance measure upward from the keel tip (m); w is the iceberg width (m) at a given z; and D is the iceberg draft (m).

To ensure correspondence between iceberg shape and scour geometry, the data was scaled to fit the mean scour width and mean scour depth measurements for the study area, which correspond to 24m and 0.5m respectively (taken from Table 4). This assumes that the mean scour width was measured at the mudline. The scaling is illustrated in Figure 38, whereby the original quadratic fit was shifted downward by a constant value to maintain the original shape of the curve.

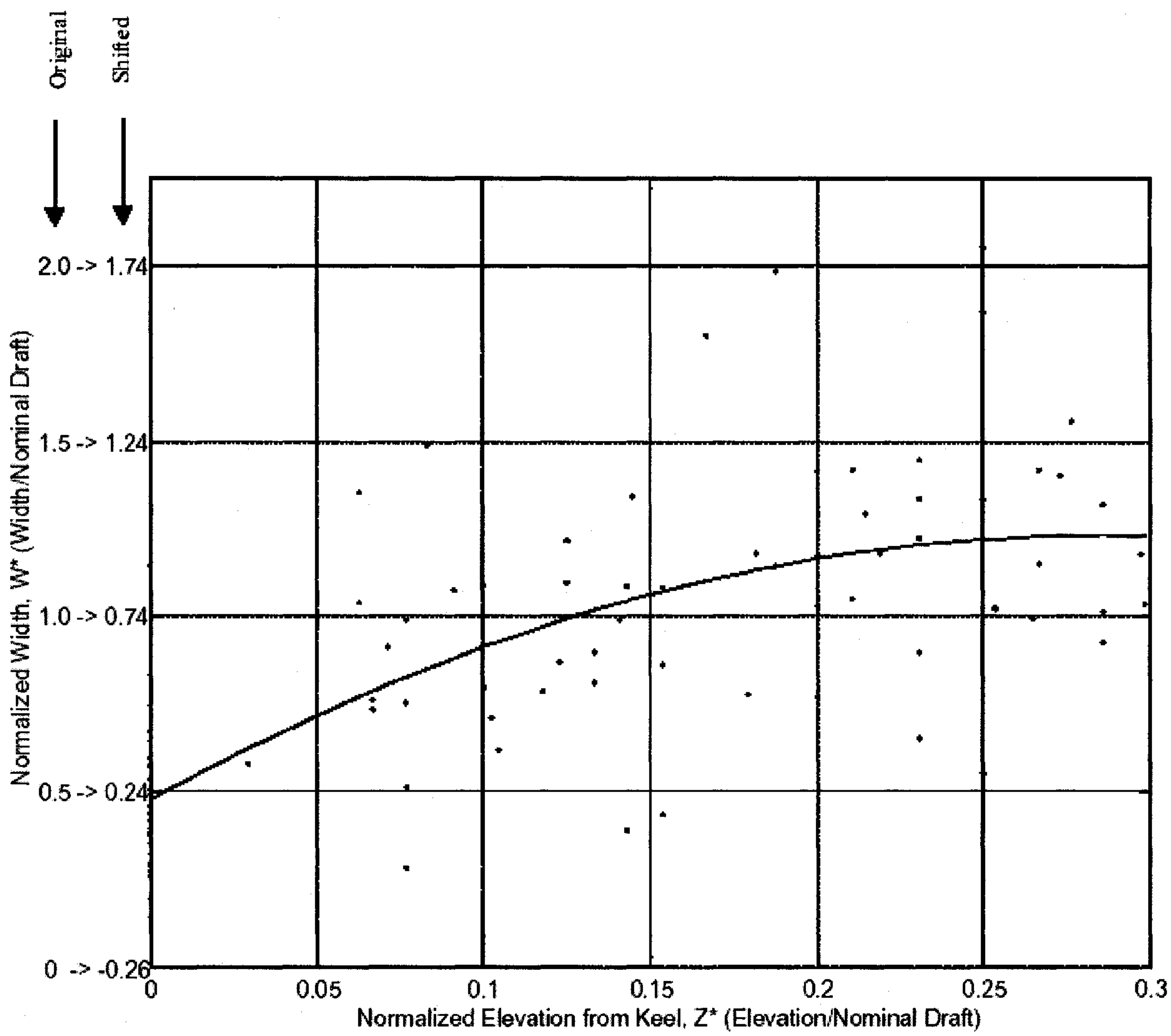

Figure 38 Keel Shape Fit to the Mobil Hibernia Development Studies (Mobil Hibernia Development Studies, 1984)

When calculating the effective keel width, the assumed iceberg draft and point of contact between the iceberg keel and the structure is important. For water depths in the range of 100m, it is reasonable to assume that the iceberg keel width increases monotonically with elevation above the bottom of the keel so unless the structure is strangely shaped the point of contact will be at the top.

A sensitivity analysis for effective keel width was carried out for a number of keel / structure interaction scenarios based on Equation (6.6). Results revealed that for freely floating icebergs, the most conservative approach was to assume that the iceberg draft is equal or slightly less than the water depth and has an effective keel width at a level equal to the top of the structure. However, freely floating icebergs capable of striking a structure above the seabed will have keels that extend from the top of the structure, d_w-h, down to a point just above the seabed, d_w (at which point you're dealing with scouring icebergs). Thus, the average keel will extend halfway down the structure with the contact point at the top of the structure as illustrated in Figure 39.

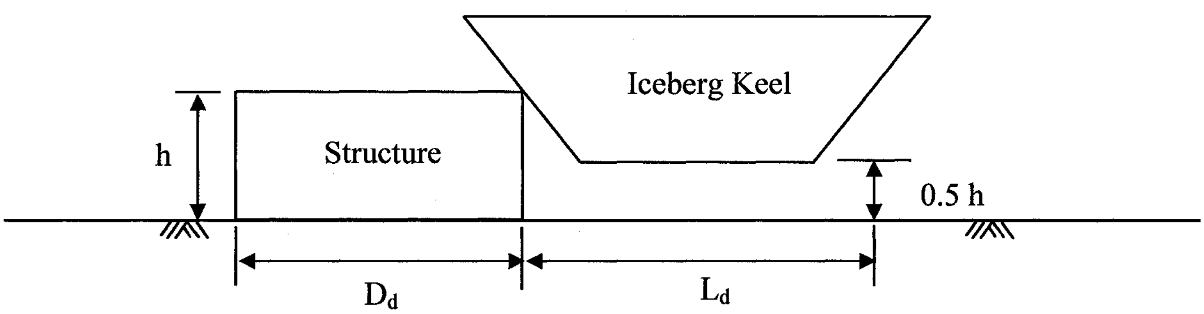

Figure 39 Iceberg Keel and Structure Interaction Arrangement for Freely Floating Icebergs

6.2.1.4 Iceberg Drift Speed

Iceberg drift velocities can be determined from iceberg sightings obtained during drilling operations on the Grand Banks. Iceberg velocities representative for the area defined by degree square 46° to 47° N and 48° to 49° W have been determined using iceberg sightings from the Marine Environmental Data Service Canadian Offshore Oil and Gas Environmental Data (MEDS, 1997) database, as well as recent sightings obtained during iceberg management operations.

Based on findings from a number of recent studies (C-CORE, 2001d; C-CORE, 2002; King, 2002; King et al., 2003) using the MEDS (1997) data and recent iceberg sighting data, average iceberg drift velocities were calculated for areas in the vicinity of Terra Nova, White Rose and Hibernia. The mean iceberg drift speeds for these areas ranged from 0.33 to 0.36 m/s, with an average of 0.34 m/s. Icebergs identified as towed or grounded were excluded from all sample analysis. As each of the study areas above fall within the area defined by degree square 46^{o} to 47^{o} N and 48^{o} to 49^{o} W, a representative mean drift speed of 0.34 m/s will be used throughout this report.

Although drift vectors can be used to generate the drift direction distributions in order to show that the iceberg drift regime varies locally (King et al., 2003), directional drift data has not been analyzed for the purpose of this study. By assuming a mean drift speed that is independent of direction and a uniform distribution of drift direction, a non-directional approach will be taken which assumes that the probability of contact with a subsea facility is equal from all compass directions.

6.2.2 Contact Frequency with Scouring Icebergs

In addition to freely floating icebergs, collisions from scouring icebergs may also occur to subsea facilities when contact is made with the structure above the mudline. The annual contact probability from scouring icebergs can be estimated from the annual scour frequency (per unit area), mean scour length, and the sum of iceberg keel and structure widths at the point of contact. C-CORE (2001b) presented the following relationship in order to calculate the annual frequency of contact for scouring icebergs with a subsea structure:

$$\eta_s = f_s(L_d + D_d)L_s \tag{6.7}$$

Where η_s is the annual contact frequency of scouring icebergs with a structure extending a distance 'h' above the mud line; f_s is the annual scour frequency per unit area; L_d is the effective width of iceberg keels in the d_W to d_W-h depth range; D_d is the effective diameter of the structure; and L_s is the mean scour length.

6.2.2.1 Annual Scour Frequency

As presented in Section 2.3.2, scour frequency can be estimated using a number of approaches (i.e. geological inference, grounding model, repetitive mapping and scour degradation). Scour rates presented in Table 3 for the northeast Grand Banks region range from 8.3×10^{-5} scours/km^2/year using lower bound geological inference (Croasdale et al., 2000) to 3.5×10^{-3} scours/km^2/year using a grounding model derived by Lewis et al. (1987). Recent grounding model work completed by King (2003) computes grounding rates that lie approximately half way in between scour rates as presented in Table 3. Using directional iceberg drift data for Hibernia and White Rose, King (2002) calculated scour frequencies of 7.8×10^{-4} and 7.3×10^{-4} scours/km^2/year, respectively.

This compares to 1.2 x 10^{-3} and 8.4 x 10^{-4} scours/km^2/year using a non-directional approach of the same grounding model.

For the purpose of this investigation, an annual scour frequency of 1 x 10^{-3} scours/km^2/year (or 1 x 10^{-9} scours/m^2/year) has been selected, which is representative for the study region. This is an average of the Hibernia and White Rose scour rates from the King (2002) grounding model assuming non-directional drift data.

6.2.2.2 Effective Keel Width

Taking a similar approach as for freely floating icebergs, the effective keel width for scouring icebergs can be calculated by assuming a mean scour depth for the study region. The mean scour depth in water depths less than 110m on the Grand Banks is 0.5m (Croasdale et al., 2000) as presented in Table 4. Using the same relationship presented in Equation (6.6), the effective keel width can be calculated based on the iceberg keel and structure interaction arrangement as presented in Figure 40.

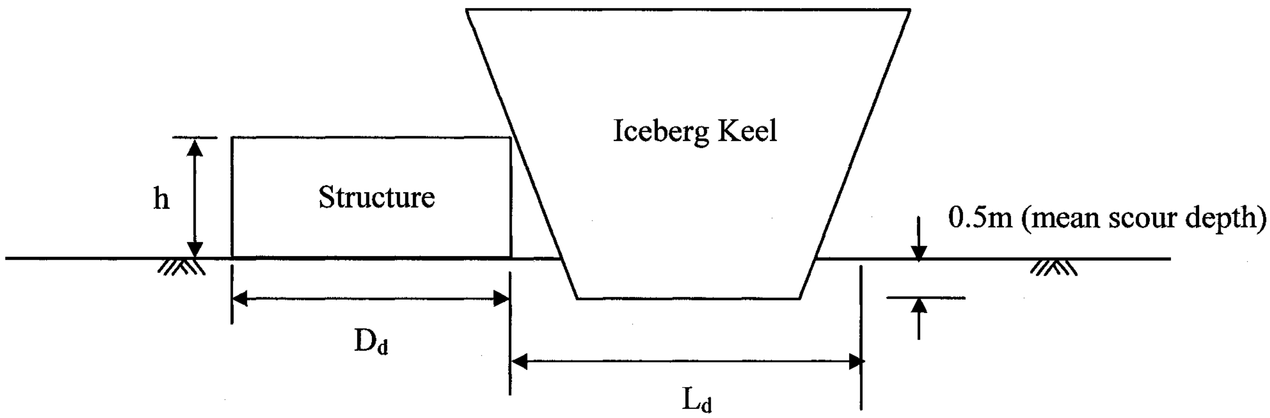

Figure 40 Iceberg Keel and Structure Interaction Arrangement for Scouring Icebergs

6.2.2.3 Mean Scour Length

The mean scour length in water depths less than 110m on the Grand Banks is 560m (Croasdale et al., 2000) as presented in Table 4. This value is considered to be an under estimate of the scour length since many of the scours were truncated by the survey (i.e. the scours extended outside the sidescan swath). C-CORE (2001d) assessed the effect of truncation on the mean scour length in order to determine a corrected mean scour length for a range of swath widths. By means of trial and error, an approximate breakdown according to swath width was used in order to determine the actual scour length distribution. Results from a two-parameter Gamma distribution and a scaled cumulative distribution function from the measured data were averaged to come up with a correction factor equal to 1.11. Applying this gives a corrected mean scour length of 1.11 x 560m = 622m.

6.3 Facilities Located Below Seabed Level

For structures located below seabed level the probability of contact from scouring icebergs decreases with increasing burial depth. In order to properly determine this probability of contact, Croasdale et al. (2000) made the distinction between small and large holes. The distinction has been made since scouring icebergs may penetrate (drop or dip) as they enter large open holes. As presented in Table 4, the mean scour width on the northeast Grand Banks for water depths ≤ 110m is 24m. Drilled holes such as cased glory holes and caisson completion systems have diameters that are generally significantly smaller than 24m in comparison to open glory holes that can have based dimensions greater than 100m. Thus, for the purpose of this investigation, any holes greater than 24m are to be considered as large open holes or glory holes, while all others will fall into the small diameter hole or structure category.

For scouring icebergs with installations below seabed, the effective keel width L_d will be assumed to be equal to the 24m. This value corresponds to the mean scour width in water depths ≤ 110m on the Grand Banks (Croasdale et al., 2000). By using the distribution of scour widths for the region, this is somewhat of a conservative approach as it assumes a mean scour width at seabed level rather than at a distance below mudline. This approach is necessary due to the lack of adequate information relating to iceberg keel widths collected to date in the region.

6.3.1 Small Diameter Hole or Structure

For a small diameter structure (≤ 24m) such as a downhole caisson wellhead, the probability of contact to a specific depth below the mudline can be determined using a modified version of Equation (6.7) (Croasdale et al. 2000). The probability of exceedance for iceberg scour depth, $P(z)_S$, determined from a fit of scour data from the1999 update of the GBSC can be applied, yielding the following relationship:

$$\eta_s(z) = P(z)_s f_s(L_d + D_d)L_s \tag{6.8}$$

where $P(z)_S = e^{-z/\mu}$; z is the depth below the mudline and; μ is the mean scour depth (0.5m as per Table 4).

It is interesting to note from the exponential distribution presented in Figure 41, the probability of scours occurring with depths greater than 3m is quite low.

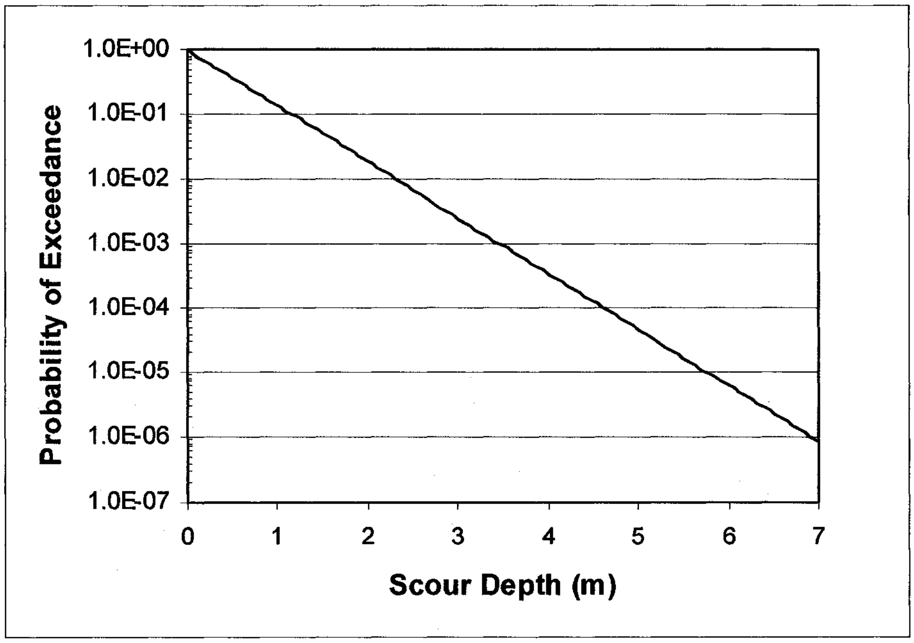

Figure 41 Probability of Exceedance for Iceberg Scour Depth (Water Depths ≤ 110m)

6.3.2 Large Open Hole or Glory Hole

The likelihood of an iceberg coming into contact with a facility located in a large open hole depends first of all, on the likelihood of an iceberg scouring directly over the hole as presented in Section 6.2.2. Given this scenario, transient and wave induced motions of scouring icebergs can result in penetrations below seabed (C-CORE, 1997).

For large diameter holes, the probability of contact to a specific depth below seabed level is again determined using a modified version of Equation (6.7) (Croasdale et al. 2000). In this case $P(z)_L$ is the probability of exceedance for the iceberg keel penetrating a depth z into the hole. The relationship thus becomes:

$$\eta_s(z) = P(z)_L f_s(L_d + D_d)L_s \tag{6.9}$$

Calculating this is complex and involves determining the keel offset from the center of mass and the heave and pitch dynamics of the iceberg as it enters the hole. The probability of exceedance $P(z)_L$ has been estimated using a number of approaches.

C-CORE (1997) conducted a study for the Terra Nova region and used a force equilibrium model to determine the heave and pitch of icebergs during steady state scouring of the seabed. The output of this model was used as input into a model of transient motions and predicted wave induced motions to estimate the maximum penetration of iceberg keels below mudline for a scouring iceberg encountering deep open holes. Probabilities of exceedance $P(z)_L$ were plotted against maximum penetration as illustrated on Figure 42 below.

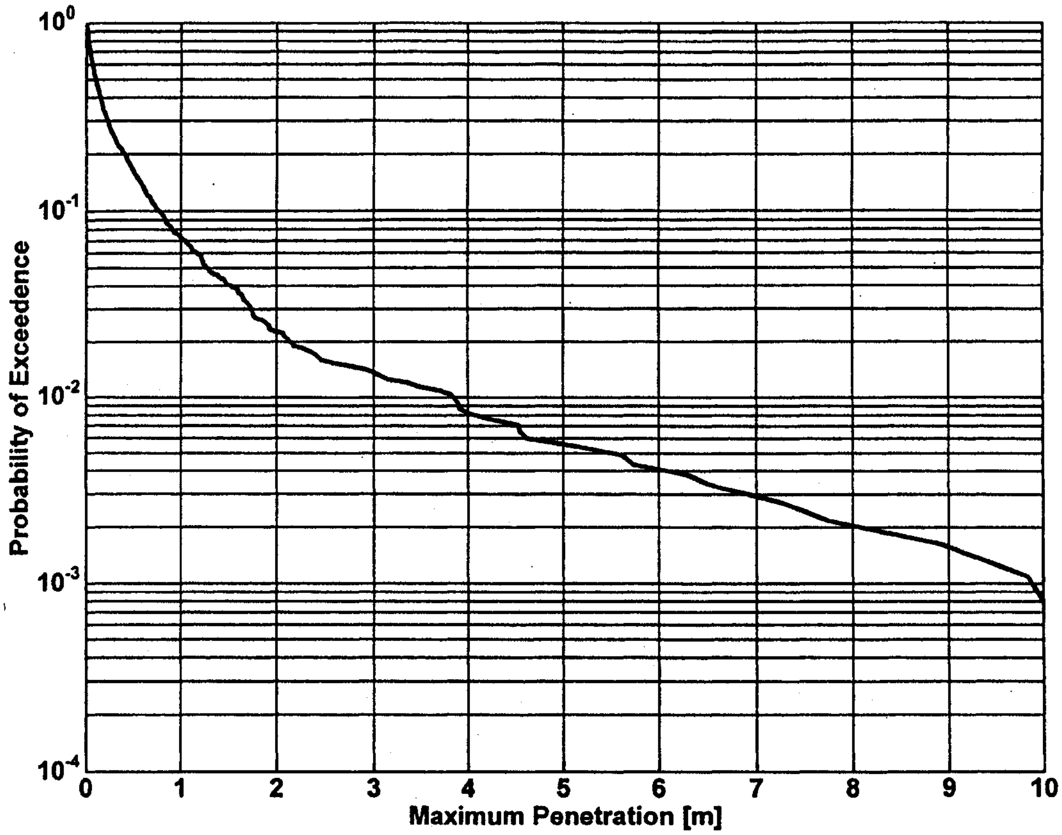

Figure 42 Exceedance Plot for Iceberg Keel Penetration Into a Glory Hole Due to Transient Motions, and Wave-induced Motions (C-CORE, 1997)

In contrast, C-CORE (2001e) estimated $P(z)_L$ from the distribution of excess drafts for scouring icebergs in the White Rose region based on information from the Grand Banks scour database (see Figure 43). The change in water depth between endpoints for measured scour marks (also called rise-up) were used as the basis for estimating the increase in draft of scouring icebergs upon reaching a large open hole. The excess draft results from a combination of heave and pitch motions of the iceberg were estimated based on seabed records from the GBSC. As it is equally likely that an iceberg may scour into a glory hole anywhere along the length of the scour, the expected excess draft of an iceberg on entry to a glory hole was assumed to be half the rise-up assuming the relationship between rise-up and scour length is linear.

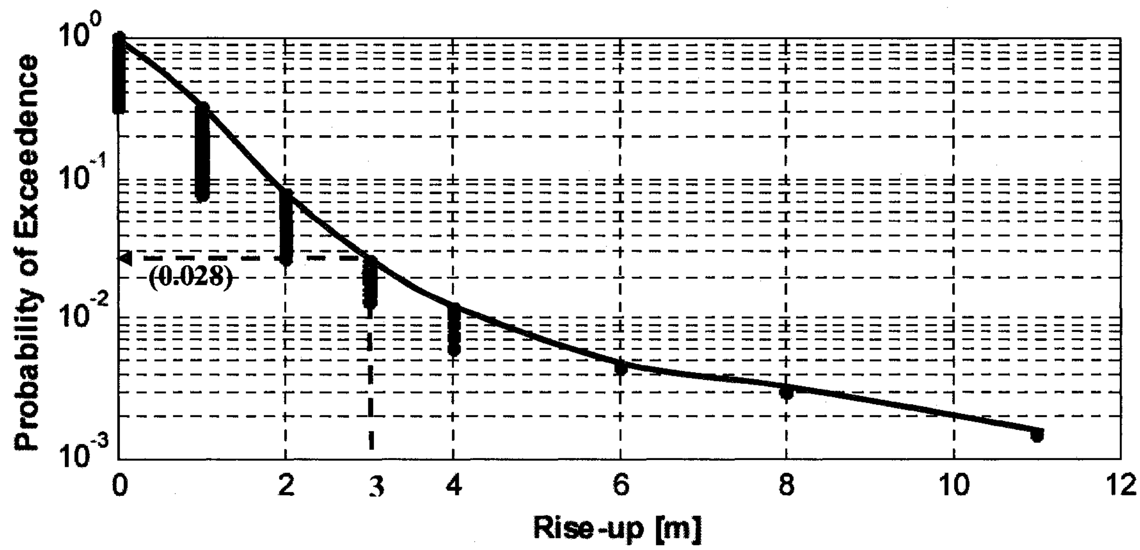

Figure 43 Measured Scour Rise-up Distribution for White Rose Region (C-CORE, 2001e)

Upon comparison of the probability of exceedance $P(z)_L$ results for each of these two approaches, it is observed that they are of a similar magnitude, with C-CORE (2001e) having a slightly higher range for excess drafts between 1m and 3m (see Figure 42 & 43). Because completely different and independent models were used in each case, it does suggest that discrepancies are expected. Due to the fact that rise-up values are actual measured data, they are deemed more appropriate in this case. Thus, the upper bound of the values plotted for the more conservative C-CORE (2001e) approach will be used for the analysis performed herein. These upper bound values are represented by the red line presented in Figure 43.

6.4 Sample Calculation of Total Contact Frequency

A sample calculation for the total contact frequency of a subsea facility located both above and below seabed level is outlined below.

6.4.1 Facility Above Seabed Level

For the structure situated above seabed level, it is assumed that the structure has a height of 5.5m and an effective diameter of 5m as illustrated in Figure 44.

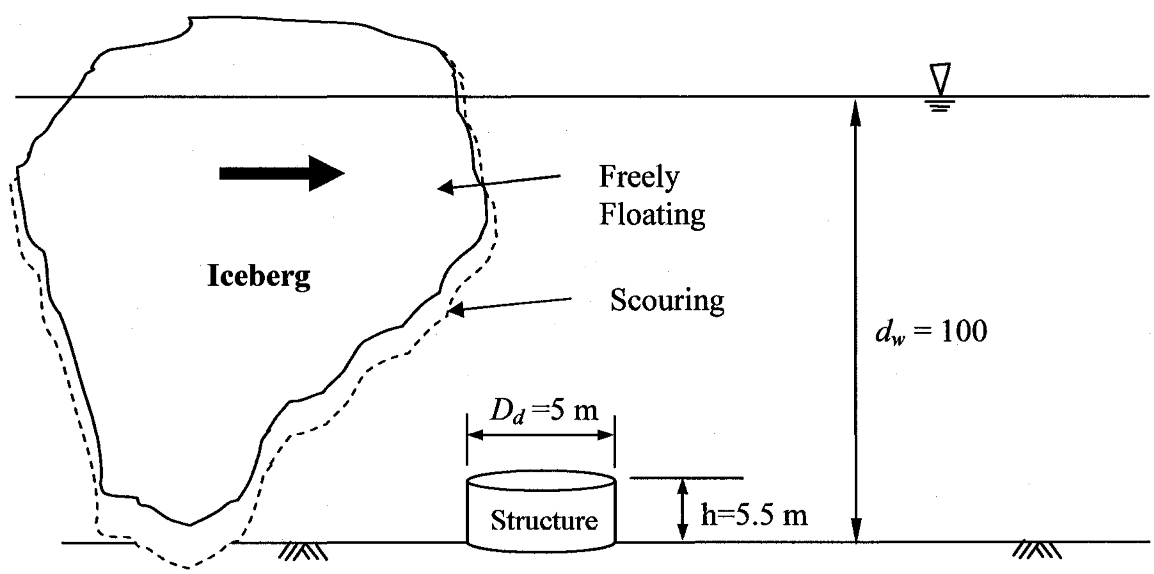

Figure 44 Schematic of Seabed Facility Located Above Seabed Level

The relevant input values are given in Table 14 overleaf.

Table 14 Input Parameters for Total Contact Probability of a Subsea Facility Located Above Seabed Level

Parameter	Symbol	Value	Source / Reference
Structure Height	h	5.5 m	Representative of Xmas tree installation
Structure Diameter (or effective diameter)	D_d	5 m	Representative of Xmas tree installation
Water Depth	d_w	100 m	Assumed representative of area
Areal Density	ρ	0.77 / degree square	Jordaan et al. (1999)
Conversion Factor	K	$3.7 \times 10^{-3}\ m^{-2}\ s$	C-CORE (2001d)
Mean Iceberg Waterline Length	L	59 m	Jordaan et al. (1995)
The Proportion of Icebergs with Drafts Between d_w and d_w-h (100m and 94.5m)	p	0.0215	King (2002) C-CORE (2002)
Effective Keel Width (freely floating icebergs)	L_d	39.1 m	Dobrocky (1984) Croasdale et al. (2000)
Mean Iceberg Drift Speed	v	0.34 m/s	MEDS (1997)
Annual Scour frequency	f_s	1×10^{-3} scours/km^2/year	King (2002)
Mean Scour Depth	-	0.5 m	Croasdale et al. (2000)
Scour length Correction Factor	-	1.11	C-CORE (2001e)
Effective Keel Width (scouring icebergs)	L_d	54.6 m	Dobrocky (1984) Croasdale et al. (2000)
Mean Scour Length	L_s	622 m	Croasdale et al. (2000)

The areal density of floating icebergs with sufficient draft to strike a subsea installation with a height of 5.5m in 100m of water can be calculated as:

$$\rho_d = 0.77 \times 0.0215 = 1.65 \times 10^{-2}$$

Assuming L_d = 39.1m (mean iceberg keel width), D_d = 5m (structure diameter), and v=0.34 m/s (mean iceberg drift speed), the encounter frequency with free-drifting icebergs can be calculated as:

$$\eta_d = 3.7 \times 10^{-3} \times 1.65 \times 10^{-2} \times (39.1 + 5) \times 0.34 = 9.18 \times 10^{-4}$$

The annual probability of contact for scouring icebergs can be calculated as:

$$\eta_s = 1 \times 10^{-9} \times (54.6 + 5) \times 622 = 3.7 \times 10^{-5}$$

Thus, the total contact frequencies for freely floating and scouring icebergs for the entire structure is calculated to be:

$$\eta = 9.18 \times 10^{-4} + 3.7 \times 10^{-5} = 9.55 \times 10^{-4}$$

Based on the results presented above, it is evident the contribution to overall contact probability from scouring icebergs is minor in comparison to free floating icebergs.

The annual probability for contacts above seabed level from freely floating icebergs is presented in Figure 45. In this graph the annual contact probability is plotted against structure diameter for a range of different structure heights (1, 2, 5 & 10 m). The plots show that the probability of contact increases with structure diameter and with structure height above seabed.

