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SUMMARY This report describes a review of various proposals for submarine transportation of Arctic resources. It also discusses the technical and economical aspects of such proposals in relation to more conventional transportation methods.

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THE FEASIBILITY OF SUBMARINE TRANSPORTATION OF ARCTIC RESOURCES

1. INTRODUCTION

Since the discovery of oil and gas in Prudhoe Bay in the late sixties, and the opening of a mine at Nanisivik on Baffin Island, NWT, in 1974 there have been several attempts to demonstrate the feasibility of shipping resources from the Arctic to markets in temperate climates. In 1969, the ice strengthened tanker 'Manhattan' negotiated the North-West passage. This was soon followed by the construction of the Trans-Alaska pipeline system (TAPS). In 1978 the 'Arctic' shipped ore southwards during the summer season. All these systems were extensions of conventional technology, but had some drawbacks when developed for Arctic use. The TAPS was five times more expensive to build than its estimates. It also raised objections from native groups who were concerned over disruptions to the environment. In 1977 the Berger commission placed a 10 year moratorium on the development of new pipeline systems in the Canadian Arctic. The pipeline also limits the market potential of Canadian crude oil, which is just as likely to end up in Europe or Japan rather than the lower 48 states of the USA.

If the pipeline is undesirable from economic and environmental considerations, the alternative must be some form of vessel system. Ships have operated in Arctic waters for many years, but so far there has only been one (MV Arctic) operating as a conventional transportation system in Canadian waters. There are several disadvantages to a surface ship system. Variations in ice features can cause speed fluctuations which can result in considerable disruption to a ship's schedule. There are also the environmental considerations of the broken channel left by the ship, which can disrupt traditional migration routes for animals and so effect the lifestyles of humans in the area.

One possible method of avoiding the surface ice is by travelling underneath it. Military submarines have operated, without any apparent difficulties, under the Arctic ice cap for many years, but so far there have been no attempts to develop submarine cargo systems beyond the feasibility study stages. There are good reasons why the use of submarine cargo ships is not more widespread. The difficulty is a fundamental problem of hydrodynamics. The resistance of a ship may be assumed to be made up of two components, one due to the viscosity of the fluid in contact with the body, and the other due to the movement of the fluid around the body. For a surface ship, this component also includes the force due to wavemaking at the free surface. The potential advantage of a submarine is the elimination of the wavemaking component of the resistance.

The ratio of the two resistance components, as fractions of the total is not constant throughout the speed range, and only at high speeds does the wavemaking resistance become significant. These speeds are typically outside the range of those considered economical for bulk cargos. The low speed performance of a submarine will be worse than that of the equivalent surface ship, since its wetted area is higher. The submarine is uncompetitive if operation in open water alone is considered. However, if the submarine can operate in circumstances which the surface ship cannot, there is the possibility that it could be economically competitive. Such a situation could be the shipping of resources from the Arctic. The purpose of this paper is to review the technical and economic considerations of this option when compared to the more conventional systems. In addition we must anticipate some of the regulations which may apply to submarine cargo ships, since they may have an effect on the operating economics.

2. PRINCIPLES OF SUBMARINE DESIGN

The design of a submarine is more complex than that of a surface ship. The principle of Archimedes states that a submarine must displace its own volume and mass of fluid in order to remain in equilibrium. The external volume of the submarine is constant, but the mass changes during a voyage as fuel and stores are consumed. The problem is further complicated by the thermal expansion or contraction of the cargo. To accommodate all these changes, the submarine must be capable of taking on and discharging ballast during the voyage.

Submarines operate at increased hydrostatic pressure relative to surface ships, due to the increased depth of water. The submarine structure must be designed to accommodate these extra loads, or it will collapse. The option taken by military submarines is to build a complete pressure hull, capable of withstanding the variation in hydrostatic loading over the operating range. This construction technique becomes very expensive as submarines increase in size since very thick high grade plates must be used.

If the pressure inside the submarine can be maintained at the same level as the external hydrostatic pressure, then the outer skin of the submarine simply becomes a membrane to contain the cargo. It can be built for a much lower cost than the pressure hull, since lower grade materials can be used. The type of cargo most suited to this approach is a liquid, since its internal pressure is naturally the same as the hydrostatic pressure, provided that the liquid fills the container. This concept can be modified slightly to provide pressure hulls inside the submarine for machinery and accommodation.

The other area which needs to be addressed is the design of a system to allow for a variable weight of the submarine or variable volume of the cargo. It is extremely unlikely that the submarine can make a round trip full of cargo in each direction. Therefore it must carry something, to maintain its neutral buoyancy. Most surface bulk carriers use sea water as ballast, since it is easily available, cheap and easy to dispose of at the end of the journey. This would also be the obvious choice for submarines. However, unless the cargo and the ballast had exactly the same densities and thermal expansion properties, it is necessary to provide empty spaces in the submarine to allow for these features. These spaces must be pressure hulls in order that they may operate partly full. The problem is greatly simplified for the designer if the cargo spaces can be used for carrying ballast, and the density of the cargo is close to that of sea water. The most effective cargo then becomes a liquid cargo, such as refined petroleum products, crude oil or methanol derived from liquified natural gas (LNG). Solid cargo would be extremely difficult to carry, since it would not withstand the hydrostatic pressure. Coal and ore could be carried in the form of a slurry, but it would require extra processing before loading. For a design to carry LNG there are additional problems, since ballast water cannot be carried in the cargo tanks. This means that the whole cargo and ballast system is built from pressure vessels, which would be expensive, or some other form of ballast must be used, which can be carried in the cargo tanks.

