Submarine cargo vessels – historical solution to Arctic hydrocarbons transportation

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With melting ice cover in the Arctic, oil and gas companies decided to move part of its interest to the region. The process was further accelerated by growing global energy resources demand. Harsh weather conditions in the Far North and its remoteness were, however, a problem. Oil and gas, extracted from Arctic reservoirs could not be easily shipped to the clients, Japan or China for instance. Even the machinery could only be transported within few months of summer, whenever the ice conditions permitted. Should the weather change – necessary supply could not be delivered. Nowadays, such problems have been solved by Arctic states investing in ice-proof offshore drilling rigs, ice-breakers and navigational infrastructure. A reliable logistic system has been created including nuclear-propelled ice-breakers and ice-class gas carriers. It is interesting, however, how the interested parties planned to deal with such a challenge in the past. One of the solutions was particularly innovative: the use of nuclear-powered submarine cargo vessels.

OUTLINE

Problem of supplying Arctic settlements with necessary goods, shipping its raw materials to more populated regions or using Arctic as a sea route connecting continents has existed ever since people populated the Far North. Solutions included multi-seasonal ship voyages with crews spending winters in extremely inhospitable environment, using great Siberian rivers for transportation, bringing railway to the region or utilising airborne transportation. For bulk shipments, however, the only reasonable solution has always been the sea transportation.

Commercial shipping is more intensive in Northern Sea Route than in Canadian Northwest Passage. The latter is used only occasionally with m/v '*Nordic Orion*' becoming the first merchant vessel to traverse it in 2013 only because an ice-breaker assistance has been rendered free of charge. Liquid natural resources of Canadian Arctic are exported mostly by pipelines – the sea route comprises numerous narrow channels which are frequently blocked by particularly thick sea ice creating so-called 'choke points' [9]. In the same time, Barents and Kara Seas of Russian continental shelf are frequented by numerous commercial ships taking advantage of Norwegian Current which makes those areas ice-free for much longer periods. In 2014, a total of 31 individual transits along the entire Northern Sea Route has been registered by its Administration. Amount of cargo transported in a region saw a significant increase in years 2010-2013, mostly due to decline of ice-covered area, pilotage and ice-breakers' assistance tariff privileges introduced by Russian Federation. Transit reduced in 2014, mostly due to lower cargo throughput [3]. It must be noted that vast majority of the traffic goes along the Eurasia's coast with routes depending on prevailing navigational and ice conditions. While the shortest route from Western Europe to Asia via Bering Strait lies close to the North Pole, only a handful of surface vessels were ever able to reach this point, mostly as a part of scientific expeditions.

The ever-existent issue for Arctic shipping was the uncertainty related to ice cover and a risk of getting stuck in the ice or necessity of abandoning the passage [1]. The situation in Russian Arctic improved with fleet of nuclear ice-breakers becoming operational as of 1959. Unfortunately, their assistance was costly and could not be provided whenever necessary. That eventually led to the introduction of a vessel combining the advantages of nuclear ice-breaker and a cargo ship: n/v '*Sevmorput*'.

NUCLEAR VESSELS AND CARGO SUBMARINES – TECHNOLOGIES SEPARATED

N/s '*Sevmorput*' (Russian for 'The Northern Sea Route') is the only nuclear cargo vessel able to operate as of January 2016, although she is reportedly laid up at the time this paper is being written. There were three other nuclear cargo vessels: American '*Savannah*', German '*Otto Hahn*', Japanese '*Mutsu*' and nine nuclear ice-breakers (eight of them being operational) with two other units scheduled for delivery. In general, operation of civilian nuclear ships proved to be safe, although not economically feasible in most cases. Operating those vessels in Arctic ice-covered seas remains their only application.

Civilian submarines are also not a common sight since there is no use of them in full-scale merchant shipping with drug smugglers being the only parties to use those vessels for their purposes. Naval submarines are also known to be used for transportation during wartime (i.e. Nazi German 'Milk Cows' [13]), but their cargo capacity remains very limited in such cases. Underwater vehicles are also used for tourist excursions in locations with extraordinarily beautiful sea life – they can accommodate up to 50 passengers.

Summing up, submarines are not extensively used in shipping industry mostly due to their high operational costs and technical challenges represented by them. Design, construction, navigation and maintenance of surface vessel is much easier and cheaper than of a submarine.

