Recent developments in LNG and ice-class tanker design and the potential application to future Arctic LNG ships

Photo courtesy of Neste Oil

Robert Tustin, Lloyd's Register Asia

Robert Tustin is Lloyd's Register Asia's Technical Manager for New Construction. His responsibilities include co-ordination and development of technical activities and capabilities for Lloyd's Register Asia in Korea, Japan and China. Previously, he was head of Busan Plan Approval Services. He has been with Lloyd's Register since 1984 and has a degree in naval architecture from the University of Southampton. He is currently in his tenth year of service for Lloyd's Register in Asia.

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Executive Summary

Russia has 31% of the world's known and currently unexploited reserves of natural gas. Of these reserves the *"Arctic and Sub-Arctic regions of Russia are extremely rich in natural resources, accounting for about 90% of Russian gas".* [2]

Over the longer term it seems likely that exploitation of the giant natural fields on the Yamal Peninsula and Yamal offshore in the Western Arctic regions of Russia will precipitate the development of Arctic LNG shipping.

Over the last five years there has been significant technical development in the LNG and ice-class tanker sectors such as:

- introduction of the first large double-acting ice-class tanker (DAT) designs (2002~3)
- development and first orders for large LNG carriers of 200,000 plus cubic metre capacity (2002~4)
- development (gas turbine) and introduction (diesel) of new dual-fuel electric propulsion systems on LNG carriers (2002~4)
- first orders for first-year ice-class LNG ships (2004)
- ArcOp research project (2003~2005)

Each technical development represents a maturing of earlier supporting research project activity. Key elements of these technical developments when combined could facilitate and enable the development of viable future large Arctic LNG ship designs for Russian Arctic service.

A number of key design issues at the conceptual and detailed design phases are considered which may have an influence on the basic design concept of future Arctic LNG ships. These issues are indicative of the depth of front-end engineering design activity likely to be required for future Arctic LNG ships and include:

- ice interaction scenarios and direct design approaches
- ice class selection
- qualification and risk reduction on application of new technologies
- LNG cargo containment system integrity with hull ice interaction
- hull structure fatigue strength for extreme wave environments
- winterisation

1 Introduction

With specific reference to likely future year-round operation of Arctic LNG ships this paper considers:

- recent technical developments and research project activities in the LNG and ice-strengthened tanker design with potential application to future Arctic LNG ships

- key design issues at conceptual and detailed design stage which may have an influence on the basic design concept of future Arctic LNG ships

- specific challenges, as well as solutions, for the classification of Arctic LNG ships.

Contents

2 Location of Arctic gas reserves and future LNG export projects

Russia has 31% of the world's known and currently unexploited reserves of natural gas. According to BP statistics[1] at the end of 2003, the volume of proven reserves in the Russian Federation stood at 47 trillion cubic metres. Of these reserves the *"Arctic and Sub-Arctic regions of Russia are extremely rich in natural resources, accounting for about 90% of Russian gas".* [2]

2.1 Unexploited natural gas reserves in the Arctic regions of Russia

Three of the largest unexploited giant natural gas fields of Russia are found in the Western Arctic regions on the shelves of the Barents Sea (Barents Sea North East offshore) and Kara Seas (Yamal offshore).

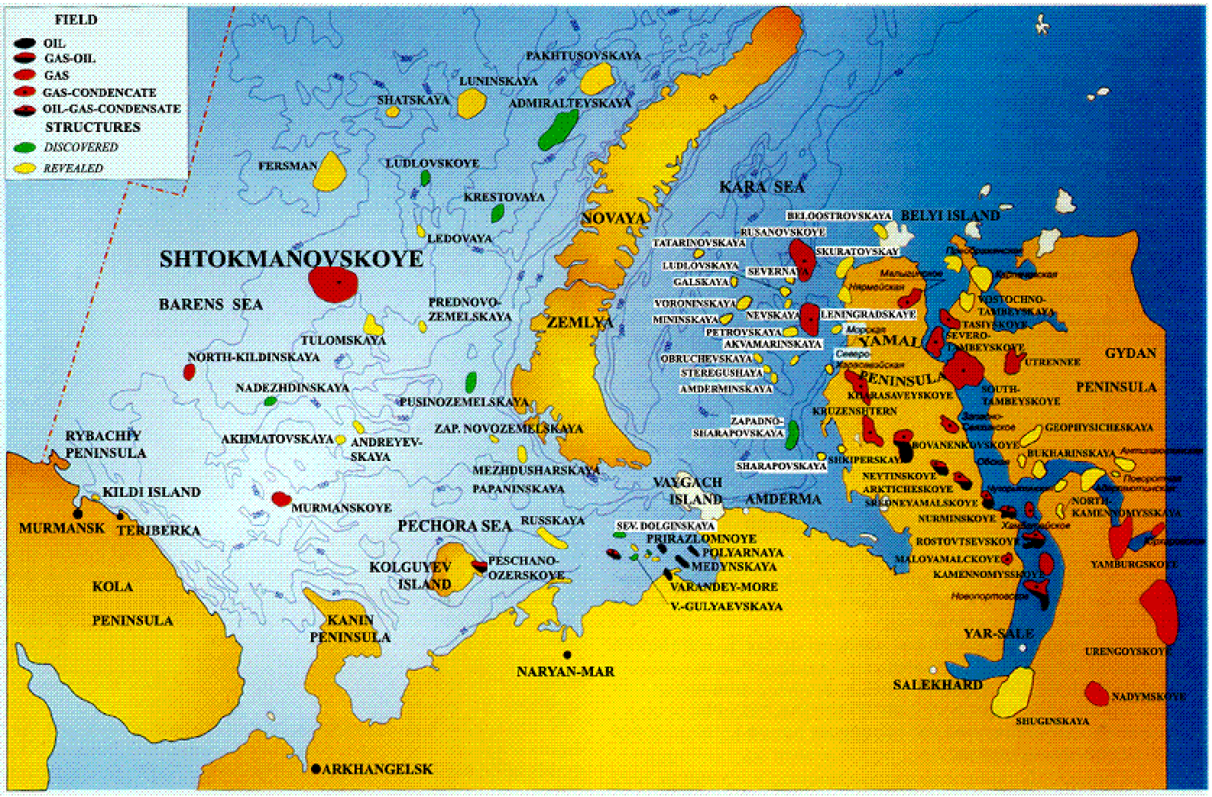

Figure 1: Gas fields (in red) of the Western Arctic regions of Russia[2] *(courtesy of CNIIMF)*

In view of the estimated available reserves the following three offshore fields have been identified[2] as having a high potential for future Arctic Sea offshore development:

- the Shtokman field in the Barents Sea, with reserves of about 3.1 trillion cubic metres[2]
- the Rusan and Leningrad fields in the Kara Sea are accessible at sea depths of up to 50 metres and are consequently likely to be a top priority for development. These two fields are estimated to have combined reserves of up to 5 trillion cubic metres[2].

In addition to these offshore fields there are extensive onshore natural gas fields on the Yamal Peninsula where up-front development costs are quoted as being three times lower[4] than offshore developments in the adjacent fields in the western Kara Sea.

2.2 Future natural gas export projects in Arctic Sea areas

The first two gas liquefaction trains in Russia are to come on stream in 2007 for export of LNG by sea from a terminal at Prigorodnoye, in Aniva Bay, on Sakhalin Island.

Gazprom[5] has identified that for export route diversification, the large-scale production of LNG may provide for direct export, both to raise the reliability of gas supply to the European market and also to allow it to enter the US market.

Development plans for US market export of Russian natural gas being considered by Gazprom involve piping gas from the Shtokman field in the Barents Sea to a liquefaction plant near Murmansk, a year-round ice-free port, to allow export by LNG ships to the US.

Alexander Ryazanov, Gazprom Deputy Chairman, remarked in a March 2004 press conference[6] that Gazprom *"see prospects … on the Yamal Peninsula … and 5, 6 may be 8 years later we'll move on to the Yamal Peninsula".* Furthermore, in its 2003 Annual Report, Gazprom[7] reported a long-term programme, up to 2030, of gas exploration work at sea for the shelves of the Barents, Pechora and Kara Seas.