The most efficient hull structure for a submarine minimizes the use of expensive pressure vessel construction to those areas which are essential, and all other tanks are based on a membrane approach.

3. LITERATURE REVIEW

Work on the development of submarines began around the beginning of the 18th century. By the middle of the 19th century, the military submarine as we know it today had been born. Development of this type of ship has continued up to the present day and sizes have been greatly increased and propulsion units made more reliable. The largest submarines sailing belong to the USSR, and have a submerged displacement of approximately 25,000 tonnes. The role of the military submarine is well developed and the vessels are highly sophisticated in terms of control and navigation systems. They have also shown that nuclear power is a practical method of propelling submarines. However there has only been one submarine built with the intention of carrying cargo on a regular basis. The submarine, called 'Deutschland', was built in 1916 for carrying strategic goods for the Kaiser's war effort. The deadweight of this ship was only 700 tonnes. There are accounts of submarines carrying fuel oil in ballast tanks during the second world war, but again this was for strategic reasons, not commercial ones.

The earliest reference to cargo carrying nuclear powered submarines was given by Russo, Turner and Wood [1]. This paper presented a parametric study covering ship deadweights between 20,000 and 40,000 tonnes at operating speeds between 20 and 40 knots. This design was not developed for Arctic operation, and as discussed above this is not likely to be competitive with surface ships. The concept was designed to carry refined petroleum products from gasoline to bunker. The general structural design was based on the concept of minimizing the amount of pressure vessel construction within the hull. The hull form was of a rectangular cross section with a beam approximately twice the depth. This was chosen, despite the degradation of resistance relative to a square section, to allow access to existing ports and terminals.

As the development of Arctic resources became a realistic concept, the potential benefits of submarine transportation systems were realized, and the basic concept described above was modified to carry crude oil from Alaska to the Eastern Seaboard of the United States. This was described by Jacobsen [2], and the study looked at two basic sizes of submarines. The smaller submarine studied had a deadweight of 170,000 tonnes, and was considered to be the largest which could be built at that time. The larger submarine had a deadweight of 250,000 tonnes, and was considered to be the largest vessel which could safely navigate the North-West Passage fully submerged. The total transportation concept included a submarine loading dock, so that the submarine would never have to surface through the ice.

The basic design was extended again in 1975 [3], to an increased deadweight of 280,000 tonnes. Since the deadweight had been increased, it was no longer possible to use the North-West Passage, and so the only practical route was under the polar ice cap. This study was used by several authors for comparisons with surface tankers and pipelines [4, 5, 6]. The basic concept of the design was still the same as the original proposal, with minimum pressure hull construction, a beam to depth ratio of two, and a submarine loading dock. However, since the deadweight had been increased, the idea of a trans-shipment terminal was introduced. The location proposed was one of the Norwegian fijords, which had sheltered deep water, relatively free of ice and was therefore ideal for the construction of such a terminal. This concept minimized the route of the expensive submarine to just the section covered by ice. The remainder of the journey could be completed by a conventional surface tanker.

The concept was modified by Court, Kumm and O'Callaghan [7] to carry methanol derived from arctic natural gas. The methanol was processed on a floating barge system towed north and installed near the production site for the gas. The propulsion unit was changed from a nuclear powered steam turbine to a fuel cell. The ship size was reduced to a deadweight of 160,000 tonnes, but the route chosen remained under the polar ice cap, rather than using the North-West Passage. This gave the potential for diversifying into the european market as well as the United States.

Another version was given by Jacobsen and Murphy [8] where the design was modified for carrying liquified natural gas, with a non-nuclear power option. The propulsion system was fueled by methane or distilate fuel oil, but the final drive system was still a steam turbine. This reference also presented a design for a 180,000 tonne deadweight crude oil tanker, with the same propulsion unit option. The design had to be modified for the transportation of LNG since ballast water could no longer be carried in the cargo spaces. This meant the hull had to be fitted with extra pressurized ballast tanks, and was therefore less efficient than the crude oil carrier.

All the above references were derived from the initial work developed by Russo, Turner and Wood. The hull design was chosen to minimize the amount of pressure vessel construction, and hence capital costs. A midship section for this type of construction is shown in Figure 1 and a typical general arrangement in Figure 2. All of the references propose a submarine docking system for loading and unloading cargo, which is shown in Figure 3.

An alternative approach was taken by MacPhail [9] in his proposal for an LNG carrier. He suggested building the complete hull as a pressure vessel. This design left very little room for ballast tanks, and so he proposed using liquid nitrogen as ballast for the north-bound trip, which would be discharged at the northern terminal. The design was powered by a gas turbine modified to burn the boil-off from the LNG. In the paper, MacPhail presents two hull options. One is a conventional submarine and the other is a barge for cargo transportation, pushed by a removable propulsion unit, which could be transferred between barges.

The original work performed by Russo et al [1], included some model experiments to establish the basic propulsive performance of the design. Although the models used were small, the results should be useful in preliminary design. A range of hull form proportions were considered, with breadth to depth ratios varying from 1.0 to 2.5. This study showed that there was little change in form drag once the breadth to depth ratio was greater than 1.5. However, the ratio was constrained to be 2.0, so that the draught was not too great to enter conventional ports. These proportions were then used exclusively by all the other references, with the exception of MacPhail, who took the optimum solution for minimum resistance, which was a body of revolution. Spencer [10] removed the draught restriction on the form given by Russo et al, and found that the optimum resistance was always with a beam to draught ratio of 1.0. It appears that the penalty of a higher form resistance is more than compensated for by minimizing the wetted area for a given displacement. Table 1 shows a comparison of the principal dimensions of each of the submarine proposals, together with the largest military submarines currently sailing.