SUBMARINE CARGO VESSELS CONCEPT

An interesting solution to the problem of easy transportation of Arctic natural resources was being considered and developed: a submarine cargo vessels navigating Arctic ocean under the ice cover. Those would have been capable of calling at some of Far North ports and offshore terminals purposely designed and constructed to accommodate them. Some would have been able to carry general cargo including containers, others – liquid hydrocarbons in bulk.

Two different approaches had been considered. First included converting military submarines, withdrawn from service, into cargo vessels. This proved to be unpractical due to engineering difficulties and possible national security breaches (revelation of a secret design). A different approach had evolved, encompassing designing and constructing purpose-built nuclear-propelled submarine cargo vessels. Nuclear propulsion was considered to be the only possible way of powering long-range submarines at least until extremely high-capacity batteries are developed, enabling vessels to traverse the oceans without recharging.

Such vessels would have been independent from extreme hydrometeorological conditions prevailing in the Arctic Ocean, including ice. Without having to overcome areas covered with thick ice layer by either detour or crushing the ice, such vessels would simply navigate under it. Shoals could be navigated on a surface or – if also blocked by ice, avoided. That would be a particularly concerning issue in Canadian Northwest Passage and in some of Russian Arctic archipelagos. Those waters, namely Dmitry Laptev and Sannikov Straits are difficult to navigate also for surface vessels. Such advantages of submarine cargo vessels would make them a perfect choice as a mean of raw materials' transportation from Arctic and supplying the industry located in high latitudes. Another application of those could also be a full-scale transportation of various cargoes between Northern Europe and Eastern Asia/West Coast of America using Arctic route, close to the North Pole. It is the shortest sea route between those regions and its users could benefit from shorter transit times similarly as some shipping companies attempt to use a slightly longer Northern Sea Route for the same reason, avoiding longer route via Suez Canal and its transit fees, but making the shipment dependent on Northern Sea Route Administration's sea pilots and ice-breakers availability. Transit fees are also applicable in Russian Arctic.

Experience gained during Cold-War arms race in nuclear submarines' design, construction and navigation [7] could be used for civilian purposes preserving working places of highly-qualified military personnel and keeping shipyards, specialized in servicing such vessels, productive. A great attention must be paid, however, to radioactive materials' management and security.

NUCLEAR VESSELS AND CARGO SUBMARINES – TECHNOLOGIES COMBINED

A leading participant of the discussion on utilising nuclear submarines for merchant purposes was a then-Leningrad-based Marine Engineering Bureau 'Malachite' whose engineers have developed some advanced concepts regarding the matter.

Firstly, not less than four different designs of underwater cargo vessels have been developed. Their main particulars are presented in Table 1. Its last column depicts data related to 2007's LNG carrier design, described below.

As can be seen, the design of 'Product tanker #2' and 'Container vessel' was most likely based on the same hull with modified interior of the craft.

Secondly, an analysis of necessary works to be done in order to adapt Arctic ports to handle cargo submarines had been performed. Finally, potential economic benefits have been calculated showing that shipping cargoes by underwater cargo vessels might be costly-effective and expenses on system's development would recoup in approximately 5 years [5]. It must be underlined, however, that such analysis was performed in mid-1990's taking into account economic conditions of that times, especially oil prices.

Similar study has also been performed by group of researchers led by A. P. Velikhov of Kurchatov Institute and presented in 2007. A conceptual design of submarine tanker has been prepared. She was to have the main particulars as indicated in Table 1 right-most column at a unit cost of approximately 600 million USD and operating time of 30 years. She would have been capable of loading and discharging LNG using underwater connection without re-surfacing. It has been calculated that subma-

Table 1. Main particulars of merchant submarines [5][6]

Name	Product tanker #1	Product tanker #2	Container vessel	General cargo vessel	2007 LNG carrier
Normal displacement, m^3	33,500	79,000	78,800	45,200	?
Total submerged displacement, m^3	58,100	92,000	92,000	49,400	277,000
LOA, m	174	238	238	207	260
Hull breadth, m	26.5	26.8	26.8	22.0	?
Height, m	19.4	20.2	20.2	17.3	?
Power plant output, hp	1×30,000	1×50,000	1×50,000	2×25,000	2×67,000
Service speed submerged/surface, knt	15/10-12	20/10-12	20/10-12	22/10-12	19/?
Ice-breaking capacity at 2 knt speed, m	< 8.0	–	–	2.0	?
Maximum cargo-carrying capacity, t	12,000	30,000	30,000	17,500	67,500
Containers capacity (TEU)	–	–	912	288	–
Mean draught, m	9.0	16.0	12.8	11.0	18.0
Crew number, persons	35	35	35	35	35
Endurance, days	50	50	50	50	unlimited

rine transportation of LNG would be cost-effective at 1 cubic meter of this commodity worth 100 USD. Nowadays (January 2016), 1 cubic meter of LNG costs around 50 USD which makes underwater transportation too costly. However, the research indicated that despite unacceptable level of transportation costs themselves, shipping of LNG by submarines might be profitable considering the fact that submarines are less vulnerable to potential terrorist attacks (by smaller both risk and potential damage) [6]. It can also be the only way of transporting natural gas, extracted from some Arctic regions, access to which is restricted by ice cover.