These remarks and reports support the view that large-scale production of natural gas by Gazprom from onshore fields on the Yamal Peninsula, as well as offshore shelf areas in the adjacent western Kara Sea, is anticipated.

Furthermore in a March 2005 news item, Tambeineftegaz, an independent gas producer was reported[26] as having submitted a plan to the Russian trade ministry for the construction of an LNG plant in the Cape Drovyanoi area on the Yamal Peninsula.

2.3 Estimates of LNG exports for Arctic Sea developments

Seaborne LNG trade is expected to more than double from about 170 billion cubic metres in 2003 to 370 billion cubic metres in 2010 (a 12% compound annual growth rate). This rapid growth will be accompanied by a shift in trade patterns with much of the shift in LNG trade associated with an expected doubling of imports of LNG to the US[3]. Longer-term prospects are similarly promising; with the International Energy Agency forecasting a six-fold increase in LNG trade from now until 2030[3].

Over this longer term it seems likely that exploitation of the giant natural gas fields of the West Arctic regions of Russia will precipitate the development of Arctic LNG shipping. The main prospect appears to be export of LNG from the Yamal Peninsula, either from onshore field development on the Yamal Peninsula itself or from development of the adjacent Rusan and Leningrad offshore fields.

Estimates of the total exports, in million tonnes of LNG, range from a low estimate of 5 million tonnes per year by 2020[8,9] to a high estimate of 5, 10, 15 and 20 million tonnes per year by 2008, 2009, 2015 and 2020[4]. The Tambeineftegaz Cape Drovyanoi proposal[26] alone is reported as 10 million tonnes per year.

2.4 Estimates of Arctic LNG ship requirements

A recent Arctic LNG ship design concept (2003) was developed for the ArcOp project[11].This concept was based on a high estimate of 20 million tonnes per year LNG export from the Yamal Peninsula to the US and envisaged between 20 to 22 dedicated Arctic LNG ships, each with five independent Moss-type tanks for 200,000 cubic metre capacity and double-acting propulsion.

In an earlier International Northern Sea Route (INSROP) working paper[10] from 1997, a feasibility study was described for export of LNG by sea from an onshore terminal with gas liquefaction trains near Cape Kharasavey on the Yamal Peninsula. In this study two transportation scenarios for LNG export by ship from the Yamal Peninsula were considered:

- **Direct export** – using fourteen 135,000 cubic metre-capacity Arctic capability LNG ships for direct export of LNG to Northern Europe

- **Shuttling to a year-round ice-free port on the Kola Peninsula** – with two ship sizes, between 10 and 14 small Arctic LNG feeder ships of about 80,000 cubic metre capacity for transport of LNG from the Yamal to the Kola Peninsula.

  Local production of the feeder LNG ships by Russian shipyards was envisaged and the employment of eight 165,000 cubic metre-capacity LNG ships for open water service for export of LNG from an ice-free port on the Kola Peninsula.

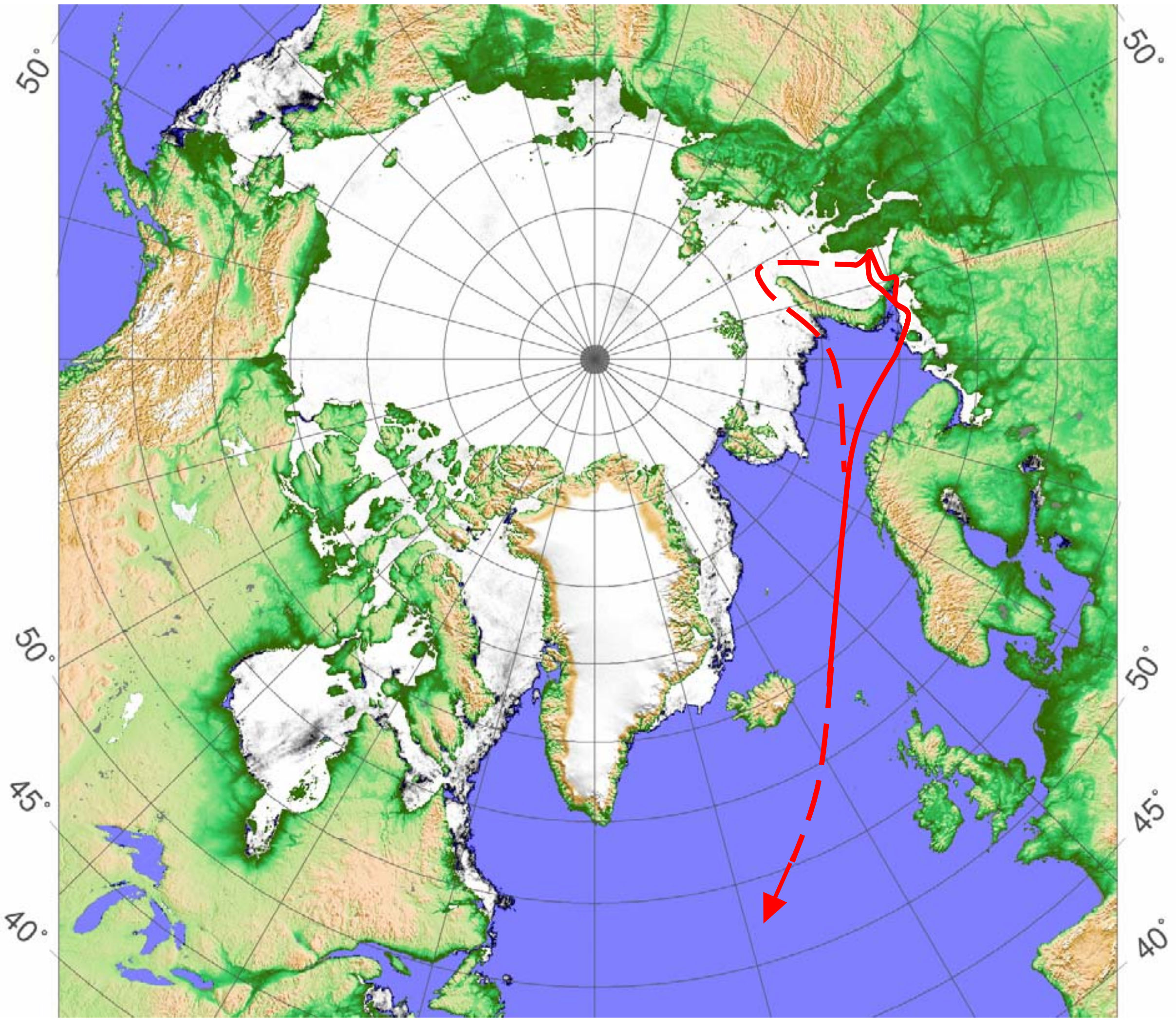

Figure 2: Voyage routes on Kara and Barents Sea for year-round operation of Arctic LNG ships from Yamal Peninsula *(Arctic Map view courtesy of IUP Bremen)*

3 Pechora Sea and western Kara Sea ice navigation of Arctic LNG ships

In this section we offer an overview of the ice conditions for navigation from the ice field edge to Cape Kharasavey for year-round operation of Arctic LNG ships to the Yamal Peninsula on the shores of the western Kara Sea in the Russian Arctic.

3.1 Ice navigation from the ice field edge in the Pechora Sea

In the INSROP feasibility study[10] a typical voyage for an Arctic LNG ship to the Yamal Peninsula would, during the period of maximum ice cover (winter to spring), encounter the ice edge of thin first-year ice at approximately the meridian of the western shore of Kolguev Island in the Pechora Sea (48^0 E). Earlier encounters with grey and grey-white drifting ice cover could be anticipated before the sea ice edge.

Due to the prevailing direction for tidal currents as well as winter seasonal storms originating in the North Cape area, the ice field in the Pechora Sea can be characterised as having a high likelihood of pressure in the ice field and pressure ridging.

3.2 Passage of the Kara Gate or Yougoursky Shar Straits

Two passages could be contemplated for entering the western Kara Sea from the Pechora Sea:

- **the Kara Gate Strait**, between Novaya Zemlya and Vaygach Island, or

- **the Yougoursky Shar Strait**, between Vaygach Island and the mainland.

