SCOTT POLAR RESEARCH INSTITUTE

UNIVERSITY OF CAMBRIDGE

Master of Philosophy in Polar Studies

Thesis

THE ARCTIC SUBMARINE, AN ALTERNATIVE TO ICE BREAKER TANKERS AND PIPELINES

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3 June 1982

Revised 10 July 1982

"The Northwest Passage could become the catalyst which opens up the resources of far northern Alaska and Canada to the world. A year-round sea route in this area could do for the Arctic areas of Alaska and Canada what the railroads did for the western U.S. - and might do it quicker".

Dr Stanley Jones
President Humble Oil
(1969)

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ABSTRACT

The dual need to discover new sources of energy and to achieve energy self-sufficiency has resulted in a search for petroleum resources in the North American Arctic by the United States, Canada, and Great Britain. Petroleum has been discovered in many localities on land, and increasingly, offshore. A number of these are potential commercial fields. A considerable amount of development has already taken place, and full production will be possible at many of the sites by the early 1990s.

However, transport systems to bring this new found wealth to world markets are as yet far from fully developed, and are a problem. While there are two and possibly three potential transport technologies, all are expensive, high risk "mega-projects" which are unlikely to be ready for transporting the petroleum when it is ready to be transported.

The author presents what he believes to be a more versatile and economically viable transport technology: the Arctic Transport Submarine. The Arctic submarine, the history of which is given in the first chapters, is an accomplished fact. Its modification for commercial purposes, given in a later chapter, can be readily achieved. The author reviews: High Arctic petroleum finds and developments, particularly offshore; the characteristics of the "mega-project" alternatives (pipelines, ice-breaker tankers, and giant submarine tankers), existent and proposed; and the obstacles--financial, political, environmental and physical--that confront any potential Arctic Transport developer. He discusses the advantages and vulnerabilities of each of the transport technologies

in face of these obstacles; and concludes with why a prototype "Arctic" submarine, with or without towed cargo containers, is now deserving of developmental attention.

INTRODUCTION

Oil, the principal source of energy upon which the industrialized countries of the world rely, was until a decade ago, cheap, easily transported, and abundant. As the industrial nations continued to grow economically, so did their consumption of oil, and they found themselves increasingly dependent upon imported petroleum to meet their needs. Their economies became increasingly sensitive to fluctuations in the price of oil and natural gas, which in turn were/are determined in large part by fluctuations in Middle Eastern politics. The result, a recession world-wide, provided motivation to change the situation.

Nations such as the United States, Canada and Great Britain began searching for new sources of energy closer to home in an effort to gain energy self-sufficiency. In the north, this led to the discovery of major producing oil fields, such as Prudhoe Bay and the expansion of the existing Norman Wells field. Unfortunately, however, dependency upon imported sources continued to increase, with the result that the Arab Oil Embargo of 1973-74, during which prices quadrupled in less than a year, from $3.00 to $12.00 per barrel (British Petroleum, 1977), had a traumatic effect on most economies. This, and the effects of the Iranian Revolution in 1979, plus the steady increase in the price of crude oil throughout, provided even further incentive to continue exploration for petroleum. A number of oil and gas deposits have now been located in the North American Arctic, and exploration is continuing. Increasingly, petroleum is being sought offshore, in deeper and deeper waters, and the results are promising.

To date, almost two billion dollars have been spent in the United States and Canada in the exploration and development of the petroleum resources of the Arctic. And yet, not a single cent has been earned in return. This is largely because there are at present, no means of delivering the petroleum from the Arctic to world markets. Just what would prove a safe and reliable transport in this severe environment has not been as obvious as the pipeline is for Prudhoe Bay and Norman Wells. Industry and government are considering several alternatives, but no full scale construction or procurement programs have as yet been launched.

The three major transport technologies which have been the subject of formal proposals so far are: pipelines; ice-breaker tankers; and very recently, a submarine super-tanker. Their characteristics, advantages and disadvantages in face of a number of obstacles, not the least of which is the Arctic itself, and the job to be done are discussed in Chapters III, V and VI.

The author is, with this thesis, submitting an additional alternative for consideration: one which he terms the "Arctic Submarine". It is of essentially the same size and has the same capabilities as the United States Navy submarines which, during the past two decades, have conclusively proved themselves capable of safe and reliable operations year round in the Arctic Ocean and its peripheral seas. In presenting his proposal, the author first traces the development of two different types of submarines: the military Arctic submarine, and the commercial submarine (Chapters I through III). He proceeds to review: the present state of Arctic petroleum exploration and development (Chapter IV); the existent and proposed transport modes for this petroleum

(Chapter V); and the obstacles which they must overcome (Chapter VI). He then presents his proposal for a new transport technology, which should begin with a prototype Arctic Transport Submarine, (Chapter VII); and concludes with an argument in its favor, (Chapters VIII and IX).

CHAPTER I

THE HISTORY OF ARCTIC AND TRANSPORT SUBMARINES THROUGH WORLD WAR II

This chapter traces the origins and evolution of two types of submarines: the Arctic submarine, designed specifically for operations in ice-covered waters; and the undersea commerce or cargo vessel. It is a history of ideas and concepts as well as one of actual vessels, for technological capability often did not keep pace with vision.

To World War I

The basic concept of an Arctic submarine is well over three hundred years old. It appears to have originated with Bishop John Wilkins, founder and first secretary of the Royal Society of London. In 1648, he published Mathematical Magick: or the Wonders that may be Performed by Mechanical Geometry, and chapter V of Book II addresses "the possibility of framing an ark for submarine navigations". Among the "many advantages and conveniences of a submarine" cited by Wilkins were: "Tis safe, from the uncertainty of tides, and the violence of tempests, which do never move the sea above five or six paces ... and from ice and great frosts, which do much endanger the passages towards the pole" (quoted in Stefansson, 1931).

More than two centuries elapsed, however, before attention again turned to the notion of submarine polar expeditions. Jules Verne's Twenty Thousand Leagues under the Sea, published in 1869, seems to have been a major stimulus for this interest.

It most certainly inspired many early submarine pioneers, amongst them a Belgian engineer, Palmaerts, who in 1880 wished to "plunge into the three dimensions of the ocean and reach the pole by submarine" (quoted in Wallace, 1981), and an American, Simon Lake. Lake made public his ideas for the utilization of a submarine for Arctic exploration in the New York Journal in early 1898. He soon followed this announcement with the preparation of designs for a submarine capable of navigating in ice-covered waters; and he applied for and received US Patent 638 342 for these designs (Lake, 1931). He later built the "Protector" which on January 20, 1904, off the coast of Newport, Rhode Island, became the first submarine in history to ever navigate beneath and break through the ice (McLaren, 1981).

At roughly the same time, D.I. Mendeleyev suggested a project to the Russian government for a submarine especially designed for navigation in the polar regions (Gorlatov and Gakkel', 1965); and in 1901, the Geographical Journal published a plan for reaching the North Pole by submarine. This plan had previously been presented by Professor Anschutz-Kampfe of Munich to the Vienna Geographical Society, and a "submarine boat" was being built at Wilhelmshaven. Anschutz-Kampfe's basic idea had, in turn, apparently originated some years earlier in Sweden. Although nothing further was ever heard of this project, Anschutz-Kampfe's estimation of the under-ice environment, and of the conditions which might be encountered, was surprisingly accurate; and his plans to overcome the difficulties posed by Arctic under-ice navigation were well thought out too. It is interesting to note that Anschutz-Kampfe later developed the gyro compass. He calculated that it could be used to overcome many of the major course determination difficulties of Arctic navigation (compasses, particularly magnetic ones, lose their directive accuracy as higher latitudes are approached). Later voyages proved his prediction.

Meanwhile, Simon Lake was busy interesting the Russian Admiralty in the idea of under-ice navigation. He suggested to them that it would be easier and safer to send "large submarines across the Arctic and off the north coast of Russia and Siberia" than conventional routes to the Pacific (Lake, 1931). In 1905-1906, Lake submitted his plans for a submarine especially suited for under-ice navigation to the Admiralty. The Russian Navy subsequently purchased six Lake submarines, several of which, such as the "Kefal", were successfully operated in ice-covered waters off Vladivostok and the Gulf of Finland in the years preceding World War I.

World War I to World War II

The German Navy were believed to have operated a few submarines in the ice of the northern Barents Sea off Spitsbergen during World War I (Mathiesen, 1954). They also began to use their submarines for supply purposes, thus laying the groundwork for the cargo submarine. By 1915 the British blockade of Germany had caused her to have a distinct shortage of raw materials, especially nickel and rubber. The State Secretary of the Treasury thought of using U-boats to bring in these vital raw materials. A similar idea had occurred to German munition and mercantile firms such as Krupp and Lehmann; and a conglomerate, Deutsche Ozean-Reederie GmbH, was formed with the government. A contract was awarded to the firm, Germania Werft, to build the first two of an 1800 ton "Merchant Cruiser" class of submarine, designated "U-200". These were, in reality, submarine freighters, and had a cargo capacity of approximately 740 tons.

The first freighter, "Deutschland", was completed and ready for sea trials in May, 1916, only six months after the contract had been placed (see Figure 1). The second submarine, "Bremen", was ready shortly thereafter. Ozean-Reederies had been purchasing rubber and other materials throughout the US, and storing it in Baltimore. "Deutschland" made two voyages between Kiel, Baltimore, and Bremen in 1916 (Preston, 1975). On her first trip she carried 163 tons of concentrated dye worth approximately $1.4 million; and on her return voyage, she carried 348 tons of rubber, 341 tons of nickel, and 93 tons of tin. The rubber alone was worth $17.5 million. That was several times the cost of building both submarines. "Bremen" sailed on her maiden voyage to Norfolk, Virginia, at the end of 1916, but was lost at sea somewhere off the Orkneys (Preston, 1975). After "Deutschland's" successful trips, six more cargo U-boats were ordered. Unfortunately, other war needs resulted in the reconversion of all of this class to the U-151 class, including the newly commissioned "Oldenberg" (Rossler, 1981).

In America, Simon Lake submitted, in 1917, plans and models for two types of cargo carrying submarines to the US Shipping Board. These were for 11,000 and 13,000 tons--larger than the present Polaris ballistic missile submarines. These were designed so as to be capable of navigating across the Arctic from the Atlantic to the Pacific. His proposal to build a fleet of these was

Deutschland.

Glossary: Hilfsmaschinenraum, auxiliary engine room; Maschinisten, engineers; Kojen, berths; Klapptisch, folding table; Trimmtank, trimming tank; Stützschott, support bulkhead; E-Masch.-R, electric motor room; Oelmaschinenraum, engine room; Laderaum, cargo compartment; Gang, passageway; Zentrale, control room; Kapitän, captain; F.T. Raum, W/T room; Obermaschinist, Chief Engineer; W.C. f. Offiz., officers' W.C.; Messe, wardroom; Vorrate, provisions; Küche, galley; Heizer, stoker; Koch, cook; F.T. Gast, W/T operator; Matrosen, ratings; Assistenten, clerks; Arzneischrank, medicine chest; Ladeluke, cargo hatch; Hilfsmasch., auxiliary engine; Akkumulatorzellen, battery cells; Lenzbrunnen, bilge well; Reglertank, regulating tank. (See also Glossary, page 372.)

Key: *After auxiliary engine room.* 1, motor for horizontal rudder propulsion; 2, motor for hydroplane propulsion; 3, auxiliary bilge pump; 5, emergency steering station; 6, oxygen bottles. *Control-room.* 1, high-pressure compressor; 2, main bilge pump; 3, auxiliary bilge – and trimming pump; 4, turbo-blower; 5, compressed air distributor; 6, main bilge valve casing; 7, auxiliary bilge valve casing 8, propulsion for flooding-doors; 9, handwheel for after hydroplane; 10, handwheel for forward hydroplane; 11, handwheel for horizontal rudder; 12, periscope winch; 13, gyro-compass; 14, repeater compass; 15, periscope hoist. *Forward auxiliary engine room.* 1, motor for hydroplane propulsion; 2, anchor-motor; 3, auxiliary bilge pump, 4, auxiliary bilge valve casing; 5, oxygen bottles; 6, propulsion for flooding-doors.

