Submarine Cargo Vessels

Opportunities for Future Transport

A dissertation
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The strategic importance of submarines from a defence perspective is generally well understood by the public and notwithstanding the secrecy surrounding their activities, they have featured in numerous newspaper articles, magazines and books. In August 1958, the world's first nuclear powered submarine *Nautilus* traversed the North Pole under the Arctic ice. Just seven months later, the *Skate* surfaced precisely at the North Pole. These remarkable achievements brought dramatically into focus the new-found capability of submarines powered by marine nuclear reactors, and for the first time, translated the autonomous submarine of Jules Verne's science fiction, into science fact.

What is not well known or understood is the use of underwater vessels to carry cargo either in a strategic military role, or in a purely commercial one. To that end, a number of proposals, business cases, and studies have been conducted over the years claiming the economic and strategic benefits of using submarines for that purpose.

In order to put this question into context, maritime shipping in its simplest form consists of transporting goods and services from A to B by the most economical route at the least possible cost. Therefore, any measures that would produce either a feasible route, a shorter route, or a more cost-effective route are all worthy of study. In the last two decades, energy savings in the maritime transport sector both from an economic and an environmental point of view have become more apparent and have taken on greater significance.

In terms of energy efficiency, true submarines for example can take advantage of routes which are not available to surface vessels, such as below the Arctic icecap. It is conservatively estimated, that such a route could reduce the passage time between Japan and Europe by more than twelve days. Also, submarines could feasibly be used on routes in the Baltic and parts of the Black Sea, North Russia and Alaska and other areas that are perennially ice-bound.

This dissertation provides a general historical outline of this aspect of submarine use for carrying cargo and looks critically at this mode of transport in contrast to conventional surface vessels.

Keywords:

Arctic, cargo, carrying, energy, fuel cell, history, icebreaker, icecap, North Pole, nuclear, oil, propulsion, ship, submersible, semi-submersible, submarine, surface, transport, underwater, vessel

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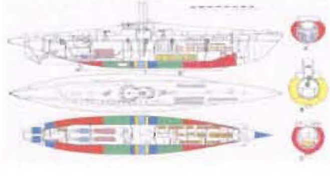	**Fig. 6. Type XIV 1940(D) U-Boat in its logistic support role, showing cargo-carrying compartments.** The XIV supplied fuel to other submarines and was thus called a "milk cow."	Heiszwolf plans. http://www.heiszwolf.com/subs/plans/plans.html	6
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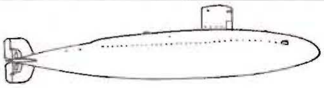	**Fig. 9. Showing the outline and basic details of *Albacore*.**	Burcher, R., & Rydill L; 1994 *Concepts in Submarine Design* p. 19.	8
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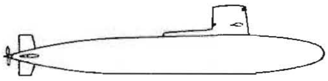	**Fig. 10. Showing the outline and basic details of *Skipjack*.**	Burcher, R., & Rydill L; 1994 *Concepts in Submarine Design* p. 20.	9
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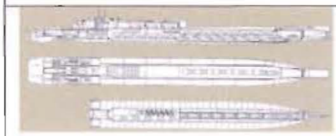	**Fig. 12. Project 621: Landing Ship Transport (LST) Submarine.** Shows the elevation and general arrangement plan and cargo distribution.	Graphic by A.D. Baker III, from Cold War Submarines. In article Soviet Giants.	12
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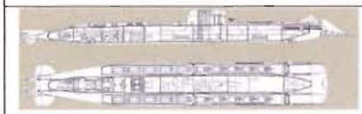	**Fig. 14. Project 748, Submarine LST.** Shows the elevation and general arrangement plan and cargo distribution.	Graphic by AD Baker III, from Cold War Submarines. In article Soviet Giants.	14
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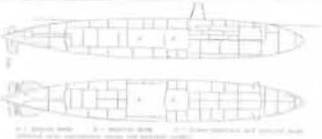
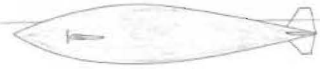
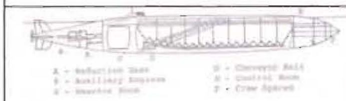
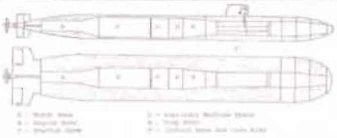
	**Fig. 16. Nuclear Powered Submarine Oil Tanker. Design by Shigemitsu, 1958.** From a paper presented to the 2nd U.N. International Conference on the Peaceful uses of Atomic Energy, June 1958	Shigemtsu M. *Nuclear Powered Submarine Tanker*: June 1958, p.26.	19
	**Fig. 17. Goro Sato's concept submarine oil tanker design: 1959.** Sketch shows, a hydrodynamic shape with control fins and stub propellers.	Goro Sato 1959. *Transport submarines with non-water pressure hull of new principle* (Tokyo) p.1	20
	**Fig. 18. Submarine Ore Carrier (Saunders-Roe), 1958.** Designed by Crewe & Hardy for Saunders-Roe Co. Ltd. in 1958.	Crewe PR & Hardy DJ; 1962 *RINA Paper No. 196221* p.6.	21
	**Fig. 19. The Russo, Turner & Wood, Submarine Tanker 1960, (S5-N-MA48a).** A concept Submarine tanker design.	Russo VL, Turner H & Wood FW 1960. Paper, *Submarine Tankers*.	22

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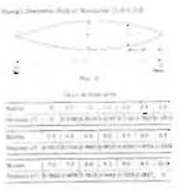
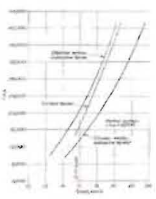
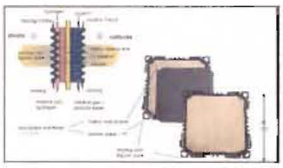
	**Fig. 21. Young's Body of Revolution.** Young's streamlined body of revolution (0, 0.5,0.2) with a table of ordinates. Taken from. ARC Technical Report, R & M, No. 2204.	Young AD & Young E 1945. *A Family of Streamlined Bodies of Revolution Suitable for High-Speed or Low Drag Requirements*	30
	**Fig. 22. Teasdale's Analysis.** Teasdale's 1959 comparative analysis of a surface vessel, a circular form submarine and an elliptical form submarine showing power requirement against speed	Teasdale J A 1959. *Characteristics & Performance of Nuclear Powered Submarine Cargo Vessels.* Institute of Marine Engineers, London.	32
	**Fig. 23. Fuel cell features & schematic.** Shows schematic and design features of a Siemens Proton exchange membrane fuel cell (PEMFC). From a Paper presented at Advanced Naval Propulsion Symposium 2006, October 30, Arlington, VA, USA.	Siemens AG, Erlangen Hammerschmidt A E 2006. *Fuel Cell Propulsion of Submarines.* www.siemens.com/marine	37
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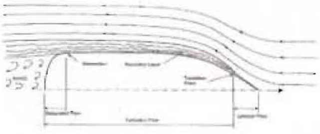
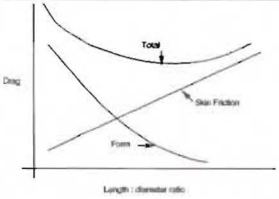
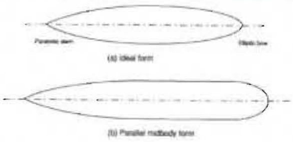
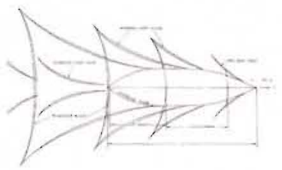
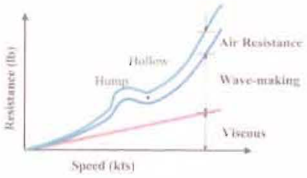
	**Fig. 1. Appendix (02). Showing fluid flows & resistances to motion.**	US Naval Academy of Naval Architecture and Ocean Engineering: Course notes 7.5-7.6 Resistance to motion.	3
	**Fig. 3. Appendix (02). Drag components for a constant volume form.** A diagram taken from a book by Burcher R & Rydill L; Concepts in submarine design.	*Concepts in Submarine Design.* Cambridge, Cambridge University Press, January 28, 1994. ISBN: 0521416817. p. 105.	4
	**Figs. 4a & 4b. Appendix (02). Ideal and parallel mid-body hydrodynamic forms.**	As above. p. 106.	4
	**Fig. 5. Appendix (02). Wave systems generated by vessels on the surface.** Diagram shows the wave train made up transverse and divergent wave systems.	Gillmer T C & Johnson B 1982. *Introduction to Naval Architecture.* Annapolis, MD, Naval Institute Press, 1982. Third printing, 1987. ISBN: 0870213180. p.20.	7
	**Fig. 7. Appendix (02). Components of resistance versus speed.**	Hornyak T 2003. US Naval Academy of Naval Architecture and Ocean Engineering: Course notes 7.5-7.6 Resistance to motion.	11

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1. INTRODUCTION

1.1 About Submarines

Submarines are actually one of a subset of underwater vessels. Therefore, in the interests of clarity it would be useful to explain that this set broadly contains three sub-types: namely submersibles; semi-submersibles; and submarines, all of which are capable of carrying some measure of cargo, however defined.

1.2 Submersibles

Submersibles are a type of underwater vessel with limited mobility, which is typically transported to its area of operation by a surface vessel upon which it relies for support (refer Fig. 1)[1]. The technical difference between a submersible and a submarine is that submersibles are not completely autonomous. Most submersibles operate with an "umbilical" or "tether" connecting it to the control centre onboard the surface vessel, which provides electrical power and communication to the submersible. Normally, these small, unmanned remotely operated vehicles (ROV's) are commonly equipped with lights, multi-axis thrusters, video cameras, electronic sensors and manipulator arms, which enable them to carry out a multiplicity of tasks such as the replacement of valves or junction boxes. ROV's are widely used in the offshore oil and telecommunication industries, in water that is too deep, or too dangerous for divers. Alternatively, ROV's can simply be used where a stable platform is required to carry heavier technical equipment such as ploughs, or high-pressure water jets used to bury fibre optic cables in the seabed, for example.

Fig. 1: Submersible ROV.

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[1] Refer Fig. 1. A remotely operated vehicle (ROV) showing a multi-function, manipulating arm about one metre long picking up a piece of cord to demonstrate it's dexterity. Source: Roper Resources Ltd, (www.roperresources.com)

1.3 Semi-submersibles

A semi-submersible is by definition a vessel that can put much of its volume underwater; unlike a submarine, such a vessel is never entirely underwater. The most common form of this vessel type is of course the floating dry dock used to repair and maintain ships.

Over the years, a number of concept vessels have been proposed in which the main body of the vessel is fully submerged but with a narrow dorsal vestigial portion of the hull rising above the surface supporting the navigation console, air plenum and engine exhausts. The main claim is that the presentation of a small streamlined pylon-like structure at the surface is less susceptible to waves and offers both high efficiency and operation in high seas.

Another type of semi-submersible is the heavy lift, or deck ship.

It has a long, low, flat well deck contained between a forward bridge area and an after machinery space. In outward appearance it looks very similar to a bulk carrier or some forms of oil tanker.

Fig. 2: Semi-submersible heavy lift ship.

Its ballast tanks can be flooded to submerge the well-deck below the water, allowing oil platforms or other floating cargo to be moved into position for loading. The tanks are then pumped out which causes the well-deck to rise above the surface, which in doing so, lifts and supports the load. In that regard, it operates on exactly the same principle as the floating dry-dock. Such a ship became widely publicised in 2004, when the *Blue Marlin*[2] was used by the US Navy to transport the guided missile destroyer *Cole* to the United States after the warship was damaged in a bombing attack in Aden on October 12 of that year. The same year the *Blue Marlin* carried the world's largest oil platform the *BP Thurso* from a shipyard in Korea to a shipyard in Corpus Christi, Texas. A different type of semi-submersible is found in the offshore drilling industry. The Shell Oil Company's Bruce Collip invented the semi-sub drilling rig in 1961, (refer Fig. 3). At that time

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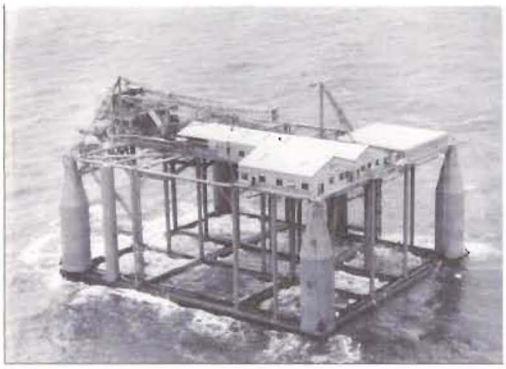
[2] Refer Fig. 2. *MV Blue Marlin* transporting the Destroyer *USS Cole*. Source: US Navy photo by PH2 Leland Comer photo gallery. (www.globalsecurity.org/military/systems/ship/flo-flo.htm)

Fig. 3: Semi-sub *Blue Water*



when drilling was moving into ever-deeper waters in the Gulf of Mexico the traditional jack-up drill rigs that were being used had reached the limit of their design in providing a stable drilling platform. Instead, semi-submersible platforms were being increasingly used which could be completely flooded to rest upon the seabed. The rig consisted usually of a drilling platform, together with accommodation, ancillary machinery and storage space supported on four vertical hollow pontoons capable of being variably ballasted[3]. As the pontoons had insufficient buoyancy to support the total weight of the rig, it was towed between locations at half draught. During these tows it was noticed that at that draught the drill platform was extremely stable due to the motions being damped out by the pontoons. It was decided that the rig was sufficiently stable to be used in floating mode. Today, semi-sub drill rigs are purpose built and can be located on site either by ground anchors or by their own propellers in conjunction with Global Positioning System (GPS) dynamic positioning.

1.4 Submarines

In contrast, submarines are by definition capable of completely submerging below the surface of the water and operating autonomously at depth for a protracted period of time. Although submarines have been used predominantly for military purposes, some have in fact been built specifically for the carriage of cargo. However, many submarine cargo ships only exist as design concepts, or at the project planning stage of a larger programme, or as patents conceived in the fertile, inventive minds of those persons claiming the value of such vessels. Most have never been built, due mainly to economic rather than technical constraints. Whatever their provenance, it is in this area of endeavour, to which we now turn our attention.

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[3] Refer Fig. 3. *Blue Water Rig No. 1* owned by the Blue Water Drilling Company USA. In 1961 this drilling rig was the first to be used as a semi-sub drilling platform in the Gulf of Mexico. Source: Courtesy of Friede & Goldman Ltd (www.fng.com).

2. A BRIEF HISTORY OF CARGO-CARRYING SUBMARINES

2.1 Germany, WWI & WWII 1914 –1945, The Blockade Runners

Shortly after the outbreak of the First World War, the British Royal Navy in conjunction with the other Entente Powers commenced the blockade of German seaports in order to cut off supplies of munitions and other logistic materials necessary for the German War effort. However, the blockade, whether initially intended or not, prevented German manufacturers acquiring other raw materials necessary for the general economy. It also dislocated German exports to other countries, particularly the United States of America, with whom Germany had up to then enjoyed a robust trading relationship.

In 1916, a private shipping company was created named Deutsche Ozean-Reederie; a subsidiary of what is now called Hapag Lloyd, in conjunction with the Deutsche Bank. The purpose of the new company was to build and operate cargo-carrying submarines, with the intention of trading in high value raw materials between the United States and Germany, while at the same time avoiding British patrols. The first mercantile submarine named *Deutschland* was built at Bremen in 1916 (refer Fig. 4). It had a cargo capacity of about 700 tons; most of which was capable of being carried outside the main pressure hull. It had a length of 66 metres and could travel at 15 knots on the surface and 7 knots while submerged. Its crew consisted of four officers and 25 ratings. It was commanded by a merchant ship captain who had previously been in command of transatlantic liners operated by Nord German Lloyd (Colorants History Organisation 2005. *Submarine Deutschland.*) & (The New York Times 1916. *The Deutschland eluded foe with $10,000,000 cargo*).

Fig. 4: *Deutschland* arrival, Baltimore Harbour, July 1916. Source: Port of Baltimore archives.

On its first trip to the United States, the submarine, having passed undetected through the English Channel, arrived safely in Baltimore on the 10 July 1916 with 163 tons of cargo comprised of medicinals, gemstones and 125 tons of chemical dyes (refer Fig. 5). These dyes were extremely expensive, reflecting both their high concentration and the high demand by the US textile industry. To give an example of its value at today's prices, the chemical dye "Indanthrene Violet RR" would probably retail at about US$2800 per kilogram (The Cargo of the submarine *Deutschland*, J. Chem. Soc., Vol. XXXV, No. 23, Dec15 1916, p 1202).

The return journey from the United States was equally uneventful, arriving at Bremerhaven on 25 August 1916 with 348 tons of rubber, 341 tons of nickel and 93 tons of tin; which provided several months supply to the German war industry. In total, the submarine had travelled 8,450 nautical miles of which 190 were submerged. The profit from the voyage netted 17.5 million Reichsmark, more than four times the building cost of the submarine.

A second journey in October-December of 1916 to New London, Connecticut was equally profitable, once again trading in gems, medicinals and securities and returning with rubber, nickel, alloys and tin. A third journey, planned for the January of 1917 was aborted after the United States entered the war against Germany.

Fig. 5: Unloading at New London, 1916. Source: Nova

A second submarine the *Bremen*, a sister ship to the *Deutschland* was launched on its first journey in the August of 1916 but failed to arrive in the US. Its fate is still debateable; although one possibility is that it might have hit a mine off the Orkney Islands. Six other similar submarines were in the process of being built when the United States entered the War with the result that further construction was either halted, or the hulls converted into submarine cruisers fitted with deck artillery used to fight when surfaced. The *Deutschland* was converted into the submarine cruiser *U-153* that successfully managed to sink 43 allied vessels by the end of the war. In December 1918 it was taken to England as a war trophy and was scrapped finally in 1921 (National Alumni 1923. *Records of the Great War, Vol. IV, Ed. Charles F. Horne*).

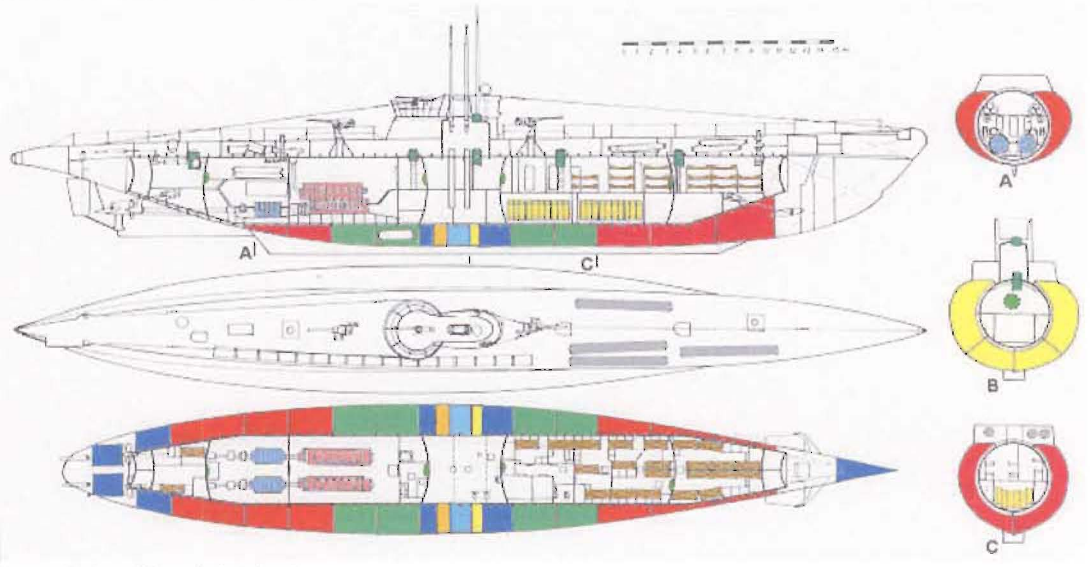
In 1916, a book about the journeys of the *Deutschland* authored by Paul Koenig, its first captain, was heavily publicised on both sides of the Atlantic with the express intention of swaying public opinion towards the idea that the submarine had a purely commercial non-combatant status. Apart from the obvious propaganda dimension, the notion probably had some merit when seen in the context of other military style U-Boats that were busily sinking allied shipping, particularly those in transit from the United States to Britain.

During World War II, the German Navy used cargo-carrying submarines nicknamed "milchkühe (milk cows)" as supply vessels. In early 1942, Admiral Dönitz began launching specially designed tanker submarines. These type XIV submarines had a surface displacement of 1668 tons, a length of 67 metres and a beam of 9.35 metres. They had an extended range of 12,350 nautical miles at 10 knots when surfaced and were capable of a maximum speed of 14.9 knots on the surface and 6.2 knots while submerged.

The primary purpose of these submarines was to refuel and act as logistic support for the U-Boat fleets in the Atlantic Ocean. Each submarine was able to carry 400 tons of diesel fuel. By the effective use of these submarine supply depots, the German Navy was able to double the at-sea periods of U-Boats. "Milk cows" provided, food, spare parts, torpedoes, medical needs, and even crew rotations. The boats were also equipped with bakeries in order to provide fresh bread for crews being resupplied (Rossler E. 2001 *The U-Boat - the evolution and technical history of German submarines*).

Acting only in an auxiliary support role these vessels were nonetheless part of the German Navy Kriegsmarine. They were manned by service personnel and were equipped with light armaments such as anti-aircraft guns. These submarines did not actively engage in commercial trade as such, but had large amounts of available cargo space compared to normal submarines of the day. As can be seen from the sketch of a typical Type XIV (refer Fig. 6) the coloured areas show cargo compartments, most of which are distributed outside the pressure hull.

Fig. 6: Type XIV U-Boat in its logistic support role – showing cargo-carrying compartments.



Source: heiszwolf.com/subs/plans/plans.

Ten submarines of this type were commissioned and were found generally to be successful. However, in 1943 the Royal Navy began equipping their ships and aircraft with newer radars, which operated on frequencies outside the bandwidth of the German warning receivers allowing them to surprise U-Boats on the surface.

The result of U-Boat losses in the Atlantic persuaded Dönitz to postpone building fourteen more Type XIV vessels and abandon the development of larger Type XX transport submarines which if built would not have been ready until the summer of 1945 (Wikipedia 2007 *German Type XIV Submarine.*).

2.2 The United States of America – The Nuclear Submarines

Nautilus, Skate, Albacore & Skipjack - "Underway on Nuclear Power"

In the early 1950's the initiative for submarine development passed to the United States. This resulted in two major developments in the field of submarine design, which effectively removed the logistical limitations imposed by an inability to remain submerged for any length of time, coupled with the inability to travel underwater at high speed. In doing so, these developments opened up new strategic roles for submarines. Apart from the military strategic benefits, it allowed for the first time the total freedom for submarines to operate in; and if required, under, perennially ice bound waters, and other areas normally denied to surface vessels. Also, for the first time, this freedom of action extended the notion of cargo carrying submarines beyond that of blockade running, or logistic military support, to the idea that the carriage of general cargo by submarines could actually be a commercial reality.

The first of these breakthrough developments was air-independent nuclear propulsion. For nearly half a century the vast majority of submarines were powered by a diesel electric system. Their range was limited by the amounts of fuel they could carry; they could remain submerged for as long as the batteries lasted, and their electric motors could operate only at slow speeds.

In 1951, engineers from the US Navy and the Atomic Energy Commission began work on a nuclear pressurised water reactor power plant, for installation into a conventional submarine hull. In January 1955, the *Nautilus* was commissioned as the world's first nuclear submarine (refer Fig. 7). Nuclear power quickly became the primary form of propulsion for United States submarines, as the reactor does not require air; eliminates the reliance on batteries; and can provide almost unlimited amounts of power on demand. When coupled with air purifying "scrubbers", nuclear power enables the submarine to remain submerged for protracted periods. In fact, modern nuclear submarines will run out of food before they run out of air, or power. The *Nautilus* travelled nearly half a million nautical miles during sea service, including in 1958 the epic first voyage underneath the North Pole. Decommissioned in 1980, *Nautilus* was named a national historic landmark and is now a museum in Groton, Connecticut, where she was built.

In August 1958, the *Skate* became the second vessel to pass under the North Pole. In March 1959, a time of the year when the Arctic pack ice is at its thickest, the *Skate* in a 12 day 3000 mile voyage forced its way through the ice 10 times including at the North Pole itself, (refer Fig. 8) (CNN 2001. *Underway on nuclear power*).

Fig. 7: *Nautilus* on trials 1955.

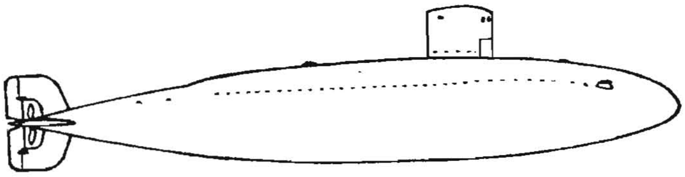
Source: US Navy National Archive.

Fig. 8: *Skate* at the North Pole 1959.

Source US Navy National Archive.

The second breakthrough development in the early 1950's was the result of research work undertaken by the US Navy at the David Taylor Model Basin on a radically new shape of submarine, that led to the design and construction of an experimental battery drive submarine called the *Albacore* (refer Fig. 9). Not a lot has been published about the *Albacore* except that Arentzen and Mandel give a full account of the "teardrop" form that contributed to the primary goal of the design: achievement of high propulsive efficiency to maximise submerged performance at the expense of surface capabilities (Arentzen E S & Mandel P 1960: *Naval Architecture Aspects of Submarine Design*). Figure 9 helps to illustrate how that goal was achieved by the use of an axisymmetric solid of revolution form of relatively small 7:1 length to diameter ratio; a large diameter screw propeller located on the main axis, running at low rpm; a small bridge fin and superstructure; and a drastic reduction in the number of holes and appendages in the external structure.

Fig. 9: The *Albacore*.



Surfaced Displacement: 1500 Tons / Length: 64.16m
Submerged Displacement: 1850 Tons / Beam: 8.38m
Surfaced Speed: 25 Knots Submerged Speed: 33 Knots

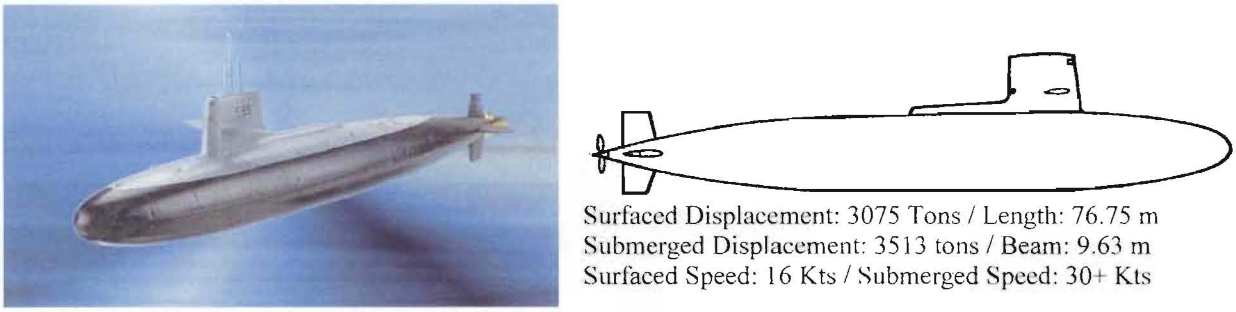
Source: New Hampshire Library.

Source: Burcher R & Rydill L 1994. *Concepts in Submarine Design* p 19.

The parallel development paths represented by the *Nautilus* and the *Albacore* were both seminal and imaginative in the development of the modern submarine. The *Nautilus* demonstrated how the pressurised water reactor (PWR) stood up to service at sea, while the main purpose of the *Albacore* was to demonstrate that a submarine of unique shape, although with some disadvantages for surface performance, could nevertheless be acceptable operationally because of its greatly improved submerged performance and superior manoeuvrability. Both submarines were capable of high speed: *Nautilus* for prolonged periods; and *Albacore* in short bursts (but sufficient for test purposes).

However, when the innovations of both submarines were combined in the *Skipjack* (refer Fig. 10), which entered service in 1958 as the first of the SSN585 class, it produced a formidable synergy of power and submerged performance (Burcher & Rydill 1994). The Skipjack class of vessels has provided navies worldwide with a design template that is now used in practically all modern military submarines and by extension, would provide an adequate basis for the design of cargo carrying submarines, certainly in terms of propulsive efficiency, hull shape, powering and endurance.

Fig. 10: *Skipjack* SSN585– Artists impression.



Surfaced Displacement: 3075 Tons / Length: 76.75 m
Submerged Displacement: 3513 tons / Beam: 9.63 m
Surfaced Speed: 16 Kts / Submerged Speed: 30+ Kts

Source: Revell models.

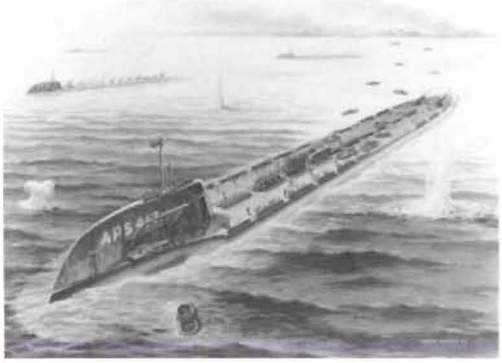
Source: Burcher R & Rydill L 1994. *Concepts in Submarine Design* p.20.

American design efforts – Landing Ship Transports (LST)

In the mid 1950's the United States Navy undertook some preliminary sketches of submarine landing ship transports partly as a reaction to the knowledge that the USSR were developing LST's for logistic support. However, they never pursued the concept to the same extent as the Soviet design bureaux.

A concept design for a Submarine LST was developed for an article produced in *Mechanix Illustrated* magazine in 1955, as presented to the Navy Department (refer Fig. 11). This was a 10,000-ton submarine, 720 feet long with a beam of 124 feet that could carry 2,240 marines, landing them by *"amphibious flying platforms"* (Polmar N 1987. *The First Soviet Giants* Article in US Navy Magazine issue 13; 1987).

Fig. 11: Artists Impression of a 10,000-ton submarine LST.



Graphic Source: Artists impression by Frank Tinsley for Mechanix Illustrated Magazine.

Conclusions

From the foregoing, it seems clear that cargo-carrying submarines are both feasible and economical, providing the cargo is of low volume and high value. It could equally be argued, that low volume, high value cargoes are also economical for surface vessels. What then remains for submarine transport, would be its strategic value, which when seen against a background of world conflict and dwindling natural resources may well become the final determinant for their use. However, what was significant then, and what will certainly be seen as significant in the future, by both the public and their respective Governments will be the issues surrounding nuclear propulsion, and more importantly, how the submarine's military/commercial role will be defined from both legal and geopolitical perspectives.

2.3 USSR (The Soviet Union)

Overview

From the early 1940's, to the final collapse of the USSR in 1991, the Soviet Navy encouraged its submarine design bureaux to develop submarines specifically for troop and cargo transportation. While many of these submarine transport concepts were not pursued to completion, it nevertheless provides us with a fascinating insight into the technical challenges met and the strategic thought inherent in this type of submarine design. The fact that these submarines, had they been built, would have been used for military logistic support does not detract from their cargo carrying ability, which could quite well have been used commercially if the circumstances had presented themselves.

World War II and after

Early in the Second World War, the Soviet Union effectively used submarines to supply the besieged Crimean port of Sevastopol. In 1941, the Soviet defences in the Crimea collapsed leaving 110,000 soldiers, sailors and marines isolated in the fortified port area of the city. Due to heavy losses in surface ships, which were supplying munitions and supplies to the city, the commander of the Black Sea Fleet in early 1942 ordered the use of submarines to evacuate wounded troops, what remained of the civilian population, and to re-supply food and munitions to the cities defenders.

The largest of the Soviet submarines (Series XIII "L" Class) was used, as they were able to carry up to 95 tons of cargo. Empty torpedo tubes and mine chutes were also filled with cargo. In all, some 80 runs were made to Sevastopol by 27 submarines, delivering over 4000 tonnes of munitions and supplies, and safely evacuating 1,300 persons. In spite of this effort, Sevastopol fell in July 1942 after a siege of eight months (Polmar N 1987).

1943 - Project 607

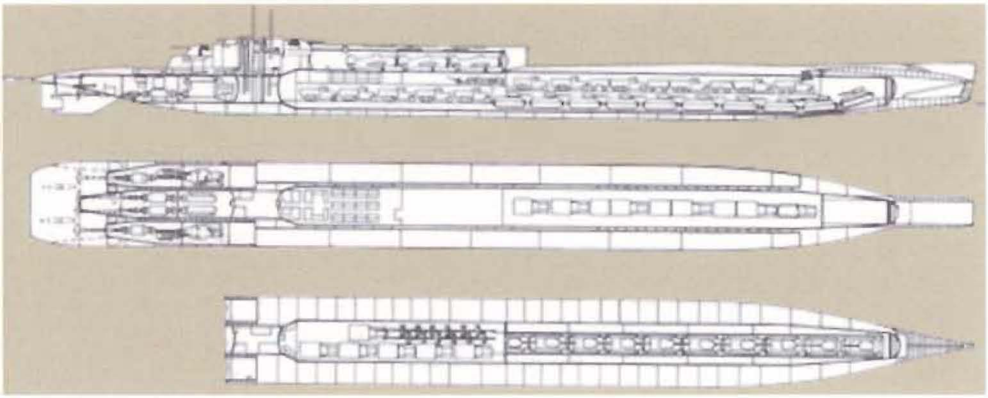
Based on the Sevastopol experience, the Soviet Navy commenced an urgent programme to build transport submarines. In July 1942 Project 607 was initiated for the design of a submarine with a capacity of 300 tonnes of solid cargo. It could also carry 110 tonnes of gasoline in four ballast tanks. Additionally, two cranes were fitted to load and discharge the cargo. In order to make use of existing design technology and to simplify construction, an expanded version of earlier VI and VI-bis submarines were used as a template. By April 1943 blueprints were issued to start construction, but by that time the military tide had turned in the favour of the Soviets, and although no technical or operational problems were envisioned in the design, underwater transports were no longer thought necessary and Project 607 was cancelled (Polmar N & Moore K J 2003. *Cold war submarines: The design and construction of US and Soviet submarines*).