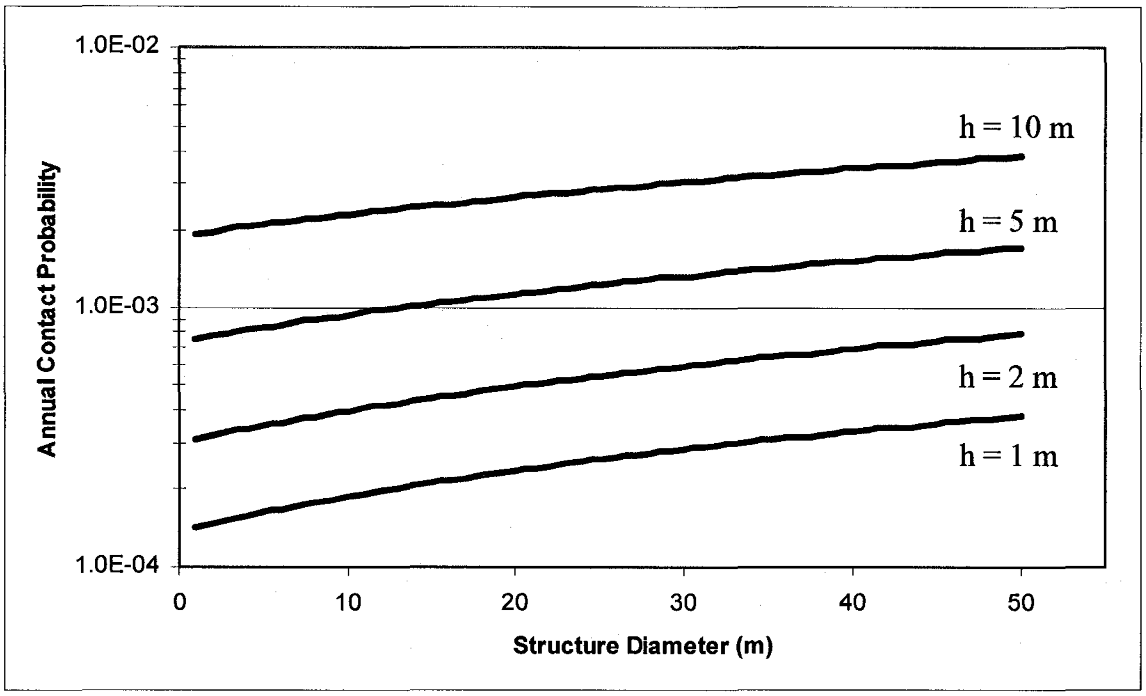

Figure 45 **Annual Contact Probabilities Calculated for Freely Floating Icebergs and Structures Above Seabed Level**

The annual probability for contacts above seabed level from scouring icebergs is presented in Figure 46, overleaf. In this graph the annual contact probability is again plotted against structure diameter for a variety of different structure heights (1, 2, 5 & 10 m). The probability of contact increases with structure diameter and structure height.

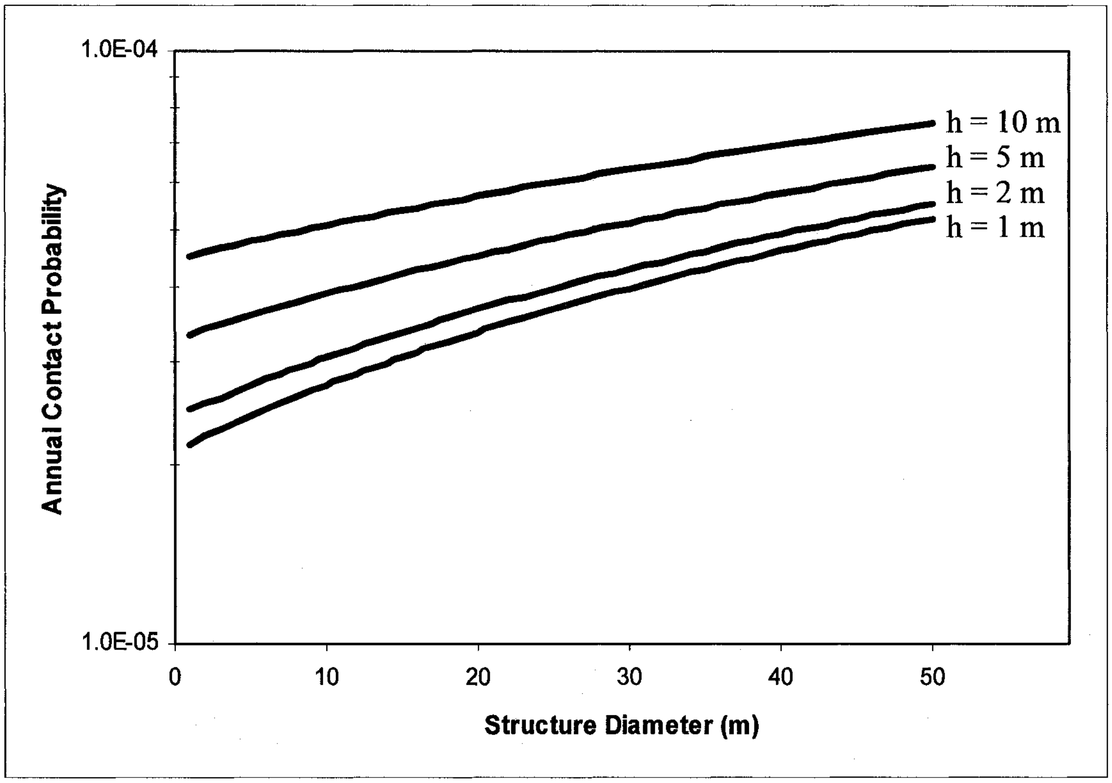

Figure 46 Annual Contact Probabilities Calculated for Scouring Icebergs and Structures Above Seabed Level

As can be concluded by comparing Figures 45 & 46, the annual contact probability for scouring icebergs is at least an order of magnitude lower than for those which are freely floating.

6.4.2 Facility Located Below Seabed Level

For the structure situated below level, it is assumed that the structure is situated in a large open hole (i.e. glory hole) with mudline footprint dimensions equal to 100m x 75m. The structure is 7m high and centrally located in a 10m deep hole, giving a clearance between top of structure to mean seabed of 3m. This arrangement is illustrated in Figure 47.

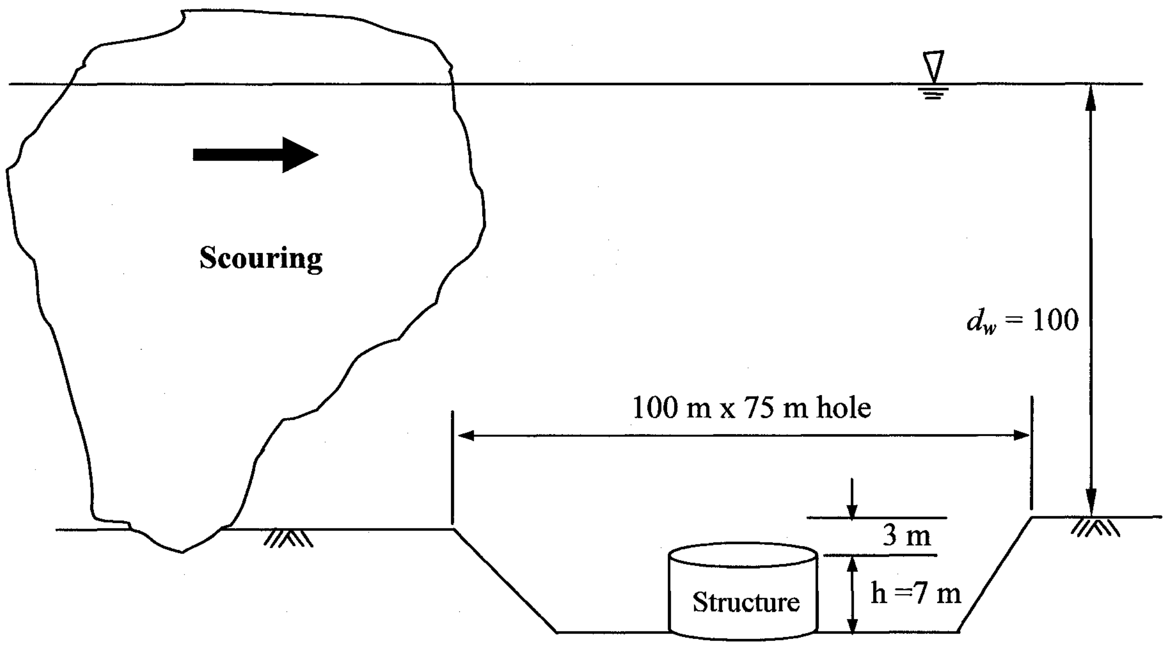

Figure 47 Schematic of Seabed Facility Located Below Seabed Level in a Large Open Hole

The relevant input values are given in Table 15, overleaf.

Table 15 Input Parameters for Total Contact Probability of a Subsea Facility Located Below Seabed Level

Parameter	Symbol	Value	Source / Reference
Structure Height	h	7 m	Representative of Xmas tree installation
Hole Effective Diameter	D_d	111 m	Representative of typical glory hole excavation
Water Depth	dw	100 m	Assumed representative of area
Probability of Exceedance for the Iceberg Keel Penetrating a depth 3m into the hole	$P(z)_L$	0.028	C-CORE (2001e),
Annual Scour frequency	f_s	1×10^{-3} scours/km^2/year	King (2002)
Mean Scour Depth	-	0.5 m	Croasdale et al. (2000)
Scour length Correction Factor	-	1.11	C-CORE (2001e)
Effective Keel Width (equal to mean scour width)	L_d	24 m	Croasdale et al. (2000)
Mean Scour Length	L_s	622 m	Croasdale et al. (2000)

The effective hole diameter can be calculated as:

$$D_d = (2/\pi)(\text{hole length} + \text{hole width}) = (2/\pi)(100 + 75) = 111 \text{ m}$$

Assuming $P(z)_L = 0.028$ (probability of exceedance for the iceberg keel penetrating a depth 3m into the hole); $f_s = 1 \times 10^{-9}$ scours/m^2/year (annual scour frequency); $L_d = 24$m (mean iceberg keel width), D_d = 111m (effective hole diameter), and L_s = 622 m (mean scour length), the total contact frequency for a structure located in a large open hole can be calculated as:

$$\eta_s = 0.028 \times 1 \times 10^{-9} \times (24 + 111) \times 622 = 2.4 \times 10^{-6}$$

Contact probabilities resulting from the model analysis of small diameter holes or structures located below the mudline are presented in Figure 48. The annual contact probability is plotted against depth below seabed level. As one would expect, the probability of contact decreases with increasing depth below seabed. Figure 48 indicates that there is very little sensitivity to the results with varying hole sizes.

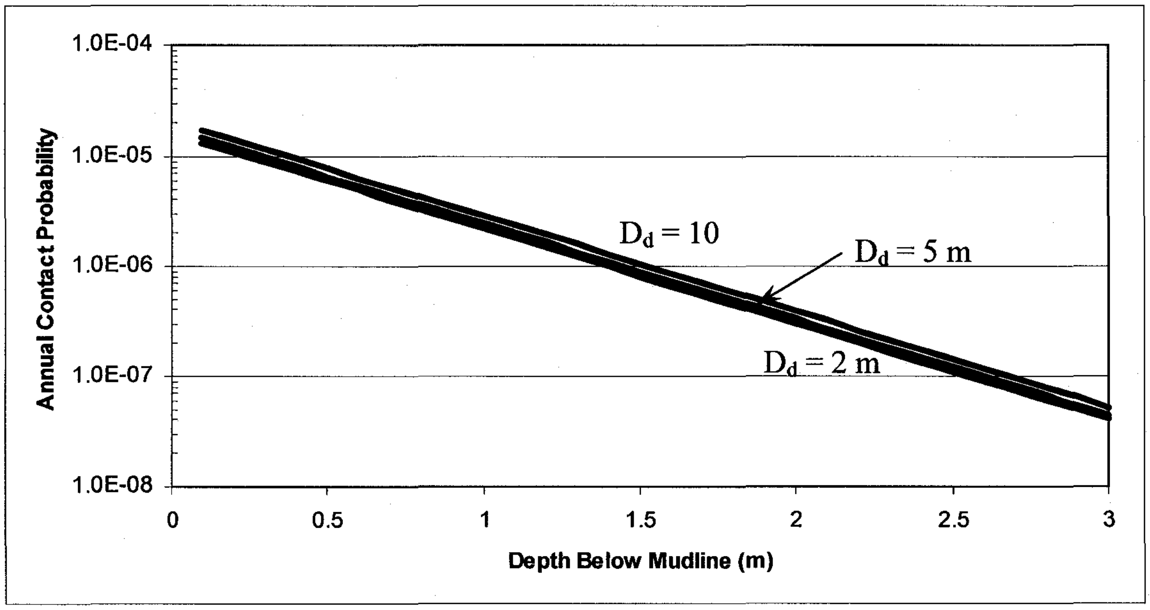

Figure 48 Annual Contact Probabilities Calculated for Scouring Icebergs with Hole Diameters ≤ 24m Below Seabed Level

Total contact probabilities resulting from the model analysis of facilities located in large diameter holes are presented in Figure 49. As given in the relationship for Equation (6.8) the annual probability that an iceberg will penetrate to a given depth in the hole is calculated by combining the excess draft of icebergs entering a large open hole (Figure 43) with the probability that an iceberg reaches the hole (Section 6.2.2). Considering a range of hole sizes, a corresponding range for the probability of iceberg penetration to various depths is obtained. It should be noted that the actual footprint of the installation inside the hole is much smaller than the chosen mudline dimensions of the hole due to the sloping sides required for stability. While it is possible that an iceberg enters the hole without damaging the wellhead, this possibility has not been considered explicitly. For the calculations an effective diameter of $(2/\pi)$(hole length + hole width) was used to represent the width of the hole by assuming equally likely scour orientations. Figure 49 overleaf indicates that there is very little sensitivity to the results with varying hole sizes more than mean scour width.

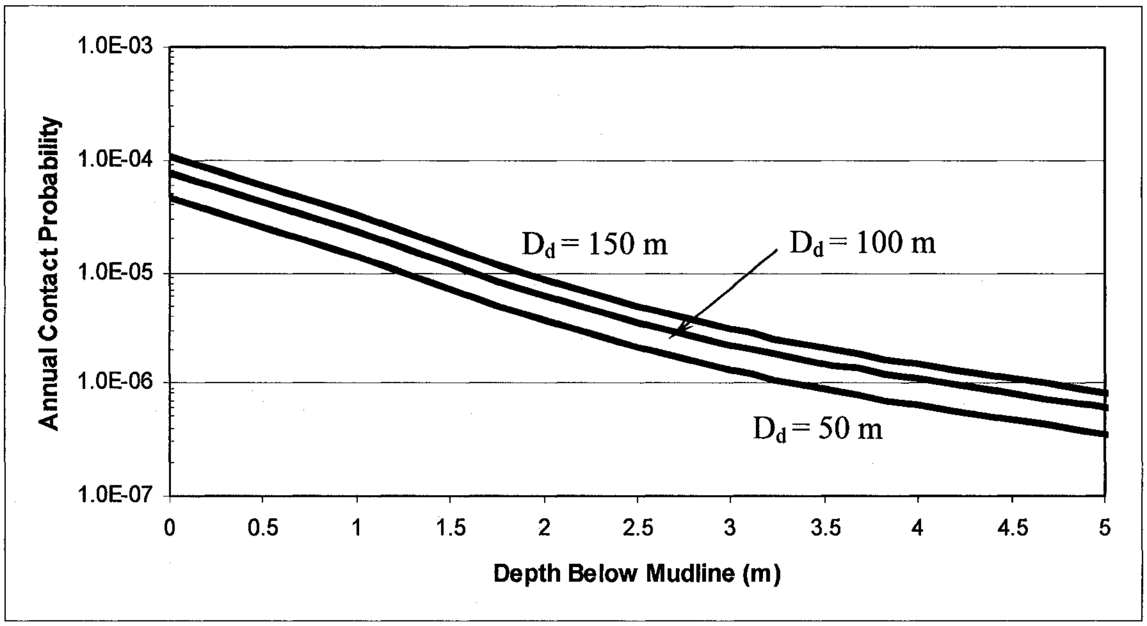

Figure 49 Annual Contact Probabilities Calculated for Scouring Icebergs with Hole Diameters > 24m Below Seabed Level

6.5 Iceberg Management

A key element to being able to work in the Grand Banks environment is active ice management. When the oil industry first began to explore for oil and gas off Canada's East coast in the late 1960's, iceberg management was almost unheard of. However, the need to protect drilling vessels from iceberg damage while at the same time, minimizing drilling downtime, quickly lead to the development of various iceberg management techniques (Crocker et al., 1998). During the past 30 years of exploration and delineation drilling on the Grand Banks, ice management techniques for managing ice and working safely in the environment have been developed and refined. The majority of the current iceberg management activities conducted on the Grand Banks are limited to iceberg deflection techniques. These being synthetic line towing, dual vessel towing for medium to large icebergs, and prop wash and water canon deflection for smaller ice masses.

Physical management systems using supply vessels and comprehensive detection techniques have been developed by oil and gas operators in the region to help reduce the risk of iceberg damage to offshore installations. Terra Nova for example, has a comprehensive ice management strategy based on detection, monitoring and deflection, to prevent iceberg encroachment into the vicinity of the field. The program employs boats, aircraft and the platform's own S-Band marine radar system to detect nearby icebergs and track their movement. However, the application of such an ice management strategy does not guarantee that the encroachment of icebergs into the area will be completely avoided. In the long term, it is envisioned that proper implementation of an iceberg management system could potentially result in an order of magnitude decrease in the annual iceberg contact probability of subsea facilities.

In practice, the potential for iceberg contacts can be reduced significantly by effective detection and physical iceberg management techniques. For subsea facilities, only relatively large icebergs with drafts equal or greater than the water depth will present a threat. Of these encroaching deep draft icebergs, only those remaining undetected, and unsuccessfully managed pose a threat to a subsea facility. This is illustrated in Figure 50 overleaf, in which the subsea installation is at risk from an "Impact".

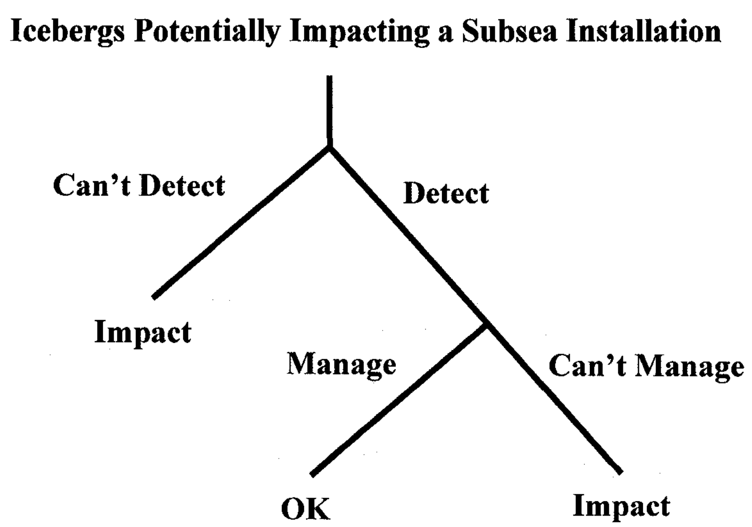

Figure 50 Decision Tree Illustrating the Influence of Iceberg Detection and Management on the Probability of an Iceberg Impacting a Subsea Installation

Mckenna et al. (2003) developed the following relationship to calculate the proportion of icebergs drifting directly toward a fixed installation that actually reach it is:

$$P_{impact} = (1 - P_{\det}) + P_{\det}(1 - P_{tow}) \tag{6.10}$$

where $P_{\det}$ is the probability of detection success and P_{tow} is the probability of success for physical management operations.

While iceberg detection and physical management success depend on a number of parameters; the most important are sea state and iceberg size. Due to the prevalence of fog on the Grand Banks, the primary means of iceberg detection is marine radar with detection success primarily dependent on range. Physical management success is based on data from past practice and depends on the time and resources available for the operation. Towing success is defined as the probability that an iceberg directed at a facility is deflected successfully. Typically, icebergs that cannot be managed are small ones in higher sea states and those that are unstable.

Notwithstanding Equation (6.10), overall tow success probability is approximately 85% based on historical data associated with drilling operations off Canada's east coast (e.g. Bishop, 1989; PERD, 2002a). Detection probabilities are typically much higher and approach 100% for short ranges from an installation. Failure to detect icebergs is most likely during storms (PERD, 2002b). If, for example, detection success is 98% and tow success is 85%, the proportion of icebergs reaching the installation is calculated from Equation (6.10) to be P_{impact} = 16.7%. For 100% detection success, the proportion of icebergs potentially reaching the installation that actually reach it would be $P_{impact} = (1 - P_{tow}) = 15\%$.

While these iceberg features are easy to detect, and may be less likely to roll or slip tow lines, the tow forces required to cause deflection are extremely large. For even medium size free floating icebergs (i.e. up to 2 million tones) and icebergs that are scouring the seabed, overall tow success is believed to be very low. In addition, the layout of subsea facilities such as satellite developments with long flowline routes may make reliable avoidance by deflection difficult. However, protection of seabed facilities for extended reach satellite wells and pipelines could be achieved through adequate towing resources and proper utilization of these resources. Although unproven, another management technique that could prove very valuable for reducing risk to subsea facilities is draft reduction, whereby the draft of an iceberg is reduced such that the resulting iceberg keel is above the top of any structure. Draft reduction methods using cutting tools are currently under research with plans for a full-scale field program in the near future. Prototype tests conducted near shore by C-CORE have offered some promising results for this technology (Ralph, 2004).

Implementation of iceberg management systems alone is unlikely to justify the safe operation of unprotected satellite wells. It will, however, mitigate economic consequences and provide assurance that a particular seabed installation meets target safety levels in spite of uncertainties associated with iceberg contact probabilities.

For calculations of overall contact probability to the various wellhead protection systems presented in Chapter 7, provisions for effective ice management activities will also be evaluated.

7.0 WELLHEAD PROTECTION SYSTEM LAYOUT & ASSOCIATED ENCOUNTER PROBABILITIES

7.1 General

As presented in Section 3.4, two representative development systems relating to a subsea marginal development on the Grand Banks have been identified. For each of these two Cases (1 & 2), a number of wellhead systems have been defined and will be evaluated based on the probability of an iceberg encounter and required target level of safety.

The single wellhead systems defined for Case 1 include:

Case 1: Single Satellite Well Development

1a) Conventional Xmas tree installed at seabed level (Base Case);

1b) Conventional Xmas tree installed at seabed level with downhole weak shear joint;

1c) Conventional Xmas tree installed in an open glory hole;

1d) Conventional Xmas tree installed in a cased glory hole;

1e) Conventional Xmas tree installed in a modified cased glory hole;

1f) Caisson wellhead completion system with sacrificial Xmas tree.

The multiple wellhead systems defined for Case 2 include:

Case 2: Clustered Mulit-well Development

2a) Six conventional Xmas trees placed at seabed level, in two rows of three and tied into a common manifold;

2b) Six conventional Xmas trees with downhole weak shear joint placed at seabed level, in two rows of three and tied into a common manifold;

2c) Six conventional Xmas trees in two rows of three and a common manifold placed in a large open glory hole;

2d) Six conventional Xmas trees placed in cased holes, in two rows of three and tied into a common manifold;

2e) Six conventional Xmas trees placed in modified cased holes, in two rows of three and tied into a common manifold;

2f) Six caisson wellhead completion systems with sacrificial Xmas tree, in two rows of three and tied into a common manifold.

The specifications on which these systems are based are described in the subsequent sections.

Due to the inherent high capital cost and increased overall risk associated with external protective barriers, they have been ruled out as being a viable protection solution and will not be considered further in this investigation. Furthermore, of the seven novel protection concepts presented in Section 4.7, only the Xmas tree with downhole weak shear plane and the modified cased glory hole options will be evaluated further as these concepts offer the most favorable features from a commercial, technical, and environmental standpoint.

The intent of this Chapter is to calculate encounter and contact probabilities for each of the single and clustered multi-well systems identified. In addition, each system will be evaluated and defined further based on the probability of iceberg contact and required target levels of safety. Summary results for all cases presented are included in Tables 16 & 17, Section 7.4.

For the initial layout of the well systems, it will be assumed that any direct iceberg contact with an Xmas tree or wellhead component will be considered to result in a blowout. In the case of a unprotected well with a downhole weak shear joint or caisson wellhead completion system, blowout is only considered to occur if the scour depth exceeds the depth of the weak shear joint / plane.

In order to account for sub-scour soil deformation effects, a sub-scour deformation allowance of one scour depth beneath the scouring iceberg keel will be assumed when specifying the location of weak shear planes / joints below the seabed level for particular installations. Thus, the shear planes and joints for installations such as cased holes and caissons will be placed at a depth twice that of the scour feature with the appropriate exceedance probability.

Relatively low iceberg collision probabilities indicate that there is little justification from an economic or environmental perspective for locating manifolds and other non-critical wellhead equipment below the influence of scouring icebergs for clustered multi-well developments. Although existing subsea developments such as Terra Nova and White Rose have located their manifolds inside open glory holes, other non-critical subsea equipment such as flowlines and risers do not have the same protection and are essentially sacrificial. For the purpose of this work, with exception to Case 2c, where the manifold is placed in a large open glory hole, all manifolds are assumed to be located above seabed level.

It must also be emphasized that the layout options presented in this Section are not fully optimized but are considered representative and adequately defined for the purpose of this high-level evaluation.

Conservatisms and limitations related to the iceberg calculations for well blowout will also be addressed in Section 7.5, followed by a detailed discussion in Section 7.6.

7.2 Single Satellite Well Development

7.2.1 Unprotected Well (Case 1a)

A conventional well with an unprotected Xmas tree located at seabed level is considered as the base case for this investigation. Specifications for this concept are as follows:

- 3.5 m x 4.5 m plan dimensions of the Xmas tree;
- An Xmas tree height of 5.5m above seabed level.

Details of Case 1a) are illustrated in Figure 51.

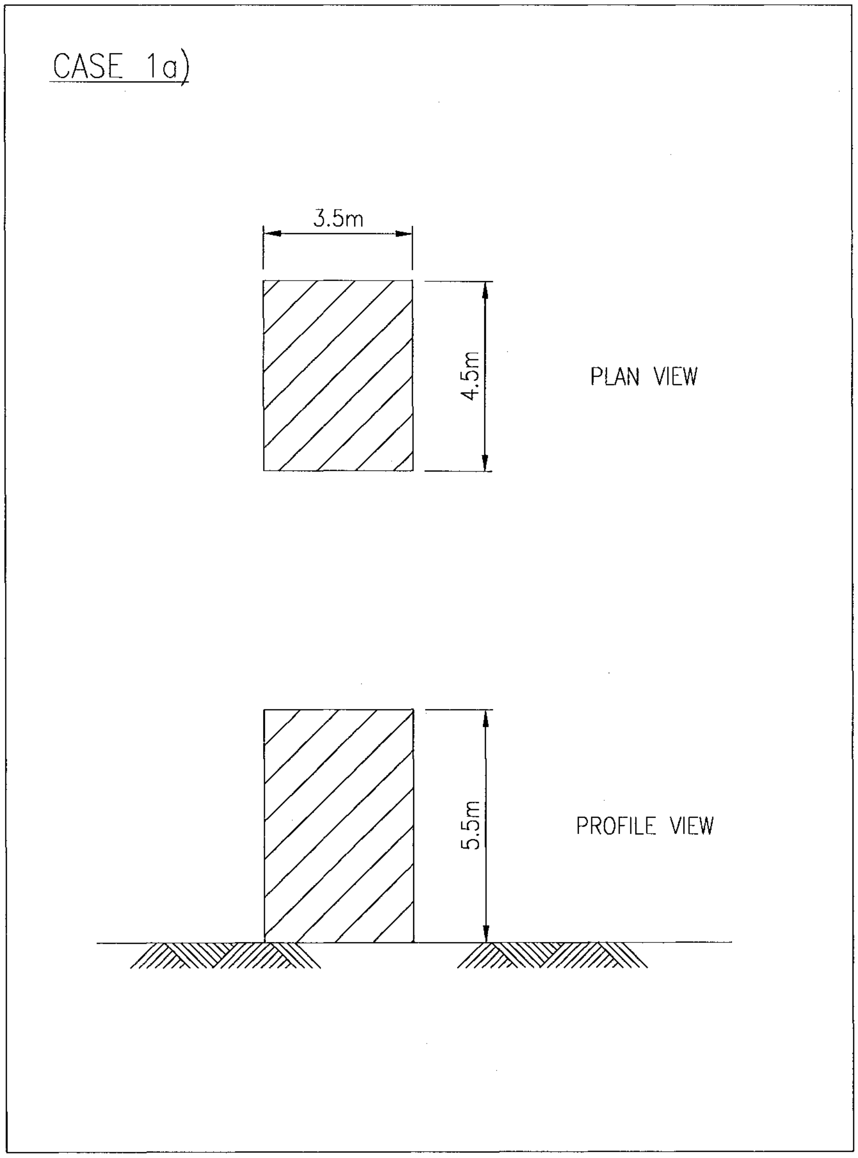

Figure 51 Case 1a - Conventional Xmas Tree Installed at Seabed Level (Base Case)

The conventional Xmas tree installed at seabed level has an effective structure diameter of 5.1 m, assuming equally likely incoming iceberg directions. For this arrangement, the Xmas tree may be impacted from both freely floating and scouring icebergs. The annual probability of contact from freely floating and scouring icebergs is 9.2×10^{-4} and 3.7×10^{-5}, respectively, for a total probability of contact of 9.6×10^{-4} (based on Figures 45 & 46).

Assuming that iceberg contact with the Xmas tree results in a blowout (i.e. SCSSV fails to perform), it is clear that unprotected wells located at seabed level do not alone provide adequate protection from iceberg contact assuming a target level of safety equal to 10^{-5} per annum.

7.2.2 Unprotected Well with Downhole Weak Shear Joint (Case 1b)

Similar to the base case, a conventional well with an unprotected Xmas tree is installed at seabed level but has an added feature located downhole in the form of a weak shear joint located in the well conductor pipe. Specifications for this concept are as follows:

- 3.5 m x 4.5 m plan dimensions of Xmas tree;
- An Xmas tree height 5.5m above seabed level;

- Downhole weak shear joint located in the well conductor pipe located at a specified minimum depth beneath seabed level.

Details of Case 1b) are illustrated in Figure 52.