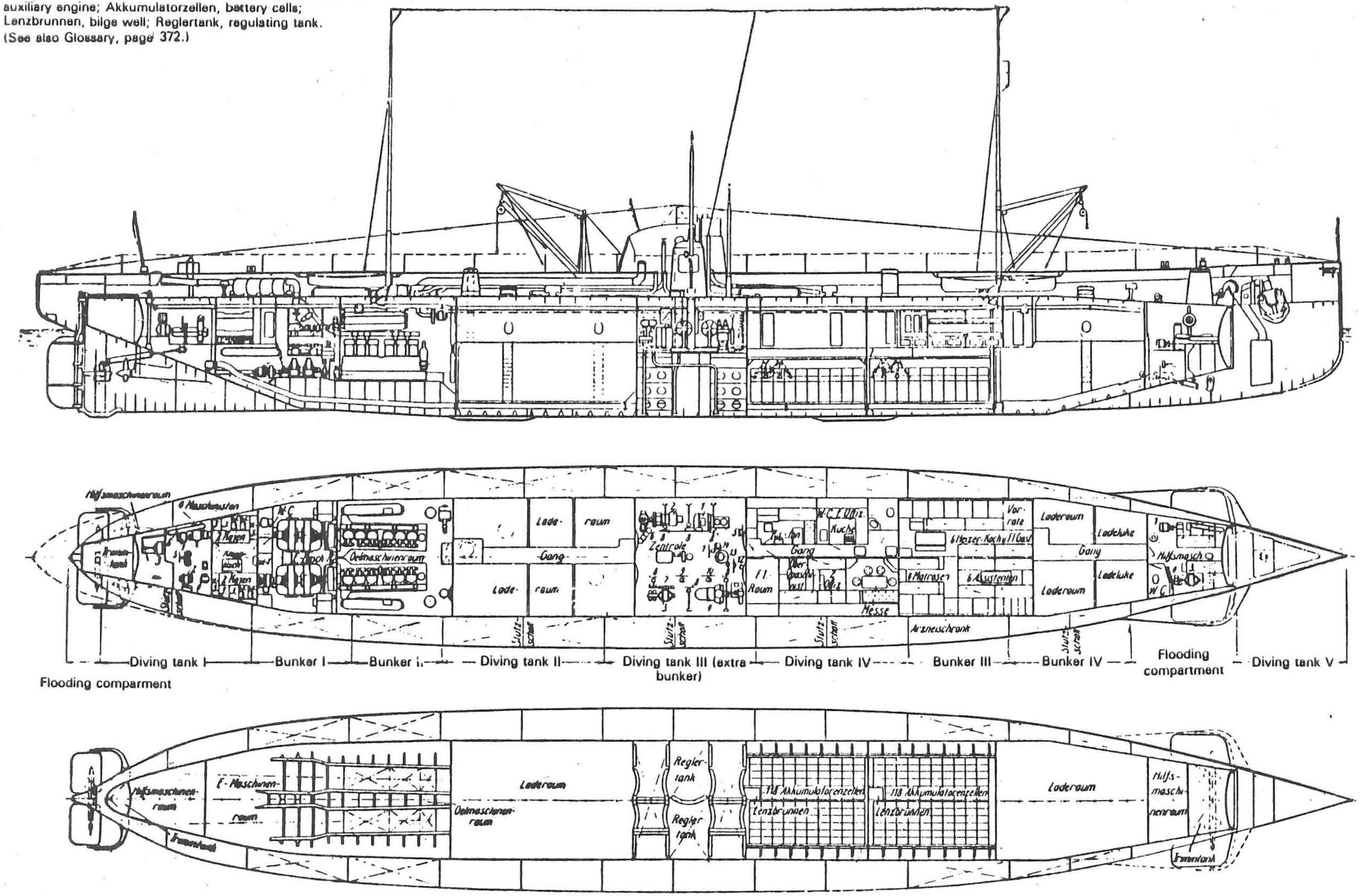


Figure 1 "Merchant Cruiser" Submarine, 1916

(after Rossler, 1981)

seriously considered by two successive heads of the Shipping Board, but no action was taken (Lake, 1931).

In Canada, the wartime Prime Minister, Sir Robert Borden, considered the use of submarines to aid and open commerce in northern areas such as Hudson Bay (Stefansson, 1931).

In the years which followed World War I, interest in and support for Arctic submarine operations declined. Nevertheless, Admiral Peary did make brief mention of the possibility during a speech before the National Geographic Society in 1919 (Stefansson, 1922). It was V. Stefansson who kept the idea alive in his discussions of the advantages of submarine trans-Arctic commerce, carried on in various international editions of his Northwest Course of Empire. But it was not until 1928, when Sir Hubert Wilkins returned from his successful flight across the Arctic, that serious attention was again given to the "Arctic submarine".

Inspired by discussions held with Stefansson during a 1913-1916 Arctic expedition, Wilkins was now convinced that the submarine was the best form of transportation for the Arctic. He began preparations for his 1931 expedition to cross the Arctic Ocean from the Atlantic to the Pacific via the North Pole, and was joined in this venture by, among others, a former US submarine officer, S. Danenhower--and Simon Lake. Lake was particularly interested to see such a voyage made, as he foresaw that it would "open up to civilization a vast Arctic territory which only needs proper transportation facilities to make it one of the most productive of the Earth's surface". He predicted that "If it were successful, in a few years thereafter, regular cargo-carrying submarines of large size would be taking the shorter Arctic route during five or six months of the year" (Lake, 1931).

Two of the main objectives of Wilkin's expedition are of particular interest:

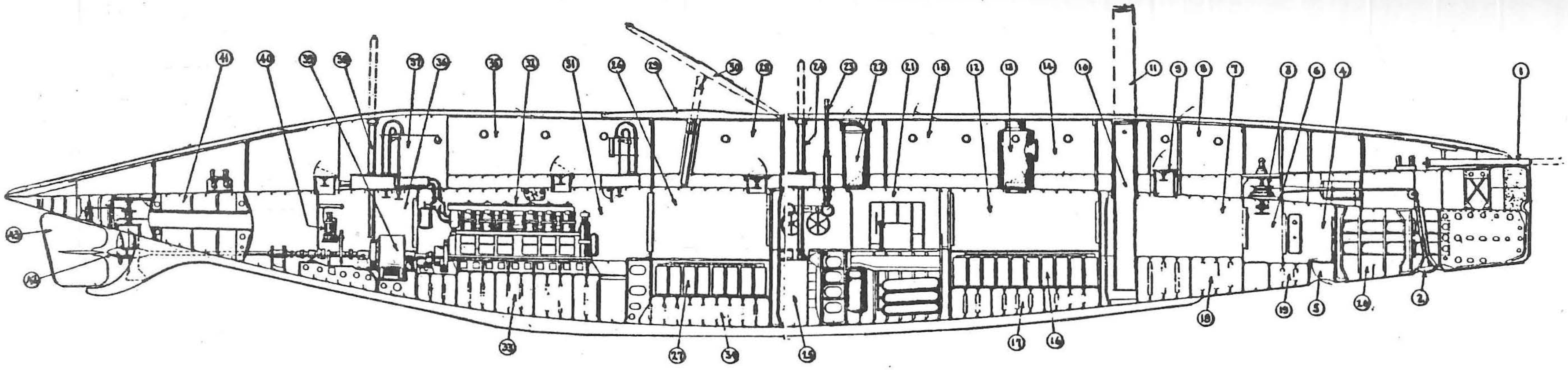
> To demonstrate dramatically the fact that submersible vessels may be used for opening up and development of the Hudson Bay district and other northern areas.

and:

> To demonstrate that submersible vessels may be used to transport at cheaper rates North American products--through the Hudson Bay route or across the Arctic--to Europe, and so benefit primary producers and industrialists.
>
> (Wilkins, 1931)

Wilkins obtained the Lake submarine "O-12" from the US Navy, and proceeded to reconvert and rename it. The "Nautilus" was 175 feet long, and 550 tons, with an estimated capacity to cruise 125 nautical miles, completely submerged, for up to three days (see Figure 2). His basic plan called for cruising submerged for sixteen out of every twenty-four hours, and then breaking or boring through ice to recharge batteries (Danenhower, 1931). Although Wilkins' expedition was well planned, it did not meet its goals. The submarine was old and inadequate; severe material failures in combination with damage which occurred in a dive under the ice and the lateness of the season meant that Wilkins had to turn back (New York Times, September 6, 8, 20 and 25, 1931). Nevertheless, public interest in Arctic submarines was aroused, and support gained. The concepts and techniques which were developed as a result of the expedition did much to ensure that submarines would one day be capable of operating throughout the Arctic (Lyon, 1963; McLaren, 1982).

Figure 2 "Nautilus", 1931



THE SUBMARINE "NAUTILUS"

[KEY TO ABOVE DIAGRAM]

1 Hydraulic cushioning bowsprit
2 Mushroom anchor
3 Anchor windlass
4 Diving compartment
5 Divers' exit door
6 Air-lock
7 Scientists' living quarters and laboratory
8 Scientists' deck cabin
9 Hatchway between scientists' deck cabin and laboratory
10 Elevating conning tower with drilling attachment at top to enable opening to be drilled up through ice
11 Dotted lines show conning tower elevated.
12 Officers' and crew's living quarters
13 Air-lock and exit hatch
14 Deck divers' compartment
15 Deck storehouse
16 Battery compartment
17 Fuel and water ballast compartment
18 Fuel and water ballast compartment
19 Water ballast compartment
20 Forward trim compartment
21 Forward control compartment
22 Fixed conning tower
23 Periscope
24 Extensible air intake tube and ice drill
25 Center main ballast compartment
26 Additional crew's quarters
27 Aft batteries
28 Crew's deck quarters
29 Cushioned guide arm to hold vessel below ice
30 Cushioned guide arm in elevated position
31 Engine room
32 Main engine
33 Fuel and ballast tanks
34 Fuel and ballast tanks
35 Deck workroom
36 Motor room
37 Engine exhaust compartment
38 Engine exhaust tube with ice drill on head
39 Electric generator and motor
40 Air compressor
41 After trim tank
42 Propeller
43 Rudder

(after Wilkins, 1931)

Developments during World War II

Military needs in World War II stimulated the next significant advances in the gradually evolving technologies of both Arctic and cargo submarines.

According to one authority, the Soviet submarine Sch-402 operating in the Barents Sea was the first to surface through the ice, in 1942; and two submarines, the Sch-311 and the Sch-324, operated in the Gulf of Bothnia (Gorlatov and Gakkel', 1965).

During the period 1941-1945, a significant number of 800 ton Type VII and 1100 ton Type IX German U-boats operated successfully in ice-covered waters around Spitsbergen, and off the Soviet coast from the eastern Barents Sea to the Laptev Sea. They rounded Novaya Zemlya and transited the Kara and Vilkitski Straits (U.S. Office of Naval Intelligence, 1951). They even conducted, from beneath the pack ice off northeast Greenland, an unsuccessful attack on a US Coast Guard cutter (U.S. Hydrographic Office, 1950). The conclusions of one of the most experienced German captains is interesting:

> A submarine is never helpless in the ice ... because it can submerge, proceed under the ice, select an open area in the ice with the aid of its high-angle periscope, come to the surface, recharge the battery ... and submerge again. It can dive and pass under all ice obstacles with the exception of the ice masses lying in shallow water.
>
> (quoted in U.S. Office of Naval Intelligence, 1951)