While it is true that the Soviet Union did not build any Project 607 submarines, the concept of cargo transport still occupied the thoughts of Soviet naval architects and there is some evidence to support the idea that Soviet design bureaux may have actually considered ocean-going cargo submarines in the mid 1940's. According to the memoirs of the United States ambassador to the USSR, Admiral WH Standley when discussing with Stalin the problems of supplying materiel for the Soviet war effort, Stalin is quoted as saying, *"Why don't you build cargo submarines? Cargo submarines could cross the ocean without interference from Nazi submarines and could deliver their supplies directly to our own ports without danger of being sunk."* Admiral Standley responded that he was *"sure that the question of building cargo submarines has received consideration in my country."* Stalin replied, *"I'm having the question of cargo submarines investigated over here"* (Polmar N 1987).

1948 - Project 621

In 1948, the Soviet design bureau TsKB-16, now a commercial private enterprise called Rubin, developed a design proposal for Project 621, which is illustrated in Fig. 12. This was conceived as a large landing ship transport (LST) submarine with a surface displacement of nearly 6,000 tonnes, whose specific purpose was to carry out landings behind enemy lines. It was furnished with two main vehicle decks and a separate hangar for aircraft situated above the main deck. In total, it could carry a battalion of 800 troops; 10 T-34 tanks; 12 trucks; 12 towed cannon, and three La-5 fighter aircraft. The troops and vehicles could be loaded and discharged through watertight doors over purpose-built bow ramps. The aircraft could be catapulted, with the launching device fitted into the deck forward of the aircraft hangar. Both conventional diesel-electric and steam-gas turbine (closed-cycle) power plants for both surface and submerged operation were considered for this project.

Fig. 12: Project 621, Landing Ship Transport (LST) Submarine.



Graphic by A.D. Baker III, from Cold War Submarines

The Cold War Period

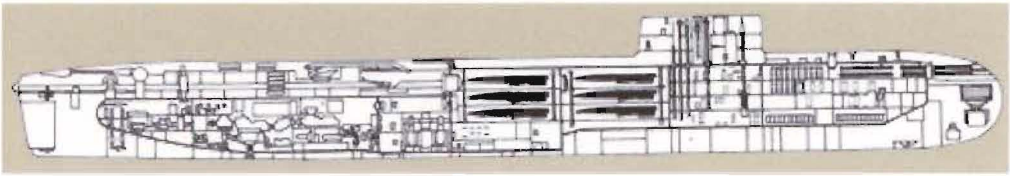
1958 - Project 648

In early 1958, the Soviet design bureau TsKB-18 now a privatised enterprise called Volna/Malakhit, proposed a design concept for a replenishment vessel to be built at the Severodvinsk shipyard in the Arctic. The design combined the same concepts that had been successfully developed by the German Navy for their "milk cow" submarines, coupled with mine-laying capability. The submarine's primary role would be to replenish and re-arm submarines attacking allied shipping. Weapons and stores were to be transferred at sea and diesel fuel was to be transferred while both submarines were submerged. The Sevastopol experience also influenced the capability to include the transport for 120 troops and their weapons, or to evacuate 150 wounded personnel. In addition to the rearmament in cruise missiles and torpedoes, the vessel was capable of carrying 34 tonnes of food, 60 tonnes of drinking water, and 1000 tonnes of diesel or aviation fuel. In July 1958 a section of the hull was fabricated containing the specialised fuel transfer system. The overall project was complex and was temporarily shelved in favour of the large-series orders for nuclear submarines, which required yard space. The emphasis towards nuclear propulsion combined with the difficulties in replenishing submarines at sea led to the eventual cancellation of Project 648 in favour of a more ambitious Project 664, described next (Polmar & Moore 2003).

1961 - Project 664

The design for Project 664, as illustrated below in Fig. 13, combined the characteristics of a submarine LST with a replenishment submarine, and would have nuclear propulsion. It would be a much larger submarine than those before it with a surface displacement of 10,150 tonnes. It would carry, for the use of other combat submarines, 20 cruise missiles and 240 torpedoes of varying types. Liquid cargo would include 1,000 tonnes of diesel or aviation fuel; 60 tonnes of lubricating oil; 75 tonnes of drinking water; and 35 tonnes of food. In its LST role, the submarine would carry 500 troops. In 1964, construction commenced at the Severodvinsk yard. In 1965, the project was halted to make way at the yard for the accelerated construction of nuclear powered strategic missile-carrying (Yankee Class) submarines. Although a proposal was made to transfer the project to a Leningrad shipyard, for reasons that are unclear, it did not eventuate.

Fig. 13: Project 664 – Submarine LST.



Graphic by A.D. Baker III, from Cold War Submarines

What is clear is that the priority at the time was focussed on the development of nuclear ballistic missile submarines. In spite of this, interest in cargo carrying logistic submarines was still supported at the highest levels of the Soviet Navy. In 1961 Admiral Yuri Pantaleyev writing in the military journal *"Voennaya Mysl"*[4] about the future technical development of submarines, calls for *"A class of special submarine tankers and submarine transports for the shipment of combat supplies, equipments and contingents of personnel"* and *"for a system of supply; and for a system for all types of underwater supply, for submarines lying on the bottom at points of dispersal and at definite depths and not moving"* (Polmar N 1987). Accordingly, in 1965 a design specification was issued by the Soviet Navy to the Volna /Malakhit bureau for the development of a new type of cargo carrying, submarine transport (Polmar & Moore 2003).

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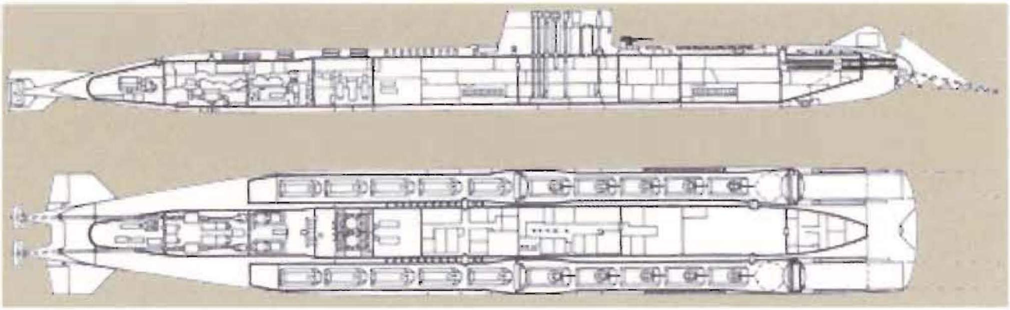
[4] Soviet Subs, *Voennaya Mysl (Military Thought)* is the senior classified Soviet military journal.

1965 - Project 748

The initial design specification for Project 748 required a large diesel electric submarine LST but the design bureau, realising the limitations of conventional propulsion, opted for a number of nuclear powered variants with surface displacements from 8,000 to 11,000 tonnes. These were contained within three separate pressure hulls mounted side by side, encased in a single outer hull. The largest variant, as shown in Fig. 14 below, had the capacity for 20 amphibious tanks and armoured personnel carriers and up to 1,200 troops and equipment. Load and discharge was to be effected through watertight doors that opened onto two electro-hydraulic operated bow ramps. The variant recommended by the design bureau was for the submarine to be powered by two OK-300 reactor plants generating 30,000 shaft horsepower.

Fig. 14: Project 748, Submarine LST.



Source: Graphic by A.D. Baker III, from Cold War Submarines.

Unfortunately construction was stalled because the Navy, the Ministry of Shipbuilding Industry and the General Staff of the Armed Forces ordered a review of all the features contained in Projects 648, 664 and 748 with a view to developing a "universal" all-capable nuclear submarine (Polmar & Moore 2003).

1971 – 1973 - Project 717

As a result of the review, the Volna/Malakhit design bureau was tasked with the development of a preliminary design for a submarine capable of carrying 800 marines, four armoured vehicles, the transport of arms, munitions fuel and provisions including 20 amphibious tanks and personnel carriers. At the time, this was to be the largest submarine yet designed with a surface displacement of 17,600 tonnes. The preliminary design effort was completed in 1969, but owing to changes and additions to the design specification by the Navy, the project was delayed until October 1971.

The Severodvinsk shipyard made preparations for constructing five submarines to this final design specification. Full-scale mock-ups were made of the control room, cargo spaces and other portions of the submarine. However this project too was cancelled when in the late 1970's because the available building docks at Severodvinsk were again needed for the construction of nuclear submarines, particularly the Project 941 *Typhoon* ballistic missile submarines that were being developed as a response to the United States *Trident D5* programme (Polmar 1987).

The cancellation of Project 717 brought to an end the design of large mine laying/transport/replenishment submarines in the Soviet Union. In spite of that, some interest was still being shown in submarine tankers. In the 1960's, Rubin undertook the design of a large submarine tanker intended primarily for commercial operation. It was to have a displacement of 24,750 tonnes and powered by two VM-4 nuclear reactors. In 1973, another attempt was made by Volna to design a nuclear propelled submarine tanker, but neither of these projects got past the design stage (Polmar & Moore 2003).

Conclusion

What is evident from the Soviet Navy's experience with military submarines is that their engineers had been successful in resolving most of the technological challenges presented for the construction of large cargo-carrying submarines; and, provided that designers were adequately resourced, enough technical expertise was readily available to convert those designs into reality.

In essence, the only real difference between a military and a commercial submarine would be its payload. What is less clear is the commercial and economic viability of such vessels. In this respect, some of those economic questions were about to be addressed by design bureaux in the post cold-war climate of the new Russian Confederation of Independent States.

Russia Post Cold War (CIS)

Overview

In early 1990's, Soviet Naval bureaux were transformed into stand-alone private enterprises designed to take the advantage of the new prosperity and economic opportunities offered in a post cold-war Russia. However, the economic reality was somewhat different. Design bureaux and their shipyards, which formerly had been heavily subsidised from central government funding, found themselves without assignments and what little work that was available from naval repair and maintenance work, received either slow or no payment at all.

In this atmosphere of diminishing funds, the naval part of the military industrial complex sought non-traditional ways to survive.

1991 to date - Project 941 & its commercial variants

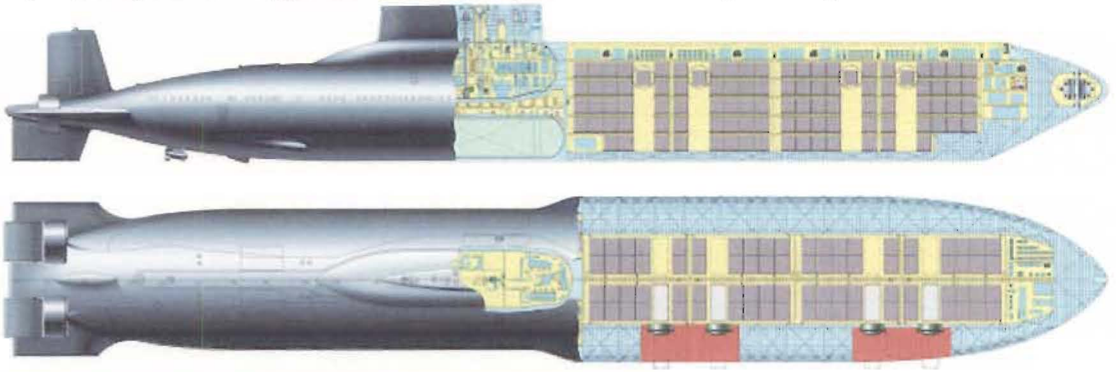
In this new economic climate, the St. Petersburg design bureau Rubin rightly concluded that any new projects would require considerable capital investment for submarine design and construction. More importantly, from a transport and logistics perspective the creation of innovative infrastructure at the ports of load and discharge would probably be required. Based on research studies, Rubin proposed concepts, which focussed on the most cost-efficient method of constructing a cargo-transporting submarine. In this regard, special attention was given to the utilisation of existing nuclear missile submarines that were currently being decommissioned by the Russian Navy. Rubin concluded, that that the most rational solution was to convert the redundant missile bays of their largest *Typhoon* submarine either with container cells, or by dividing the space into a hold for the carriage of liquid or solid cargo. An illustration of the *Typhoon* container variant is shown in Fig. 15 (The Rubin Central Design Bureau for Marine Engineering; St Petersburg; 2001).

In the same context, the St. Petersburg design bureau Malakhit, which held several patents for submarine tankers and containerships, put forward a preliminary design for a cargo submarine by re-constructing a *Typhoon* class submarine into an underwater tanker with a service speed of 20 knots. The length of the hull was to be increased from 175 to 238 metres yielding a freight carrying capacity of 30,000 tonnes of petroleum, which could be loaded and discharged at either surface or underwater terminals. The reconstruction was to be performed in the Sevmash yard in Severodvinsk at a cost of US$210 million. The container variant was designed to carry 912 standard (20 foot) TEU's loaded in 30 hours through 4.5 metre diameter side hatches, assisted by an internal conveyance system (Kudrik Forseth R & I; 1997 *Civilian use of nuclear powered subs:* The Bellona Foundation).

The rationale and the economic driver for all these developments was to enable high value cargoes such as nickel concentrate (currently priced at about US$11,000 per tonne), or liquid gas found in abundance in northern Russia, to be transported beneath the arctic ice as a viable alternative to an existing transportation system, based on nuclear icebreaker technology. It was envisaged that these submarine transports would also dive under the polar icecap to travel directly between Far East and European ports and possibly Canada. The designers noted that: *"Given equal cargo capacity; the efficiency of an underwater container ship is* *considerably higher, for example, than that of an icebreaker transport ship of the Norilsk type"*, and in the same circumstances *"the underwater tanker is competitive"* (Polmar 1987).

In the 1990's, the Russian company Norilsk Nickel, the world's largest producer of nickel with annual profits in excess of 1 billion US dollars, proposed to rebuild *Typhoon* class nuclear submarines into cargo vessels, for the transport of metal concentrate from the port of Dudinka in the Siberian Arctic to Murmansk. The plan was to load the submarine with 12,000 tonnes of nickel and sail it 560 kilometres north of the Yenesei River to the Kara Sea, turning south for the 1700 kilometre voyage to the ice-free port of Murmansk on the Kola peninsular; where the cargo could be transferred to conventional ships.

Fig. 15: Project 941 – *"Typhoon"* conversion plan for the carriage of freight containers.



Built: Severodvinsk, Russia 1981
Length: 175m **Beam:** 24m **Draft:** 12.5m
Displacement: On Surface 24,500 tonnes
Submerged 48,000 tonnes
Cargo capacity: 15,000 tonnes

Machinery: Two Nuclear Pressurised water reactors with steam turbines driving two shrouded 7 blade screws; 90,000 shaft horsepower
Speed: Surfaced: 2-3 knots
(With solid ice cover up to 2.6 metres)
Submerged 27 knots

Source: US Navy & Rubin Central design bureau

The idea was shelved, when the Finnish designers at Aker Arctic Technology Inc. developed a conventionally powered ice-breaking cargo vessel based on the patented double acting ship concept. Since 2005, these vessels purpose built for MMC Norilsk Nickel Inc. have replaced the ageing SA-15 type "Norilsk" ships formerly used for the last twenty years; details of which, are given in Appendix (01).

Conclusion

There are clear indications that the use of nuclear submarine propulsion technology for the transport of cargo could be viable economically, reducing passage times by two to three times, and offering a cheaper alternative to the use of nuclear ice breakers or nuclear powered surface transports during the high arctic winter. However, all of these plans came to nothing in the financial hard straits, which followed the dissolution of the Soviet Union as it made the difficult transition towards a more modern economy.

3. DESIGN STUDIES & PROPOSALS FOR SUBMARINE TRANSPORT OPTIONS (1958-1990)

3.1 Overview

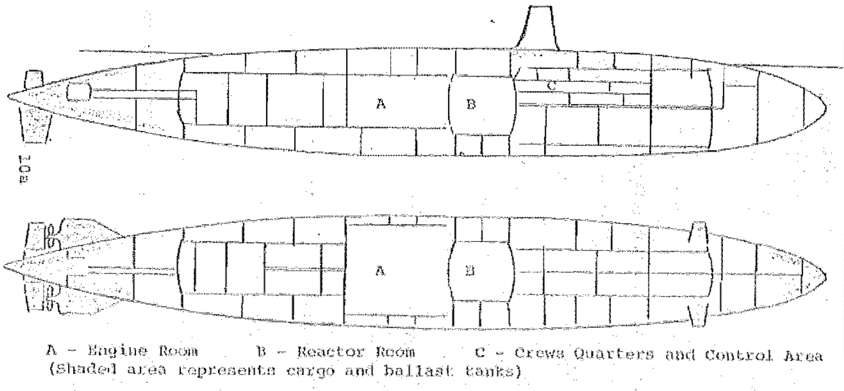
During the late 1950's, there was a great deal of interest worldwide in the use of nuclear power for non-military applications. In 1958, many of these new ideas coalesced at the Second United Nations International Conference on the Peaceful uses of Atomic Energy. At that conference, the enormous potential for using nuclear power plant for cargo transport became increasingly clear. Therefore it was not surprising that that a number of studies were initiated about this time, particularly by the larger maritime-oriented nations. Selected design studies and general proposals for submarine transport options are briefly reviewed below.

3.2 Shigemitsu 1958

Michiya Shigemitsu conducted one of the first of these studies, when employed as a design engineer for Kobe Shipyard and Engine Works; a subsidiary of Mitsubishi Heavy Industries Ltd. The study was published for the Second United Nations International Conference on the Peaceful Uses of Atomic Energy in July 1958.

The study focussed on the engineering and design feasibility of nuclear powered cargo-carrying submarines. His design incorporated a body of revolution outer non-pressurised hull, containing the cargo; combined with an inner pressure-resisting hull, containing the reactor, control room and inhabitable places as shown in Fig. 16.

Fig. 16: Nuclear Powered Submarine Oil Tanker. Design by Shigemitsu, 1958.



Length: 180m **Depth:** 24m

Displacement: 48,000 tonnes

Cargo: 30,000 tonnes

Speed: Submerged 22 knots

Crew: 13 Officers; 37 Ratings

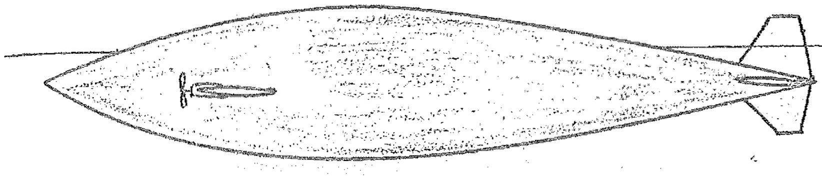
Source: Shigemtsu M. *Nuclear Powered Submarine Tanker*: 2nd U.N. International Conference on the Peaceful uses of Atomic Energy, June 1958, p.26.

Because of volume and design limitations, the study considered and rejected the carriage of dry cargo and passengers, but did see a legitimate role for the carriage of liquid cargoes such as oil. Shigemitsu proposed a submarine oil tanker, capable of transporting up to 30,000 tons at a speed of 22 knots when submerged, powered by one nuclear reactor developing 40,000 shaft horsepower (SHP). The economic viability of such a proposal was not discussed in any depth, but Shigemitsu did correctly identify that in order to be competitive with surface tankers the submarine tanker had to have a large cargo capacity and be capable of high-sustained speed. Franklin Varley makes an interesting comment in his 1972 research paper that *"It is a reflection on the level of engineering development of the time that Mr. Shigemitsu saw the only unsolved problems as being the perfection of nautical instruments; counter-radio activity measures in the completely enclosed hull, and an adequate reactor plant cooling system when the submarine was submerged"* (Shigemtsu 1958) & (Varley 1972).

3.3 Sato 1959-1960

At about the same time another Japanese submarine designer Goro Sato published and patented a number of submarine tanker designs based on two principles he had been working on since 1944. The first principle was the principle of three-dimensional movement, which Sato likened to an aircraft with its aerodynamic shape and control surfaces making it *"truly manoeuvrable in its element."* His design was unique in that its two propellers were mounted on small wing-like shapes mounted on each side of the submarine set about a quarter of the ships length from the bow. The bridge sail was retractable and the stern fitted with horizontal and vertical control surfaces; again similar to an aircraft, as shown in Fig. 17. The second principle was that of the *"non-water pressure hull."* Sato envisaged what was in effect a lightweight hydrodynamic-shaped casing surrounding a heavier inner pressurised core, the space between the two being available for the carriage of liquid cargo. In this principle, Sato clearly foresaw a way to reduce both the hull weight and the overall cost of manufacture at the same time. More importantly, it enabled greater cargo weight to total weight ratio by equalising the pressure difference between cargo tanks and the outside water pressure. Sato's US Patent filed in Sept 1960 details the compensating valve mechanisms required in order to keep pressure equalisation constant.

Fig. 17: Goro Sato's concept submarine oil tanker design: 1959



Length: 242 m
Hull Dia.: 24 m (max)
Displacement: 80,000 tonnes
Speed: 40 Knots U/Water

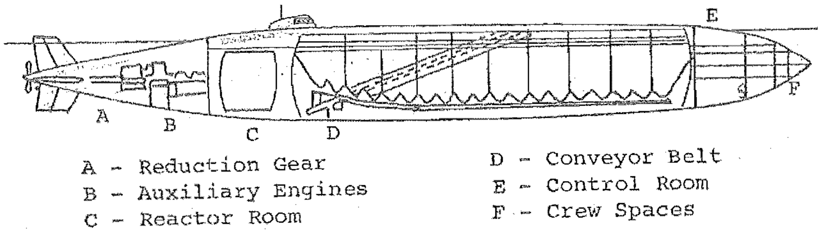
Source; Goro Sato 1959 *Transport submarines with non-water pressure hull of new principle* p. 1.

Without doubt, Sato's contribution was to advance the state of the art in submarine design rather than develop an actual design proposal. Notwithstanding, he did establish some of the principles necessary for the commercial carriage of cargo in non-pressurised tanks and had correctly predicted the optimised design for speed and control now commonly used in modern military submarines (Goro Sato 1959. *Transport submarines with non-water pressure hull of new principle*) & (Goro Sato 1960-1963. *Non- pressure hull type transport submarine with backbone*. United States Patent Office No. 3102504, Sept 1963).

3.4 Crewe & Hardy (Saunders-Roe) 1958

In 1958 a British company Saunders-Roe Ltd. was commissioned to undertake a feasibility and design study for the development of a submarine cargo ship of sufficient capacity to transport iron ore concentrate from Canada to the United Kingdom. The study initially identified a number of limitations. These were primarily restrictions imposed by port and harbour depths, and more particularly, the depth of water alongside the terminals, both of which would ultimately determine the maximum possible hull diameter of the vessel. Also, with a dry cargo, the submarine would have to surface to enter the port facility in order to load and discharge its cargo. These arguments when balanced alongside the size and power of pressurised water reactors of the time, caused Saunders-Roe to arrive at an optimised design as illustrated in Fig. 18. Saunders–Roe based their engineering and economic feasibility study around these parameters, but in an attempt to minimise the fully loaded surface draft they also considered a second design of 14,000 tons deadweight, approximately half of the original. In order to put these cargo carrying capacities into context, the *Sagamore*, an ore carrier that the author served in as a navigating officer in 1965 trading between Canada and the United Kingdom, could load about 16,000 tons and was considered to be of average size. Vessels capable of carrying 30,000 tons were at that time considered to be large.

Fig 18: Submarine Ore Carrier (Saunders-Roe) 1958.



Length: 184.1m

Hull Dia.: 21.94m (max)

Deadweight: 28,000 tons

Speed: 25 Knots U/Water

Source: Crewe PR & Hardy DJ; 1962 *RINA Paper No. 196221.*

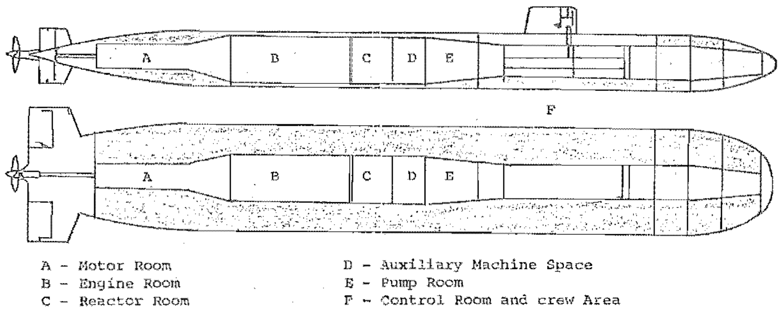
What is interesting about this particular study was that it was the first to start with specific requirements but looked for holistic solutions, one of which was how to keep the terminal at the Canadian end ice-free. Their solution involved laying a network of pipes under the wharf through which compressed air could be bubbled; the idea being that the bubbles would tend to break up the surface and prevent ice forming. This method has been effectively used today by a number of Antarctic survey and passenger vessels, which produce a constant bubble curtain through pipes located in the lower part of the hull.

This study was the first to lay the foundations of an economic as well as an engineering evaluation for submarine transportation. Their conclusions showed that a submarine cargo vessel could compete economically with a surface vessel in the Arctic but in order to do this, the design should be weighted in favour of large size and high speed (Varley 1972) & (Crewe PR & Hardy DJ 1962. *The Submarine Ore Carrier* The Royal Institute of Naval Architects (RINA), Paper No. 196221).

3.5 Russo, Turner & Wood 1960

Probably the most comprehensive study carried out during this period, was outlined in a paper entitled *Submarine Tankers*, presented by Vito Russo, Harlan Turner and Frank Wood at the annual meeting of the Society of Naval Architects and Marine Engineers in 1960. The paper was a technical feasibility study, which featured tankers ranging from twenty to forty thousand tons deadweight (dwt) and speeds ranging between twenty to forty knots submerged. The most promising of these designs is shown in Fig. 19. The design, designated rather cryptically *S5-N-MA48a* by the United States Marine Administration, featured a hull of rectangular cross section. It consisted of an inner pressure hull centred on the main axis of the vessel together with smaller variable cargo and trim tanks. Surrounding the pressure hull, were the main and auxiliary cargo tanks located at the four corners of the rectangular outer hull.

Fig. 19: The Russo, Turner & Wood Submarine Tanker, 1960, (S5-N-MA48a).



Length: 172.21m **Beam:** 24.38m

Depth: 12.19m **Draft:** 10.82m

Deadweight: 20,000 tons

Shaft Horsepower: 35,000

Speed: 20+ Knots U/Water

Source: Russo VL, Turner H & Wood FW 1960. *Submarine Tankers.*

This hull design was the result of extensive calculations verified by tank testing at the Davidson Laboratory of the Stevens Institute of Technology. Franklin Varley, in his 1972 paper on cargo submarines explains why the rectangular hull was the preferred choice. *"The rectangular hull was the answer to a major problem. On one hand, the body of revolution hull was well established as the most efficient hydro-dynamically. On the other hand, to achieve the desired deadweight tonnage in a body of revolution hull would have resulted in hull diameters well in excess of existing shipyards and dry-docks."* He goes on to say that, *"The rectangular design was costly in terms of the power required to overcome the vastly increased drag"* (Varley F C 1972).

Russo and his colleagues concluded on this point that "The top speed for rectangular-form submarine tankers with a surface draft limited to about thirty six feet, (10.97m) in surface condition, loaded, is not much above thirty knots." This conclusion was based on their opinion that *"180,000 SHP was the upper limit for present day [1960] feasibility in such hull forms"* and furthermore they noted *"that in the smallest 20,000 dwt. vessel of the design series, this limit is 120,000 SHP because the addition of a third propeller in this vessel requires a beam/length ratio which results in an impossible arrangement and such high effective horsepower (EHP) that no appreciable increase in speed could be obtained"* (Russo, Turner & Wood 1960).

In this study, the authors did not conduct an economic analysis although they did remain within the state of the art for 1960; that is, no unproven concepts designs, or materials were involved. However, the design criteria did reflect the fact that this type of commercial submarine did not have to dive to the depths expected of military vessels and for the same reason consideration was given to the use of lower grade nuclear fuel.

What the authors did not and could not know at the time was that by the mid 1970's surface super tankers were being constructed in new or refurbished shipyards with a capacity of 250,000 to 400,000 tons and with load draughts in excess of twenty-five metres. Furthermore, many of these new tankers now loaded at floating storage platforms miles offshore and similarly discharged their cargo through a pipeline to a shore side installation at specially constructed mooring buoys anchored well off the port in deep water. At both load and discharge points these vessels are completely unrestricted by draught. In effect, the much-vaunted problem of draught restriction forcing a power trade-off by using a rectangular hull would no longer be an issue. If the circumstances allowed, a fast cargo-carrying submarine with a body of revolution hull of thirty metres in diameter could be handled today at such installations with comparative ease. Additionally, the extra internal volume would allow for larger power plant and greater shaft horsepower. Notwithstanding, Russo et al. detailed research and analysis did provide a major contribution in the development of submarine tanker design.

3.6 Teasdale Submarine Comparison Study 1959-1960

In 1959, John Teasdale, a naval architect working for the Furness Shipbuilding Company in the United Kingdom and a member of the British Ship Research Association (BRSA) team investigating the application of nuclear power at Harwell, wrote a defining paper called the *Characteristics & Performance of Nuclear Powered Submarine Cargo Vessels* which he presented to the North East Coast Institution of Engineers on the 24th April 1959.

Teesdale's study provides us with a good technical comparative analysis, to which we will return later in the dissertation, when evaluating the resistances to motion of submarine and surface vessels. However, the reason why this research paper was so important is because for the first time an economic evaluation was made between the likely characteristics and performance of a submarine tanker in comparison with a surface tanker of the same deadweight: both vessels being propelled by nuclear power. He chose a surface vessel of 47, 000 tons deadweight, simply because there were many vessels of this type being built at the time for the carriage of crude oil through the Suez Canal and thought it appropriate to adopt it as a basis of comparison. The submarine hull characteristics were based on the ideal "teardrop", body of revolution shape developed by Young & Young in 1945.

Teasdale's principal criterion in comparing vessels was that the hull form should be as close as possible to the optimum for minimum resistance, but acknowledged that the practical design of a submarine tanker was influenced by the limitations imposed by existing terminal ports and canals. In deference to these limitations, he proposed a hull with an elliptical cross section to be used for comparison, in addition to the optimum circular hull shape.

The general conclusions reached were that subject to some modifications, the elliptical–section form could conform to the same dimensional limitations as the surface vessel. However its performance was found to be *"inferior over the range considered and was likely to be so up to the fineness limits of the surface ship"* (Teasdale 1959). He suggested that the only factor which could counteract an increased fuel bill would be a capital building cost less than that of a corresponding surface vessel, but thought that unlikely, as the building costs at the time were estimated to be twice that of a corresponding surface tanker. His research however did confirm that the circular section submarine tanker was the optimum form for underwater propulsion and that it had superior performance over both the elliptical form submarine and the surface vessel, but that *"the extent of the superiority is not overwhelming at normal speeds, certainly not sufficient to justify an increased capital cost, insurance and wages"* (Teasdale 1959). He also felt, as did his contemporary Russo, that the most serious failing of the circular form submarine was the fact that it could not conform to the draught restrictions imposed on surface vessels, without sacrificing superior performance. He concluded on that basis that it was *"not likely to be an economic competitor of the surface oil tanker"*. Interestingly, he thought that if there were no draught restrictions it could be used, but that such a vessel would be forced to follow the Cape route in the carriage of oil from the Persian Gulf to the United Kingdom. Again, what he could not have known at the time was that from 1967 to 1975 the Suez Canal was closed due to the Arab-Israeli conflict. This event required surface tankers bound for European refineries from Middle East oil ports to use the Cape route. It was during this eight-year period, that necessity drove both innovation and economies of scale, resulting in the creation of modern deep draught super tankers.

Given the limitations cited by Teesdale's study, clearly a more compelling set of circumstances would be needed to change the economic balance. Fortuitously, the discovery of oil in Alaska in 1967 caused the subject of submarine tankers to be revisited.

3.7 The Alaskan North Slope Development & the Electric Boat Company

In April 1967, the Atlantic Richfield Company commenced production of the Prudhoe Bay No. 1 well on the North Slope of Alaska close to the shore of Arctic Ocean. Today, the total Barrow Arch reserves are estimated to hold in excess of thirteen billion barrels of crude oil and twenty-five trillion cubic feet of natural gas (Gibson Consulting 2007. *Oil Industry Statistics*). The initial problem post-discovery was how to transport the oil from well head to refinery, given that the northern shores of Prudhoe Bay were perennially ice-bound and the overall climatic conditions in this part of Alaska were extremely challenging with temperatures well below freezing for most of the year. The two options at the time were divided between an ice breaking tanker and an overland pipeline. In 1969, the *Manhattan* a 300 metre long super tanker (106,000 dwt.) operated by the Humble Oil & Refining Company was modified with a thick protective steel belt and an armoured bow designed to ride up on the pack ice so that the weight of the massive ship could descend and break it apart. With the help of an escort icebreaker and scouting helicopters the voyage from Prudhoe Bay to Philadelphia carrying a symbolic one-barrel of oil was successful, demonstrating that the Northwest Passage could be used for commercial shipping purposes. Unfortunately, the ship experienced a lot of ice damage and it was not considered to be a cost–effective shipping method at the time. Consequently, Humble joined with the other oil companies in funding the 800-mile Trans-Alaskan pipeline between Prudhoe Bay and Valdez at a cost of $US 1.5 billion (Sunship Organisation 2008. *SS Manhattan and the Northwest Passage*).

