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Arctic Offshore Loading Downtime Due to Variability in Ice Drift Direction

Basile Bonnemaire

(*Norwegian University of Science and Technology*)
(Barlindhaug Consult AS)
(Email: basile.bonnemaire@barlindhaug.no)

Four arctic offshore loading concepts are selected, loading from the corner of a platform, loading in the wake of a loading tower, Submerged Turret Loading (STL) and Single Anchor Loading (SAL). The influence of variations in the ice drift direction on the performance of these concepts is discussed and critical drift events are determined. Ice drift measurements from eight ARGOS/GPS buoys deployed in the Pechora Sea in winters 1995 and 1998 are analysed to estimate downtime rates of these loading systems due to ice drift heading changes. Depending on the location in the Pechora Sea and the chosen concept, downtime rates range from 6 to 72%. A discussion on how these rates will vary with different assumptions, different ice conditions or different ice management is given. Finally the loading concepts are compared through a qualitative risk analysis.

KEY WORDS

1. arctic offshore loading, 2. ice drift direction, 3. downtime.

1. INTRODUCTION. Arctic offshore oil production will increase in the future. With regards to exploration and onshore production, technology is rather up-to-date to cope with the arctic environmental conditions. Experiences with year-round drilling and production platforms or vessels in ice-covered seas are however sparser. The export of the produced hydrocarbons remains a major challenge in heavily ice-infested waters. This tends to penalise arctic offshore production activities. Shipping and pipelining are two possible alternatives for the export of the hydrocarbons. Gudmestad and Løset (2004) conclude that shipping often can be an attractive solution. As reported by Jolles et al. (1997), analysis of risks during arctic marine transportation determined that the loading operations are the most important development issue. Many arctic offshore loading concepts have been proposed for areas where heavy sea ice conditions govern any design that should be operable year-round. These concepts can be innovative designs or adaptations of systems used in ice-free seas.

When operating in drifting ice, the loading terminal is exposed to variable conditions such as changing ice thickness or varying drift speed and direction. Some of these conditions may be hazardous when a tanker is connected to the terminal, as mooring loads may become excessive or the collision risks with a structure may get unacceptable. In order to cope safely with these fluctuations, the tanker may have to disconnect from the loading terminal until safer drift conditions are predicted. This will penalize the efficiency of the loading operations.

Arctic offshore loading is of high interest in the Pechora Sea. The export of onshore production and the future export from the Prirazlomnoye field and other offshore fields as the Dolginskaya field are of concern. The Pechora Sea presents shallow waters and severe ice conditions. Ice is found in the area 2/3 of the year with a maximum level ice thickness of 1·6 m and drift speeds up to 1·0 m/s. Icebergs are not present in this area but ridges with 12–18 m deep keels are expected (Løset et al., 1997).

With the development of new arctic fields, different loading concepts will have to be compared to find the most suitable one for each particular case. The winter operability rate of a particular system is critical when establishing its profitability. This rate will highly depend on the ice properties and drift conditions in the area. Within the framework of the Northern Gateway Terminal Study, eight ARGOS buoys equipped with GPS receivers were deployed in the Pechora Sea in winters 1995 and 1998 (see Løset and Onshuus, 1999; DeFranco et al., 2001; Bonnemaire, 2005). After a review of arctic offshore loading concepts and a discussion on critical drift events for loading operations, these ice drift data are used to assess the downtime of different arctic offshore loading concepts due to the variability in the drift direction in different regions of the Pechora Sea.

2. REVIEW OF ARCTIC OFFSHORE LOADING CONCEPTS.

Many design solutions for arctic offshore loading have been presented in the literature in the past decades. A first category of concepts proposes to moor and load the tanker in the wake of a structure. The structure can be the production platform itself equipped with loading arms. This technology is planned for use on the Prirazlomnoye platform (Malyutin et al., 2003); the loading arms will be at the corners of the square Gravity Base Structure (GBS). The tanker is then moored at a fixed point on the structure, and has a limited manoeuvrability range to stay in the platform lee without disconnecting. This is an economical solution but it may suffer from operational risks linked to impact between the tanker and the production platform. The structure can alternatively be circular, as in the case of a circular GBS or a narrow loading terminal, around which the tanker can vane; the anchoring point can then rotate around the structure (see e.g. Gudmestad et al., 1999; Spencer et al., 1997). If an independent loading tower is considered, it has to be designed to resist ice loads, thus this might be an expensive solution in areas presenting severe ice conditions. A rigid mooring system that can take compression forces can be used with this concept, and might be stronger than a flexible mooring system. Model tests showed that collision risks due to a sudden change in the ice direction are still present with a rigid arm (Machemehl, 1987). The loading terminal can be designed as a small harbour which tankers enter to load (Tsinker, 1995). Ice accumulations and entry difficulties in drifting ice penalise this concept.