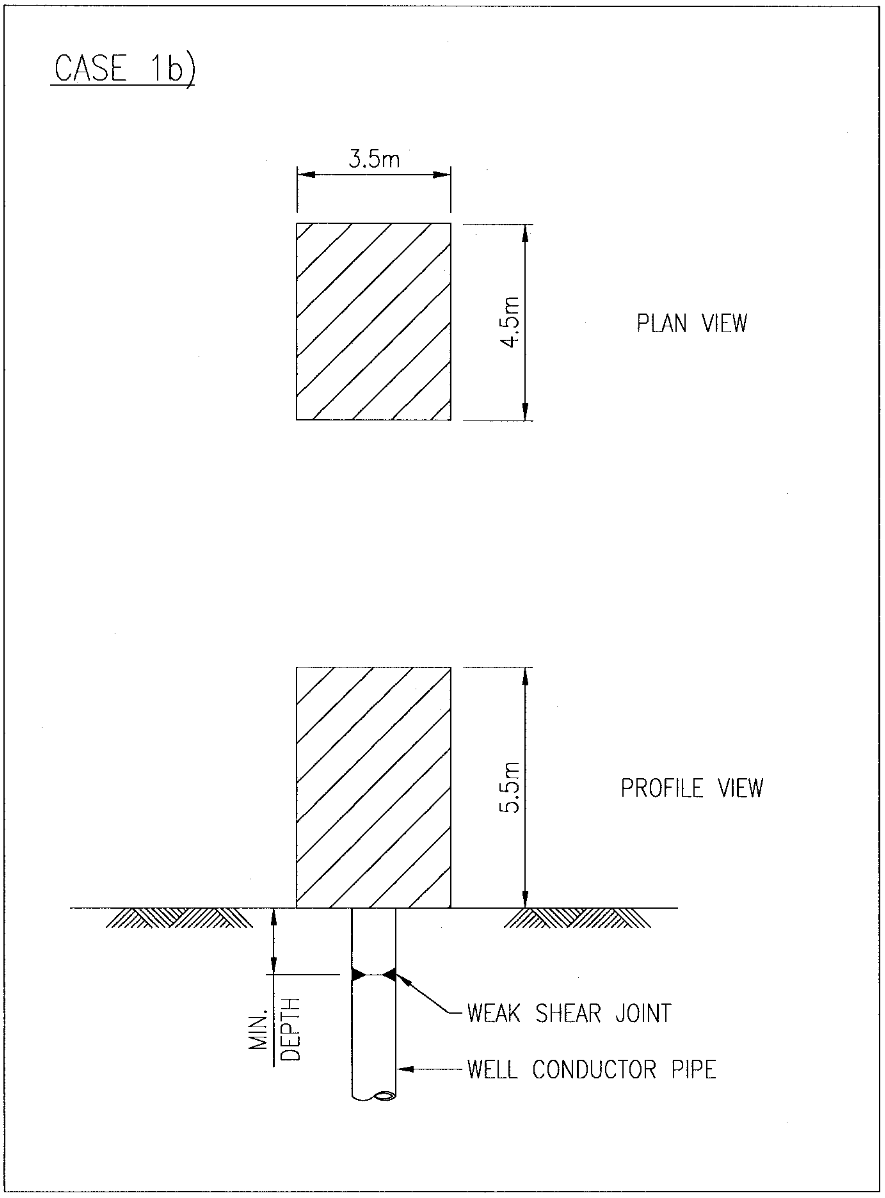

Figure 52 Case 1b - Conventional Xmas Tree Installed at Seabed Level With Downhole Weak Shear Joint

As for Case 1a, the a total probability of contact to the conventional Xmas tree from both from freely floating and scouring icebergs is 9.6 x 10^{-4}. In order to satisfy the required target level of 10^{-5} per annum, the weak shear joint must be located at a minimum depth of 0.6m below the mudline, allowing for 0.3 m scour depth (based on Figure 48) and an equivalent clearance between the bottom of the scour and the shear joint to allow for sub-scour soil deformation. For this particular condition, it is assumed that the Xmas tree and wellhead facilities located at seabed level are sacrificial, while the integrity of the well downhole relies on proper performance of the weak shear joint.

7.2.3 Open Glory Hole (Case 1c)

For this protection concept, the Xmas tree is installed below the mudline in a large diameter open glory hole. The top of the tree is sufficiently deep to minimize the risk from scouring icebergs. Specifications for this concept are as follows:

- 7 m deep hole;
- Mudline glory hole dimensions of 52m x 52m;
- 10 m by 10 m glory hole base dimensions (allows adequate ROV clearance around tree at operational level);
- Slope for sides of glory hole - 3H:1V;
- 3.5 m x 4.5 m plan dimensions of Xmas tree;
- Xmas tree height 5.5m above base of hole;
- Top of Xmas tree 1.5 m below mudline.

Details of Case 1c) are illustrated in Figure 53.

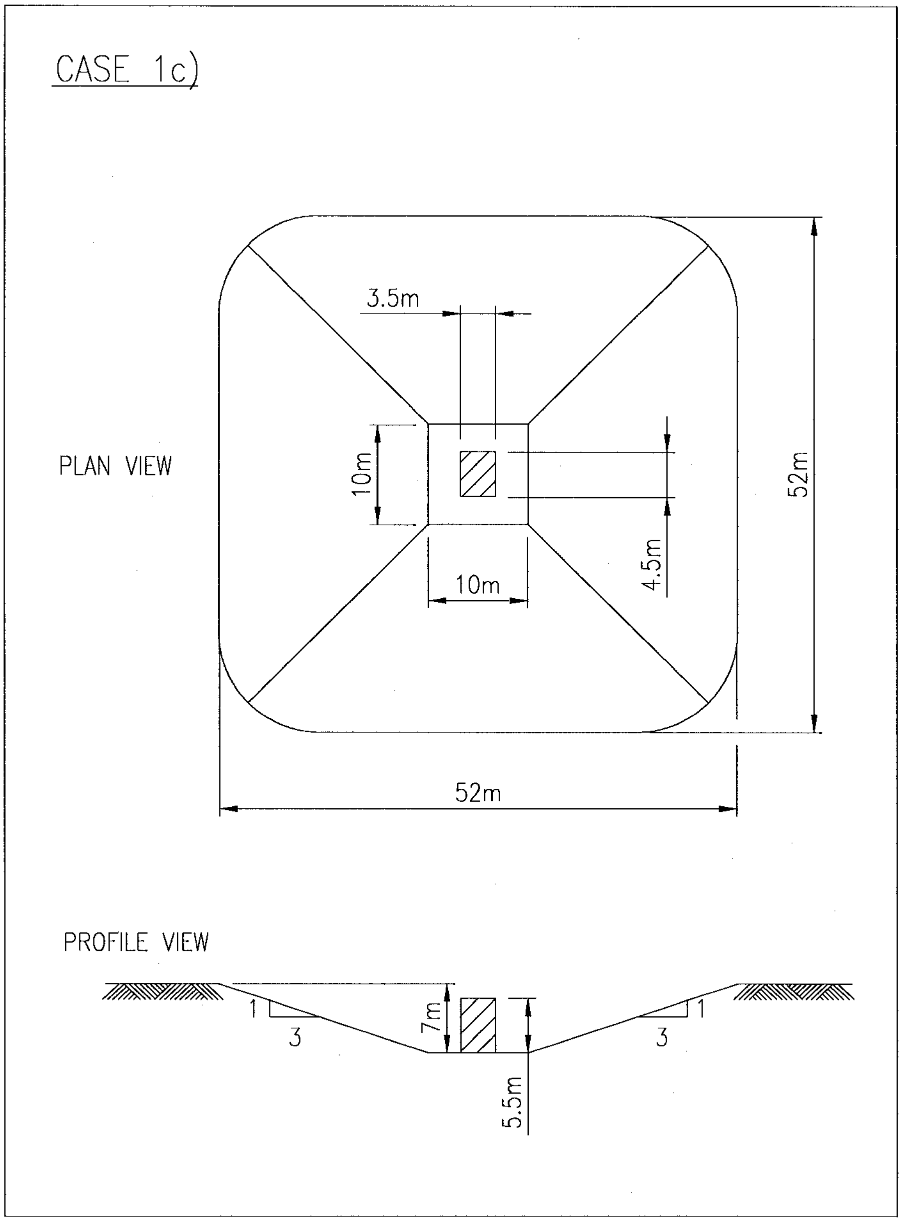

Figure 53 Case 1c - Conventional Xmas Tree Installed in an Open Glory Hole

The open glory hole with mudline plan dimensions of 52 m by 52 m has an effective diameter of 66.2 m, assuming equally likely incoming iceberg directions. The open glory hole concept can only be affected by scouring icebergs. The annual probability of a scouring iceberg entering the open glory hole is 5.6 x 10^{-5}. In order to satisfy the required target level of 10^{-5} per annum, the minimum depth of the top of the Xmas tree below the mudline is 1.45 m (based on Figure 49).

7.2.4 Cased Glory Hole (Case 1d)

In this installation, the Xmas tree is installed below the mudline in a drilled and cased glory hole. The top of the tree is sufficiently deep to reduce the risk from scouring icebergs. The casing has a weak shear plane above the top of the tree. Specifications for this concept are as follows:

- 10 m deep hole;
- 7.3 m outside diameter casing;
- Casing extends 1 m above mudline;
- Casing weak shear plane located at a minimum depth beneath seabed level;
- 3.5 m x 4.5 m plan dimensions of Xmas tree;
- Xmas tree height 5.5m above base of hole.

Details of Case 1d) are illustrated in Figure 54.

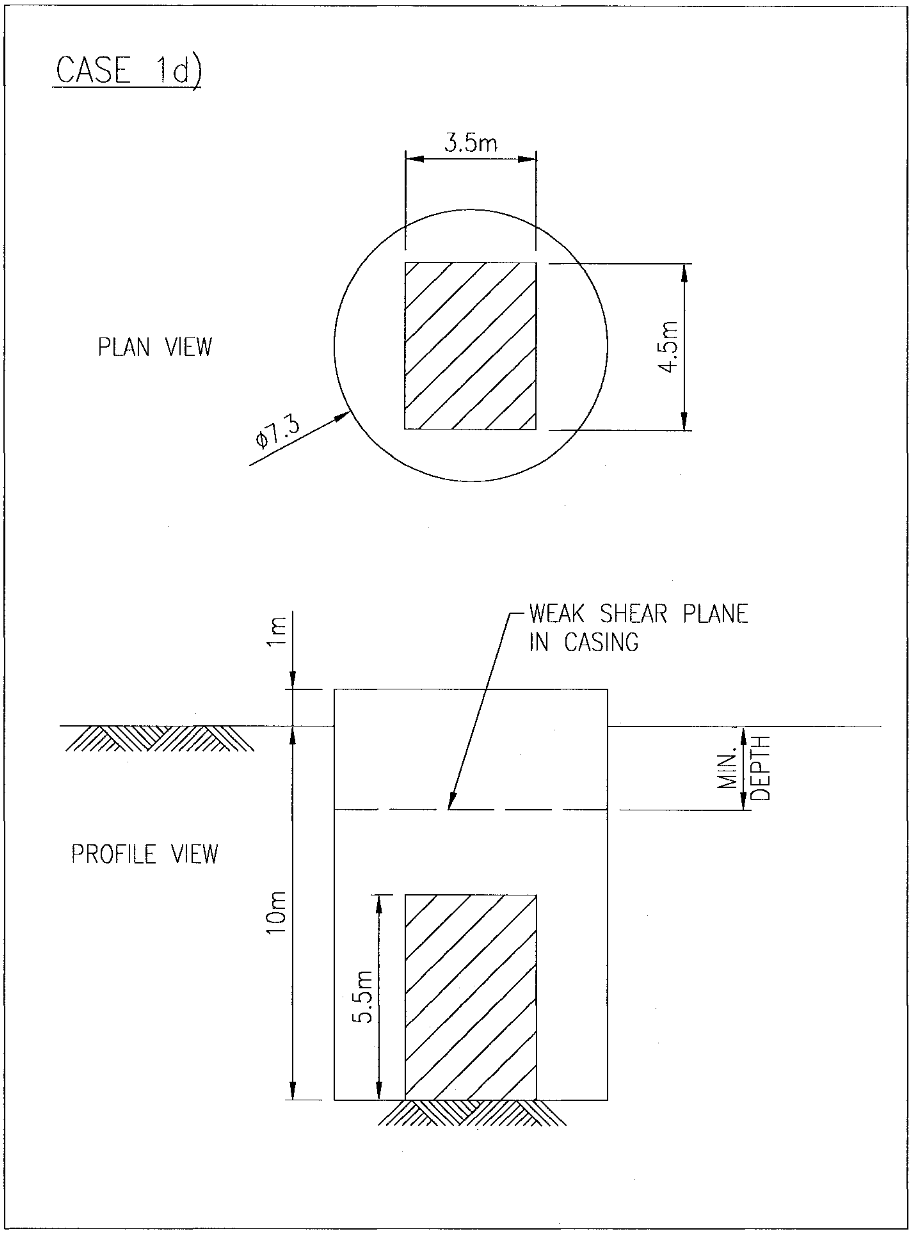

Figure 54 Case 1d - Conventional Xmas Tree Installed in a Cased Glory Hole

The cased hole, with a diameter of 7.3m and a height of 1 m above the mudline may be impacted from both freely floating and scouring icebergs. The annual encounter probability from freely floating and scouring icebergs is 1.7×10^{-4} and 2.6×10^{-5}, respectively, for a total probability of 2×10^{-4} (based on Figures 45 & 46). In order to satisfy the required target level of 10^{-5} per annum, the weak shear plane is located at a minimum depth of 0.8 m below the mudline, allowing for 0.4 m scour depth (based on Figure 48) and an equivalent clearance between the bottom of the scour and the shear joint to allow for sub-scour soil deformation.

7.2.5 Modified Cased Glory Hole (Case 1e)

Similar to the cased glory hole, the Xmas tree is installed below the mudline in a modified cased glory hole. The top of the tree is sufficiently deep to reduce the risk from scouring icebergs. The vertical casing for this concept only extends to 1.0 m above the Xmas tree, thereby eliminating any requirements for a shear plane. Specifications for this concept are as follows:

- 10 m deep hole;
- 7.3m outside diameter casing;
- Hole plan dimensions of 16 m dia. at mudline and 7.3 m dia. at base;
- Vertical casing up to 6.5 m from the base of the hole;
- Side slopes equal to 40 degrees will be assumed for the top 3.5 m portion of the hole;
- Soil reinforcement fabric installed on upper side slopes (if required);
- Inner protective shield installed 1m above the Xmas tree;
- 3.5 m x 4.5 m plan dimensions of Xmas tree;
- An Xmas tree height of 5.5m above base of hole;
- Top of Xmas tree located at 4.5m beneath seabed level.

Details of Case 1e) are illustrated in Figure 55.

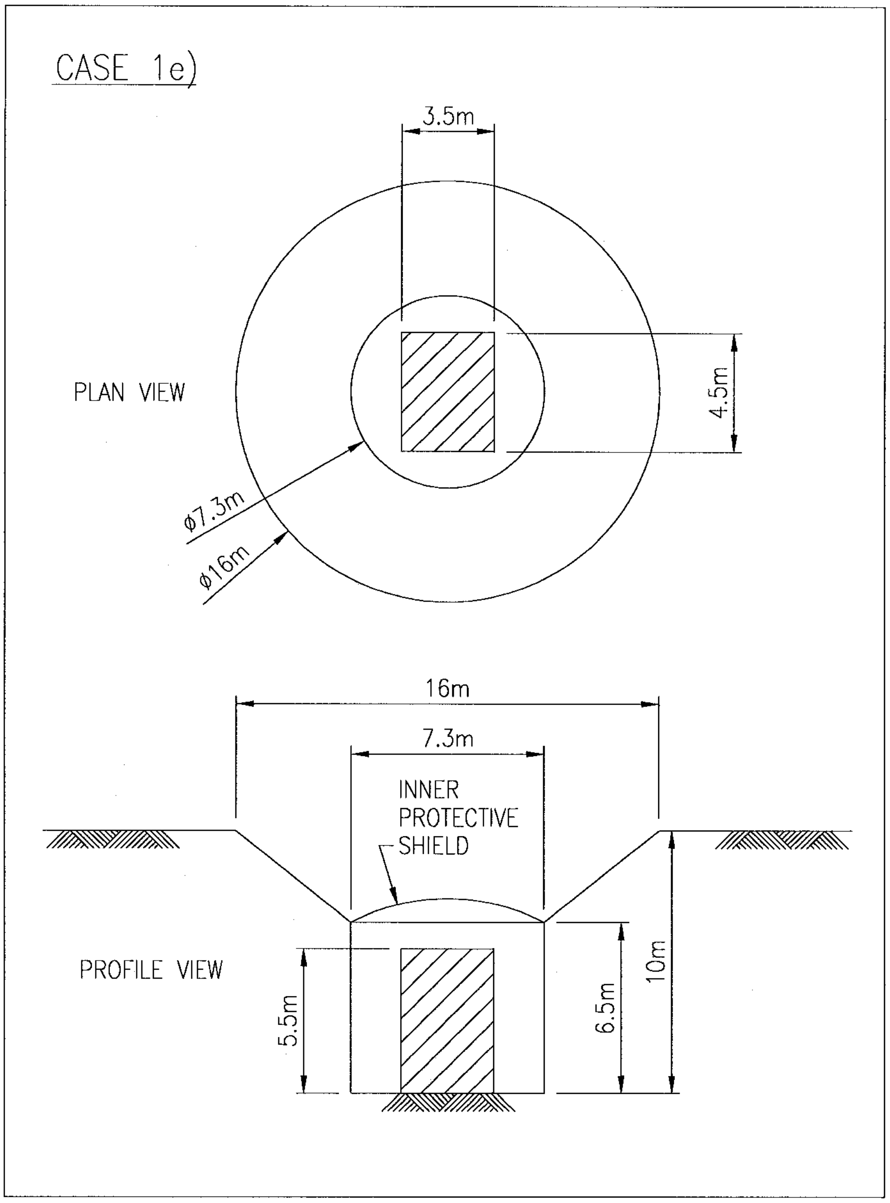

Figure 55 **Case 1e - Conventional Xmas Tree Installed in a Modified Cased Glory Hole**

The modified cased hole, with a diameter of 16 m can only be affected from scouring icebergs. The annual probability of a scouring iceberg entering the cased glory hole is 2.5 x 10^{-5}. In order to satisfy the required target level of 10^{-5} per annum, the minimum depth of the top of the Xmas tree below mudline is 0.5 m (based on Figure 48).

7.2.6 Caisson Wellhead System (Case 1f)

The shearable caisson system with the sacrificial tree has a conventional tree installed at the mudline with a caisson that extends approximately 5 m below the mudline. The caisson has a weak shear joint located at sufficient depth to minimize the probability of iceberg damage to the wellhead below it. Specifications for this concept are as follows:

- 1.5 m outside diameter caisson;
- Weak shear joint located at a minimum depth below the mudline;
- Top of the wellhead is located 4.5 m below seabed level;
- Top of Xmas tree 5.5 m above mudline;
- 3.5 m x 4.5 m plan dimensions of Xmas tree.

Details of Case 1f) are illustrated in Figure 56.

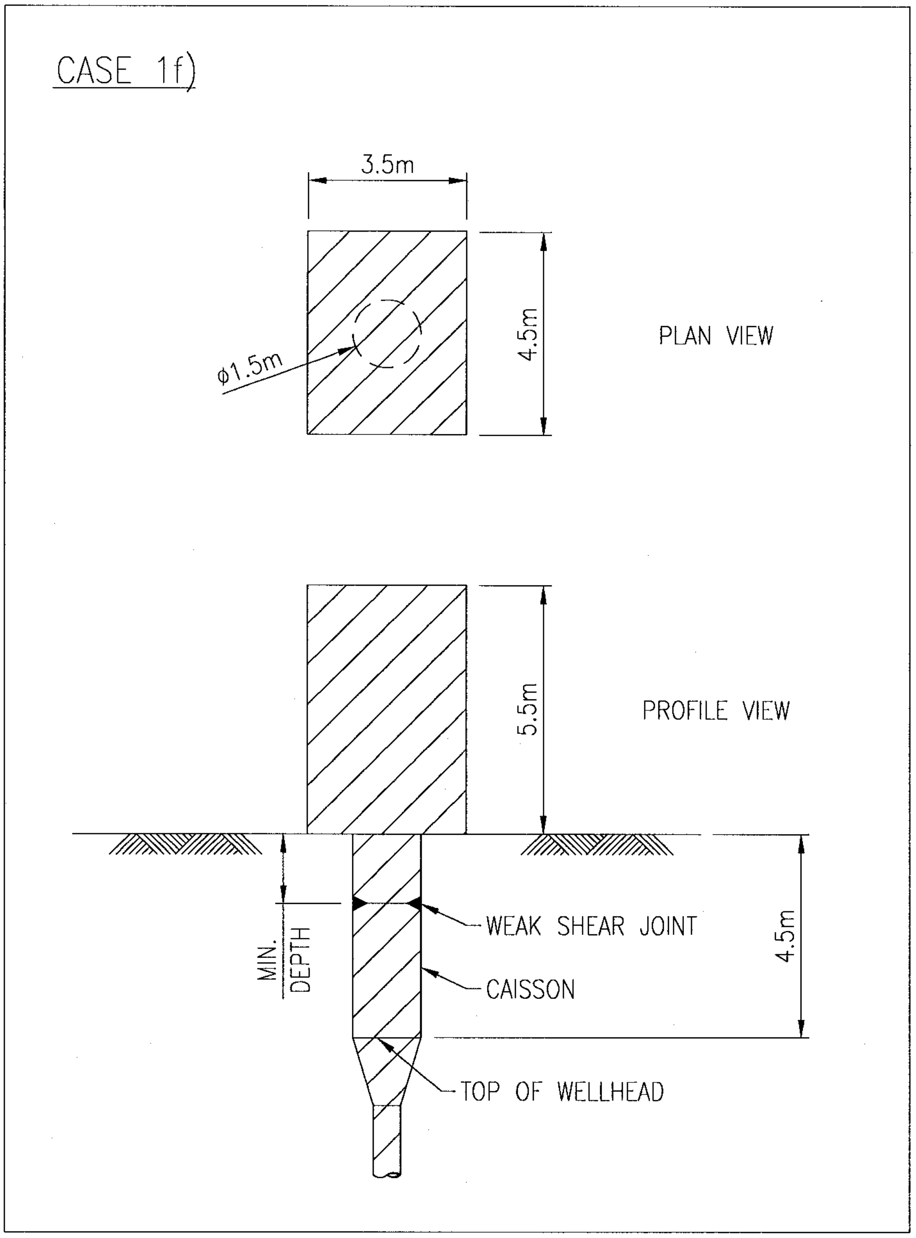

Figure 56 Case 1f - Caisson Wellhead Completion System With Sacrificial Xmas Tree

The caisson completion system Xmas tree, with 3.5 m by 4.5 m plan dimensions, has an effective structure diameter of 5.1 m, assuming equally likely incoming iceberg directions. The 5.5m high Xmas tree may be impacted from both freely floating and scouring icebergs. The annual probability of contact from freely floating and scouring icebergs is 9.2 x 10^{-4} and 3.7 x 10^{-5}, respectively, for a total probability of contact of 9.6 x 10^{-4} (based on Figures 45 & 46). In order to satisfy the required target level of 10^{-5} per annum, the weak shear joint in the caisson must be located a minimum depth of 0.6 m below the mudline, allowing for 0.3m scour depth (based on Figure 48) and an equivalent clearance between the bottom of the scour and the shear joint to allow for sub-scour soil deformation. For this condition, it is assumed that the Xmas tree and wellhead facilities located at seabed level are sacrificial and the integrity of the well relies on proper performance of the weak shear joint.

7.3 Clustered Multi-well Development

7.3.1 Unprotected Wells (Case 2a)

Six conventional wells with unprotected Xmas trees at the mudline represent the base case for the clustered multi-well development. The six conventional wells and Xmas trees are placed in two rows of three around a common manifold at seabed level. Specifications for this concept are as follows:

- 6 wells in total (2 rows of 3);
- Each well system as per Case 1a;
- Manifold plan dimensions equal to 10 m x 5 m;
- Manifold located at seabed level central to well cluster;
- A minimum distance of 25 m between Xmas trees and all other permanent equipment.

Details of Case 2a) are illustrated in Figure 57.

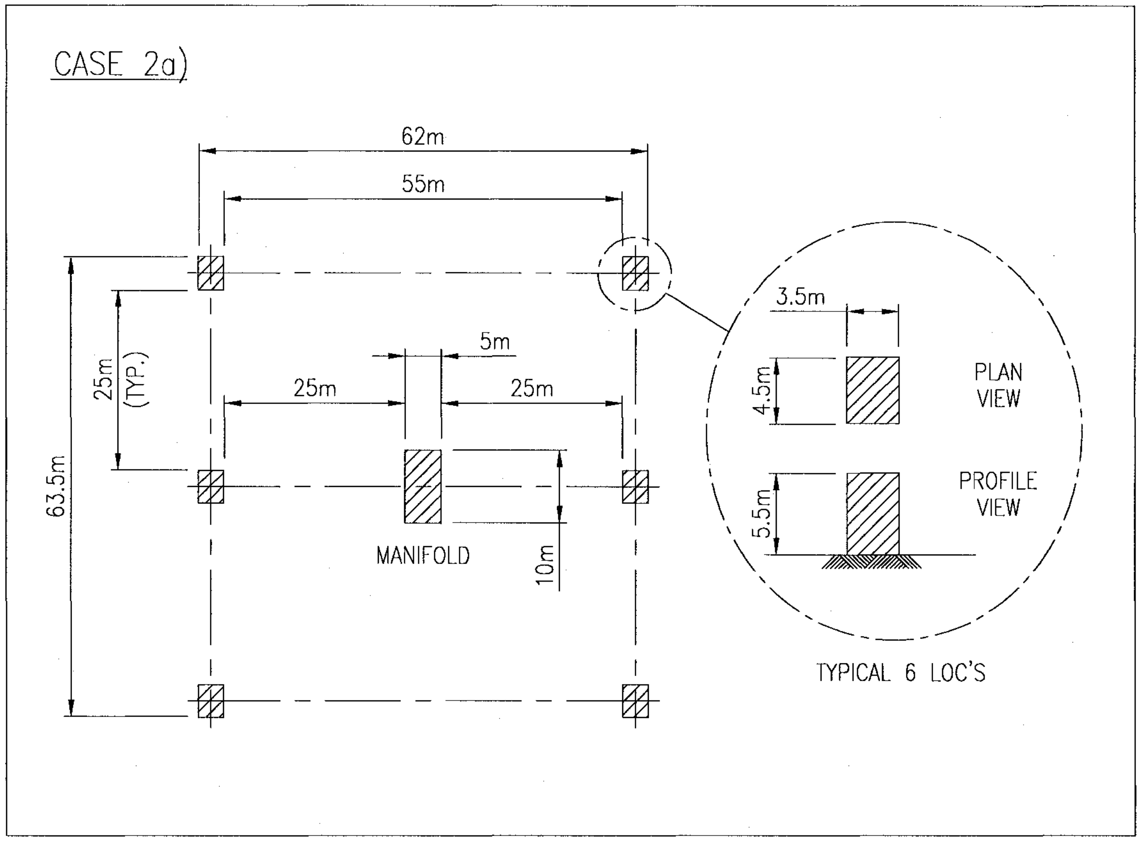

Figure 57 Case 2a – Clustered Wells with Unprotected Xmas Trees Placed at Seabed Level (Base Case)

The total plan layout area for the cluster of six unprotected wells is 63.5 m by 62 m. Assuming equally likely incoming iceberg directions, this equates to an effective diameter of 80 m. The unprotected wells may be impacted from both freely floating and scouring icebergs. The annual probability of encountering the well cluster and making contact with one or more wells from freely floating and scouring icebergs is 2.5×10^{-3}

and 8.4 x 10^{-5}, respectively, for a total probability of 2.6 x 10^{-3} (based on Figures 45 & 46).

Assuming that iceberg contact with the Xmas tree results in a blowout (i.e. SCSSV fails to perform), it is clear that an unprotected multi-well cluster located at seabed level do not alone provide adequate protection from iceberg contact assuming a target level of safety equal to 10^{-5} per annum.

7.3.2 Unprotected Wells With Downhole Weak Shear Joint (Case 2b)

Similar to the base case multi-well concept (Case 2a), six conventional wells with unprotected Xmas trees are installed at seabed level but a weak shear plane located downhole in the well conductor pipe is incorporated. The six conventional wells and Xmas trees are placed in two rows of three around a common manifold. Specifications for this concept are as follows:

- 6 wells in total (2 rows of 3);
- Each well system as per Case 1b;
- Downhole weak shear joint in each well conductor pipe located at a minimum depth beneath seabed level;
- Manifold plan dimensions equal to 10 m x 5 m;
- Manifold located at seabed level central to well cluster;
- A minimum distance of 25 m between Xmas trees and all other permanent equipment.

Details of Case 2b) are illustrated in Figure 58.