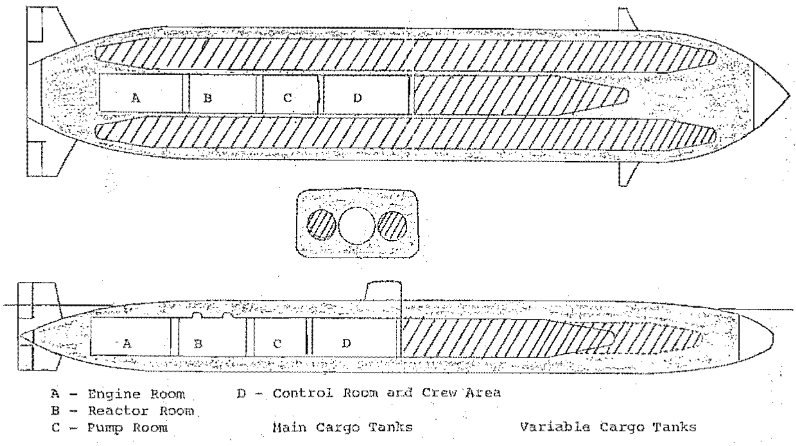
During this period the Electric Boat Company a division of the General Dynamics Corporation, made a proposal to the five major oil companies involved in the North Slope reservoir. The fundamental concept of their proposal was that oil would be pumped from Prudhoe Bay via a submerged pipeline to an undersea loading terminal about sixty nautical miles offshore in the Beaufort Sea. At the undersea terminal a submarine tanker would anchor itself to a large horizontal ring and once stable though negative buoyancy it would connect to the pipeline by a series of valves through which it would take on its cargo of crude oil. Once loaded, the submarine would disengage from the terminal and proceed under the polar icecap to a similar undersea transhipment point, possibly in Southern Greenland, where the crude oil would be offloaded and taken by a conventional tanker to refineries located on the East Coast of the USA. L.R. Jacobsen of General Dynamics-Electric Boat Division presented a general discussion paper based on this proposal in 1971, at the Offshore Technology Conference in Dallas, Texas (Jacobsen LR 1971. *Subsea Transport of Arctic Oil –A technical and Economic Evaluation.* Offshore Technology Conference, Dallas; Texas, April 1971).

The submarine proposed, was based on the *S5-N-MA48a* design developed by Russo Turner and Wood, but with greatly increased dimensions as shown in Fig. 20. Two sizes were evaluated. *"The smaller vessel of 170,000 tons deadweight was considered the largest that could be built at existing yards and the larger at 250,000 tons deadweight because it was considered to be the largest that could safely transit the Barrow Straits while submerged"* (Varley 1972). It was envisioned, that as nearly all of this operation would be submerged due to ice cover, the submarine would navigate through fixed "flight" corridors, delineated by sound transponder beacons located on the seafloor to supplement and update the on-board inertial guidance system.

Based on a production rate of 1.8 million barrels of oil per day the Electric Boat Company proposed a fleet of either eighteen 170,000 dwt, or thirteen 250,000 dwt tankers. On the expectation of one load and discharge per day and with the remaining fleet in transit, an optimum operating speed of between 16 and 19 knots was deduced from analyses of operating expense per barrel delivered.

Jacobsen in his paper asserts, *"Economic studies continue to uphold the conviction that the submarine tanker is a viable and attractive means for transporting crude oil from the Western Arctic to North Atlantic ports. Further, it appears that lower costs for moving Arctic oil can be achieved than with alternate systems"* (Jacobsen 1971).

Fig. 20: Under Arctic Icecap, 250,000 deadweight Submarine Oil Tanker.



Length: 260m **Beam:** 40m

Depth: 25m **Draft:** 17m

Deadweight: 250,000 tons

Shaft Horsepower: 45,000

Speed: 16-19 Kts. U/Water

Source: Jacobsen 1971. Subsea transport of arctic oil.

If we accept Jacobsen's argument as being valid, then why were the oil companies reluctant to accept this proposal? One reason could be the fact that the oil companies had already invested heavily in research and development and already had made a financial commitment to a pipeline solution sometime in 1971. Another possible reason was that the Atlantic

Richfield Company; a principal player, was already in the process of constructing a 100,000 barrel $100 million refinery near Bellingham in Washington State ready for the pipeline completion in 1972; and had placed orders for three 120,000 dwt tankers to supply the refinery from Valdez in Southern Alaska (Moreau J W 1970. *Problems and developments in Arctic Alaskan Transportation*).

What is clear from the literature is that the "big five" oil companies "understood" pipelines and refineries. Perhaps it was this overriding sense of familiarity with existing technology more than anything else that offered both the companies and their respective shareholders the comfort of certainty. With the building of the Trans Alaska pipeline the prospect of a submarine tanker solution became redundant. But in spite of that, the concept of submarine transportation had for the first time come tantalisingly close to a commercial reality.

An important aspect of submarine transport that is often overlooked is its flexibility and ability to adapt to new situations. Without doubt, the possibilities of oil or natural gas discoveries in the Arctic regions are very real. Many of the deposits originally thought to be either uneconomic, or out of reach on the continental shelf below the Arctic ice, are generating increasing interest as the world's oil supply diminishes. It is estimated that the entire Russian continental shelf covers 6.2 million square kilometres. Russia's extractable offshore hydrocarbon resources are approximately 100 billion tonnes equivalent to 733 billion barrels; eighty percent of which is located in Arctic. However there are a number of sovereignty issues which currently require resolution; in particular the Lomonosov ridge, the ownership of which is disputed by Russia, Canada and Denmark. In addition, there are also some jurisdictional questions that need clarification in respect of the right of free passage through those nations territorial waters (Yenikeyeff S M & Krysiek T F 2007. *The Battle for the Next Energy Frontier: The Russian Polar Expedition and the future of Arctic Hydrocarbon*). Another important hydrocarbon source, which will become increasingly important, is the extraction of oil from oil sands and shale. Northern Alberta contains North America's largest tar-sand deposits of 175 billion recoverable barrels, second only to Saudi Arabia's 260 billion (Government of Alberta 2008. *Alberta Energy: Oil Sands*). It also has the most hostile, remote and challenging environment on the planet. It is entirely possible that submarine tankers in the not too distant future, may be able to offer the operational flexibility necessary for either the transportation of oil product below the polar icecap, or as an alternative to the capital cost of multiple overland pipelines.

3.8 Conclusions

Based on the case study overview provided above, the information gathered appears to support the following conclusions.

From a naval architecture and marine engineering viewpoint, a submarine oil tanker of up to a quarter of a million tonnes deadweight is completely feasible and would involve no new technologies or significant uncertainties in either operation or construction.

To be attractive economically such a submarine would require an environment where surface transportation is restricted either physically or geopolitically. The physical situation currently exists in the Arctic regions where weather and perennial ice cover present severe limitations on surface operations, which in spite of the predicted effects of global climatic change will still require surface icebreakers into the foreseeable future. Similarly, from a geopolitical viewpoint any unresolved dispute over sovereignty or jurisdiction over coastal waters may require vessels to remain in international waters, which in the case of the Arctic is likely to be below the polar icecap.

The cargo submarine could provide an operational flexibility that cannot be achieved with either a surface vessel or a pipeline.

4. THE ROLE OF HULL DESIGN

4.1 Introduction

So far we have looked at the historical development of cargo carrying submarines in both military and commercial roles. The principal advantages claimed by those developing submarines for commercial purposes are; greater submerged speed, and in contrast to surface vessels, independence from weather conditions and the absence of wave-making resistance. This claim is generally correct, but as with most generalities it is conditioned by a number of factors, which must be taken into account when designing a submarine, or in making direct comparisons with surface vessels. For example, it is not commonly known that submarines in both World Wars were actually slower underwater than on the surface, mainly because they were designed as surface vessels but with the capacity to submerge. Most of the time the submarine operated and fought on the surface, only submerging to avoid detection. The fact that submarine deck guns were responsible for most of the merchant ship casualties, in the early part of the last war confirms this point (Rossler 2001).

In order to make any meaningful comparison between submarines and surface vessels, it is necessary to have a basic understanding of the hydrodynamic forces at play; and in particular the resistances to motion experienced by vessels both above and below the waterline. In that regard, much of our current knowledge on hull resistance is due to the definitive experiments conducted by Gertler at the Taylor Test Tank in the United States and Todd at the Ship Research Centre in the United Kingdom during the 1950's and 60's (Gertler 1950) & (Todd 1960). The total hull resistance of both submarines and surface displacement vessels is made up of a number of components, which due to a variety of causes interact with each other in a complex way. An appreciation of these resistances, their causes, differences and interactions is dealt with in greater depth in Appendix (02), but broadly speaking the total resistance of an immersed body is caused by two components: namely, pressure resistances and skin friction.

(Gertler M 1950. *Resistance experiments on a systematic series of streamlined bodies of revolution, for application to the design of high-speed submarines,* TMB report C-297 (declassified), April 1950) & (Todd F H 1967, Chapter VII Resistance and Propulsion *(Bodies of revolution; deeply submerged), p* 356 in Principles of Naval Architecture, SNAME 1967).

4.2 Pressure Resistances

When a deeply immersed vessel is in motion through a fluid, the diversion of the streamlines causes variations in pressure around the surface of the hull. The normal pressures at the forward end of the hull usually exceed those on the after portion with the consequence that the vessel experiences a resistance known as "form drag". If the vessel then approaches the sea surface, waves begin to be generated and the resulting change in the distribution of hull surface pressures produces what is known as "wave-making resistance". The energy that must be supplied by the vessel to continuously re-create a surface wave train is equivalent to the wave-making resistance at any given speed and is a limiting factor in the speed of any vessel. As the speed increases, the height of the waves will also increase and by extension so does the energy required to produce these waves. It follows that the energy expended to maintain these waves represents lost energy that could have been used to make the ship travel faster through the water. It is often claimed that submarines are immune to wave making resistance once submerged. However some resistance although small is still felt, but which rapidly diminishes in value until the submarine is about three diameters submerged (approximately 50 metres). Preliminary analysis by Crago of the results obtained from a series of model tests shows that wave-making resistance is dependent on: the depth of water;

depth of immersion; size and operational speed (Crago M A 1958. Test results on submarine tankers, Impulse). To illustrate that wave-making although small does in fact exist; submarines that are fully submerged even at depth leave a telltale wave called a "Bernoulli hump" on the surface of the water that can be discriminated by satellite remote sensing. This phenomenon has been successfully used as one method of anti-submarine detection (Wren G G & May D 1997. *Detection of submerged vessels using remote sensing techniques.*).

4.3 Skin Friction

This is due to the frictional resistance of water as it passes over the submerged part of a vessel's hull contained within a thin layer close to the surface of the hull called the boundary layer. As such, it applies equally to surface ships and submarines. It can be seen, by even the casual observer, that the eddying motion in the water close to a moving vessels hull increasing in extent from bow to stern translates into energy that is being absorbed by frictional resistance. This energy loss due to friction is a function of water viscosity, speed, and the wetted surface area of the ship. William Froude's test tank experiments in 1872 and 1874 clearly showed that even in smooth new ships it accounts for 80% to 85% of the total resistance in slow-speed ships and as much as 50% in high-speed ships. Frictional resistance is the largest single component of the total resistance of any vessel and is reason why large amounts of theoretical and experimental time have been devoted to it over the years (Froude W, Experiments on Surface Friction, British Association Reports, 1872 & 1874. In - Principles of Naval Architecture. ISBN: 0685564983.)

The ideal underwater shape offering the lowest total drag is a teardrop form of circular cross section with an elliptical bow and parabolic stern terminating at a point. It is for exactly the same reason that this aerodynamic form was chosen for dirigible airships such as Graf Zeppelin and Hindenberg in the 1930's.

Fig 21: Young's Body of Revolution.

Young's Streamline Body of Revolution (0, 0·5, 0·2)

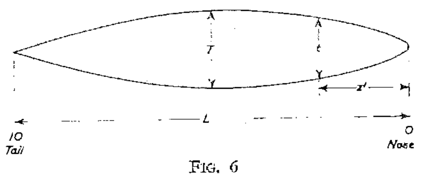


FIG. 6

TABLE OF ORDINATES

Station	0	0·5	1·0	1·5	2·0	2·5	3·0
Ordinate t/T	0	0·3480	0·5039	0·6197	0·7154	0·7987	0·8715

Station	3·5	4·0	4·5	5·0	5·5	6·0	6·5
Ordinate t/T	0·9313	0·9743	0·9967	0·9959	0·9709	0·9224	0·8528

Station	7·0	7·5	8·0	8·5	9·0	9·5	10·0
Ordinate t/T	0·7662	0·6676	0·5610	0·4483	0·3258	0·1827	0

The "teardrop shape" is largely based on work developed by Young & Young in 1945 on *Streamlined Bodies of Revolution Suitable for High-Speed or Low Drag Requirements*, as shown in Fig. 21 and latterly confirmed and augmented by Townsin in his 1958 paper *The Fully Submerged Tanker*. Intuitively, John Holland's submarine in 1899 anticipated many of these features in his design, such as low length to diameter ratio and an axisymmetric circular form. However, in practice, departures from this ideal shape prove necessary to accommodate machinery and other space considerations. An added problem with a form that has a continuously changing diameter along the total length, is that its lines are difficult to fair, which adds significantly to the building cost. In order to avoid this, a parallel midbody is introduced to most designs, which can be accommodated without detriment to the overall design.

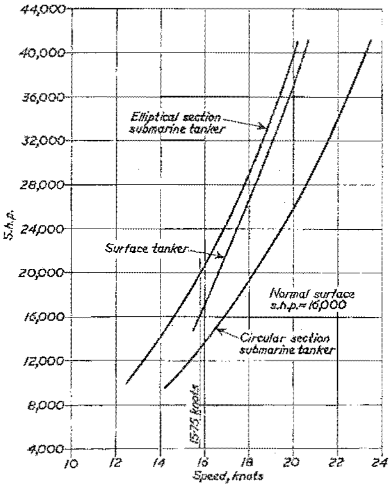
Professor E V Telfer's critique of the Saunders-Roe Study in 1962 succinctly points out, that a submarine can certainly be a beautifully streamlined object, but what is not appreciated generally, is how grossly inefficient it is in the provision of displacement per unit of wetted surface and *"it can easily be shown, that the provision of a given displacement by a circular-sectioned submarine requires* ($\sqrt{2}$) *times* [or 41%] *more wetted surface than a semi-circular surface vessel having the same approximate shape"* i.e. prismatic curve of areas. From this he deduces; *"this initial defect, not only more than outweighs any reduction in wave making resistance that complete submergence may bring"*, and by the same token, it also means that *"operational roughening, general deterioration and fouling of the shell plating would require [41%] more power increase than the surface vessel"* (Telfer EV critique, in Crewe & Hardy 1962).

Although submarines are primarily designed with an emphasis for submerged speed, they are nevertheless required at some stage during a sea passage to operate on the surface. This occurs normally when entering or leaving port, or sometimes on longer coastal transits from a port to a safe diving area. Submarines can be also constrained by their draught, which can be as much as 20 metres, so that submerged travel may not always be possible in coastal areas like the English Channel or many areas of the Irish Sea for example. To illustrate this point, a super tanker with a draught of 20 metres can only negotiate the English Channel on passage to Rotterdam via the Western approaches during high spring tides. At other times, these vessels must go around northern Scotland and thence down the North Sea to their destination. Submarines when on the surface are of course subject to the same resistances as surface vessels, but paradoxically the short fat axisymmetric form that makes it ideal for submerged performance is quite unsuitable when on the surface. Submarines are also relatively small vessels and this means that to make any decent speed on the surface they would be operating at a high Froude number i.e. (speed to length ratio), so that the wave-making component of the total resistance, in spite of the submarines smooth and streamlined form, would quickly become the dominant surface resistance. Also, the full form elliptic bow optimised for underwater performance does not perform well on the surface as it causes a large upwelling of a bow wave right across the foredeck reaching back as far as the bridge fin. Additionally, this tends to drive the hull beneath the surface, which requires the submarine to run at a large stern trim and use its forward hydroplanes as a means of keeping the bow up out of the water. As a consequence, both of these actions add to surface resistance (Burcher. & Rydill 1994).

These problems could of course be solved by simply making the form more ship shaped and by the introduction of a pointed flared bow – Typically, the shape of WWII submarines; which, were capable of a greater surface speed than some of the modern nuclear submarines operating on the surface. Unfortunately, a design change towards a more ship shape militates against a submarine hull form designed optimally for an environment where submerged performance is paramount.

John Teasdale's 1959 study provides us with a good technical comparative analysis of the resistances to motion of submarine and surface vessels. For his analysis, he chose three hull forms all of 47,000 tons deadweight; a surface tanker and two teardrop shaped submarines; one having a circular, the other an elliptical cross-section. Teasdale's principal criterion in comparing vessels was that the hull forms should be as close as possible to the optimum for minimum resistance. The general conclusions reached were; that subject to some modifications, the elliptical–section form could conform to the same dimensional limitations as the surface vessel. However its performance was found to be *"inferior over the range considered and was likely to be so up to the fineness limits of the surface ship"*. His research however did confirm that the circular section submarine tanker was the optimum form for underwater propulsion and that it had superior performance over both the elliptical form Submarine and the surface vessel as illustrated graphically in Fig. 22 but that *"the extent of the superiority is not overwhelming at normal speeds, certainly not sufficient to justify an increased capital cost, insurance and wages"* (Teasdale 1959).

Fig. 22: Teasdale's Analysis.



In 1960, F H Todd of the National Physical Laboratory, in the United Kingdom wrote a highly technical paper entitled *Submarine Cargo Ships and Tankers.*

Unlike previous studies, Todd's study did not focus on specific submarine design but rather performed a very thorough analysis of submarine tankers in comparison with nuclear and conventional powered surface ships. Because Todd's study is considered to be especially authoritative and unbiased, excerpts from his general conclusions are quoted below.

"The general conclusion which can be drawn from all the above evidence is that submarine cargo ships and tankers of circular cross section could be designed to compete with surface ships of the same deadweight as regards their power requirements, especially when one takes into consideration the effects of rough weather, from which the submarine would be immune. Such submarine ships would have excessive drafts, however, and if this is avoided by using elliptical sections, then the submarine's superiority soon disappears. However, up to such speeds as those for which an economical surface ship can be designed, say of the order of 25 to 30 knots, the cost of the submarine; of the necessary docking facilities; and of the provision of offshore terminals could not at present be justified on economic grounds. The case for the submarine would be even less favourable at this time if we were to compare it with a conventionally propelled surface tanker," and *"The greatest commercial incentive for submarine ships at the moment would appear to be their use on special routes where the attraction of making special profits. Leaving aside economic questions, there is no doubt as to the extreme advantage of having such craft for military use and for the transport of valuable cargoes in wartime. It may well be that some government will build a craft of this type very soon both for its military potential and national prestige, and to gain experience in the operation of such ships"* (Todd 1960) & (Varley 1972).

4.4 Conclusions

From the foregoing it can be seen that optimum hull shape for surface vessels and that of submarines are clearly not the same. A hull form optimised for submerged speed and efficiency performs poorly when operating on the surface and conversely for a ship shaped vessel optimised for surface operation performs poorly once submerged.

The main advantages claimed for submarines, in contrast to surface vessels, is the elimination of wave-making resistance and independence from the effect of weather. However, volume for volume, the submarine has a greater wetted surface than the surface vessel and therefore starts off with the handicap of greater frictional resistance. The absence of wave making resistance does not start to take effect until fairly high speeds are reached around 25-30 knots. Most of the concept proposals for commercial submarines have been for the carriage of liquid cargoes such as oil or high value ores, both of which do not require high speeds of transport.

When all of the hydrodynamic factors are taken into consideration the energy required to propel the submarine and the surface ship are roughly equivalent (Todd 1967). The fact that submarines are required to make some of the passage on the surface, where the effect of weather and wave-making resistance would have a proportionally greater effect than on a surface vessel designed specifically for that environment; should always to be taken into consideration when making an overall comparison of the total passage time between terminals.

However, since 1960 there have been significant shifts in the economic paradigms used by Todd in his original assumptions. In 1960 for example, the cost of oil was US$12 per barrel as opposed to nearly $106+ at today's prices. Secondly, and most significantly from a technical point of view, nuclear propulsion was then and still is very costly to purchase and operate, which, notwithstanding security barriers to entry, potentially puts it beyond the reach of commercial operators.

Since 1960, there has been considerable interest in the development of non-nuclear air independent propulsion systems; the commercial use of which could in my view provide the necessary catalyst to make submarine cargo vessels a more attractive proposal.

5. SOLVING THE POWER GENERATION DILEMMA

5.1 Introduction

This section describes the submarine power generation options available to non-nuclear nations. Modern conventional ships are nearly all powered by diesel engines. In simple terms, a diesel engine combusts diesel with air to produce power. This power is harnessed to drive the vessel directly through the propeller shaft and indirectly through generators to produce electricity to power all the ship's systems.

Submarines while submerged cannot use diesel engines without a source of air. Since the advent of submarines, this has resulted in a dilemma that engineers have tried to solve. The study of what options are available to engineers has led to the development of submarine Air Independent Propulsion systems (AIP). The following section describes submarine power generation options available and their relative merits for this mode of transport.

5.2 History

For over a hundred years a primary goal for naval architects and marine engineers has been to increase the range and submerged time capability of submarines. During and between the World Wars submarines were powered by diesel-electric generation, supplemented with battery banks, which are necessary for powering the submarine when submerged. In order to recharge the batteries, submarines need to be surfaced to allow sufficient fresh air to run the diesel generators. Towards the end of the Second World War experimental trials were conducted with mixed success by a number of navies using a separate airway, which could be used at periscope depth. The pressing requirement was a truly air independent power system which allowed the submarine to be operational and remain submerged for a protracted period.

This goal remained elusive until the introduction of nuclear propulsion in the mid 1950's. Unfortunately, for all but five of the world's navies nuclear propulsion was, and still is too costly. The *Nuclear Non-Proliferation Treaty* also restricts nuclear powered submarines to those five navies who happen to have permanent seats on the UN Security Council. So for the 30 or so other navies, diesel electric power is their only viable option. Consequently, it is those navies, particularly the European ones, who have been challenged with the research and development of AIP systems.

The development of AIP systems actually began during WWII when both the Soviet Union and Germany developed AIP systems for their submarines. The Soviets used liquid oxygen (LOX) in conjunction with a closed cycle diesel engine (CCD) whereas the Germans used highly concentrated hydrogen peroxide in conjunction with a "Walter" steam turbine. Unfortunately, both systems were plagued with technical and safety problems, particularly the safe handling of hazardous hydrogen peroxide.

After the War, the United States, the United Kingdom and the Soviet Union started to develop and experiment with captured German technology using the Walter steam turbine. However by the mid 1950's nuclear propulsion systems were being developed so that the value of AIP diesel electric systems became redundant. About this time the UK abandoned AIP in favour of nuclear power. The Soviets continued with AIP development until the mid 1970's but following a series of explosions on Quebec Class and DP617 submarines, they decided finally to shelve further development in favour of the "safer" nuclear option. For most other navies the cost of nuclear power was not only prohibitive, but also the costs were exacerbated by the fact that only the major navies could afford the research budget needed for AIP development. (Walsh D 2003 *The AIP alternative*: Article; Navy League of the United States).

5.3 AIP's today

Submarine design groups and public private partnerships in Germany, Sweden and France have managed to significantly advance AIP development based around four different systems as outlined in Table 1.

Table 1. Main propulsion systems used today.

Power Type	Fuel	Manufacturer
Fuel Cell	Hydrogen (H_2) Liquid Oxygen (LOX)	Germany:(HDW) Kiel Howaltswerke-Deutsche Werft
Closed Cycle Diesel (CCD)	Diesel +LOX + Argon	Germany: (TNSW) Emden Thyssen Nordsee Werke
Stirling Engine	Diesel + LOX	Sweden: Kockums, Malmo
Steam Turbo Electric (MESMA)	Ethanol + LOX	France: DCNI

As can be seen, all AIP's require a fuel and an oxidant. Available fuels include hydrogen, diesel and ethanol; and all systems use liquid oxygen.

Today many of the world's submarines are powered by hybrid systems centred on these four systems, i.e. a combination of technologies. Submarines powered by nuclear energy have also integrated AIP elements into their submarines and have benefited generally from this research.

At the forefront of AIP development is the German Submarine Consortium (GSC) which is made up of shipyards HDW of Kiel and TNSW of Emden; the IKL Design Bureau and Siemens Electric who between them have over 30 years designed and built 122 submarines for 16 navies (Siemens, A G 2004 *Sinavy^{CIS} PEM Fuel Cell for submarines*).

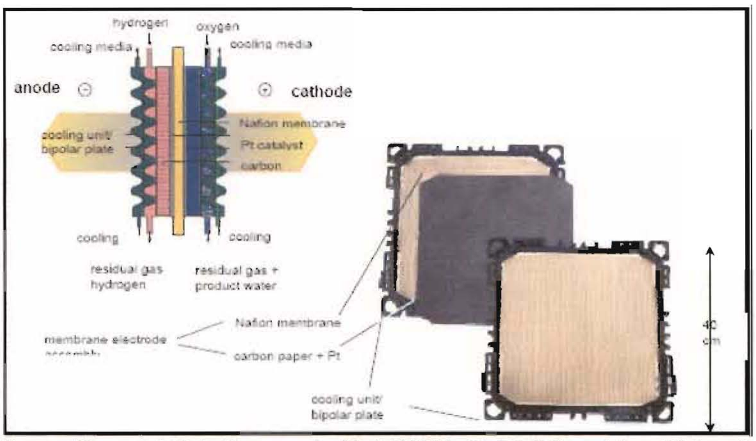
The simplest AIP sources are of course batteries, which are integral to all submarine design. Battery efficiencies have improved significantly from the older lead acid type but all still require to be recharged.

The Stirling Engine; CCD; and MESMA steam turbine systems are all mechanical devices relying on moving parts which offer a lower potential fuel and oxidant efficiency, i.e. have low relative efficiency. In contrast a fuel cell offers the greatest potential for submerged operation for submarines (Lakeman J B & Browning D J 2003 *The role of fuel cells in the supply of silent power for operations in littoral water* (declassified).

Fuel Cells

What is a fuel cell? The gas voltaic battery; later called the fuel cell, was invented by Sir William Grove in 1839. A fuel cell is a device that converts the chemicals hydrogen and oxygen into water, and in the process produces electricity. Another electrochemical device that we are more familiar with is the battery. Batteries have all their chemicals stored inside which the battery converts into electricity. This means, that a battery eventually "goes dead" and you either throw it away, or recharge it. With a fuel cell, chemicals constantly flow into the cell so it never goes dead. As long as there is a flow of chemicals into the cell electricity will be produced (Nice K & Strickland J 2003). Figure 22 shows the design features of a Siemens PEM Fuel cell. Additional information on fuel cell technology is given in Appendix (03).

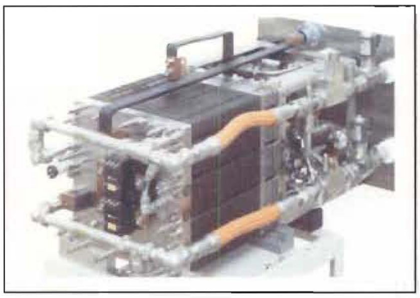
Fig. 23: Fuel cell features & schematic.



Source: Siemens A G, in Hammerschmidt A E 2006. *Fuel Cell Propulsion of Submarine.*

Fuel cells convert fuel and an oxidant directly into electricity by an electrochemical process, which is in theory up to 100% efficient (the basic fuel cell stack has no moving parts). However, practical considerations limit efficiency between 40%-68%. Fuel cells are silent, low maintenance, safe, and have a long operational life. An example is shown in Fig. 24 of a Siemens PEMFC module as used on the German 212 AIP submarine.

Fig. 24: Siemens PEM Fuel Cell & specifications.



Specifications
Rated Power 120 KW Voltage range 208-243V
Efficiency at rated load approx 58%
Efficiency at 20% load approx 68%
Operating Temperature 80 deg. C.
H_2 pressure 2.3 Bar abs .O_2 pressure 2.6 Bar abs.
Dimensions H = 50 cm. W = 53 cm. L = 176 cm.
Weight without module electronics = 900kg.

Source: Siemens & Howaltswerke-Deutsche Werft (HDW).

Cell Fuels

There are a number of different fuel cell types in existence. Of these, the proton exchange membrane fuel cell (PEMFC) offers the greatest potential for submarine applications.[5] It has the added advantages of instant start-up with an operating temperature of 80° C. The fuel of choice is hydrogen as it is the most energy dense fuel; around three times more effective than diesel, and over five times more effective than methanol[6] (Lakeman & Browning 2003). Hydrogen has the advantage of simplicity; when it combusts it produces electricity and only water as a by-product. However there are some disadvantages: hydrogen because of its flammable nature does pose safe handling problems, and also the volume taken up by the system in the overall submarine design is relatively high. A number of storage techniques are currently in use, all of which use some type of gas cylinder as containment. Storage of hydrogen in cylinders can be done in a number of ways. The common methods are by the direct compression or liquefaction of the gas or by absorbing the gas in either reversible metal hydrides or in carbon graphitic nano-fibres; or the use of any of those methods after reforming hydrogen from methanol or diesel.

Of these, the HDW German-built 212 Class submarines use the **reversible metal hydride storage system**. Each submarine has 18 hydride tanks each weighing 4.4 tonnes with a volume of 1200 litres each tank; this provides 1MW/h of energy per container. The tanks, which operate at 10-15 atmospheres, are intrinsically safe as there is virtually no free gas, and as the desorption of gas is endothermic, a rupture of the storage container will only result in a controlled loss of hydrogen which becomes progressively smaller as the tank cools. The tanks are mounted between the main hull and the outer casing; they are capable of resisting dive pressure and are maintenance free (Lakeman & Browning 2003). An alternative storage system uses **carbon/graphitic nano-fibre technology**. This is still in the development stage but the hydrogen storage capability is claimed to be very high. In 1996, the inventors Baker and Rodriguez claimed to have made a new form of carbon that can theoretically store up to three times its own weight. Although further research has revised the claim downwards they still report 68% hydrogen absorption and a release of between 43-58% without heating. Given the estimated density of the charged nano-fibres is extremely small, about 0.5 $g.cm^{-3}$ this translates to a volumetric storage density of 0.29 tonne of hydrogen per cubic metre. The predicted specific energy for a conservative system storing 50% hydrogen is 5.7 megawatt hours per tonne. This is an astonishing amount and is one of the most exciting technological advances in the last decade. Typically, the next best storage method using reversible metal hydrides can only store between 2-4% by weight (HiTech Developments Ltd. 2005 *Hydrogen storage: Carbon structures*) & (Chamber et al. 1998).

Baker and Rodriquez's work on this technology has been since been confirmed by Singapore researchers Tan (Chen 1999) and Liu (Liu 1999) using catalyst-doped graphite fibres and single walled nano-tubes respectively, although they were only able to cycle 20% of hydrogen by weight. Research development by Baker & Rodriquez at North Eastern University using stacked graphite plates has demonstrated the potential to store over 50% by weight of hydrogen or 9300 watt hours per kilogram (Chen P, Wu X, Lin J & Tan KL 1999 *High H_2 uptake by alkali doped carbon nano-tubes under ambient pressure and moderate temperature*) & (Browning D 1999).

Oxidants

In contrast oxygen storage is a very mature technology, which has been accepted by most navies as a favoured option. Primary storage of oxygen in liquid form is considered to be the optimum choice. The Swedish Navy has been using insulated liquid oxygen tanks in their AIP systems successfully since 1967. The Germans use them in their 212 Class submarines mounted between the pressure hull and outer casing made of the same material as the pressure hull designed specially and capable of withstanding both shock loads and diving pressure. Additionally, each tank is fitted with its own evaporator, which ensures that oxygen in liquid form does not enter the submarine and thus threaten the safety of the crew (Hammerschmidt A, 2006) & (Wursig I & Petersen L 2003).

5.4 Conclusion

Of all the current AIP power generation options the Proton Exchange Membrane Fuel Cell (PEMFC) is by far the most fuel-efficient option for all platform sizes due to its complete scalability. The best fuel/oxidant option at present would be hydrogen stored in reversible metal hydrides combined with oxygen stored as a liquid. Carbon nano-fibre hydrogen storage has still some way to go, but could well revolutionise the use of fuel cells across a range of transport applications both on land and sea. This technology in order to be competitively priced compared to petrol powered land vehicles needs to cost about $35 per kilowatt currently the projected high volume production price of fuel cells is $110 per kilowatt (Garman D 2006).

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5 PEM Fuel cells offer the highest gravimetric and volumetric power density of all the fuel cell technologies; better than 700 watts/kg and 1100 watts/dm^3.

6 The energy density of hydrogen is rated at 33 KWh/kg compared to diesel and methanol rated at 13.2 and 6.2, respectively.

6. PROPULSION

6.1 Propeller systems

The design of a propulsor is a highly complex specialist task that largely determines the overall propulsive efficiency of any vessel. It is of equal importance in the design of submarines and surface ships. At the early design stage, the size and the shape of the vessel determines the power required and hence the size and type of power plant. The function of the propulsor is to translate the energy delivered by the power plant into thrust, overcoming resistance, and propelling the vessel forward. A common method of achieving this is by using a screw propeller; as shown in Fig. 25. To that end, a considerable amount of time and study has been devoted in the last forty years to improving the design efficiencies of screw propellers.

However, the single open screw propeller is not the only, or necessarily the best, way to achieve good propulsive efficiency. One problem is that the action of the screw also imparts a rotational motion, or swirl to the water downstream, which wastes energy. The propulsor also interacts with the water flowing over the hull, which requires the propulsor and hull form to be properly matched in order to produce optimal efficiency.

A number of alternatives are currently in use, which help in dealing with some of these complex problems. One method for recovering lost energy due to "swirl" and for balancing the torque, is to use contra-rotating propellers or by the incorporation of an upstream stator as shown in Fig. 26.

Fig. 25: Open Screw propeller.