A second category of concepts are subsea designs, they minimize interactions with the drifting ice. Loire and Chow (1985) or Pollac (1985) proposed different

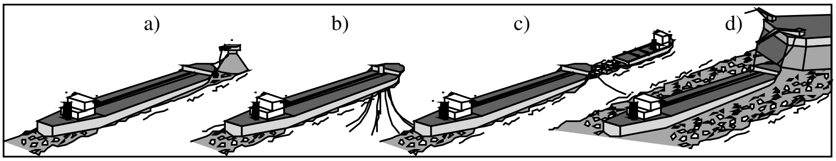

Figure 1. Sketches of the different selected loading concepts; a) tower loading, b) Submerged Turret Loading (STL), c) Single Anchor Loading (SAL) with an icebreaker for ice management, d) platform corner loading.

adaptations of Single Point Mooring (SPM) systems for arctic waters. More recently, a Single Anchor Loading (SAL) system, where the hawser for bow loading is protected in a lobster, was introduced (Di Tella, 1996; Di Tella and Juurmaa, 1997). A SAL system with a non-protected reinforced hawser was built by APL (Advanced Production and Loading AS) and installed in the Pechora Sea offshore Varandey in 2002 (APL, 2003). These surface piercing concepts, though protected, have a limited capacity to resist ice forces and will not be operational in severe ice conditions unless effective ice management is available (Løset et al., 2003). The use of Multiple Buoy Mooring (MBM) was also mentioned by Buslov et al. (2004); however, the tanker moored at the aft and bow would not be able to weather vane and ice forces would be very large when ice is moving sideways. Finally, an adaptation of the Submerged Turret Loading (STL) system is presented by e.g. Jensen et al. (2000), Bonnemaire et al. (2003) and Bonnemaire (2005). Protected by a flexible armour, the riser will not interact directly with incoming ice that is broken by the vessel.

The experience with arctic offshore production and oil export is limited. At the Northstar Production Island in Alaska, a buried pipeline transfers the oil to shore (Lanan and Ennis, 2001). At the Terra Nova Field offshore Newfoundland, tandem offloading from the aft of the FPSO (Floating Production Storage and Offloading unit) is performed (Lever et al., 2001). In this part of the Grand Banks, drifting icebergs are of concern but the presence of sea ice is limited. Tandem offloading is not suitable for heavily ice-infested waters. In the Vityaz Complex offshore Sakhalin Island, a standard Single Anchor Leg Mooring buoy is used to transfer oil from the GBS Molikpaq to a Floating Storage and Offloading (FSO) unit. Oil export is shut down during winter as the buoy cannot withstand ice forces. The SAL system installed offshore Varandey is used to export a limited amount of oil (600 000 tons the first year).

As demonstrated above, experience with arctic offshore loading is limited as few of the mentioned concepts have been used, however, it is expected that some will be used in the future. Four concepts were therefore selected for comparison in the rest of the study (see sketches in Figure 1). These concepts are loading behind a tower (with a soft mooring), Submerged Turret Loading, Single Anchor Loading and loading from a platform corner (named hereafter "tower loading", "STL", "SAL" and "platform corner loading" respectively). This selection was based on including the concepts probably best suited for operations in heavy arctic offshore conditions (tower loading and STL) or on their actual or planned use in the arctic offshore (platform corner loading and SAL). Safety and economical considerations will determine the choice of a particular concept for a given project and many parameters will interfere such as for instance the location, the production stage (early or full production), the vessel type and the environmental conditions. When year-round operations are considered, an important aspect is the operability rate in winter conditions.

3. LOADING OPERABILITY IN DRIFTING ICE.

3.1. *Parameters influencing a terminal winter operability.* During the ice-free season, the terminal performance will depend, among other factors, on the local wind, wave and current conditions and the rate of the loading pumps (CanMar, 1984). In winter, the terminal downtime will often be linked to the presence of ice. The ice interacting with the terminal may cause excessive mooring forces or increase the risk for a collision between the tanker and a fixed structure. The vulnerability of a concept to these events will depend on the following parameters:

- *The tanker design and its manoeuvring capabilities*. The icebreaking capabilities of the vessel will most often govern the loads in the mooring system. Connected to the terminal, the tanker will be subjected to variable ice drift regimes and its ability to manoeuvre in different ice conditions is essential. This ability may be enhanced with proper hull, steering and propulsion designs (e.g. spoon shaped bow or azimuthal propulsion). Nevertheless, tanker ships present a long parallel mid-body and manoeuvrability improvement will be limited.
- *The terminal design and the operational stages associated with its use*. The time and manoeuvres needed to perform the final approach, to clear possible rubble accumulation, to moor and to connect to the terminal will vary from one concept to another. Manoeuvring and waiting phases caused by relocation operations will also alter the terminal operability rate.
- *Ice management*. In heavy ice conditions, the support of icebreakers will be essential to ensure good performances of the terminal. In level ice conditions, ice management can reduce ice loads to a level comparable with loads in pack ice (Spencer et al., 1997). As seen from full scale experience with the drilling unit Kulluk in the Beaufort Sea (Wright et al., 1998), ice management will however have its limits and may not be able to cope with extreme ice conditions. Ice management has to be scaled properly to ensure a good operability rate without excessive costs.
- *Ice conditions at the loading terminal*. During the winter season, presence of ice may cause the highest mooring loads. These will increase with for example the ice concentration, thickness, speed or the compression in the ice cover (Wright et al., 1998; Comfort et al., 1999). High concentration of thicker ice features, such as ice ridges or rafted ice, might as well impede effective operations. Finally, the ice regime is of importance; in case of non-landfast ice, the variability in the ice drift will govern most of the concept downtime. Change in drift direction may result in increase of mooring loads and/or collision risks between the tanker and the loading structure.

Danielewicz et al. (1995) present a model to estimate the downtime of tankers loading from Arctic platforms; they estimate that highest mooring loads are due to changes in ice drift direction but did not study how various rates of ice drift direction change will affect these loads. The rest of the study focuses on the vulnerability of the selected loading concepts to ice drift heading variability.