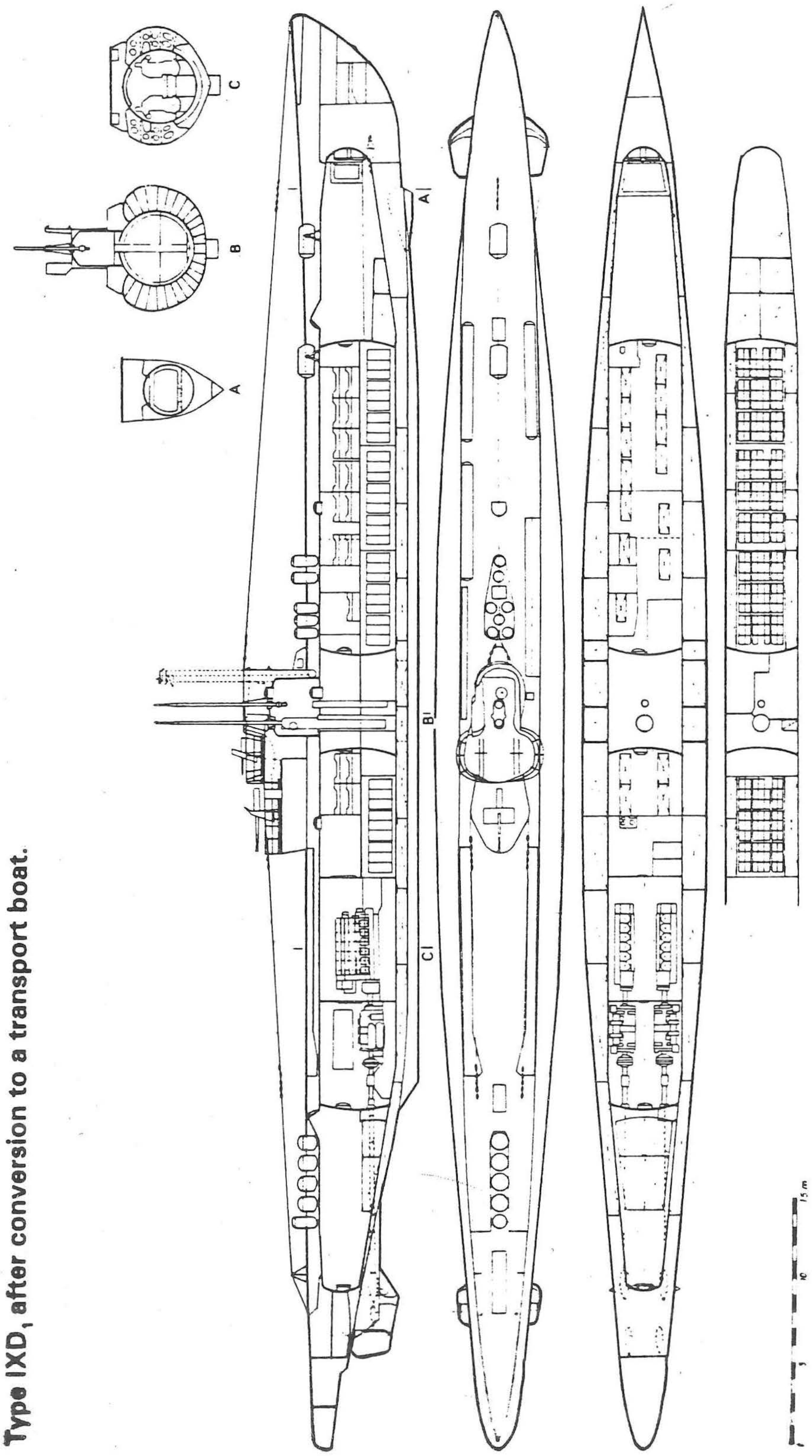
Other observations, and needs cited by the German submariners, such as for under-ice acoustic detection equipment, resulted in the development of the basic requirements for a special Arctic submarine able to conduct "non-combat operations in the Arctic regions" (U.S. Office of Naval Intelligence, 1951). Interestingly, most of the requirements have now been fully incorporated into modern nuclear submarines.

World War II saw the first major building and use of submarines for cargo. The Axis powers designed and built several different classes of submarine tankers and transports during this period. The German firm of A.G. Weser launched the 1700 ton IXD Class, of which U-180 and U-195, snorkel equipped, were used to transport fuel oil from Japan during 1944. Several others of this class and of the Type IXC (U-178, U-188, U-843, U-861, U-510, and U-532)--some of which had cruising ranges of almost 24,000 miles (Moore, 1976)--were employed to import vital stocks of tin, molybdenum and rubber during the last years of the war (Rossler, 1981) (see Figure 3).

In response to a 1940 request from Admiral Dönitz, the German Supreme Naval Commander, Deutsche Werke of Kiel built a dedicated 1900 ton Type XIV submarine tanker. This "milch cow" class was capable of carrying 432 tons, or 3200 barrels, of fuel oil, and 45 tons of supplies (Rossler, 1981). This was sufficient for reprovisioning four or five U-boats, thus enabling them to stay at sea twice as long as usual (Preston, 1975). Although successful, all ten of this class were combat losses (Moore, 1976) (see Figure 4).

A German design done specifically for transport, as opposed to combat, was for a 2,500 ton U-boat, designated Type XIX. It was scheduled to receive a new type of diesel propulsion system. As problems beset this new propulsion system, the proposed submarine was abandoned in favor of another, designated Type XX, which would take the well tried Type XIV propulsion system.

Figure 3 Type IXD Transport Boat, 1942



Type IXD, after conversion to a transport boat.

(after Rossler, 1981)

This was toward the end of 1942. A total of thirty of these Type XX submarines, each having a cargo load of 800 tons, was ordered during 1943, to be delivered at a rate of three per month from August, 1944 onwards. Also, a 4,000 ton cargo submarine was proposed by an engineer named Kohrs, but it was never built (Rossler, 1981) (see Figure 5).

In addition to designing and building new submarines for transport, the Germans reconverted ten Italian submarines, the "Aquila" project, for the same purpose. The Italians also used a considerable number of submarines for transport purposes, mainly to carry supplies to North Africa. In 1942, they began to build a special "Romolo" transport class. As well as submarine designs, the Germans designed containers to be submerged and towed behind U-boats. Some of these were built, and in 1944, tests of those with 90 and 300 ton capacities were successful. Orders were placed for a series of fifty. Events of the last year of the war and higher priorities prevented their completion (Rossler, 1981).

The first U-boat to transport supplies from the Far East to Europe was a Japanese submarine cruiser, I-30, in 1942. In 1943 and 1944, Japan sent four more of the many submarines they had converted to Europe, laden with raw materials. The Japanese also developed a special D-1 Class to resupply their Pacific Island garrisons (Preston, 1975).

By the war's end, German designers such as Professor U. Gabler (now of IKL, Lubeck) had design studies in hand for the revolutionary long range, high speed submarine classes, Type XXID, XXIE, and XXIT. The prototypes of these actually got to sea during the last months of the war (Rossler, 1981) (see Figure 6). These submarines were

Figure 4 Type XIV Submarine Tanker, 1943

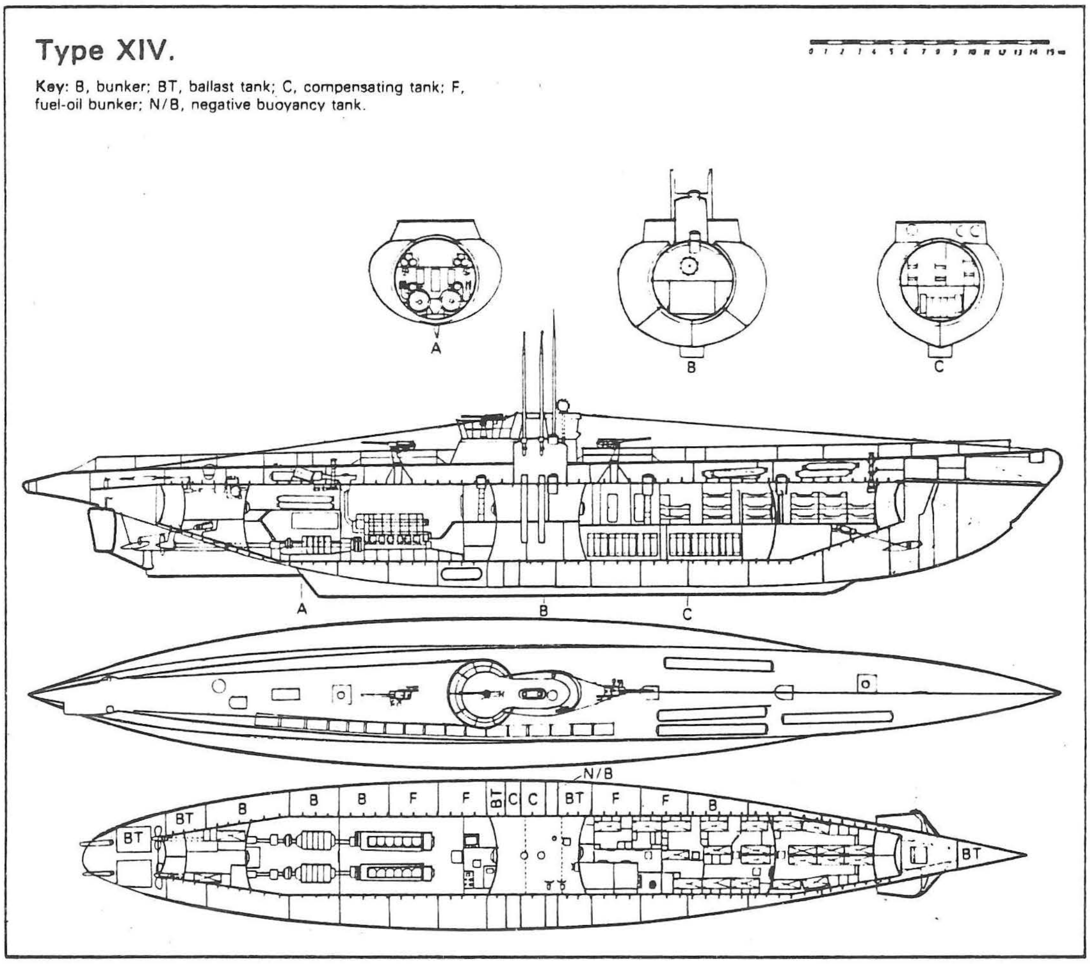
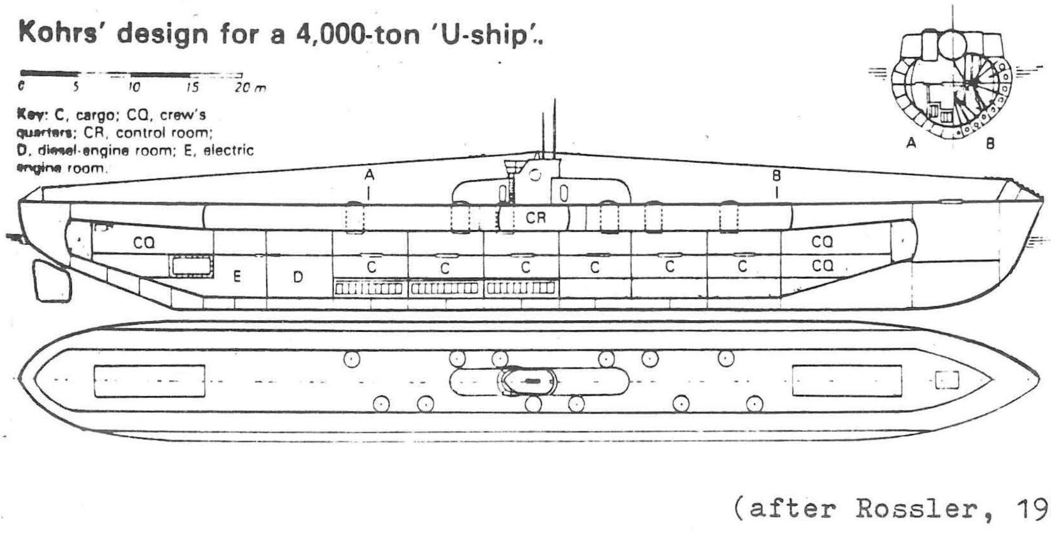