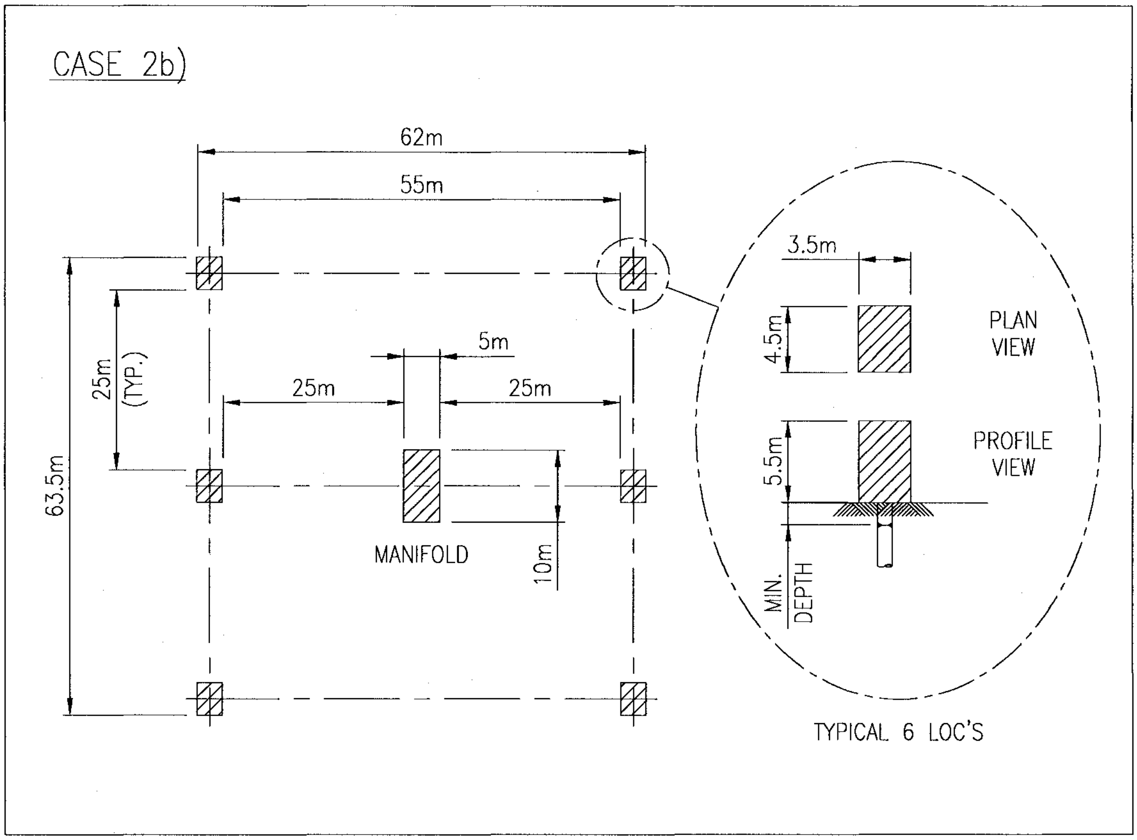

Figure 58 Case 2b – Clustered Wells with Xmas Trees Unprotected Placed at Seabed Level

As for Case 2a, the a total probability of encountering the well cluster and making contact to one or more conventional Xmas trees from both from freely floating and scouring icebergs is 2.6 x 10^{-3}. In order to satisfy the required target level of 10^{-5} per annum for the well cluster, the weak shear joints in the conductor pipes must be located at a minimum depth of 3.2 m below the mudline, allowing for 1.6 m scour depth and an equivalent clearance between the bottom of the scour and the shear joint to allow for sub-scour soil deformation.

7.3.3 Open Glory Hole (Case 2c)

For this protection concept, six Xmas trees are installed below the mudline in a large diameter open glory hole. The six conventional wells and Xmas trees are placed in two rows of three around a common manifold. The top of the trees is sufficiently deep enough to minimize the risk from scouring icebergs. Specifications for this concept are as follows:

- Clustered multi-well system as per Case 2a positioned in an 8 m deep glory hole;
- Mudline glory hole dimensions of 122m x 120m;
- 74 m by 72 m glory hole base dimensions (allows adequate ROV clearance around tree at operational level);
- Slope for sides of glory hole - 3H:1V;
- Top of Xmas tree 2.5 m below mudline;
- Manifold plan dimensions equal to 10 m x 5 m;
- Manifold located in open glory hole central to well cluster;
- A minimum distance of 25 m between Xmas trees and all other permanent equipment.

Details of Case 2c) are illustrated in Figure 59.

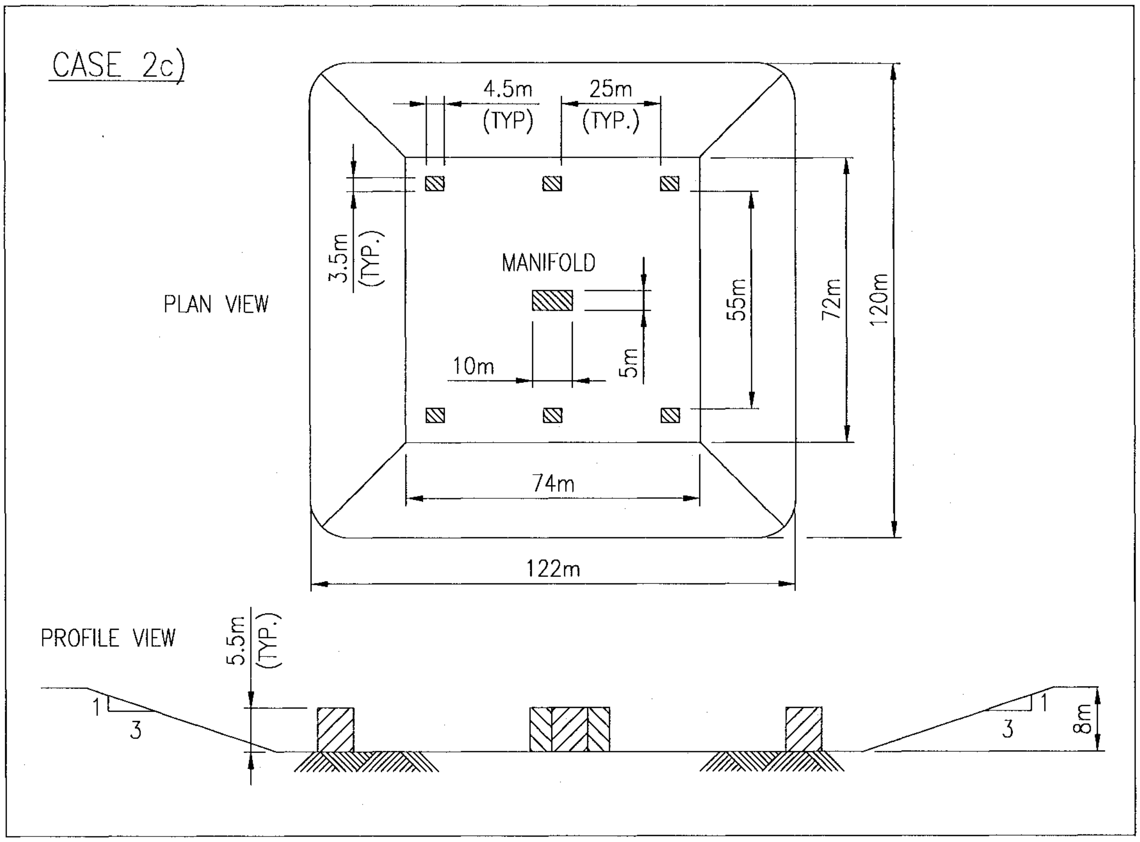

Figure 59 **Case 2c – Clustered Wells with Xmas Placed in a Large Open Glory Hole**

The open glory hole has mudline dimensions of 122 m by 120 m, equating to an effective structure diameter of 154 m, assuming equally likely incoming iceberg directions. The open glory hole concept can only be affected by scouring icebergs. The annual probability of a scouring iceberg entering the open glory hole is 1.1×10^{-4}. In order to satisfy the required target level of 10^{-5} per annum, the minimum depth of the top of the Xmas tree below the mudline is 2 m (based on Figure 49).

7.3.4 Cased Glory Holes (Case 2d)

Six conventional wells are placed in cased glory holes for this protection concept. The six cased holes are placed in two rows of three and tied into a common manifold. Each well and Xmas tree arrangement is identical to the Case 1c system. Specifications for this concept are as follows:

- 6 wells in total (2 rows of 3);
- Each well system as per Case 1d;
- Casing weak shear plane located at a minimum depth beneath seabed level;
- Manifold plan dimensions equal to 10 m x 5 m;
- Manifold located at seabed level central to well cluster;
- A minimum distance of 25 m between holes and all other permanent equipment.

Details of Case 2d) are illustrated in Figure 60.

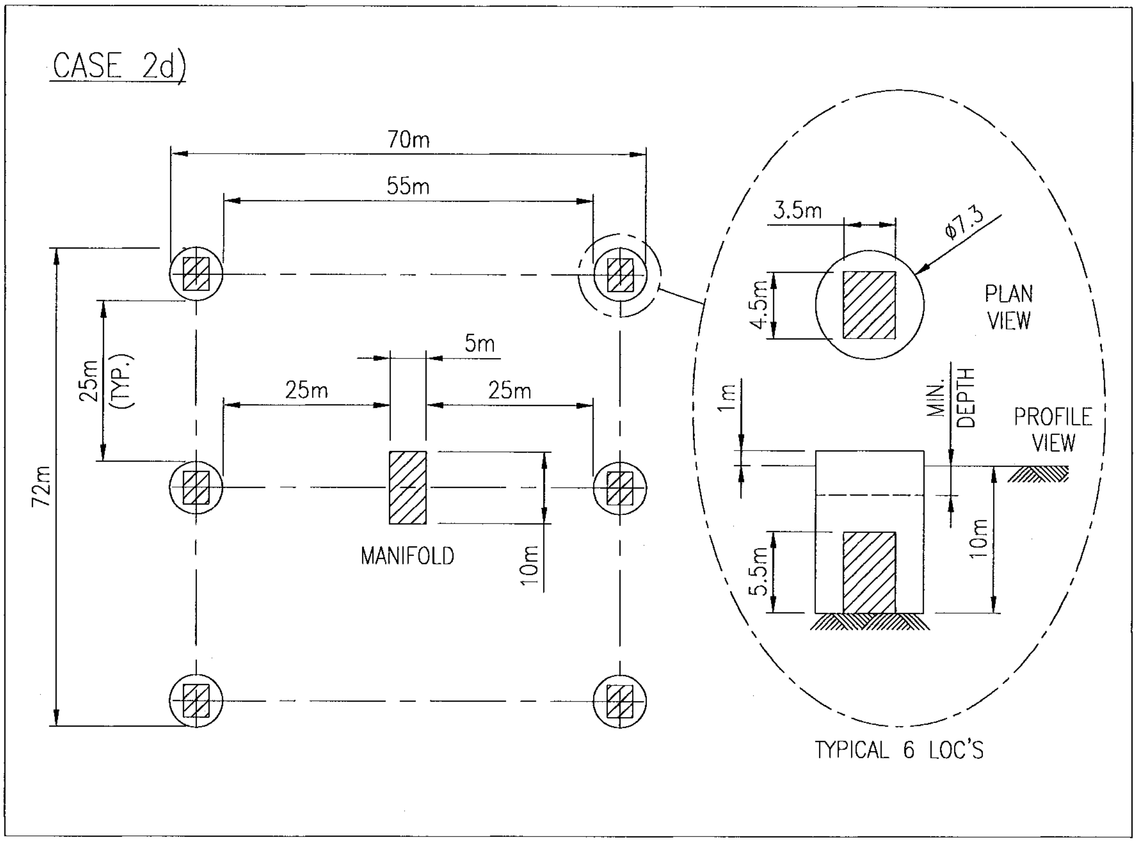

Figure 60 Case 2d – Clustered Wells with Xmas Trees Placed in Cased Glory Holes

The cluster of six 7.3 m diameter cased glory holes occupies a plan area measuring 72 m by 70 m, for an effective diameter of 90 m assuming equally likely incoming iceberg directions. The cased holes may be impacted from both freely floating and scouring icebergs. The annual probability of encountering the well cluster and making contact with one or more wells from freely floating and scouring icebergs is 5.7 x 10^{-4} and 7.7 x 10^{-5}, respectively, for a total probability of 6.5 x 10^{-4} (based on Figures 45 & 46). To achieve the annual target level of safety of 10^{-5} for one or more wells, the shear plane of the casing must be a minimum of 3.4 m below the mudline. This includes equal provisions for scour and sub-scour deformations.

7.3.5 Modified Cased Glory Holes (Case 2e)

Similar to the cased glory holes, the six Xmas trees are installed below the mudline in modified cased glory holes. The six cased holes are placed in two rows of three and tied into a common manifold. Each well and Xmas tree arrangement is identical to the Case 1d system. Specifications for this concept are as follows:

- 6 wells in total (2 rows of 3);
- Each well system as per Case 1e;
- Top of Xmas tree located at 4.5m beneath seabed level;
- Manifold plan dimensions equal to 10 m x 5 m;
- Manifold located at seabed level central to well cluster;
- A minimum distance of 25 m between holes and all other permanent equipment.

Details of Case 2e) are illustrated in Figure 61.

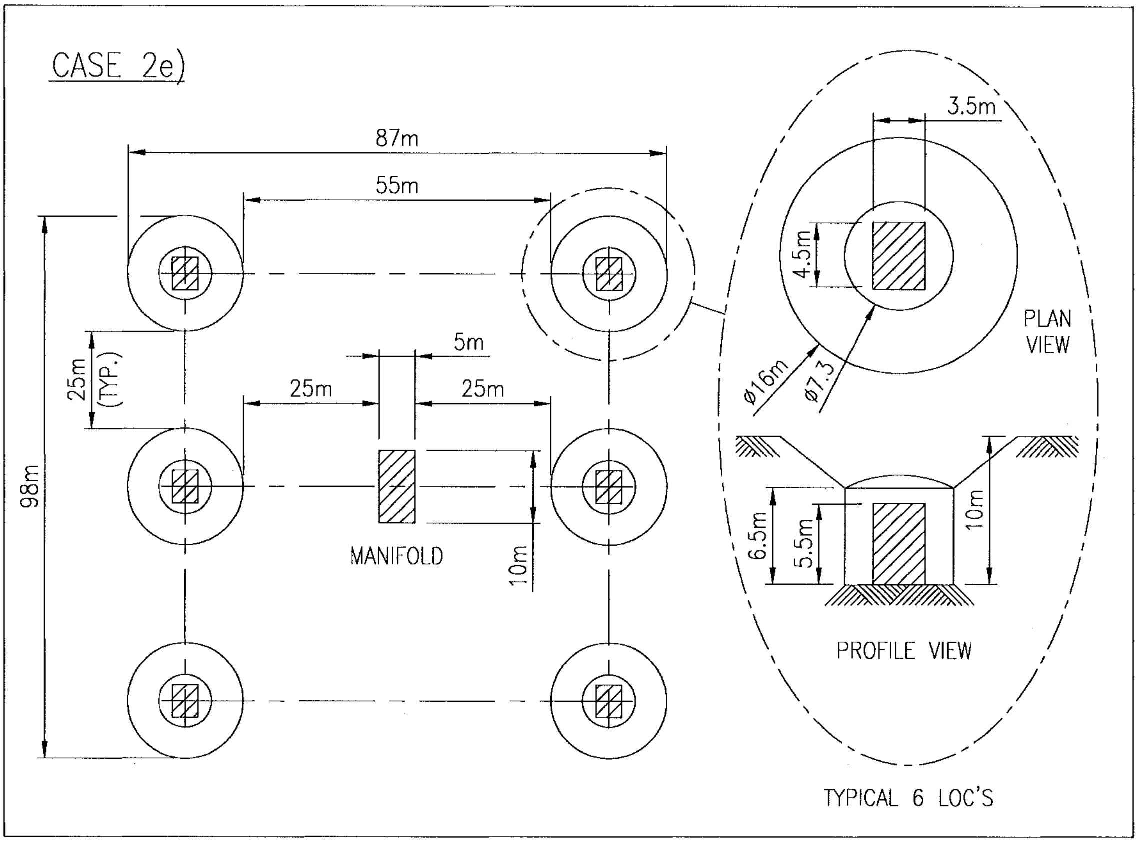

Figure 61 Case 2e – Clustered Wells with Xmas Trees Placed in Modified Cased Glory Holes

The cluster of six modified cased holes, with a diameter of 16 m occupies a plan area measuring 87 m by 98 m, for an effective diameter of 118 m assuming equally likely incoming iceberg directions. The modified cased holes may be impacted from scouring icebergs only. The annual probability of encountering the well cluster and entering one or more wells is 8.8×10^{-5}. To achieve the annual target level of safety of 10^{-5} for one or more wells, the top of the Xmas trees must be a minimum of 1.8 m below the mudline.

7.3.6 Caisson Wellhead Systems (Case 2f)

This installation consists of six shearable caisson systems in two rows of three tied into a common manifold. Each of the caisson completion systems are identical to the one described for Case 1f. Specifications for this concept are as follows:

- 6 wells in total (2 rows of 3);
- Each well system as per Case 1f;
- Weak shear plane located at a minimum depth below mudline;
- Manifold plan dimensions equal to 10 m x 5 m;
- Manifold located at seabed level central to well cluster;
- A minimum distance of 25 m between Xmas trees and all other permanent equipment.

Details of Case 2f) are illustrated in Figure 62.

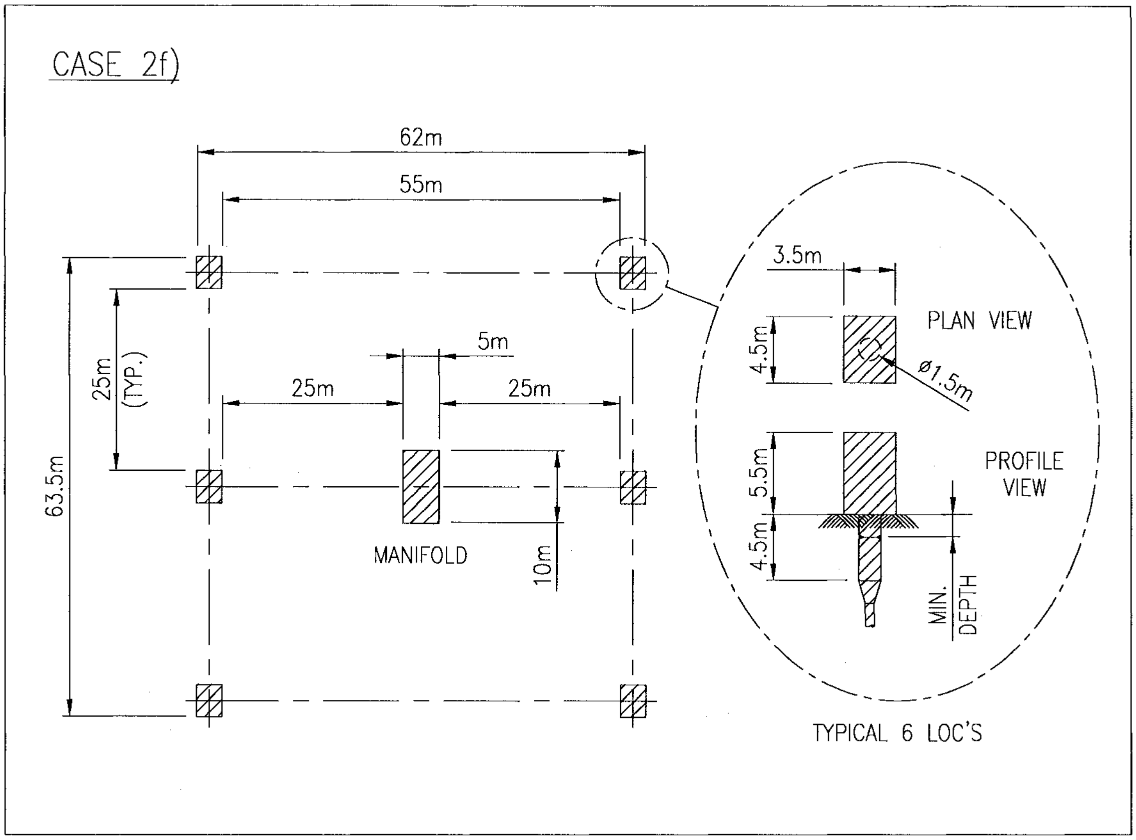

Figure 62 Case 2f – Clustered Wells with Caisson Wellhead Completion Systems

The cluster of six caisson completion systems occupies an area measuring 62 m by 63.5 m, for an effective diameter of 80 m assuming equally likely incoming iceberg directions. The caisson systems may be impacted from both freely floating and scouring icebergs. The annual probability of encountering the well cluster and making contact with one or more caissons from freely floating and scouring icebergs is 2.5×10^{-3} and 8.4×10^{-5}, respectively, for a total probability of 2.6×10^{-3} (based on Figures 45 & 46). To achieve the annual target level of safety of 10^{-5} for one or more wells, the shear plane of the caisson must be a minimum of 3.2 m below the mudline. This includes equal provisions for scour and sub-scour deformations.

7.4 Summary of Iceberg Encounter Results

The approach taken in this Chapter with respect to probability of iceberg encounter accounts for the expected range of iceberg and environmental conditions for the study area (defined by degree square 46° to 47° N and 48° to 49° W) and the physical features of the installations. As outlined in Chapter 5, an annual target level of safety of 10^{-5} against blowout was established for both the single well and clustered multi-well developments. A summary of the iceberg encounter results for the single and multi-well systems as evaluated in Sections 7.2 & 7.3 are presented below in Tables 16 & 17, respectively.

The effectiveness of iceberg management for reducing the likelihood of iceberg encounter has also been considered in the results presented in Tables 16 & 17 by applying an overall success rate of 85%. Iceberg management essentially reduces the probability of iceberg contact by an amount proportional to the probability of success. For this investigation, calculations of contact probability with iceberg management has assumed that physical management would only be effective for floating icebergs as it is unlikely that a scouring iceberg would respond to existing iceberg deflection techniques. The scouring component in the calculation for overall annual encounter probability is therefore not reduced.

Table 16 Summary of Iceberg Encounter Results - Single Satellite Well Developments

Case	Description	Iceberg Management Effectiveness	Annual Encounter[1] Probability	Required Depth[2] to Satisfy TLS Against Blowout[3]
1a	Unprotected Well	0%	9.6×10^{-4}	-
		85%	1.8×10^{-4}	-
1b	Unprotected Well w/ Weak Shear Joint	0%	9.6×10^{-4}	0.6 m
		85%	1.8×10^{-4}	
1c	Open Glory Hole[4]	0%	5.6×10^{-5}	1.45 m
		85%	5.6×10^{-5}	
1d	Cased Glory Hole	0%	2×10^{-4}	0.8 m
		85%	5.2×10^{-5}	
1e	Modified Cased Hole[4]	0%	2.5×10^{-5}	0.5 m
		85%	2.5×10^{-5}	
1f	Caisson Wellhead System	0%	9.6×10^{-4}	0.6 m
		85%	1.8×10^{-4}	

Notes:

1. "Encounter" occurs when a scouring iceberg enters an open glory hole or modified cased hole, or when a floating or scouring iceberg contacts a cased glory hole or the Xmas tree of a caisson system, or unprotected tree.

2. The "Required Depth" is the minimum depth required to the top of the Xmas tree, shear plane or shear joint in order to satisfy the annual target level of safety (TLS) of 10^{-5}.

3. "Blowout" occurs when a scouring iceberg penetrates deep enough into an open or glory hole or modified cased hole to contact the protected Xmas tree, scours deep enough to impact below the shear joint/plane in the unprotected well with downhole shear joint, caisson system or cased glory hole, or contacts an unprotected Xmas tree.

4. Open glory hole and modified cased hole installations are only affected by scouring icebergs.

Table 17 Summary of Iceberg Encounter Results - Clustered Mulit-well Developments

Case	Description	Iceberg Mgnt Effectiveness	Annual Encounter[1] Probability	Required Depth[2] to Satisfy TLS Against Blowout[3]
2a	Unprotected Wells	0%	2.6×10^{-3}	-
		85%	4.6×10^{-4}	-
2b	Unprotected Wells w/ Weak Shear Joint	0%	2.6×10^{-3}	3.2 m
		85%	4.6×10^{-4}	
2c	Open Glory Hole[4]	0%	1.1×10^{-4}	2.0 m
		85%	1.1×10^{-4}	
2d	Cased Glory Holes	0%	6.5×10^{-4}	3.4 m
		85%	1.6×10^{-4}	
2e	Modified Cased Holes[4]	0%	8.8×10^{-5}	1.8 m
		85%	8.8×10^{-5}	
2f	Caisson Wellhead Systems	0%	2.6×10^{-3}	3.2 m
		85%	4.6×10^{-4}	

Notes:

1. "Encounter" occurs when a scouring iceberg enters an open glory hole or modified cased hole, or when a floating or scouring iceberg contacts a cased glory hole or the Xmas tree of a caisson system, or unprotected tree.

2. The "Required Depth" is the minimum depth required to the top of the Xmas tree, shear plane or shear joint in order to satisfy the annual target level of safety (TLS) of 10^{-5}.

3. "Blowout" occurs when a scouring iceberg penetrates deep enough into an open or glory hole or modified cased hole to contact the protected Xmas tree, scours deep enough to impact below the shear joint/plane in the unprotected well with downhole shear joint, caisson system or cased glory hole, or contacts an unprotected Xmas tree.

4. Open glory hole and modified cased hole installations are only affected by scouring icebergs.

In contrast to single well developments, it is possible for more than one well to be contacted by an iceberg that encroaches into the area occupied by a multi-well development. Determining an average number of hits is difficult and depends on a number of factors including:

- Layout of the multi-well cluster;
- Dimensions of Xmas tree;
- Iceberg varying keel width;
- Iceberg travel condition (i.e. free floating or scouring);
- Orientation of iceberg motion with respect to the cluster;
- Mass of the iceberg; and
- Iceberg Response when contact is made with one or more wells.

Although the probability is quite low, it is possible that all six wells of a clustered multi-well development could be hit during one iceberg event. Based on the layouts presented in Section 7.3 and iceberg keel characteristics as presented in Section 6.2.1.3, it is physically possible for an encroaching iceberg to sweep through the area and contact all six wells. For example, the area occupied by the well clusters in Section 7.3 consists of two rows of three wells, separated by a dimension equal to 55 m. A scouring iceberg with the base of its keel 0.5 m beneath seabed has an effective keel width of 55 m at a position 5.5 m above seabed level (height of Xmas tree), making this scenario possible.

7.5 Conservatisms and Limitations in Well Blowout Calculations

For all well systems considered, it was assumed that any iceberg contact with an Xmas tree was to result in a blowout. For unprotected wells with a downhole shear joint, caisson completion systems and cased glory holes, contact or influence of the iceberg below the shear joint/plane was also assumed to result in a blowout. This is quite conservative considering that any substantial damage caused by iceberg contact with an Xmas tree or well will result in the activation of reliable failsafe systems such as SCSSV's. As a result, a significant amount of conservatism was introduced into the results presented in Tables 16 and 17 by assuming blowout upon iceberg contact and by not considering the effectiveness of SCSSV's. This is possibly the greatest source of conservatism in the iceberg encounter calculations.

No provisions have been made in the calculations to account for the mechanical strength of the installations or the possibility of ice failure upon contact. For all systems, there is a probability of an iceberg "glancing" upon contact causing only minimal damage to the facilities and no loss of hydrocarbons. Direct impacts may only result in damage to secondary components, leaving key components such as the wellhead or master valves structurally unaffected. If this effect were to be included in the calculations, a reduced probability of blowout could be achieved.

For the systems with weak shear planes and joints located below the mudline, they have been assumed to work perfectly for iceberg contacts above the shear plane/joint (assuming some allowance of sub-scour deformations). While this is a realistic assumption, perfect operation of these weak planes/joints cannot be guaranteed. On the other hand, iceberg incursion below the shear plane will most likely result in loss of pressure and activation of the SCSSV and/or the master valve. The net effect of these factors is expected to result in a substantially reduced blowout probability than stated in Tables 16 and 17.

The influence of both bathymetric filtering and bathymetric shielding has not been taken into consideration in the probability of encounter calculations. A conservative approach has been taken by not modifying the distribution of iceberg drafts to account for icebergs with drafts greater that the water depth that will ground and be filtered out of the keel population. In addition, installations are assumed to be exposed to incoming icebergs right down to the mudline. In practice, there will be bathymetric shielding at some locations that will reduce the overall probability of iceberg contact.

Values of iceberg areal density ranging from 0.6 to 0.77 icebergs / year / degree square have been documented based on data collected over different time periods (1960-2000 vs. 1981-2000). The more conservative value of 0.77 for areal density has been used in the calculations for the purpose of this investigation.

Iceberg drift directionality has not been considered. A non-directional approach has been taken with respect to iceberg drift data, which assumes that the probability of contact with a subsea facility is equal from all compass directions. By considering the distribution of iceberg drift directions, the probability of contact can be potentially be reduced.

For scouring icebergs with installations below seabed, the effective keel width L_d has been assumed to be equal to 24m. This value corresponds to the mean scour width in water depths ≤ 110m on the Grand Banks (Croasdale et al., 2000). This is a somewhat conservative approach because it corresponds to the width of a scouring iceberg at seabed level. The width of an iceberg at any point below the mudline could be less, especially at the very base of an iceberg keel, which would result in an overall lower probability of contact for scouring icebergs.

In calculating encounter and contact probabilities for open glory holes, the actual footprint of the wellhead installation at the base of the hole is much smaller than the mudline dimensions. While it is possible that an iceberg enters the hole without damaging the wellhead, this possibility has not been taken into consideration. Similarly, when calculating the depth of a shear planes or shear joints for multi-well clusters, the total occupied plan area of the installation is assumed. While it is possible that an iceberg enters the occupied area of the multi-well installation without making contact with any one or more wells, this possibility has also not been considered. Both of these assumptions increase calculated impact probabilities.

The effect of iceberg management has been factored into the iceberg encounter calculations summarized in Tables 16 and 17. Although successful iceberg management systems are currently in place on the Grand Banks, the achievable success rates for satellite type developments may be somewhat lower due to the larger coverage areas and additional amount of required resources. Although iceberg management will have an effect to reduce overall risk, success rates less than 85% could be expected for satellite type developments.

As more data is collected relating to iceberg drift and scour on the Grand Banks, the trend seems to be pointing towards an overall reduction in interaction probabilities. This is due to a number of factors including access to a larger sample of data over a longer period of time and refinement of existing conservatisms through additional research in key areas, both resulting in the refinement of existing prediction methods to determine risk to subsea facilities.

As a result of the issues discussed above, it is apparent that there is a high degree of conservatism inherent in the iceberg encounter and subsequent well blowout estimates calculated for the systems presented in this Chapter.

7.6 Discussion

As summarized in Section 7.5, there is a large amount of conservatism built into the calculations performed for the various well systems presented. Making such allowances may not always be practical, especially from a commercial, economic and project development standpoint. Although the environmental and economic consequences of an uncontrolled blowout, for example, are extreme, the risk estimates of such an event occurring must be realistic, even while taking a conservative approach and "erring on the side of caution".

The intent of this discussion is to investigate two key issues presented in Section 7.5 that offer a high level of conservatism, in an attempt to further understand and illustrate the level of conservatism built-in current probability estimates associated with subsea installations in general.