The choice of strait passage is very much dependant on the prevailing ice conditions during the period of maximum ice cover (winter to spring). The ice conditions in the straits tend to be more severe[12] than in the adjacent seas that the straits themselves join and these conditions make the straits passable only with icebreaker escort[10].

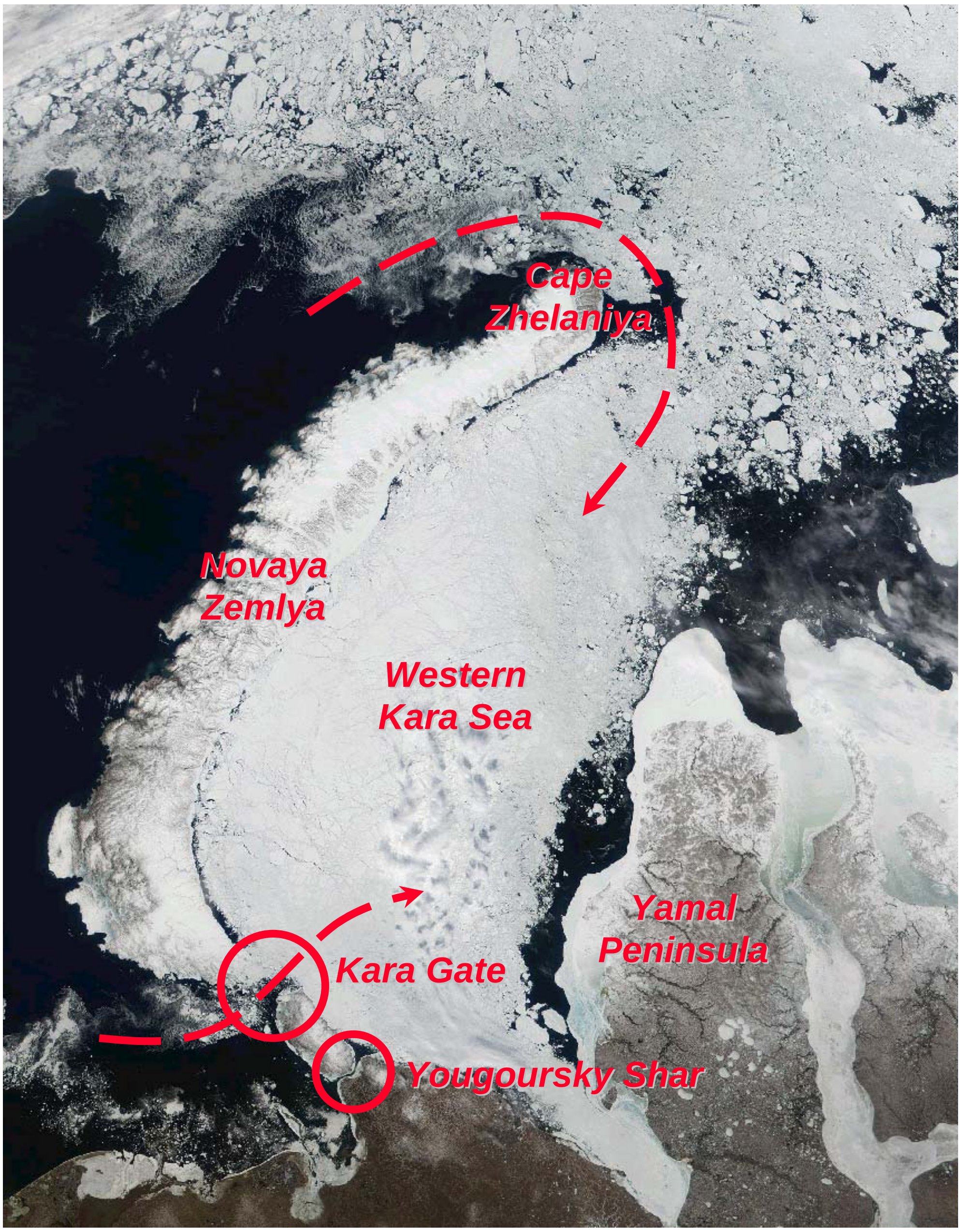

Figure 3: Satellite photo of Novaya Zemlya and western Kara Sea during 2002 winter session showing ice cover and probable routes for Arctic LNG ship operations
(24-04-2002 satellite photo courtesy of NASA: Visible Earth website)

Environmental factors in these straits, such as local currents and prevailing winds, can give rise to variable ice cover in the straits with strong ice compression and pressure ridging and shore-fast ice floes and ridged ice fields.

For the Kara Gate Straits, for example, the Litke current runs in a southwesterly direction down the eastern shores of Novaya Zemlya, exporting ice from the western Kara Sea through the Kara Gate Straits into the Pechora Sea. This can lead to a build up of ice pressure fields and ridged ice in the Kara Gate Straits.

For the Yougoursky Shar Strait, for example, the prevailing southwesterly storm winds during the winter to spring season lead to a build up of shore-fast ice floes and ridged ice fields in the approaches to the Yougoursky Shar Strait that make passage[10] through the Kara Gates Strait more realistic for entering the western Kara Sea.

Furthermore, the Yougoursky Shar Strait is a narrow and shallow strait about one and a half miles across with water in places only 10 metres deep,[10] and this makes navigation with large Arctic LNG ships unlikely. In the case of large Arctic LNG ships an alternative access route to the western Kara Sea, in case the Kara Gate Straits are impassable due to severe winter ice conditions, would be to route past Cape Zhelaniya[10] at the northern tip of the north island of Novaya Zemlya.

3.3 Ice navigation through the western Kara Sea

The western Kara Sea is a shallow water sea with the Yamal Peninsula on its eastern shoreline and on its western shoreline the north and south islands of Novaya Zemlya. Ice cover in the western Kara Sea typically consists of medium first-year ice (by World Meteorological Organization definition) which first forms in October and increases in thickness until May when it reaches a thickness of between 0.7 to 1.3 metres.

In the winter and spring season, at the maximum extent of ice cover, the prevailing southwest Litke current brings multi-year ice coverage into sea areas adjacent to Novaya Zemlya from the Central Polar Basin.

The break up of the ice cover begins in June with the formation of open water (polynias) areas and the eventual clearing of the sea ice cover along the west coast of the Yamal Peninsula. In such conditions navigation without icebreaker assistance becomes possible from July for the summer navigation season.

	Ice navigational season, months and days duration		**Level Ice thickness, metres**		**Four coldest months (December to March) ambient temperature, °C**		**Voyage distance & duration (assisted navigation) from ice edge to terminal**
	Typical ice season	Ice season duration	Average Ice cover	Heavy Ice cover	Maximum & Minimum	Average	
Western Kara Sea	October to June	260 to 280 Days	0.7 to 1.3	1.6 to 1.9	-15 to –35 °C	-25 °C	390 miles (Average 70 hrs) (From Barents Sea ice edge)
La Perouse Strait & Aniva Bay	January to March	60 to 100 Days	0.3 to 0.7	0.5 to 0.7	-9 to –25 °C (98% probability)	-19 °C	50 miles (Average 6 hrs) (From La Perouse Strait ice edge)

Table 1: A comparison of Ice navigation conditions for LNG Projects [10, 12, 14]

A simple comparison of the Kara Sea, Yamal LNG project, with those prevailing in the La Perouse Strait and Aniva Bay for the Sakhalin II LNG project is shown in Table 1 based upon a pooling of published data on ice navigation conditions.

3.4 Cape Kharasavey ice conditions and port ice management

The west coast of the Yamal Peninsula is particularly prone to land or shore-fast ice[10]. During the autumn and winter seasons the prevailing meteorological conditions cause extensive pressure ridging and hummocking in the land-fast ice field which can extend up to five kilometres offshore.

Ice management whilst vessels are loading at the Cape Kharasavey LNG terminal will probably require dedicated tugs and procedures to ensure that safe berthing and loading operations can be carried out year round. Consideration of port ice management procedures will be essential if year-round LNG export operations are to be maintained.

4 Operational solutions for Arctic LNG Ships in the Northern Sea Route

Two EU-funded research projects, the Arctic Development Voyage (ArcDev) completed in 1998, and the current Arctic Operational Platform (ArcOp) project which completes later in 2005 have also identified operational tactics and transportation solutions for operation of Arctic LNG ships and some of these solutions and experiences are described here.