Figure 5 Cargo Submarine Design, 1944

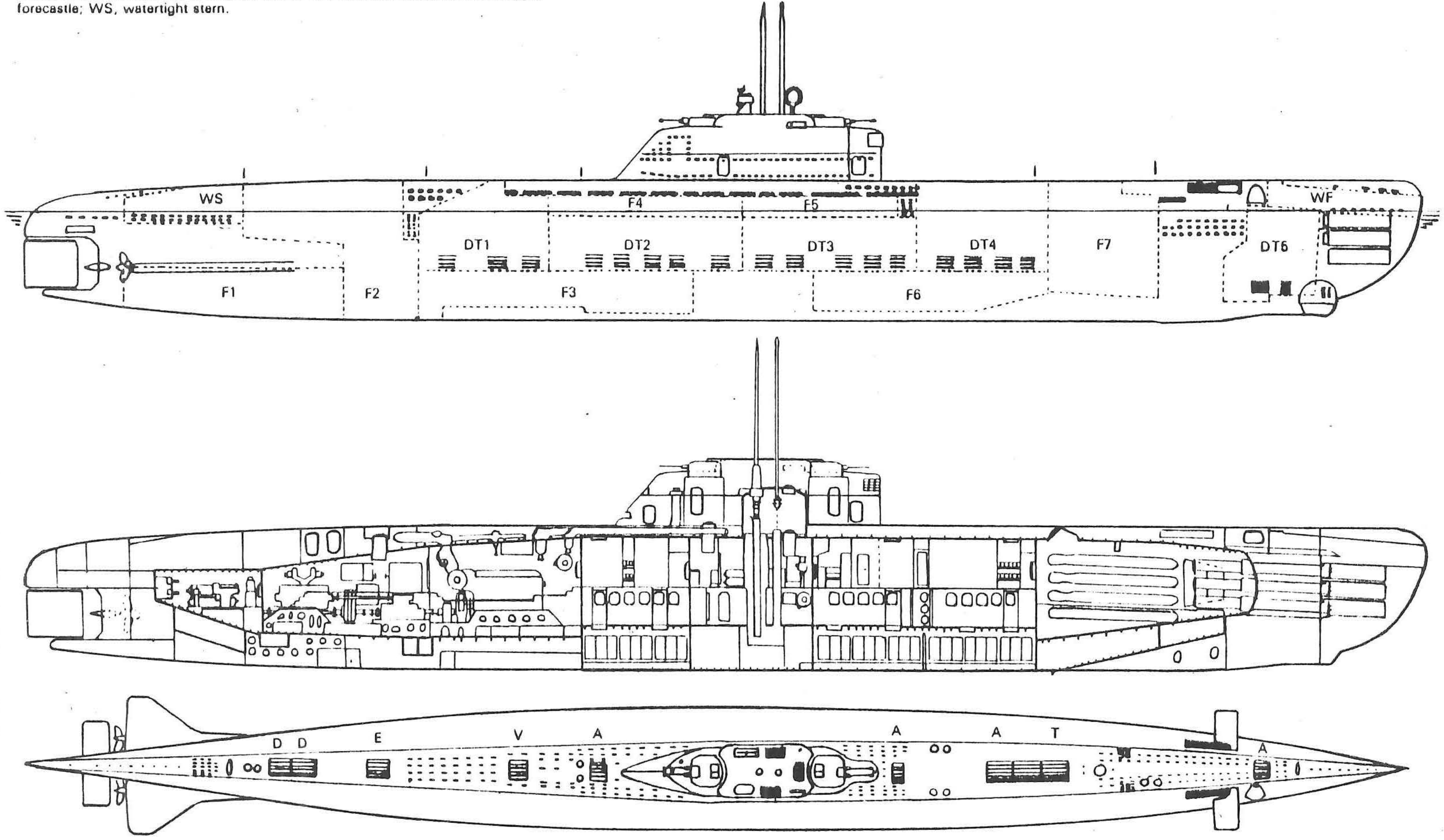


(after Rossler, 1981)

<u>Figure 6</u> Type XXI Submarine, 1945

Type XXI electro-boat.

Key: A, accumulator hatch; D, rubber dinghy; DT, diving tanks; E, electrics hatch; F, fuel-oil bunkers; T, torpedo hatch; V, ventilation hatch; WF, watertight forecastle; WS, watertight stern.



(after Rossler, 1981)

not only capable of remaining submerged for several days, but also of transiting at snorkel depth at twelve knots for over 10,000 miles (Moore, 1976). Thus the needs of World War II contributed greatly to the advance of submarine technology in general; and to experience and knowledge in regard to both Arctic and cargo submarines.

CHAPTER II

POST WORLD WAR II: THE DEVELOPMENT OF A "TRUE" ARCTIC SUBMARINE

The years immediately following World War II saw an increased interest in the Arctic regions. They also saw the initiation of several projects by the US Navy which were to have profound implications for the ultimate development of a "true" Arctic submarine.

US Navy Arctic Operations with Conventional Submarines

From 1946 to 1953, the US Navy conducted a series of operations in the Arctic, using conventionally powered submarines built during World War II. These operations were for scientific research, and to develop under-ice operating techniques and equipment. The USS "Boarfish" (SS327) made the first excursion under pack ice in August, 1947, in the Chukchi Sea; and in September, 1948, the USS "Carp" (SS338) made a fifty-four mile penetration inside the Chukchi ice pack. During this time it developed techniques for making vertical ascents into the leads and lakes of open water which dotted the pack ice; and techniques for submerging from these polynyas (Lyon, 1959). In the summers of 1952 and 1953, the USS "Redfish" (SS395) conducted extensive oceanographic pojects in the Beaufort Sea, as far as to Banks Island on one voyage. This completed the series of experiments with conventional submarines (McLaren, 1982).

The First Nuclear Submarines

During this same period, a US Navy group at Oak Ridge, Tennessee, headed by Captain (now Admiral) H.G. Rickover made the decision to create the world's first nuclear power plant. Their goal was to achieve a "true" submarine, one that would be capable of cruising the world's ocean depths for months at a time, completely submerged. A special "Naval Reactors" organization was established in 1947 which had authority in both the Atomic Energy Commission and the US Navy. Under its auspices an extensive research and development effort was launched; and it produced, during the next six years, the design, construction and testing of a prototype submarine reactor plant, the STR Mark I. The testing, conducted in 1953, included a simulated non-stop, full-power crossing of the Atlantic (Kintner, 1959). An STR Mark II was subsequently installed in a submarine especially built for it; and on January 17, 1955, the world's first "true" submarine, the USS "Nautilus", was underway (Anderson, 1959).

Then came a series of Arctic expeditions with nuclear-powered submarines. In the summer of 1957, the USS "Nautilus" (SSN571), outfitted with the under-ice acoustic equipment of the "Redfish", departed for the first of three deep penetrations beneath the Arctic ice. These culminated with the first crossing of the Arctic Basin via the North Pole in August, 1958. "Nautilus" thus became the first "true" Arctic submarine, and ushered in a new era of submarine under-ice voyages for exploratory and research purposes. As Dr W. Lyon, senior scientist on this and all subsequent cruises, said: "The trans-Arctic submarine, which five years ago was often called fantastic is now a demonstrable fact, and consequently the Arctic Ocean becomes an operating area for the submarine" (quoted in McWethy, 1958).

Of the voyages which immediately followed, those by the USS "Skate" (SSN578) in 1958 and 1959 were particularly important. Not only did she reach the North Pole nine days after the "Nautilus"; she also carried navigational equipment which enabled her to maneuver at will in high latitudes while still maintaining an accurate position. Moreover, she conducted the first winter operation in the Arctic, and on March 17, 1959, became the first ship in history to surface--through the ice--at the North Pole (Calvert, 1961).

In early 1960, the USS "Sargo" (SSN583) entered the Arctic Basin and successfully transited nine hundred miles across the shallow (water depths of forty to sixty meters) Bering-Chukchi Sea shelf. "Sargo" also proved the submarine's capability to safely navigate between deep ice ridges, in some cases extending nearly to the bottom, through the use of newly developed under-ice piloting sonar (Lyon, 1963). She spent a total of thirty-one days in the Arctic during February and March, 1960; and surfaced some sixteen times through thick ice, and in total darkness. She also conducted the first submerged transit survey of the Beaufort Sea entrance to the "Northwest Passage", the M'Clure Strait (McLaren, 1982). Truly the "Sargo" on this journey demonstrated the great capability of the nuclear submarine for Arctic use.

During the summer of 1960, a fourth nuclear submarine, the USS "Seadragon" (SSN584), became the first submarine to pass beneath icebergs. Many of these exceeded several million tons, and were of deep draft. She was also the first submarine to complete the classic "Northwest Passage", from east to west, by way of the Parry Chennel. "Seadragon's" under-ice navigation and piloting capabilities enabled her to locate and survey a safe all-season deep water passage through the Barrow Strait (Steele, 1962).

This era came to a dramatic conclusion in the summer of 1962 when the USS "Skate", coming from the Atlantic by way of the Nares Strait and the Lincoln Sea (the first submarine transit of these waters), rendezvoused with the USS "Seadragon", which had come from the Pacific, at the North Pole (Lyon, 1963). On her return, the "Skate" made the first transit of the "Northwest Passage", west to east, by way of the Parry Channel (McLaren, 1982).

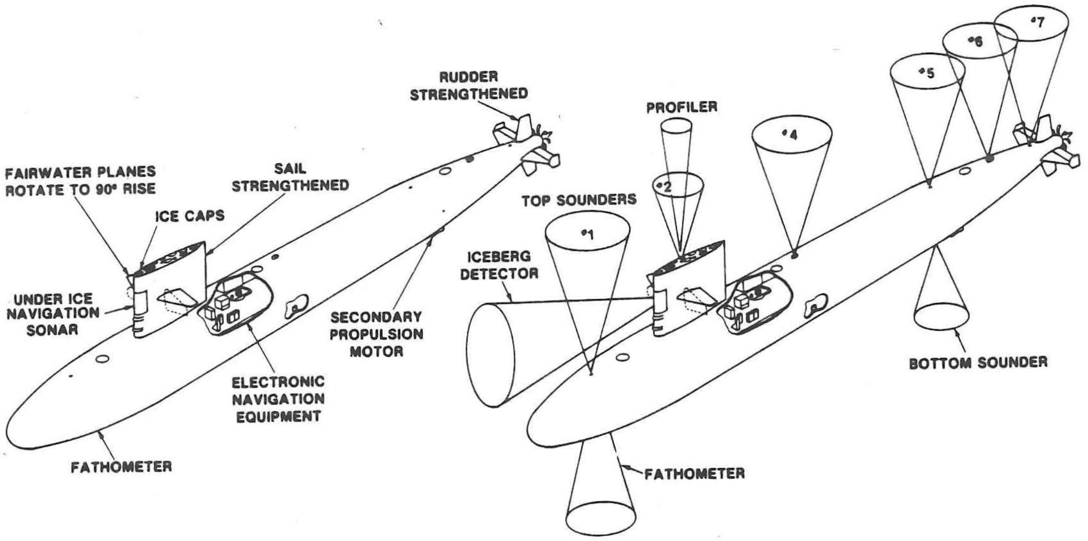
During the period from 1957 to 1962, United States' nuclear submarines had travelled over fifty thousand kilometers under the Arctic ice (Sater, 1969). By 1963, as Dr W. Lyon (1963) stated: "The Arctic Ocean has become the private sea of the submariner who is free to move in any direction and at any speed under the ice covering the sea ... ."

The "Sturgeon" Class of Nuclear Submarine

In 1963, construction began on a new "Sturgeon" Class of nuclear attack submarine. Thirty-seven were to be built, and all were to have the capability of year round Arctic operation. Here are the special features which they possess:

> The top of the sail and rudder is strengthened (with HY 80 steel), the masts have special ice caps, and sail planes can be rotated for surfacing through ice. The class also possesses a recessed secondary propulsion motor that can be lowered and used for precise maneuvering. The general characteristic of the under-ice sonar can be seen from the accompanying figure (see Figure 7). In a typical surfacing evolution, a polynya of the requisite

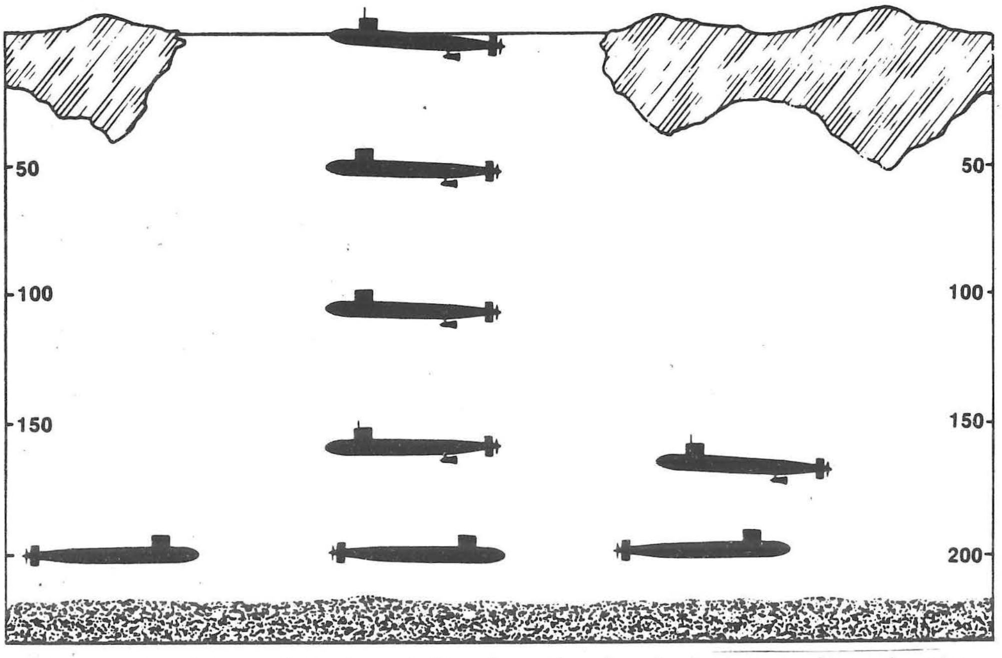
Figure 7 "Sturgeon" Class Special Under-Ice Operating Features



This schematic shows the characteristics of under-ice sonar. The iceberg detector continuously scans ahead of the submarine for icebergs or deep projections of ice. The cones (1 through 7) are acoustic projectors used to measure ice thickness above the main deck prior to surfacing. The profiler is used for precise measurement of ice thickness overhead during transit. The two cones pointing downward are the fathometers.