7.6.1 Effectiveness of SCSSV's

The effectiveness of SCSSV's and other existing fail-safe systems should not be ignored when assessing the overall probability of blowout to a well from iceberg contact. As presented in Section 4.2, under normal operating conditions SCSSV's are quite reliable with a MTTF of 36.7 years, which corresponds to an overall reliability of 0.973. However, during events such as an iceberg contact with a well, the reliability of these safety devices comes into question due to the potential for load transfer to components downhole such as the conductor, casings and production tubing.

C-CORE (2001b) conducted an investigation in order to determine the potential damage effects to a well in the case of iceberg contact with a conventional Xmas tree and wellhead located above seabed. Annual contact frequencies from free floating and scouring icebergs were calculated and combined with structural response calculations to yield annual frequencies for events likely to result in permanent damage to the well outer

36" conductor and 20" casings downhole. A schematic of the well installation considered for this study is presented below in Figure 63.

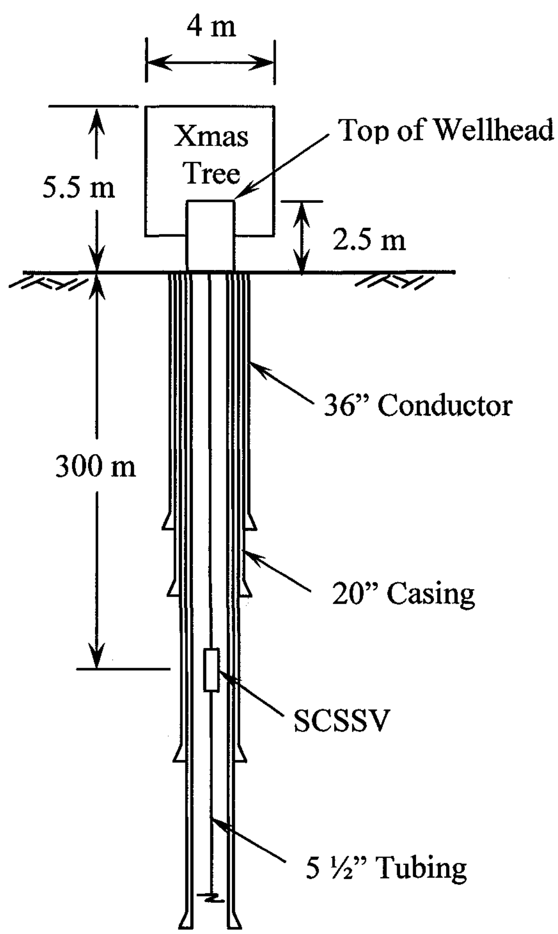

Figure 63 Schematic of Well Installation (C-CORE, 2001b)

Although a number of conservative assumptions were made, the annual frequencies associated with iceberg events that caused permanent damage to the outer well conductors (damage events) ranged between 5×10^{-5} and 2×10^{-4}. It was concluded that corresponding strains to this inner 5 ½" production tubing would be quite small and would not likely be compromised under these conditions. Furthermore, even large deformations of the outer casing are not likely to damage the SCSSV, positioned some

300 m below. The only situation of concern is if the tubing string is pulled out of the hole a significant amount. Further work concluded that by considering the stiffening effect of the guide base at the mudline and the beneficial effect of an additional 48" conductor extended to a depth of 20m, the likelihood of plastic deformation of the constructor string reduced significantly. Resulting annual frequencies of damage events ranged from 1.5 x 10^{-5} to 2.9 x 10^{-5} per well installation, assuming an ice management effectiveness of 86% (C-CORE, 2001c).

Applying the results of the C-CORE (2001c) study to a conventional unprotected well reveals some interesting trends. Assuming a level of ice management of 86%, the annual contact frequency for C-CORE (2001b) was approximately 3 x 10^{-4} per well installation. By dividing the annual frequency of a damage event occurring by this value, the probability of permanent damage given that contact has occurred can be calculated. Using this approach, the probability of permanent damage given that contact has occurred ranges between 5 x 10^{-2} and 9.7 x 10^{-2} per annum. For a conventional unprotected well located on the Grand Banks in 100 m of water as presented in Section 7.2.1, the necessary maximum probability of downhole damage in order to satisfy an annual target level of safety of 10^{-5} is roughly 1.1 x 10^{-2} per annum (assuming an annual probability of contact of 9.6 x 10^{-4} per well as calculated in Section 7.2.1 and an SCSSV reliability of 0.973). If one were to assume that permanent damage to the upper wellbore causes failure to the SCSSV, which in practice is unlikely to be the case, the annual target level of safety against blowout is nearly achieved in this case without relying on any form of wellhead protection or considering the conservatisms presented in Section 7.5.

7.6.2 Refinement of Safety Class Designation

As presented in Chapter 5, the target level of safety of 10^{-5} was established based on a Safety Class 1 designation as outlined in the CSA S471-04 standard. For Safety Class 1, the consequence of failure would result in great risk to life or a high potential for environmental damage. In this case, great risk of human life is not a concern, however, high potential of environmental damage is. The standard also states, "If loading hazards can be predicted sufficiently ahead of time to carry out a predefined emergency response plan that ensures personnel safety and environmental protection, then, for that particular loading condition, the structure may be Safety Class 2." Furthermore, "…a structure designated Safety Class 1 as a whole may have certain of its structural elements designated Safety Class 2."

In terms of predicting an iceberg contact (or encroachment) sufficiently ahead of time, this could be achieved to a certain degree through iceberg detection and management techniques that currently exist in the region. However, although iceberg detection and management does provide a level of protection against iceberg risk, there is insufficient justification to re-classify a subsea installation as Safety Class 2 based solely on the current effectiveness of iceberg management and further uncertainties associated with undeveloped satellite type developments in the region.

As for the designation of safety classes for subsea installations such as a conventional unprotected well, all exposed elements of the Xmas tree and wellhead up to now have been classified as Safety Class 1. Plan and profile dimensions have been selected for probability estimates performed in section 7.2 & 7.3, which make no distinction between critical and secondary components of the installation. This approach however, is considered conservative as the outer perimeter of typical subsea Xmas trees generally consists of primary components / members that if damaged or destroyed, will not have a significant impact on the integrity of the well causing an uncontrolled blowout.

Figure 64 proposes a more refined breakdown of Safety Class for an unprotected Xmas tree installation, which assumes a decrease of 1.0 m for the overall length, width and height dimensions for the Safety Class 1 area.

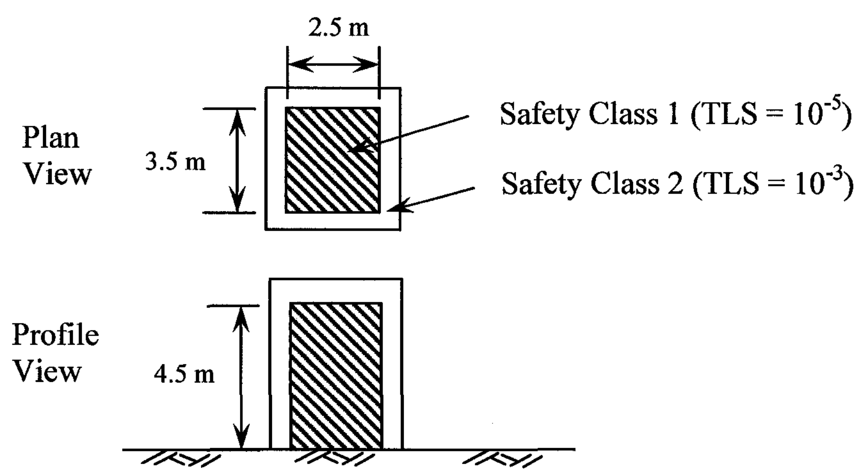

Figure 64 Breakdown of Xmas Tree into Safety Classes

The overall dimensions of the installation stays the same but the outer 0.5 m perimeter falls into the Safety Class 2 category. Based on this approach, a reduction in overall contact probability from freely floating and scouring icebergs equal to 17% is achieved for the safety Class 1 designated area. Similarly, if plan and profile overall dimensions are reduced by 2.0 m for the Safety Class 1 area, a decrease in overall contact probability of 35% is achieved.

7.6.3 Subsea Equipment Layout

As presented in 7.3, layouts for the proposed clustered multi-well developments were established based on a minimum subsea well spacing of 25m from any other permanent equipment. Although this distance has been established to ensure that wellheads are protected from falling drilling and workover equipment, in many cases wells are located in much closer proximity to other permanent equipment.

The decision to locate wells in close proximity is largely driven by overall cost savings relating to subsea equipment, construction and drilling operations. For multi-well installations incorporating an open glory hole protection scheme, reducing the wellhead spacing would have a considerable impact on the glory hole based dimensions. This in turn would reduce the overall volume to be excavated, thus resulting in significant overall cost savings.

In addition, the effect of optimizing the layout for multi-well clusters will ultimately reduce the overall risk from free floating and scouring icebergs. By reducing the spacing, aspect ratio and effective diameter of the installation, the overall probability of a well blowout can be reduced. For example, if a minimum well spacing of 10m were assumed for each of the multi-well development layouts as presented in Section 7.3, the reduction in overall probability of contact to each installation is presented in Table 18.

Table 18 Reduction in Contact Probability for 10m Well Spacing

Case	Description	Original Installation Effective Diameter (m)	Revised Installation Effective Diameter (m)	Reduction in Overall Contact Probability to Installation (%)
2a	Unprotected Wells	80	42	47
2b	Unprotected Wells w/ Weak Shear Joint	80	42	47
2c	Open Glory Hole	154	116	21
2d	Cased Glory Holes	95.5	52	32
2e	Modified Cased Holes	118	80	26
2f	Caisson Wellhead Systems	80	42	47

Based on results of Table 18, it can be seen that the greatest risk reduction is associated with unprotected wells whereby the overall probability of blowout is reduced by almost 50%. This information is quite valuable when deciding upon the layout and well spacing for clustered multi-well developments.

7.6.4 Results

By considering the results of Sections 7.6.1 & 7.6.2, the reduction in overall probability of iceberg contact to a conventional unprotected well and subsequent blowout is considerable. This is demonstrated below in Table 19.

Table 19 Refinement to the Probability of Blowout for a Conventional Unprotected Well Located Above Seabed Level

Description	Unit	Probability	Comments
Original Probability of Blowout	per well-year	9.6×10^{-4}	As calculated in Section 7.2.1
Reduction in Contact Probability Due to Refinement of Safety Class Designation	per tree	0.83	A reduction in overall contact probability of 17% from freely floating and scouring icebergs assuming a 1m reduction in Xmas tree overall dimensions
Probability of Permanent Damage to SCSSV Given Iceberg Contact has Occurred	per contact	0.097	Reference C-CORE (2001b & 2001c)
SCSSV Probability of Failure	per SCSSV	0.027	SCSSV Reliability = 0.973, Reference Molnes (2000)
Revised Probability of Blowout	per well-year	$\mathbf{9.7 \times 10^{-5}}$	Assumes that downhole permanent damage is required in order to affect the operation of the SCSSV

In this case, a reduction in the annual probability against blowout by a full order of magnitude is achieved. This is without considering any effectiveness relating to iceberg management and neglecting all the other conservatisms in the calculations as presented in Section 7.5. Although aspects of this evaluation require further investigation and research, by considering realistic allowances for existing failsafe systems and refining the safety class designation, a significant effect on the overall risk to subsea installations against blowout can be achieved.

By incorporating additional well safety features such as positioning the SCSSV at great depths (~1000m), employing dual SCSSV's on production wells and implementing a weak shear joint in the conductor pipe located downhole as for Case 1&2b, the likelihood of blowout can be further reduced. It is envisioned that a reduction in the overall probability against blowout by a full order of magnitude can be comfortably achieved over the current estimates.

It shall be noted that the probabilities of blowout calculated only relate to iceberg impact events, while the safety classes presented in CSA S471-04 pertain to all causes of installation failure. Thus, for any given subsea installation, the probability of well blowout as a result of iceberg events shall be added to all other installation failure causes to ensure the overall TLS of 1×10^{-5} is achieved.

8.0 CONSEQUENCE SCENARIOS

There are numerous consequences resulting from an iceberg encounter or contact with subsea facilities ranging from minor damage requiring repairs to major damage leading to blowout of one or more wells. Damage to critical well components such as Xmas trees, wellheads and master value assemblies could potentially arise from such an event, which could require repair, re-entry and/or re-drilling of a well and environmental clean-up. Estimating the damage extent from a particular incident is difficult to quantify and will not be addressed as part of this investigation.

The purpose of this Chapter is to identify the potential consequences of an iceberg encounter or contact as it relates to each of the wellhead systems evaluated in Chapter 7.0. The subsequent cost evaluation and comparison of each concept, given the various consequence scenarios as presented in this Chapter, will be addressed in Chapter 9.0.

Flowcharts associated with the different scenarios are presented in Figures 65 through 70. In addition, a summary of the consequence scenarios resulting from an iceberg encounter or contact for both single satellite well developments and clustered mulit-well developments are presented in Tables 20 and 21, respectively. Unlike the risk calculations performed in Section 7.2 & 7.3, consideration will be given in each scenario to the performance of SCSSV's.

8.1 Unprotected Well (s)

For the conventional unprotected Xmas tree installed at seabed level, two contact scenarios have been identified. The first scenario assumes that upon iceberg contact with the Xmas tree, the tree and well are damaged beyond repair; however, the SCSSV performs properly and shuts the well in. In the second scenario, the iceberg contacts the tree resulting in destruction of the tree; however, the SCSSV does not perform, resulting in a blowout.

For a multi-well development, a single iceberg has the potential to contact between one and six wells during the same event. The manifold is assumed to be sacrificial for this and all similar well arrangements where the manifold is located at the mudline.

A flowchart illustrating the consequences of iceberg contact is presented in Figure 65.

8.2 Unprotected Well (s) With Downhole Weak Shear Joint

For the conventional unprotected Xmas with downhole weak shear joint, three contact scenarios have been identified. The first scenario assumes that upon iceberg contact with the Xmas tree, the tree is damaged beyond repair; however, the weak shear joint separates correctly and ensures the SCSSV performs properly and shuts the well in. For this case, it is assumed that when a conductor shears successfully, the SCSSV will perform and shut the well in. For the second scenario, the weak shear joint does not separate correctly, however, the SCSSV does perform and shuts the well in. In the third scenario, the iceberg contacts the Xmas tree resulting in destruction of the tree, but failure of both the weak shear joint and the SCSSV to operate correctly results in a blowout.

For a multi-well development, a single iceberg has the potential to contact between one and six wells during the same event.

A flowchart illustrating the consequences of iceberg contact is presented in Figure 66.

8.3 Open Glory Hole

For the Xmas tree installed in a large diameter open glory hole, three potential consequences of iceberg impact have been identified. The first assumes that the iceberg enters the hole, but does not penetrate deep enough to hit the top of the Xmas tree. In this instance, soil will be pushed into the hole with no damage to the Xmas tree. Only clean-up costs to clear the hole of debris are incurred. For the second, the iceberg contacts the Xmas tree resulting in destruction of the tree, however, the SCSSV performs and the well is shut-in. In the third scenario, the iceberg contacts the Xmas tree resulting in destruction of the tree, but failure of the SCSSV results in a blowout.

For a multi-well development, a single iceberg has the potential to contact between one and six wells during the same event. The manifold in this case is assumed to be sacrificial as it is situated at the base of the glory hole.

A flowchart illustrating the consequences of iceberg contact is presented in Figure 67.

8.4 Cased Glory Hole(s)

For the Xmas tree installed in a cased glory hole, three scenarios have been identified. The first assumes that the casing is contacted by a scouring iceberg above the shear point resulting in proper separation of the casing weak shear plane. In this event, the casing requires substantial repairs while the Xmas tree and wellhead suffer no damage. In the second scenario, the casing shears improperly as a result of a deep scouring iceberg and the Xmas tree is damaged beyond repair; however, the SCSSV performs properly and shuts the well in. The third scenario is similar to the second; however, the SCSSV fails to operate properly, resulting in destruction to Xmas tree and a well blowout.

For a multi-well development, a single iceberg has the potential to contact between one and six casings in a single event.

A flowchart illustrating the consequences of iceberg contact is presented in Figure 68.

8.5 Modified Cased Glory Hole(s)

For the Xmas tree installed in a modified cased glory hole, three scenarios have been identified. The first assumes that a scouring iceberg enters the hole above the casing and inner protection shield. In this instance, soil will be pushed into the hole with no damage to the Xmas tree. Only clean-up costs to clear the hole of debris are incurred. In the second scenario, the casing is contacted as a result of a deep scouring iceberg and the Xmas tree is damaged beyond repair; however, the SCSSV performs properly and shuts the well in. The third scenario is similar to the second; however, the SCSSV fails to operate properly, resulting in destruction to the Xmas tree and a well blowout.

For a multi-well development, a single iceberg has the potential to contact between one and six modified cased holes in a single event.

A flowchart illustrating the consequences of iceberg contact is presented in Figure 69.

8.6 Caisson Wellhead System(s)

For the caisson wellhead system, three scenarios have been developed. In the first scenario, the iceberg impacts the mudline tree resulting in a proper shearing of the sacrificial section of the caisson assembly. The first scenario assumes that upon iceberg contact with the Xmas tree, the tree is damaged beyond repair; however, the weak shear joint separates correctly and ensures the SCSSV performs properly and shuts the well in. In the event of this type of failure, the well can be tied back in once the caisson is repaired and the lost sacrificial tree has been replaced before restarting the well. In the second scenario, a deep scouring iceberg impacts the caisson in such a manner as to fail the caisson in a mode other than shear. In this instance, the impact results in loss or extensive damage to the Xmas tree, however, proper performance of the SCSSV shuts the well in. The third scenario is similar to the second, however, failure of the downhole master valve and SCSSV results in a blowout of the well.

For a multi-well development, a single iceberg has the potential to contact between one and six caisson wellhead systems during the same event.

A flowchart illustrating the consequences of iceberg contact is presented in Figure 70.

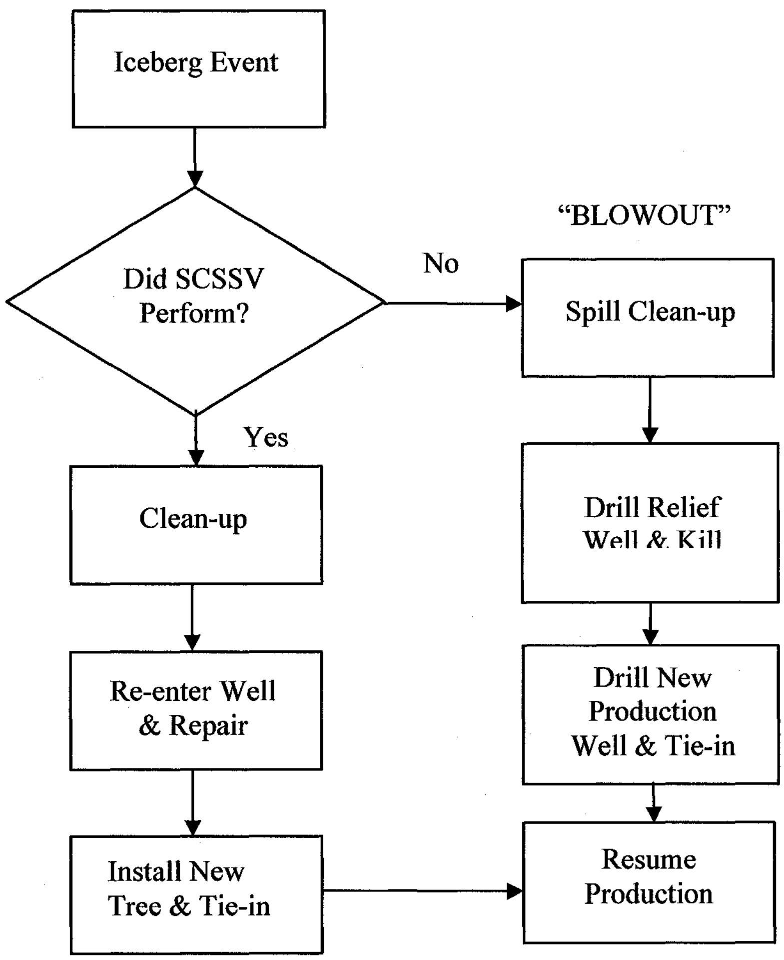

Figure 65 Flowchart - Unprotected Well(s)

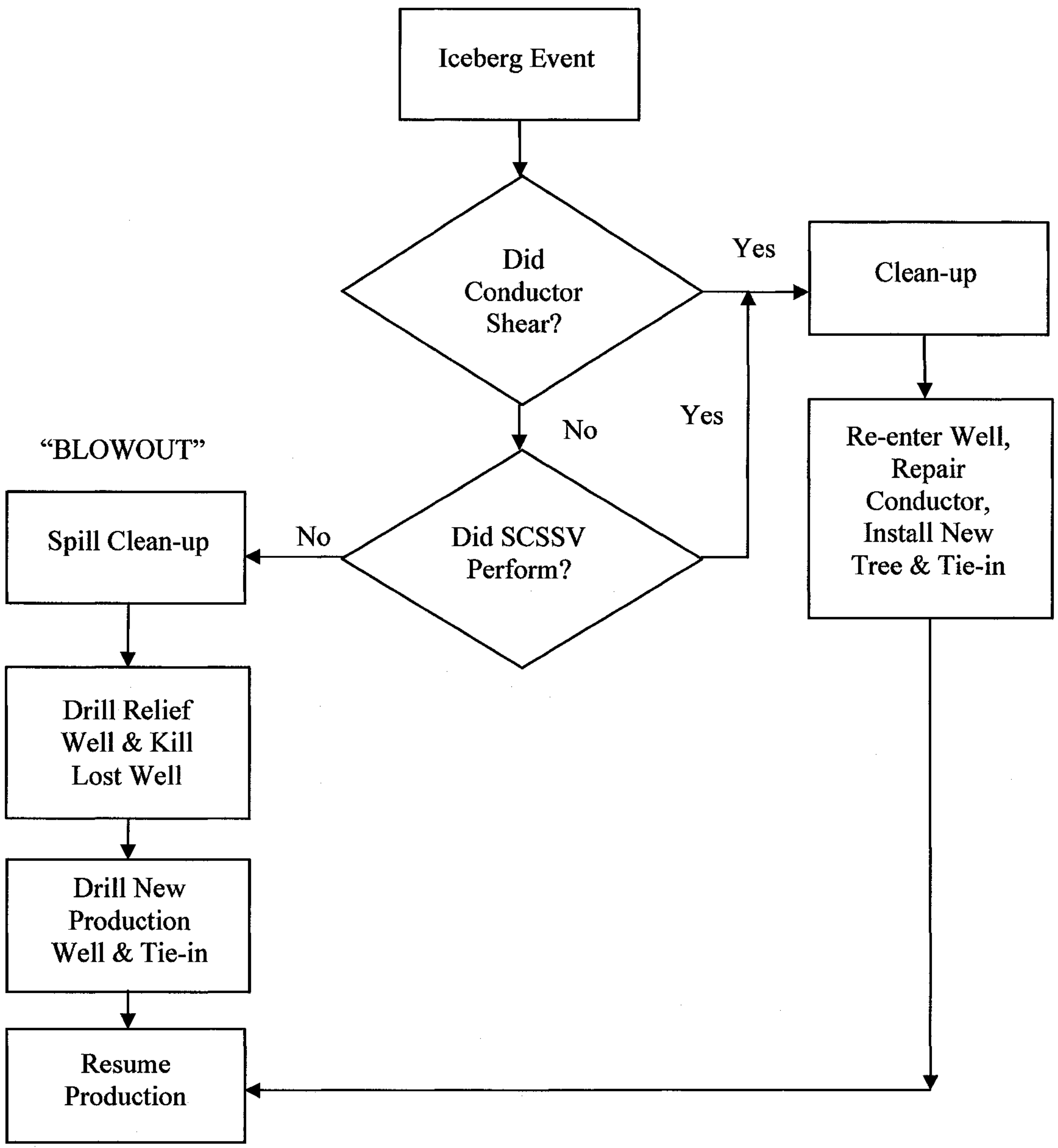

Figure 66 Flowchart – Unprotected Well(s) With Downhole Weak Shear Joint

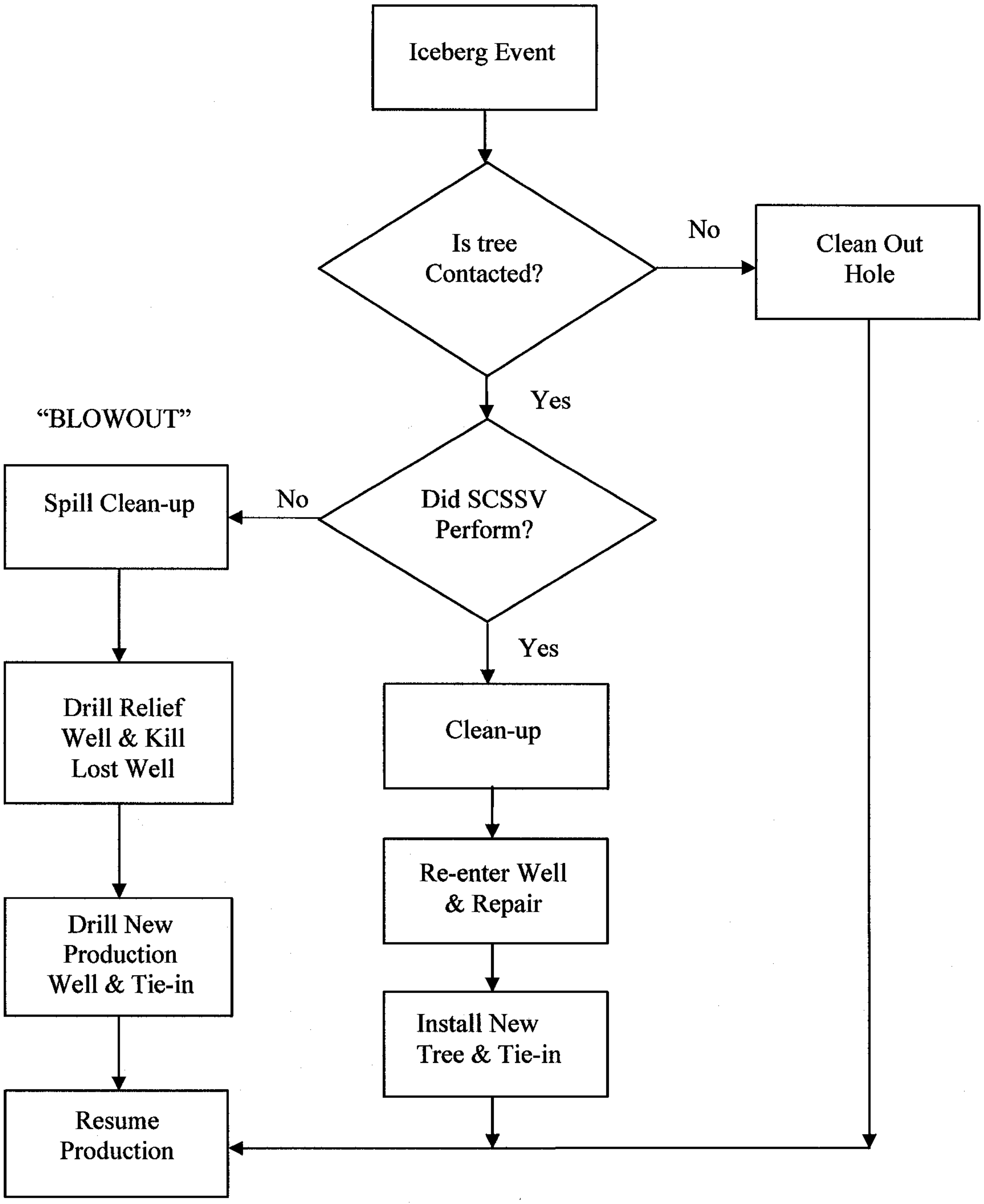

Figure 67 Flowchart – Open Glory Hole

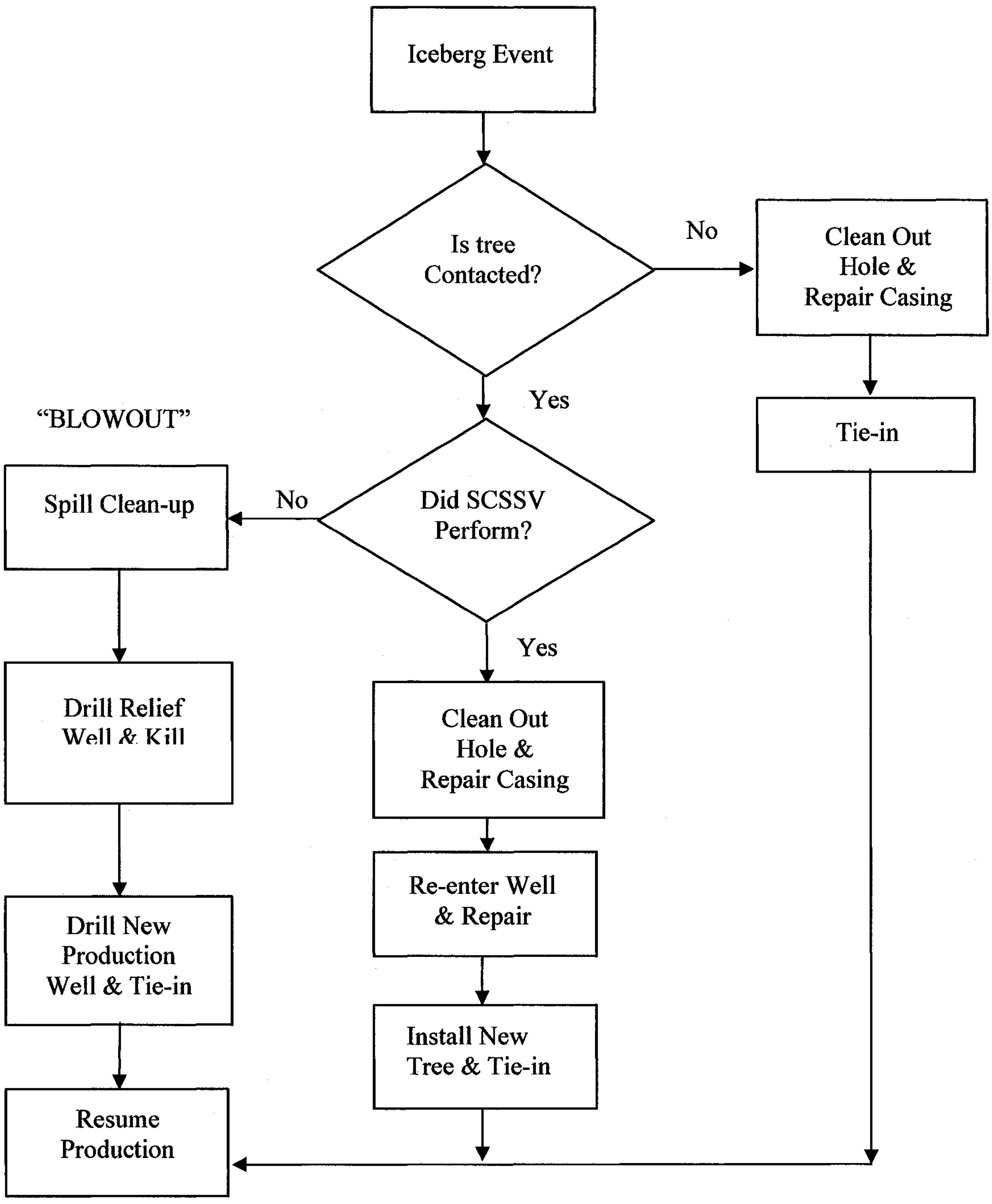

Figure 68 Flowchart – Cased Glory Hole(s)