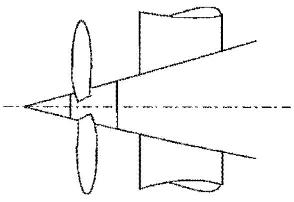
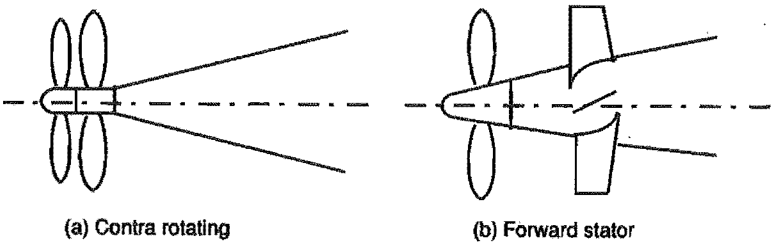


Fig. 26: Propeller types.



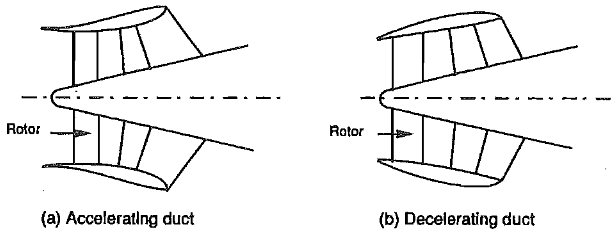
(a) Contra rotating

(b) Forward stator

Source: Concepts in submarine design; Burcher & Rydill.

Another alternative to the use of open propellers is to enclose them in a shroud or duct. This increases the efficiency of the propeller(s) by eliminating energy losses due to cavitation and other rotational losses called "tip vortices" downstream of the propellers. One clear advantage of ducted propellers is that they offer a measure of protection to the propellers from debris and ice damage. Some duct variations are shown in Fig. 27.

Fig. 27: Ducted Propellers.



Source: Concepts in submarine design; Burcher & Rydill.

6.1 Magneto hydrodynamic propulsion

One method of propulsion worthy of mention, which is still under development, is the magneto hydrodynamic drive system (MHD). The principle of MHD propulsion is based on Maxwell's theory, that there is an orthogonal (quadrangular) relationship between an electric current, a magnetic field and motion in a conducting fluid. Seawater conducts electricity; so that if a magnetic field can be set up so that an electric current field is generated at right angles, there will be a flow of water perpendicular to both fields. This flow of water is harnessed to provide the thrust to propel the vessel forward. This principle using Fleming's Left-hand electromagnetic rule is demonstrated in Appendix (04). The device can be designed to operate within a separate duct contained within the vessel or enclosed in pods mounted on the hull if desired.

The MHD was popularised as a "caterpillar drive" in the 1990 film adaptation of Tom Clancy's novel *The Hunt for Red October* as an undetectable silent drive intended to achieve stealth. In reality, the MHD is detectable by virtue of the current travelling through the water, which creates noise, and gas bubbles. Furthermore, the high-density magnetic field produced would produce a readily detectable magnetic signature. However the idea is attractive and inherently efficient because it has no moving parts. This means that potentially a design can be optimised, which could be reliable and inexpensive to manufacture. When used in conjunction with fuel cell technology it could offer enhanced environmental benefits as well as operational efficiency. The MHD's main problem is that at its present level of technological development, it produces less power than a conventional engine.

In 1968 Westinghouse Electric Corporation published a paper in the Journal of Hydronautics outlining the application of electromagnetic propulsion for large submarine tankers. The paper proposed that increased propulsive efficiency could be achieved using 6-pole superconducting magnets. Westinghouse looked at submerged displacements of 25,000; 50,000 and 100,000 metric tonnes. Theoretical calculations suggested that at 29 knots the thrust power is estimated to be 86% of the electric power supplied at 100,000 tons and that values of 90% are reached at 20 knots (Way S 1968 *Electromagnetic propulsion for cargo submarines*: Westinghouse Electric Corporation, Pittsburgh Pa. In Journal of Hydronautics Vol. 2 No.2; April 1968).

In 1991 the Ship and Ocean Policy Research Foundation in Japan completed the first working MHD prototype called the *Yamato 1*. During the early 1990's, Mitsubishi built and tested several more prototypes propelled by a MHD system; unfortunately, these vessels were only able to reach speeds of 15 kilometres per hour despite higher projections. The plans of the 185 tonne; 30 metre *Yamato 1*, together with a schematic of the MHD propulsion system are shown in Appendix (05).

7. CONCLUSIONS

Based on the historical and case study overviews, a number of general conclusions as to the provenance, utility and future possible use of cargo-carrying submarines can be reasonably determined. There is also some evidence which gives rise to speculation about the nature of future transport systems, and whether a submarine cargo vessel could in fact play some effective part if given the opportunity.

From a marine engineering and naval architecture point of view, a cargo-carrying submarine of up to a quarter of a million tonnes deadweight is completely feasible and would involve no new technologies or significant uncertainties in either operation or construction. What is less clear is that from an economic perspective, the case studies tend to be more speculative than analytical when making comparisons, but commonly agree that in order to achieve economic parity with surface vessels any submarine design has to be weighted in favour of large size and high sustainable speed.

Almost all of the studies saw the transport of liquid cargoes such as crude oil or methanol as the most commercially attractive cargo for submarine use, but there were some who also supported other types of low volume high value cargoes such as nickel or palladium for example as outlined in the Norilsk Nickel proposal.

To be attractive economically any cargo-carrying submarine would require an environment where surface transportation is restricted either physically or geopolitically.

The physical situation currently exists in the Arctic regions where weather and perennial ice cover present severe limitations on surface operations. Without doubt the Arctic's hostile environment and geography combine to make it one of the least accessible areas in the world to conventional means of bulk transport, which in spite of the predicted effects of global climatic change will still require surface icebreakers into the foreseeable future. Similarly, from a geopolitical viewpoint any unresolved sovereignty or jurisdiction disputes over coastal waters may require vessels to remain in international waters, which in the case of the Arctic, is likely to be below the Polar icecap. For the moment, the carriage of bulk cargoes by surface vessels is likely to remain the cheapest way to deliver seasonal bulk cargo in the coastal littoral areas inside the Arctic circle, but should year-round transportation of crude oil from the Arctic to North American or European refineries on a scheduled basis prove to be a strategic necessity, then a submarine tanker could possibly provide a practical and attractive alternative to either surface tankers or pipelines.

What is clear from the literature is that the Arctic and sub-Arctic represent the next energy frontier. The United States Geological Survey and the Norwegian company Statoil share the view that the Arctic holds 25% of global undiscovered hydrocarbon resources. Whatever the true potential of the Arctic, it is agreed generally by most experts including Statoil that Russia will dominate the production of Arctic hydrocarbons. Russia holds 69% of Arctic reserves and according to the Wood-Mackenzie/Fugro-Robertson report Russia will play a dominant role in Arctic gas, eventually accounting for three quarters of peak production. An in depth analysis is given in Appendix (06). (Yenikeyeff SM & Krysiek TF 2007 *Oxford Energy Comment, Aug. 2007*: Oxford Institute of Energy Studies).

If we accept the proposition that under restricted circumstances the submarine transportation of bulk cargoes is both feasible and economic, then the burning question that remains, is why has it not been realised? There are a number of reasons for this.

Investment

What is perhaps not well understood generally is that a submarine cargo vessel cannot be evaluated in isolation, but should be seen as part of an overall transportation system of which it is only one element. Without doubt direct economic and energy-power comparisons between submarines, surface cargo vessels and icebreakers is an important first step in determining commercial viability. But it is the economic evalution of the whole supply chain structure that ultimately determines the risk and whether or not investors will put their capital at hazard. Investors are generally not risk averse but they are certainly averse to risk when it is combined with uncertainty and this may partially explain a reluctance to invest.

The obvious key to the commercial development of hydrocarbon resources in the Arctic and sub Arctic regions lies in the economic access to the point of dispatch. Necessity tends to drive innovation but innovation is much more than creativity. In fact ideas may not be the problem at all but getting those ideas implemented often is. It should be remembered, that multibillion-dollar investments such as these are not limited to just one company, but can require the agreement of multi and transnational corporations. In some cases, the economies of whole countries may be involved, which would require government approval. In my view, it would require a very large profit margin, a large potential loss, or dire necessity to produce a paradigm shift away from existing technology. A prime example is the case of The North Slope Development in Alaska. Oil companies when faced with a pipeline, or consideration of a submarine cargo-carrying option chose to build the 800 mile Trans-Alaskan pipeline over some of the worlds most challenging terrain between Prudoe Bay and Valdez. It cost 1.5 billion dollars together with a new refinery; wharf infrastructure and a fleet of 120,000 dwt tankers estimated to cost more than 200 million dollars. Without doubt, the consortium of oil companies involved considered a number of options, which included submarines, but in the end came down in favour of what they knew best. It is possible to conclude, that this overriding sense of familiarity with existing technology more than anything else, provided both the shareholders and their companies with the comfort of certainty and more importantly, encouraged and confirmed their confidence to invest.

Nuclear Power

Nuclear powered engines offer capabilities that simply cannot be matched by those powered by fossil fuels. Nuclear fission requires no oxygen, produces no exhaust gases and provides a compact source of continuous heat that can last many years without refuelling. It is because of these capabilities, that navies possessing the technology to power their military vessels in this way have encouraged the development of nuclear powered systems without much regard to cost. Clearly, if the desired outcome is to produce a high-speed, long endurance submarine for strategic defence purposes then economic concerns are of low importance. In contrast, the economics of a nuclear powered cargo-carrying submarine are of critical importance to its commercial viability. To date, there have been only four nuclear-powered cargo ships built. Sadly, the development of these merchant vessels has not been a commercial success.

The *Savannah* built by the United States in 1962 was a technical success, but due to high maintenance and running costs it was not considered an economic proposition and was consequently decommissioned after eight years of service.

The *Otto Hahn* built by Germany in 1968 was configured to carry ore and passengers. In its nine years of nuclear powered operation, it steamed 650,000 nautical miles and visited 33 countries. However, it became too expensive to operate and was converted to diesel power. Finally, in 1983, it was recommissioned as the container ship *Trophy*.

The *Mutsu* built by Japan in 1972, was plagued by technical and political problems. Serious problems with the reactor shielding initially caused the commissioning to be postponed on safety grounds and after Japanese fishermen engaged in massive anti-nuclear demonstrations, the official commissioning was finally abandoned. After repairs and lengthy delays, the ship undertook only a few short voyages, including four research voyages from 1990 to 1992. Although there were some positive results, it was thought generally to be an embarrassing failure and in 1995 the ship and its reactor were decommissioned (Adams RM; 1995 *Nuclear power for commercial ships*).

The only nuclear powered merchant ship currently in service is the Russian-built *Sevmorput*, which operates successfully on the specialised North Eastern sea routes within the Arctic Circle. As part of Atomflot, the vessel operates in conjunction with a fleet of nuclear powered icebreakers all of which are heavily subsidised by the Russian government and manned by quasi-military personnel.

For all of these vessels, space was not really a problem, so they are able to use reactors using low-enriched uranium fuel of between 4 to 6 percent pure similar to land-based commercial reactors. However, in submarines, because of space restrictions and in order to provide optimum power density in a small volume, the fuel used is highly enriched uranium. United States submarines use uranium-235, which at 95% pure is just a few percent less than weapons grade (The Uranium Information Centre). It is unlikely in the foreseeable future that near-weapons grade uranium will become available commercially. Moreover, the reactor core technology together with its specialised moderation and shielding is highly classified, requiring the services of specially trained and security-cleared personnel.

It is this author's view that until a viable non-nuclear air independent power source such as fuel cells are fully developed; commercial cargo-carrying submarines are unlikely to be considered a realistic option in the short term. For the future, one can only speculate. It is possible, that in a world of finite hydrocarbon resources and rapid geopolitical change other transport options including those of submarines may be forced upon us not because of commercial expedience but out of strategic necessity.

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Footnotes

1 A remotely operated vehicle (ROV) showing a multifunction, manipulating arm about one metre long, picking up a piece of cord to demonstrate its dexterity. Source: Roper Resources Ltd, (www.roperresources.com).

2 Refer Fig. 2. *MV Blue Marlin* transporting the Destroyer *USS Cole*. Source: US Navy photo by PH2 Leland Comer photo gallery. (www.globalsecurity.org/military/systems/ship/flo-flo.htm)

3 *Blue Water Rig No.1* owned by the Blue Water Drilling Company USA. In 1961 this drilling rig was the first to be used as a semi-sub drilling platform in the Gulf of Mexico. Source: Courtesy of Friede & Goldman Ltd, (http://www.fng.com/)

4 Soviet Subs, *Voennaya Mysl (Military Thought)* is the senior classified Soviet military journal.

5 PEM Fuel cells offer the highest gravimetric and volumetric power density of all the fuel cell technologies, better than 700 watts/kg and 1100 watts/dm^3.

6 The energy density of hydrogen is rated at 33 KWh/kg compared to diesel and methanol rated at 13.2 and 6.2, respectively.

APPENDICES

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APPENDIX (01)

1) ARCTIC CONTAINER VESSEL FOR MMC NORILSK NICKEL

2) OPENING UP THE ARCTIC – DOUBLE ACTING TECHNOLOGY

Arctic Container Vessel for MMC Norilsk Nickel

Aker Finnyards is building an Arctic Container Vessel for MMC Norilsk Nickel, Russia, for operation on the Northern Sea Route of Russia. This new vessel will be delivered in early 2006 for final ice trials in the intended area of operation.

MAIN PARTICULARS

Length, oa	169.5 m
Breadth	23.1 m
Draught, at dwl	9.0 m
Ice-breaking capacity	1.5 m
Deadweight at dwl	14,500 t
Number of containers	650 TEU
Gross tonnage	approx. 16,000
Classification	Russian Maritime Register, ice class LU7

THE DOUBLE-ACTING CONCEPT

The double-acting concept is based on the idea that the vessel makes its path in heavy ice conditions the stern ahead, which will be possible through the use of electrical podded propulsion systems. Thus the stern and the propulsion units need to be dimensioned as for icebreakers, however at the same time making it possible to use an optimised open-water hull form in the bow. This arrangement offers good ice-breaking capabilities with a reduced power level and practically gives access to independent ice operation without compromising the open water performance of the ship. Experience has shown that compared to conventional ships, this has resulted in a reduction in fuel consumption, which will be further enhanced through the pulling mode of the propeller.

The new vessel is the prototype for a potential series of several vessels, which are to replace the current SA-15 type ships that have been successfully used on the northern sea route for the last twenty years. Operations in the arctic area are increasing, and Norilsk Nickel is in the need of new cost-efficient vessels with a modern design and technology. The new Arctic Container Vessel will transport metallurgical products from Dudinka on the river of Yenisey to Murmansk in Russia.

The newbuilding concept is based on the patented double-acting ship concept developed by Aker Arctic and ice model tests performed in their arctic research centre. Several feasibility studies were conducted and ice model testings performed at the arctic technology laboratory to find out the best economical and technological solutions for the vessel.

AKER ARCTIC TECHNOLOGY INC (AARC)

Aker Arctic Technology Inc is the arctic R&D unit of Aker Yards. The unit has been engaged in research with its own ice model basin for decades and been involved in numerous projects wherever freezing waterways are found. A third generation technology centre is currently under construction with plans to replace the existing laboratory in 2006. The most advanced ship designs, such as the double-acting ship concept, originate from Aker Yards.

APPENDIX 01

OPENING UP THE ARCTIC

Recent contracts have provided the commercial confirmation of the success of the technological breakthroughs made by Aker Finnyards, as Kvaerner Masa-Yards will be known from 2005 onwards, in the design of ships for use on Arctic shipping routes. Aker Finnyards' double-acting technology is now set to become an industry standard for ships navigating in ice – making regular service at high latitudes a practical reality at very reasonable cost.

Double-acting technology showed its superiority at full scale for the first time in 2003, when two 106,000 dwt oil tankers, the 'Tempera' and the 'Natura', operated independently the entire winter in the eastern Gulf of Finland, loading crude at the newly opened Primorsk terminal north of St. Petersburg. Both vessels exceeded all performance criteria in conditions that saw up to 70 cm of level ice and ice ridges up to 13 metres deep.

More recently, Aker Finnyards has won contracts for a 14,500 dwt. Arctic container vessel to be delivered in winter 2006 to JSC GMK Norilsk Nickel in Russia, and for the initial design of two 70,000 dwt Arctic shuttle tankers for a Gazprom and Rosneft subsidiary.

The Norilsk Nickel ship will be used to guarantee year-round transport of nickel and palladium from the Yenisei river port of Dudinka to a new distribution centre in Murmansk; while the two shuttle tankers will be used for offshore production on the Northern Russian shelf.

Aker Finnyards is building a double acting 13 MW icebreaker to serve Exxon Mobil's Orlan oil production platform in the Sakhalin offshore field.

Long traditions

Arctic navigation and icebreakers represent one of Aker Finnyards' core businesses. The company's Helsinki shipyard has built more than 60% of all the world's icebreakers. The latest, a 13 MW double-acting supply and stand-by icebreaker, will be delivered in spring 2005 to Russia's Far East Shipping Company (FESCO), and will be the first newly built icebreaker in use in the Sakhalin offshore oil field.

Aker Finnyards assisted the Norwegian Coast Guard in the design of the latest patrol icebreaker for Spitzbergen recently, and is providing input for a new icebreaker for the U.S. Coast Guard for use on the Great Lakes.

Aker Finnyards' Arctic Technology Unit – MARC – is the only research centre of its type worldwide run by a private company, and plays an important role in providing shipowners and shipyards with access to new technologies for Arctic conditions. Recent customers include oil companies such as Exxon Mobil, Shell, BP, Norsk Hydro, Conoco Phillips, Agip, Marathon, Statoil, Sakhalin Energy, Gazprom, LUKoil, Fortum, and China's Bohai Oil (CNOOC). Many engineering groups, including Bechtel and Tecnomare, also rely on Finnish expertise.

Fortum Shipping's two new 105,000 dwt DAS crude carriers have performed very well in ice, and have very low fuel consumption in open water as well.

A new propulsion system

Another important part of Aker Finnyards' work has been the development of an azimuthing electric propulsion system. The first prototype of the system, marketed under the Azipod® brand today, was built and installed in 1990.

The first full-size unit, rated at 11.4 MW, was installed in 1993 in the 'Uikku', a 16,000 dwt Finnish tanker. This was followed two years later by a second unit in her sister ship, the 'Lunni'. To date, these two ships have put in some 100,000 hours of trouble-free operation using the system.

Since then, Azipods have been installed in several new icebreakers: the AFY-built Caspian supply icebreakers, the 'Arcticaborg' and the 'Antarticaborg', the newest Finnish Baltic icebreaker, the 'Botnica', as well as the Norwegian 'Svalbard'. Several new icebreakers with electrical pod drives are currently building, among them a 13 MW twin-pod supply icebreaker due to enter service in spring 2005 and a twin-pod 9 MW terminal icebreaker for Exxon Neftegaz, and two 15 MW supply icebreakers for Sevmorneftegaz.

Aker Finnyards recently won contracts to build the world's first Arctic container carrier, and design the first true Arctic crude oil carriers.

Onwards to double-acting and oblique ships

Combining the advantages of electric propulsion with superb manoeuvrability, very low noise and vibration levels, and valuable savings in machinery space, Azipod drives represent a major step forward in ship propulsion. They have also provided the inspiration for a totally new concept – the double-acting ship.

Traditionally, when designing a bow, designers have always had to balance the needs of open water and ice operation requirements. If they focus on good icebreaking capability, the result will be poor open water performance and bad sea-keeping properties, and vice versa. Pod drives change all this, however.

A fully rotating pod gives the designer a unique possibility to design the bow of a ship to be good in open water, and the stern to be good at breaking ice The result: the 'double acting ship' (DAS) concept.

The bow design of Aker Finnyards' DAS concept incorporates experience built up with conventional vessels, and is an efficient, ice-strengthened open-water bow, offering open water performance some 10-15% better than that of a conventional ice-breaking bow. In icebreaking mode, a DAS vessel enters a ridge field at slow or moderate speed, and lets its pulling propeller chew up the ridge and slowly pull the vessel through.

As a new, cost-efficient technology, DAS opens up a number of possibilities in Russia's Far North, as well as in Alaska and Northern Canada. Studies have shown that maritime transport using DAS vessels is cheaper and more reliable than conventional tankers assisted by icebreakers, not to mention new pipelines.

Aker Finnyards have now gone even further, and created the 'oblique icebreaker'. Based on the idea of breaking ice with the entire side of a vessel, using a new oblique hull form and three propeller units, a ship of this type could be capable of breaking a channel 50 metres wide.

Underwater view of an ice model test, showing the flushing stream created by the forward propeller. Reducing ice friction in this way is central to cutting power needs in modern icebreaking.

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(Published in High Technology Finland 2005)

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APPENDIX (02)

1) EVALUATING THE RESISTANCES TO MOTION OF SUBMARINES AND SURFACE VESSELS

APPENDIX 02

EVALUATING THE RESISTANCES TO MOTION OF SUBMARINES AND SURFACE VESSELS

Introduction

In order to make any meaningful comparison between submarines and surface displacement vessels, it is necessary to have a basic understanding of the hydrodynamic forces at play; and in particular the resistances to motion experienced by vessels both above and below the waterline. In that regard, much of our current knowledge on hull resistance is due to the definitive experiments conducted by Gertler at the Taylor Test Tank in the United States and Todd at the Ship Research Centre in the United Kingdom during the 1950's and 60's (Gertler M 1950) & (Todd FH 1960).

Types of resistance

The total resistance of a vessel's bare hull is made up of a number of components, which due to a variety of causes interact with each other in a complex way. In order to deal with them in a simpler way, it is usual to separate the total resistance into its component parts. It was Englishman Sir William Froude who in 1868 first recognised the practical necessity of doing this. It is mainly due to his experiments, and those of Sir Osborne Reynolds at the British Association Test Tank in Torquay during the 1870's and 80's that we owe much of our knowledge of hydrodynamics (Todd F H 1967; in Principles of Naval Architecture; SNAME).

Total Resistance can be broken down into five major components, which are:

- Viscous resistance
- Eddy resistance
- Wave-making resistance
- Air resistance
- Other resistances – wind, wave action & currents.

Viscous resistance

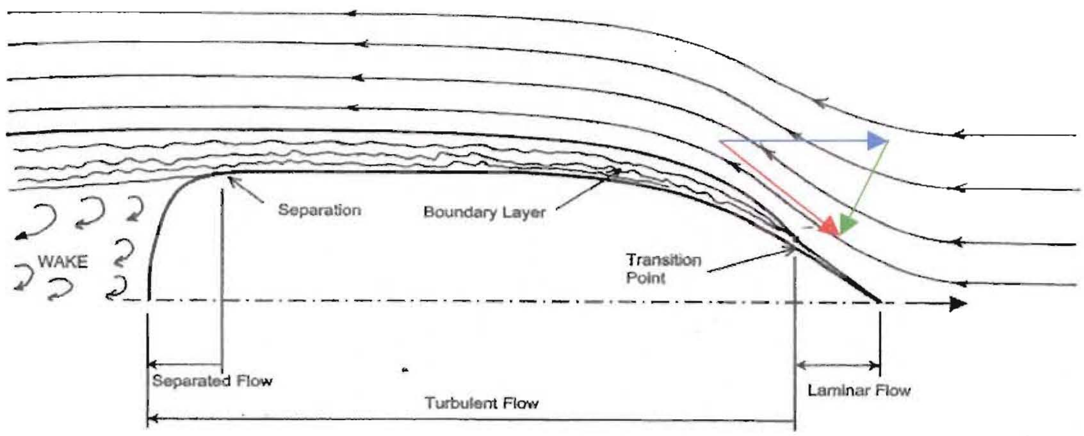
This is due to the frictional resistance of water as it passes over the submerged part of a vessel's hull contained within a thin layer close to the surface of the hull, called the boundary layer. As such, it applies equally to surface ships and submarines. It can be seen, by even the casual observer, that the eddying motion in the water close to a moving vessel's hull increasing in extent from bow to stern translates into energy that is being absorbed by frictional resistance. This energy loss due to friction is a function of water viscosity, speed, and the wetted surface area of the ship. William Froude's test tank experiments in 1872 and 1874 clearly showed that even in smooth new ships it accounts for 80% to 85% of the resistance in slow speed ships, and as much as 50% in high speed ships. Frictional resistance is the largest single component of the total resistance of a ship and is reason why large amounts of theoretical and experimental time have been devoted to it over the years (Froude W "Experiments on Surface Friction" British Association Reports 1872 & 1874).

Viscous resistance is made up of two types; "friction drag", and "form drag" as shown below in Fig. 1.

Friction drag: acts parallel to the surface of the hull and is caused by a net force "skin friction" opposing the motion of the water. In order to reduce the effect of friction drag, it is important (from a design point of view) that the exposed surface area is reduced as much as is practicable. It is also important to avoid surface roughness and sharp discontinuities.

Form drag: or viscous pressure drag, on the other hand acts perpendicular to the hull. Its' effect is felt through the build-up of pressure gradients, which oppose the motion of the water. The effect is unique to the shape of the hull form. Form drag can be minimised by having a gently curving form over a long body tending towards a needle shaped hull even though it would have a greater surface area to volume ratio.

Fig. 1: Showing fluid flows & resistances to motion.



Source: US Navy NAOE 2003.

Total →

Form drag →

Friction drag →

Therefore, for a given displacement volume; as it becomes longer and thinner the form drag is reduced but in doing so its surface area increases as does the frictional drag. Consequently, because of the relationship of water viscosity to both friction drag and form drag, opposing requirements are demanded for a hull form offering the least resistance.

Fig. 2: Young's streamline body of revolution.

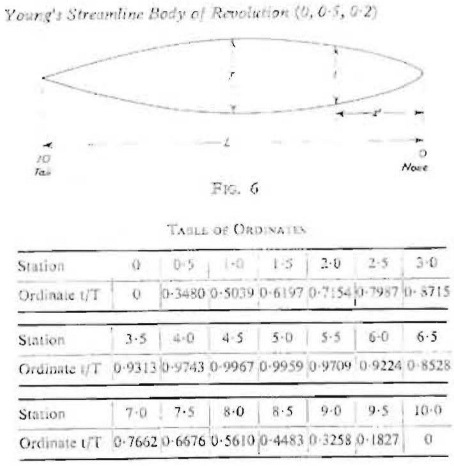


FIG. 6

TABLE OF ORDINATES

Station	0	0·5	1·0	1·5	2·0	2·5	3·0
Ordinate t/T	0	0·3480	0·5039	0·6197	0·7154	0·7987	0·8715

Station	3·5	4·0	4·5	5·0	5·5	6·0	6·5
Ordinate t/T	0·9313	0·9743	0·9967	0·9959	0·9709	0·9224	0·8528

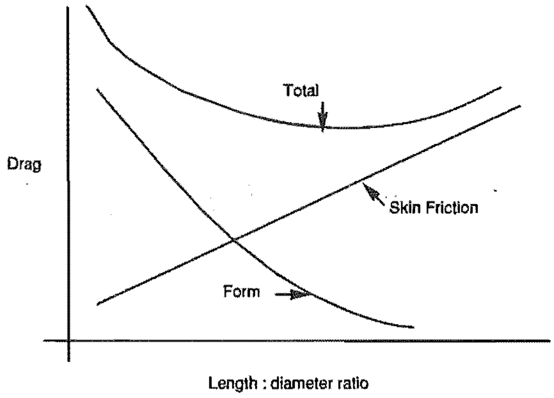
Station	7·0	7·5	8·0	8·5	9·0	9·5	10·0
Ordinate t/T	0·7662	0·6676	0·5610	0·4483	0·3258	0·1827	0

The ideal underwater shape offering the lowest total drag is a teardrop form of circular cross section with an elliptical bow and parabolic stern terminating at a point. It is for exactly the same reason that this aerodynamic form was chosen for dirigible airships such as Graf Zeppelin and Hindenberg in the 1930's. The "teardrop shape" is largely based on work developed by Young & Young in 1945 on *Streamlined Bodies of Revolution Suitable for High-Speed or Low Drag Requirements*, as shown in Fig. 2 and latterly confirmed and augmented by Townsin in his 1958 paper, *The Fully Submerged Tanker*.

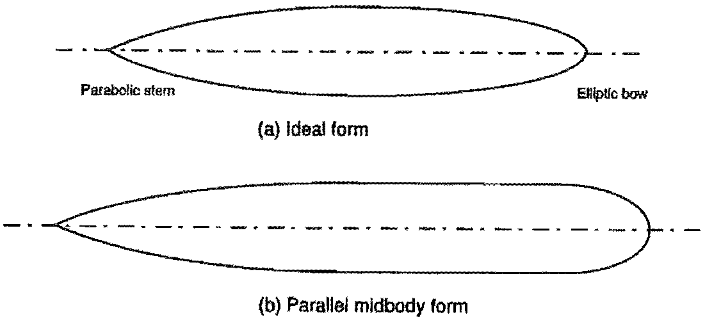
As can be seen in Fig. 3 there is an optimum range where the length to diameter ratio produces the lowest total drag. Ideally this is 6:1 for an axisymmetric hull form (Burcher RK & Rydill RJ 1994 Concepts in Submarine Design) & (Todd F H 1967).

Intuitively, John Holland's submarine in 1899 anticipated many of these features in his design, such as low length to diameter ratio and an axisymmetric circular form. However, in practice, departures from this ideal shape prove necessary to accommodate machinery and other space considerations. An added problem with a form that has a continuously changing diameter along the total length, is that its lines are difficult to fair, which adds significantly to the cost of manufacture. In order to avoid this, a parallel midbody is introduced to most designs, as can be seen from Fig. 4(b). It can also be seen from Fig. 3, that the curve of total resistance is quite flat, which offers an optimum range within which a mid-body section can be accommodated without detriment to the overall design.

Fig. 3: Drag components for a constant volume form.



Figs. 4: (a)&(b) – Ideal and Parallel midbody hydrodynamic forms.



(a) Ideal form

(b) Parallel midbody form

Source: Figs.3 & 4. (Burcher R & Rydill L 1994 *Concepts in Submarine Design*. Cambridge University Press: ISBN: 0521416817).

Professor E V Telfer's critique of the Saunders-Roe Study in 1962 succinctly points out, that a submarine can certainly be a beautifully streamlined object. But what is not generally appreciated is how grossly inefficient it is in the provision of displacement per unit of wetted surface and "*it can easily be shown, that the provision of a given displacement by a circular-*

sectioned submarine requires ($\sqrt{2}$) *times [or 41%] more wetted surface than a semi-circular surface vessel having the same approximate shape"* i.e. prismatic curve of areas. From this he deduces; *"this initial defect, not only more than outweighs any reduction in wave making resistance that complete submergence may bring"*, and by the same token, *it also means that "operational roughening, general deterioration and fouling of the shell plating would require 41% more power increase than the surface vessel*" (Crewe PR 1962).

Although the axisymmetric cigar-shaped form for a submarine is optimised for minimum resistance and thereby greater submerged speed; the bare hull on its own is actually directionally instable, with the shorter fatter profile the least stable. In order to provide directional stability, fins are fitted at the stern. These are fitted in conjunction with bilge keels, bridge fin towers, rudders and hydroplanes, which act as directional control surfaces. All of these additional but necessary appendages produce viscous drag, which even in the best streamlined hulls can vary between 4 and 14 percent of the total resistance. Burcher & Rydill make the point that "*It may be that a longer slender body will entail less drag from its required stabilisers. Hence, it is not necessarily true that the "ideal form" gives the least resistance when stabilisation is taken into account*" (Burcher & Rydill *Concepts in submarine design* 1994).

Eddy resistance

Eddy resistance is caused by turbulence due to discontinuities at the hull surface. As water flows over the hull it forms a boundary layer, which becomes detached from the hull at some point. This usually this occurs near the stern where the increase in curvature is too great for the boundary layer to remain in contact with the hull. Fig. 1 shows the space between the smooth flowing water and the hull filled with eddies which comprise the ships wake. Due to viscosity, the wake is drawn behind the ship, which increases the resistance. This is referred to as separation resistance. The point at which separation takes place is a function of speed and hull shape. As can be seen in the ideal submarine shape in Fig. 4a the hull has a fine parabolic curve into the stern. The separation point will therefore be further aft and as a consequence, the wake narrower. As a general statement a fuller shape has a larger form drag, than a slender ship. It is important to point out that any sharp discontinuity can cause increased eddying or separation resistance. Openings to the hull unless properly faired can cause serious additional drag resistance problems caused by the turbulence of the water flowing in and through them. One of the worst problems is caused by a phenomena ON known as "eddy shedding" whereby the forward facing plate edge on the aft end of an opening splits the water flow causing the fluctuating eddies to be shed. This is similar to the process used to create sound as air flows across an organ pipe. The problem is exacerbated by the fact that the resonance built up, can cause unwanted noise within the hull and in the worst cases vibrational fractures. Finally, we have assumed for the sake of all the foregoing arguments that the submerged body moves at all times along its longitudinal axis. However due to weight distribution or operational requirement, the "angle of attack" may deviate from the norm. These changes of attitude have the tendency to introduce cross-flow drag components, all of which add to the overall resistance to motion. (Burcher RK & Rydill RJ 1994)

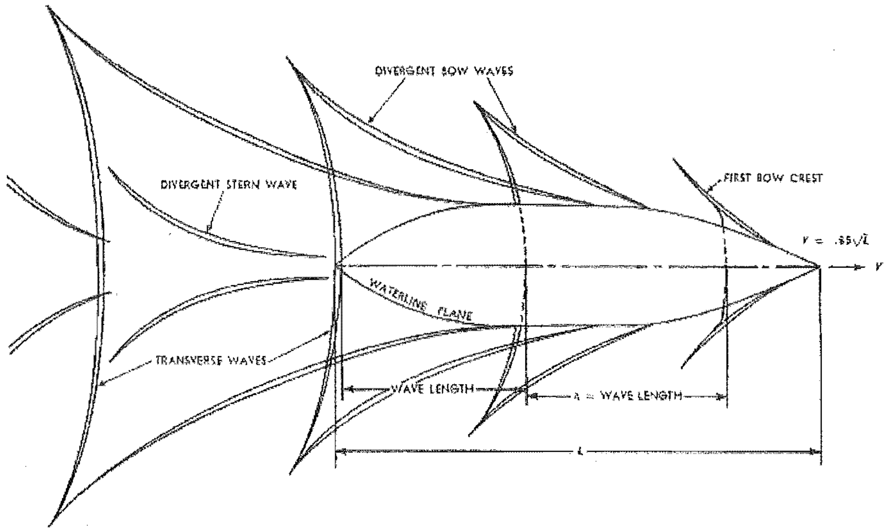
Wave making resistance

This is the resistance due to waves caused by the ship's motion. This applies mainly to surface displacement vessels, but it also applies to submarines when they are on, or near to the surface. It is function of beam to length ratio, displacement, hull shape and a dimensionless form of velocity known as the "Froude Number" derived from the length to speed ratio parameter $\mathbf{V/\sqrt{gL}}$ named in honour of Sir William Froude (1810-1878) one of the pioneers in ship model testing.