(after McLaren, 1981)

Figure 8 Diving and Surfacing in the Arctic



In a typical surfacing evolution in a suitable polynya, the submarine is maneuvered into a hovering position beneath its center; once the top sounders indicate open water or appropriately thin ice overhead, a vertical ascent is commenced into the polynya.

(after McLaren, 1981)

> length is located, course is reversed, depth is decreased, and the submarine is maneuvered into a hovering position beneath its center. The secondary propulsion motor is used to make last-minute adjustments to ensure avoidance of large blocks of ice overhead. Once the sounders indicate "all clear", or indicate ice sufficiently thin overhead, a vertical ascent is commenced into the polynya (see Figure 8).
>
> (McLaren, 1981)

The first of these submarines to test its Arctic capabilities was the USS "Queenfish" (SSN652). She departed for the Davis Strait and Baffin Bay in January, 1967, and spent a week in ice-covered, iceberg-infested waters. The shakedown cruise of this new class of submarine concluded with a successful surfacing through ice.

The voyages which followed the 1967 "Queenfish" cruise were made by submarines with virtually identical operational characteristics and scientific research capabilities. The principal cruises conducted between 1967 and 1981 are:

Date	Submarine	Area	Major Accomplishments
Feb 1967	USS "Queenfish"	Baffin Bay	First single-screw nuclear submarine operations in and under the ice
Apr-May 1969	USS "Whale" USS "Sargo"	Arctic Basin	Surfacing through thick ice
Aug 1970	USS "Queenfish"		Extensive shallow water operations using satellite navigation
Nov 1970	USS "Hammerhead"	Nares Strait, Arctic Basin	First autumn cruise
Mar 1971	HMS "Dreadnought"	Arctic Basin North Pole	First UK Arctic operation
Feb-Mar 1971	USS "Trepang"	Denmark Strait, Greenland Sea	*
Mar-Apr 1972	USS "Hawkbill"	Northern Bering Sea	Shallow water operations
Mar 1975	USS "Bluefish"	Greenland Sea, Arctic Basin	*
Mar 1976	USS "Gurnard"	Arctic Basin Beaufort Sea	Extensive shallow water operations
Sep 1976	HMS "Sovereign"	Arctic Basin Greenland Sea	
Mar 1977	USS "Flying Fish"	Greenland Sea Arctic Basin	*
Oct 1978	USS "Pintado"	Arctic Basin, Kara Sea	*
Mar 1979	USS "Archerfish"	Baffin Bay, Nares Strait	*
Nov 1981	USS "Silversides"	Greenland Sea Arctic Basin	The 100th nuclear submarine

* Because of security constraints, details on these expeditions cannot be given.

(After McLaren, 1982)

It is interesting to note that the one hundredth nuclear submarine, the USS "Silversides", with a cruising range of 400,000 miles, could travel six times the distance of the first nuclear submarine, the USS "Nautilus" (General Dynamics, 1970). Without a doubt, the voyages from 1967 to 1981 proved that nuclear submarines are capable of operating successfully throughout the Arctic Basin and its peripheral seas, and in the Canadian archipelago year round, and over extensive periods.

CHAPTER III

THE DEVELOPMENT OF TRANSPORT SUBMARINE CONCEPTS FOLLOWING WORLD WAR II

Unlike the dramatic progress that was made in regard to "Arctic" submarines after World War II, the development of tanker or cargo submarines for commercial purposes has been relatively slow. Briefly, it would seem that the military, which was the impetus and funding behind the "Arctic" submarine and associated research, was not interested in submarines for transport purposes; private industry, which occasionally may have been interested, did not see how a commercial submarine could offer cost-effective transport, and therefore did not invest in pursuing their development. Nevertheless, there have been some interesting proposals and designs, and they are the subject of this chapter.

Submarine Tanker Concepts: Proposals and Responses

The polar cruises of the nuclear submarines discussed in the last chapter, particularly the cruises of the USS "Nautilus" and the USS "Skate", triggered speculations about the possibilities of submarine use for commercial purposes. The successful completion of a 36,000 mile, eighty-three day, completely submerged circumnavigation of the world by the USS "Triton" (SSN586) provided further stimulation. This was in 1960, and the 442 foot long "Triton" was the world's largest nuclear submarine (General Dynamics, 1970). Over a dozen serious proposals were made for commercial submarines between 1957 and 1960 (Crewe and Hardy, 1962).

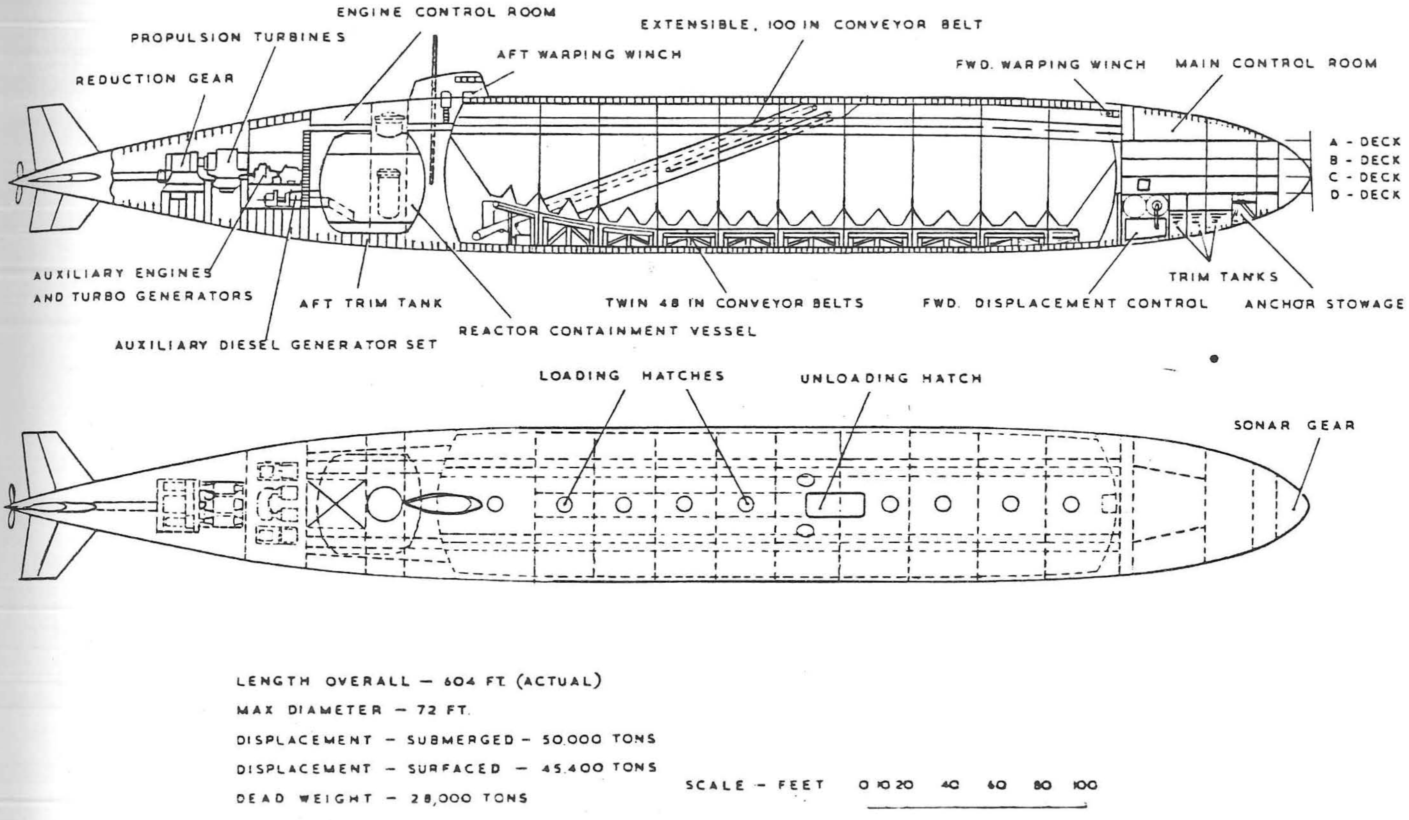
One of the earliest and most complete proposals was a detailed investigation and economic analysis of a range of transport submarine designs. It was done in 1958 and 1959 for Mitchell Engineering Ltd by Saunders-Roe, a division of Westland Aircraft Company. The purpose was to design submarines especially for the transport of iron ore from the Diana Bay region, northern Quebec, to Great Britain year round, irrespective of ice conditions. Proposed capacities ranged from 15,000 to 60,500 deadweight tons. The study ultimately focussed on plans for a 50,000 ton nuclear submarine cargo vessel capable of carrying 28,000 tons of pelletized iron ore. It concluded that such a vessel would be quite feasible using existing materials and knowledge; and that if operated year round on the route considered, it would be economically justified (Crewe and Hardy, 1962) (see Figure 9).

Despite this promising assessment, apparently nothing was done toward further development. Had the proposed vessel been built, it probably would have been eminently suitable for meeting the transportation requirements of Canada's new Polaris mine on Little Cornwallis Island, just off the "Northwest Passage" in the Arctic Islands (Malcolm, 1982).

In 1958 and again in 1962, the United States Maritime Administration selected General Dynamics to conduct feasibility studies on a submarine tanker concept. Both times, the conclusion was that the concept was a sound one; but both times, no further steps were taken (Truitt, 1970).

In 1970, following the Prudhoe Bay discoveries, General Dynamics proposed to five major oil companies "to build a fleet of [sixteen nuclear powered] super submarine tankers" that would transport the rich deposits on the North Slope to refineries

Figure 9 General Arrangement - Submarine Cargo Vessel, 1958



—GENERAL ARRANGEMENT—SUBMARINE CARGO VESSEL

(after Crewe, 1958)

in the continental United States. Each submarine was to be 900 feet long, with beams of 140 feet and a hull depth of 85 feet; they would be capable of carrying 170,000 tons, or 1,275,000 barrels, of oil, and travel beneath the sea and ice at speeds up to eighteen knots (Truitt, 1970).

Although General Dynamics felt their studies proved that a submarine tanker could transport oil to United States East Coast ports--something that had not been achieved despite need--at lower cost than other systems proposed, such as pipelines and icebreaker tankers, the oil companies said "No". They opted instead for the Trans-Alaskan Pipeline System.