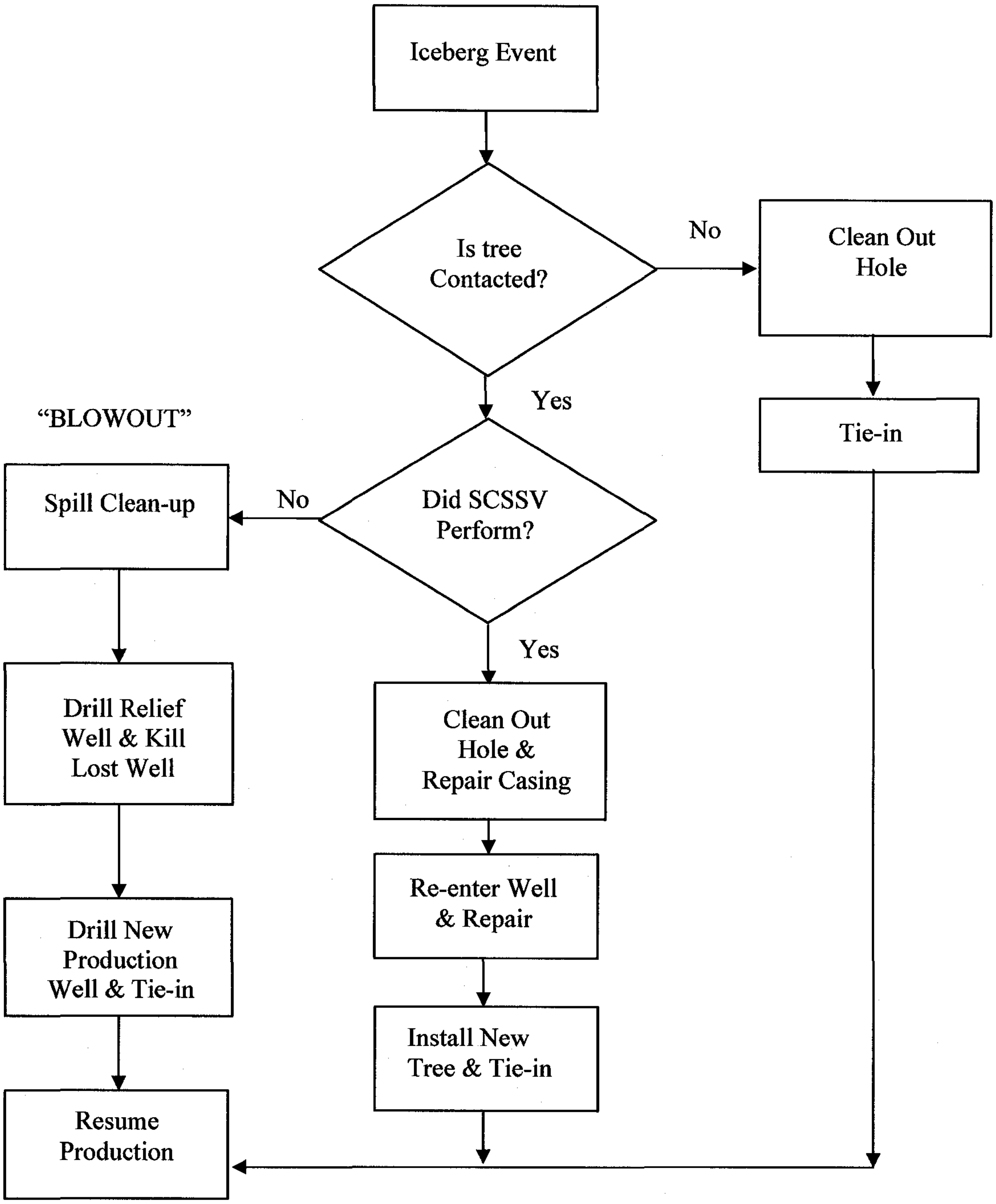

Figure 69 Flowchart – Modified Cased Glory Hole(s)

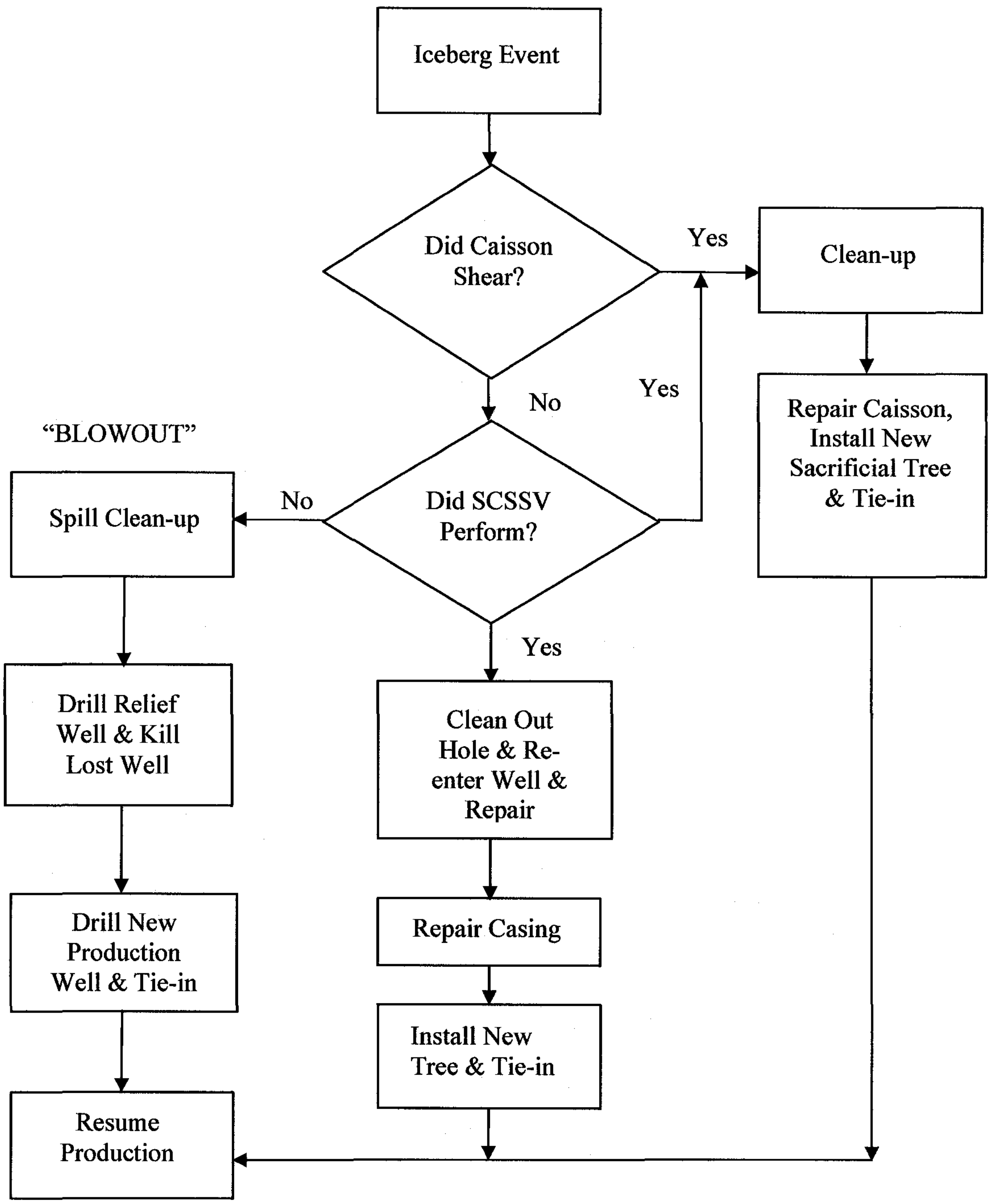

Figure 70 Flowchart – Caisson Wellhead System(s)

8.7 Summary of Consequence Scenarios

A summary of the consequence scenarios resulting from iceberg contact for both single satellite well developments and clustered mulit-well developments are presented below in Tables 20 and 21. Consequences indicate only if the well incurs a blowout.

Table 20 Single Satellite Well Consequence Scenario Summary

System	Case	Scenario	Consequence
Unprotected Well	1a	Iceberg Contacts Xmas Tree – SCSSV Performs	No Blowout
		Iceberg Contacts Xmas Tree – SCSSV Doesn't Perform	Blowout
Unprotected Well w/ Shear Joint	1b	Iceberg Contacts Xmas Tree – Conductor Shears Properly	No Blowout
		Iceberg Contacts Xmas Tree - Conductor Doesn't Shear – SCSSV Performs	No Blowout
		Iceberg Contacts Xmas Tree - Conductor Doesn't Shear – SCSSV Doesn't Perform	Blowout
Open Glory Hole	1c	Iceberg Enters Glory Hole	No Blowout
		Iceberg Contacts Xmas Tree – SCSSV Performs	No Blowout
		Iceberg Contacts Xmas Tree – SCSSV Does't Perform	Blowout
Cased Glory Hole	1d	Iceberg Contacts Casing Above Shear Plane - Casing Shears Successfully	No Blowout
		Iceberg Contacts Casing Below Shear Plane & Shears into Xmas Tree - SCSSV Performs	No Blowout
		Iceberg Contacts Casing Below Shear Plane & Shears into Xmas Tree - SCSSV Doesn't Perform	Blowout
Modified Cased Glory Hole	1e	Iceberg Contacts Above Casing	No Blowout
		Iceberg Contacts Below Top of Casing & Shears into Xmas Tree - SCSSV Performs	No Blowout
		Iceberg Contacts Below Top of Casing & Shears into Xmas Tree - SCSSV Doesn't Perform	Blowout
Caisson Wellhead System	1f	Iceberg Contacts Xmas Tree – Caisson Shears Properly	No Blowout
		Iceberg Contacts Caisson Below Shear Joint & Caisson Fails – SCSSV Performs	No Blowout
		Iceberg Contacts Caisson Below Shear Joint & Caisson Fails – SCSSV Doesn't Perform	Blowout

Table 21 Clustered Multi-well Consequence Scenario Summary

System	Case	Scenario	Consequence
Unprotected Wells	2a	Iceberg Contacts One or More Xmas Trees – SCSSV's Perform	No Blowout
		Iceberg Contacts One or More Xmas Trees – SCSSV's Doesn't Perform	Blowout
Unprotected Wells w/ Shear Joint	2b	Iceberg Contacts One or More Xmas Trees – Conductor Shears Properly	No Blowout
		Iceberg Contacts One or More Xmas Trees - Conductors Doesn't Shear – SCSSV's Perform	No Blowout
		Iceberg Contacts One or More Xmas Trees - Conductors Don't Shear – SCSSV's Doesn't Perform	Blowout
Open Glory Hole	2c	Iceberg Enters Glory Hole	No Blowout
		Iceberg Contacts One or More Xmas Trees – SCSSV's Perform	No Blowout
		Iceberg Contacts One or More Xmas Trees – SCSSV's Doesn't Perform	Blowout
Cased Glory Holes	2d	Iceberg Contacts One or More Casings Above Shear Plane- Casing Shears Successfully	No Blowout
		Iceberg Contacts One or More Casings Below Shear Plane & Shears into Xmas Tree – SCSSV's Perform	No Blowout
		Iceberg Contacts One or More Casings Below Shear Plane & Shears into Xmas Tree – SCSSV's Doesn't Perform	Blowout
Modified Cased Glory Holes	2e	Iceberg Contacts One or More Installation Above Casing	No Blowout
		Iceberg Contacts One or More Installation Below top of Casing & Shears into Xmas Tree – SCSSV's Perform	No Blowout
		Iceberg Contacts One or More Installation Below top of Casing& Shears into Xmas Tree – SCSSV's Doesn't Perform	Blowout
Caisson Wellhead Systems	2f	Iceberg Contacts One or More Xmas Tree – Caisson Shears Properly	No Blowout
		Iceberg Contacts One or More Caisson Below Shear Plane & Caisson Fails – SCSSV's Perform	No Blowout
		Iceberg Contacts One or More Caisson Below Shear Plane & Caisson Fails – SCSSV's Doesn't Perform	Blowout

9.0 COST ANALYSIS

9.1 General

The cost of doing business on the Grand Banks is considerably higher than in many other offshore areas of the world, largely due to the presence of icebergs and pack ice. The economic and risk trade-offs that are associated with protecting wellheads from the threat of icebergs make it a key issue for oil and gas development in this region. The aim of this section is to undertake a cost analysis in order to support the selection and decision making process when considering wellhead protection concepts for subsea marginal developments on the Grand Banks.

The methodology used in this analysis for the selection of a wellhead protection concept involves a full comparison of capital expenditure (CAPEX) including those costs associated with equipment installation. More uniquely, the selection process incorporates the risks associated with iceberg contact. Consequences resulting from an iceberg contact such as lost production, environmental cleanup and replacement / repair costs are factored by the probability of that event occurring. This approach is further detailed under Section 9.2. Life of field operation expenditure (OPEX) and major repair/maintenance costs for the various protection concepts have not been taken into consideration in this cost analysis.

All costs presented herein are in money of the day based on 2nd quarter, 2006. Because the amount of detailed cost data available in the public domain is limited, notional rates and norms acquired from local oil and gas companies and other reliable sources have been used. Where cost information is available but is dated, the costs are inflated to arrive at a present value (PV) by assuming an annual inflation rate of 5%. It must also be noted that all costs relating to this evaluation are assessed in 2006 Canadian dollars.

The input parameters associated with the various protection concepts are outlined in Section 9.3 with a summary of results presented in Section 9.4 & 9.5. In addition, the sensitivity of the cost comparisons to various parameters is explored in Section 9.6.

9.2 Analysis Methodology

The basis of comparison for the various wellhead protection options is the incremental costs over and above those of a conventional unprotected well system (i.e. Base Case). For a single well, an unprotected system consists of a conventional Xmas placed at the mudline. For multiple wells, the unprotected system consists of an arrangement of conventional Xmas trees distributed around a single manifold at seabed level.

The net cost of a particular system can be calculated from the following expression:

$$N = C + C_R \tag{9.1}$$

Where N is the net incremental system cost, C is the incremental CAPEX (or upfront development cost) and C_R is the cost of risk resulting from iceberg events. The cost of risk can be expressed as:

$$C_R = p_f\left(R + E + L_p\right)T \qquad (9.2)$$

Where p_f is the annual probability of the iceberg event, R is the equipment repair / replacement cost, E is the environmental and equipment cleanup cost, L_p is the cost of lost production and T is the life of the field.

As presented in Chapter 8.0, there are a number of possible iceberg event consequence scenarios associated with each wellhead protection concept. Consequences range from contact causing minor damage to a complete well blowout event requiring killing of a well and re-drilling and spill clean- as summarized in Tables 20 & 21. For example, the entry of an iceberg into an open glory hole would induce only minor damage, while contact with an Xmas tree could result in activation of the downhole SCSSV or even worst, a well blowout. Each consequence scenario associated with an iceberg event varies in annual probability of occurrence and comes with different repair / replacement, clean-up and lost production costs. The overall cost of risk is the sum of the annual probability of the iceberg event times the associated repair/replacement, cleanup and lost production costs, all multiplied by the life of field. Thus, the relationship for cost of risk becomes:

$$C_R = \sum_{i=1}^{n}\left[p_{fi}\left(R_i + E_i + L_{pi}\right) + \ldots + p_{fn}\left(R_n + E_n + L_{pn}\right)\right] \cdot T \qquad (9.3)$$

The analysis presented herein has also incorporated provisions for iceberg management, assuming an overall success rate of 85% as presented in Section 6.5. Calculations of risk with iceberg management has assumed that iceberg management would only be effective for floating icebergs as it is unlikely that a scouring iceberg would respond to iceberg management. The scouring risk component in the calculation for overall annual probability of contact is therefore not reduced.

9.3 Input Parameters

In order to undertake the cost analysis a variety of key input parameters are required. These include:

- Annual Probability of an Iceberg Event
- Capital Expenditure (CAPEX)
- Repair / Replacement Costs
- Cleanup Costs
- Lost Production Costs

9.3.1 Annual Probability of an Iceberg Event

As presented in Chapter 8.0, there are a number of possible iceberg consequence scenarios associated with each wellhead protection concept. The consequence scenarios can be broken down into three distinct iceberg events, each having its own annual probability of occurrence. These include:

A: Iceberg Encounter: occurs when a scouring iceberg enters an open glory hole or modified cased hole, or that a floating or scouring iceberg contacts the Xmas tree of a caisson system, cased glory hole or unprotected Xmas tree.

B: Contact (SCSSV Performs): occurs when a scouring iceberg penetrates deep enough into an open or glory hole or modified cased hole to impact the protected Xmas tree, scours deep enough to impact below the shear joint/plane in the unprotected well w/ downhole shear joint, caisson system or cased glory hole, or contacts an unprotected Xmas tree. For this iceberg event, the SCSSV performs properly and shuts the well in.

C: Contact (SCSSV Don't Perform – "Blowout"): occurs when a scouring iceberg penetrates deep enough into an open or glory hole or modified cased hole to impact the protected Xmas tree, scours deep enough to impact below the shear joint/plane in the unprotected well w/ downhole shear joint, caisson system or cased glory hole, or contacts an unprotected Xmas tree. For this iceberg event, the SCSSV does not perform, resulting in a well blowout.

Refer to Appendix A (Tables A1 & A2) for a summary of the annual probabilities associated with each iceberg event as identified above. Provisions for iceberg management, assuming an overall success rate of 85% are also included. The basis behind the calculation for iceberg annual contact probability is also presented in Appendix A (Tables A3 & A4).

9.3.2 CAPEX

CAPEX includes those costs associated with equipment and installation and, in general, make up the majority of the overall net system cost. The incremental CAPEX associated with the various well development options for both single and multi-well developments are summarized below in Tables 22 & 23. Additional details that include a breakdown of rates and norms associated with equipment requirements and subsea construction activities associated with the various wellhead protection concepts can be found in Appendix B (Table B1). In addition, duration estimates for various offshore operations are also presented.

Table 22 Incremental CAPEX - Single Well Developments

Case	Description	Incremental CAPEX [$MM CDN]
1a	Unprotected Well	0
1b	Unprotected Well w/ Weak Shear Joint	1.3
1c	Open Glory Hole	8.5
1d	Cased Glory Hole	2.0
1e	Modified Cased Hole	2.0
1f	Caisson Wellhead System	3.0

Table 23 Incremental CAPEX - Clustered Multi-well Developments

Case	Description	Incremental CAPEX [$MM CDN]
2a	Unprotected Wells	0
2b	Unprotected Wells w/ Weak Shear Joint	7.5
2c	Open Glory Hole	24.1
2d	Cased Glory Holes	12.0
2e	Modified Cased Holes	12.0
2f	Caisson Wellhead Systems	18.0
<u>Note:</u> For each of the clustered multi-well developments, protection for all six wells (3 x production & 3 x water injection) has been assumed.		

For the Grand Banks region, there is likely to be more uncertainty with the costs associated with cased hole concepts compared to those of open glory hole and caisson wellhead systems. This is because open glory hole and caisson wellhead completions have been successfully implemented on the Grand Banks previously and these costs have been documented. Based on previous experience in the region uncertainties relating to soil conditions add to the cost uncertainties for excavated systems such as open and cased glory holes and shall be taken into consideration for evaluating such systems. Consideration must also be given to the fact that while standard drilling tools can be used for the caisson completion systems, specialized dredging equipment is required for excavation of the cased and open glory hole concepts.

Subsea equipment installation and construction works make up a significant portion of the overall capital cost for typical subsea development projects. Costs associated with installation generally range anywhere from 20 - 50% of the overall capital cost of the subsea development.

Currently, the East coast of Canada does not have the required infrastructure in place to support the local availability of large specialized offshore construction-type vessels that are required for development of subsea marginal fields for the region. Vessels that are hired for subsea installation and construction works will likely require mobilization from the North Sea, Gulf of Mexico or other regions around the world. Considering the high day-rate of these vessels, and the lengthy transit durations, mobilization/demobilization costs are accordingly very high.

Semi-submersible drilling vessels will most likely be active in the region during the anticipated development and operating life of the field. Thus, there is potential for these drilling vessels to be used for initial wellhead protection system construction or even equipment installation, thereby offering considerable cost savings in terms of mobilization/demobilization.

Costs associated with sacrificial subsea equipment such as flowlines, control umbilicals and control systems have not been included because they are common to each system proposed.

9.3.3 Repair / Replacement Costs

Costs associated with repair / replacement include those associated with such activities as drilling a new production well, replacement of the well protection system, re-entering a well and performing repairs. The rates and norms such as unit costs and activity durations associated with repair / replacement of single and multi-well developments are presented in Appendix B (Table B1). It should be noted that Costs associated with repair / replacement include those associated with mobilization of vessel, equipment, and manpower required to complete the works.

In order to undertake the cost analysis, a number of assumptions have been made in relation to damage and subsequent repair / replacement of both single and multi-well subsea installations. These assumptions include:

1) Any contact between an iceberg and Xmas tree results in damage of the Xmas tree hardware beyond repair and must be replaced.
2) The weak shear joint of a caisson always shears properly except in the case of deeply scouring icebergs.
3) When a blowout occurs, a relief well must be drilled to stop the flow of oil, the original well is then killed, and the original and relief wells are capped before a new production well is drilled.
4) The weak shear plane of a cased glory hole will shear properly without damaging the wellhead except in the case of deeply scouring icebergs.
5) When a Xmas tree or system is hit, the flowline connected to it breaks away without damage at a weak link connection to the Xmas tree. Tie-in costs reflect the costs incurred in reconnecting a flowline to the tree and/or manifold. Cost of the flowline(s) or manifold(s), if lost, are not accounted for.

6) Any backfill of an open or cased hole with debris does not damage the Xmas tree. The hole requires only removal of debris and subsequent cleanup.

9.3.4 Cleanup Costs

Costs associated with cleanup include those relating to equipment, debris and the environment. The rates and norms such as unit costs and activity durations associated with cleanup of single and multi-well developments are presented in Appendix B (Table B1).

Cleanup associated with equipment, debris and the environment is required for a number of scenarios. These include:

- Iceberg contact with an Xmas tree and/or any other equipment making up the subsea installation whereby damage is incurred;
- Iceberg scouring results in a hole being partially filled with debris;
- Any contact between an iceberg and an installation, which results in a well blowout and subsequent oil spill.

Blowout consequence costs are mainly a function of oil spill volume and spill location. Spill volume can be estimated as spill rate (see Table 24 below) times duration of the spill. It can take several weeks to locate and mobilize a mobile offshore drilling unit (MODU) to drill a relief well. A relief well kill operation would take at least two or three months and could require up to a year, which means the spill volume could be several million barrels (Goldsmith, 2005).

9.3.5 Lost Production Costs

The cost of lost production as a result of an iceberg event has also been considered in this analysis. Lost production is expressed as a function of the consequence scenario assumed and factored by the time required to restore production. In order to calculate the financial loss due to lost production a netback per barrel of $10 CDN has been assumed which is multiplied by both the peak daily production rate and the number of days of lost production.

In the case of a blowout, the well blowout rate has been taken as five times the peak daily well production rate. Table 24 presents production data for both single and multi-well developments (Case 1 & 2).

Table 24 Production Data

Description	Case 1	Case 2
Peak Daily Well Production Rate (bopd)	15,000	40,000
Spill/Blowout Rate (bopd)	75,000	200,000
Netback per Barrel ($ CDN per barrel)	10	10
Notes: Blowout rate for the multi-well development assumes that three wells result in a blowout condition for a single iceberg encounter.		

Durations for activities associated with a well blowout, environmental cleanup and subsequent lost production are presented in Appendix B (Table B1).

9.4 Consequence Scenario Costs

Based on the list of assumptions presented above and unit costs, activity durations and production data presented in Appendix B, costs associated with the various consequence scenarios were computed for both single and multi-well developments. These results for the various wellhead protection systems chosen are presented in Appendix C (Tables C1 through C6). A summary of these results are presented below in Tables 25 and 26.

Table 25 Summary of Consequence Scenario Costs – Single Well Development

Case	Description	Consequence Scenario Cost ($MM CDN) A: Iceberg Encounter	B: Contact (SCSSV Performs)	C: Contact (SCSSV Don't Perform)
1a	Unprotected Well	99.0	99.0	302.0
1b	Unprotected Well w/ Weak Shear Joint	76.5	99.0	
1c	Open Glory Hole	11.6	115.1	
1d	Cased Glory Hole	19.0	115.6	
1e	Modified Cased Hole	15.5	112.1	
1f	Caisson Wellhead System	36.3	85.2	

Table 26 Summary of Consequence Scenario Costs – Multi-well Development

Case	Description	Consequence Scenario Cost ($MM CDN) A: Iceberg Encounter	B: Contact (SCSSV Performs)	C: Contact (SCSSV Don't Perform)
2a	Unprotected Wells	349.5	349.5	975.6
2b	Unprotected Wells w/ Weak Shear Joint	282.0	349.5	
2c	Open Glory Hole	21.1	369.1	
2d	Cased Glory Holes	74.5	406.9	
2e	Modified Cased Holes	58.8	401.7	
2f	Caisson Wellhead Systems	135.0	276.6	

9.5 Summary of Results & Cost Comparison

As discussed in Section 9.2, evaluation of the different wellhead protection systems is based on the incremental CAPEX incurred over and above the cost for the base case installation plus the cost of repair / replacement, cleanup and lost production costs which are all factored by the probability of an iceberg event and the life of the field.

A detailed summary of the net incremental system cost results for the proposed single and multi-well protection concepts are presented in Appendix C, Tables C7 & C8.

9.5.1 Single Well Development

A summary of the net system costs for single well developments are presented in Table 27.

Table 27 Summary of Net System Costs – Single well Development

Case	Description	Net System Cost ($MM CDN)	Net System Cost 85% Iceberg Mgnt ($MM CDN)
1a	Unprotected Well[1]	2.28	1.24
1b	Unprotected Well w/ Weak Shear Joint[1]	3.40	2.47
1c	Open Glory Hole	9.55	9.55
1d	Cased Glory Hole	3.19	3.05
1e	Modified Cased Hole	3.02	3.02
1f	Caisson Wellhead System	4.85	4.16

Notes:
1. Does not meet established TLS = 10^{-5}

Although Cases 1a has the lowest net system cost at \$2.28 MM, it is unacceptable in terms of probability of iceberg contact as established in Chapter 5.0. With a net system cost of \$3.02 MM, the modified cased hole is the most cost effective solution using a cost of risk approach when compared to all other solutions. The open glory hole with a net system cost of \$9.55 MM does not appear to be feasible option for a single well development.

As expected, the Net System Costs reduced in magnitude when assuming an iceberg management overall success rate of 85%. However, the overall cost benefits of providing iceberg management for a single well development is relatively low and may not be economically desirable. Cases 1c and 1e remained unchanged because they consist only of a scouring iceberg component and do benefit from the effectiveness of iceberg management.

In order to further understand the contribution of each component to the net incremental system cost, a graph presenting unit normalized values of both the incremental CAPEX and cost of risk components have been presented in Figure 71.

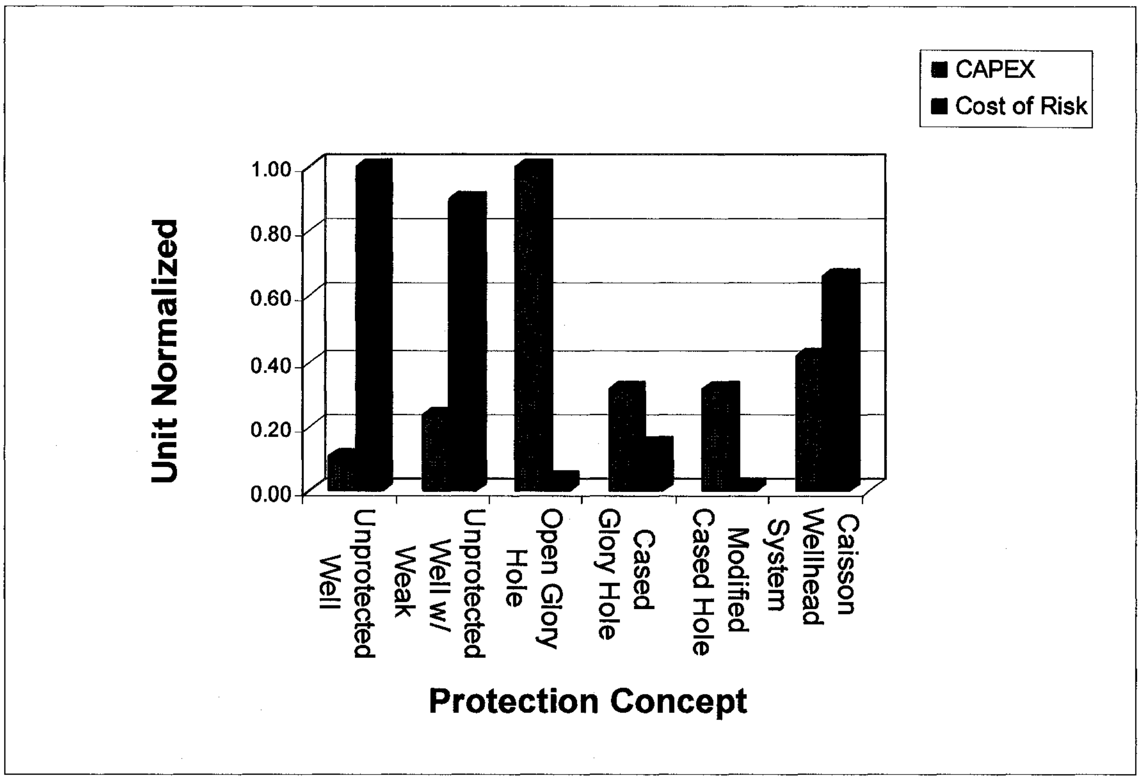

Figure 71 Single Well Development – Unit Normalized

As can be concluded, the modified cased hole concept offers the optimum solution for a single satellite well development in terms of normalized CAPEX and cost of risk components. Although the unprotected well has the lowest CAPEX, its cost of risk however is substantially higher than all other alternatives. In comparison, the open glory hole concept has the highest CAPEX but its cost of risk is relatively low compared with all other concepts.