4. TECHNICAL EVALUATION

4.1 Hull Structure Design

Having reviewed the various proposals, we may now consider what options have the most chance of successful application, given these considerations, and potential legislation which may affect the concept. As we have discussed, the most probable application of a submarine cargo vessel will be for liquid cargos, such as crude oil or methanol. The hull structure is reasonably efficient provided that ballast water can be carried in the cargo tanks. This was the approach taken by Russo et al, and with one exception, has been generally adopted as the most feasible method. However, since that proposal was prepared, the IMO introduced legislation concerning the segregation of ballast from cargo tanks for all tankers with deadweights greater than 20,000 tonnes. It also requires the ships to have double skins, to minimize the risk of cargo spillage if the outer hull is damaged.

Although the IMO regulations do not apply specifically to submarines, it is reasonable to assume that submarine construction would not be allowed to go ahead without meeting at least the spirit of the regulations. The basic concept of the membrane hull could be extended to allow for a double skin, but it would of course have to be full of sea water for both load and ballast conditions. If the requirement for ballast segregation was taken literally, it would probably kill the submarine concept before it started. Since the densities of, say, crude oil and water are within a few percent of each other, the volume of the cargo tanks and ballast tanks would be similar. This means that the volume of the submarine with segregated ballast would be approximately twice that of the submarine with unsegregated ballast. This has the extra disadvantage that all these tanks must be pressurized, so that they can be run partly full to maintain neutral buoyancy in all conditions. The surface ship avoids this problem by running at a reduced draft in the ballast condition with virtually no degradation in performance.

The most likely solution to this dilema is to convince the legislators that the submarine could be safely operated with a ballast water treatment plant at the northern terminal. The ballast water would be cleaned and oil residue removed, before clean water was disposed of. Several of the later authors [8, 9, 10] make allowances for the double skin in the general arrangements, but only Spencer makes any allowance for the treatment of the ballast.

The other regulation which apply to ships operating in the Canadian Arctic are the Canadian Arctic Pollution Prevention Regulations (CASPPR). These regulations cover such aspects of ship design as installed power, shell plating strength, and navigation and safety systems. Again these regulations are not formulated for submarines, and in this case most of the problems encountered by surface ships are avoided. It is likely that the legislation would be updated to cover hull strengths for emergency surfacing in ice covered water or grounding situations where the submarine accidentally sits on the bottom. Other areas are likely to be crew evacuation and safety systems, especially if the submarine was nuclear powered.

4.2 Main Machinery Arrangement

It is unlikely that existing fossil fuel burning systems could be adapted for use in large submarines. There are two problems with such systems. The first is the requirement for oxygen to support the combustion of the fuel, and the second is the disposal of the products of combustion. The first is solved by carrying quantities of liquid oxygen in addition to the fuel. Although valuable cargo capacity is lost, it is technically feasible and relatively easy to implement. The second problem is potentially more difficult. Exhaust gases cannot be disposed of without compressing them to greater than the hydrostatic pressure. Since this pressure is very high the compression system is a large capital investment. One alternative to compression is cleaning systems, which would overcome combustion products and allow the exhaust gases to be recycled. Another option would be to dissolve the exhaust products in water which could then be discharged easily. Some work has been done on both these options, but again extra capital investment is required for the treatment equipment.

The one option of submarine propulsion which has demonstrated that it can operate completely submerged for extended periods is the nuclear powered steam turbine. This type of unit first came into operation in the mid-fifties, and soon demonstrated that it could be used for under ice operation. The first submarine to sail under the Arctic ice cap was the USS Nautilus in 1957. Such units could easily be supplied to provide the power requirements for large cargo carrying submarines, even allowing for the other demands on the system, such as accommodation, ballast handling pumps and other ship systems. Although most of the operational data for such ships is based on military applications, where there is considerable secrecy, there appears to be a reasonable safety record for such systems.

Although nuclear powered submarines have demonstrated that they can operate for long periods under water, there is a growing reaction against them from environmental considerations. The fuel cell is one system which shows potential for solving some of the problems of submarine propulsion without using nuclear power. The fuel cell is a device similar to the lead acid battery, but with the fundamental difference that it does not need recharging by electro-mechanical methods. Instead, the system is based on a chemical reaction. The reactants are hydrogen at the anode and oxygen at the cathode. The system is recharged by replacing the oxygen at the anode on a continuous basis, and the products of the reaction are DC electric power, water and heat. Phosphoric acid is used as an electrolyte and hydrogen is provided from a fuel source, either directly or from a hydrogen rich gas such as methane. The oxygen is provided directly. The dimensions of such a system are similar to those of the equivalent nuclear powered system, and therefore suitable for use in submarines. Although this system has only been developed on a small scale there are several potential advantages for submarine systems. The products of reaction are easy to dispose of, unlike fossil fuel burning systems. In addition the system lends itself to small scale experimentation more readily than nuclear power, and so would be more suitable for pilot projects. Possible disadvantages are the need to carry two potentially hazardous fuels, both of which are highly flammable. The development needed to realize such a system is described by Court et al.