3.2. *Critical drift events.* A loading concept would normally be tested during its design phase in different ice conditions such as different ice thicknesses, speeds or other ice features (e.g. ridges). The effect of the variation in the drift heading is difficult to reproduce in an ice tank as it requires two degrees of freedom in the horizontal plane, and has not often been studied. Reviewing ice model test data for moored structures, Comfort et al. (1999) report on different ice tank manoeuvring tests performed with turret moored ships and tankers moored at a loading tower. These tests are of two types, ARC (slowly varying arcs or vaning) and COD (sudden Change Of Direction) tests. The tests on turret moored ships showed increasing mooring loads for ice concentrations over 80%, presenting a maximum when the ship's heading in the drifting ice is 30–40°. For the tankers moored to a loading tower "*loads increased with the amount of heading change, not very sensitive to the type of heading change* (*ARC vs. COD tests*)". ARC tests presented by Danielewicz et al. (1995) show increasing loads with decreasing ice curvature radii for a tanker moored at a circular loading terminal.

So the effect of ice drift heading variability on mooring loads has been little studied. Nevertheless, some ice drift events can be listed as potentially critical for loading operations in drifting ice; these events are:

- *Sudden drift heading change*. If a sudden change in ice drift heading occurs (e.g. over 135° abrupt heading change, thereafter named COD of 135°), the ice will start pushing the tanker from the stern. For the concepts including a fixed structure, the collision risk will then increase as the tanker may be pushed against the structure. For the other concepts (SAL and STL), the tanker will eventually start to vane, at some point the tanker will be transverse to the ice drift, the mooring forces will be high, maybe excessive. Depending on the severity of the ice conditions, disconnection and relocation might have to be performed.
- *Stationary ice*. A similar criterion for disconnection and relocation, as suggested by DeFranco et al. (2001), is the nullity of the drift speed. When the ice stops, it might start drifting again with any heading; a tanker would disconnect by precaution. If reliable ice forecasting can be performed at the site, this type of event can be predicted as critical only when the drift change will be large. Nevertheless, the forecasting has to be extremely reliable so one can trust it without increasing the hazard risks.
- *Slow heading change*. If the ice drift speed remains significant while the heading changes (this corresponds to the ARC type of tests), the tanker will have to manoeuvre to follow the drift pattern. When the ice drift curvature decreases, the mooring forces will increase and can get excessive if the limits of the manoeuvring capabilities of the tanker are reached. However, if the tanker is behind a structure, the wake will increase the manoeuvring abilities of the tanker (Spencer et al., 1997).
- *Absolute heading change*. When moored at the corner of a square platform, the tanker will have to move from corner to corner in order to stay in the platform wake; each change of corner implies a disconnection and reconnection.

Little was found on the ice drift curvature criterion in the literature, consequently a discussion on different practical aspects related to this criterion is given.

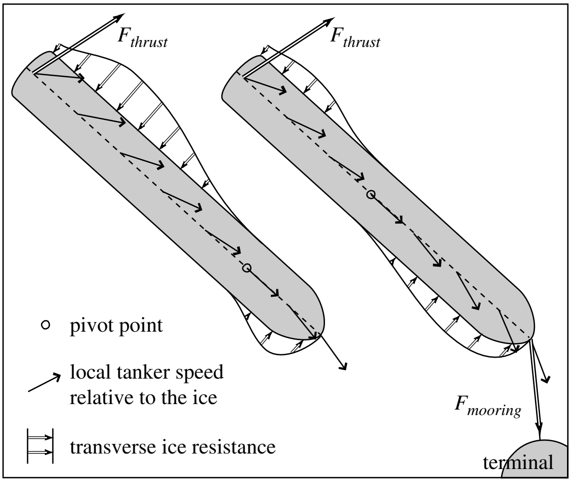

Figure 2. Distribution of transverse ice forces along the hull and position of the pivot point of a free going tanker and a tanker moored to a terminal in drifting ice.

4. THE ICE DRIFT CURVATURE RADIUS CRITERION.

4.1. *Ice drift curvature and tanker steady-state turning circle.* When moored to a terminal, a tanker will have a better loading performance if it can cope with fast variations in the ice drift direction. A usual way to assess the manoeuvring performance of ships in open water or in ice covered waters is to study their steady-state turning circle diameter. This can be determined experimentally (see e.g. Shimoda et al., 1997) or estimated using empirical formulas (see e.g. Sodhi et al., 1995). The turning diameter will increase with the ice thickness and eventually the ship will reach its manoeuvrability limit due to its limited propelling power.

Care should be taken when comparing the turning circle diameter of an icebreaker tanker and the curvature radius of the ice drift at the terminal location. The manoeuvring capabilities of a ship will differ for a sailing and a moored ship. As reported by Peirce and Peirce (1987), in steady-state turning conditions, the thrust forces have to compensate alone for the resistance from both hydrodynamic and ice forces. When moored, the forces from the mooring line(s) at the forepart will add to the thrust forces giving an increased turning moment to the ship (see Figure 2). The position of the pivot point will change, and if closer to midship, the hydrodynamic and ice resistance couple will be lower. This manoeuvrability gain is difficult to quantify as it will depend on the hull geometry and the resulting ice forces (varying with different ice failure modes along the hull). When moored, a tanker will be able to vane with a smaller curvature radius than its free-going turning circle radius.

4.2. *Ice drift curvature radius and actual tanker turning radius.* When a ship is moored in drifting ice, it should be noticed that the ice drift curvature radius might differ from the ship's turning radius. When the ice drift presents a very small curvature radius, the icebreaker tanker will not follow the ice path; she will break a lead that will allow her to turn more smoothly. This is illustrated in Figure 3 showing the path followed by a tanker moored to a loading tower during a 90° COD test (from

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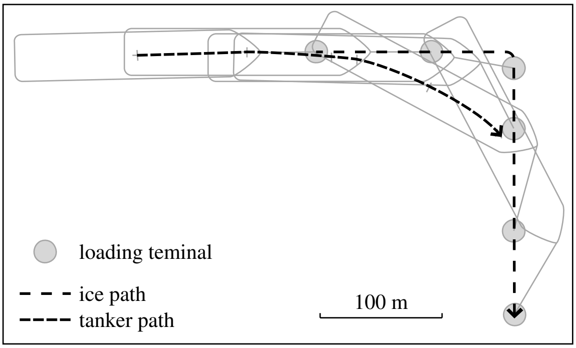

Figure 3. Tanker evolution when moored to a loading tower during a 90° COD (sudden Change of Direction) model test (from Spencer et al., 1997).