9.5.2 Multi-well Development

The net system costs for clustered multi-well well developments are presented in Table 28. For all multiple well options excluding the open glory hole, the CAPEX is essentially 6 times the costs for that of a single well. In addition, although quite unlikely it is assumed that all six wells of a clustered multi-well development are contacted during one iceberg event (as discussed in Section 7.4).

Table 28 Summary of Net System Costs – Multi-well Development

Case	Description	Net System Cost ($MM CDN)	Net System Cost 85% Iceberg Mgnt ($MM CDN)
2a	Unprotected Wells[1]	17.12	3.85
2b	Unprotected Wells w/ Weak Shear Joint[1]	23.22	10.10
2c	Open Glory Hole	25.55	25.55
2d	Cased Glory Holes	15.86	13.71
2e	Modified Cased Holes	13.37	13.37
2f	Caisson Wellhead Systems	29.33	20.83

Notes:
1. Does not meet established TLS = 10^{-5}

A similar trend for the multi-well developments was observed using the same approach. This is primarily due to the large influence of CAPEX on the sensitivity of the overall results. With a net system cost of $13.37 MM, the modified cased hole development is once again the most optimum solution from a cost of risk basis assuming the unprotected wells (Cases 2a & 2b) are unacceptable in terms of probability of iceberg contact.

It can be concluded from Table 28 that the influence of iceberg management on multi-well developments has a greater influence on reducing the overall Net System Cost in comparison to single wells. Thus, iceberg management becomes more important from an economic standpoint for developments with a large number wells.

A graph presenting the unit normalized values of both cost components for the multi-well development options are presented in Figure 72.

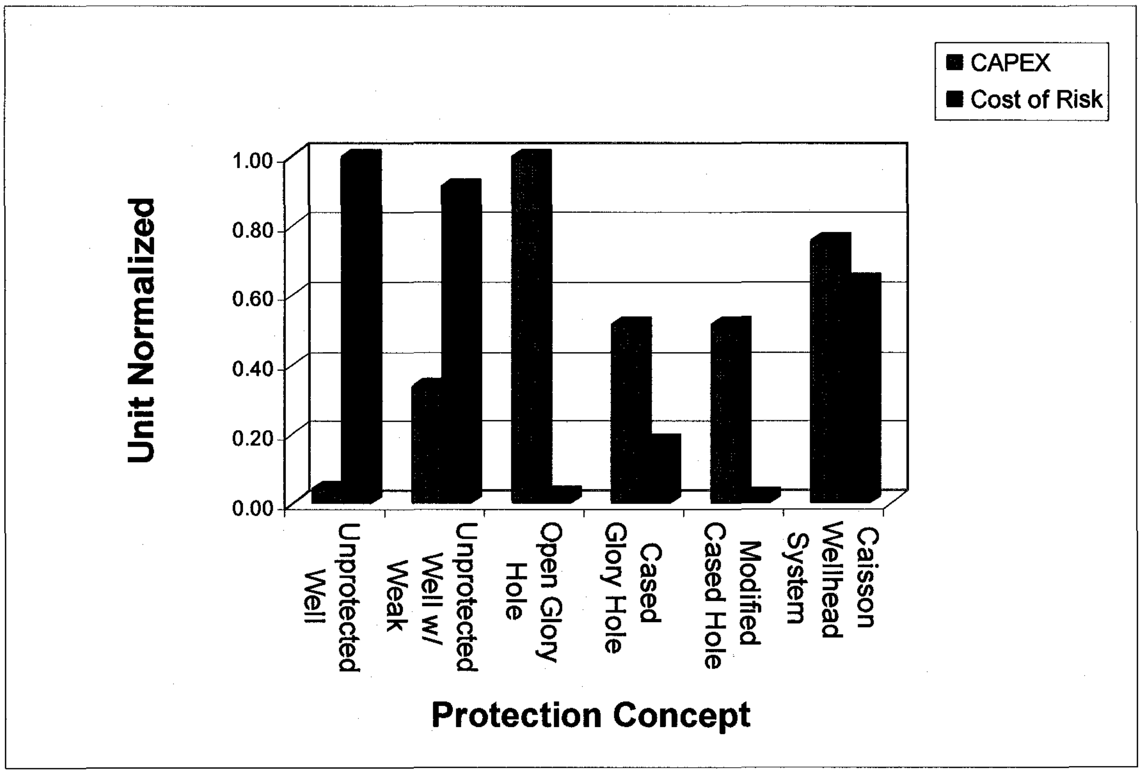

Figure 72 Multi-well Development – Unit Normalized

As concluded for single well developments, the modified cased hole concept also offers the most optimum solution for multi-well developments in terms of normalized CAPEX and cost of risk components. The open glory hole has the highest CAPEX but its cost of risk is equal to that of the modified cased hole.

9.6 Cost Sensitivity

As presented in Section 9.5, the net system cost of the various protection systems is driven primarily by the incremental CAPEX. This is because the repair/replacement, cleanup and lost production costs are all factored by very low probability of iceberg contact and subsequent damage.

Based on the results utilizing the cost of risk approach, it is clear that much effort should be spent defining assumptions and estimates relating to CAPEX as it is the key driver when determining the net system cost.

9.7 Discussion

Although the analysis presented in this section focuses on costs associated with somewhat defined repair and clean-up operations in the event of a major incident such as a blowout, the real cost to an operator is very difficult to quantify and can potentially be significant. Disasters such as the Exxon Valdez and more recently the fire at BP's Texas refinery fire bare classic examples of this. The damage to reputation in itself can be even more significant from a financial perspective than those associated with repair, clean-up and loss production costs. Repercussions from an uncontrolled well blowout on the Grand Banks could also result in the following:

- Consumer rejection of products;

- Loss of share value;
- Penalties;
- Payouts to affected stakeholders (i.e. the fishing industry);
- Investor loss of confidence for future prospects;
- Higher standards (and therefore costs) for future developments;
- Longer and more difficult approval process for future projects;
- Requirements for retrofits/modifications to existing infrastructure;
- Requirements for more stringent (and costly) operating procedures;
- Shut down of adjacent facilities until containment and cleanup are complete;
- Reduced tourism to the Province.

Although implications such as these are readily identifiable, the associated costs are very difficult to quantify and have thus not been incorporated into the cost analysis. It is also worth noting that such repercussions apply equally across all concepts presented and will not have a significant impact on concept comparisons.

While much of the emphasis of this investigation was focused on physical solutions for wellhead protection, one option for subsea developments in the region is to adopt a "unprotected" well installation approach, wherein the small probability of contact from freely floating and scouring icebergs to subsea facilities (i.e. wellheads, trees, manifolds etc.) is accepted. In addition, reliance on existing failsafe systems such as SCSSV's (as analyzed in Section 7.6) and the implementation of downhole weak shear joints to reduce downhole structural responses shall be considered when evaluating such systems. In doing so, large reductions in development CAPEX can be realized, thus improving the overall development economics, especially when considering marginal subsea fields. This approach obviously has its drawbacks when considering the potential repercussions that could unfold if something were to go seriously wrong. As a minimum, these include:

- Overall business/financial consequence (i.e. Lost production, damage repair and replacement costs);
- Adverse environmental consequences due to potential well blowout;
- Negative public perception, media exposure and tarnished public image of local oil and gas industry.

In deciding to implement an "unprotected" well installation on the Grand Banks, potential oil and gas developers need to be reminded of the basic equation developed by Peter Sandman, a pre-eminent risk communication consultant:

$$\text{Risk} = \text{Hazard} + \text{Outrage}$$

"Hazard" refers to the technical risk engineers are trained to assess. "Outrage" is the public's perception of risk. "Outrage" is made up of factors such as trust, responsiveness, control, etc. Clearly, with the difficulties experienced by the developers of some projects in obtaining local approval, a successful approach must balance technical and economic feasibility with political realities specific to each location. In the case of a subsea well installation, the "Outrage" factor of the risk equation must be managed as effectively as the "Hazard" factor (Rankin & Mick, 2005). A blowout or loss of life impacts everyone and tarnishes the image of the whole industry. The cost to cleanup an oil spill and outrage costs associated with the lost sales and a tarnished public image can vary from a few hundred dollars per barrel to tens of thousands (Goldsmith, 2005).

Even though a number of issues require further research and evaluation in order justify implementing an "unprotected" well installation, the topic definitely deserves serious consideration by operators and regulatory authorities alike. The questions must be asked, "Are we too conservative in our technical requirements for existing subsea systems?" and "As a developing oil and gas province, how much risk are we willing to take in our pursuit for exploitation of the vast reserves located on the Grand Banks?".

Although not addressed as part of this work, an overall life cycle cost associated with each of the protection concepts should also be addressed and incorporated into the decision making process. This would involve taking into account OPEX, well workover costs and Abandonment Expenditure (ABEX) for each of the options. Each of these costs will be phased over the life of the field or occur at a later date and shall be discounted to arrive at a Net Present Value (NPV). In addition, drilling expenditure (DRILLEX) and well costs for multi-well developments may be phased over the life of the field to maintain plateau rather than drilled all at once shall also be considered.

10.0 CONCLUSIONS

Based on the work performed as part of this study, a number of conclusions have been reached. They are as follows:

- Reliance on SCSSV's & other fail-safe systems offers an obvious solution for reduction in overall risk & up-front development costs for subsea well installations.
- Effective ice management has potential to reduce overall risk levels by approx one order of magnitude but is alone unlikely to justify the safe operation of unprotected satellite wells.
- Refinements to areas such as safety class designation & well spacing's within clustered developments offer reductions to overall iceberg contact probability.
- The cost analysis performed indicates that the "Modified Cased Hole" protection concept to be the most attractive protection solution from a combined cost & risk approach for both single and multi-well developments.
- The influence of iceberg management has a greater effect on reducing the overall Net System Cost for multi-well developments in comparison to single wells. This is important from an economic standpoint for developments with a large number wells.
- Using a cost of risk approach, Net incremental system costs for both single and clustered satellite well developments are primarily driven by CAPEX.
- A conventional "unprotected" subsea well installation for the Grand Banks may prove to be a feasible development scenario given further research and analysis.

- The economic and risk trade-offs that are associated with protecting subsea wellheads from the threat of icebergs is important to understand in order to support design and the decision making process.

11.0 RECOMMENDATIONS

The recommendations that have been drawn from this work have been broken down into a number of key areas as presented below.

11.1 Analysis, Testing and Research

In order to fully understand well downhole structural response mechanisms given iceberg contact with a conventional Xmas tree and/or wellhead system, it is recommended that a finite element analysis model be undertaken for a typical well installation. As a minimum, the following parameters associated with a conventional well installation installed on the Grand Banks shall be considered and incorporated into the model:

- Typical Xmas tree and wellhead design configurations (i.e. main components, dimensions, layout etc.);
- Well design (i.e. foundation, conductors, casings and tubing etc.);
- Bond strength between conductor and grout;
- Strength of Xmas tree and connection to wellhead (i.e. force, moment, shear torsion);
- Soil properties.

To complement this analysis work, it is also recommended that a physical model test be undertaken in order to cross-reference and refine the results obtained from the finite analysis work. Ideally, full scaled modeling of the well installation that was fully instrumented could be performed.

The reliability of SCSSV's have improved dramatically over the past decade, however, further study and research is required in order to determine the limit states that affect the operability and reliability of these units that are located 100's or even 1000's of meters beneath the seabed. Innovative technology such as electrically operated SCSSV's are currently being developed and may offer some added advantages to the existing hydraulically operated units which also warrants research. In addition, it is recommended that the use of dual SCSSV's situated downhole be studied in order to determine the effect to the overall reliability of the system given this redundancy.

Identification and better understanding of the inherent conservatisms & limitations related to well blowout probability calculations should be given considerable attention. This understanding could have a significant impact on the probability estimates for iceberg contact with well installations and subsequent risk of well blowout.

Ongoing monitoring of icebergs using aerial surveys, satellite or radar is recommended in order to add to the current database associated with iceberg frequency, drift speeds, iceberg size distributions etc. The ongoing collection of data such as high quality seabed survey data is also very important for building a more comprehensive data set associated with iceberg sour depth distribution and other important scour characteristics such as length and width.

An overall life cycle cost estimate incorporating additional cost components such as OPEX, ABEX and DRILLEX shall also be undertaken for each of the protection concepts and incorporated into the overall decision making process. For multi-well developments, the analysis should take into account that the development may be phased over the field life and costs discounted to arrive at a NPV to enable comparison of options.

11.2 Establishment of Criteria

Acceptable levels of risk specifically dealing with ice effects on sea floor facilities such as wellheads need specific attention as it is not covered explicitly by any of the existing national/international codes and standards or by the local regulatory authority. It is thus recommended that fully defined risk acceptance criteria be established by local oil & gas operators and regulatory bodies for subsea installations specific to the iceberg infested waters of the Grand Banks.

12.0 REFERENCES

Allen, S. (2000). Global Analysis of Wellhead Protection Glory Holes For Terra Nova, OTC 2000, paper 11919, 1p.

Allyn, N. (2000). The Use of Codes for Ice Loads on Structures on the Grand Banks, PERD/CHC Report 11-38, September 2000.

Ames, T.J., Ott, R.E., Lunn, I.S., and Batenburg, L. (1987). Subsea Multiwell Silo Drilling/Production System. Proc. Offshore and Arctic Operations Symposium, Dallas TX.

API Recommended Practice 17A (2002). Design and Operation of Subsea Production Systems, 3rd Edition.

Bishop, G. (1989). Assessment of Iceberg Management for the Grand Banks Area: Analysis of Detection and Deflection Techniques," Mobil Oil Canada Properties, Property Development Department, Hibernia Producing Operations.

Blenkarn, K.A. and Knapp, A.E. (1969). Ice Conditions on the Grand Banks. Ice Seminar, Petroleum Society of CIM, Calgary, Alta., May 6-7, 1968. Special Vol. 10, 1969, pp. 61-72.

Brown, R.D. (1993). Implications of Global Climate Warming for Canadian East Coast Sea-ice and Iceberg Regimes Over the Next 50-100 Years. Canadian Climate Centre, 1993.

Cammaert, A. B. and Muggeridge, D. B. (1988). Ice Interactions with Offshore Structures. Van Nostrand Reinhold, New York.

Canadian Seabed Research Ltd. (2000) The 1999 update of the Grand Banks Scour Catalogue. Contract report for the Geological Survey of Canada, Atlantic.

Canadian Standards Association (CSA) (2004). S471-04 General Requirements, Design Criteria, the Environment, and Loads.

CANATEC, ICL Isometrics, CORETEC & Westmar (1999). Compilation of Iceberg Shape and Geometry Data for the Grand Banks Region. PERD/CHC Report 20-43.

CanOcean Engineering Ltd. (1990). Terra Nova Subsea Facilities Reassessment Study (Vol 1& 2). Submitted to Petro-Canada Inc., May 1990.

C-CORE (1997). Behavior of Icebergs Entering an Open Glory Hole, Terra Nova Report 97-008. C-CORE Publication 97-C11, 109p.

C-CORE (1998). Probability of iceberg contact with trenched flow lines at Terra Nova, Contract Report Prepared for Petro-Canada, C-CORE Publication 98-C14.

C-CORE (2001a). Iceberg Scour Characteristics at White Rose. C-CORE Publication 00-C44 (Version 2), May 2001.

C-CORE (2001b). Iceberg Loads on a Subsea Well Installation at Hibernia. C-CORE Publication R01-C01 (Version 2), June, 2001.

C-CORE (2001c). Iceberg Loads on a Subsea Well Installation at Hibernia – Addendum Report. C-CORE Publication R01-C01 (Addendum, Version 1), June, 2001.

C-CORE (2001d). Iceberg Risk to Pipelines at White Rose. C-CORE Publication 00-C45 (Version 2), May 2001.

C-CORE (2001e). Iceberg Penetration Into Open Glory Holes at White Rose. C-CORE Publication 00-C46 (Version 2), May 2001.

C-CORE (2002). Iceberg Risk to Flowlines at Terra Nova. C-CORE Publication R-02-008-183 (Version 1), July 2002.

Center for Frontier Engineering Research (CFER) (1988). Iceberg Collision Damage Susceptibility of a Subsea Caisson Completion System. Terra Nova Development Studies 1988. Submitted to Petro-Canada July 1988.

C-NOPB (2006). Canada-Newfoundland Offshore Petroleum Board Annual Report 2005-2006, 20p.

Comfort, G. and Verbit, S. (2005). PERD Iceberg Sighting Database Update and Quality Assurance: 2004-2005, BMT report submitted to the National Research Council. PERD/CHC Report 20-86.

Comfort, G. and Verbit, S. (2003). Update, Quality Assurance and Query Results for the PERD Grand Banks Database: 2003, FTL report 5432 submitted to the National Research Council. PERD/CHC Report 20-71.

Croasdale, K. R. & Associates, Ballicater Consulting, Canadian Seabed Research, C-CORE & Ian Jordaan & Associates (2000). Study of Iceberg Scour & Risk in the Grand Banks Region. PERD/CHC Report 31-26, 2000.

Crocker, G., Wright, B., Thistle, S., and Bruneau, S., (1998). An Assessment of Current Iceberg Management Capabilities. Contract Report for: National Research Council Canada, Prepared by C-CORE and B. Wright and Associates Ltd., C-CORE Publication 98-C26.

Devegowda, D., and Scott, S. L. (2003). An Assessment of Subsea Production Systems. SPE Annual Technical Conference and Exhibition 2003, paper 84045.

Dobrocky Seatech Ltd. (1984) 1984 Iceberg Field Survey, Mobil Hibernia Development Studies.

Frederking, R., Brown, T. and Grant, R. (2004). Updating the Canadian Standards Association Offshore Structures Code. Intl. Offshore and Polar Engineering Conference 2004, pp 775 -780.

Fuglem, M., Jordaan, I. and Crocker, G. (1996). Iceberg – Structure Interaction Probabilities for Design. Can. J. Civ. Eng., Vol 23, pp. 231-241.

Garner, J., Martin, K., McCalvin, D. and McDaniel, D. (2003). At the Ready: Subsurface Safety Valves. Schlumberger Oilfield Review Journal, Winter 2002/2003.

Geonautics Limited (1991). East Coast Repetitive Mapping, 1979/1990. Environmental Studies Research Funds Report, Ottawa.

Gilbert, D. and Hampton, P. (1990). Terra Nova Project Studies 1990 – O-90 Cased Glory Hole Field Trial Report. Terra Nova Report No. 90-017.

Gilbert, D., McGregor, I. and Vargas, K.G. (1989). Beaufort Sea Cased Gloryhole Drilling. Proc. The Eight International Conference on Offshore Mechanics and Arctic Engineering. The Hague, The Netherlands, March, 1989, 451p.

Goldsmith, R. (2005). Deepwater Wells: High Production, High Risk – Risk Assessment Mitigates Potential Loss, Offshore Magazine, March 2005, pp. 30-34.

Guttormsen, T.R. and Wikdal, J.A. (1994). Foundation of the Tordis Submarine Silo. BOSS 1994, Vol 1, pp. 189-203.

Hill, B.T. (1999). Historical Record of Sea Ice and Iceberg Distribution Around Newfoundland and Labrador, 1810-1958. Proc. OMAE, ASME, 7p.

Husky Oil Operations Ltd. (2000). White Rose Development Application – Volume 5, Appendix A: Target Levels of Safety. July 2000.

IIP (2005). Ice Patrols Iceberg Counts. http://www.uscg.mil/lantarea/iip/General/icebergs.shtml

International Organization for Standardization (ISO) (2003). ISO 19902: Petroleum and Natural Gas Industries - Fixed Steel Offshore Structures (Draft International Standards 2003).

Jordaan, I.J., Fuglem, M., Crocker, G., and Olsen, C. (1995). Canadian Offshore Design for Ice Environments, Volume 1, Environment and Routes, Prepared for Department of Industry, Trade and Technology, Canada-Newfoundland Offshore Development Fund, Government of Newfoundland and Labrador, September, 1995.

Jordaan, I.J., Press, D., Milford, P. (1999) Iceberg Databases and Verification, PERD/CHC Report 20-41, March, 1999.

King, A.D. (2002). Iceberg Scour Risk Analysis for Pipelines on the Labrador Shelf. M.Eng. Thesis, Memorial University of Newfoundland, St. John's, Newfoundland, Canada.

King, A.D. et al. (2003). A Model for Predicting Iceberg Grounding Rates on the Seabed. Proceedings of the 17th International conference on Port and Ocean Engineering under Arctic Conditions (POAC), Trondheim, June 16-19, 2003.

Kollmeyer, R.C. (1977). West Greenland Glaciers: Iceberg Sources. Iceberg Utilization: Proceedings of the First International conference. A.A. Husseiny (e.), October 2-6, Ames, Iowa, pp. 25-28.

Lever, J.H. and others, (1989). Iceberg/Seabed Interaction Events Observed During the Digs Experiment. OMAE 1989, Vol IV, pp. 205-220.

Lewis, C.F.M., Parrott, D.R., d'Apollonia, S.J., Gaskill, H.S., and Barrie, J.V. (1987). Methods of Estimating Iceberg Scouring Rates on the Grand Banks of Newfoundland. Ninth International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), August 17-22, Fairbanks, Alaska, 1987, (vol. 3). pp. 229-254.

Lewis, C.F.M. and Blasco, S.M. (1990). Character and distribution of sea-ice and iceberg scours, *in* Proceedings of the Workshop on Ice Scouring and Design of Offshore Pipelines, Calgary, Alberta. pp. 56-101.

Marko, J.R. and Others (1991). Implications of global warming for Canadian east coast sea ice and iceberg regimes over the next 50 to 100 years. Atmospheric Environment Service, Canadian Climate Centre Report No. 91-9.

Marko, J.R. and Others (1994). Iceberg Severity Off Eastern North America: Its Relationship to Sea Ice Variability and Climate Change. Journal of Climatology, Vol. 7 No. 9, pp. 1335-1351.

McIntosh, I., Birarda, G. and Jonasson, W.B. (1987). Caisson Wellheads Allow For Future Use Offshore Exploration Wells. JCPT Jan-Feb 1987, pp. 81-85.

Mckenna, R., Ralph, F., Power, D., Jordaan, I. and Churchill, S. (2003). Modelling Iceberg Management Strategy. Proceedings of the 17th International conference on Port and Ocean Engineering under Arctic Conditions (POAC), Trondheim, June 16-19, 2003.

MEDS (1997). Canadian Offshore Oil and Gas Environmental Data. Marine Environmental Data Service, National Energy Board, March 1997 (CD-ROM).

Mobil Hibernia Development Studies (1984). Iceberg Field Survey. Contract Report Prepared by Dobrocky Seatech Limited, St. John's Newfoundland.

Molnes, E. and Strand, G. (2000). Application of a Completion Equipment Reliability Database in Decision Making. SPE 2000, paper 63112, 3p.

Myers, R., Sonnichsen, G. V. and Campbell, P. (1996). Terra Nova Development Studies 1995: Seafloor Repetitive Mapping Analysis. Prepared for Petro-Canada, 44p.

NORSOK Standard Z-013 (2001). Risk and Emergency Preparedness Analysis. Rev. 2, September, 2001.

North Atlantic Offshore Engineering Alliance (NAOEA), (1996). Subsea Wellhead Protection Systems in Iceberg Infested Waters.

Nuttall, D. (1991). Safety Systems in Subsea Completions. Journal of Petroleum Technology, Jan 1991, SPE paper 19478, pp. 80-83.

O'Brien, S. (2003). Personal telephone communications with Scott O'Brien of Petro-Canada, October 2003.

Offshore Magazine (2004). Petro-Canada Investigates Flow Assurance Challenges. September, 2004.

PERD (2001). Update and Quality Assurance of the PERD Grand Banks Iceberg Database. Prepared by Fleet Technology Limited for the National Research Council of Canada. PERD/CHC Report 20-59.

PERD (2002a). Comprehensive Iceberg Management Database, PERD/CHC Report 20-69, PAL Environmental Services.

PERD (2002b). Greenland Iceberg Management: Implications for Grand Banks Management Systems, PERD/CHC Report 20-65, AMEC Earth & Environmental.

Petro-Canada (1984). Grand Banks Pre-Development Studies 1984: Iceberg Collision and Scour Damage Risk for Subsea Installations. Petro-Canada Report.

Petro-Canada (1998). Petro-Canada Target Levels of Safety (TLS) for the Terra Nova Field, Report TN-IM-SA02-X00-070.

Ralph, F. (2004). Personal communications with Freeman Ralph of C-CORE, October 2004.

Rankin, R.L. and Mick, M.B. (2005). Buried, Subsea Line Advanced as LNG Alternative, Oil and Gas Journal, November 14, 2005, pp. 57-60.

Reddy, D.V. et al. (1980). Monte Carlo Simulation of Iceberg Impact Probabilities. Cold Regions Science and Technology, Vol 1: pp. 293-297.

Sanderson, T. J. O. (1988). Ice Mechanics, Risks to Offshore Structures. Graham & Trottman, London.

Schlumberger Website: http://www.slb.com/press/inside/print_article.cfm?ArticleID=109

Shields, R. (1994). Large-Diameter Glory Hole Drilling: Evolution From 12- to 20-ft Diameter. SPE Drilling & Completion, June 1994.

Singh, S., Green, S., Ennis, T. Comfort, G., and Davidson, L. (1998). PERD Iceberg Database for the Grand Banks Region. Fleet Technology Ltd. for National Research Council, PERD/CHC Report 20-36, 29p.

Singh, S., Li, X. and Comfort, G. (1999). PERD Grand Banks Iceberg Database Update, Fleet Technology Ltd report 4901 submitted to the National Research Council.

Statoil Snøhvit website©: http://www.statoil.com/STATOILCOM/snohvit/svg02699.nsf?OpenDatabase&lang=en

Stewart, H.R. and Goldby, H.M. (1984). Gloryhole Excavation: Present Techniques and Future Concepts. OTC 1984, paper 4802, 227p.

Terra Nova Development Plan (1997). http://www.terranovaproject.com/html/tn_docs/dev_pla.html

Verbit, S. and Comfort, G. (2001). Update and Quality Assurance of the PERD Grand Banks Iceberg Database, FTL report 5186 submitted to the National Research Council.

Verbit, S., Trott, B. and Comfort, G. (2002). Update and Quality Assurance of the PERD Grand Banks Iceberg Database:2002, FTL report 5273 submitted to the National Research Council.

Verbit, S., Trott, B., Gong, Y. and Comfort, G. (2000). PERD Grand Banks Iceberg Database Update II, FTL report 5068 submitted to the National Research Council.

Wells, G (1996) Hazard identification and risk assessment. Institution of Chemical Engineers, U.K.

WOAD Statistical Report (1998) Worldwide offshore accident databank. Veritas Offshore Technology & Services, 1998, Høvik, Norway.

Wright, B., Croasdale, K. and Fuglem, M. (1997). Ice Problems Related to Grand Banks Petroleum Fields. PERD / CHC Report 20-6, November, 1997.

Appendix A

Iceberg Annual Probability Summary

Table A1: Summary of Iceberg Event Annual Probabilities - Single Satellite Well Developments

Case	Description	Annual Encounter[1] Probability (A)	Annual Contact[2] Probability (SCSSV Performs) (B)	Annual Contact[2] Probability (Blowout) (C)	(A) - 85% Iceberg Mgnt	(B) - 85% Iceberg Mgnt	(C) - 85% Iceberg Mgnt
1a	Unprotected Well	9.60E-04	8.43E-04	1.17E-04	1.80E-04	1.58E-04	2.18E-05
1b	Unprotected Well w/ Weak Shear Joint	9.60E-04	8.43E-04	1.17E-04	1.80E-04	1.58E-04	2.18E-05
1c	Open Glory Hole	5.60E-05	4.92E-05	6.80E-06	5.60E-05	4.92E-05	6.80E-06
1d	Cased Glory Hole	2.00E-04	1.76E-04	2.43E-05	5.20E-05	4.57E-05	6.31E-06
1e	Modified Cased Hole	2.50E-05	2.20E-05	3.03E-06	2.50E-05	2.20E-05	3.03E-06
1f	Caisson Wellhead System	9.60E-04	8.43E-04	1.17E-04	1.80E-04	1.58E-04	2.18E-05

Table A2: Summary of Iceberg Event Annual Probabilities - Clustered Multi-well Developments

Case	Description	Annual Encounter[1] Probability (A)	Annual Contact[2] Probability (SCSSV Performs) (B)	Annual Contact[2] Probability (Blowout) (C)	(A) - 85% Iceberg Mgnt	(B) - 85% Iceberg Mgnt	(C) - 85% Iceberg Mgnt
1a	Unprotected Well	2.60E-03	2.28E-03	3.16E-04	4.60E-04	4.04E-04	5.58E-05
1b	Unprotected Well w/ Weak Shear Joint	2.60E-03	2.28E-03	3.16E-04	4.60E-04	4.04E-04	5.58E-05
1c	Open Glory Hole	1.10E-04	9.66E-05	1.34E-05	1.10E-04	9.66E-05	1.34E-05
1d	Cased Glory Hole	6.50E-04	5.71E-04	7.89E-05	1.60E-04	1.41E-04	1.94E-05
1e	Modified Cased Hole	8.80E-05	7.73E-05	1.07E-05	8.80E-05	7.73E-05	1.07E-05
1f	Caisson Wellhead System	2.60E-03	2.28E-03	3.16E-04	4.60E-04	4.04E-04	5.58E-05

Notes:

1. **"Encounter"** occurs when a scouring iceberg enters an open glory hole or modified cased hole, or when a floating or scouring iceberg contacts a cased glory hole or the Xmas tree of a caisson system, or unprotected tree.
2. **"Contact"** occurs when a scouring iceberg penetrates deep enough into an open or glory hole or modified cased hole to impact the protected Xmas tree, scours deep enough to impact below the shear joint/plane in the unprotected well w/ downhole shear joint, caisson system or cased glory hole, or contacts an unprotected Xmas tree.