The western Kara Sea is administered by the Northern Sea Route (NSR) administration. Regulations and guides published by the NSR Administration also prescribe operational measures for ice navigation in the Russian Arctic including compulsory provision of icebreaker assistance in certain sea areas and straits. The applicable regulations are briefly outlined.

4.1 Transportation solutions for ice navigation in the Northern Sea Route

A specific focus of the EU-funded ArcOp project is the development of infrastructure to support an integrated transportation system for year-round export of oil by shuttle tankers from the port of Varandey on the south eastern shores of the Pechora Sea.

Physical infrastructure elements studied by the Project include ice metrology support for ice pilotage and navigation, icebreaking assisting vessels and infrastructure to support the management of shuttle tanker traffic.

It is expected[12] that the introduction of these transportation solutions for ice navigation to the Pechora Sea will facilitate the development and introduction of year-round navigation into the western Kara Sea and enable export of LNG from the Yamal Peninsula to be feasible sometime after 2010.

4.2 Ice metrology and ice pilotage in the Northern Sea Route

The development of ice information collection and forecasting methods into a tool for Arctic ice navigation and voyage routeing is an objective of one of the work packages in the ArcOp project.

This work package will be carried out during 2005 and will draw on methods developed in Russia as well as in the Baltic. It will also develop the recommendations and build on the conclusions of the fourth EU framework ICE ROUTES[15] project completed in 1998.

The provision of an ice pilot for liaison, with lead escorting icebreakers, to advise the LNG ship master on procedures for navigation in ice is also likely to be required at appropriate way points during the passage from the ice edge to the LNG terminal at Cape Kharasavey.

4.3 Ice breaker assistance in the Northern Sea Route

Compulsory icebreaker assisted pilotage[17] is established by the "*Regulations for Navigation … of the NSR"* for four straits in the eastern Kara and Laptev Seas where stable areas of summer ice, so-called 'ice massifs', can block these straits.

Prevailing ice conditions in the Kara Gates Straits and Yougoursky Shar Strait for entering the western Kara Sea from the Pechora Sea during the period of maximum ice cover extent (winter to spring) make them passable only with icebreaker assistance[10].

This reported requirement for icebreaker assistance is also supported by the experiences from the ArcDev project carried out in a period of very heavy ice conditions, reported as being the worst for 30 years[16], prevailing at the time of the voyage from the Ob River estuary on the Yamal Peninsula through the western Kara Sea and Kara Gate Straits.

Tactical procedures employed by the two escorting icebreakers on the ArcDev voyage for the passage of the tanker *Uikku* involved icebreaker route reconnaissance, prior channel breaking, icebreaker leading, breaking out the *Uikku* when stuck in ice and finally short towing.

On breaking out operations the following was reported: *"Breaking out operations were most frequent in the passage from the Yamal Peninsula towards the Kara* [Gate] *Strait … spending more than 4 hours for the release of stuck ships (on ten separate occasions)"*. [16]

Both the INSROP working paper[10] as well as actual operational experience from ArcDev support the conclusion that a transportation system with assisted navigation by escorting icebreakers is necessary for Arctic LNG ship operation from the Yamal Peninsula in the western Kara Sea.

The usual practice for assisting large vessels such as Arctic LNG ships through ice is for the escorting icebreaker to break a lead ahead of the vessel being assisted. Ideally the escorting icebreaker will break a lead wider than the vessel being assisted. Otherwise a high ice resistance due to ice crushing occurring on the shoulders of the vessel being assisted may be experienced. A wider channel will also enable the assisted vessel to turn in ice.

For a large Arctic LNG ship, where a 50-metre moulded breadth could be anticipated for a large 200,000 cubic metre size vessel, the escorting practice of the assisting fleet of icebreakers would probably require a pair of escorting icebreakers. This is because the beam of current generation icebreakers is too narrow to break a sufficiently wide lead ahead of the assisted large vessel.

This solution was demonstrated along with escorting techniques in a full-scale trial in the winter of 2002 winter using an ice-strengthened Aframax tanker and two escort icebreakers in first-year ice conditions off Sakhalin Island in Aniva Bay and the Tatar Straits.

4.4 Northern Sea Route regulations

Commercial ship operations in the western Kara Sea area, and probably in future for the Pechora Sea area[12], are within coastal waters administered by the Russian NSR administration (note that the full title for NSRA is the "*Administration of the Northern Sea Route and State Hydro-graphic Department of the Ministry of Transport of Russian Federation")*.

The applicable regulations and guides for commercial ships operating in the NSR[15] are:

- **Regulations for Navigation on the Seaways of the NSR, 1991**: the original regulations approved for opening up the NSR to foreign vessels.

- **Guide for Navigation through the NSR, 1996:** a guide developed by Russian contributors under the INSROP research programme which incorporates, among other sections, the following ones:

    - **Rules of Navigation;** which incorporates the following regulations:

        - Regulations for Navigation on the Seaways of the Northern Sea Route *(originally approved by the USSR Minister of Merchant Marine on 14th September 1990)*
        - Regulations for Icebreaker and Pilot Guiding of Vessels through the Northern Sea Route.

    - **Practice of Navigation in Ice;** which incorporates the following guidelines:

        - Icebreaker-Assisted Navigation
        - Ice Navigation without Icebreaker Assistance.

    - **Requirements for the Design, Equipment and Supplies of Vessels Navigating the Northern Sea Route.**

In addition to the regulations of the NSR administration the International Maritime Organization[18] **"Guidelines for Ships Operating in Arctic Ice-Covered Waters"** provide additional safety and pollution prevention recommendations beyond the existing SOLAS Convention that take into account the climatic conditions of Arctic ice-covered waters.

5 Recent developments and trends in LNG and Ice-class tanker design

Over the last five years there has been significant research project work and technical development in the LNG and ice-class tanker sectors such as:

- **introduction of the first large double-acting ice-class tanker (DAT) designs** (2002~3)
- **development and first orders for large LNG carriers of 200,000 plus cubic metre capacity** (2002~4)
- **development (gas turbine) and introduction (diesel) of new dual-fuel electric propulsion systems on LNG carriers** (2002~4)
- **first orders for first-year ice-class LNG ships** (2004)
- **ArcOp research project into transportation solutions for Arctic operation LNG ships and tankers** (2003~2005)

Each technical development represents a maturing of earlier supporting research project activity. Key elements of these technical developments and research project activities could facilitate and enable the development of a viable future large Arctic LNG ship design for western Kara Sea service.

In addition some of the underlying trends for LNG and ice-strengthened tanker designs are described as it is likely that these trends will also influence the specification and design of future Arctic LNG ships.

5.1 Introduction of the first large double-acting ice-class tanker designs

The key technical development in ice-strengthened tanker design with potential application to Arctic LNG ships was the introduction of the first large ice-class DAT design at the end of 2002.

Figure 4: *Mastera:* double-acting tanker operating in astern mode in first year Baltic ice *(courtesy of Neste Oil)*

5.1.1 Double-acting principle

Operating experience indicates improved ice-breaking effectiveness with bow propellers. This has been reported[19] as being due to a combined effect of a decrease in hull ice resistance and improved ice-breaking performance. The mechanisms by which these performance improvements are achieved are:

- bow lubrication for decreased hull ice resistance due to water flow aft from the bow propeller
- pressure drop below the ice field ahead of the icebreaker due to water flow into the bow propeller for icebreaking performance improvements.

Full-scale trials with Baltic icebreakers have proven that minimum ice resistance occurs when 100% of the power is directed to the bow propellers[19] (proven by running astern on full power). Note that older Baltic icebreakers fitted with bow propellers can typically distribute up to 40% of propulsive power to the bow propeller (note that the latest designs of Baltic icebreakers are generally fitted with Azipods).

When developing hull forms for operation in ice, naval architects have typically had to make a compromise between optimal hull performance in open water and optimal hull performance for ice operation.

The double-acting principle combines the knowledge of bow propeller effectiveness in ice operation with two modes of operation:

- **astern operation in ice**
- **ahead operation in open water.**

With these two operation modes an optimised hull form can be designed for operation astern in ice and ahead in open water.