Spencer et al., 1997). Whereas the ice drift curvature radius is close to zero, the tanker turning radius is around 120 m. Thus being equal at high radii, the ice drift curvature and the ship turning radii will differ at small ice drift curvature radii. Nonetheless, the ice drift curvature radius remains a good criterion for loading downtime, as for given ice conditions, the mooring forces will increase with a decreasing ice drift radius.

4.3. *Ice drift curvature and ice drift speed.* When the ice drift heading is changing, an important parameter is the ice drift speed. This may affect the mooring loads or the ice management efficiency. Assuming a uniform distribution of the drift velocity in an ice field, the ice curvature radius R_{ice} can be defined as (Bonnemaire, 2005):

$$R_{ice} = \frac{v^2}{a_N} \tag{1}$$

where v is the ice drift speed and a_N the ice drift acceleration component normal to the velocity. The ice drift curvature radius will be minimal ($R_{ice,min}$) when the acceleration is normal to the drift velocity (then $a_N = ||\mathbf{a}||$ – the norm of the ice drift acceleration). The ice cover acceleration is estimated from the momentum balance as:

$$Ma = \tau_a + \tau_w + \tau_c + \tau_i + \tau_t \tag{2}$$

where M is the ice mass (per unit area), and the right hand side terms are respectively the air stress, the water stress, the Coriolis force, the internal ice stress and the force due to the ice tilt (forces per unit area). Usually the air stress, the water stress and the Coriolis force are the dominant forces acting on the ice (Wadhams, 2000). Air and wind stresses have magnitudes in the order of 0·1 Nm^{-2} and the Coriolis force is in the order of 0·01 Nm^{-2} (1 m thick ice moving at 0·1 ms^{-1}). If all these components are acting collinearly and perpendicularly to the ice drift direction, the normal acceleration is maximal, but it still will be physically limited. The minimum ice drift curvature radius ($R_{ice,min}$) is then proportional to the square of the ice drift speed (from Eq. 1). $R_{ice,min}$ (for a 1 m thick ice sheet) is plotted in Figure 4 together with ice drift curvature radii measured in the western Pechora Sea by an ARGOS/GPS buoy in 1998 (buoy no. 06640, details on estimations of the curvature radius from buoy drift measurements are found in a companion paper, Bonnemaire (2005)). As expected, the measured ice drift curvature radii are well above $R_{ice,min}$. Events

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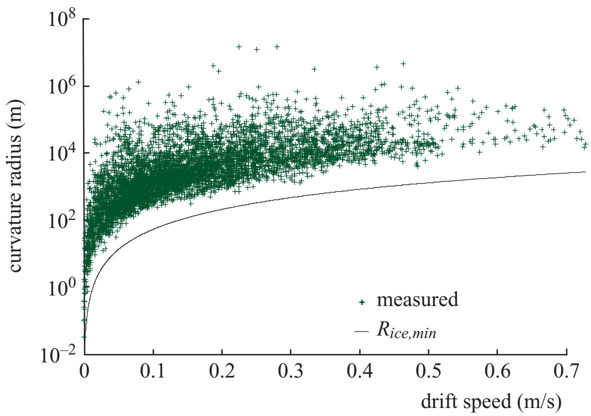

Figure 4. Minimum possible ice drift curvature radius ($R_{ice,min}$) and ice drift curvature radii measured with a ARGOS/GPS buoy in the western Pechora Sea in 1998.

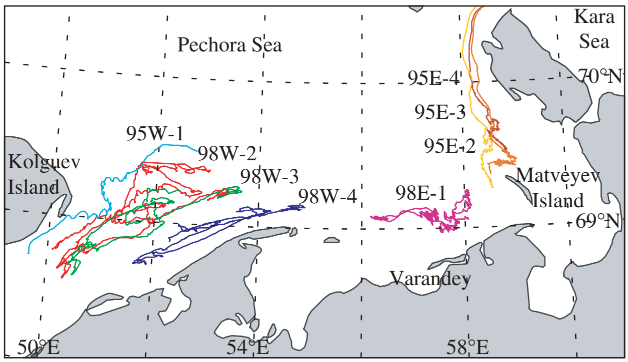

Figure 5. Paths of the ARGOS/GPS buoys deployed in 1995 (95W-1, 95E-2, 95E-3 and 95E-4) and in 1998 (98E-1, 98W-2, 98W-3 and 98W-4) in the Pechora Sea (see Bonnemaire, 2005, for more details).

presenting a small ice drift curvature radius will necessarily be associated with low ice drifting speed, it will ease the tanker ice-vaning and the ice management.

In drifting ice, a moored tanker will thus be able to cope with ice drift curvature radii much lower than the vessel's steady-state turning radius. This is favourable for efficient arctic marine operations.