5. TERMINAL DESIGN AND ROUTE SELECTION

There are two proven sources of oil in the Canadian Arctic. Firstly there is the Beaufort Sea, and secondly there is the Sverdrup Basin, where natural gas has been the main find to date, but significant oil reserves have been identified. In addition, seismic surveys of Lancaster Sound and Baffin Bay look promising for future development. The indications are that the three fields of the Beaufort Sea are the most likely for initial development. There are three major markets for Canadian oil. The domestic North American market would mostly likely be served with an east coast terminal in Canada or the United States. The European market could be serviced from Rotterdam. The other likely market is Japan, who, with no natural resources of its own, is looking for politically stable sources of oil and gas. The Beaufort Sea is approximately the geographic centre of these three markets, with distances of approximately 3700 nautical miles to each one.

The North American ports have relatively shallow water, approximately 12m, and this would be too shallow for submarines and large surface ships. One option to solve this problem would be to use a single point mooring in deep water offshore. The vessel could tie up to the point, either a gravity based tower or a floating buoy, to discharge cargo. The European and Japanese ports have very deep water, and so access directly to the port would be possible, but only in surface operation. If the route of the expensive submarine or icebreaker was to be limited to the northern section, and the journey completed in conventional surface tanker, the requirement to include a trans-shipment terminal would have to be considered.

The selection of the appropriate terminal type is important to the overall operability of the transportation system. Since the development of Arctic resources is a very recent idea, there are no existing terminal facilities for surface ships or submarines. It would be necessary to construct the appropriate facility for either system. To maximize efficiency, as much construction as possible would probably be done in temperate regions and the prefabricated units would be towed to the final erection site. It is important to review the design alternatives for the various terminal options to see which would be the most feasible.

In order to avoid the complex control systems needed to maintain neutral buoyancy when loading or discharging cargo, it is preferable to design the submarine with positive or negative buoyancy for this condition. The options then become either a surface system or a submerged system. A submarine system for the Arctic terminal has the advantage of never having to surface the submarine through the ice sheet. In addition, it maintains the local climate, which would be effected by the presence of quantities of open water. It also means that the amount of reinforcing of the submarine hull is minimized, which is desirable when using the 'soft' hull option. However, there are some considerations which work against the submarine docking system. Not least is the one of manoeuvring such a large submarine into a specific location underwater. The inertia of such a vessel is considerable, and docking procedures would have to be initiated up to 35 km away from the site. A sophisticated network of sonar sensors linked to the ships control system would be needed to direct the submarine onto its dock. Since any failure of this system could be catastrophic, there would have to be fail-safe back-up systems with high levels of redundancy.

The cost of the submarine and surface terminal options may not be greatly different. As discussed above the submarine tanker would not be effective unless it could carry cargo in ballast tanks. It would therefore need some facilities at the terminal for cleaning and storing dirty ballast water to meet IMO regulations for ballast discharge. The surface ship option would however, need to be equipped with larger storage tanks than the submarine system, since the probability of the tanker not being able to get to the dock would be higher. Similar considerations would have to be made for the unloading or trans-shipment port at the southern end. Since this is likely to be in ice-free water some of the above considerations are irrelevant. If conventional terminals could be adapted to submarine cargo ships there could be some potential cost savings. However, since these ports are usually very busy, it would be necessary to surface a long way from the terminal to avoid collisions. In addition, if a submarine loading system was used at the northern end, it would mean the added complication of having the ship negatively buoyant at the northern end, and positively buoyant at the southern end.

There are several factors which must be considered when selecting the route for the submarine. The submarine must have adequate water depth for safe navigation. It is important to consider both the clearance between the keel of the vessel and the ocean floor and the clearance between the top of the submarine and the bottom of the ice cover including pressure ridges. A reasonable clearance in each direction would be one hull depth, making the minimum hull water depth between the bottom of the ice and the ocean floor three hull depths. This may be too small to avoid the effects of the boundaries on the fluid, and so the preferred water depth would be up to seven hull depths, for the majority of the route.

If we take this depth of water, we find that two possible routes from the Arctic are not feasible for submarines. There is insufficient water depth in the North-West Passage and the Bering

Strait for the safe operation of submarines. This leaves the only possible route to be under the polar ice cap. So the shipping of Arctic oil to Japan by submarine is not likely to be economical, simply because of the geography. As already discussed it would not be easy to provide submarine access to conventional ports, and so a dedicated deep water trans-shipment terminal would have to be considered. There are two possible locations for such a terminal. One is in Trinity Bay, Newfoundland, and the other is Bodo, Norway. Both ports have very deep water, are sheltered, and relatively ice free. The trans-shipment terminal could be surface or submerged, depending on what option was chosen for the northern terminal.

Other considerations for the route can be related to social, environmental and economic factors. The route should create as little disturbance as possible to the delicate arctic environment, and especially breeding grounds for animals and fish. Busy shipping lanes and areas of offshore activity should be avoided, and so should areas of high iceberg concentration. All of these factors indicate that a route under the polar ice cap to Norway, or around Greenland to Newfoundland are the most suitable for submarines.

The discussion above relates entirely to the technical aspects of the design of a submarine transportation system. It appears that the system is feasible, allowing for a reasonable extrapolation of existing technology. However, there is only one practical route for a submarine tanker, and that is directly under the polar ice cap, as shown in Figure 4.