The practical propulsion solution for the two modes of operation has been to fit an Azipod (**Azi**muthing **Po**dded **D**rive) - a podded, electric propulsion unit that rotates (azimuths) through a full 360^0 circle - incorporating an electric motor and direct-drive propeller that allows full torque to be developed over the full speed range.

At the end of 2002 the first of two Aframax size double-acting ice-class tankers was delivered to Neste Oil by Sumitomo Heavy Industries to Lloyd's Register class.

In the ArcOp workshop paper[11] a design concept for a double-acting LNG ship for western Kara Sea service is presented. Accumulated experience and knowledge from satisfactory operation of such vessels could enable application of the double-acting principle to future designs of large Arctic LNG ships.

5.2 Recent developments in LNG ship design

Taking each recent development in turn in LNG ship design:

- development and first orders for large LNG carriers of 200,000 plus cubic metre capacity (2002~4)
- development (gas turbine, 2004/5) and introduction (diesel, 2004) of new dual-fuel electric propulsion systems on LNG carriers
- first orders for first year ice-class LNG ships (2004).

5.2.1 Development of large LNG carriers of 200,000 cubic metre capacity

At the end of 2004 initial contracts were made for the Qatar Gas train II project in the three largest shipyards in Korea for large LNG carriers of two sizes – a 209,000 cubic metre capacity design at Daewoo Shipbuilding and Marine Engineering (DSME) (GTT Gaz Transport NO96 membrane type) to be built to Lloyd's Register classification and a 216,000 cubic metre capacity design to be built at Hyundai Heavy Industries (HHI) and Samsung Heavy Industries (SHI) (GTT Technigaz Mk III membrane type).

The principal dimensions and cargo-carrying capacity of these vessels, the so-called *Qflex* design, were derived from consideration of optimal operational expenditure for long-haul voyages for LNG export from the Middle East to the eastern US ports. This, with a 50,000 cubic metre capacity increase compared with the maximum size of a conventional LNG of about 150,000 cubic metre cargo capacity.

Key technical factors to be considered for the design of large LNG carriers include selection of tank size and number and propulsion alternatives (which will be discussed later).

Tank sizing and associated numbers of tanks become important for membrane-type containment systems in view of the increased breadth and overall length of the cargo tank, which require special consideration from the point of view of pressure loads on the containment system due to cargo fluid motion in a laden tank.

A conservative approach adopting five tanks of conventional length was finally chosen for these projects following a series of comparative tank model tests which determined that the highest pressure loads are associated with diagonal fluid motions in the tank.

Lengthening the tank and, hence, the tank diagonal length increased pressures on the tank membrane approaching the collapse strength capability of the membrane and reduced the associated design safety factors against membrane collapse.

The adoption of a five-tank configuration retains tanks of conventional length; and consequently mitigates pressure loads due to tank diagonal fluid motions; however, overall fluid motion pressures in the tank due to fluid motions due to ship roll are increased.

Feasible design countermeasures for these increased fluid motion pressures include containment system strengthening. Furthermore, the higher overall LNG flow velocities in larger tanks increase the pump mast drag, necessitating design countermeasures.

Large LNG carriers of 200,000 cubic metre capacity optimised for long-haul routes to ports in the US clearly indicate potential ship size and tank numbers for future designs of Arctic LNG ships.

5.2.2 Introduction of new dual-fuel electric propulsion systems

Alternative propulsion options for LNG ships have been considered for a number of years. Drivers for the adoption of propulsion alternatives include fuel economy as well as concerns over the availability of steam qualified engineers.

For large LNG ships, a twin-skeg, twin-screw hull form arrangement has evolved to overcome the hydrodynamic limitations that occur for efficient propeller design for 50-metre beam single-skeg hull forms with a design draught of 12 metres.

This in turn has precipitated the adoption in 2004 of propulsion system alternatives to traditional steam turbine propulsion with LNG cargo boil off burning in the main boilers of the steam-raising plant. In part this decision has been driven by capital expenditure considerations, as well as the overall technical complexity of a twin-screw steam turbine arrangement with multi-input gearbox and very large steam-raising plants.

A number of propulsion alternatives have been studied and the following dual-fuel electric systems are specifically highlighted as potential propulsion solutions for ice navigation by Arctic LNG ships:

- **dual-fuel diesel electric:** first systems being introduced in 2004
- **gas turbine electric:** detail design development underway in 2005

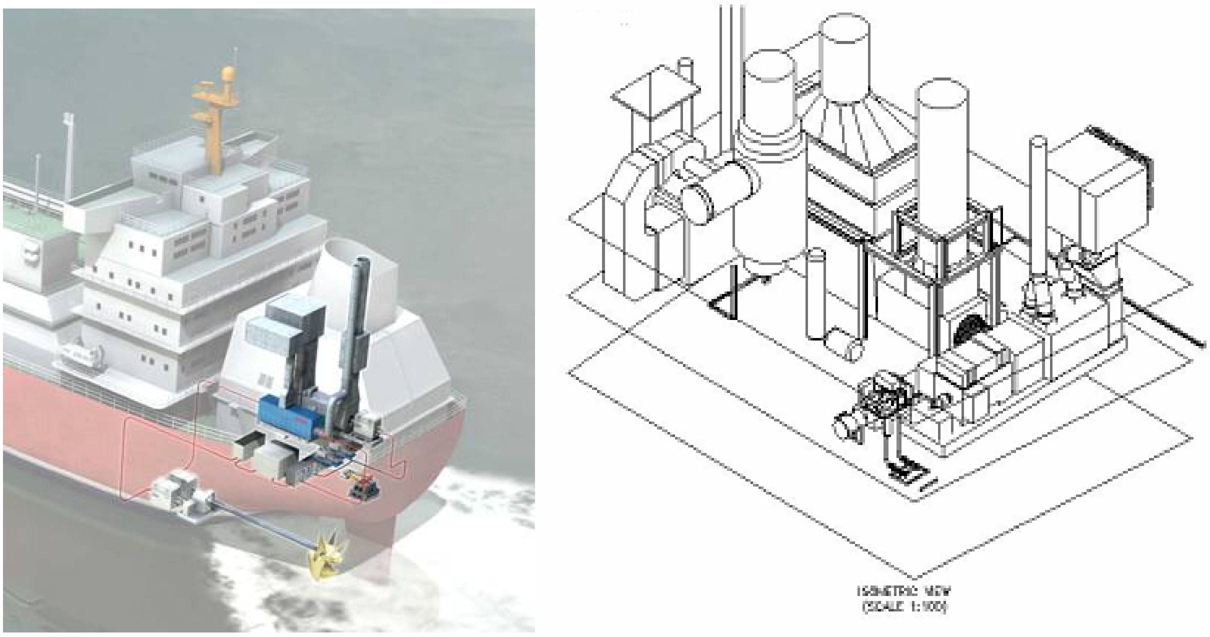

Figure 5: Artist impression and isometric view of proposed gas turbine electric propulsion system for a large LNG ship *(impression and isometric view courtesy of Rolls Royce)*

5.2.3 First orders for ice-class LNG ships for first-year ice in Russian Far East

Exploitation of gas reserves in Russia is currently focused on the Sakhalin Energy *'Sakhalin II'* project, a two-train 9.6 million tons per annum LNG facility which is due to start production in 2007.
The Prigorodnoye gas export terminal for *'Sakhalin II'* is located in Aniva Bay, on the southern shores of Sakhalin Island, where first-year ice conditions prevail in a 90-day average ice season.

To support the export of LNG from the Prigorodnoye gas export terminal on Sakhalin Island, orders for first-year ice-class LNG ships were placed during 2004, four of which are being built to Lloyd's

Register class at two shipyards in Japan, Mitsubishi Heavy Industries (MHI) and Mitsui Engineering & Shipbuilding (MES), and one shipyard in Korea, Hyundai Heavy Industries (HHI).

These ice-class LNG ship orders are believed to involve specification modifications to existing standard designs with a conventional vessel layout and a single screw. The hull form for these projects is also likely to be optimised for open water performance, i.e. a conventional hull form is adopted with minimal ice design of the hull.