FROM CONCEPT STAGE TO REAL WORLD?

In 1981, General Dynamics disclosed that it had been discussing construction of 28 submarine tankers for LNG transportation from Arctic to North America and Europe together with support facilities located in United States and West Germany. Plans were to use either nuclear power or methane to propel them. Cost of one vessel was estimated at around 700 million USD at that time [10]. They were planned to have operational depth of 200 meters and a crew of 32 men [12]. Outline of nuclear-powered General Dynamics LNG carrier is shown in Fig. 1.

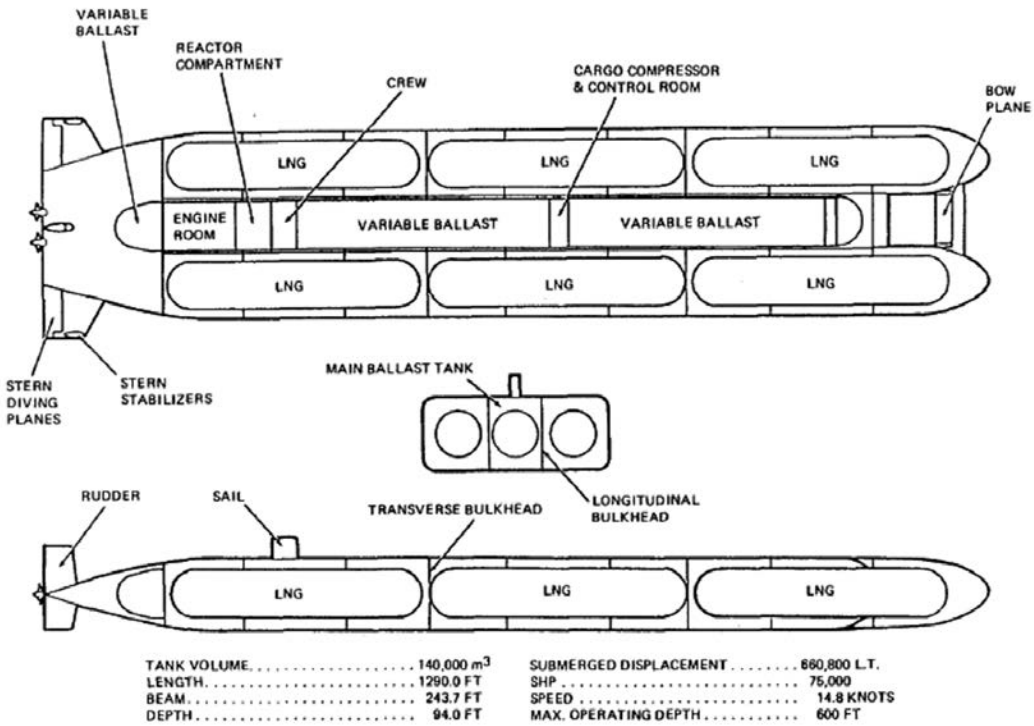

Fig. 1. Nuclear LNG tanker layout [4]

Another approach was presented by American-based company Werner Offshore in 1996. In order to facilitate exploitation of hydrocarbon deposits located in Kara Sea, a fleet of 22 submarine LNG carriers has been proposed to ship the gas to global market. They were to be built in Vladivostok shipyard. The idea was to extract gas from deposits in Yamal Peninsula and pump it by underwater pipeline to liquefaction and export plant in Novaya Zemlya archipelago. LNG would then be transported by submarines to Alaska's St. Matthew Island where it would be transhipped to conventional surface LNG tankers. Manned by a crew of 14 and propelled by diesel engines, subs could carry as much as 170,000 cubic meters of LNG. First voyage was expected to occur by May 2004 [13].