By way of explanation, the forward movement of a vessel on the surface of the water creates a wave pattern, which spreads out behind the vessel. Waves are produced at the bow and stern and are propagated outwards from the vessel. The wave train is made up **transverse** and **divergent** wave systems as illustrated in Fig. 5 (Todd FH 1967).

The energy that must be supplied by the vessel to continuously re-create this wave train is equivalent to the wave-making resistance at any given speed and is a limiting factor in the speed of a vessel. As the speed increases the height of the waves will also increase and by extension so does the energy required to produce these waves. It follows that the energy expended to maintain these waves represents lost energy that could have been used to make the ship travel faster through the water. It is often claimed that submarines are immune to wave-making resistance once submerged, however some resistance although small is still felt but which rapidly diminishes in value until the submarine is about three diameters submerged (approximately 50 metres). Preliminary analysis by Crago of the results obtained from a series of model tests shows that wave making resistance is dependant on the depth of water; depth of immersion; size and operational speed (Crago MA; 1958 *Test results on submarine tankers*: Impulse). To illustrate that wave-making although small does in fact exist; submarines that are fully submerged even at depth, leave a telltale wave called a "Bernoulli hump" on the surface of the water that can be discriminated by satellite remote sensing. This phenomenon has been successfully used as one method of anti-submarine detection (Wren G & May D 1997).

Fig.5: Wave systems generated by vessels on the surface.



Source: Gillmer T C & Johnson B 1982. *Introduction to Naval Architecture*: Annapolis, MD, Naval Institute Press, 1982. Third printing, 1987. ISBN: 0870213180.

The transverse wave system

The transverse wave system is particularly important to the overall wave-making resistance. The transverse wave travels at approximately the same speed as the ship producing it. At slow speeds, the transverse wavelength is short with several crests appearing along the ships length. As the hull moves faster, the length of the transverse waves increases, which results in a reduction in the number of wave crests contained within the ships length. As the wavelength approaches the ships length, the wave-making resistance increases very rapidly. Once this point is reached, the vessel is contained in the trough between to bow and stern wave crests, which move along at the same speed as the forward motion of the ship. This is called the "hull speed". This speed can be exceeded, but the amount of power required by the ship to break out of the envelope is enormous relative to the power that was initially required to reach that condition.

The speed at which the wavelength matches the waterline length of the vessel is in direct proportion to the square root of the waterline length as derived from the Froude ratio $V/\sqrt{gL}$. From this relationship it can be clearly seen, that the longer the waterline length the higher the achievable hull speed. This relationship of length to speed is important to the ship designer as it also directly relates to the power needed to reach design speed.

The following example illustrates the effect that wave-making resistance has on the powering of a vessel.

A fast frigate with a waterline length of 408 feet (124m) is powered by two gas turbines that produce approximately 41,000 shaft horsepower for a published maximum speed of 29 knots. At a speed of approximately 27 knots the length of the transverse wave is nearly the same as the length of the ship. With one gas turbine in operation (20,000 SHP) the ship is capable of about 25 knots. It therefore takes an additional 20,000 SHP (double the shaft horsepower) to increase the speed by four knots! That increase in required horsepower is directly related to the effects of wave-making resistance (US Navy NAOE 2003).

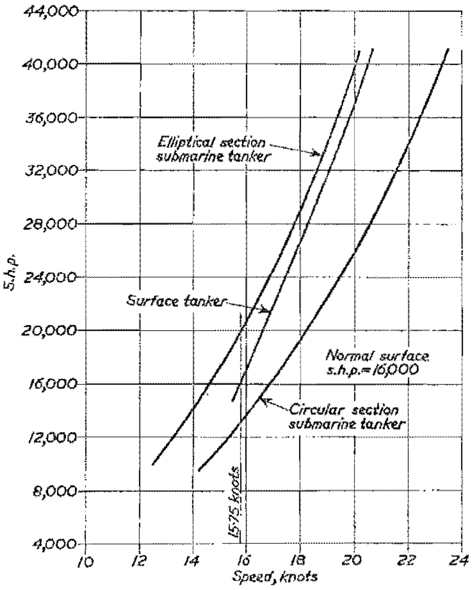
Although submarines are primarily designed with an emphasis for submerged speed, they are nevertheless required at some stage during a sea passage to operate on the surface. This normally occurs when entering or leaving port, or sometimes on longer coastal transits from a port to a safe diving area. Submarines can be also constrained by their draught, which can be as much as 20 metres, so that submerged travel may not always be possible in coastal areas like the English Channel or many areas of the Irish Sea, for example. To illustrate this point, a super tanker with a draught of 20 metres can only negotiate the English Channel on passage to Rotterdam via the Western approaches during high spring tides; at other times, these vessels must go around northern Scotland and thence down the North Sea to their destination. Submarines when on the surface are of course subject to the same resistances as surface vessels, but paradoxically the short fat axisymmetric form that makes it ideal for submerged performance is quite unsuitable when on the surface.

Submarines are also relatively small vessels and this means that to make any decent speed on the surface they would be operating at a high Froude number (i.e. high speed to length ratio), so that the wave-making component of the total resistance, in spite of the submarines smooth and streamlined form, would quickly become the dominant surface resistance. Also, the full form elliptic bow optimised for underwater performance does not perform well on the surface as it causes a large upwelling of a bow wave right across the foredeck reaching back as far as the bridge fin. Additionally, this tends to drive the hull beneath the surface, which requires the submarine to run at a large stern trim and use its forward hydroplanes as a means of keeping the bow up out of the water. As a consequence, both of these actions add to surface resistance (Burcher RK & Rydill RJ 1994).

These problems could of course be solved by simply making the form more ship shaped and by the introduction of a pointed flared bow, typically the shape of WWII submarines that were capable of a greater surface speed than some of the modern nuclear submarines operating on the surface. Unfortunately, a design change towards a more ship shape militates against a submarine hull form optimally designed for an environment where submerged performance is paramount.

John Teasdale's 1959 study provides us with a good technical comparative analysis of the resistances to motion of submarine and surface vessels. For his analysis, he chose three hull forms all of 47,000 tons deadweight, a surface tanker and two teardrop shaped submarines; one having a circular, the other an elliptical cross-section. Teasdale's principal criterion in comparing vessels was that the hull forms should be as close as possible to the optimum for minimum resistance.

Fig. 6: Comparison of resistances.



Source: Teasdale 1959.

The general conclusions reached were; that subject to some modifications, the elliptical–section form could conform to the same dimensional limitations as the surface vessel, however its performance was found to be "*inferior over the range considered and was likely to be so up to the fineness limits of the surface ship*".

His research however did confirm that the circular section submarine tanker was the optimum form for underwater propulsion. He found it had superior performance over both the elliptical form submarine and the surface vessel, as graphically illustrated in Fig. 6 but that "*the extent of the superiority is not overwhelming at normal speeds, certainly not sufficient to justify an increased capital cost, insurance and wages*" (Teasdale JA 1959).

The divergent wave system

The divergent wave system on the other hand, consists of bow and stern waves as shown in Fig. 5. The interactions of these waves over the speed range create the humps or hollows on the resistance curve, as shown in Fig. 6. The hump is caused when the crests of the bow and stern waves are in phase creating a larger divergent wave system. Conversely, the hollow is caused when the bow and stern waves are 180 degrees out of phase. i.e., the crests match the troughs, so that smaller divergent wave systems are formed.

Again, for submarines operating on the surface these humps and hollows become significant, because the short fat form is unsuited to the surface speed range, and it quickly leads to operation near the main hump of the resistance curve. To solve this, an increase in length would be required to bring the vessel back down the steep part of the resistance curve. Unfortunately, this solution would be counter-productive because increased surface area brings with it a corresponding increase in skin friction, which in turn would have a negative effect on submerged performance.

Calculating total wave-making resistance in practice

The parameters affecting total wave-making resistance are beam to length ratio; hull shape; displacement and Froude number. Unfortunately the calculation of a single coefficient from a theoretical or empirical equation is complex, difficult to determine and inaccurate. In the last two decades computers and the science of computational fluid dynamics (CFD) have made significant advances, but because of the complexity, wax model tests in a towing tank and Froude expansion are still normally needed to calculate the wave-making resistance of the real ship.

Air resistance

This is experienced by the above water part of the main hull and superstructure due to the motion of the ship through the air with no wind present. Ships with low hulls and small sail areas such as submarines will consequently have less air resistance than say an cruise liner or a Roll-on Roll-off (RORO) vessel, which have high hulls and large amounts of exposed sail area. Resistance due to air is normally in the range of 4 to 8 percent of the total ship resistance for general cargo vessels, but can be as much for 10 percent for high-hulled vessels. Hulls and superstructures can in certain circumstances be streamlined to reduce air resistance. However, the power benefits and fuel savings associated with constructing a streamlined ship tend to be outstripped by added construction costs. Conversely, because submarines are already streamlined, air resistance is a very small component of the total resistance to motion; on average, less than four percent.

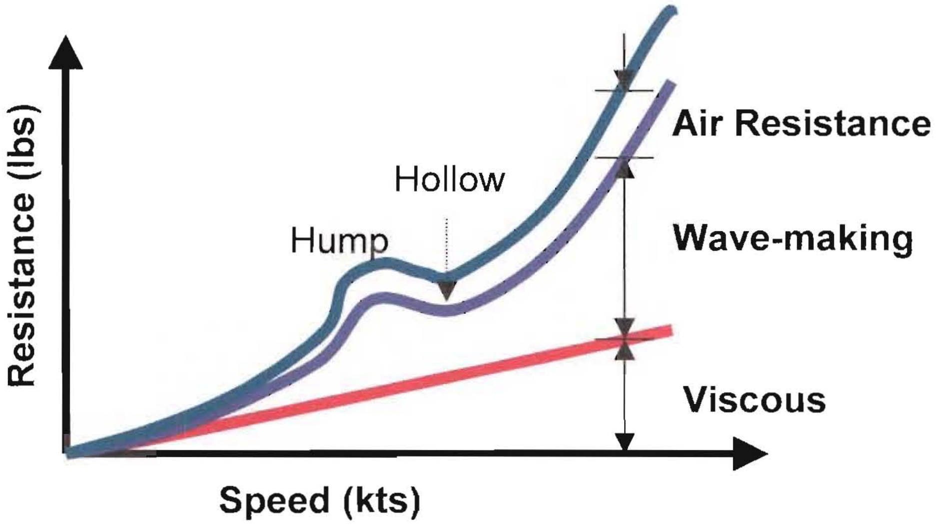
A typical chart showing the bare hull total resistance and the relative magnitude of components for vessels on the surface is given in Fig. 7. It can be seen that the amount of each resistance component will vary according to speed. The main rationale for quantifying the total resistance is so that the effective horsepower (EHP) needed to drive the vessel can be calculated. From this, the size and type of the prime mover together with its location and fuel source can then be decided upon.

At low speeds, viscous resistance dominates; but at higher speeds the total resistance curve rises dramatically upwards as the resistance due to wave-making becomes more dominant.

The hump and hollow locations are a function of ship length and speed and are due to interactions in the ships wave train.

This information is particularly useful to naval architects who use the hollows to determine the on-surface service speed where total resistance is least.

Fig. 7: Components of resistance versus speed.



Source: Hornyak T, US Navy NAOE 2003.

Wind and current resistance

Both wind and currents can have a significant effect on ship resistance.

Wind

Geoff. Hughes carried out significant work on the wind resistance of ships in the 1930's for the Institute of Naval Architects in conjunction with the British Ship Research Association (BSRA) these estimates are summarised in Table 1 below (Hughes G 1930 *Model experiments on the wind resistance of ships*, Institute of naval Architects, INA).

Table 1: Wind resistance of surface vessels.

Vessel Type	Disp. Tons	EHP H.P.	Service Speed Knots	Wind 20Kts	Wind 40Kts	Diff Kts 20	Diff Kts 40	Diff % 20	Diff % 40
Tanker	16000	1207	10.0	8.89	6.73	1.11	3.27	**11.1%**	**32.7%**
Cargo Ship	14800	2815	14.0	13.13	11.76	0.87	2.24	**06.2%**	**16.0%**
Cruise Liner	38000	3500	25.0	24.17	23.27	0.83	1.73	**03.3%**	**06.9%**

Source: extracted from (Hughes G 1930 *Model experiments on the wind resistance of ships*: Institutes of Naval Architects).

These estimates apply only to a headwind and give the additional wind resistance only; ignoring any effects of seas, which would accompany high winds. For winds up to 30 degrees of the bow the additional resistance to ahead motion caused by the fore and aft component of the wind on the longitudinal projected sides of the ship may be 30 percent greater than the values given in Table 1.

Submarines with their low surface profile, hydrodynamic shape, streamlined superstructures and smooth hull offer very little resistance to wind typically less than 2 percent.

Currents

the author's

Currents can have significant impact on the ship's resistance and the power required to maintain its service speed. For example the Benguela and Agulhas currents off South Africa sometimes reach speeds of 4 knots. However, from my personal experience many of these ocean currents have associated counter-currents running in the opposite direction closer to the shoreline that can be taken to advantage by the prudent mariner. Submarines operating as they do in three dimensions have an added advantage of being able to get below some current layers or even take advantage of currents running counter to the surface current at depth. One well known vertically separated density current system is found in the straits of Gibraltar where the direction of surface current runs counter to the current located about one hundred feet below the surface. This was used to great effect by German U-boats during WWII who traversed the straits in both directions, without the use of engines by just simply changing depth and letting the current do the rest.

Conclusions

From the foregoing it can be seen that optimum hull shape for surface vessels and that of submarines are clearly not the same. A hull form optimised for submerged speed and efficiency performs poorly when operating on the surface and conversely for a ship shaped vessel optimised for surface operation performs poorly once submerged.

The main advantages claimed for submarines, in contrast to surface vessels, is the elimination of wave-making resistance and independence from the effect of weather. However, volume for volume, the submarine has a greater wetted surface than the surface vessel and therefore starts off with the handicap of greater frictional resistance. The absence of wave-making resistance does not start to take effect until fairly high speeds are reached around 25-30 knots. Most of the concept proposals for commercial submarines have been for the carriage of liquid cargoes such as oil or high value ores, both of which do not require high speeds of transport.

When all of the hydrodynamic factors are taken into consideration the energy required to propel the submarine and the surface ship are roughly equivalent (Todd FH 1967).

The fact that submarines are required to make some of the passage on the surface, where the effect of weather and wave-making resistance would have a proportionally greater effect than on a surface vessel designed specifically for that environment; should always to be taken into consideration, when making an overall comparison of the total passage time between terminals.

In 1960, FH Todd of the National Physical Laboratory in the United Kingdom wrote a highly technical paper entitled *Submarine Cargo Ships and Tankers.*

Unlike previous studies, Todd's study did not focus on specific submarine design but rather performed a very thorough analysis of submarine tankers in comparison with nuclear and conventional powered surface ships. Because Todd's study is considered to be especially authoritative and unbiased, excerpts from his general conclusions are quoted below.

"*The general conclusion which can be drawn from all the above evidence is that submarine cargo ships and tankers of circular cross section could be designed to compete with surface ships of the same deadweight as regards their power requirements, especially when one takes into consideration the effects of rough weather, from which the submarine would be immune. Such submarine ships would have excessive drafts, however, and if this is avoided by using elliptical sections, then the submarine's superiority soon disappears. However, up to such speeds as those for which an economical surface ship can be designed, say of the order of 25 to 30 knots, the cost of the submarine; of the necessary docking facilities; and of the provision of offshore terminals could not at present be justified on economic grounds. The case for the submarine would be even less favourable at this time if we were to compare it with a conventionally propelled surface tanker. The greatest commercial incentive for submarine ships at the moment would appear to be their use on special routes where the attraction of making special profits. Leaving aside economic questions, there is no doubt as to the extreme advantage of having such craft for military use and for the transport of valuable cargoes in wartime. It may well be that some government will build a craft of this type very soon both for its military potential and national prestige, and to gain experience in the operation of such ships*" (Todd FH 1960 *Submarine cargo ships and tankers*: 3rd Symposium on Naval Hydrodynamics, Office of Naval Research, Dept. of Navy, ACR-65, 1960), & (Varley F 1972 *The cargo submarine*: US Naval War College; RI).

However since 1960 there have been significant shifts in the economic paradigms used by Todd in his original assumptions. In 1960 for example oil cost $12 U.S. per barrel as opposed to nearly $100 at today's prices.

Secondly, and most significantly from a technical point of view, nuclear propulsion was then and still is very costly to purchase and operate; which, potentially puts it beyond the reach of commercial operators. Since 1960 there has been considerable interest in the development of non-nuclear air independent propulsion systems; the commercial use of which could in my view provide the necessary catalyst to make submarine cargo vessels a reality.

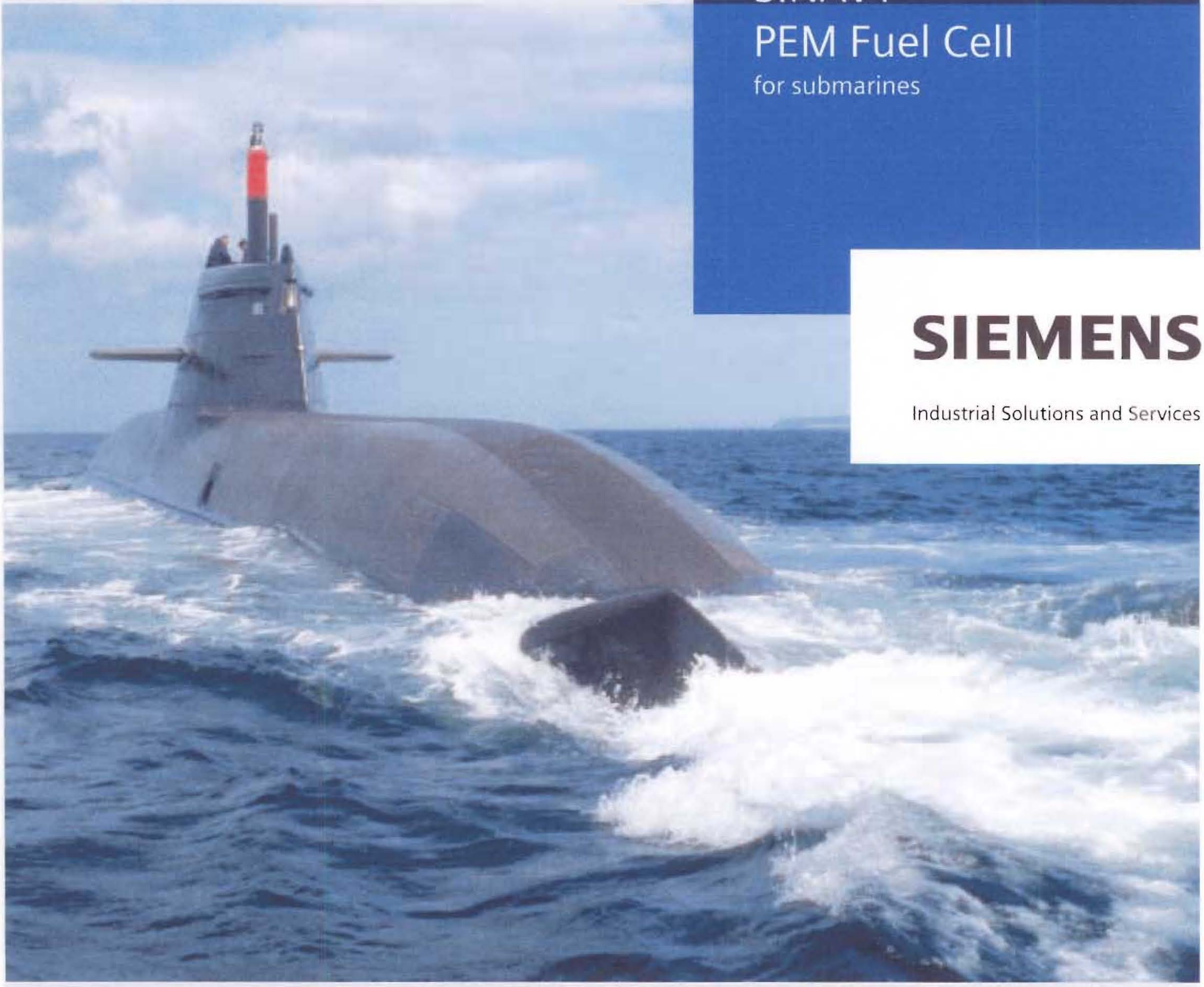
APPENDIX (03)

1) SINAVY ^{CIS} PEM FUEL CELL FOR SUBMARINES

2) FUEL CELL PROPULSION FOR SUBMARINES

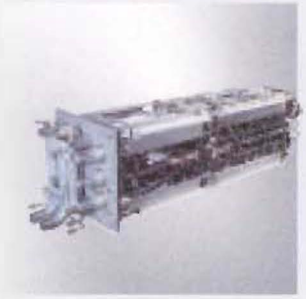
Completely Integrated Solutions
for the Navy

SINAVY^{CIS}
PEM Fuel Cell
for submarines



SIEMENS

Industrial Solutions and Services



Your Success is Our Goal

Application Potential

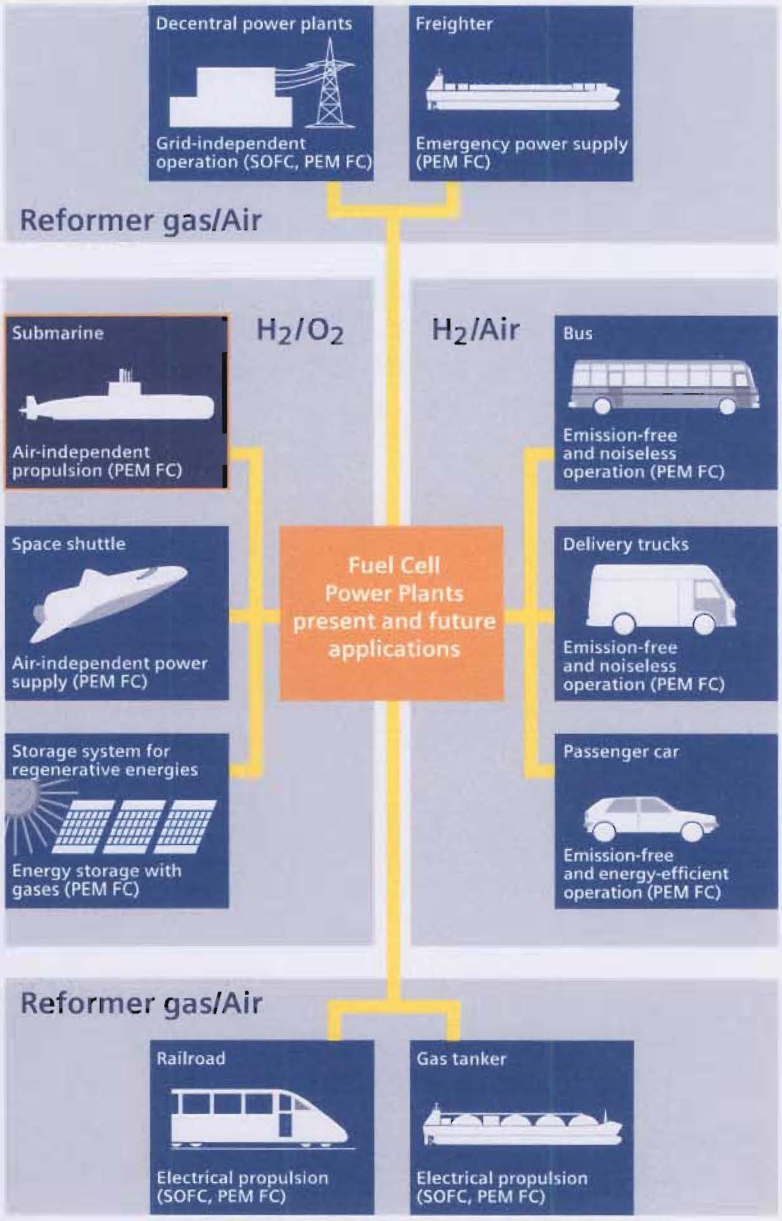


Fig. 1: Possible applications for fuel cell power plants

SINAVY^{CIS} – Completely Integrated Solutions for the Navy

As a comprehensive industry-specific solution for naval vessels, our SINAVY^{CIS} product family integrates all the products and services you need for sustained maximization of your ship's performance.

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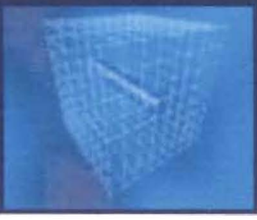
- vertically integrates the ship's information and security management end-to-end, helping to make better-founded decisions
- and, at the same time, is designed for optimal vessel-specific maintenance and comes with assured further development over the whole life cycle

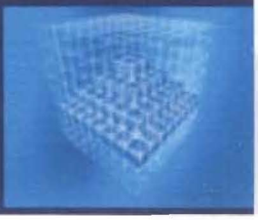
Due to this unique combination of horizontal, vertical and life cycle dimensions, our solutions all carry the genes of an exhaustive and sustained plant productivity in their very core.

For More Stability. More Availability. More Power. Completely Integrated Solutions from Siemens.

Horizontal Integration



Vertical Integration



Life Cycle Integration

Cover photo: BZM 34 module (left)
and BZM 120 module (right)

Introduction

Fuel cells allow the direct generation of electric power from hydrogen and oxygen with a considerably better efficiency and no pollutant emission compared to conventional combustion engines. Their operation is noiseless.

In addition to these basic advantages, the fuel cell with a solid, ion-conducting, polymeric membrane (Polymer Electrolyte Membrane – PEM) has further positive properties:

- Quick switch-on, switch-off behavior
- Low voltage degradation and long service life
- Favorable load and temperature cycle behavior
- Overload possibility
- Low operating temperature (80 °C)
- Absence of a liquid-corrosive electrolyte.

All these characteristics make the SINAVY^{cs} PEM Fuel Cell an ideal power unit.

Aboard submarines they show their outstanding advantages against conventional AIP systems (Air-Independent Propulsion) using oxygen and hydrogen, carried on board.

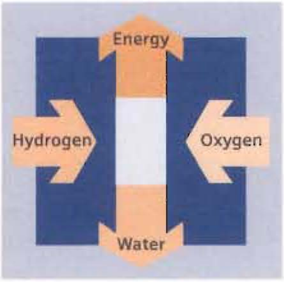


Fig. 2

Siemens has two types of SINAVY^{cs} PEM Fuel Cell modules for you to choose from. The BZM 34, with a rated power of 34 kW, as well as the BZM 120, with a rated power of 120 kW.

The new submarines of class U 212 A are equipped with BZM 34 modules, which have been developed since 1985 on behalf of the German Ministry of Defense. The new 214-class submarines – up to now for Hellenic Navy and the Republic of Korea Navy – will be fitted with BZM 120 modules which have been developed by Siemens in a next step.

Existing submarines can be upgraded with an additional fuel cell power plant during refit, thus getting the benefits of the Air-Independent Propulsion (AIP) at a much lower price than for new submarines.

The Hellenic Navy has placed an order for modernizing three submarines of class 209 by installing fuel cell AIPs – among other measures of refit.

The suitability of fuel cell technology on board submarines has been demonstrated by earlier tests and now on board of submarines of classes U 212 A and 214.

Further possible applications of SINAVY^{cs} PEM Fuel Cell for power generation are listed below (see also fig. 2):

Using hydrogen and oxygen

- Operation in spacecrafts
- Component in a long-term energy storage system (consisting of solar cells, an electrolyser system and a hydrogen/oxygen storage system)

Using hydrogen and air

- Zero-emission operation of electrically driven vehicles

Using reformer gas and air

- Power supply far distant from a public power supply system
- Safe, low-emission power supply on cargo vessels especially in harbor
- Utilization of boil-off gases aboard gas tankers
- Power supply e.g. for drives on rail vehicles

Concentrating on manufacture and development of fuel cells for AIP applications, Siemens demonstrated its technological competence in projects for air-breathing fuel cells, e.g.

- Fork lift truck
- Micro co-generation
- Propulsion systems for busses.

The Siemens R&D activities in regard of other types of fuel cells like Solid Oxide Fuel Cells (SOFC) are not presented in this brochure.

PEM Fuel Cell: function and design

Both the basic function and the design of the SINAVY^{cis} PEM Fuel Cell are very simple (fig. 3): the electrochemical element at which the chemical energy is converted into electrical energy is the membrane electrode unit. It consists of the polymer electrolyte, the gas diffusion electrodes with a platinum catalyst and carbon sheets on each side.

After the abstraction of the electrons from hydrogen – they flow from the anode via the electrical load to the cathode – the resulting protons migrate from the anode to the cathode where they combine with oxygen (and the electrons) to water. The theoretical voltage of an H_2/O_2 fuel cell is 1.48 V (referred to the upper heat value of hydrogen). At zero load conditions, slightly more than 1 V per cell is available.

The cooling units or bipolar plates in combination with carbon diffusion layers distribute the reactants uniformly across the area of the cell, conduct the electrons across the stack, remove the heat from the electrodes and separate the media from each other.

Fig. 4 shows the two core components of a cell with outside dimensions of 400 mm x 400 mm. As used in BZM 34 modules.

Fig. 5 compares the bipolar plate of the BZM 34 modules to the BZM 120. Two cells of the BZM 120 produce about twice the power of one cell of the BZM 34 type with nearly the same active area.

The in principle high development potential in regard to the membrane material is shown in fig. 6. With improved materials the power density can nearly be doubled.

The voltage of a SINAVY^{cis} PEM Fuel Cell referred to the operating time is stable, degradation rates are less than 2 µV/h for the BZM 34 module (fig. 7).

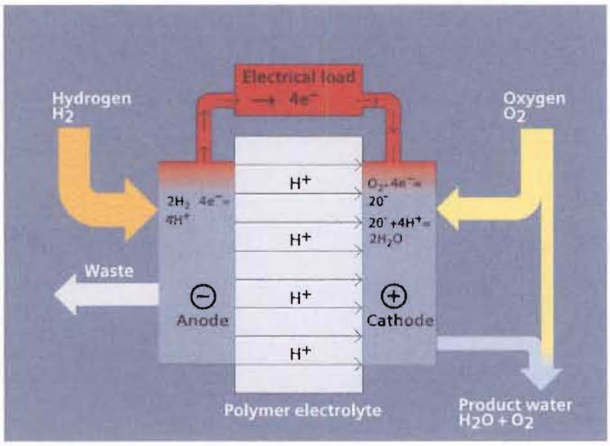


Fig. 3: Functional principle

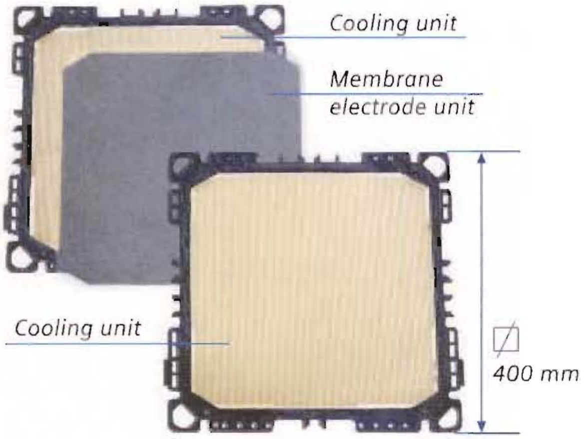


Fig. 4: Components of cell

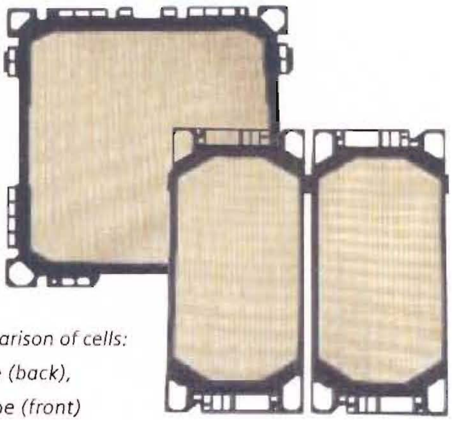


Fig. 5: Comparison of cells:
BZM 34 type (back),
BZM 120 type (front)

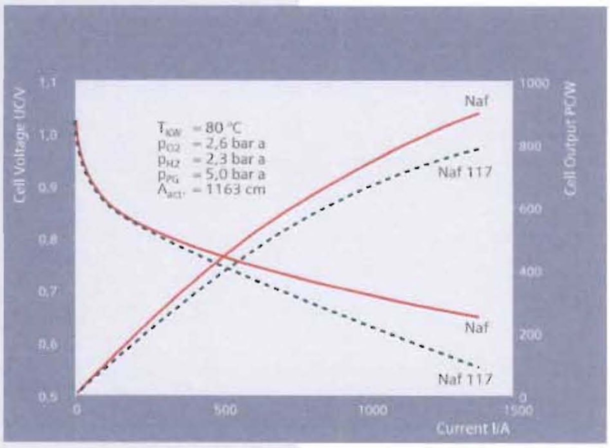


Fig. 6: Potential output increases by using various electrolytes

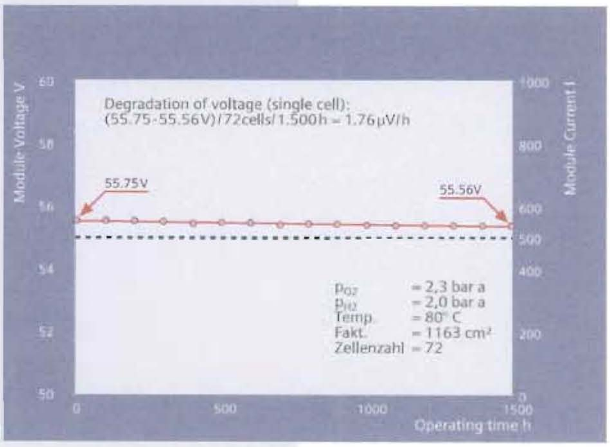


Fig. 7: Voltage degradation

PEM Fuel Cell modules and power plant

PEM Fuel Cell modules

The fuel cells need additional auxiliaries for their operation. The PEM Fuel Cell stack, valves, piping and sensors form the PEM Fuel Cell module, the corresponding module electronics controls the proper operation of the PEM Fuel Cell process. The ancillaries comprise the equipment for supplying H_2, O_2 and N_2, for reactant humidification, for product water, waste heat and residual gas removal. The PEM Fuel Cell stack and the ancillaries are installed in a container which is filled with inert gas (N_2) at 3.0 bar abs. to prevent a release of H_2 and/or O_2 in the case of leakage.