Accumulated engineering experiences in the design, construction and operational phases for the ice-class LNG ships for *'Sakhalin II'* will provide an invaluable reference for the development of specifications and designs of future Arctic LNG ships.

5.3 ArcOp research project

ArcOp is a research and development project co-funded by the EU. The objective of the project is to find practical solutions for establishing a system of ice operation for LNG and crude oil shipping in the Russian Arctic (including the Barents and Kara Seas).

5.3.1 Research inputs from the INSROP, ArcDev and ICE ROUTES projects

ArcOp aims to utilise the findings of three earlier research projects:

- **INSROP** – a Russian, Norwegian and Japanese-funded project to investigate the NSR passage
- **ICE ROUTES**[15] – an EU-funded ice meteorology study for the NSR passage
- **ArcDev**[16] – an EU-funded arctic development voyage project using an ice strengthened tanker for transport of condensate from the Ob River estuary on the Yamal Peninsula to Rotterdam assisted in navigation by Russian icebreakers in the western Kara Sea.

5.3.2 The four key research areas of the ArcOp project

There are four key research and development areas in the ARCOP project that are addressed by four work packages (1 to 4).

- **Work Package 1:** the development of ice information collection and forecasting methods into a tool for Arctic ice navigation and routeing
- **Work Package 2:** the development of a common understanding between the EU and Russia on the terms and conditions for the use of the NSR
- **Work Package 3:** the development of an integrated marine transportation system for the NSR
- **Work Package 4:** the development of an environmental protection and management system for the Arctic

Lloyd's Register is the only Classification Society participating in the ArcOp project and has participated in Work Package 2 research activities. Some of the findings of this work are presented in sections on ice interaction and ice class selection for Arctic LNG ship designs in the next section.

The development of an integrated transportation system for year-round export of oil by shuttle tankers from the Pechora Sea is an objective of the ArcOp project. Success with the introduction of such a transportation system will facilitate the development and introduction of year-round navigation into the western Kara Sea for export of LNG by future Arctic LNG ships.

5.4 Underlying ordering trends in LNG ship and ice-strengthening tanker design

There are also underlying trends in LNG ships and ice-strengthened tanker specifications and design evident from the ordering pattern of new ships including:

- **adoption of membrane-type containment systems for LNG ship orders[3]:** with membrane types accounting for about 75% of the orderbook backlog of LNG carriers

- **larger capacity tanks for LNG ship orders[3]:** for large LNG orders for long-haul trades, as well as conventional LNG ship orders (first orders in 2004 for 150,000 cubic metre capacity conventional LNG ship designs)

- **adoption of alternative propulsion solutions for LNG orders[3]:** orders placed in the second half of 2004 showed an emerging trend for the adoption of alternative (to steam turbine with main boiler burning of LNG boil-off gas) propulsion solutions such as slow-speed propulsion with large reliquefaction plant and dual-fuel (diesel) electric propulsion

- **large size ice-strengthened tankers[20]:** the rapid rise in the orderbook for large Aframax and Suezmax size ice-strengthened tankers, principally for first-year ice service for export of oil from Primorsk in the Gulf of Finland, as well as for Sakhalin island service

- **adoption of de facto standards for ice-class Rule application[20]:** particularly in the orderbook for large size ice-strengthened tankers where, due to a combination of trading flexibility and technical and regulatory requirements, the Finnish-Swedish Ice Class Rules (FSICR) have become the de facto standard for first-year ice operation.

These underlying technology trends, in addition to the technical developments described above, are also likely to be specified and considered for application to future designs of Arctic LNG ships.

6 Development of future Arctic LNG ship designs

In this section, the following are briefly examined:

- **design concepts for Arctic LNG ships** and a comparison with recently ordered first-year ice class and large LNG ships

- **other key design issues for Arctic LNG ship design** that may require further detailed engineering consideration, as well as the likely necessity for engineering qualification and risk reduction activities at the design concept stage.

6.1 Design concepts for Arctic LNG ships

Design concepts for Arctic LNG ships will address basic fundamentals of LNG ship design for the purposes of project feasibility studies such as:

- **required LNG cargo tank capacity for trade routes**
- **selection of LNG cargo containment system design**
- **selection of optimal LNG cargo tank numbers and size and development of hull general arrangement**
- **selection and development of arrangements of propulsion system.**

A comparison of technical features and principal particulars of INSROP and ArcOp project design concepts for Arctic LNG ships, as well as recently ordered projects for first-year ice-class LNG ships and large LNG ships of greater than 200,000 cubic metre capacity, are shown in Table 2. Two artist's impressions of the ArcOp project design concept are also shown in Figure 6.

Figure 6: Artist's impressions of large double-acting LNG ship design concept developed for ArcOp project

6.2 Other key design issues for Arctic LNG ship design

A number of key design issues at the conceptual and detailed design phases are considered in this section, some of which may have an influence on the basic design concept of future Arctic LNG ships.

It is not intended that this be a comprehensive list of design issues as such, rather, it is intended to be indicative of the depth of front-end engineering design activity likely to be required for future Arctic LNG ships.

- ice interaction scenarios and direct design approaches
- ice class selection
- qualification and risk reduction on application of new technologies
- LNG cargo containment system integrity with hull ice interaction
- hull structure fatigue strength for extreme wave environments
- winterisation.

Table 2: A comparison of design concepts for Arctic LNG ships with recently orders for first year Ice Class and large LNG ships

Project		**INSROP**			**ARCOP**	**Sakhalin II**		**Qatar Gas II**	
Designer/Builder		CNIIMF	CNIIMF	CNIIMF	KMY	MHI	HHI	DSME	HHI/SHI
Project No./ Yard No.		NGM-135A	NGM-79A	NGM-165	-	2229/2230	1729	2245-2248	HHI:1791/92 SHI:1605/06
Project design work date (year)		1997	1997	1997	2003/4	2004/5	2004/5	2003~5	2003~5
Project status		Concept	Concept	Concept	Concept	Ordered	Ordered	Ordered	Ordered
Intended service/ Scenario of operation		Yamal to N. Europe	Yamal to N. Europe	Yamal to N. Europe	Yamal to USA	Sakhalin to Japan/USA	Sakhalin to Japan/USA	Qatar to UK/USA	Qatar to UK/USA
Hull form design		Ice bow	Ice bow	Open water	Double Acting	Open water optimized	Open water optimized	Open water	Open water
LNG cargo capacity, m^3		137,900	80,000	165,000	200,000	147,500	150,000	209,000	216,000
LNG containment system type		Moss	Moss	Moss	Moss	Moss	GTT Mk III	GTT NO96	GTT Mk III
Number of LNG cargo tanks		5	5	4	5	4	4	5	5
Principal Particulars metres	LOA	292.0	-	286.0	328.0	288.0	-	315	-
	LBP	281.0	232.0	275.0	-	274.0	275	303	303
	B	44.8	38.0	50.5	50.0	49.0	44.2	50.0	50.0
	D	25.0	22.0	27.0	23.4	26.8	26.0	27.0	27.0
	T	11.4	10.6	12.3	12.0	12.3	11.35	12.0	12.0
Ice Class	Hull	RMRS ULA	RMRS ULA	RMRS L3	Not known	FSICR 1B	RMRS LU2	None	None
	Machinery	RMRS ULA	RMRS ULA	RMRS L3	Not known	RMRS LU2	RMRS LU2	None	None
	Installed Power	RMRS ULA	RMRS ULA	RMRS L3	Not known	RMRS LU2	RMRS LU2	None	None
Propulsion System	Type	Direct drive	Direct drive	Direct drive	Electric	Turbine	Turbine	Direct drive	Direct drive
	Main Engine	Slow Speed Diesel	Slow Speed Diesel	Slow Speed Diesel	Diesel	Steam	Steam	Slow Speed Diesel	Slow Speed Diesel
	Dual Fuel (Y/N)	No	No	No	Yes	Main boilers burning LNG cargo boil off	Main boilers burning LNG cargo boil off	No	No
	Installed Power	~ 28-31 MW	~ 21 MW	~ 42 MW	~35 MW	Not known	~29.4 MW	~33 MW	~34.6 MW
	No of Propellers/ Propulsion units	2	Not known	Not known	2	1	1	2	2
	Type of Propeller/ Propulsion unit	CPP	CPP	CPP	AZIPOD	Fixed pitch	Fixed pitch	Fixed pitch	Fixed pitch

References: INSROP working paper[10], ARCOP WP 3 Workshop report[11], Shipbuilder performance records[21]

6.2.1 Ice interaction scenarios and direct design approaches

Ice-class Rules define a minimum standard of safe design for hull structural strength, principally the ice belt (defined by load and ballast waterlines), to accommodate ice pressure loads due to hull ice interaction.