6. ECONOMIC EVALUATION

Having determined that a submarine transportation system is technically feasible, we must now review its operating economics in relation to the surface ship and pipeline options. The initial work by Russo et al [1] did not make any attempt at an economic evaluation. There was some discussion when the paper was presented, which indicated that the submarine option would be up to 4.5 times more expensive than the equivalent surface tanker. It is important to remember that this was not based on Arctic operation, and so the surface tankers were only to normal specification. In addition, it was before the IMO legislation was introduced, and so the tanker construction costs would be lower than the equivalent IMO tanker today.

Jacobsen [2] compares his two submarine proposals with an icebreaking surface tanker, of 250,000 tonnes deadweight. Although there were only two submarines and one icebreaker, the study presented the required freight rates for a range of acquisition cost and ship speed for each case. In general the acquisition cost of the submarine option was more than twice the cost of the surface ice-breaker. However, if the surface tanker could not average a speed of more than six knots, the submarine option should have a lower transportation cost. If the surface tanker can maintain an average speed of between 6 and 10 knots the two systems are comparable. It is difficult to establish absolute values, since no details of the economic evaluation are given. Also, no allowance is made for the capital cost of the terminals at either end of the route.

The basic design prepared in [3] was used for three seperate comparisons with alternative transportation methods. Taylor and Montgomery [4] compare the submarine tanker, using either a direct route to the Eastern Seaboard or trans-shipment in Norway, with an icebreaking tanker and a pipeline. The icebreaking tanker uses either a direct route through the North-West Passage, or trans-shipping to conventional tankers in Greenland or Iceland. The pipeline options are either trans-Alaska with tankers to the eastern seaboard, or trans-Canada directly to the east coast. The results showed that even though the capital cost was approximately twice that of the surface ship, the required freight rate for the submarine system was comparable to the icebreaking tanker. If we use the icebreaker as the standard, for both ships going direct, the submarine option was 17% higher than the surface ship. If trans-shipment was used, the submarine was 8% lower. The pipeline is considered to be up to 55% higher than the best surface ship option. The same information was presented by Montgomery and Jordan [5], but with the addition of a mobile trans-shipment terminal. This shortened the route of the submarine, and reduced the required freight rate of the submarine to 16% below the surface icebreaking tanker.

Several surface ship options were compared with the submarine system by German, Macphearson, Meakin and Parker [6], for carrying crude oil or methanol from the Beaufort Sea to the Eastern Seaboard. The surface ship options were divided into two basic categories. The first consists of Class 3 tankers loading in the Beaufort Sea, and travelling westward through the Bering Strait. These then had the option of trans-shipping at the Unimak Pass, lightering into vessels capable of going through the Panama Canal, or going around Cape Horn, to ports on the Eastern Seaboard. The second option was to use Class 8 tankers through the North-West Passage, directly to the Eastern Seabord, or trans-shipping in Greenland. The submarine option was as described above in [4]. The surface ship sizes were varied from 60,000 to 400,000 tonnes deadweight for the crude oil option. The methanol option assumed that the ships would be the same size, but the deadweight range would be reduced to 54,000 to 360,000 tonnes. The results showed that the required freight rate for the submarine and the Class 3 icebreakers were comparable if the cargo was crude oil. The Class 8 tankers were slightly more expensive, by about 20%. If the cargo was methanol, the submarine was approximately 12% more expensive than the best Class 3 tanker but the submarine and the Class 8 tanker had similar required freight rates. Another option was considered for the surface tanker, and that was LNG carriers of the same classification on the same routes. This was not compared with the submarine since these authors did not consider it economical to ship LNG by submarine. The ship sizes for LNG varied between 75,000 and 175,000 cubic metres. The surface ship route options are shown in Figures 5 and 6.

The analysis of the methanol carrying tanker given by Court et al, using the polar route and trans-shipping in Norway, concludes that it is more economical to ship by submarine than by surface ship. It also considers it to be more economical to ship methanol from the Arctic by submarine than by conventional tanker from the Persian Gulf. The rider to the study is that it is only economical to ship the methanol by submarine if it is used as an automobile fuel or additive, based on the cost of gasoline at the time of the study. There are however, substantial reserves of natural gas in southern Canada and the United States, which could also be processed for automobile fuel. Although not covered by the study, intuitively one feels it would be cheaper to produce methanol from these sources rather than from Arctic gas. In addition, it concludes that shipping LNG directly would not be cost effective.

The results of the economic analyses generally agree that shipping of Arctic crude oil or methanol by submarine is comparable with the icebreaking tanker, but it shows no significant advantage. It is also accepted that the acquisition cost of a submarine is much higher than a surface ship of equivalent deadweight. There is some contradictory evidence, for example the transportation of methanol, but even in that case neither system appeared to have a significant advantage over the other. Neither of the proposals for the shipping of LNG by submarine directly [8, 9] include an economic analysis, but other authors [6, 7] state that it would not be economically viable when compared to other technical options. It is difficult to make a full review of the economics, since very little data is given in the references, but it is hoped that the relative comparisons within a given reference are not biased in favour of one system or another. The one independant study available was given by Spencer, and this also indicated that the submarine system had a lower required freight rate for the transportation of crude oil than surface icebreaker.