The PEM Fuel Cell module can be operated at various static load currents. Currents below 650 A for BZM 34 modules or below 560 A for BZM 120 modules respectively can be applied in continuous operation. The output power/current characteristics for BZM 34 modules are shown in fig. 8.

For currents above the rated current the loading time is limited due to the insufficient heat removal at such working points. Even loads up to the double of the rated current can be applied for a short time.

At the rated operating point, the overall efficiency is approximately 59% referred to the lower heat value of H_2 (LHV). It increases in the part load range, reaching a maximum of approximately 69% at a load factor of some 20% of the rated current (approx.100 A) (fig. 9).

The properties of the BZM 34 and BZM 120 modules are listed in the table.

PEM Fuel Cell power plant

Suitable operating conditions for fuel cell modules are provided for submarine application by a fuel cell system in which fuel cell modules are connected

- to the hydrogen and oxygen supply
- to disposal units such as for
  - cooling
  - residual gas
  - reaction water
- to auxiliary systems such as for
  - inert gas drying
  - nitrogen supply
  - evacuating system
- to the propulsion/ship's system as the purpose of the whole PEM Fuel Cell system.

Operator control and visualization of the fuel cell system are effected by the integrated platform management system, or directly by the control panel of the fuel cell system. Fig. 10 gives a simplified impression of the AIP system.

The fuel cell system in its entirety – the complete fuel cell power plant, especially the supply and disposal systems described above for AIP operation including spatial and functional integration on board – has been developed by HDW (Howaldtswerke Deutsche Werft AG).

The new submarine classes U 212 A and 214 are equipped with the new fuel cell power plant by HDW with the SINAVY^{cis} PEM Fuel Cell modules by Siemens. An AIP section with SINAVY^{cis} PEM Fuel Cell modules can be added into existing submarines.

Fig. 11 shows SINAVY^{cis} PEM Fuel Cell modules assembled in a test rack.

Technical data	BZM 34	BZM 120
Rated power	34 kW	120 kW
Voltage range	50–55 V	208–243 V
Efficiency at rated load, approx.	59%	58%
Efficiency at 20% load, approx.	69%	68%
Operating temperature	80 °C	
H_2 pressure	2.3 bar abs.	
O_2 pressure	2.6 bar abs.	
Dimensions	H = 48 cm W = 48 cm L = 145 cm	50 cm 53 cm 176 cm
Weight (without module electronics)	650 kg	900 kg

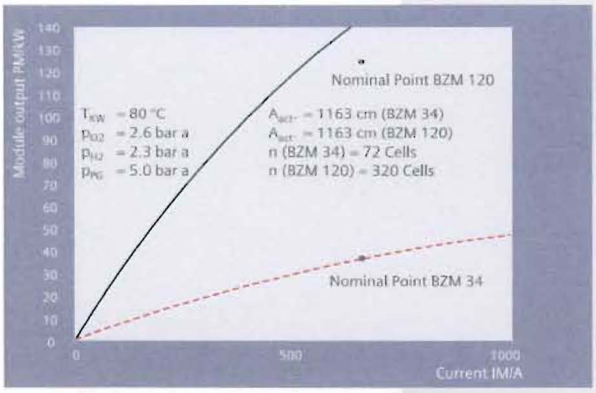


Fig. 8: Module output refers to load current

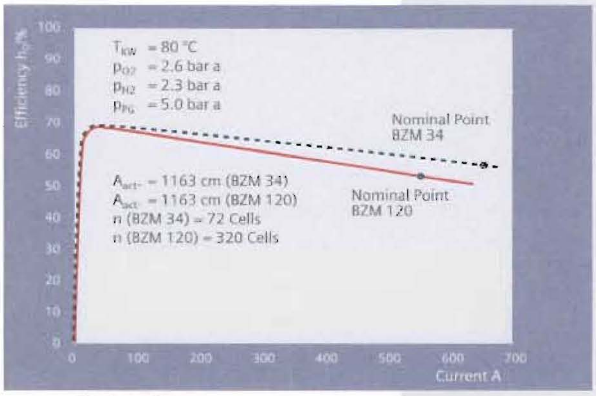


Fig. 9: Efficiency

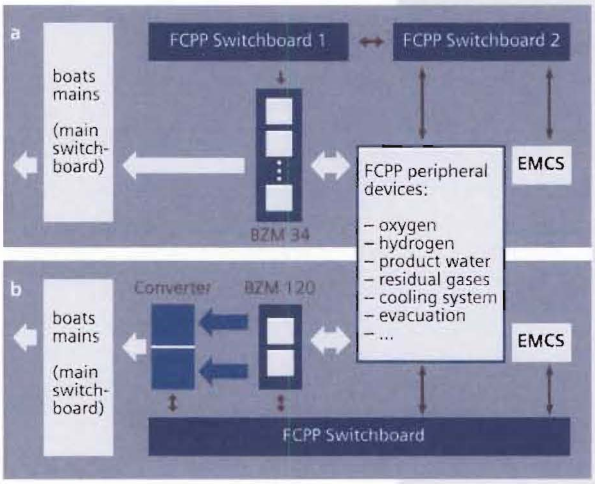


Fig. 10: Two types of fuel cell power plants (FCPP)
a: fuel cell battery with BZM 34;
direct coupling of FC voltage to boats mains
b: fuel cell battery with BZM 120;
coupling via converter

Fig. 11: PEM Fuel Cell modules assembled in a test rack

Outlook

After the successful development the SINAVY^{cs} PEM Fuel Cell modules are now ready for application. They have proven their performance and reliability in extensive tests including long-term tests and on board of submarine U31 of the Federal German Navy. They are an integral part of an AIP system for modern submarines like that of class U 212 A and 214. An AIP section with SINAVY^{cs} PEM Fuel Cell modules can be added into existing submarines.

The field for use of SINAVY^{cs} PEM Fuel Cell will be widened when suitable reformers produce hydrogen from liquid fuels, e.g. methanol. Then it may be possible that fuel cells can become the sole power source of submarines of the future.

Using SINAVY^{cs} PEM Fuel Cell and replacing oxygen with air, they are an interesting alternative for environmental-friendly power generation, e.g. for vehicles in cities.

A transportable 160-kilowatt fuel cell system for emission-free power generation on board of ships has been designed. The system is housed in a container, which allows it to be brought for demonstrations and tests and to be easily connected to the ship's power supply. It is to be delivered in spring, 2005.

In general: the excellent operating performance of SINAVY^{cs} PEM Fuel Cell like high efficiency and noiseless operation can lead to a promising future upon further reduction in manufacturing and operating costs.

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21.08.2006

Fuel Cell Propulsion of Submarines

Dr. Albert E. Hammerschmidt, Siemens AG, Erlangen

Polymer-Electrolyte-Membrane (PEM) Fuel Cells are known for the efficient conversion of chemical energy stored as hydrogen and oxygen into electricity. Comparative studies of fuel cells and other air independent propulsion (AIP) systems such as Stirling engines, closed cycle diesels, and steam turbine systems in conventional (non-nuclear) submarines have clearly shown the superiority of the low temperature fuel cells to combustion-based solutions. The PEM fuel cell was selected to provide a new generation of conventional submarines with an AIP system enabling heretofore unattainable durations for submerged operations together with exceptional acoustic performance.

Siemens PEM fuel cells are based on metal technology with a compact design, fully meeting the volume constraints of the submarine designer (Figure 1). Additionally, the technology allows high power density together with excellent thermal management of the cells. The latter is an important prerequisite to acceptable service life.

The two fuel cell designs currently installed in active submarine construction programs are the Product Family SiNavy$^{(cis)}$ PEM Fuel Cells, BZM 34 and BZM 120, operating in the rated power range of 34 and 120 kW respectively. The BZM 34 (Figure 2a) was designed for the Type 212 submarine, which is being delivered to both the German and Italian Navies at present and has been successfully integrated into a fuel cell power plant configured to feature redundancy. The subsequent development of the BZM 120 (Figure 2b) enabled an application suitable for the Type 214 export submarines in addition to upgrade or retrofit programs of previous submarine designs (e.g. Type 209).

Electrical and mechanical data of both fuel cell modules are listed for comparison in Table 1. As the data illustrates a significant improvement of integration density was realized from the BZM 34 to the BZM 120 design.

The fuel cells show excellent dynamic behavior (Figure 3) with a capability to accept short-term overload conditions. The reduced efficiency apparent in the BZM 120 compared to the BZM 34 is a design compromise between achievable technical performance (size, power) and economic requirements (cost).

The following table gives an overview of essential process interface data:

Oxygen @ ~ 2.3 to 2.6 bar (abs)
Oxygen purity ~ 99.5 %
Hydrogen @ ~ 2.3 to 2.6 bar (abs)
Hydrogen purity ~ 99.99 %, no S, no CO
Cooling water – secondary cooling loop
Ambient pressure ~ submarine atmosphere pressure
Residual gases oxygen/hydrogen: extremely low quantities to be released uncontained into the submarine's breathable atmosphere

The automated safety feature of the fuel cell module is achieved by maintaining an inert gas in the void between the container wall and the fuel cell stack at higher pressure than all media inside the stack. In the event of leakage (gaskets, etc.) the inert gas will penetrate into the stack creating conditions (pressure increase, voltage drop, and similar physical parameters) recognized by the control system to initiate emergency shutdown.

The design principles follow the demand for high power, low volume fuel cells and can be summarized in the following way:

High Current / Power density
  ~ 600 mA/cm2 @ 0.72 V (BZM 34)
  ~ 1000 mA/cm2 @ 0.70 V (BZM 120)
Water cooling of each metal bipolar plate
Thickness of single cell ~ 2.2 mm
Dead-ended system for hydrogen and oxygen
Integration of gas humidification into the fuel cell stack
Control of process and safety-related functions

Oxygen is stored in liquid form and hydrogen in metal hydride canisters to feed the fuel cell power plant. Storage quantities are sufficient to enable continuous production of electricity and support sustained submerged operations measured in weeks (Figure 4). The fuel cells generate electricity for low speed propulsion, the operation of the electrical equipment during silent run and for battery recharge. In case of high power demand, e.g. for escape purposes, the lead acid batteries provide burst speed capability.

In Type 212 submarines the fuel cell stack, which consists of nine fuel cell modules, is connected directly to the ship's main power system. Redundancy is achieved through an installed spare module which engages automatically in the event of a fault in any of the installed modules (Figure 5, right side).

In Type 214 submarines the two BZM 120 fuel cell modules are connected to the ship's power system via a DC/DC converter allowing adaptation of the fuel cell power plant to different battery voltage levels (Figure 5, left side). This becomes important in retrofit projects in which an integrated fuel cell system, consisting of the fuel cells, oxygen and hydrogen storage tanks, control system, process equipment and product water tanks, is integrated into an already existing submarine during a major overhaul. The DC/DC converter allows flexible adjustment of the fuel cell power plant to the electrical requirements of the retrofitted submarines varying significantly across different navies and different hull designs.

This submarine fuel cell system design can be considered as the first commercial application of PEM fuel cells without subsidies. The following submarines equipped with fuel cell power plants are on order or have already been delivered:

Class 212 (BZM 34, 9 modules/sub)
4 submarines for the German Navy (to date 3 submarines commissioned)
2 submarines for the Italian Navy (to date 1 submarine commissioned)

Class 214 (BZM 120, 2 modules/sub)
4 submarines (+ 1 land based test station) for the Hellenic Navy
2 submarines for the South Korean Navy

2 (+1) submarines for the Portuguese Navy (called 209 modified)

Class 209 MIDLIFE Conversion (Plug-In section)

3 plug-in sections for the Type 209 (Neptune retrofit)

Several additional contracts will be concluded in the near future.

Summary and Conclusions:

Siemens hydrogen/oxygen consuming SiNavy PEM Fuel Cells have been developed for the power range of 34 and 120 kW for application as Air Independent Propulsion systems for conventional submarines. These service proven components completely satisfy military specification requirements with respect to magnetic signature, low electrical stray field characteristics, system safety standards, acoustic properties, and shock/vibration criteria. Continuing interest in this application of fuel cell technology demonstrates its viability and has established PEM fuel cells as the standard for AIP solutions for conventional submarines.

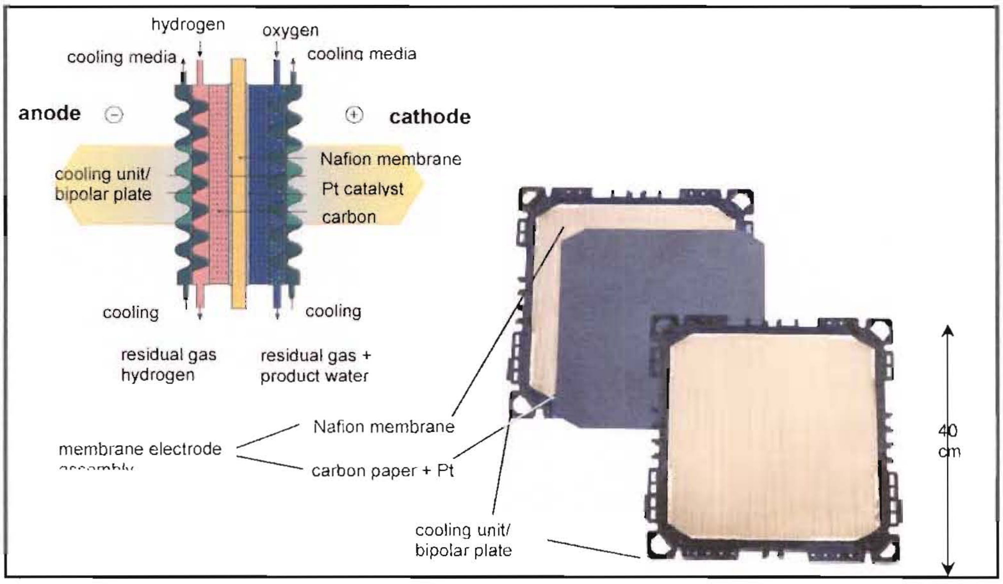


Fig. 1: Design features of a Siemens PEM fuel cell

Fig 2 a: SiNavy$^{(cis)}$ PEM Fuel Cell BZM 34

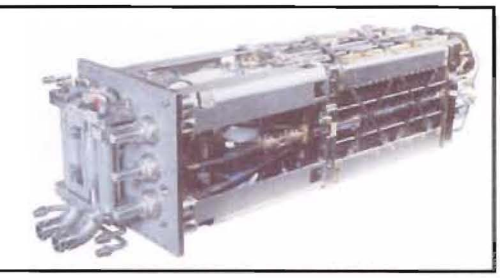


Fig 2 b: SiNavy$^{(cis)}$ PEM Fuel Cell BZM 120

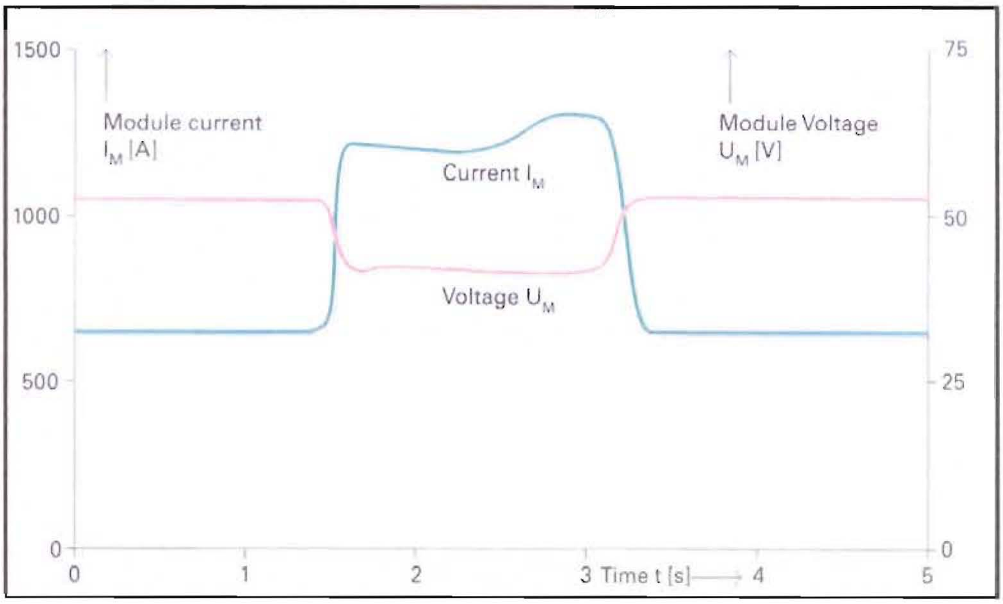


Fig. 3: Dynamic and overload behaviour of BZM 34

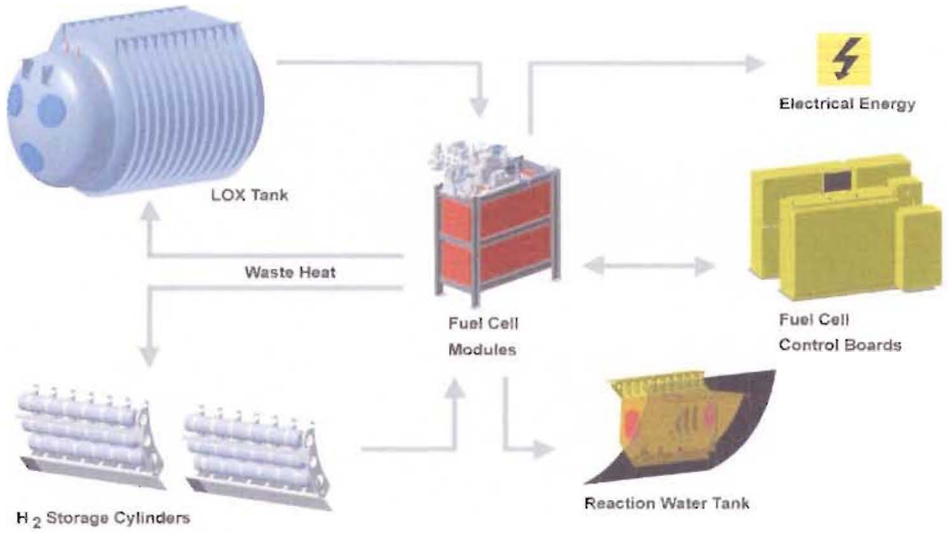


Fig 4: Main components of fuel cell power plant (FCPP) for a submarine (example: FCPP for a type U 214 submarine). Source: Howaldtswerft Deutsche Werft - HDW

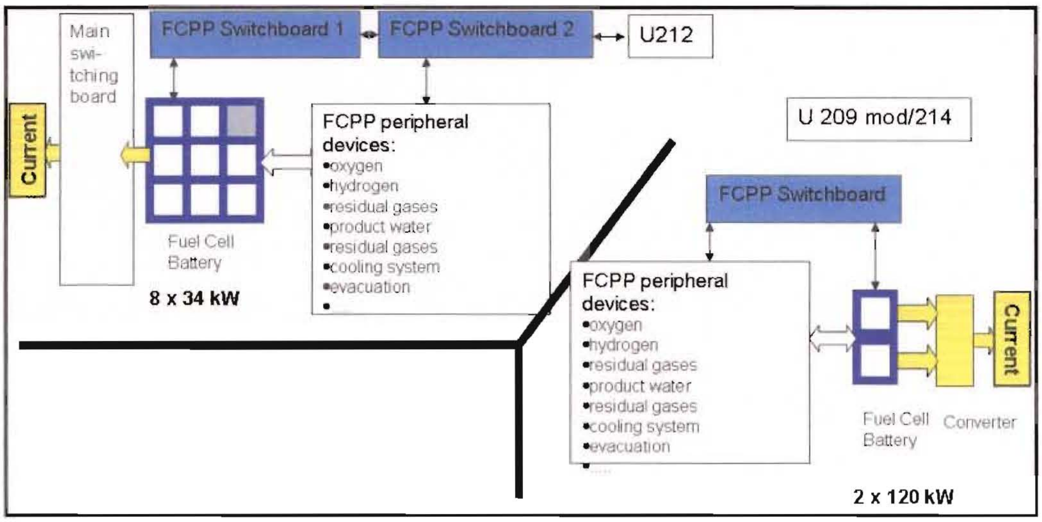


Fig. 5: Fuel Cell Power Plant: Block Diagram U212 (left side) and 209mod/214 (right side)

	BZM 34	**BZM 120**
Rated Power	34 kW	120
Number of Cells	72	320
Rated Current	650 A	560 A
Rated Voltage	52,3 V	215 V
Hydrogen Pressure	2,3 bar a	2,3 bar a
Oxygen Pressure	2,6 bar a	2,6 bar a
Working Temperature	70 - 80°C	70 - 80°C
Size	47x47x143 cm3	176x53x50 cm3
Weight (incl. press. container)	650 kg	900 kg
Efficiency at full load	62%	56%
Efficiency at 20% load	72%	68%

Tab. 1: Comparison of Electrical Properties of BZM 34 vs. BZM 120

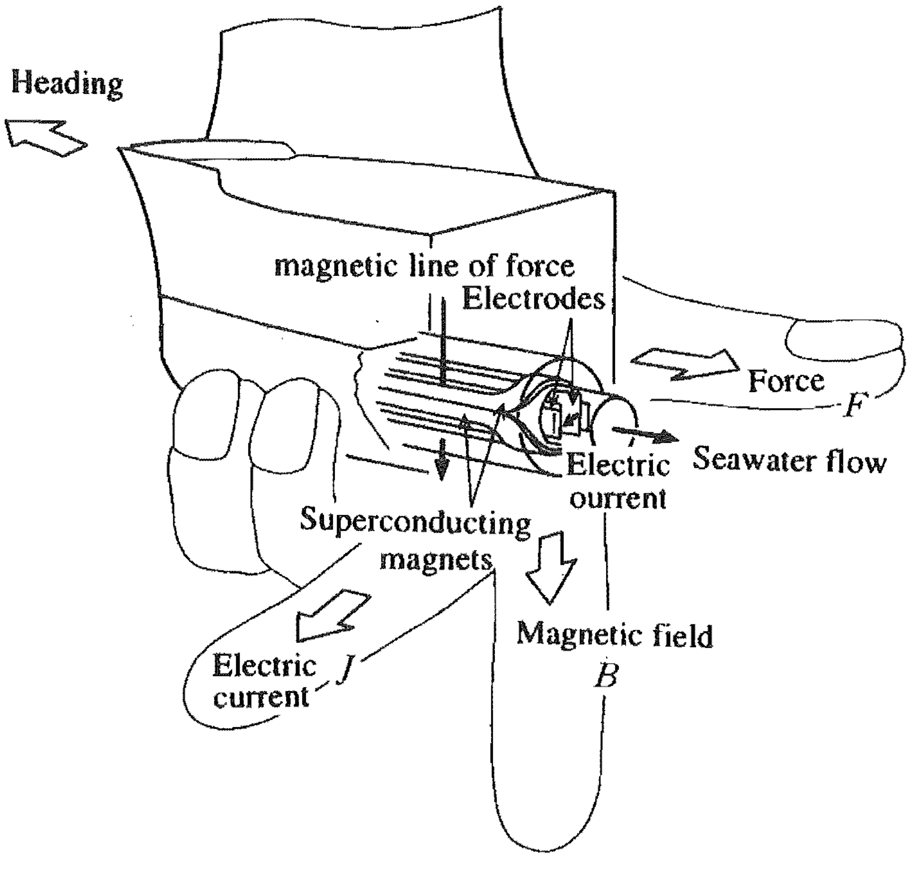
APPENDIX (04)

1) ELECTRO MAGNETO-HYDRO-DYNAMIC PROPULSION (EMP)
(Fleming's left hand rule)

APPENDIX 04

MAGNETO HYDRODYNAMIC PROPULSION

Fleming's left hand rule: showing magnetic field; electric current; and fluid motion



APPENDIX (05)

1) OPERATION OF THE THRUSTER FOR SUPERCONDUCTING ELECTROMAGNETOHYDRODYNAMIC PROPULSION SHIP *YAMATO 1*

Operation of the Thruster for Superconducting Electromagnetohydrodynamic Propulsion Ship "YAMATO 1"*

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* *

The Ship & Ocean Foundation set up "a research and development committee for MHD ship propulsion" in 1985 and started an extensive R& D studies, and to construct an experimental ship to demonstrate that a ship can really be propelled by MHD thrusters with all the necessary machinery and equipments on board. The experimental ship,named the YAMATO 1, was completed in the fall of 1991 and was actually propelled successfully by MHD thrusters in the summer of 1992 in KOBE harbour.

There are many complete different handlings & operational sequences required for the operation of Superconducting MHD thruster in comparison with usual one. This paper describes the manner & results of initial cooling down and exciting & demagnetization of the superconducting magnets, and compares measured data on the BOLLARD test with values calculated theoretically, and reports the agreement with them.

1. Preface

"YAMATO 1" is the first superconducting electro-magnetohydrodynamic (MHD) propulsion ship in the world. The ship was designed to be propelled by directly using electromagnetohydrodynamic force generated by sending electric current through a magnetic field cre-ated in seawater by superconducting magnets. The sea-trials were completed in the summer of 1992 success-fully in order to verify the propulsion system while being watched by many researchers in the world with keen intersest.

"YAMATO 1" is a ship built for the purpose of verifying possibilities of actualizing superconducting MHD propulsion ships. A committee named Superconducting MHD Propulsion Ship R&D Committee was organized by the Ship & Ocean Foundation in 1985 and had been engaged in develop-ment of this ship.

The superconducting MHD propulsion system requires an entirely different method of handling and operation as compared with conventional propulsion systems. The outline of "YAMATO 1" is presented in this paper. Also reported in this paper are operation of the propulsion system as well as the results obtained through bollard tests.

2. Principle of Propulsion

The principle of MHD propulsion is to apply the Heming's left hand rule of electromagnetics to seawater directly. As shown in Fig.1, a magnetic field is created in seawater by magnets fixed on a hull. When elec-tric current is sent to seawater at right angles to the magnetic field, and electromagnetic force (Lorentz force) acts on seawater in the direction perpendicular to both the direction of magnetic field and that of electric current. Propulsion force is gained as a reaction force of this Lorentz force.

The Lorentz force F (N) which is the source of thrust force T is given by the following formula:

$F = Jv\ J\ X\ B\ dv$ (N) ....(1)

where J is a current density vector of infinitesimal volume dv and B is a magnetic flux density vector of the same.

When J and B are constant over the entire volume V (m3) of the working part where magnetic field and electric current interact, Eq.

(1) can be expressed by the following formula:

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$F = J X B X V$ (N) ....(2)

MHD propulsion systems may be classified into those of external field type and those of internal field type depending on the space where interaction occurs.

In the case of "YAMATO 1", a DC internal field type is adopted and the working part is formed in a duct passing through the hull in order to minimize the magnetic field leaking to the inside and outside of the hull as much as possible.

The Lorentz force F is a pure force generated in a part where electromagnetohydrodynamic force acts and the thrust force T generated by an MHD propulsion sys-tem is of a value obtained by subtracting friction forces of fluid in the duct and fluid losses at the inlets, nozzles, contracted pipes, etc. from the Lorentz force.

3. Outline of "YAMATO 1"

The principal design and specifications of "YAMA-TO 1" have already been reported in detail in the references 1)- 9). Therefore, the outline of the specifications, principal arrangement and major system diagrams are presented in this paper.

3.1 Outline of hull part and machinery part

The principal particulars are shown in Table 1 and the general arrangement and the outline diagram of propulsion system are shown in Figs.2 and 3 respective-ly. The outline of machinery arrangement is described hereu nder.

In the wheel house, a console is installed at the for-ward center and maneuvering equipments such as steering wheels and thruster output control levers as well as verious control and monitoring apparatus for main generators, auxiliary generator, etc. are incorporated in this console.

In the electric power panel room, two sets of electric power panels are installed. These panels are to convert AC generated by the main generators to DC and to supply to the electrodes of propulsion system.

Each one set of thruster is arranged in bulged parts on each side of the engine room under the water line.Seawater inlets are provided on the fore side of these thrusters and outlet nozzles are provided on the aft side. For astern operation, a system is provided on each side to get astern propulsion power by changing the polarity of electrodes for sending electric current through sea-water. In addition to this system, an astern operation unit of a bucket lifting and lowering type is provided at the aft side of the seawater outlet nozzles also.

On the upper deck center of the engine room, two main generators for thrusters are installed fore and aft and an anxiliary generator for general service onboard is arranged on the starboard side aft.

3.2 Outline of propulsion system

The propulsion systems are composed of superconducting magnets, persistent current switches, helium refrigerator units, seawater pipes electrodes, etc. and each one set of these systems is arranged on the port and starboard sides of the ship respectively. The super-conducting magnets are of a six-linked ring construction with six saddle type superconducting coils being arranged on a concentric circle in a helium vessel. The leakage of magnetic field around magnets are made small as much as possible by mutually combining magnetic fluxes of each coil.

The magnet I and magnet II are of the same basic specifications having the same performance and the same dimensions for mounting on the hull, however, their detailed specifications are different to some extent due to differences in the desigh concept of respective

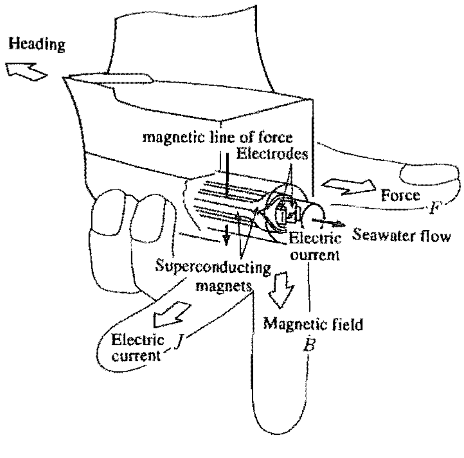


Fig. 1 Principle of MHD Propulsion Ship

Table 1 Principal Particulars of "YAMATO 1"

Particulars of "YAMATO 1"

Item		Specification
Length, overall		30.00m
Breadth, moulded		10.39m
Designed draught, moulded		1.50m
Displacement		185t
Navigation area		Smooth water area
Design speed		About 8kn
Thruster	Type	6-linked ring internal magnetic field type ×2units
	Output	Total Lorentz force About 16kN
	Electric current through seawater	About 3600kW
Onboard refrigeration system	Refrigerator	Turbo expansion Claud type×2units
	Helium compressor	Hydraulic screw type× 1units
Main generator		2000kW×2units
Auxiliary generator		1800kW×1unit
Complement	Crew	3
	Others (Test personnel, etc.)	7

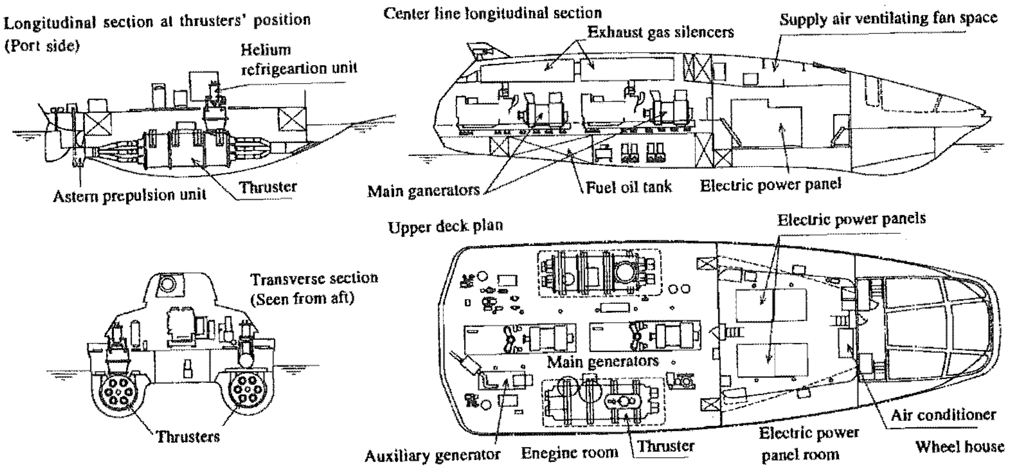


Fig. 2 General Arrangement of "YAMATO 1"

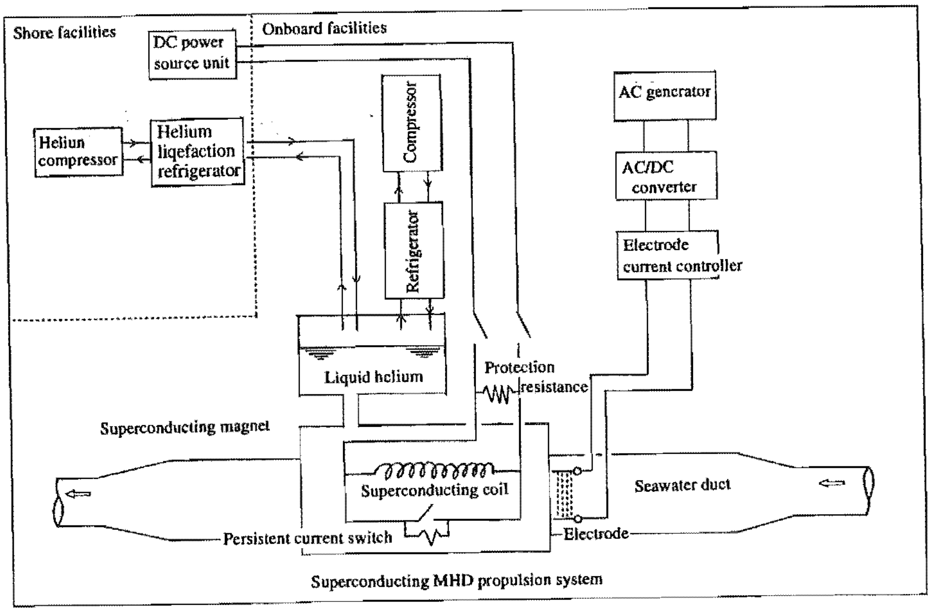


Fig. 3 Outline Diagram of Propulsion System "YAMATO 1"

manufacturer of these magnets. Details of the magnets are described hereunder using the magnet I as an example.