In addition, ice-class Rules define a standard of safety and strength for the propeller and shafting system to accommodate propeller ice impact loads. Ice-class Rules may also define installed power requirements relative to the envisaged ice operational scenario of the vessel e.g. navigation in a channel made with icebreaker assistance.

Current ice-class Rules have developed over time and incorporate both theoretical derivations of requirements from expected ice interaction scenarios as well as practical operating experiences from ships in service. A simple comparison in table 3 below shows ice interaction and powering requirements for various ice-class Rules.

Table 3: Simple Comparison of Ice Interaction and Powering Requirements for Ice Class Rules

		Ice Interaction and Powering Requirement Scenarios			
		Ice Belt Design	Shaft System & Propeller Design	Hull Girder Strength	Installed Power
RMRS 1999 Ice Class Rules Note 1	Independent Operation	Ice Floe Impact	Propeller Ice Piece Impact	-	Minimum to avoid vessel being stuck in ice whilst independently operated
	Icebreaker Assisted				
IACS Polar Rules Note 2	Independent Operation	Ice Floe Impact	Propeller Ice Piece Impact	Ice Ramming	-
	Icebreaker Assisted				
Finnish Swedish Ice Class Rules FSICR	Independent Operation	Level Ice interaction	Propeller Ice Piece Impact Note 3	-	-
	Icebreaker Assisted				5 knots in brash ice channel

Note 1: Based upon equivalencies in RMRS 2003 paper[22] at ArcOp workshop
Note 2: Based upon equivalencies in LR 2004 paper[23] at ArcOp workshop
Note 3: Draft methodology for direct design approach for ice piece interaction circulated to industry for comment in 2004

Where limited ice-class Rule application knowledge or service experience exists, the adoption of direct design approaches for hull structural strength and propulsion system elements using realistic and probable ice interaction and operating scenarios is appropriate to supplement design by prescriptive Rule requirements.

Ideally, direct design approaches should be contemplated at initial concept and basic design phases. As a minimum direct design approaches should be contemplated where:

More severe loads may be anticipated than those derived from a Rule design basis: e.g. ice-interaction scenarios on Azipod structures in astern mode for double-acting propulsion, to account for ramming loads on the hull whilst in independent navigation.

Where ice interaction occurs which is not envisaged by the Rule design basis: e.g. hull bottom areas where ice entrapment could be anticipated in shallow water shelf areas of the western Kara Sea.

Specific safety-critical elements of the design under ice interaction loads that are not explicitly addressed by the prescriptive Rules: e.g. hull structure deformation and limiting deflection criteria for LNG cargo containment system integrity (note that risk assessment techniques are also now available to address specific concerns such as this, see later).

6.2.2 Ice class selection

In the reference sections of the **“Guide for Navigation through the Northern Sea Route, 1996”** there are **“Requirements for the Design, Equipment and Supplies of Vessels Navigating the Northern Sea Route”.** Sections 3.4 and 4.1 of these requirements indicate that:

Section 3.4 … *“Ice strength and design of the hull of ships intended for navigation along the Northern Sea Route are to meet the requirements of RMRS current Rules … or the equivalent requirements of other classification societies”*

Section 4.1 … *“Machinery installations are to meet the requirements of RMRS Rules or equivalent Rules of foreign classification societies for ships of the corresponding categories”*

Lloyd’s Register, the sole classification society participating at working party level in the ArcDev[24] and ArcOp[23] projects, has contributed to projects to:

- develop recommendations for ice class for application to LNG and oil tankers operating year round in the Kara Sea to Barents Sea.
- assess classification society ice-class Rules for navigation in the Russian Arctic and investigate equivalency between each Rule set applicable to these regions.

Based upon the work carried out by Lloyd’s Register[23,24] and Helcom[25], as well as published references[22] for 1999 and 1981 RMRS Rule set equivalencies the following tables, Table 4 & 5, compare the ice-class requirements for Kara Sea service based upon two seasonal ice conditions, winter to spring (ice navigation) season and summer to fall season.

Table 4: Comparison of Ice Classes for Kara Sea winter – spring seasonal ice conditions

		Navigation Conditions in Kara Sea: Winter – Spring Season			
		Extreme	Heavy	Medium	Easy
RMRS 1999 Ice Class Rules	Independent Operation	LU8	LU8	LU7	LU6
	Icebreaker Assisted	LU7	LU7	LU6	LU5
IACS Polar Rules Notes 1 & 4	Independent Operation	PC2	PC2	PC3	PC5
	Icebreaker Assisted	PC3	PC3	PC4	PC6 Note 3
RMRS 1981 Ice Class Rules Notes 1 & 2	Independent Operation	-	-	ULA	UL
	Icebreaker Assisted	ULA	ULA	ULA	UL Note 3
Finnish Swedish Ice Class Rules FSICR Note 1	Independent Operation	-	-	-	-
	Icebreaker Assisted	-	-	-	1AS Note 3

Extreme navigation conditions: mean re-occurrence time once in ten years
Heavy, medium and easy navigation conditions: mean re-occurrence time once in three years
Note 1: Based upon recommendations[24] for Ice Class for safe navigation from Ob Bay to Murmansk
Note 2: Based upon equivalencies in RMRS 2003 paper[22] at ArcOp workshop
Note 3: Up to December/January only[24]
Note 4: Based upon equivalencies in LR 2004 paper[23] at ArcOp workshop

Table 5: Comparison of Ice Classes for Kara Sea summer – fall seasonal ice conditions

		Navigation Conditions in Kara Sea: Summer – Fall Season			
		Extreme	Heavy	Medium	Easy
RMRS 1999 Ice Class Rules Note 5	Independent Operation	LU6	LU5	LU5	LU5
	Icebreaker Assisted	LU6	LU5	LU5	LU4
IACS Polar Rules Notes 1 & 4	Independent Operation	PC4	PC5	PC6	PC6
	Icebreaker Assisted	PC4	PC6	PC6	PC7
RMRS 1981 Ice Class Rules Notes 1 & 2	Independent Operation	ULA	ULA	UL	UL
	Icebreaker Assisted	ULA	UL	UL	L1
Finnish Swedish Ice Class Rules FSICR Note 1	Independent Operation	-	-	-	-
	Icebreaker Assisted	-	-	-	1A

Extreme navigation conditions: mean re-occurrence time once in ten years
Heavy, medium and easy navigation conditions: mean re-occurrence time once in three years
Note 1: Based upon recommendations[24] for Ice Class for safe navigation from Ob Bay to Murmansk
Note 2: Based upon equivalencies in RMRS 2003 paper[22] at ArcOp workshop
Note 3: Up to December/January only[24]
Note 4: Based upon equivalencies in LR 2004 paper[23] at ArcOp workshop
Note 5: Based upon equivalencies in Helcom Recommendation 25/7, March 2004

Grey shaded cells in the Tables 4 & 5 indicate suggested ice-class standards for seasonal navigation. For year round assisted navigation in the western Kara Sea the appropriate RMRS and IACS ice classes, based upon Table 4 winter-spring ice season, are:

- RMRS Rule: **LU7 Ice Class**
- IACS Polar Ship Rule: **PC3 Ice Class**

6.2.3 Qualification and risk reduction on applications of new technologies

Extensive research and development activity was required for introduction of the new technological developments described in the earlier section of this paper. For some of these developments Lloyd's Register has been involved in evaluating the safety and integrity of systems through a formal process of risk assessments.

A selection of risk assessments carried out by Lloyd's Register for LNG and DAT systems is shown in Table 6 below. The historical precedent for application of risk assessment techniques shown is the fault tree analysis work carried out for design concepts of Arctic LNG ships for export of LNG from Melville Island in the Canadian Arctic, the so-called Arctic Pilot Project.