Together with carriers, gas terminals had to be built or adapted to serve submarine tanker fleet. In addition to common concept of conventional berth with manifold, it was planned to build submerged buoys or sea bottom connections so that submarine carrier would not need to resurface at any stage of the voyage. Otherwise, should the terminal basin be covered with ice, harbour ice-breakers would have to be employed. Underwater navigation in close proximity of the terminal might be facilitated by hydroacoustic aids to navigation. Depending on the actual places of LNG origin and destination, construction of transhipment terminal was planned in such location that submarine tankers would only be used in heavy ice conditions and in regions where water depth permits their operation [8].

There is a number of reasons associated with the fact that above plans had never come to existence and no underwater transportation system has been created to date in Arctic.

INTERNAL TECHNICAL CONSIDERATIONS

It has been acknowledged that civilian submarines would have to deal with specific problems which might threaten their safe and cost-effective operations. Those are listed below:

- Hydrodynamic issues: since resistance to motion of the ship is made up of two components - one due to the viscosity of the fluid in contact with the hull and the other due to the movement of the fluid around the hull – fully submerged underwater vehicle are featured by larger wetted areas than those of surface vessels. This in combination with significantly greater resistance during low-speed operations worsens the vessel's performance;
- Archimedes' principle, stating that a submarine must displace its own volume and mass of fluid in order to remain in equilibrium in consequence requires merchant subs to carry ballast water in amount virtually equal to potential cargo mass during cargo-free voyages in order to remain submerged;
- As such ballast could not be accommodated in LNG cargo tanks for many reasons (greater specific gravity of water than of the LNG, need of drying and cleaning the tanks after discharging the ballast), large and separated ballast tanks would have to provided;
- Relative pressure exerted on the submarine's hull by seawater and associated stresses can be counteracted by the very fact that cargoes carried can be stored in pressure tanks (a feature which does not apply to solid cargoes i.e. containers). Moreover – merchant subs need not to submerge deeply into to the ocean, a depth sufficient for avoiding a few meters-thick ice is enough;
- Burning fossil fuels including LNG cargo is not considered feasible for powering the merchant submarines due to requirement to supply sufficient amount of oxygen and removing exhaust gases. Although technically possible, solutions to those problems would require extra capital investments. On the other hand, utilising nuclear power for LNG carrier propulsion can provide enough energy for re-liquefying the cargo during the passage (with possibility of keeping LNG temperature above -163°C as in today's surface tankers as a balance for hydrostatic pressure should membrane-type cargo tanks be used) [8].

EXTERNAL CHALLENGES AND THREATS

Although the fact that human civilization has a great impact on our planet's climate is still not fully acknowledged by all scholars, it can be observed that ice-covered area in the Arctic has reduced in last decades. It is also not clear whether or not this trend will continue in next years, but the unquestionable fact is that hydrometeorological conditions in Far North have improved and year-round surface navigation is now possible even without ice-breaker's assistance for purpose-built vessels. As a matter of fact, LNG carriers capable of navigating along the Northern Sea Route all around the year, with or without ice-breakers' assistance (depending on actual ice conditions), are being built in Korea and are scheduled for delivery in 2017.

Secondly, no full-scale mineral resources deposits exploitation has been launched east of Norilsk. Big copper and nickel mine located in that city's outskirts creates significant cargo flows which is operated by numerous cargo vessels, assisted by nuclear ice-breakers. Another main sources of bulk minerals are hydrocarbon deposits, which exploitation projects are being developed, namely Prirazlomnaya oil rig in Pechora Sea and Yamal LNG in Yamal Peninsula. Those can be easily accessed from the west, a sea route being generally warmer and able to support year-round navigation. As can be seen in Fig. 2 & 3, northern coast of Alaska is more likely to be hydrocarbon-rich than Far-Eastern part of northern Russia. Major oil fields are located in Prudhoe Bay, but oil is exported from there using pipelines instead of ships. It is understandable that easily-accessible fields are developed first due to their lower operational and transport costs. Those more difficult to access are scarce and do not create logistic potential big enough to justify creation of a brand new cargo system utilizing submarine gas carriers and associated infrastructure.