Table 2 shows the particulars of the six-linked ring magnet and Fig.4 shows the general assembly drawing of the six-linked ring magnet. Fig.5 shows the cross section of seawater pipe.

The seawater pipes are blow passages of seawater through the hull and are subjected to seawater pressure and electromagnetic force. Furthermore, the seawater pipes are required to be with a good insulating character against electricity in order to hold electrodes and bus bars for sending electric current. For these reasons, the seawater pipes are made of epoxy resin GFRP.

Titanium alloy is used as the base metal of the electrodes with the anode of DSA and the cathode plated with platinum. The length of electrodes is 3.4m.

3.3 Outline of shore support base

Because the superconducting magnets are to be operated in a persistent current mode during navigation, no facilities are required onboard for initial cooling of

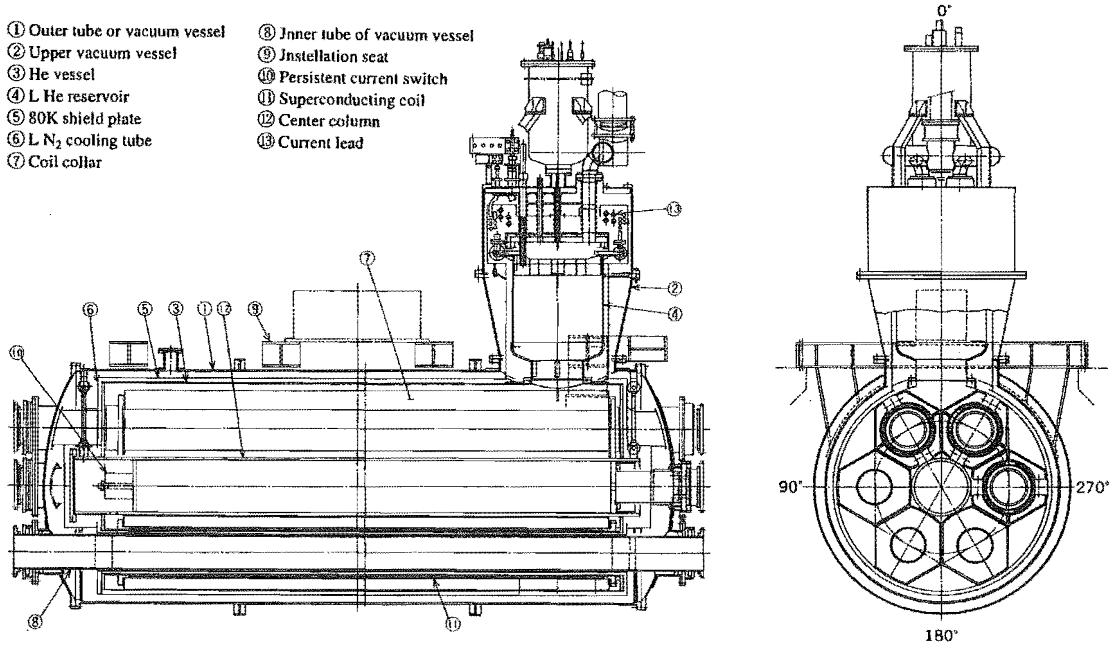


Fig. 4 General Assembly of 6-linked Ring Magnet

the superconducting MHD propulsion system from room temperature to the liquid helium temperature and for magnetization and demagnetization. Therefore, these facilities are installed ashore and it has been planned to reduce the weight of "YAMATO 1" and to simplify the propulsion system onboard.

The general arrangement of shore support base is shown in Fig.6 and the particulars of major facilities on shore are shown in Table 3.

Table 2 Particulars of 6-linked Ring Magnet

Item		Specification
Type		6-linked ring internal magnetic field type superconducting electromagnet
Superconducting coil		Dipole coil 6
Performance	Magnetic flux density at duct center	4T at 3770A
	Inductance	3.0H
	Electromagnetic energy	21.3MJ
Dimensions	Inside diameter at ambient temperature	260mm
	P.C.D of Bore at ambient temperature	1050mm
	Outer diameter of vacuum vessel	1850mm
	Overall length of vacuum vessel	5400mm
Cryostat	Type of insulation	L N_2 and vacuum shield
	Coil cooling	L He immersion
	Material	Stainless steel (L He vessel) Al alloy (vacuum vessel)
Accessories		Coil control panel (including quenching detection and control system) Protection resistor (0.6Ω) Persistent current switch Power lead Protection lead

4. Cooling method and cooling result of propulsion system

Unit coils were cooled for magnetization tests by submerging in L N2 and then submerging in L He. However, the 6-linked ring magnets are of a complicated construction, therefore, they were cooled by G He from room temperature to about 20K. In this method of cooling, air in the He vessel for the propulsion system was replaced with G He at first. Upon confirming that dew point became lower than -45oC and O2 content

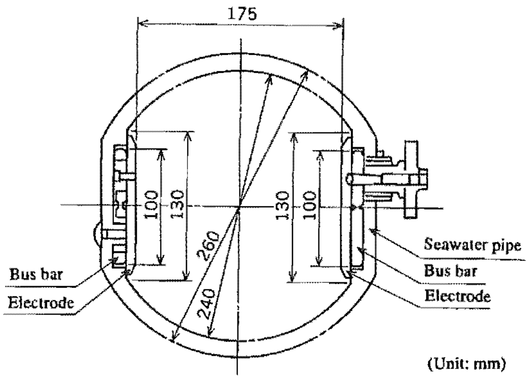
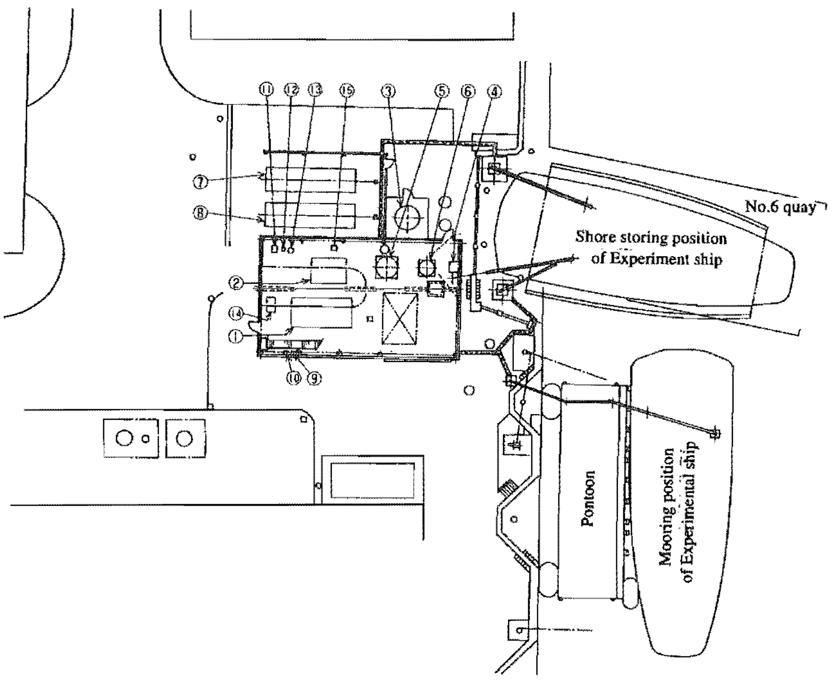


Fig. 5 Cross Section of Seawater Pipe



NO.	Name
①	Helium compressor
②	Recovery compressor
③	Liquid nitrogen tank
④	Recovery gas heater
⑤	Recovery tank
⑥	Ballast tank
⑦	Gas supply manifold
⑧	Recovery gas tank
⑨	Power distribution board
⑩	Lighting swith board
⑪	Control air compressor
⑫	Dryer
⑬	Air reservoir
⑭	High voltage motor control panel
⑮	Moisture condenser

Fig. 6 General Arrangement of Shore Support Base

reached below 50ppm, G He was then refined further to have a dew point of lower than -80t and an O_2 content of 1ppm through a G He refiner. Cooling of the magnets was then started. Prior to start cooling, the procedure for cooling was determined by making cooling simulation calculations and thermal stress analyses.

The cooling G He supply pipe is designed to blow out G He against an end plate fitted at the aft bottom part of the He vessel and G He used for cooling of coils, etc. is returned to the refrigerator by being sucked from the upper part of the L He reservoir. This G He supply pipe is designed to be commonly used also as the discharge pipe when discharging L He.

The magnets are to be cooled by circulating cooling G He, however, in order not to damage the propulsion system by thermal stresses caused by excessive temperature differences (in particular, temperature difference in the He vessel between the inner tube which cools down slowly and the outer tube which cools down fast),the temperature of supply cooling G He was gradually lowered step by step so that the temperature differences did not exceed 40K by monitoring temperatures of coils and various parts of the He vessel.

Table 3 Particulars of Major Facilities in Shore Support Base

Name of equipment	Number of units	Capacity and type
Helium compressor	1	1,950 Nm³/h 16 atm
Helium liquefier	1	300 W, 100ℓ/h
Helium recovery compressor	1	70 Nm³/h 150 kgf/cm²
Gas Bag	1	70m³ ~ 150 kgf/cm²
Liquid nitrogen tank	1	20m³ vertical type
Cooling water supply unit	1	125 tons of refrigeration
DC power source panel	2	4,800 A. 10V

Cooling was continued until the representative temperature of coils reached about 20K and then the super-conducting coils were cooled to about 4K by filling L He to the full level. L He filling was done by connecting L He Dewar to the L He filling port of the large He refrigerator on shore.

The results of initial cooling tests are shown in Fig.7 and the result of L He filling is shown in Fig.8.

5. Procedure and results of magnetization and demagnetization of propulsion system

The electric circuit diagram of the 6-linked ring magnets is shown in Fig.9. In the figure, P-1 - P6 are coils. The persistent current switch (PCS) is of a thermal type and turns to the OFF position when sending current to the PCS heater and to the ON position when stop sending current to the PCS heater and cooled to the L He temperature.

For magnetization, the PCS is to be set at the OFF position. Electric current is to be raised by handling the DC power source panel and the PCS is to be switched to the ON position when the current has reached the

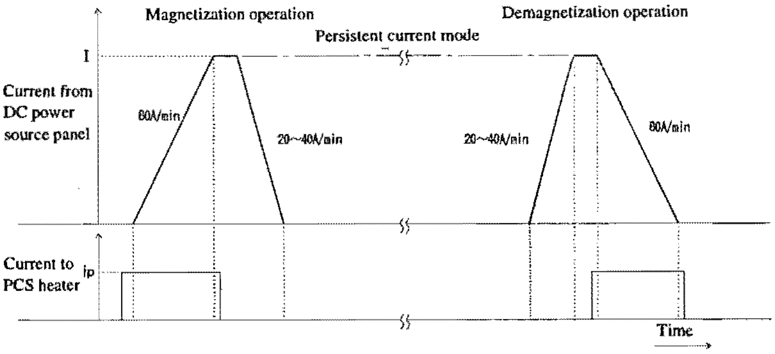


Fig. 10 Magnetization/Demagnetization Current Patern

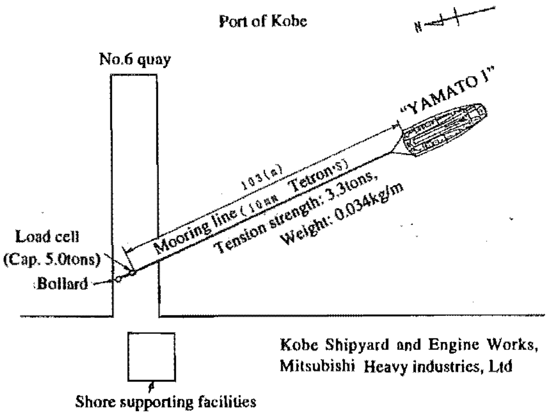


Fig. 11 Amangement of Bollard Test

reached a predetermined value, the PCS is to be switched to the OFF position and the current is to be lowered to O A.

The current patterns for magnetization and demagnetization are shown in Fig.10.

6. Thrust performance (Bollard test results)

6.1 Procedure for bollard test

As shown in Fig.1 1, the experimental ship with the superconducting magnets in a magnetized condition was moored to a quay by mooring lines fitted with ten-sion meters. Under this condition, electric current was sent between the electrodes and the generated pull force and pressure in the thruster duct were measured.

6.2 Calculation method for estimating thrust force

This ship is of superconducting MHD propulsion of an internal magnetic field type with a king of water jet propulsion system.

Thrust force T (N) generated by water jet is expressed by the following formula in general:

$T=pQ(Un-U_\infty)$ ....(3)

where T: thrust force (N)
p: Seawater density (kg/m^3)
Q: Flow in duct (m^3/s)
Un: Jet stream velocity from nozzle (m/s)
U_∞: Ship speed (m/s)

In the case of this ship, the propulsion system is composed of two ducts passing through the hull fore and aft with water flow being ejected into water at the stern. Therefore, in estimating the actual thrust force,the effects of pressures at the inlet and outlet of these ducts were taken into account additionally and the fol-lowing formula was used10):

$Td=p.Q(Un-Ui)+Pn.An-pi.Ai$.....................(3a)

where Td: Actual thrust force (N)
Vi: Inlet flow velocity (m/s)
Pn, Pi: Nozzle outlet pressure and inlet pressure respecti vely (N/m^2)
An, Ai: Nozzle outlet area and inlet area respectively (m2)

By applying the Bernoullis' equation to each part of the duct system from the inlet to the nozzle outlet, the following formula can be obtained:

$1/2.Ui^2\ 1/p+gH$
$=1/2.Un^2+1/p.Pn+f.1/2.Ui^2$ ....(4)

where H (m) is a head given to sea Water at the workjng part, g is the acceleration of gravity, and f is the total loss factor in the duct including the inlet and nozzle.

The Bernoullis' equation applied over the range between an infinitely forward point and the inlet becomes the following formula:

$1/2.U_\infty{}^2+1/p.P_\infty=1/2.Ui^2+1/p.Pi$
.............................(5)

From Eq.s (4) and (5), the following formula is obtained:

$gH=-1/2.U_\infty{}^2+1/2.(x^2+D.Ui^2+1/p.Pa$
................................(6)

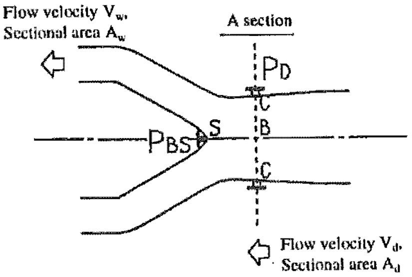


Fig. 12 Pressure Measuring Positions in 6 Branch Pipes

	1 T	2 T
Lorentz force	+	×
Bollerd pull force	○	●
Thrust force (calculated from pressure in the duct)	□	▣
Thrust force (estimated by calculation)	——	- - - -

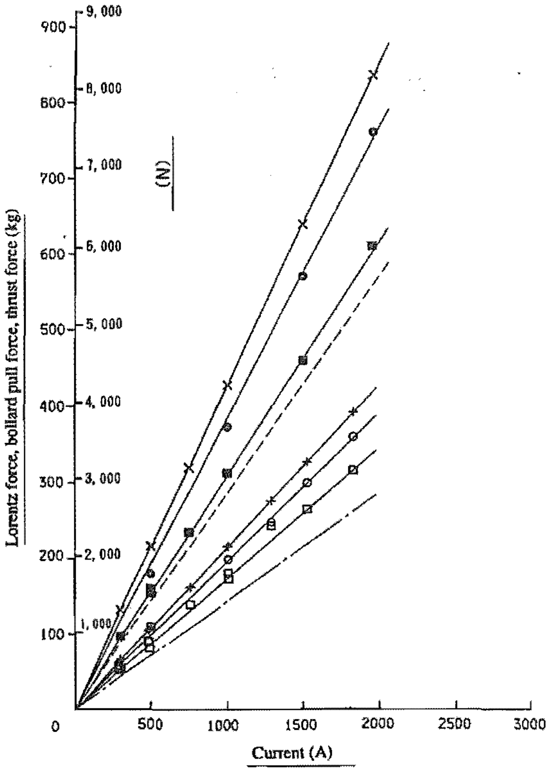


Fig. 13 Results of Bollard Pull Force Measurement

	Marks			Linearly approximated gradient		
	1 T	2 T	1 & 2 T	1 T	2 T	1 & 2 T
F	—○—	- -△- -	——·——	0.9108	0.8961	0.8994

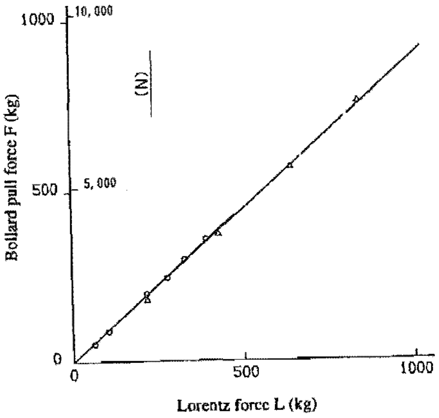


Fig. 14 Bollard Test Results (Lorentz Force vs. Bollard Pull Force)

where x: the ratio of flow velocity at the nozzle outlet against that at the inlet

P_a:P_n-P_∞

P_∞: Pressure at an infinitely foreward point (N/m^2)

It has been found from the test results that interference between ship speed and jet stream velocity can be neglected and that the following formula holds:

$$Pa \fallingdotseq \rho \bullet K_2 \bullet 1/2 \bullet U_n{}^2 \cdots\cdots (7)$$

From Eq.s (6) and (7), the following formula is obtained:

$$1/2 \bullet U_i{}^2 = (gH + 1/2 \bullet U_\infty{}^2) \div \{(1+K_2)x^2+f\} \cdots\cdots (8)$$

Likewise, the following formula is obtained by substituting Eq. (8) into Eq(5):

$$1/\rho \bullet P_i = -(gH+1/2 \bullet U_\infty{}^2) \div \{(1+K_2) \bullet x^2+f\} + 1/2 \bullet U_\infty{}^2 + 1/\rho \bullet P_\infty \cdots\cdots (9)$$

On the other hand, the head H given to seawater at the working part is expressed by the following formula:

$$H = F/\rho \bullet g \bullet A_\omega = J_s \bullet B \bullet b/\rho \bullet g \bullet A_\omega \cdots\cdots (10)$$

where Aw: Sectional area of working part (m^2)

Js: Electric current to electrode (A)

B: Magnetic flux density at working part (T)

b: Distance between electrode (m)

Consumed power at the working part is given by the following formula:

$$W = J_s \bullet E$$
$$= J_s \bullet \{B \bullet U_\omega \bullet b + b \bullet J_s/\sigma \bullet a \bullet l\} \cdots\cdots (11)$$

where W: Consumed electric power

E: Voltage between electrodes (V)

	Marks			Linearly approximated gradient		
	1 T	2 T	1 & 2 T	1 T	2 T	1 & 2 T
T_{EXP}	—○—	--△--	— - —	0.8298	0.7272	0.7527
T_{CAL}	----------------			0.6697	0.6698	0.6698

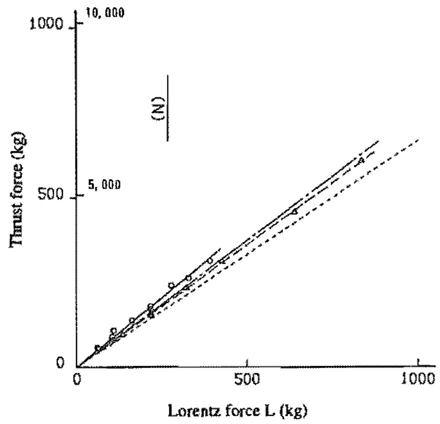


Fig. 15 Bollard Test Results (Lorentz Force vs. Thrust Force)

a, 1: Width and length of electrodes, respectively (m) Uw: How velocity at working part (m/sec)

As for the method to obtain thrust force from the results of pressure measurements, Vd is to be calculated using the following formula, then Ui, Un, etc. are to be calculated and the actual thrust force is to be calculated by the Eq. (3a) using the measured values of Pi and Pn:

$$v_d = \ * \sqrt{2g(p_{Bs} - P_d} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where PBs and PD are static pressure (N/m2) at the position shown in Fig. 12 and a is 0.8432 obtained from the result of model tests.

With respect to the method to estimate thrust force by calculation, when the consumed power is given, UOO =0 in the case of bollard tests, therefore, Ui, Js H, etc.can be obtained from Eq.s (8), (9), (10), (11), etc. and the actual thrust force can be calculated using Eq. (3a).In this series of calculation, Un is calculated from An.Un=Ad.Vd usin9 the value of Vd calculated by Eq.(12) with measured values of Pss and PD at bollard tests, then K2 is obtained from Eq. (7) using this value of Un and the Pressure Pa measured at the nozzle part.

6.3 Results of bollard tests

Fig.13 shows the results of bollard pull force measurements and the results of calculation for the Lorentz force and thrust force. It can be seen from the figure that bollard pull force and thrust force increase proportionally to increase of electrode current. Bollard pull

force increases more than duct generated thrust force,however, this is the same phenomenon at found in the case of ordinary ships with screw propellers in moored conditions also and is due to pressure distribution around the hull which is different from that in navigating conditions.

Figs.14 and 15 show the results of bollard pull force measurements and those of thrust force calculations against Lorentz force respectively.

For thrust forces. TExp obtained from the results of measuring pressures in the ducts and TcAL estimated by calculation are listed together, however, the latter shows somewhat lower values than the former. For the convenience of arrangement, etc., pressure measuring points in the ducts for thrust force calculation were positioned a little inside of the inlets and nozzles.Furthermore, there were some grids installed at the inlet. Considering that the pressures were measured at such positions and that these grids should have some effects on thrust force generated, it is presumed that the thrust force actally generated in the ducts is smaller than TExp and it may be stated that the results of measurement well agreed with the results of theoretical calculation.

7. Closing remarks

R&D on superconducting M HD propulsion ships were started from basic investigation since the Ship & Ocean Foundation (formerly the Japan Shipbuilding Industry Foundation) set up the Superconducting MHD Propulsion Ship R&D Committee (Chairman: Mr. Y.Sasakawa) in 1985 and basic experiments, model tests,etc. were continued. On the basis of the results obtained through these efforts, "YAMATO 1" was built and various tests including cooling tests, magnetizatioNdemagnetization tests, bollard tests and sea trial were complet-ed as planned successfully while being watched with keen interest by those persons concerned.

In order to make superconducting ships practically available, it is necessary to develop higher magnetic field larger size superconducting magnets and to study to improve electricconductivity of seawater from the viewpoint of increasing thrust force and improving propulsion efficiency. Furthermore, it is necessary to study systems which make special shore support bases unnecessary by installing initial cooling facilities and magnetization/demagnetization facilities also onboard.It is highly expected that these facilities will be developed before long and such ships will be actually built for commercial service.

In closing this paper, the authors wish to express their gratitude to those concerned with the aforementioned committee including Messrs. Motora and Imaichi for their valuable advice in many years.

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APPENDIX (06)

1) OXFORD ENERGY COMMENT, AUGUST 2007
(The Battle for the Next Energy Frontier)

Oxford Energy Comment

August 2007

The Battle for the Next Energy Frontier:

The Russian Polar Expedition and the Future of Arctic Hydrocarbons

By Shamil Midkhatovich Yenikeyeff and Timothy Fenton Krysiek[*]

Energy markets are in a state of flux. The high price of oil and gas, instability in the energy-producing regions, surging demand in the Asia-Pacific region, and reserve depletion in the OECD zone, has made both consuming and producing nations highly sensitive to developments that could challenge their position on the global energy scene.[1] Declining onshore reserves will force resource-rich nations to develop undersea oil and gas hydrocarbons. According to some forecasts, roughly 40 percent of global oil and gas will be produced offshore by 2015.[2] The dynamics of the global energy industry explain why Russia's recent polar expedition made international headlines. Moscow's objective was to assert its claim to the vast natural resources of the Arctic Ocean. By 2030–2040 global warming will melt enough of the polar ice cap to make the extraction and transportation of undersea oil and gas possible. Most of the Arctic thaw is taking place in Russia's territorial waters and the Russian Northern Sea Route will probably be open to commercial shipping in 2025–2030.[3]

These developments have the potential to seriously impact the global energy scene, especially in terms of investment and technology distribution in upstream and downstream activities and the delivery of oil and gas resources to markets. This paper assesses the implications of Russia's Arctic expedition in late July–early August 2007 and identifies the key factors that will determine the future of Arctic hydrocarbon development.

Russia's Arctic Potential

The entire Russian continental shelf covers 6.2 million square kilometres. Russia's extractable offshore hydrocarbon resources are approximately 100 billion tonnes, 80 percent of which are located in the Arctic. The key problem with estimating the true potential of Russian offshore hydrocarbons is the fact that geological data, on most features, covers only about 9–12 percent of the territory.[4] The only well studied offshore area is the western part of the Arctic, which accounts for 75 percent of all discovered Russian offshore hydrocarbon resources.

Various sources have offered diverse forecasts of the potential of Artic hydrocarbon reserves. In *Future of the Arctic: A New Dawn for Exploration,* Wood Mackenzie and Fugro

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Robertson take a rather cautious approach and estimate the Artic share of global hydrocarbon potential at 29 percent of undiscovered gas and 10 percent of oil.[5] The study asserts that yet-to-find (YTF) Artic resource pools total 166 boe (billion barrels of oil equivalent) while already discovered resources make up 233 billion boe.[6] At the same time, *Future of the Artic,* argues that Arctic reserves predominately contain gas. Gas constitutes 85 percent of the discovered resources and 74 percent of the YTF potential.

The U.S. Geological Survey and the Norwegian company Statoil share the more optimistic view that the Arctic holds 25 percent of global undiscovered hydrocarbon resources.[7] In a similar manner, the Russian Ministry of Natural Resources states that the Russian part of the Arctic contains around 80 billion tonnes of hydrocarbon deposits or 586 billion boe. If Moscow is successful in its bid for more Artic territories, its hydrocarbon share could increase by at least 10 billion tonnes (73.3 boe) or two-thirds of the global annual energy consumption.[8] Some Russian experts also argue that future exploration of the Arctic could result in the discovery of further large hydrocarbons resources.[9]

Whatever the true potential of the Arctic, most experts, including Statoil, Wood Mackenzie and Fugro Robertson, agree that Russia will dominate the production of Arctic hydrocarbons because approximately 69 percent of Arctic reserves belong to Russia.[10] According to the Wood Mackenzie/Fugro Robertson report, Russia will play a dominant role in Arctic gas, accounting for three-quarters of peak production.

Arctic Resource Survey

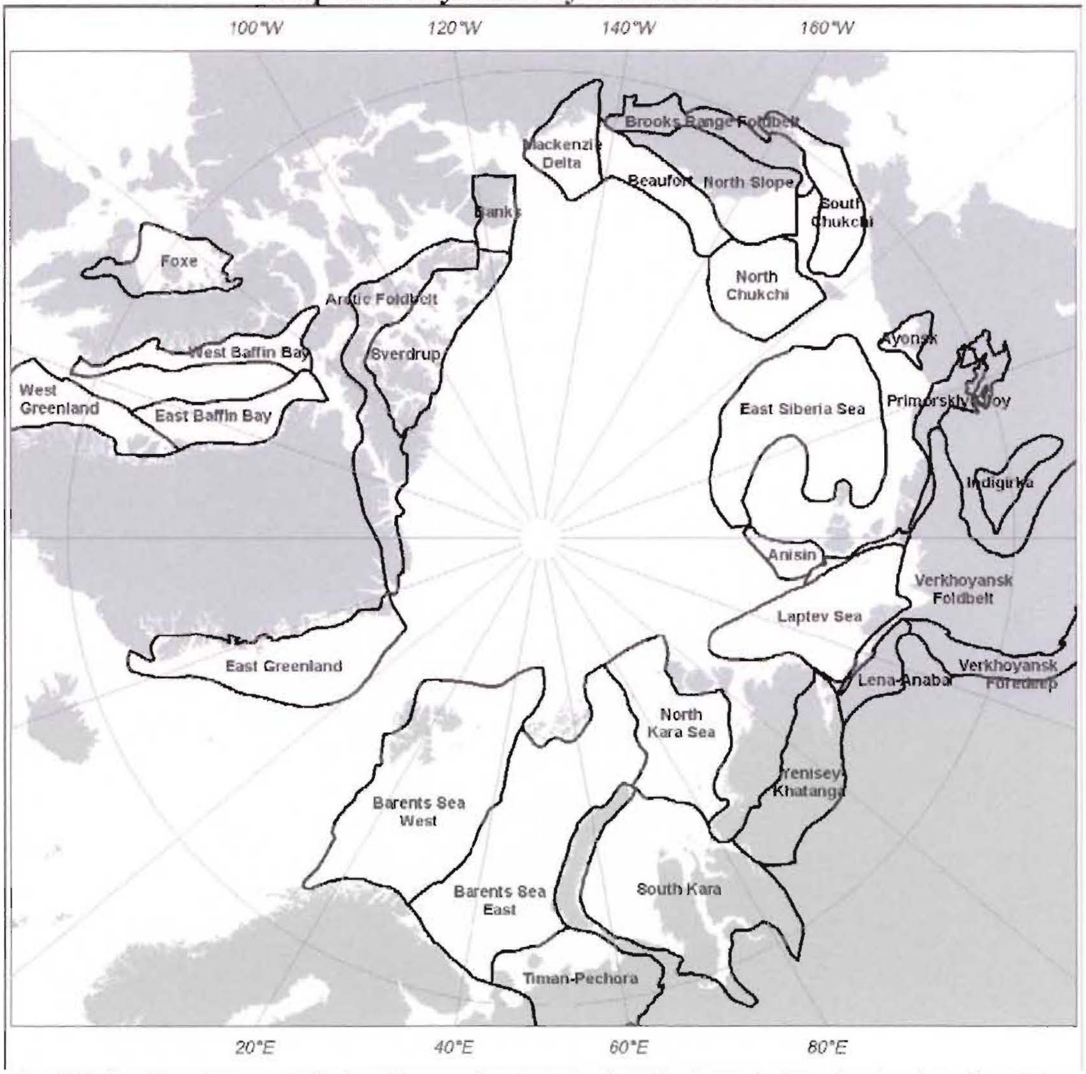
The size of the Arctic shelf is approximately 4.5 million square kilometres. The Arctic Ocean is subdivided into several bodies of water, including the Barents, Kara, Laptev, East Siberia, and Chukchi Seas and their adjacent waterways.

The western part of Arctic Russia is considered to be one of the federation's most important future oil and gas provinces, containing about 8.2 billion tonnes of hydrocarbons. Thus far, significant oil and gas reserves have been discovered in the Barents, Pechora and Kara Seas and in the Timan–Pechora basin. The Barents Sea includes Shtokman gas and condensate field (3.2 trillion cubic meters of gas and 31 million tonnes of gas condensate) and Prirazlomnoye oil field (about 610 billion barrels of oil). Russia's state-owned gas company, Gazprom, controls both fields.

The Kara Sea basins also possess a substantial hydrocarbon potential. They include the massive Russanov and Leningrad gas and condensate fields, each of which may contain more hydrocarbons than the giant Shtokman field.[11] In the coming decades, oil and gas production from these areas is expected to grow as production declines in traditional Russian hydrocarbon regions, such as the Volga and Urals. Altogether, the western part of the Artic contains 18.4 percent of Russia's oil reserves and 7.6 percent of its gas. Total regional reserves of crude oil, gas-condensate and natural gas are estimated at 53.3 billion barrels of oil equivalent.[12] Despite the region's great promise, the Timan–Pechora basin, which includes the Nenets AO and parts of the Archangelsk Region and the Komi Republic, is the only part of Barents Russia currently producing oil and gas.

The East Siberia and Laptev Seas include several basins, some of which are offshore extensions of the Vilyuy gas basin and may contain further hydrocarbon resources.[13] Minor oil and gas deposits have been discovered in the onshore territories near the Bering Sea, indicating that there may be more hydrocarbons in the adjacent seabed. However, due to the severe climate, this area has not been properly explored.

Map One. Key Arctic hydrocarbon basins.



Source: Kristin Rønning and Geirr Haarr, *Exploring the Basins of the Arctic,* Statoil ASA, 2005 (http://www.cge.uevora.pt/aspo2005/abscom/Abstract_Lisbon_Ronning.pdf).