7. THE FUTURE OF SUBMARINES FOR ARCTIC TRANSPORTATION

It appears that the Arctic submarine is technically feasible given the current state of the art of the major ship systems, and there is evidence to indicate that it could be at least as economical a transportation system as the surface icebreaker. The final question to ask is, will it be accepted by the industry as a reasonable alternative to existing systems? The transportation of natural resources from the Arctic by submarine represents a new concept in transportation systems. It is also a complete departure from techniques which have evolved from the shipping industry, such as ice breaking bulk carriers or pipelines. These systems have demonstrated that they are able to operate in the Arctic environment. The economic evaluation of the concept suggests that to be competitive with surface ships, the submarine must have a submerged volume at least ten times larger than the largest submarine built to date. Since this step is so large, it would be more likely that an uneconomic pilot project would be built to develop the design, construction, and operating techniques on a smaller scale.

Even a pilot project could experience some difficulties. The reduced size may simplify hull construction, but the selection of propulsion unit may pose some problems. The only propulsion unit which has demonstrated that it can operate in a polar environment under water is the nuclear powered steam turbine. The disadvantage of such a unit is that it is not economical for small scale operation, since its capital cost per unit of power is much higher than the equivalent non-nuclear system. The fuel cell system may be preferred since the environmental risk is smaller, and it would be easier to produce a small scale unit, but more development work would have to be done in order to provide a functioning system of the powers required. An existing military system of nuclear power could be used, but this would not provide the required power output, unless the pilot project was for a very small design, or a substantial loss of speed was accepted.

The submarine system is a very inflexible system. The requirement to maintain neutral bouyancy means that the hull structure, cargo type and ballast arrangement must be very carefully tuned. This means that it is difficult to change cargo type, even between different liquids such as crude oil and methanol. In addition there is only one practical route out of the Arctic ocean which can be guaranteed to have sufficient water depths for all ice conditions, and that is directly under the polar ice cap. An icebreaking bulk carrier however, if built to the appropriate ice class, could navigate any of several routes out of the Arctic ocean, and if necessary, it could also carry several cargos. The M.V. Arctic was recently converted from a dry bulk carrier to a combined oil and bulk cargo carrier. The surface icebreaker could carry a wide variety of equipment on deck which would resupply northern social and industrial requirements. This would be extremely difficult to incorporate into a submarine design.

The economic evaluation of the submarine concept is based entirely on estimates. None of the studies published are beyond the feasibility stage, and so detail design work still has to be done. The TAPS when finally completed cost approximately five times the original estimates, but now there is expertise and experience in that field. Similarly for the icebreaking tanker, there is a certain amount of experience, based on supply boats, government icebreakers and one bulk carrier. There is no actual data for the construction costs of a submarine cargo ship together with the terminal and trans-shipment ports. It is likely that there will be unforeseen complications and costs, which could well make the submarine system less competitive than the surface ship.

Given all the above considerations, it is extremely unlikely that a submarine system would be used in the initial development of Arctic resources. The system could be more efficient than a surface system, but it is unlikely that any company would take a risk with so much unproven technology until the development of the Arctic is more established. Perhaps the best hope for the submarine lies with the legislators. The advantage of the submarine is that it can operate without disturbing the surface ice. Any disruptions to the surface ice conditions could permanently change factors such as breeding grounds for wildlife and hunting and transportation patterns for Inuit. If legislation was passed to prevent the disturbance of the Arctic environment, then the submarine would be the system with the least disruption to the delicate Arctic infra-structure.

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TABLE 1

PRINCIPAL DIMENSIONS OF SUBMARINE PROPOSALS

REFERENCE	CARGO CAPACITY	CARGO TYPE	LENGTH (m)	BEAM (m)	DEPTH (m)	SUBMERGED VOLUME (m^3)	INSTALLED POWER (kw)
Typhoon Class (USSR)	-	-	170.0	23.0	11.5	24,500	60,000
Ohio Class (USA)	-	-	170.7	12.8	10.8	18,200	45,000
[1]	20,000 DWT	P	170.0	24.0	12.2	46,000	14,000
[1]	40,000 DWT	P	216.4	36.6	12.2	79,000	53,300
[2]	170,000 DWT	C	274.0	42.7	26.8	248,000	101,000
[2]	250,000 DWT	C	310.0	52.0	28.5	361,000	101,000
[3]	278,000 DWT	C	304.8	54.9	29.0	414,000	84,000
[7]	160,000 DWT	M	260.0	46.6	24.7	260,000	160,000
[8]	180,000 DWT	C	311.0	51.8	24.7	368,000	74,500
[8]	140,000m^3	LNG	448.0	74.3	28.6	721,000	74,500
[9]	52,000m^3	LNG	213.4	24.4	24.4	83,000	15,000
[10]	440,000 DWT	C	335.0	50.0	50.0	714,000	112,000

CARGO TYPE - C: Crude Oil
LNG: Liquified Natural Gas
M: Methanol
P: Petroleum Products