Furthermore, there are some social and political issues still to be addressed. Recent incidents including global terrorism or Fukushima Daiichi nuclear accident have created strong opposition to any nuclear-related project in most of the countries. It became apparent that Chernobyl disaster was not completely an exemption to the rule stating that any complex piece of machinery, including nuclear power plant, can fail sooner or later, costs of such failure being unpredictable. Another examples of

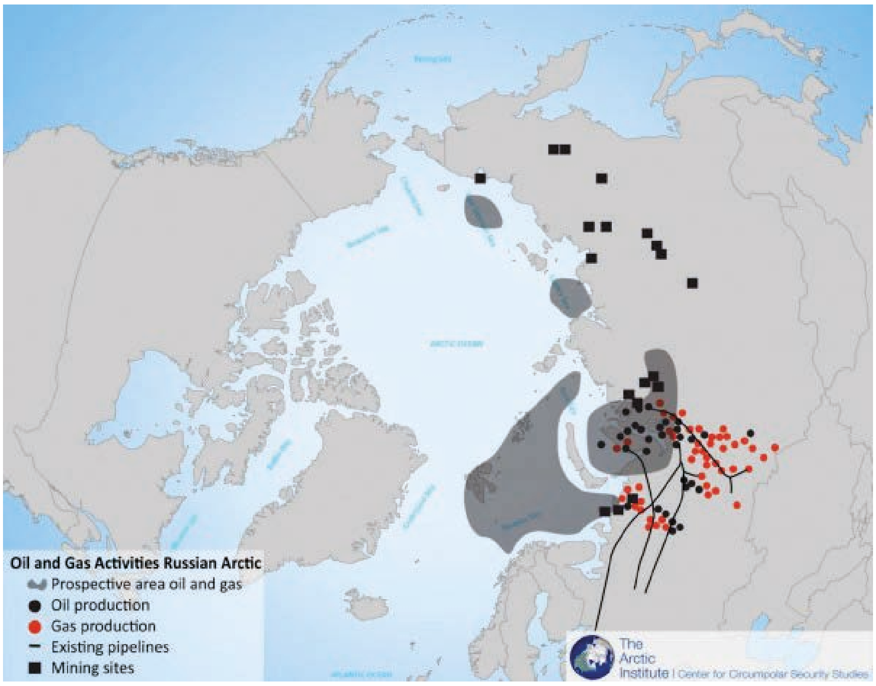

Fig. 2. Prospective oil and gas deposits in Russian Arctic [14]

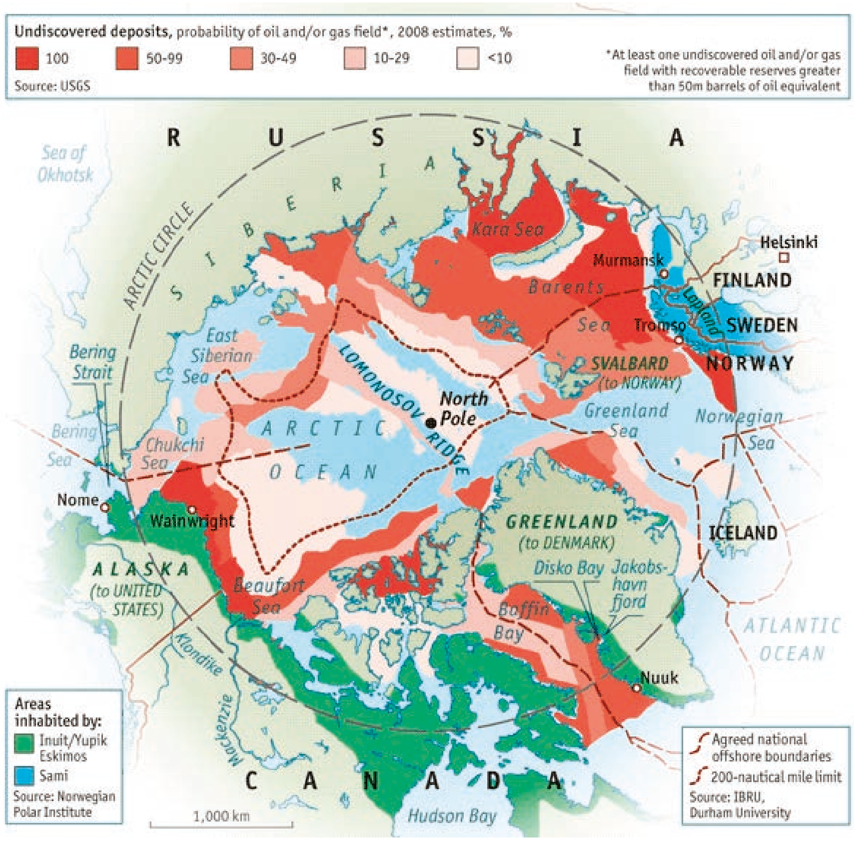

Fig. 3. Estimated probability of discovering new oil and gas deposits in Arctic [11]

nuclear accidents involving military submarines are complete loss of coolant aboard Soviet submarine *K-19* and non-nuclear explosion of the reactor aboard another Soviet ship *K-431*. Other submarines were also involved in non-nuclear incidents which created a risk for their power plants, explosion and fire aboard '*Kursk*' and collision of USS '*Oklahoma City*' with LNG carrier for instance.