Table A3: Basis for Calculation for Iceberg Risk - Single Satellite Well Developments

Description	Annual Probability						Comments
	1a	1b	1c	1d	1e	1f	
(A) - Original Risk of Iceberg Encounter	9.60E-04	9.60E-04	5.60E-05	2.00E-04	2.50E-05	9.60E-04	As per Table16
(A) - 85% Iceberg Mgnt Effectiveness for Original Risk of Blowout	1.80E-04	1.80E-04	5.60E-05	5.20E-05	2.50E-05	1.80E-04	Assumes iceberg management overall success rate equal to 85%
Risk of Permanent Damage Given That Iceberg Contact with a Unprotected Well Installation has Occurred	9.70E-02	9.70E-02	9.70E-02	9.70E-02	9.70E-02	9.70E-02	Reference C-CORE (2001b & 2001c)
SCSSV Reliability	9.73E-01	9.73E-01	9.73E-01	9.73E-01	9.73E-01	9.73E-01	SCSSV Reliability = 0.973, Reference Molnes (2000)
(B) - Revised Risk - Iceberg Contact, No Blowout (SCSSV Performs)	8.43E-04	8.43E-04	4.92E-05	1.76E-04	2.20E-05	8.43E-04	Assumes that downhole permanent damage is required in order to affect the operation of the SCSSV
(C) - Revised Risk - Iceberg Contact, Blowout (SCSSV Don't Perform)	1.17E-04	1.17E-04	6.80E-06	2.43E-05	3.03E-06	1.17E-04	Assumes that downhole permanent damage is required in order to affect the operation of the SCSSV
(B) - 85% Iceberg Management Effectiveness	1.58E-04	1.58E-04	4.92E-05	4.57E-05	2.20E-05	1.58E-04	Assumes iceberg management overall success rate equal to 85%
(C) - 85% Iceberg Management Effectiveness	2.18E-05	2.18E-05	6.80E-06	6.31E-06	3.03E-06	2.18E-05	Assumes iceberg management overall success rate equal to 85%

Table A4: Basis for Calculation for Iceberg Risk - Clustered Multi-well Developments

Description	Annual Probability						Comments
	2a	2b	2c	2d	2e	2f	
(A) - Original Risk of Iceberg Encounter	2.60E-03	2.60E-03	1.10E-04	6.50E-04	8.80E-05	2.60E-03	As per Table 17
(A) - 85% Iceberg Mgnt Effectiveness for Original Risk of Blowout	4.60E-04	4.60E-04	1.10E-04	1.60E-04	8.80E-05	4.60E-04	Assumes iceberg management overall success rate equal to 85%
Risk of Permanent Damage Given That Iceberg Contact with Unprotected Well Installations has Occurred	9.70E-02	9.70E-02	9.70E-02	9.70E-02	9.70E-02	9.70E-02	Reference C-CORE (2001b & 2001c)
SCSSV Reliability	9.73E-01	9.73E-01	9.73E-01	9.73E-01	9.73E-01	9.73E-01	SCSSV Reliability = 0.973, Reference Molnes (2000)
(B) - Revised Risk - Iceberg Contact, No Blowout (SCSSV Performs)	2.28E-03	2.28E-03	9.66E-05	5.71E-04	7.73E-05	2.28E-03	Assumes that downhole permanent damage is required in order to affect the operation of the SCSSV
(C) - Revised Risk - Iceberg Contact, Blowout (SCSSV Don't Perform)	3.16E-04	3.16E-04	1.34E-05	7.89E-05	1.07E-05	3.16E-04	Assumes that downhole permanent damage is required in order to affect the operation of the SCSSV
(B) - 85% Iceberg Management Effectiveness	4.04E-04	4.04E-04	9.66E-05	1.41E-04	7.73E-05	4.04E-04	Assumes iceberg management overall success rate equal to 85%
(C) - 85% Iceberg Management Effectiveness	5.58E-05	5.58E-05	1.34E-05	1.94E-05	1.07E-05	5.58E-05	Assumes iceberg management overall success rate equal to 85%

Appendix B

Rates & Norms

Table B1: Rates and Norms

Item	Description	Cost ($CDN) / Rate	Unit	Comments
Equipment Costs				
1	Replacement of Conventional Xmas tree	$13,500,000	per tree	included in cost of new well (base case). includes installation and hardware costs
2	Replacement of Caisson Sacrificial	$8,000,000	per well	includes installation and hardware costs
3	Construction Vessel c/w WROV	$350,000	per day	repair casing
4	Dredge Vessel c/w WROV	$340,000	per day	excavate dredged open hole and cleanup of dredged open hole
5	Dive Support Vessel (DSV) c/w WROV	$315,000	per day	includes diving spread
6	Drill Rig c/w ROV	$1,000,000	per day	used for installing caisson and cased systems
Construction Costs				
7	Caisson Tree Hole Prep	$3,000,000	per hole	incremental costs over base case; includes incremental rig time, tree costs, drilling components & downhole weak shear plane
8	Cased Glory Hole Prep	$2,000,000	per hole	incremental costs over base case - assumes holes drilled using 7.3m bit
9	Modified Cased Glory Hole Prep	$2,000,000	per hole	incremental costs over base case - assumes holes drilled using 7.3m bit
10	Downhole Weak Shear Joint Prep	$1,250,000	per well	includes 1 day extra drill rig time and $CDN 250,000 in extra equipment costs
11	Open Glory Hole Excavation (single well)	$8,500,000	per hole	includes constuction vessel and mob / demob costs
12	Open Glory Hole Excavation (multi-well)	$24,140,000	per hole	includes constuction vessel and mob / demob costs
13	Drill a Production Well	$82,000,000	per well	includes all costs incurred in drilling and completing new production well. The Xmas tree cost is included. Hole preparation costs are added incrementally as indicated above
14	Drill a Relief Well	$50,000,000	per well	includes all costs associated with drilling and completing a relief well
15	Re-enter Well & Repair	$50,000,000	per well	includes all costs associated with re-entering a well and performing repairs
16	Re-enter Well & Repair Conductor	$27,500,000	per well	includes all costs associated with re-entering a well and performing repairs to upper portion of conductor
17	Repair Casing	$2,450,000	Each	includes casing - assumes construction vessel will be used
18	Tie-In Cost for a Well in a Cased Hole	$1,145,000	per well	includes DSV and tie-in materials for 3 days
Services				
19	Spill Clean Up Rate (single well)	$1,500,000	per day	assume spill does not reach land
20	Spill Clean Up Rate (multiple wells)	$3,000,000	per day	assume spill does not reach land
Activity Duration Times				
21	Vessel Mob / De-mob	20	days	assumes 10 day transit each way from either North Sea / Gulf of Mexico
22	Drill a Relief Well	45	days	costs covered under construction costs for drill relief well
23	Drill a New Production Well	60	days	costs covered under construction costs for production well
24	Kill a Well	45	days	account for rig time only
25	Re-enter Well & Repair	45	days	costs covered under construction costs for re-enter well and repair
26	Install a New Tree	10	days	accounts for rig time only
27	Tie-in a well	3	days	account for DSV c/w WROV, services and equipment only
28	Clean Out a Dredged Open Glory Hole	14	days	assume dredge vessel c/w WROV
29	Clean Out a Cased Glory Hole	10	days	assume DSV c/w WROV
30	Clean Out a Caisson Hole	5	days	assume drill rig c/w WROV
31	Repair / Install a New Caisson Sacrificial	5	days	upper caisson, upper HP riser, surface Xmas tree
32	Excavate Open Glory Hole (single well)	5	days	dredge vessel c/w WROV assuming an average excavation rate of 1500 m^3/d for a theroetical volume of 7756 m^3
33	Excavate Open Glory Hole (multi-well)	51	days	dredge vessel c/w WROV assuming an average excavation rate of 1500 m^3/d for a theroetical volume of 76800 m^3
34	Repair Casing	7	days	construction Vessel c/w WROV
35	Spill Cleanup	60	days	assuming a well blowout condition
36	Cleanup Damaged Tree	12	days	assumes tree is contacted but blowout does not occur & drill rig is used to perform cleanup
Production Data				
	Case 1 - Single Well Installation:			
37	Peak Daily Well Production Rate	15,000	bbl/day	used to calculate loss production costs
38	Spill/Blowout Rate	75,000	bbl/day	used to account for production lost to spill
39	Netback per Barrel	$10	per bbl	used to calculate loss production costs
	Case 2 - Multi-well Installation:			
49	Peak Daily Well Production Rate	$40,000	bbl/day	used to calculate loss production costs
41	Spill/Blowout Rate	$200,000	bbl/day	used to account for production lost to spill
42	Netback per Barrel	$10	per bbl	used to calculate loss production costs

Appendix C

Cost Summary

Table C1: Consequence Scenario Costs: Case 1&2a - Unprotected Well(s)

Incremental Development Cost:	Case 1	Case 2	
Item	Cost ($MM CDN)	Cost ($MM CDN)	Comments
Installation cost of single unprotected well	$0.0	$0.0	Base case - no incremental cost
Consequence Scenario:			
A: Iceberg Encounter	n/a	n/a	Assumes that upon iceberg contact with the Xmas tree, the tree and well is damaged beyond repair; however, the SCSSV performs properly and shuts the well in.
Cleanup	$12.0	$36.0	
Re-enter Well & Repair	$50.0	$150.0	
Install New Tree	$23.5	$70.5	
Tie-in well	$3.0	$9.0	Tie flowline back into tree loacted at mudline.
Lost Production	$10.5	$84.0	
B: Iceberg Contact - SCSSV Performs (No 'Blowout')			Assumes that upon iceberg contact with the Xmas tree, the tree and well is damaged beyond repair; however, the SCSSV performs properly and shuts the well in.
Cleanup	$12.0	$36.0	
Re-enter Well & Repair	$50.0	$150.0	
Install New Tree	$23.5	$70.5	
Tie-in well	$3.0	$9.0	Tie flowline back into tree loacted at mudline.
Lost Production	$10.5	$84.0	
C: Iceberg Contact - SCSSV Don't Perform ('Blowout')			Assumes the iceberg contacts the tree resulting in destruction of the tree; however, the SCSSV does not perform, resulting in a blowout.
Environmantal spill cleanup	$90.0	$180.0	
Drill Relief Well & Kill	$95.0	$285.0	
Drill New Production Well & Tie-in	$85.0	$255.0	
Lost Production	$32.0	$255.6	
Totals:			
A: Iceberg Encounter	**$99.0**	**$349.5**	
B: Contact - SCSSV Performs (No 'Blowout')	**$99.0**	**$349.5**	
C: Contact - SCSSV Don't Perform ('Blowout')	**$302.0**	**$975.6**	

Table C2: Consequence Scenario Costs: Case 1&2b - Unprotected Well(s) w/ Weak Shear Joint

Incremental Development Cost:	**Case 1**	**Case 2**	
Item	**Cost ($MM CDN)**	**Cost ($MM CDN)**	**Comments**
Installation cost of single unprotected well w/ downhole weak shear joint	$1.3	$7.5	Incremental cost to install downhole weak shear joint.
Consequence Scenario:			
A: Iceberg Encounter			Assumes iceberg makes contact with tree and conductor shears correctly and the SCSSV performs and shuts the well in.
Cleanup	$12.0	$36.0	
Re-enter Well & Repair Conductor	$27.5	$82.5	
Install New Tree	$23.5	$70.5	
Tie-in	$3.0	$9.0	Tie flowline back into tree loacted at mudline.
Lost Production	$10.5	$84.0	
B: Contact - SCSSV Performs (No 'Blowout')			Assumes the weak shear joint does not separate correctly, however, the SCSSV does perform and shuts the well in.
Cleanup	$12.0	$36.0	
Re-enter Well & Repair	$50.0	$150.0	
Install New Tree	$23.5	$70.5	
Tie-in	$3.0	$9.0	Tie flowline back into tree loacted at mudline.
Lost Production	$10.5	$84.0	
C: Contact - SCSSV Don't Perform ('Blowout')			Assumes the iceberg contacts the Xmas tree resulting in destruction of the tree, but failure of both the weak shear joint and the SCSSV to operate correctly results in a blowout.
Environmantal spill cleanup	$90.0	$180.0	
Drill Relief Well & Kill	$95.0	$285.0	
Drill New Production Well & Tie-in	$85.0	$255.0	
Lost Production	$32.0	$255.6	
Totals:			
A: Iceberg Encounter	**$76.5**	**$282.0**	
B: Contact - SCSSV Performs (No 'Blowout')	**$99.0**	**$349.5**	
C: Contact - SCSSV Don't Perform ('Blowout')	**$302.0**	**$975.6**	

Table C3: Consequence Scenario Costs: Case 1&2c - Open Glory Hole

Incremental Development Cost:	Case 1	Case 2	
Item	Cost ($MM CDN)	Cost ($MM CDN)	Comments
Glory hole excavation	$8.5	$24.1	Incremental cost to excavate open glory hole.
Consequence Scenario:			
A: Iceberg Encounter			Assumes that the iceberg enters the hole, but does not penetrate deep enough to hit the top of the Xmas tree.
Mob / De-mob Dredge Vessel c/w WROV	$6.8	$6.8	Assumes 10 day transit each way from either North Sea / Gulf of Mexico.
Clean-up	$4.8	$14.3	Clean out of glory hole after iceberg event required.
B: Contact - SCSSV Performs (No 'Blowout')			Assumes the iceberg contacts the Xmas tree resulting in destruction of the tree, however, the SCSSV performs and the well is shut-in.
Cleanup	$26.0	$50.0	
Re-enter Well & Repair	$50.0	$150.0	
Install New Tree	$23.5	$70.5	
Tie-in	$3.0	$9.0	Tie flowline back into tree loacted inside glory hole..
Lost Production	$12.6	$89.6	
C: Contact - SCSSV Dont Perform ('Blowout')			Assumes the iceberg contacts the Xmas tree resulting in destruction of the tree, but failure of the SCSSV results in a blowout.
Environmantal spill cleanup	$90.0	$180.0	
Drill Relief Well & Kill	$95.0	$285.0	
Drill New Production Well & Tie-in	$85.0	$255.0	
Lost Production	$32.0	$255.6	
Totals:			
A: Iceberg Encounter	**$11.6**	**$21.1**	
B: Contact - SCSSV Performs (No 'Blowout')	**$115.1**	**$369.1**	
C: Contact - SCSSV Dont Perform ('Blowout')	**$302.0**	**$975.6**	

Table C4: Consequence Scenario Costs: Case 1&2d - Cased Glory Hole(s)

Incremental Development Cost:	Case 1	Case 2	
Item	Cost ($MM CDN)	Cost ($MM CDN)	Comments
Cased glory hole excavation	$2.0	$12.0	Incremental cost to excavate cased glory hole.
Consequence Scenario:			
A: Iceberg Encounter			Assumes that the casing is contacted by a scouring iceberg above the shear point resulting in proper separation of the casing weak shear plane. The casing requires substantial repairs while the Xmas tree and wellhead suffer no damage.
Mob / De-mob DSV c/w WROV	$6.3	$6.3	Assumes 10 day transit each way from either North Sea / Gulf of Mexico.
Clean-up	$3.2	$9.5	Clean out of glory hole after iceberg event.
Repair casing	$2.5	$7.4	
Tie-in well	$1.1	$3.4	Tie flowline back into tree loacted in cased hole.
Lost Production	$6.00	$48.00	
B: Contact - SCSSV Performs (No 'Blowout')			Assumes the casing shears improperly as a result of a deep scouring iceberg and the Xmas tree is damaged beyond repair; however, the SCSSV performs properly and shuts the well in.
Cleanup	$29.0	$87.0	
Re-enter Well & Repair	$50.0	$150.0	
Install New Tree	$23.5	$70.5	
Tie-in	$1.1	$3.4	Tie flowline back into tree loacted in cased hole.
Lost Production	$12.0	$96.0	
C: Contact - SCSSV Don't Perform ('Blowout')			Assumes the casing shears improperly as a result of a deep scouring iceberg and the Xmas tree is damaged beyond repair. The SCSSV fails to operate properly, resulting in destruction to Xmas tree and a well blowout.
Environmantal spill cleanup	$90.0	$180.0	
Drill Relief Well & Kill	$95.0	$285.0	
Drill New Production Well & Tie-in	$85.0	$255.0	
Lost Production	$32.0	$255.6	
Totals:			
A: Iceberg Encounter	**$19.0**	**$74.5**	
B: Contact - SCSSV Performs (No 'Blowout')	**$115.6**	**$406.9**	
C: Contact - SCSSV Don't Perform ('Blowout')	**$302.0**	**$975.6**	

Table C5: Consequence Scenario Costs: Case 1&2e - Modified Cased Glory Hole(s)

Incremental Development Cost:	Case 1	Case 2	
Item	Cost ($MM CDN)	Cost ($MM CDN)	Comments
Modified cased glory hole excavation	$2.0	$12.0	Incremental cost to excavate modified cased glory hole.
Consequence Scenario:			
A: Iceberg Encounter			Assumes that a scouring iceberg contacts the hole above the casing and inner protection shield.
Mob / De-mob DSV c/w WROV	$6.3	$6.3	Assumes 10 day transit each way from either North Sea / Gulf of Mexico.
Cleanup hole	$3.2	$9.5	Clean out of cased glory hole after iceberg event.
Tie-in well	$1.1	$3.4	Tie flowline back into tree loacted in modified cased hole.
Lost Production	$4.95	$39.60	
B: Contact - SCSSV Performs (No 'Blowout')			Assumes the casing is contacted as a result of a deep scouring iceberg and the Xmas tree is damaged beyond repair; however, the SCSSV performs properly and shuts the well in.
Cleanup	$22.0	$66.0	
Repair casing	$2.5	$7.4	
Re-enter Well & Repair	$50.0	$150.0	
Install New Tree	$23.5	$70.5	
Tie-in	$1.1	$3.4	Tie flowline back into tree loacted in modified cased hole.
Lost Production	$13.1	$104.4	
C: Contact - SCSSV Don't Perform ('Blowout')			Assumes the casing is contacted as a result of a deep scouring iceberg and the Xmas tree is damaged beyond repair. The SCSSV fails to operate properly, resulting in destruction to the Xmas tree and a well blowout.
Environmantal spill cleanup	$90.0	$180.0	
Drill Relief Well & Kill	$95.0	$285.0	
Drill New Production Well & Tie-in	$85.0	$255.0	
Lost Production	$32.0	$255.6	
Totals:			
A: Iceberg Encounter	**$15.5**	**$58.8**	
B: Contact - SCSSV Performs (No 'Blowout')	**$112.1**	**$401.7**	
C: Contact - SCSSV Don't Perform ('Blowout')	**$302.0**	**$975.6**	

Table C6: Consequence Scenario Costs: Case 1&2f - Caisson Wellhead System(s)

Incremental Development Cost:	**Case 1**	**Case 2**	
Item	**Cost ($MM CDN)**	**Cost ($MM CDN)**	**Comments**
Caisson wellhead system installation	$3.0	$18.0	Incremental cost to install a caisson wellhead system.
Consequence Scenario:			
A: Iceberg Encounter			Assumes that upon iceberg contact with the Xmas tree, the tree is damaged beyond repair; however, the weak shear joint seperates correctly and ensures the SCSSV performs properly and shuts the well in.
Cleanup	$5.0	$15.0	
Repair caisson	$5.0	$15.0	
Install new sacrifical tree	$18.0	$54.0	
Tie-in well	$3.0	$9.0	Tie flowline back into sacrificial tree loacted at mudline.
Lost Production	$5.25	$42.00	
B: Contact - SCSSV Performs (No 'Blowout')			Assumes a deep scouring iceberg impacts the caisson in such a manner as to fail the caisson in a mode other than shear, however, proper performance of the SCSSV shuts the well in.
Cleanup	$5.0	$15.0	
Re-enter Well & Repair	$50.0	$150.0	
Repair caisson	$5.0	$15.0	
Install new sacrifical tree	$18.0	$54.0	
Tie-in well	$3.0	$9.0	Tie flowline back into sacrificial tree loacted at mudline.
Lost Production	$4.20	$33.60	
C: Contact - SCSSV Don't Perform ('Blowout')			Assumes a deep scouring iceberg impacts the caisson in such a manner as to fail the caisson in a mode other than shearfailure of the downhole master valve and SCSSV results in a blowout of the well.
Environmantal spill cleanup	$90.0	$180.0	
Drill Relief Well & Kill	$95.0	$285.0	
Drill New Production Well & Tie-in	$85.0	$255.0	
Lost Production	$32.0	$255.6	
Totals:			
A: Iceberg Encounter	**$36.3**	**$135.0**	
B: Contact - SCSSV Performs (No 'Blowout')	**$85.2**	**$276.6**	
C: Contact - SCSSV Don't Perform ('Blowout')	**$302.0**	**$975.6**	

Table C7: Comparison of Net Costs for Single Well Developments

Case	Description	Incremental CAPEX (*C*) [$MM CDN]	Annual Probability of Iceberg Event (*Pf*)	Consequence Cost (*R+ E+ Lp*) [$MM CDN]	Field Life (*T*) [Years]	Cost of Risk (*Cr*) [$MM CDN]	Net System Cost (*N = C + Cr*) [$MM CDN]	Unit Normalized *C*	Unit Normalized *Cr*
1a	Unprotected Well	1.0	A: 9.60E-04 B: 8.43E-04 C: 1.17E-04	99.0 99.0 302.0	6	**1.282**	2.282	0.105	1.000
1b	Unprotected Well w/ Weak Shear Joint	2.3	A: 9.60E-04 B: 8.43E-04 C: 1.17E-04	76.5 99.0 302.0	6	1.153	3.403	0.237	0.899
1c	Open Glory Hole	**9.5**	A: 5.60E-05 B: 4.92E-05 C: 6.80E-06	11.6 115.1 302.0	6	0.050	9.550	1.000	0.039
1d	Cased Glory Hole	3.0	A: 2.00E-04 B: 1.76E-04 C: 2.43E-05	19.0 115.6 302.0	6	0.189	3.189	0.316	0.147
1e	Modified Cased Hole	3.0	A: 2.50E-05 B: 2.20E-05 C: 3.03E-06	15.5 112.1 302.0	6	0.023	3.023	0.316	0.018
1f	Caisson Wellhead System	4.0	A: 9.60E-04 B: 8.43E-04 C: 1.17E-04	36.3 85.2 302.0	6	0.851	4.851	0.421	0.664

Notes:

1. Annual Probability of Iceberg Event: A: Iceberg Encounter, B: Contact (SCSSV Performs), C: Contact (SCSSV Don't Perform – "Blowout").
2. A 6-year and 8-year life of field has been assumed for both the single well and multi-well development, respectively.
3. The "Cost of Risk" is the sum of the annual probability of iceberg events times the total repair/replacement, cleanup and lost production costs, all multiplied by the life of field.
4. In order to undertake a unit normalized comparison of options, a value of $1.0 MM has been added to incremental CAPEX for each option

Table C8: Comparison of Net Costs for Multi-well Developments

Case	Description	Incremental CAPEX (*C*) [$MM CDN]	Annual Probability of Iceberg Event (*Pf*)	Consequence Cost (*R+ E+ Lp*) [$MM CDN]	Field Life (*T*) [Years]	Cost of Risk (*Cr*) [$MM CDN]	Net System Cost (*N = C + Cr*) [$MM CDN]	Unit Normalized *C*	Unit Normalized *Cr*
2a	Unprotected Wells	1.0	A: 2.60E-03 B: 2.28E-03 C: 3.16E-04	349.5 349.5 975.6	8	**16.120**	17.120	0.040	1.000
2b	Unprotected Wells w/ Weak Shear Joint	8.5	A: 2.60E-03 B: 2.28E-03 C: 3.16E-04	282.0 349.5 975.6	8	14.716	23.216	0.338	0.913
2c	Open Glory Hole	**25.1**	A: 1.10E-04 B: 9.66E-05 C: 1.34E-05	21.1 369.1 975.6	8	0.408	25.548	1.000	0.025
2d	Cased Glory Holes	13.0	A: 6.50E-04 B: 5.71E-04 C: 7.89E-05	74.5 406.9 975.6	8	2.863	15.863	0.517	0.178
2e	Modified Cased Holes	13.0	A: 8.80E-05 B: 7.73E-05 C: 1.07E-05	58.8 401.7 975.6	8	0.373	13.373	0.517	0.023
2f	Caisson Wellhead Systems	19.0	A: 2.60E-03 B: 2.28E-03 C: 3.16E-04	135.0 276.6 975.6	8	10.326	29.326	0.756	0.641

Notes:

1. Annual Probability of Iceberg Event: A: Iceberg Encounter, B: Contact (SCSSV Performs), C: Contact (SCSSV Don't Perform – "Blowout").
2. A 6-year and 8-year life of field has been assumed for both the single well and multi-well development, respectively.
3. The "Cost of Risk" is the sum of the annual probability of iceberg events times the total repair/replacement, cleanup and lost production costs, all multiplied by the life of field.
4. In order to undertake a unit normalized comparison of options, a value of $1.0 MM has been added to incremental CAPEX for each option

Table C9: Comparison of Net Costs for Single Well Developments (85% Iceberg Mgnt Effectiveness)

Case	Description	Incremental CAPEX (C) [$MM CDN]	Annual Probability of Iceberg Event (Pf)	Consequence Cost ($R+E+Lp$) [$MM CDN]	Field Life (T) [Years]	Cost of Risk (Cr) [$MM CDN]	Net System Cost ($N = C + Cr$) [$MM CDN]	Unit Normalized C	Unit Normalized Cr
1a	Unprotected Well	1.0	A: 1.80E-04 B: 1.58E-04 C: 2.18E-05	99.0 99.0 302.0	6	**0.240**	1.240	0.105	1.000
1b	Unprotected Well w/ Weak Shear Joint	2.3	A: 1.80E-04 B: 1.58E-04 C: 2.18E-05	76.5 99.0 302.0	6	0.216	2.466	0.237	0.899
1c	Open Glory Hole	**9.5**	A: 5.60E-05 B: 4.92E-05 C: 6.80E-06	11.6 115.1 302.0	6	0.050	9.550	1.000	0.209
1d	Cased Glory Hole	3.0	A: 5.20E-05 B: 4.57E-05 C: 6.31E-06	19.0 115.6 302.0	6	0.049	3.049	0.316	0.204
1e	Modified Cased Hole	3.0	A: 2.50E-05 B: 2.20E-05 C: 3.03E-06	15.5 112.1 302.0	6	0.023	3.023	0.316	0.094
1f	Caisson Wellhead System	4.0	A: 1.80E-04 B: 1.58E-04 C: 2.18E-05	36.3 85.2 302.0	6	0.160	4.160	0.421	0.664

Notes:

1. Annual Probability of Iceberg Event: A: Iceberg Encounter, B: Contact (SCSSV Performs), C: Contact (SCSSV Don't Perform – "Blowout").
2. A 6-year and 8-year life of field has been assumed for both the single well and multi-well development, respectively.
3. The "Cost of Risk" is the sum of the annual probability of iceberg events times the total repair/replacement, cleanup and lost production costs, all multiplied by the life of field.
4. In order to undertake a unit normalized comparison of options, a value of $1.0 MM has been added to incremental CAPEX for each option

Table C10: Comparison of Net Costs for Multi-well Developments (85% Iceberg Mgnt Effectiveness)

Case	Description	Incremental CAPEX (*C*) [$MM CDN]	Annual Probability of Iceberg Event (*Pf*)	Consequence Cost (*R+ E+ Lp*) [$MM CDN]	Field Life (*T*) [Years]	Cost of Risk (*Cr*) [$MM CDN]	Net System Cost (*N = C + Cr*) [$MM CDN]	Unit Normalized *C*	Unit Normalized *Cr*
2a	Unprotected Wells	1.0	A: 4.60E-04 B: 4.04E-04 C: 5.58E-05	349.5 349.5 975.6	8	**2.852**	3.852	0.040	1.000
2b	Unprotected Wells w/ Weak Shear Joint	8.5	A: 4.60E-04 B: 4.04E-04 C: 5.58E-05	282.0 349.5 975.6	8	2.604	11.104	0.338	0.913
2c	Open Glory Hole	**25.1**	A: 1.10E-04 B: 9.66E-05 C: 1.34E-05	21.1 369.1 975.6	8	0.408	25.548	1.000	0.143
2d	Cased Glory Holes	13.0	A: 1.60E-04 B: 1.41E-04 C: 1.94E-05	74.5 406.9 975.6	8	0.705	13.705	0.517	0.247
2e	Modified Cased Holes	13.0	A: 8.80E-05 B: 7.73E-05 C: 1.07E-05	58.8 401.7 975.6	8	0.373	13.373	0.517	0.131
2f	Caisson Wellhead Systems	19.0	A: 4.60E-04 B: 4.04E-04 C: 5.58E-05	135.0 276.6 975.6	8	1.827	20.827	0.756	0.641

Notes:

1. Annual Probability of Iceberg Event: A: Iceberg Encounter, B: Contact (SCSSV Performs), C: Contact (SCSSV Don't Perform – "Blowout").
2. A 6-year and 8-year life of field has been assumed for both the single well and multi-well development, respectively.
3. The "Cost of Risk" is the sum of the annual probability of iceberg events times the total repair/replacement, cleanup and lost production costs, all multiplied by the life of field.
4. In order to undertake a unit normalized comparison of options, a value of $1.0 MM has been added to incremental CAPEX for each option