5. LOADING PERFORMANCE ESTIMATIONS.

5.1. *Ice drift data.* Little information is available on the changes of drift direction (Danielewicz et al., 1995). To estimate the importance of the different events and their possible effect on the different loading concepts, ice drift measurements from the Pechora Sea in winters 1995 and 1998 are analysed. Eight ARGOS/GPS buoys were deployed, half of the buoys each winter, four in the western part and the four in the eastern part of the Pechora Sea (see the map in Figure 5). Pritchard and DeFranco

Table 1. Suggested downtime criteria due to ice drift heading variability. (Note that a thorough risk analysis accounting for all ice properties should be carried out to confirm these values).

	Minimum ice management					Permanent ice management				
	$R_{l,min}$[1] [m]	COD[2] [°]	α_{max}[3] [°]	v_{min}[4] [ms^{-1}]	Case no.	$R_{l,min}$[1] [m]	COD[2] [°]	α_{max}[3] [°]	v_{min}[4] [ms^{-1}]	Case no.
Tower loading	100	135		0·01	①		135		0·01	④
STL	200	135		0·01	②		135			⑤
Platform corner		135	70	0·01	③		135	70	0·01	③
SAL							135		0·01	④

[1] minimum permissible ice drift curvature radius under loading operations,
[2] maximum COD in 30 min,
[3] maximum ice drift heading change,
[4] minimum ice drift speed, characterise stationary ice events.

(1995) and DeFranco et al. (2001) analysed the positions of the 1995 buoys and reported on ice velocities histories, spectra and statistics, and acceleration statistics. Løset and Onshuus (1999) and Løset and Økland (2000) present drift speed analysis derived from the ARGOS positions of the 1998 buoys and estimated drift speeds for different return periods for the area. An analysis of these data is presented in a separate paper (Bonnemaire, 2005) and looks at the frequency of the drift events presented in Section 3.2. Though ice conditions differed between the two winters, similar frequencies are found. Different frequencies were found for the eastern and western Pechora Sea, critical drift events are more frequent and the periods between the occurrences are shorter in the eastern Pechora Sea.

5.2. *Critical drift event characterisation.* To estimate the downtime of each loading concept in ice drift conditions as recorded in the Pechora sea, critical drift events must be characterised. The criticality of each event for each concept is correlated with other ice properties, such as ice thickness, drift speed, ice concentration and compression in the ice cover; realistic quantification of the events cannot be done independently of the ice properties. The ice drift measurements covered limited periods from 10 to 70 days (Bonnemaire, 2005), and constant ice properties were then assumed and the criteria listed in Table 1 were used to estimate the downtime of each concept for the measured ice drift conditions; these are thought to be valid for relatively severe ice conditions (e.g. over 8/10 concentration but without extreme compression in the ice cover).

Table 1 proposes drift events quantifications in two ice management configurations. "Minimum ice management" describes the situation when ice management is available, an icebreaker is present at the site, but its main duty is not to permanently manage ice for the loading tanker. It may be committed to other tasks at the nearby production platform for instance. The icebreaker is used only in delicate situations (e.g. relocation manoeuvres and hook-up operations). The SAL concept cannot be used in such a configuration unless ice conditions are very light; all incoming ice has to be managed to reduce the ice loads on the mooring hose. "Permanent ice management" refers to the case when an icebreaker is only committed to the ice management for the loading tanker. This situation may require a second icebreaker in stand-by.

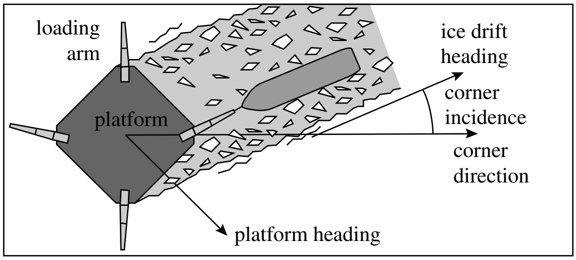

Figure 6. Top view of the platform corner loading concept with definition of angles and directions.

The following considerations motivated the criteria choices:

- For all concepts, sudden COD are dangerous; a COD of 135° in 30 min was then chosen as an event that should provoke disconnection of the tanker. For the STL with full ice management, this limitation might be too conservative; during sudden COD, the ice speed will be low, and the ice management may be efficient enough to avoid too high loads.
- In case of platform corner loading, the tanker will have to disconnect as soon as the drift incidence towards the platform corner exceeds a certain value (see Figure 6); the tanker has to manoeuvre to a loading arm in another corner to avoid being pushed against the structure. A corner incidence tolerance of $\pm 70°$ was chosen. Depending on the orientation of the platform relative to north, performance may vary also at a specific site. The downtime of this concept due to ice drift variation was estimated for all possible platform headings to determine the heading giving best results. Permanent ice management will not change the downtime criteria.
- For the STL and tower loading concepts, the curvature radius of the ice drift will influence the mooring loads. Breaking a channel in front of the tanker and thus reducing ice forces on the vessel, the tower will help the tanker to cope with smaller radii than in the STL case. On the other hand, the STL mooring will be stronger (several mooring lines in a star configuration) and can take higher ice loads. With this in mind, a minimum curvature radius of 100 m was chosen for the tower loading and 200 m for the STL concept. In exceptional cases, smaller radii were allowed with these two concepts if the drift angle shift was low (less than 30°, later named "acceptable COD"). Under permanent ice management, the performance of these concepts will not be affected by the curvature radius.
- Stationary ice events will provoke disconnection of the tanker (as explained in Section 3.2). Due to inaccuracy in the ice drift measurements used in the study, stationary ice events are characterised by an ice drift speed lower than $0{\cdot}01\ ms^{-1}$. An STL tanker can perform an emergency disconnection within 15 min. By applying Equation 2, with the values cited in Section 4.2, it is seen that the ice will drift less than 200 m in 15 min from the time it starts drifting again. It is then considered that the ice management and the flexibility of the mooring will prevent too-high loads before disconnection is performed. Stationary ice is not considered as critical in this case. Short time reliable ice forecasting will give the same scenario.