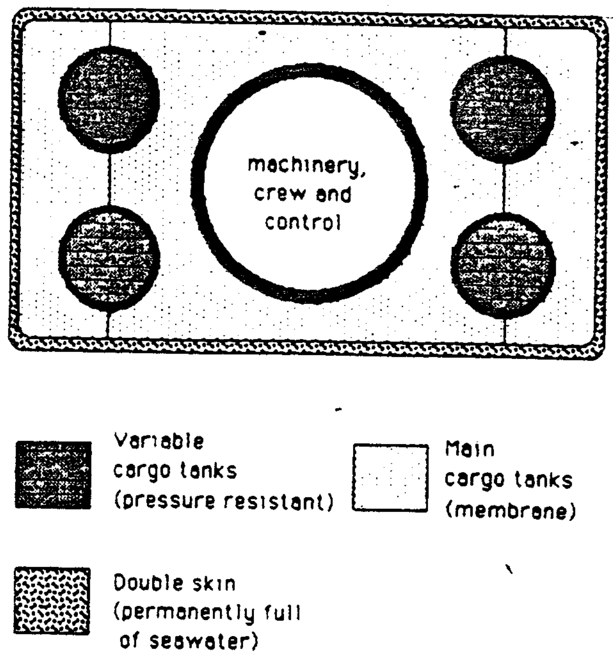

Figure 1

Midship Section Through Membrane Type Submarine

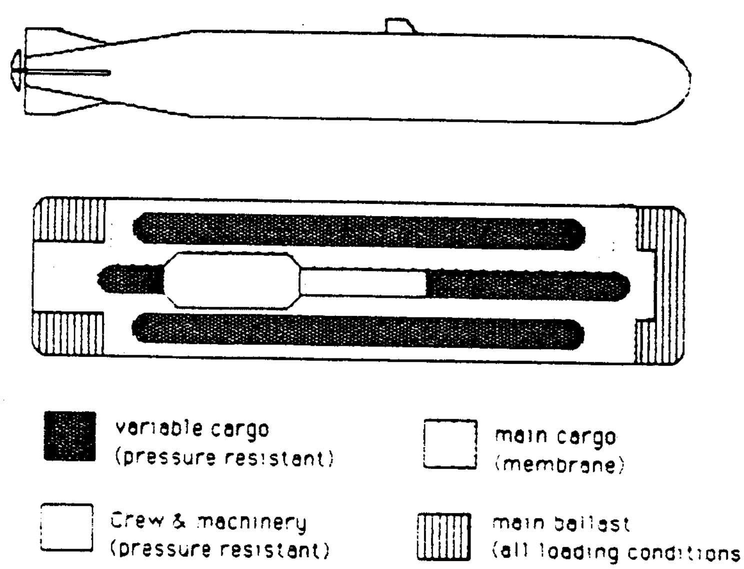

Figure 2

General Arrangement - Membrane Construction

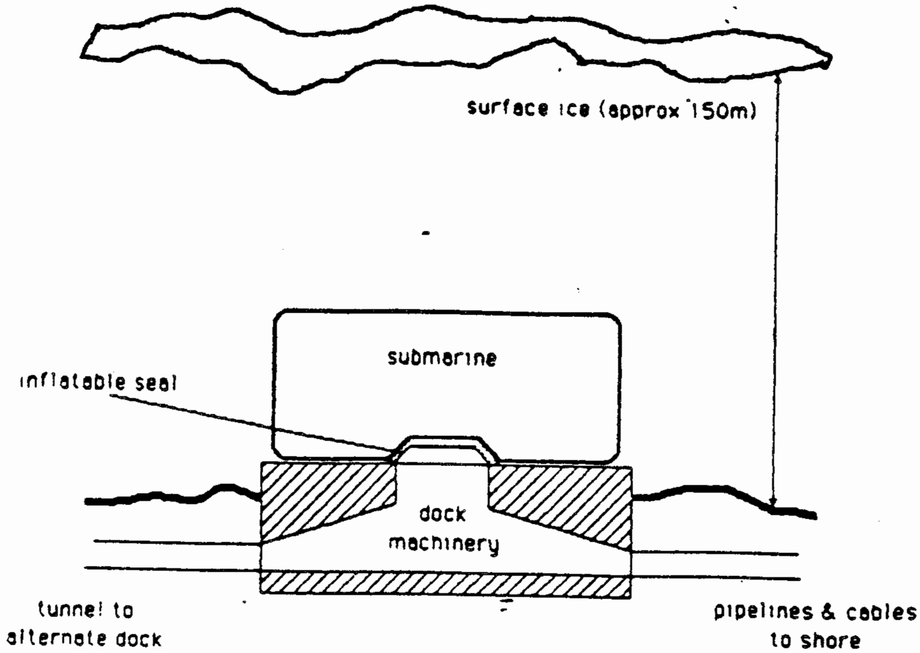

Figure 3

Submarine Docking Arrangement