That decision was probably made with some of the same considerations in mind which were cited by the United States Department of Interior in its statement concerning marine transportation alternatives. In its "Final Environmental Statement" (1972) made in response to the application of Alyeska Pipeline Service Company to "Design, construct, operate, and maintain a Trans-Alaskan Pipeline System", the U.S. Department of Interior noted:

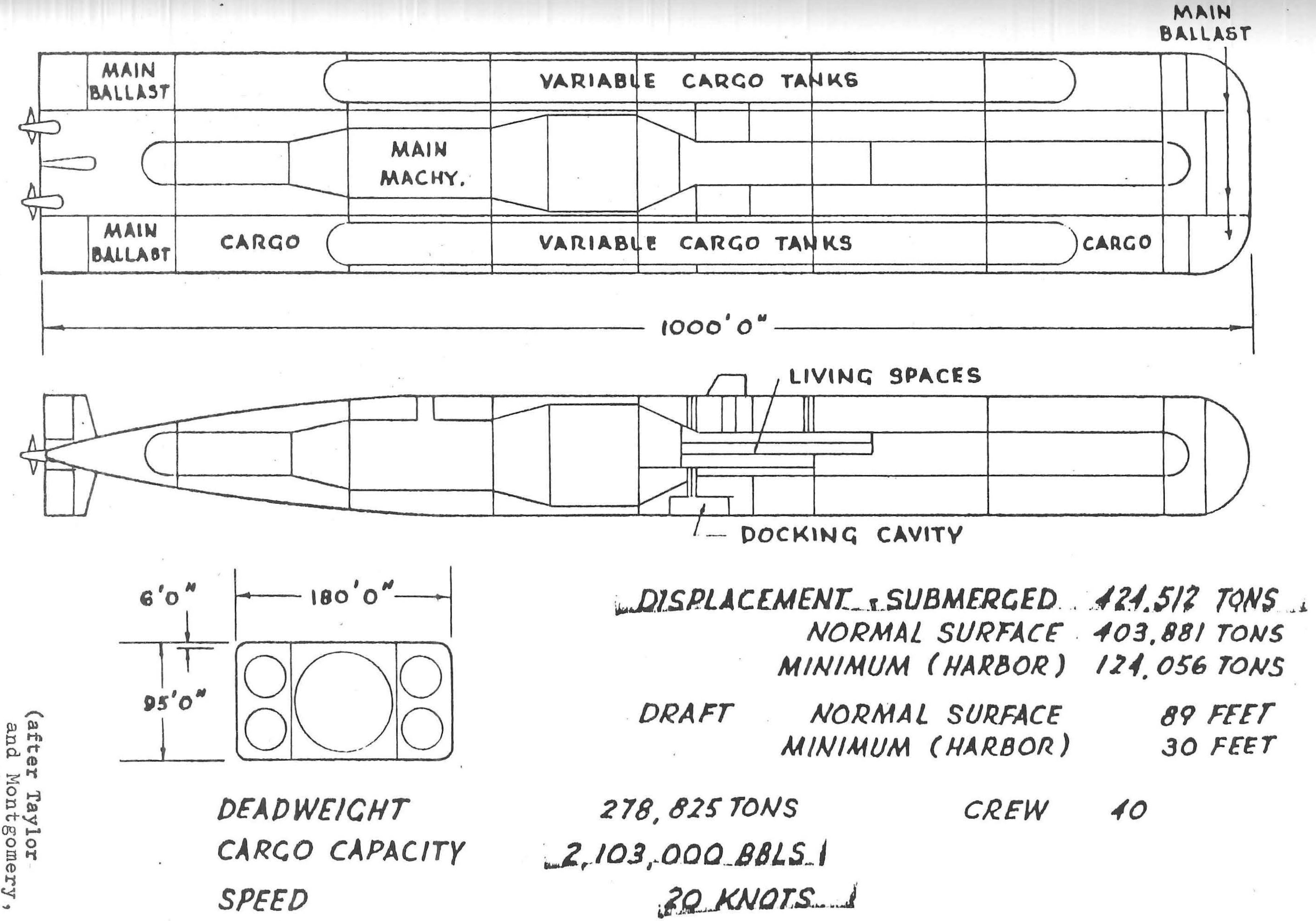
1. the technical problems posed by having to develop a tanker loading terminal in shallow coastal waters suitable for more than seasonal operation.
2. that even experimental subsurface tankers had not yet been developed, and safe passages to either coast were not well defined.
3. that large submarine tankers would be severely limited in both lateral and vertical movements from Point Barrow to the Pribilof Islands, and among the Arctic Islands.
4. concern about past transport tanker oil pollution problems, and concern with the potential impact of similar casualties on a not-well-understood Arctic marine environment.

In 1973, Canada announced an intention to develop within five years an expertise and capability for operating in and below ice-covered waters such that it would elicit international acclaim. The Minister of Transport commissioned a study to examine and make recommendations "as to the suitability, applicability, and relevant economics of marine subsurface and submarine vessels for the transport of oil, gas, and minerals from the Canadian Arctic ... to world markets" (Courtney, 1977).

In 1974, alarmed by the first Arab oil embargo which had caused crude oil prices to increase dramatically, from approximately $3.00 to $12.00 per barrel (British Petroleum, 1977), the United States Department of Commerce commissioned a study to explore the feasibility of an Arctic submarine transportation system to deliver oil directly to the East Coast (Werner, 1981). The study was conducted under the auspices of the United States Maritime Administration, which acts as a "ship broker" for the government and generally oversees the operation of the United States Merchant Marine. It was conducted by an industry team composed of Newport News Shipbuilders, Westinghouse Electrical Company, Bechtel, Inc., and Mobile Shipping and Transport Company.

The study developed designs for nuclear submarine tankers, ranging in size from 100,000 to 900,000 tons submerged displacement. It settled upon a 1,000 foot long, rectangular hull design which had a displacement of 424,512 tons. It could carry a cargo of 2,103,000 barrels of API 27 to API 37 oil, at "service speeds" of twenty knots (Figure 10).

The study also addressed in some detail the system suitability questions raised previously by the U.S. Department of Interior.



SUBMARINE TANKER CONFIGURATION

Figure 10 Submarine Tanker Configuration, 1974

(after Taylor and Montgomery, 1977)

It concluded "that submarine tanker systems are technically feasible, offer an attractive rate of return, and compare favorably with other delivery systems in terms of transportation costs" (Taylor and Montgomery, 1977). However, as in the case of General Dynamics' scheme, the petroleum industry gave no positive reply to this -- the first serious attempt by the United States government to stimulate development of an Arctic submarine transport system.

General Dynamics' Submarine Super-Tanker

The most recent conceptual design to be generally publicized is by General Dynamics for an Arctic Liquified Natural Gas (LNG) submarine super-tanker. The tanker transport system was first proposed publicly at a technical conference in Germany in early October, 1981 (Lippman, 1981).

This proposal, which explores the technical and economic feasibility of submarine tankers and puts forth a design concept for one, draws heavily upon General Dynamics' previous work in this area. Both nuclear and conventional propulsion versions were adapted from earlier submarine tanker designs; General Dynamics states that they have been "hydrodynamically verified" in extensive engineering studies of Arctic cargo submarine systems (Veliotis and Reitz, 1981a).

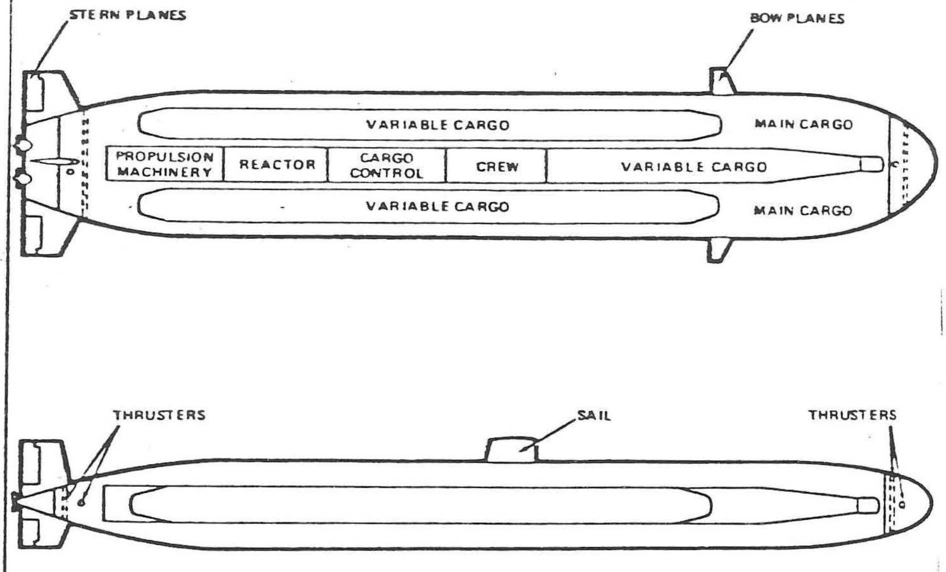
There are two versions: one utilizing a nuclear propulsion system; the other, a conventional one. Both versions would have a minimum cargo capacity of 125,000 cubic meters, or thirty-seven million gallons, of LNG, chilled to minus 260° Fahrenheit (Newsweek, 1981). This is to be carried in six 341 foot long, 57.1 foot diameter, 990 nickel-steel cargo tanks (Veliotis and Reitz, 1981a). The proposed tankers are very large--almost five times as long as "Trident", which is itself very large by submarine standards. General Dynamics' proposal calls for a fleet of fourteen to seventeen of these super-tankers; or perhaps as many as twenty-eight (Robb, 1982). Below is a table showing the characteristics of the two versions. Also, see Figure 11.

CHARACTERISTIC	VERSION I	VERSION II
Propulsion	methane gas-fired steam	nuclear
Length Overall	1470 feet	1270 feet
Beam	228 feet	same
Depth	92 feet	same
Shaft Horsepower	50,000 (25,000 each shaft)	75,000 (37,500 each shaft)
Submerged Displacement	860,649 metric tons	713,122 metric tons
Cargo Capacity	59,695 metric tons	same
Estimated Cost	$700,000,000	$725,000,000
Speed	12 kts	15 kts

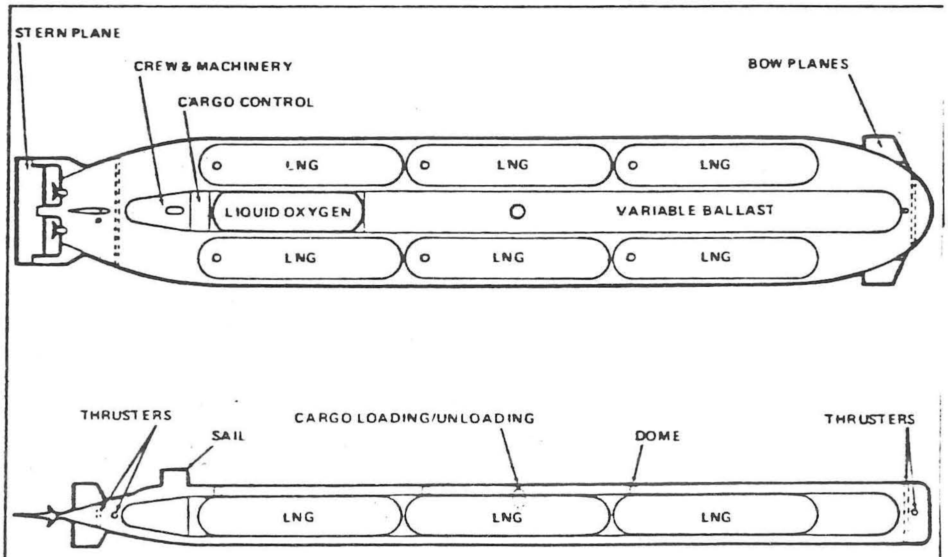
(after Veliotis and Reitz, 1981a)

The super-tankers are to carry LNG from submerged terminals located forty miles offshore in the Beaufort Sea, to ice-free Canadian or European ports (Lippman, 1981). General Dynamics hopes the proposal will be considered a more attractive alternative for supplying the United States' market from the Beaufort Sea than the Arctic Pilot Project (see Chapter V, p.56) which Petro-Canada is proposing. It is also seen as an alternative to a 4,800 mile, $43 billion Alaska Highway Pipeline planned from

Figure 11 General Dynamics' Submarine Super-Tanker, 1981



GENERAL DYNAMICS 181,400 DWT SUBMARINE OIL TANKER DESIGN
(NUCLEAR PROPULSION)



GENERAL DYNAMICS 140,000 M^3 SUBMARINE LNG TANKER DESIGN
(NON-NUCLEAR PROPULSION)

(after Oilweek, December 14, 1981)

Prudhoe Bay through Canada to terminals in both San Francisco and Chicago. The General Dynamics proposal was, apparently with the support of the United States government, also directed to the West German government and ship building industry (Huxley, 1981; Hargreaves, 1981); it was presented as an alternative to a Siberian Pipeline, which might bring Russian natural gas to West Germany and to other European countries (Huxley, 1981). Since then, however, West Germany, France, and Italy have selected the Siberian pipeline plan (Norman, 1981; Dodsworth, 1981; Buxton, 1982).

General Dynamics estimates that "a submarine tanker would be an economically viable alternative to surface icebreaking tankers and pipeline systems through its ability to deliver a constant cargo volume at uniform, predictable schedule intervals year round, regardless of surface ice and weather conditions" (Veliotis and Reitz, 1981a). General Dynamics also claims that submarine tankers are the most acceptable answer environmentally because they do not require any inland construction, nor would they break-up the ice packs along shipping routes (Huxley, 1981). In testimony to a Congressional subcommittee, General Dynamics claimed that "a fleet of submarines could be built for billions less [than the proposed Alaska natural gas pipeline]" (Kronholm, 1981).