In addition, when the tanker has to connect or disconnect, time will be lost (with each loading concept). Based on indications given by Jolles et al. (1997), a manoeuvring and connecting time of 2 h and a disconnection time of 15 min were considered. These durations would vary a lot depending on the concept, the vessel manoeuvring capabilities or the ice conditions.

Finally, as listed in Table 1, five case studies (numbered from ① to ⑤) cover all the mentioned scenarios.

5.3. *Ice drift downtime estimations*. The ice drift data from the ARGOS/GPS buoys were processed as explained by Bonnemaire (2005). A shape-preserving piecewise cubic Hermite interpolation (Fritsch and Carlson, 1980) was applied on latitudes and longitudes to get position estimates every 15 minutes. Figure 7 presents what would be the operability rates of the different concepts assuming the quantification of Table 1 and that downtime was only caused by these drift events. The operability rates are plotted against minimum loading window duration ($t_{l,min}$). A tanker may indeed not connect to a loading terminal unless a minimum loading time is foreseen. The operability rate decreases rather fast with increasing of the minimum loading window duration, especially in the eastern Pechora Sea. In the eastern Pechora Sea, and with the platform corner loading concept in general, loading windows have a short average duration; from a loading performance point of view, this would favour the use of small tankers.

The time needed to load a tanker is of the order of 10 h depending on the tanker size and the loading rate capacity of the terminal. Downtimes associated with loading windows of at least 10 h are substantial (40% and 71% average downtime in the western and eastern part of the Pechora Sea, respectively); it is then crucial to accept to load in several steps making use of smaller windows in order to get a good winter operability rate. However this will increase the number of disconnection, relocation and reconnection; and thus may increase the operational risks. Table 2 gives average downtime rates for the eastern and western Pechora Sea, assuming that a minimum loading window, $t_{l,min}$, of 3 h has to be foreseen before connecting to the terminal (more details are found in Bonnemaire (2005) where values are given for each buoy for both 3 h and 10 h minimum loading windows. Downtime values for minimum loading windows from 1 to 20 h can be estimated on the plots in Figure 7). Higher rates are found in the eastern Pechora Sea (1·5 to 2 times higher rates); this is coherent with the higher frequency of critical drift events in the Pechora Sea mentioned by Bonnemaire (2005). The three cases with minimum ice management present higher downtime (or lower operability rate in Figure 7). Platform loading has the lowest performance, and permanent management does not improve this. This concept suffers from the high frequency in ice drift heading shift (Bonnemaire, 2005). With permanent ice management, SAL and tower loading present relatively low downtime (although their 10 h loading window downtime remains high); best performance is reached with the STL concept (which is assumed to not be affected by events with stationary ice).

The STL or the tower loading concepts (with minimum ice management, cases ① and ②) are vulnerable to drift events with small curvature radii whereas the platform corner loading concept suffers from absolute drift heading changes. Figure 8 presents the minimum permissible ice drift curvature radius that give the STL or the tower loading systems the same downtime rates as the platform corner loading. It is seen that a tanker (in case ① or ②) that has to disconnect for events with curvature radii

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Table 2. Downtime rates due to variability in the ice drift heading in the Pechora Sea (considering a minimum loading window $t_{l,min} = 3$ h; averages over each Pechora Sea part).

	Minimum ice management			Permanent ice management		
	West	East	Case no.	West	East	Case no.
Tower	0·19	0·34	①	0·12	0·24	④
STL	0·25	0·40	②	0·06	0·13	⑤
Platform	0·51	0·72	③	0·51	0·72	③
SAL				0·12	0·24	④

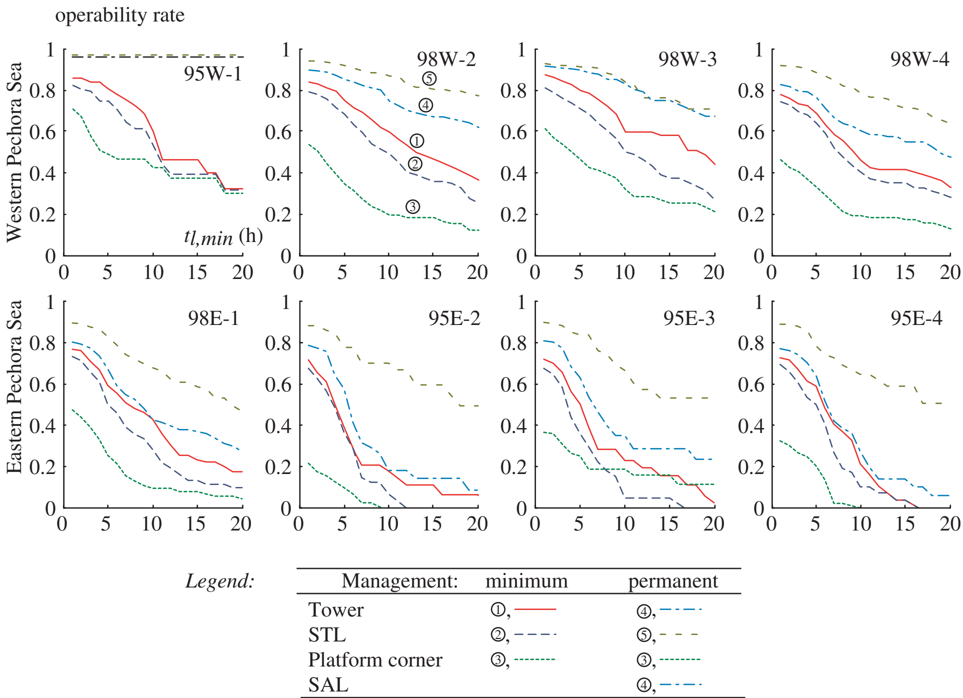

Figure 7. Ice drift direction operability rate estimations vs. minimum loading window $t_{l,min}$ for the different concepts at each buoy location (approach and connection time of 2 h, departure time of 15 min, acceptable COD of 30° (for STL and tower loading) and corner incidence tolerance of ±70°).

under 2–2·5 km will present the same downtime rate as in a platform corner loading configuration ($t_{l,min} = 3$ h). Therefore, a tanker in an STL or tower loading configuration has to present a very low manoeuvrability to be less effective than in a platform corner configuration.