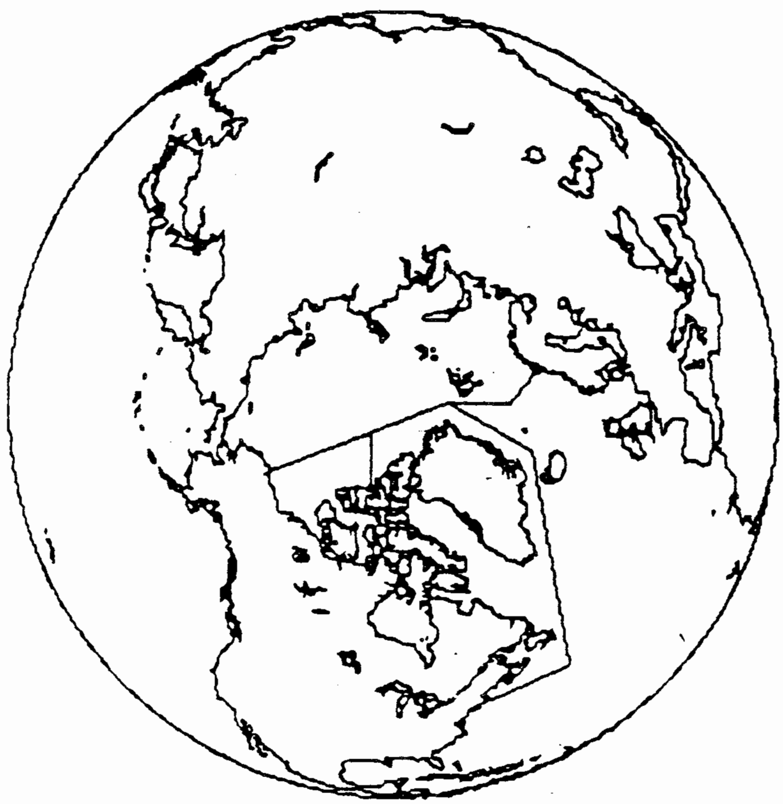

Figure 4

Routes for submarine tankers

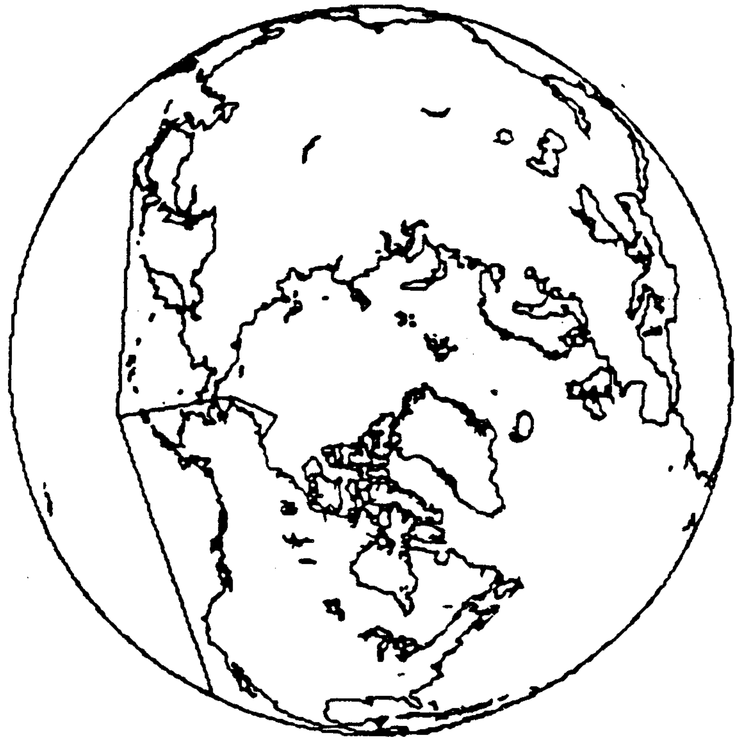

Figure 5

Routes for Class 3 tankers

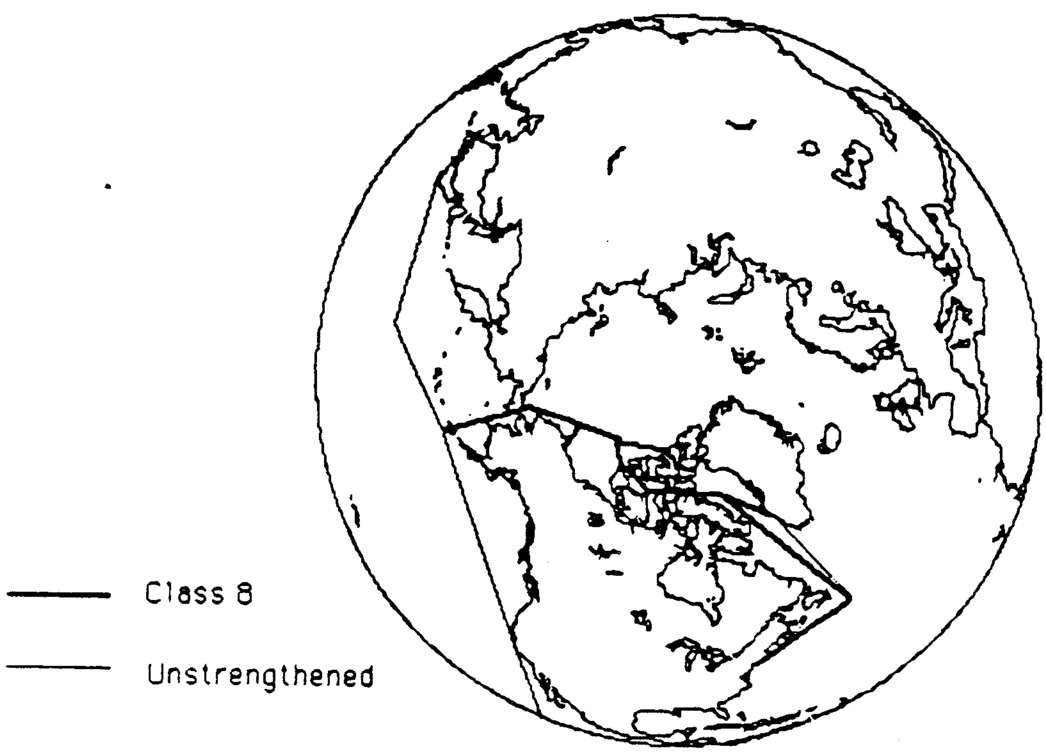

Figure 6

Routes for combination of Class 8 and Unstrengthened tankers