Whether or not General Dynamics' proposal meets the same fate as all previous proposals for submarine tankers remains to be seen.

CHAPTER IV

PETROLEUM RESOURCES IN THE NORTH AMERICAN ARCTIC

The difficulties that accompany remote access and severe physical conditions such as dark periods, extreme cold, pervasive permafrost, and heavy concentrations of sea ice and snow, have until recently deterred exploration for exploitable oil and gas deposits in the North American Arctic. The necessity of conducting military operations in the Arctic during World War II resulted not only in increased awareness of the potential economic importance of the northern regions of Canada, Alaska, and Greenland, but also in major developments in technology necessary for living and operating in these areas. Because of this progress, and because of the increased need to cut down dependence on foreign oil sources, the United States and Canada have in the past decade become increasingly active in their exploration and development of Arctic petroleum resources.

This chapter will examine the proven and potential petroleum resources in only those areas of the North American Arctic where submarine transport is a desirable, if not absolutely essential feature of their developmental technology. They are the same areas where United States' nuclear submarines have already proven their capability to operate year round.

ALASKA

By the end of the last decade, Alaskan offshore petroleum prospects were looking even more promising than those that had been discovered on land (CIA Polar Regions Atlas, 1978).

United States government studies conducted in 1977 indicated that as much as one-third of the total undiscovered petroleum reserves in the United States may exist on the continental shelf of Alaska (Lindburgh and Provoise, 1977). US Federal Leases have already been purchased for the Alaskan portions of the Beaufort Sea inner continental shelf (Turner, 1979); companies such as Exxon and British Petroleum have exploratory drilling programs in progress (Gamble, 1979). British Petroleum, for example, drilled several exploratory wells from offshore islands in the Beaufort Sea, and discovered oil from their first well, Challenge Island. Two more wells were drilled in 1981 to help determine the best method for developing earlier discoveries (British Petroleum, 1981). Amco Production Company is drilling at "No Name" Island; Chevron, at Jeanette Island; and SOHIO, at Alaska Island H 1 (Alaska Construction and Oil, April, 1982).

Recent seismic surveys west of Alaska in the Bering and Chukchi Seas have revealed several basins which may contain large volumes of oil. Although not a single exploratory well has been drilled as yet to confirm their potential, it is estimated that the Navarin Basin in the Bering Sea could contain as many as seven billion barrels of oil. The surveys have also revealed potential oil-bearing basins in the Chukchi Sea (O'Toole, 1980). The Bureau of Land Management's present leasing plan calls for opening the Navarin basin for lease in late 1984, and the Chukchi Sea in 1985 (Alaska Industry, October, 1979).

Since the last 1940s, the Beaufort Sea off Alaska, and the Bering and Chukchi Seas have all been extensively explored by American diesel and nuclear submarines. United States Navy nuclear submarines have time and again proven the feasibility of access and year round operations in both the shallow, to depths of forty meters, and deep portions of these seas with both confidence and safety (McLaren, 1982).

CANADA

Reserves of potentially exploitable oil and gas are to be found in seven areas of the Canadian Arctic. Three areas, the Beaufort Sea, the Arctic Islands, and Lancaster Sound/Baffin Bay, are particularly suitable for submarine transport. Nearly fifty per cent of Canada's total petroleum reserves are estimated to be in the Arctic and more than half of Canada's Arctic petroleum resources lie offshore (Canadian Indian Affairs and Northern Development, 1980; APOA, 1981). The Canadian Arctic Resources Committee estimates the offshore reserves to be between sixty and seventy billion barrels (Arctic Seas Bulletin, July, 1979).

Each of the areas possesses unique features and natural conditions which require tailor-made petroleum exploration, production, and transportation systems. They in turn require technology which differs from conventional techniques (APOA, 1981).

The Beaufort Sea

The ice conditions of the Beaufort Sea make it one of the most hazardous of Arctic environments for offshore drilling. Much of the Sea is covered by the Polar pack circulating slowly around the Polar Basin. In addition, pressure ridges created by wind and ocean currents frequently occur along with large ice fragments. Moreover, permafrost may be widespread in the bottom sediments of the shallow continental shelf (Pimlott et al, 1976; Wadhams, 1981b). These conditions have made exploration more difficult, but they have not deterred it. The "whale pasture", as the Beaufort Sea has been called (Foster, 1980), is being increasingly probed for the resources it holds. The Beaufort Sea Project studies, 1975 and 1976, substantially increased knowledge on matters vital to petroleum exploration, and resulted in development of ice monitoring and movement prediction techniques (Pallister, 1981).

In 1961 the Canadian government decided to open parts of the Arctic to petroleum exploration; the Beaufort Sea was one of the areas opened. The major oil companies acquired Federal exploration permits in all areas, but there was little active interest in the Beaufort Sea because it was covered with ice for eight months of the year. The Prudhoe Bay discovery in 1968, however, quickly caused relative apathy to change to interest. The Mackenzie Delta, 600 miles east of Prudhoe Bay and south of the Beaufort Sea, immediately assumed a new importance (Pimlott, 1976). Exploration and discovery of petroleum beneath the Mackenzie Delta brought encouraging but not spectacular finds. Instead, geophysical surveys began indicating that the offshore Beaufort Sea offered more promise of finding large hydrocarbon deposits. Thus it became the first offshore area in the Arctic to attract the oil industry (Pimlott et al., 1976).

By 1972, geophysical and seismic prospects looked sufficiently promising for the oil companies to start exploratory drilling. Esso Resources Canada Ltd. (Imperial Oil Ltd.) began building the first of sixteen artificial islands from which to drill.

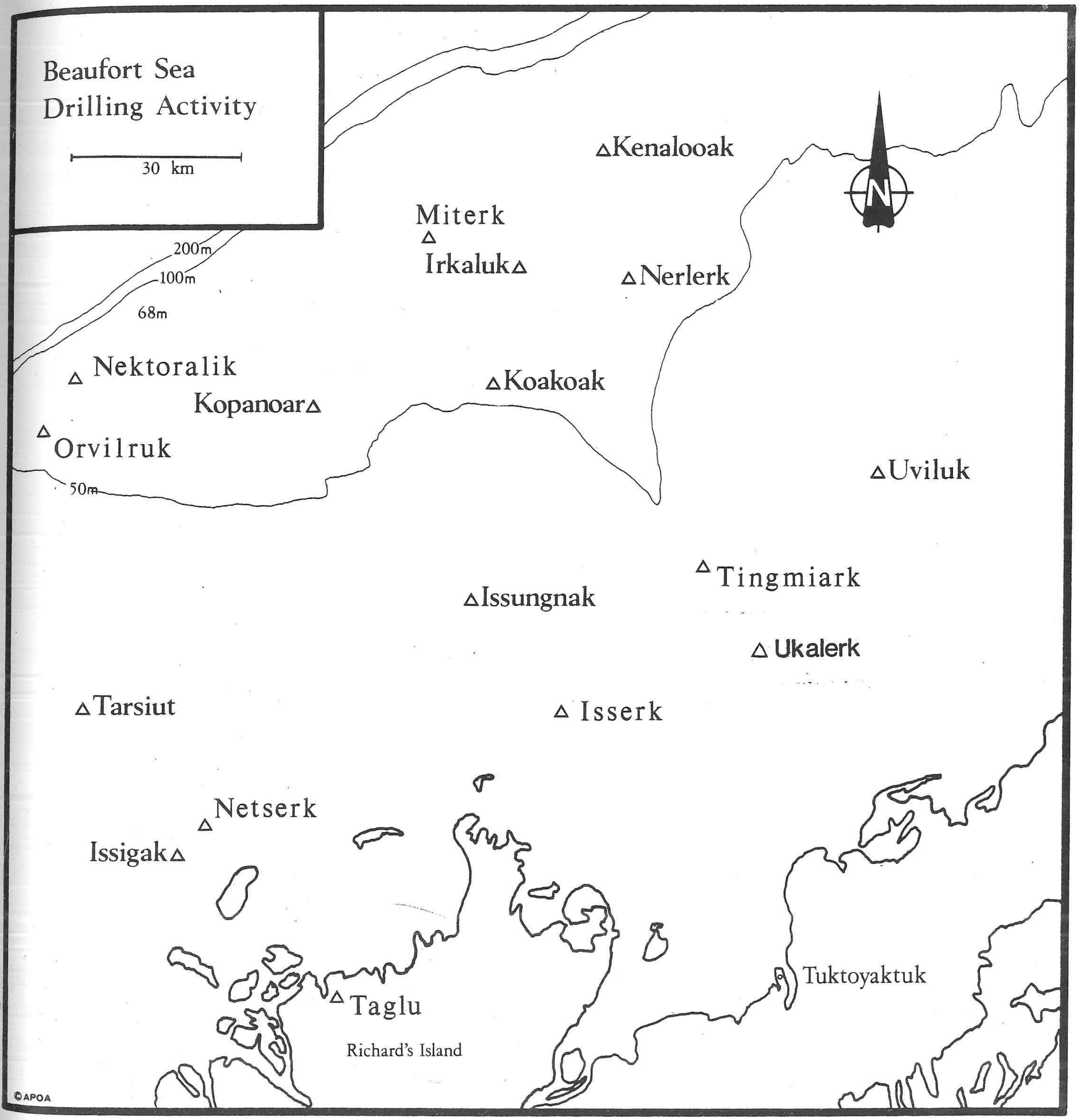
Called Immersk, it was located two kilometers offshore in three meters of water (Oilweek, January 18, 1982). The first Beaufort Sea oil and gas discovery made offshore was at another well, ADGO (Pimlott et al, 1976). Subsequently, Esso discoveries were made at Nektoralok, Ukalerk, and at their largest well, Issungnak. Issungnak was only recently completed and is thirty-two kilometers offshore in nineteen meters of water (Imperial Oil, 1982). A recent step-out well, Issungnak 2061, recorded a flow of 6,456 barrels per day (Oilweek, December 14, 1981). Esso plans to continue constructing and exploring from artificial islands (APOA, May, 1981), and estimates that 6.3 billion barrels of oil lie beneath the Beaufort Sea (Oilweek, April 5, 1982). See Figure 12 for site locations.

Dome Petroleum started offshore drilling using ice-reinforced drill-ships in 1976; they struck gas in three wells during the 1977 drilling season. One well tested at 480,000 cubic meters of gas per day and an oil test flow from another offshore well was over 1,000 barrels per day (Miles and Wright, 1978).

By 1978, proved reserves discovered as a result of the combined companies' activities totalled some 1.5 billion barrels of oil and 200 billion cubic meters of natural gas. These figures are for the shallow waters of the Beaufort Sea, in combination with the Mackenzie Delta. Following these shallow water successes, exploratory drilling began to examine the even more promising geological structures in the deeper offshore waters despite opposition from environmental groups (CIA Polar Regions Atlas, 1978).

By the end of 1978, Dome Petroleum had completed two and

Figure 13 Beaufort Sea Exploration Well Locations



(from APOA, spring/summer, 1982)

started four more exploratory wells, this time in water from twenty-five to sixty-seven meters (APOA, July, 1979). They also began to develop new drill-ship designs with features which would permit drilling to continue over a substantially longer season in the Beaufort Sea, and year round in the Arctic Islands (APOA, November, 1978). In September, 1979, one of the wells, Koponoar M-13 in fifty-eight meters of water, hit what proved to be a major oil find. Consultants estimated that production on a sustained basis could exceed 12,000 barrels per day. Dome considered this to be commercially significant, and began drilling a step-out well, Koponoar I-44. Tests were conducted on three other wells--Tarsuit, Nerlerk, and Ukalerk, with encouraging results and Ukalerk indicated a flow of 85,000 cubic meters of natural gas per day (APOA, November, 1979).

Dome then began constructing more permanent and durable caisson reinforced artificial islands from which to conduct exploratory and, eventually, production drilling. The first of these, Tarsiut N-44, was completed in twenty-three meters of water in 1981 (APOA, May, 1981).

In late 1981, Dome reported quite promising results from the wells at Koponoar and Koakoak. Koponoar, in sixty to sixty-five meters of water, yielded 1,670 barrels of oil per day, with an estimated daily output of 5,000 to 10,000 barrels under normal operating conditions. The potential total recovery was calculated to be 1.8 to 4.5 billion barrels. Koakoak, in forty to forty-eight meters of water, yielded 3,330 barrels per day. Estimates put the flow at 5,000 barrels per day under normal operating conditions, and the total at 2 to 5 billion recoverable barrels.