5.4. *Parameter variation study*. The results presented in Section 5.3 depend on the assumptions made in Section 5.2. Figure 9 shows results of different parameter variation analyses. Figure 9a illustrates how variation of the minimum permissible ice

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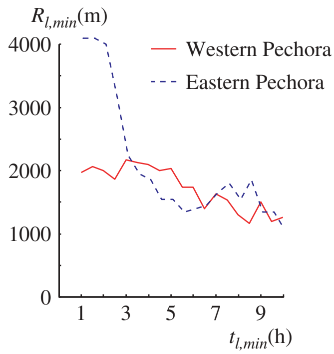

Figure 8. Permissible ice drift curvature radii ($R_{l,min}$) giving an STL tanker or a tanker connected to a loading tower the same ice drift direction downtime rate as in the platform corner loading configuration for different minimum loading window $t_{l,min}$.

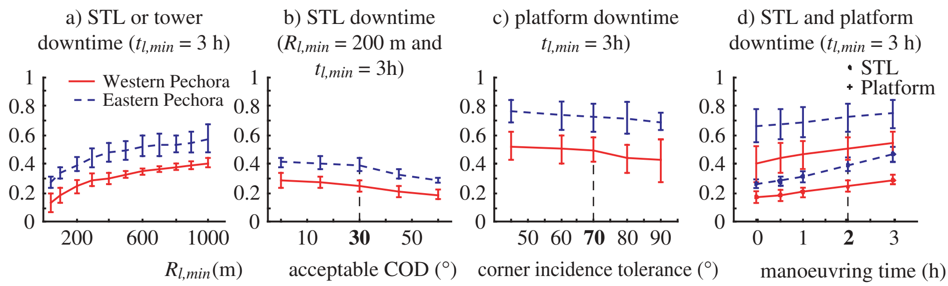

Figure 9. Parameter variation analysis; a) effect of $R_{l,min}$ on the STL or tower loading performance (case ①or ②), b) effect of the acceptable COD on the STL performance (case ①), c) effect of the corner incidence tolerance on the platform performance (case ③), and d) effect of the manoeuvring time on the STL and platform corner loading performances (case ①and ③), (mean values with standard deviation; values in bold are those used in the comparison study).

drift curvature radius will influence the downtime of an STL or tower loading concept (with minimum ice management, cases ① and ②). It increases with the minimum radius, at a rate close to 3% per 100 m. In Figure 9b, it is seen that variation of the acceptable COD for the STL or tower loading has a limited influence on the downtime rate (−2% per 10°). It is indeed seldom that the drift heading change remains small over 15 min (the interpolation time step) when the ice curvature radius gets small. Increase of the corner incidence tolerance for the platform corner loading system will give better performance (Figure 9c; average rate of −2% per 10°), but this would also increase the collision risks. Finally, the time needed to manoeuvre, connect and departure will influence the operability rate. Figure 9d shows the influence of the approach time on the performance of the STL and platform corner loading concepts (average rate of 4·5% per 30 min). When estimating the performances of each concept, it is assumed that approaching manoeuvres should be performed prior to the beginning of the next loading window if possible. The influence of this parameter on the performance indicates that there is usually little time between two consecutive windows; this favours a concept presenting a short manoeuvring time for relocation between a disconnection and a reconnection.

6. DISCUSSION.

6.1. *Performance comparison.* The results presented in Figure 7 suggest a ranking of the loading concepts. Nevertheless, the assumptions behind these results can be criticized; different assumptions may have given different results:

- It was seen that ice conditions would affect the manoeuvring capabilities of a tanker at a loading terminal and thus the performance of the system. Constant ice conditions were assumed over the measuring period in the eastern and western Pechora Sea. Ice conditions vary over the winter in concentration, thickness, compression and strength (as between e.g. cold ice and decaying ice). In very heavy ice conditions, the concepts offering the shelter of a structure will perform better as some of the ice loads will be taken by the structure. Performances of the STL and to a lower extent of the tower loading concepts will be reduced and will be vulnerable to higher ice drift curvature radii. In lighter ice conditions (at the beginning and end of the winter or in light winter as in 1995, see Pritchard and DeFranco, 1995), a turret moored tanker may not have to disconnect if ice loads remain low. Concepts including a structure will still have to disconnect to avoid collision risks. In the tower loading case (with minimum ice management), the tanker may cope with very small curvature radii but not with important COD. The platform loading will not increase its performance much as the tanker will still have to change corner as the drift heading is changing. The effect of permanent ice management will also be damped. Ice conditions in the eastern Pechora seem to be heavier than in its western part (Bonnemaire, 2005), so different assumptions may have been made for the two areas. This is not in favour of the performances of loading operations in the eastern Pechora.
- Same manoeuvring times for final approach, connection or disconnection have been assumed for all the concepts. This is of course too simple; these times will vary with the ice conditions and the concepts. As seen in Figure 9d, reducing these times will have a noticeable influence on the performance of the system. With the platform corner loading system for example, if smooth transition from one loading arm to another can be achieved and there is no ice accumulation to clear, these times will be reduced dramatically; the concept may be more competitive.
- The criteria choice will depend on the detail design of each concept. In case of the tower loading, for example, if a rigid frame is used for the mooring, it may be able to take very high forces. The system will be less vulnerable to low ice drift curvature radii.