Civilian vessels also contributed to this infamous record i.e. minor gamma ray and neutrons leak from n/s '*Mutsu*' shielding system. Nevertheless, nuclear technology is still improving with reactors and associated equipment becoming safer – this progress is partly driven by lessons learned from incidents themselves. Experiences gained during almost 60 years of merchant nuclear vessels' and military ships' service proved that they can be operated in a safe manner, although it is costly and problematic [8]. Consequences of nuclear submarine's malfunctions can be extremely serious and proper risk assessment, crew training and supervision would have to be performed before any of those comes into operation.

Although modern low reached uranium (LEU) fuel is not suitable for creating nuclear weapons, an event of terrorists gaining access to spent fuel and creating a dirty bomb is possible. However unlikely that situation would be, the easiest way of mitigating such a risk is by reducing the number of civilian nuclear power users including maritime industry.

There are even more concerns: some coastal countries might not accept any nuclear-powered vessel to call at their ports at all thus reducing her operational capabilities; sufficient number of engineers would have to be trained to supervise nuclear reactors; P&I clubs would have to accept all related risks and provide shipping industry with reasonable insurance rates; progress in fast reactor technology would have to be made to secure sufficient uranium supply for increased number of customers; special attention shall be paid to proper decommissioning of the nuclear reactors with related HSE risks and costs [2].

Safe navigation of submarines under ice is another issue. With satellite navigation systems not available, the only available method is less accurate dead reckoning, at least until Simultaneous Localization and Mapping (SLAM) or other alternative techniques are developed to enable more precise navigation. Nevertheless, naval experience shows good record of safety of navigation under the ice. Procedures for surfacing through it have also been developed during the Cold War.

Legal issues concerning underwater navigation of merchant nuclear submarines in Arctic involve the fact that virtually no reference to such activities in any of major international maritime conventions can be found. Ships' operators would then have to follow existent regulations as far as it would be practically possible or adhere to classification societies' standards, DNV-GL's 'Rules for classification – Underwater technology' for instance. Those have been, however, developed only in recent years and did not exist when merchant submarines were proposed. What did exist at that time was United Nations Convention On Law of the Sea with its Article 20, stating specifically that '*In the territorial sea, submarines and other underwater vehicles are required to navigate on the surface and to show their flag*'. The very idea of introducing merchant submarines into trade between underwater terminals or in areas considered to be coastal states' territorial or internal waters (Canadian Northwest Passage or some straits in Russian Arctic) clearly contradicts this Article. It can be anticipated that these provisions could be altered by bilateral agreements.

Last but not least, it has been indicated [8] that underwater commercial cargo vessels can only be cost-effective if no other mean of transportation can be provided. Problem of shipping natural resources from either Russian, Canadian or Alaskan Arctic seemed to be a potential candidate where such solution could be implemented. However, due to reasons listed above, different approaches have been chosen: building pipelines from Prudhoe Bay to Valdez and from Yamal Peninsula to Europe or introducing purposely designed and constructed ice-class LNG carriers for instance. It has been proven that hydrocarbons can be transported by other means and thus submarine LNG carriers are not feasible. It would be embarrassing for shipping companies to invest billions of dollars in development of submarine tankers fleet only to find that their job can be done by slightly modified surface LNG carriers.

On the other hand, utilising nuclear energy to provide submarine cargo vessels with power has lower environmental impact than using any of fossil fuels for such purpose. With current pressure on reducing carbon dioxide and other gaseous pollutants by shipping, nuclear energy is one of possible ways of achieving the goal.

CONCLUSIONS

Feasibility of creating a transportation system for underwater shipping of Arctic natural resources has been studied by many authors at least since 1980s. Although no prototype had ever been built, studies proved that utilising nuclear- or diesel-powered merchant submarines in this application might be technically possible and cost-effective. The reasons for which such system has not been created are associated with social and natural environment including melting Arctic ice cover and concerns about safety of nuclear energy. Although it has not been used in cargo submarines, nuclear energy still can have its place in shipping industry during times of increased efforts aiming in greenhouse gases emission reduction.

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