Most of the recent safety cases for LNG systems have been executed to fulfil oil major specification requirements for qualification and risk reduction when applying new technologies in LNG shipping projects. Application of formal risk assessment techniques could reasonably be anticipated for the development of designs of Arctic LNG ships for service to the Yamal Peninsula.

The selection of the most appropriate risk assessment technique as well as careful consideration of the scope of application is essential when applying risk assessments. For example, the safety case approach (combining a Hazard Identification Study and a Hazard Operability Study) has been found to be particularly suitable for assessment of front-end engineering, conceptual design work prior to detail design development as well as for identification of safety critical elements of the design.

Table 6: A selection of risk assessments carried out by Lloyd's Register for LNG and Double Acting Tanker systems

Project & System examined			Risk Assessment Technique			
Project	System examined	Year	Fault Tree Analysis	Failure Mode & Effects Analysis	Hazard Identification (HAZID) Study	Hazard Operability (HAZOP) Study
Arctic Pilot LNG Ship	Major systems and sub systems including cargo, cargo containment and propulsion	1979	FTA			
LPG/ Condensate FSO	LPG/condensate combined cargo tank arrangement	2000	FTA			
LNG FSRU	LNG re-gasification system design	2001			**Safety Case** HAZID + HAZOP	
Double-acting tanker	Bridge watch-keeping control system	2002/3		FMEA		
Large LNG Ship	Fuel system for dual fuel diesel electric plant	2004/5		FMEA	**Safety Case** HAZID + HAZOP	
Large LNG Ship	Fuel system for gas turbine electric plant	2004/5			**Safety Case** HAZID + HAZOP	
Large LNG Ship	Large LNG re-liquefaction plant	2004/5			**Safety Case** HAZID + HAZOP	

Lloyd's Register, with extensive references for such work, is well positioned to offer advice on risk assessment methods appropriate to the particular scope and goals identified. Lloyd's Register can also facilitate the execution of such risk assessments.

Early involvement of a classification society can also derive downstream benefits in focusing the scope and extent of design approval and survey activities.

6.2.4 LNG cargo containment system integrity with hull ice interaction

A key design issue at the conceptual and detailed design phases is the integrity and safety of the LNG cargo containment system with hull ice interaction. Engineering evaluation carried out for this issue will influence the selection of cargo containment and the basic design concept of future Arctic LNG ships.

In previous concept design studies the use of independent (type B Moss) tanks for Arctic LNG ships for operation in the Kara Sea in the Russian Arctic has been advocated. Perceived advantages of the independent (type B Moss) tanks have been reported as reduced vulnerability (compared with membrane tanks) to hull deformation and vibration due to hull ice interactions. Hull deformation and vibration and the effect of ice interactions on containment integrity are each considered in turn in what follows.

6.2.4.1 Hull deformation effects on LNG cargo containment system integrity

In the event of a sharp deformation inwards of the inner hull both membrane and Moss-type LNG cargo containment systems are at severe risk of gross failure. However, both systems could feasibly sustain some inner hull deformation before gross failure.

In the case of GTT GazTransport membrane system types there is actual service experience with inner bottom deformation from a heavy grounding incident of one vessel off Spain in the early 1970s.

For both membrane and Moss-type systems a critical situation will occur when the amount of inner hull deformation reduces the tank volume by the tank vapour space (usually 1% to 2% of tank volume). At this point cargo pressure will increase rapidly causing failure due to tank over-pressurisation.

6.2.4.2 Vibration effects on LNG cargo containment system integrity

Hull ice interactions are understood to cause low frequency vibration (frequencies of around 3 to 5 Hz). Membrane containment systems are only potentially at risk from higher frequency vibration effects, specifically in the case of GazTransport N096. Excessive settling of the perlite insulation could possibly occur at frequencies of around 40Hz.

Cargo tank pump masts may also be susceptible to low frequency vibrations from hull-ice interactions; however, design countermeasures can be used to address this effect.

6.2.5 Hull structure fatigue strength for extreme wave environments

Another issue that may have a strong influence on the selection of LNG cargo containment system and hull layout specific to the envisaged scenario of operation is the hull structure detail design from fatigue strength aspects.

Consider the likely operation of future Arctic LNG ships for export of LNG from the Yamal Peninsula to the USA. For extended periods of service on voyages from the Barents Sea across the northern parts of the North Atlantic to US east coast ports the wave environment could be characterised as extreme from fatigue considerations.

Specifically, in the case of independent Moss-type tanks for ships of conventional arrangement, the structural configuration is such that the deck is constructed of higher yield steels designed to their full stress range capacity with consequent limitations on structural detail design for fatigue strength.

A detailed engineering evaluation of fatigue strength aspects for the extreme wave environment envisaged may then indicate that a membrane-type configuration would be advantageous for structural detail design from fatigue aspects.

Alternatively non-conventional arrangements for a Moss-type tank ship, such as, for example, the Aker Finnyards continuous-cover design might overcome high deck stress ranges and fatigue strength limitations of a Moss-type tank ship of conventional arrangement.

6.2.6 Winterisation

The adoption of specific technical solutions and measures for year-round Arctic operations, often termed ‘winterisation’ measures, will need special consideration for future Arctic LNG ships.

Some appropriate winterisation measures follow. Note that this is not a complete list but indicates some of the issues to consider at the specification and design stage:

- **specification of steel grades for exposed hull structure** to withstand low design ambient temperatures
- **consideration at the design stage of deck ice accumulation and stability aspects** including appropriate measures for de-icing
- **consideration at the design stage of hull appendages for ice operations** including protection of appendages e.g. ice knife, rudder stoppers
- **specification of suitable arrangements for crew operation in enclosed spaces** e.g. space heating, enclosed bridge wings with heated windows, thermal insulation
- **specification of suitable precautions for low temperature operation of deck machinery and deck systems** such as fire fighting and cargo and ballast systems, by selection of suitable materials, local heating arrangements
- **specification of suitable precautions for low temperature operation of main machinery and systems** such as the design and arrangement of sea chests to prevent ice blockage (note that

special consideration may be needed for double-acting operation since this will be in the forward region during astern operation), air inlet heating for main engine operation

- **specification of ice abrasion resistant and low ice friction hull coatings** for the immersed areas of the shell ice belt
- **consideration of safe access to working areas on deck and to emergency escape routes** including possible provision of enclosed spaces for working areas for mooring equipment
- **specification of searchlights and consideration of improved visibility** for ice operations at night, when under escort or assistance of icebreakers, and when manoeuvring in port in ice.

Figure 7: Close up view of deck and wheelhouse of Neste Oil double-acting tanker showing enclosed bridge wing arrangement (photo courtesy of Neste Oil)

Operational risk assessment methods have also been advocated[14] to determine suitable winterisation measures and such an approach would appear to be suitable and appropriate to the operation of future Arctic LNG ships.

7 Concluding Remarks

This paper has considered recent technical developments and research project activities in the LNG and ice-strengthened tanker design with potential application to future Arctic LNG ships including:

- introduction of the first large ice-class DAT designs (2002~3)
- development and first orders for large LNG carriers of 200,000 plus cubic metre capacity (2002~4)
- development (gas turbine) and introduction (diesel) of new dual-fuel electric propulsion systems on LNG carriers (2002~4)
- first orders for first-year ice-class LNG ships (2004)
- ArcOp research project (2003~2005)

These technical developments when combined could facilitate and enable the development of viable future large Arctic LNG ship designs.

This paper has also considered a number of key design issues at the conceptual and detailed design stages which may have an influence on the basic design concept of future Arctic LNG ships including:

- ice interaction scenarios and direct design approaches
- ice class selection
- qualification and risk reduction on application of new technologies
- LNG cargo containment system integrity with hull ice interaction
- hull structure fatigue strength for extreme wave environments
- winterisation.

These design issues are intended to indicate the depth of front-end engineering design activity likely to be required for future Arctic LNG ships. Some specific challenges, as well as solutions, for the classification of Arctic LNG ships have also been considered and described.

8 List of Figures and Tables

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