So the previously announced results may vary when considering varying ice conditions and more particular designs. More reliable results may be found if considering a probabilistic approach. The results are also based on measurements made during only two winters with similar ice drift conditions (Bonnemaire, 2005). Extrapolation to other winters might be hazardous. In any case, some comparison trends will hold:

- Due to the necessary corner shift with the platform loading concept, loading windows will be rather short with this concept. This will favour the use of small tankers and require short manoeuvring times.

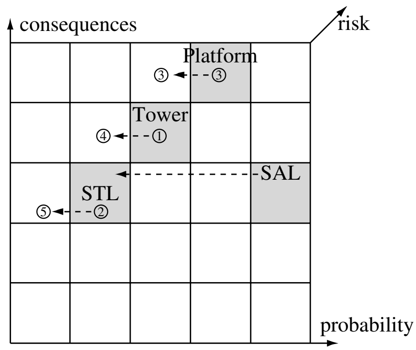

Figure 10. Qualitative risk analysis of the different loading concepts. The arrows represent the possible reduction in risk due to maximum ice management.

- With minimum ice management, the tower loading will present slightly lower downtime rates than the STL concept in heavy ice conditions, though operational risks are lower with the latter concept. In light ice conditions, the STL concept will perform better.
- STL, tower loading or SAL can perform better thanks to permanent ice management. The performance gain can be substantial, and may overcome the additional costs, especially areas with rougher ice conditions (e.g. the eastern Pechora Sea). Alternatively, in areas with light ice conditions, permanent ice management might not be economically justified.
- The ice drift conditions in the eastern Pechora are worse for offshore operations than in its western part. Ice conditions will also usually be heavier in the eastern part.

6.2. *Risk comparison.* The present study gives indications on the downtime rates of the different selected concepts due to variability in the ice drift. Although it may not allow the drawing of final conclusions, the study results may also be used as a basis for a qualitative risk analysis of winter offshore loading operations. The analysis of ice drift variability has given us indications on the hazard probabilities for the different concepts. In Figure 10 a risk matrix for the concepts considered is suggested. The grey squares indicate the concepts risks with minimum ice management.

Consequences may be personal, environmental or economical. Acceptance criteria for personal or economical damages may be expressed in terms of injuries, fatal accident or loss of asset values. Depending on knowledge about the area and natural resources at risk, the environmental consequences may be quantified in terms of acceptable level of discharge or environmental damage (Statoil, 2004). The platform corner loading presents the highest consequences, as it involves an expensive, manned production structure with storage facilities. In case of a loading tower, it is a smaller structure with no or few persons on board. When considering the STL or SAL concepts; personal consequences in case of mooring rupture are low and if proper emergency valves are installed at the extremity of the riser, environmental consequences will be reduced. Finally, economical consequences will be lower than with the other concepts.

The STL system will present the lowest probability of accident as in most cases an emergency disconnection would avoid any hazard. With the other concepts, an emergency disconnection will not always reduce the collision risk with a structure. The platform corner concept presents a high hazard probability as each time the tanker has to disconnect, it is to avoid collision. The arrows in Figure 10 indicate how the risks may evolve with a permanent ice management; the hazard probabilities will decrease and consequences remain constant. The SAL concept with no full ice management will be extremely vulnerable to incoming ice and present very high hazard probability.

From a risk point of view, sub-sea concepts are favoured, the STL being the best example here. Surface piercing concepts and concepts involving a structure will suffer higher risks. The high frequency of rapid important COD (Bonnemaire, 2005) imposes large risks on concepts sensible to this kind of events.

7. CONCLUSIONS. Although past experiences with arctic offshore loading are sparse, a probable upcoming need for new arctic offshore terminals was the motivation for a comparison of different concepts presented in the literature.

- As ice drift variability may impede loading operations, critical drift events were assessed for four loading concepts; loading from the corner of a platform, loading in the wake of a loading tower, Submerged Turret Loading (STL) and Single Anchor Loading (SAL).
- From the analysis of ice drift measurements from the Pechora Sea, downtime associated with variability in the ice drift direction were estimated. With minimum ice management, tower loading presents lower downtime rates (27%) than STL (32%) which again shows better performance than the platform corner loading (61·5%). With permanent ice management, lower downtime rates are reached (STL: 10%; tower loading or SAL: 18%), except for the platform corner loading concept. The STL concept then performs best. Higher downtime rates are found in the eastern Pechora than in its western part where for example the Prirazlomnoye field is located. There for instance, the performance enhancement from permanent ice management can allow good operability rates with an STL system.
- Nevertheless this ranking is the result of assumptions the validity of which, for example, will vary with changing ice conditions. Thus extrapolation of these results to other seasons or locations is hazardous.
- If comparing risks associated with these different loading concepts, sub-sea concepts are favoured as presenting lower risks.

The bases for comparison of the downtime of different arctic offshore loading concepts due to ice drift variability were presented here. If a particular site and more precise designs are selected, more reliable assumptions can be made. When knowing how they will vary with other parameters as other ice properties, more precise results may be provided. A probabilistic model estimating downtime of various origins would then be able to compare the different loading concepts.

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