In addition to the Russian areas, offshore Arctic regions belonging to Denmark and the United States also have an interesting hydrocarbon potential. This is especially true of the Kronprins Christian basin off Eastern Greenland which has prospective resources of over 10 billion barrels of oil equivalent.[14] The northern shelf of Alaska alone contains about 6 billion barrels. The beginning of production from the National Petroleum Reserve Alaska (NPRA) in 2007 is projected to increase Alaskan oil production from 830,000 bpd to 900,000 bpd by 2014. Alaskan production is projected to decline thereafter, but if the Arctic National Wildlife Refuge (ANWR) is opened for exploration and production it could stabilize America's Arctic oil output.[15]

Overall, Wood Mackenzie and Fugro Robertson predict that by 2030 Arctic hydrocarbon production will reach 10 million boed. Russian experts contend that gas production in the region will total around 800 million cubic meters of natural gas per day (more than half of the current rate of gas production in Russia).[16]

Russia's Arctic Strategy

The Russian expedition to the North Pole highlighted the uncertain legal status of the Arctic region. Five countries—Russia, the United States, Canada, Norway and Denmark (by virtue of its control over Greenland)—claim sovereign territory within the Arctic Circle. According to the United Nations Convention on the Law of the Sea (UNCLOS), states are entitled to an exclusive economic zone (EEZ) of 320 nautical kilometres (200 nautical miles) beyond their coastline. A coastal state has the exclusive right to exploit all natural resources within its EEZ, including subsoil hydrocarbon resources. If a state can prove to the UN Commission on the Limits of the Continental Shelf that its undersea shelf extends beyond its EEZ, it has the right to exploit that seabed's resources. Russia claims that the Arctic Ocean seabed is a projection of the Siberian continental platform. The Kremlin has petitioned the UNCLOS committee on continental shelf boundaries to recognize Russia's exploration rights to over 1.2 million square kilometres (460,000 square miles) of Arctic undersea territory, including the Lomonosov Ridge and Mendeleyev Ridges. Thus far, the committee has denied the Russian request. A primary objective of Russia's recent Arctic expedition was to gather scientific evidence to support Russia's territorial claims.

The exploration and development of new offshore resources in the Arctic could present Russia with a vital opportunity to boost its gas and oil reserves. This is important given the projected decline of Russian gas output from existing fields from 545.1 bcm in 2004 to 344 bcm in 2020.[17] In terms of oil, Russia remains the world's second largest producer after Saudi Arabia, however, its proved oil reserves are estimated at just 79.5 billion barrels, while the Saudi reserves are 264.3 billion barrels.[18] For this reason, potential Arctic oil reserves could prove highly valuable to the Russian oil sector.

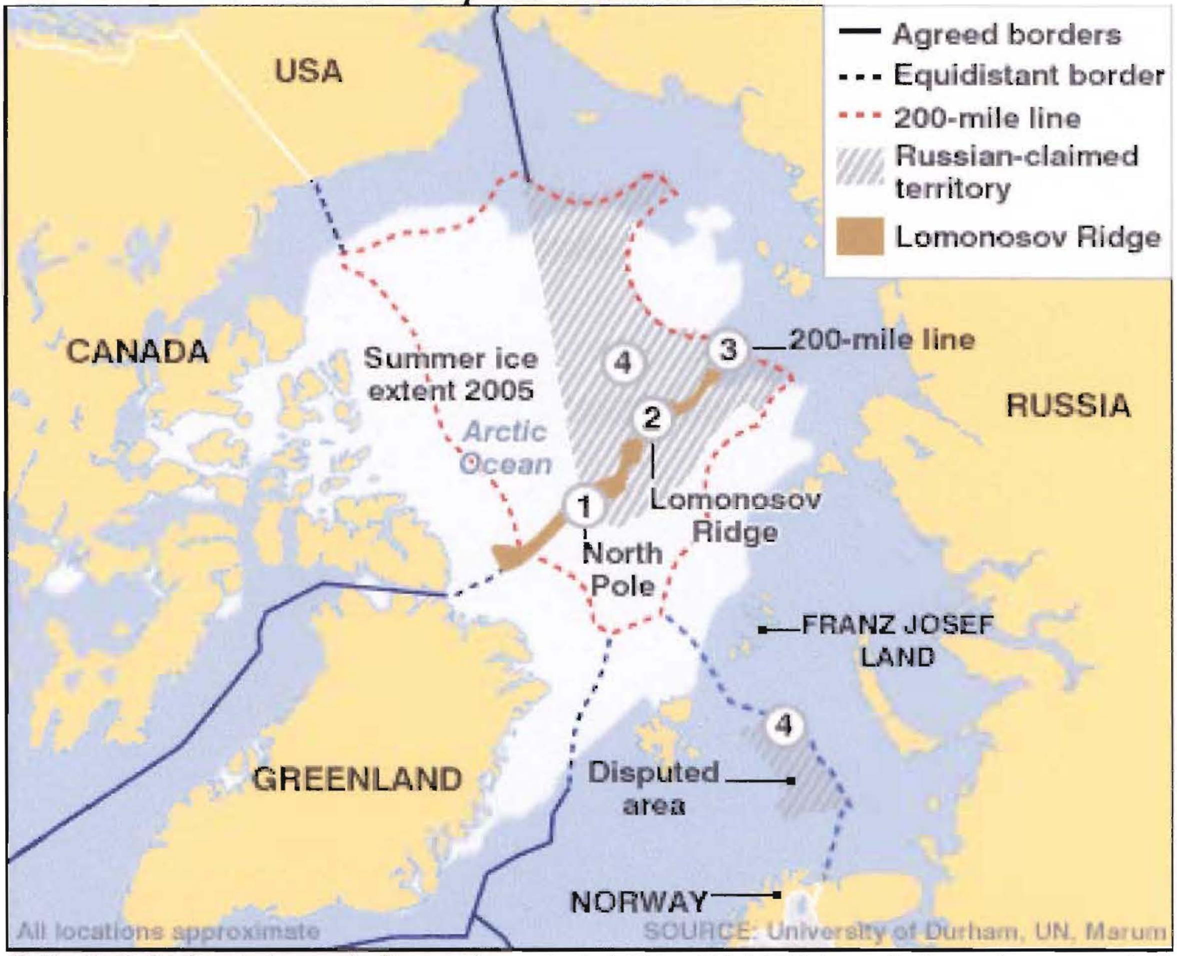
Circumpolar Reaction to the Russian Expedition

Russia's Arctic expedition appeared to catch U.S., Canadian and Danish officials by surprise. The voyage has sparked a chain reaction of expeditions from other circumpolar states. Over the past two weeks, Washington, Ottawa and Copenhagen have reiterated their Arctic claims and recalibrated their regional strategies and capabilities. The Russian expedition to the North Pole has elevated the importance of Arctic issues in each of the littoral states. In the coming months, regional governments will attempt to enhance their presence in the Arctic through further scientific expeditions and military manoeuvres and by investing in icebreakers and geological surveys.

The U.S. government's reaction to the Russian expedition reveals Washington's indecision over its arctic strategy. Since 1982, the U.S. Senate has failed to ratify the U.N. Convention on the Law of the Sea. The Bush administration supports the treaty but has not yet been able to rally the votes necessary to ensure its ratification. John Bellinger, the State Department's senior legal counsel, recently claimed that if the U.S.A. ratified the law, it could claim sovereignty over 600 miles of seabed off the Alaskan coast and exert diplomatic influence on the Convention committee responsible for determining continental shelf borders. Support for the Law of the Sea appears to be growing in the Senate. Russia's recent Arctic expedition has presented the Bush administration and other proponents of the Law of the Sea with a valuable political opportunity to push for the treaty's ratification.

Just days after the Russian explorers planted a flag on the Arctic seabed, the United States government launched its own expedition. On 6 August, the U.S. Coast Guard icebreaker Healy left Seattle for the Bering Sea. According to government officials, the Healy's mission is to study global warming and its consequences for the region. The Healy is one of just four operational U.S. government icebreakers and it is the only ship in the fleet that is routinely able to complete its missions. The Coast Guard's scramble to find a seaworthy ship capable of sailing to the Arctic on short notice has drawn further attention to the critical condition of the U.S. icebreaking fleet. A growing number of U.S. representatives and senators are backing legislation to increase funding for U.S. Coast Guard icebreakers and expand the size of the fleet. Russia's recent Arctic manoeuvres have exposed the weaknesses in U.S. Arctic strategy, but they are likely to bolster congressional support for the Law of the Sea and increased Coast Guard funding.

Map Two. Russia's Arctic Claim.



1) North Pole: Russia leaves its flag on the seabed, 4,000m (13,100ft) beneath the surface, as part of its claims for oil and gas reserves
2) Lomonosov Ridge: Russia argues that this underwater feature is an extension of its continental territory and is looking for evidence
3) 200-nautical mile (370km) line: Shows how far countries' agreed economic area extends beyond their coastline. Often set from outlying islands
4) Russian-claimed territory: The bid to claim a vast area is being closely watched by other countries. Some could follow suit.

Source: http://news.bbc.co.uk/2/hi/europe/6927395.stm

The Russian expedition to the North Pole provoked a passionate response from several Canadian leaders. Prime Minister Steven Harper has continually stressed the need to use military power to protect Canada's Arctic interests; he toured the Northwest Territories and Nunavut in the days following the Russian expedition. Foreign Minister Peter MacKay immediately dismissed Russia's polar expedition as a meaningless gesture and stated that

Canadian sovereignty over the Arctic was longstanding and well established. The political fallout in Canada over the Russian expedition prompted the government to launch a 'sovereignty operation' known as Operation Nanook in the Canadian Arctic on 7 August. Nanook consisted of two surface ships, a submarine and 700 military personnel performing manoeuvres in Nunavut, Frobisher Bay, Hudson Strait and Davis Strait. The Harper government's swift reaction to developments in the Arctic reflects the increasing importance of Arctic issues in Canada. During the 2006 federal election, Harper and the Conservative Party outlined a multi-point plan to protect the Northwest Passage and energy resources in the Far North. The strategy included three new icebreakers capable of transporting hundreds of military personal, a deep-water Arctic port for military and commercial use, new military bases in the region and a Arctic National Sensor System capable of detecting foreign submarines and surface ships. In July, the Prime Minister announced that the government would purchase six to eight armed patrol ships for the Navy to patrol Canada's territorial waters. In addition to physically defending its waters, Canada must act quickly to defend its legal claims to Arctic territory. Under the terms of the UNCLOS, Canada has until 2012 to submit scientific evidence to support its claims to the continental shelf. However, given the poor condition of its icebreaking fleet, the government may be forced to hire foreign icebreakers to support its fact-finding operations. Harper has long championed Canada's Arctic claims and continually cited the enormous potential value of the natural resources that lie beneath Canada's icy northern waters. As the scramble for Arctic hydrocarbons intensifies, the Harper government will be quick to defend Canada's interests.

In response to Russian, American and Canadian actions, the Danish government launched an Arctic expedition on 12 August. A multinational team of 40 scientists, including 10 Danes, set sail from the Norwegian island of Svalbard for the North Pole aboard the Swedish icebreaker Oden. The government instructed the Danish scientists to gather evidence that the Lomonosov Ridge is an underwater extension of Greenland, rather than Russia. Expedition leader Christian Marcussen confirmed that the research would be used to support Denmark's territorial claims in the Arctic. Denmark is likely to continue its scientific research in the region; it may also respond to recent Canadian military manoeuvres with its own show of force. In recent years, Denmark and Canada have both launched military missions to plant their flags on tiny Hans Island, an uninhabited knoll strategically located in the middle of the Nares Strait, the waterway that links Baffin Bay and the Arctic Ocean. Hans Island is likely to re-emerge as a flashpoint in Arctic geopolitics in the near future.

Thus far, the Norwegian government has been conspicuously absent from the international dispute over Arctic territory, due in large measure to Norway's ongoing cooperation with Russia over offshore hydrocarbon development in the region. The emerging strategic relationship between Oslo and Moscow over regional oil and gas development helps to explain the Norwegian government's muted reaction to Russia's recent polar expedition. Since 2002, the Norwegian and Russian governments have signed a series of declarations outlining Norway's role as Russia's strategic partner in Arctic hydrocarbon development. Norwegian companies Statoil and Norsk Hydro have 35 years of experience drilling wells in extreme conditions in the northern continental shelf. Norwegian expertise and capital could prove extremely valuable to Russian state champions Rosneft and Gazprom as they proceed with offshore development projects in the Arctic.

Potential Beneficiaries of the Arctic Energy Frontier

Today, national oil companies (NOCs) control almost 80 percent of global oil and gas reserves. This has forced international oil companies into a fierce competition with one another for the development rights to increasingly scarce hydrocarbon reserves. As a result, resource-rich nations generally enjoy considerable leverage in choosing partners or service companies for their oil and gas projects. However, in the case of the Arctic hydrocarbon development, Russia and the other circumpolar nations will be forced to choose from a handful of companies with the technological expertise and sub-Arctic experience necessary to extract oil and gas from the Arctic seabed. The Russian state energy champions, Gazprom and Rosneft, have limited experience with such complicated and remote projects. It is uncertain how rigorous Arctic exploration and production will be, but there are a few companies that have demonstrated the basic competencies necessary to tackle Arctic offshore hydrocarbon projects.

The Norwegian firms Statoil and Norsk Hydro have unsurpassed experience developing offshore resources and are leaders in the relevant technologies. Both companies have been successful in utilising new technologies in severe climates, while remaining sensitive to environmental concerns. Through the Snøhvit and Ormen Lange projects, Statoil and Norsk Hydro have developed the skills and technology necessary to successfully drill in the Arctic.[19] Despite the differences in climate and geological conditions between the Norwegian and potential Russian projects, the Norwegians have the potential to adjust their operations for hydrocarbon ventures in the Arctic.

In addition to the Norwegian firms, the Anglo-American supermajors are well positioned to benefit from Arctic energy development. Exxon, BP and Shell each have experience operating high-technology projects in extreme northern conditions. Among these firms, Exxon arguably holds the best position. Exxon has proven itself a competent operator of the Sakhalin-1 oil and gas project in the Russian Far East. Despite strong upstream inflationary pressures, the Exxon-led project at Sakhalin-1 has proceeded more or less on time and at a relatively reasonable cost. Furthermore, Exxon has developed a strong working relationship with Rosneft, one of the two Russian state-owned firms with exclusive offshore development rights in the Arctic. Exxon also enjoys a strong presence in Alaska and northern Canada through its gas projects at Prudhoe Bay, Point Tompson and the Mackenzie Delta and its oil operations at Cold Lake and the Kearl tar-sands. No one can predict just how difficult Arctic exploration and production will be, but Exxon's strong financial position, technical know-how and extensive experience operating in sub-Arctic conditions make it a strong candidate to take on future projects farther north.

Like Exxon, Shell and BP have experience managing complex projects in challenging cold-weather conditions. Shell is a major player in the Athabasca oil sands project in northern Alberta and, until recently, the Anglo-Dutch major managed Sakhalin-2, the largest integrated oil and gas project in the world. BP has been a prominent player in Alaska for decades and it has invested heavily in Western Siberia and Sakhalin. Despite their considerable familiarity with complicated sub-Arctic projects, each company has experienced difficulties political and technical difficulties with their northernmost ventures in recent years. Shell's reputation in Russia is still tarnished by the cost overruns and environmental violations that occurred during its tenure as operator of Sakhalin-2. BP's environmental infractions in Alaska have been the subject of U.S. criminal investigations and TNK-BP recently lost a showdown with the Kremlin over the development rights to the Kovykta gas field in Eastern Siberia. Over the past year, Shell and BP have attempted to reinforce their positions in Russia by announcing major partnerships with Rosneft. Shell is also fighting in U.S. federal court to drill exploratory wells in Alaska's Beaufort Sea. Despite their recent political difficulties, Shell and BP have the potential to implement Arctic hydrocarbon projects over the long-term.

Challenges to Arctic Development

At present, Russia's offshore operations only add up to 0.5 percent of the total domestic oil production.[20] By 2020, Russia's strategy on continental shelf development seeks to increase the offshore share in domestic oil and gas output to 20 percent. The Arctic will play a key role in this process. The main question here is whether Russia is capable of active development of the Arctic with its severe polar climate and vulnerable habitats in the foreseeable future. In this respect, the key obstacles include the lack of relevant experience and technologies, virtual absence of all essential industrial equipment and vital infrastructure in the Arctic regions, a problematic regulatory regime and the fiscal environment.

Geological data

The lack of geological data in the Russian section of the Arctic is a serious problem. Most of the current hydrocarbon resources in the Russian part of the Artic, such as the Shtokman and Prirazlomnoye fields, were discovered by Soviet geologists in the late 1970s and the 1980s. After the collapse of the USSR in 1991, the Russian federal government ceased state funding of geological expeditions. As a result, in early 2007, the Russian part of the Arctic contained only 58 wells, whereas the Norwegians had already drilled about 1,500 wells in their section.[21]

Today, Russia's strategy on continental shelf development seeks to boost geological work in the Arctic through a combination of public and commercial financing with the bulk of financing coming from corporate entities. Recently, the Russian government planned to introduce a number of measures to encourage offshore exploration by allowing the finders of new hydrocarbon reserves to claim exploration rights without an auction. These plans, however, may have been shelved due to Moscow's intention to assign exclusive offshore exploration rights to the Kremlin-controlled companies, Gazprom and Rosneft.

Nevertheless, international oil companies are likely to get involved in joint exploration ventures with Russian partners. In July 2007 Rosneft's president Sergei Bogdanchikov stressed that his company is likely to honour the 'memorandum of understanding' reached with BP in 2006 on joint exploration of the Arctic.[22] Although so far the memorandum has not resulted in any concrete mechanisms for BP's involvement in Rosneft's ventures, the supermajor could get up to 49 percent in the joint partnership.

Technology and infrastructure

When the time comes to develop the technology and vital infrastructure for its Arctic hydrocarbon ventures, Russia will have two choices: either to do most of the required work on its own, or to invite foreign partners on board. Domestic development of new technologies could considerably increase costs and reduce the competitiveness of Russian Arctic projects, but in the long run could boost socio-economic development in the adjacent regions. The military industrial complex, which is involved, for example, in the modernisation of platforms for the Russian oil and gas industry, could also benefit.

By 2020, according to Rosneft's estimates, Russia's offshore projects that are already in existence will require 49 platforms.[23] At the moment, it is unclear whether Moscow is capable of developing these on its own, especially if one takes into account, that currently Gazprom is using Norwegian-built drilling equipment on its Shtokman field.

Investments and taxation.

The cost of developing both offshore and onshore hydrocarbon reserves in the Russian Arctic is particularly high. Tapping the oil and gas reserves of the greater Barents region alone will require total capital investments of about $65 billion—$5 billion for geological surveys, $50 billion for exploration and development, and $10 billion for vital infrastructure, such as export pipelines and port facilities.[24] However, it is important to remember that these figures are just initial estimates. The price of implementing Russian Arctic projects could well skyrocket as happened with Sakhalin-2 and the Norwegian Snøhvit project.

According to the Russian Ministry of Natural Resources the high costs of Arctic exploration and expenditures on prospecting will be compensated by massive volumes of hydrocarbons. Some experts value the Russian Arctic resource potential as high as $7 trillion.[25] However, these estimates are made under current oil and gas price conditions. In this respect, the future of the Arctic shelf development will be determined by the dynamics of world oil prices in the next twenty years. However, future prices will also be driven by Russia's role in the development of its continental shelf.[26]

In the next decade, rather than opting to finance the offshore exploration and production on its own, Moscow may decide, or will be compelled by circumstances, to invite foreign investment. In this case, Russia will need to send the right signals to foreign capital by displaying transparency in its regulatory regime and policies. At the moment, the Yukos affair and the Kremlin's growing interference (often of an informal nature) in the oil and gas sector only fuel foreign investors' anxiety. Russia has not ratified the Washington Convention of 1965 which establishes international legal mechanisms for foreign investors to resolve investment disputes. The Russian government has not, so far, offered adequate tax and other incentives to foreign companies to guarantee foreign investors stable taxes for the duration of the specific project.

Environment

Environmental issues will pose significant challenges for companies seeking to pursue large-scale Arctic oil and gas development. The Artic includes unique habitats of indigenous Northern cultures, landscapes, fauna and flora, and marine life. Recent environment concerns over Sakhalin-2, the North Slope of Alaska and the Alaskan National Wildlife Refuge have prompted a response by local and international environment groups highlighting the potential problems companies are likely to face with their Arctic offshore projects. In order to proceed with their Arctic hydrocarbon ventures, companies will need to facilitate a full-scale international cooperation with local indigenous communities, environment organisations, government agencies, and academic institutions dealing with environment research, climate change, oceanography, marine biology, to mention just a few. Addressing environmental issues will almost certainly add to the costs of Arctic hydrocarbon development.

The Arctic Midstream: The Northern Sea Route and the Northwest Passage

The melting polar ice cap will not only make it possible to extract hydrocarbon resources from the Arctic seabed, it will also open strategic shipping lanes connecting the polar region to major energy markets. The opening of the Northern Sea Route and the Northwest Passage has the potential to transform global shipping patterns.

The Northern Sea Route (NSR), also described as the Northeast Passage, is a shipping passage stretching from the North Atlantic, along the Siberian coast, to the Russian Far East and the Pacific Ocean.

In comparison with traditional southern sea routes via the via Suez or Panama Canals, the NSR offers a considerable reduction (about 40 percent) in the travelling distance between Europe and the west coast of North America, Northeast Asia and the Far East.[27] For example, the traditional southern route (via the Suez Canal) between Hamburg and Yokohama is 11,430 miles; the Northern Sea Route reduces this distance to only 6,900 miles. In a similar manner, the distance between an important Arctic sea port, Murmansk, and the Canadian east coast is only half the distance from Abu Dhabi on the Persian Gulf to the port of Galveston in Texas.[28]

Map Three. The Northern Sea Route and the traditional Southern Route.

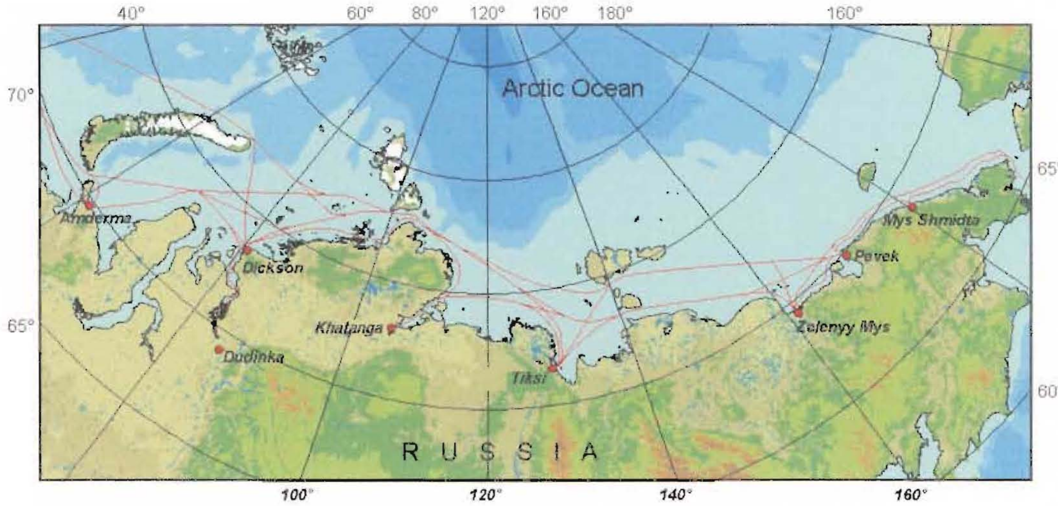
Source: International Northern Sea Route Programme, http://www.fni.no/insrop/

At present, the Northern Sea Route is accessible only during the summer. However, within the next 20–30 years, global warming is projected to make the route fully operational all year round.

Apart from the melting ice, other factors make the Northern Sea Route an attractive option for commercial shipping: political instability in the Middle East, congestion in the Suez and Panama Canals, and piracy in strategic waterways in South East Asia.[29] Russia has opened the NSR to foreign vessels, but a few key issues must be resolved in order to make the NSR a competitive and attractive transport route for commercial goods and hydrocarbons. At present, the NSR lacks the surface infrastructure, navigation support systems, environmental safeguards, and transparent tax and tariff system required of a world-class waterway. Large capacity vessels with icebreaking capabilities will still be necessary in the NSR for the foreseeable future.[30]

Until the ice melts, Russia will require several Arctic class tankers, such as EC-10 and EC-15 to facilitate effective and environmentally stable transportation of hydrocarbons through the NSR.[31] The first of these vessels, the Mikhail Ulyanov, is scheduled to start serving the west Arctic Prirazlomnoye field in 2009.[32] Russian companies Sovkomflot and Primorsk Shipping Corporation between them already have a dozen Ice Class 1A tankers that are technically close to the Arctic class.

Map Four. Russia and the Northern Sea Route.



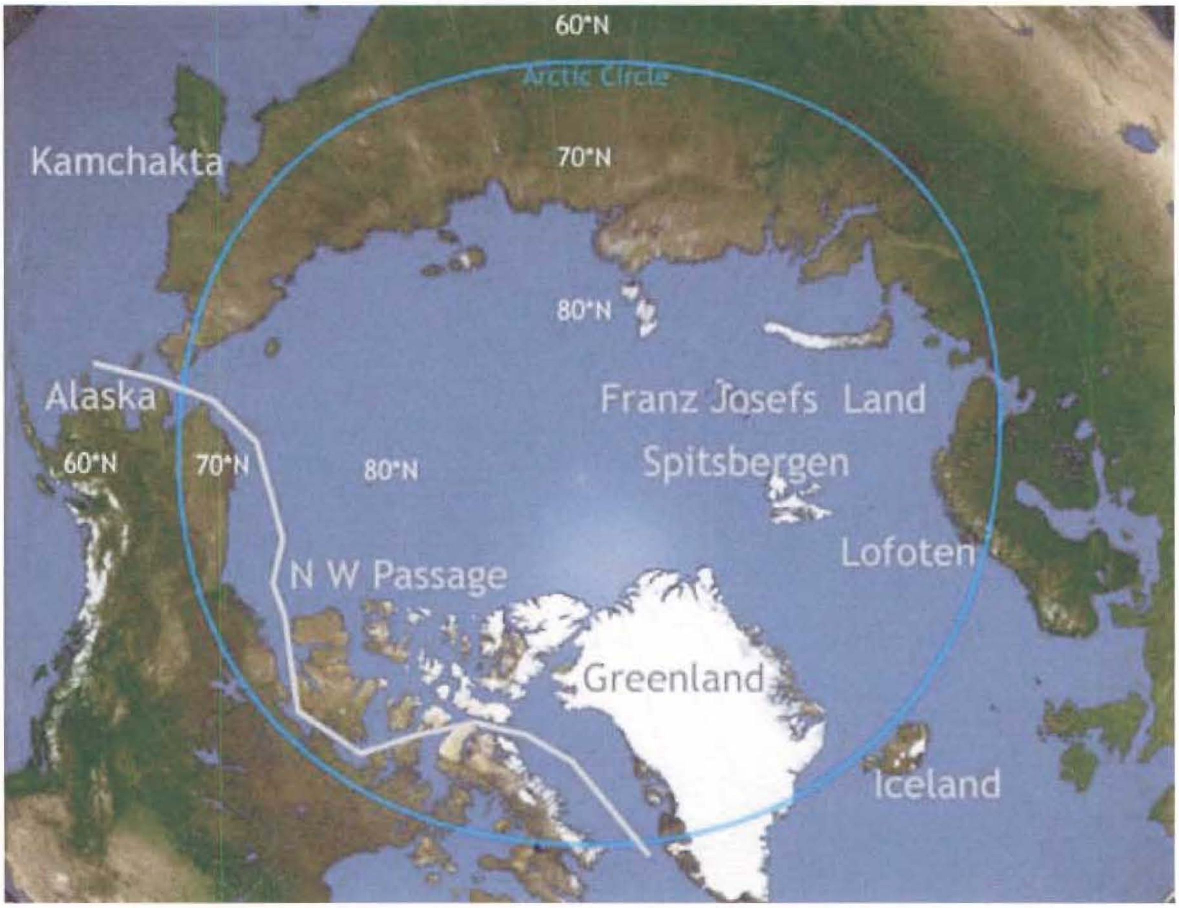
Source: Taken from the International Northern Sea Route Programme (INSPOR) (http://www.fni.no/insrop/).

According to the 2006 Ice Class Tanker Sector Report and the 2007 Ice Class Shipping Report, Arctic offshore developments may have already boosted the building of new Ice Class 1A/1AC tankers, of which as many as 167 have already been ordered.[33] The full opening of the NSR is likely to stimulate the development of hydrocarbon reserves in the Arctic, Siberia and the Russian Far East by providing an efficient export route to world markets.

The Northwest Passage (NP) runs through the Canadian Archipelago and connects the Atlantic and Pacific Oceans. Due to dense ice, commercial ships are unable to traverse the passage without the assistance of icebreakers. However, over the next 20 to 30 years, the Arctic ice pack will melt at such a rate that ships will be able to sail the waterway without assistance. By the end of the century, the NP is expected to be open 120 days a year. In ice-free conditions, the passage could reduce the trip from London to Tokyo by 5,000 kilometres (3,000 miles) compared with the Suez Canal route, or 8,000 kilometres (5,000 miles) compared with the Panama Canal route. The Canadian government claims sovereignty over its archipelagic waters, but the U.S.A. and the E.U. consider the NP to be international waters.

In order for Arctic hydrocarbon development to become economically practicable on a large scale, transportation costs must be minimized. For instance, to deliver resources from Timan–Pechora basin and the Barents Sea to Europe, it might be necessary to use icebreakers to open a shipping route for ice-resistant supertankers to travel from the Pechora Sea port of Varandey to the European seaboard. If such a shipping lane were established, it could facilitate the development of offshore fields in the Barents, White, Pechora and Kara Seas and reduce the pressure on Russia's ageing overland pipeline system.[34]

Map Five. The Northwest Passage



Source: http://www.pelagic.co.uk/newsinfo/chronpressrels/050728_nwp_indexpage.htm

Conclusion

The international reaction to Russia's recent polar expedition has highlighted the Arctic's potential as a future hydrocarbon resource base for global energy markets. Simultaneously, it unveiled once again the realities of global warming which is speeding up the melting of the polar ice cap and so opening up Arctic mineral treasures for exploration. Faced with a depletion of their own oil and gas resources, polar nations will seek a share in northern offshore hydrocarbon reserves long before 2025–2030, when the Arctic thaw will be at its peak. In this respect the Kremlin is better positioned than the rest. It was the first to state its claim and most of the resources are located in its territorial waters. Russia also appears to be the only polar nation to have a centrally directed development strategy in relation to the Arctic. What Russia lacks is the essential technology for hydrocarbon exploration. This factor may play a crucial role in defining a future international system of Arctic hydrocarbon production. Under the current state of its technological evolution, Russia is unlikely to adopt a mercantilist system of oil and gas exploration in the Arctic, and is bound to seek cooperation with other polar nations in joint hydrocarbon production.

APPENDIX.

Timeline of Arctic Exploration and Development

- 1903–05 – Norwegian explorer Roald Amundsen is the first to successfully navigate the Northwest Passage.
- 1909 – American explorers Robert Peary and Matthew Henson are the first to reach the North Pole.
- 1909 – Canada claims legal rights to the territory from its Arctic Sea shore to the North Pole.
- 1910–1915 – The Imperial Russian Navy explores and maps the Northern Sea Route in the hope of opening the passage for commercial shipping.
- 1924 – The U.S.A. claims that the North Pole is an underwater continuation of Alaska.
- 1926 – The U.S.S.R. claims the territory from the Kola Peninsula, across the North Pole to the Bering Strait. The other circumpolar states do not dispute this Soviet declaration.
- 1954 – The Soviet Arctic Institute discovers mountain ranges below the surface of the Arctic Ocean.
- 1958 – The U.S. submarine Nautilus sails underneath the Arctic ice cap and crosses the North Pole.
- 1958 – The U.S. submarine Skate becomes the first vessel to surface at the North Pole.
- 1963 – Significant iron ore deposits found on Baffin Island.
- 1968 – U.S. companies discover oil at Prudhoe Bay on Alaska's Arctic coast.
- 1969 – The U.S. tanker Manhattan and an icebreaker sail through the Northwest Passage. Canadian nationalists protest against the voyage.
- 1970 – Canada passes the Arctic Waters Pollution Act and extends its Arctic territorial claims from 3 to 12 miles from its coastline, effectively claiming sovereignty over several key straits in the Northwest Passage.
- 1977 - The Alaska Pipeline is completed and oil fields at Prudhoe Bay begin large-scale production.
- 1982 – The U.N. passes the Convention on the Law of the Sea (UNCLOS).
- 1985 – The U.S. Coast Guard icebreaker Polar Sea sails through the Northwest Passage. Canada responds by reasserting its sovereignty over the Arctic Archipelago.
- 1988 – The U.S. and Canada sign the Arctic Cooperation agreement stating that U.S. icebreakers require permission from the Canadian government before traversing the Northwest Passage.
- 1994 – UNCLOS comes into effect.
- 1996 – Norway ratifies the UNCLOS.
- 1997 – Russia ratifies the UNCLOS.
- 2000 – Russia lays claim to the Lomonosov and Mendeleev Ridges, increasing its continental shelf claim to 1.2 million square kilometers.
- 2003 – Canada ratifies the UNCLOS.

- 2004 – Denmark ratifies the UNCLOS. Copenhagen declares the Lomonosov Ridge is a continuation of Greenland but does not submit its claims to the U.N.
- 2005 – A U.S. nuclear submarine allegedly passed through Canadian Arctic waters without permission from Ottawa.
- 2006 – Norway files an application with the UN claiming 250,000 square kilometers of continental shelf in the Norwegian and Barents Seas.
- May–August 2007 – Russian scientists gather evidence to support their claims that the Lomonosov and Mendeleev Ridges are extensions of the Russian continental shelf. The U.S.A., Canada and Denmark respond with Arctic expeditions.

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[14] Martin Clark, op. cit.

[15] Clark, 32.

[16] Shamil Idiatullin., op. cit.

[17] Jonathan P. Stern, *The Future of Russian Gas and Gazprom,* Oxford: OUP, 2005, p. 32.

[18] *BP Statistical Review of World Energy 2007*, pp 6, 8.

[19] See http://www.statoil.com/statoilcom/snohvit/svg02699.nsf?OpenDatabase&lang=en

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[20] Sergei Donskoi, op. cit.

[21] '15 arkticheskikh mestorozhdenii ne privlekayut investorov iz-za ekstremal'nykh prirodnykh uslovii', *Neft' Rossii,* 25 February 2007.

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