These are comparable to many Arab oil fields, and are of unquestionable commercial potential. Dome estimates that a threshold of 400 million barrels of recoverable oil are required for commercial production (APOA, December, 1981). During 1982, the structures beneath both wells will be evaluated fully by Dome's four drilling ships, with test and delineation wells (Oilweek, December 14, 1981; APOA, spring/summer, 1982).

Dome also expects to complete three other wells during 1982: Irkaluk B-35, Kenaloak J-94, and Orviruk P-30 (Oilweek, April 12, 1982). The company believes that the Beaufort Sea holds reserves of between 30 and 40 billion barrels of oil (Meisler, 1979); and production could exceed 1.2 million barrels per day by 1990 (Harrison, 1979).

Gulf has participated in eleven exploratory wells in the Beaufort Sea, and as a partner of Esso and Dome has shared in the recent discoveries at Issungnak, Koponoar, Koakoak, and Tarsiut (APOA, December, 1981). Drilling activity in the deeper waters of the Beaufort Sea moved to a year round operation when Gulf began spudding a step-out well at Tarsiut in December, 1981. Gulf also drilled a wildcat well at Uviluk in 1982 from an artificial island constructed in the deepest water yet, thirty-one meters (Oilweek, February 22, 1982). Gulf is presently having two new drilling systems built for exploring the deeper waters of the Beaufort Sea in 1983 or 1984: a floating conical drilling unit, and a mobile Arctic caisson which will rest on a dredged subsurface and can operate year round in water depths of twenty-one to thirty-six meters (APOA, September and December, 1981).

Gulf, like Dome, believes that the Beaufort Sea will in time become one of the world's major petroleum producing areas. It has estimated reserves of 1.5 trillion cubic meters of gas, and 6 billion barrels of oil (APOA, May, 1981).

All three companies have recently (1981) submitted to the government a development plan with a supporting environmental impact statement (EIS) which projects their activities to the year 2000. The plan, which has been referred to a Federal Environmental Assessment and Review Panel (EARP), covers activities leading up to the full-scale production and transportation of offshore gas and oil from the Beaufort Sea. Three phases are outlined as follows:

Phase	Major Elements
1. Pre-Production (1982-1985)	30 additional offshore exploration and delineation wells, drilled from artificial islands in shallow waters
	drill-ship and other deep water drilling systems for year round exploration and delineation
	construction of production islands, platforms, facilities, and systems
	development of transport system
2. Early Production (1986-1990)	40 exploration and delineation wells
	160 offshore production wells, potentially producing up to 500,000 barrels per day
	emphasis on oil production and transportation
	possibly, build 5 more exploration, and 5 more production islands
3. Final Development (1991-2000)	80-100 exploration and delineation wells
	400 production wells, from 8 systems, fixed and mobile, producing up to 1,250,000 barrels per day.

(APOA, December, 1981)

The group anticipates that full-scale natural gas production in the Beaufort Sea will be achieved by 1992.

The capability of submarines to operate in both the deep and shallow portions of the Beaufort Sea has been proven by the United States Navy during the past twenty-two years. As stated earlier, the USS "Redfish" operated there in the early 1950s; the USS "Sargo" explored portions during the winter of 1960; the USS "Seadragon" explored other portions during the summers of 1960 and 1962; and in the summer of 1976, the USS "Gurnard" spent almost a month operating in the shallower portions (McLaren, 1982).

The Arctic Islands

The world's most northerly wells at present have been drilled in the Canadian Archipelago. By 1973, Panarctic discovered four significant gas fields: Drake Point, Hecla, Thor, and Kristoffer, which are estimated to contain between .3 and .4 trillion cubic meters of gas (Miles and Wright, 1978). The first discovery was on Thor Island in 1972 (Panarctic Oils, etc., 1981a). Followed by promising discoveries at 43° API crude oil at Bent Horn, Cameron Island, in April 1974 (Panarctic Oils, 1981b). By October 1975, Panarctic obtained a flow of 3,000 barrels per day of high grade crude oil from the field (Miles and Wright, 1978). Follow-on step-out wells drilled in 1975 and 1976 resulted in estimated reserves of approximately 300 million barrels, of which 100 million are considered proved (Miles and Wright, 1978). During 1979 and 1980, Panarctic made additional offshore discoveries of oil and gas from wells at Whitefish, to the southwest of

Lougheed Island and at Char, south of Ellef Ringnes Island (Panarctic, 1981b). In 1981, Panarctic made three major new discoveries with wells drilled from offshore ice platforms. These were: Skate B-80 well, located in the northern MacLean Strait eighteen kilometers northeast of Lougheed Island. Oil and gas were discovered at MacLean I-72 well, located in the MacLean Strait twenty-seven kilometers east of Lougheed Island, with a flow of 775 barrels a day of crude oil, and an estimated reserve of up to 280 million barrels. Oil and gas were also discovered at Cisco B-66, sixteen kilometers west of Lougheed Island. It is a major find with a flow of nearly 4,000 barrels per day of oil, and an estimated reserve of 1 billion barrels of oil (Panarctic Oil, 198ab; Oilweek, December 14, 1981, and January 18, 1982).

As of 1981, a total of eleven gas fields have been discovered in the Arctic Islands (Panarctic Oil, 1981a). Over 0.3 trillion cubic meters of natural gas were found in the Melville Island area. Moreover, Panarctic expects their Drank field, located off the northern Sabine Peninsula of Melville Island, to ultimately yield as much as 2.8 trillion cubic meters of gas (Urquahart, 1982b); that is equal to one half of the United States proved gas reserves. It is interesting to note that Drake F-76, completed in 1978, was the world's first under-ice well. It subsequently became the first Arctic subsea producing well in forty-five meters of water. The Drake discoveries demonstrate how extensive gas reserves offshore as distant as twenty-four kilometers and in 457 meters of water could be developed.

Having concluded that the best potential lies in deeper waters yet, Panarctic has expanded its program of research and exploration in the Arctic Islands. During 1982, it is drilling from four ice platforms, and expects to have three more in operation by 1983. Additionally, Panarctic is arranging for a deep drilling rig, capacity to 7000 meters, to be delivered during 1982 (APOA, December, 1981). See Figure 13. C. Hetherington, Panarctic's president, is of the opinion that Canada may be producing oil as well as gas from the Arctic Islands by the 1990's, before production starts in either the Beaufort Sea or the Hibernian (off Newfoundland) fields (Urquahart, 1982b).

Because of relatively stable ice conditions and deep water approaches, the areas just discussed should be particularly amenable to the pickup and transport of petroleum by submarine. The water depths and physical conditions permit easy access for submarine transports via the following deep water passages: Prince Gustaf Adolf Sea, Byam Channel, Austin Channel, and Byam Martin Channel.

Lancaster Sound/Baffin Bay

The area is the eastern deep water entrance to the "Northwest Passage". The dynamic sea conditions--icebergs, moving pack ice and rapid surface currents--of Lancaster Sound and northern Baffin Bay are in sharp contrast to the calmer, relatively ice-locked waters of the Arctic Islands (Pallister, 1980).

Large scale seismic surveys, conducted since the late 1960's, have revealed some fifty promising geological structures. They are estimated to contain eight per cent of Canada's total potential oil and gas reserves. Oil and gas permits have been awarded

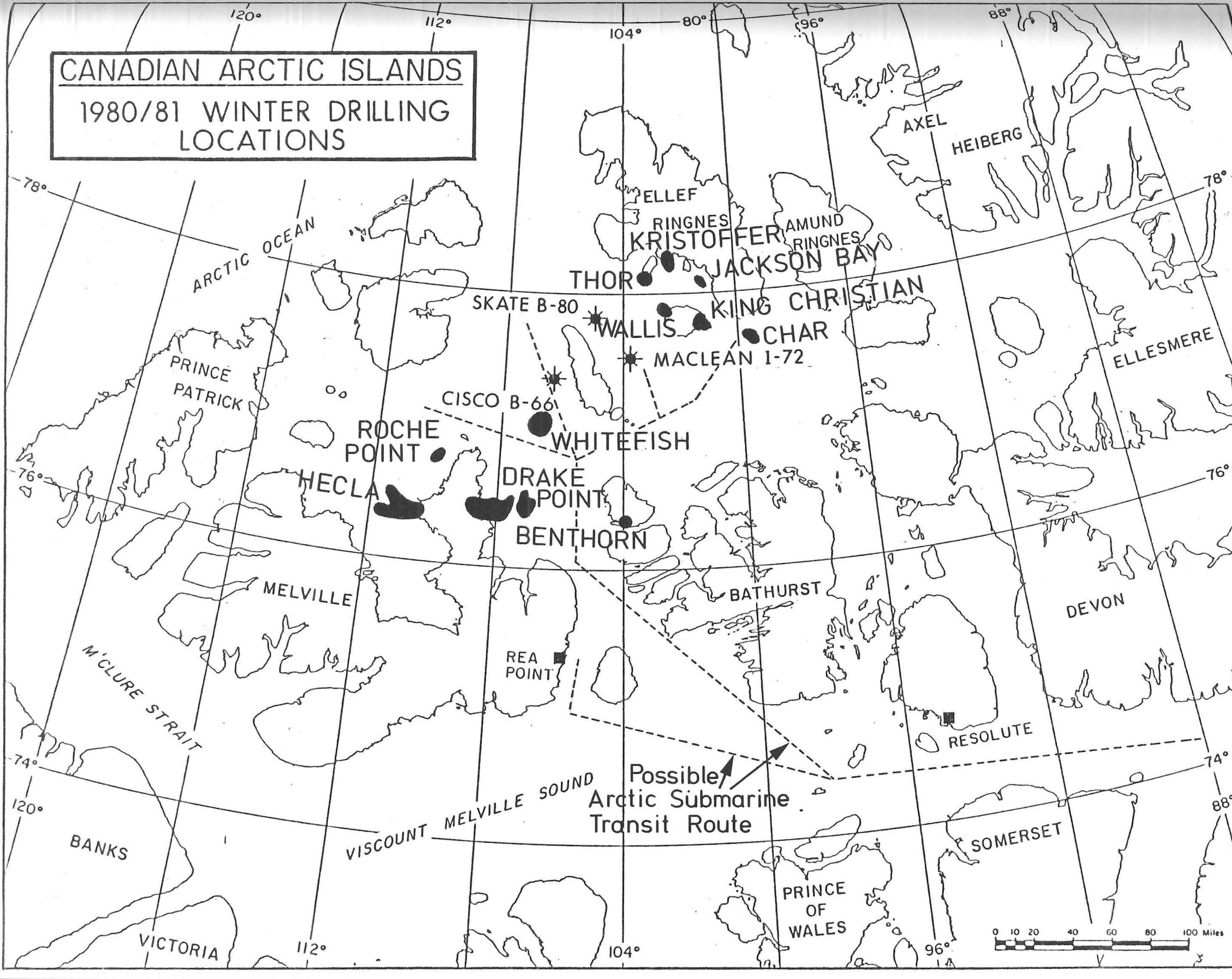


Figure 13 Arctic Islands Petroleum Discovery Sites

(after Panarctic, 1981)

for areas within Lancaster Sound and the approval to start drilling has not yet been given by the Department of Indian and Northern Affairs.

In 1974, Norland Petroleum Ltd., proposed to drill an exploratory well on the Dundas structure, one of the largest, located in 770 meters of water. The proposal was referred to the Federal Environmental Assessment and Review Office, and the Lancaster Sound EARP Panel was set up to determine the proposal's acceptability. The proposal was denied in 1979 and a recommendation was made that the government issue a statement on the most appropriate use of Lancaster Sound. An examination of the entire northwest sea route including preliminary papers and public hearings was conducted by the Canadian government, and it is expected to release a final "Green Paper" soon (Canadian Arctic Resources Committee, 1979b; Canada Indian and Northern Affairs, 1982). In the meantime, Petroleum Canada Exploration, Inc. has during 1981 and 1982, continued seismic studies in Lancaster Sound and north Baffin Bay region (APOA, August, 1980). Results to date indicate favorable geological structures, three of which Petro-Canada hopes to test by exploratory drilling in water depths from 380 to 850 meters, using dynamically positioned drill-ships. Petro-Canada expects to submit its proposal with a supporting Environmental Impact Statement, during 1982 (Pallister, 1981).

Since no exploratory wells have yet been drilled in either Lancaster Sound or northern Baffin Bay, proven petroleum resource figures and potential field estimates are unavailable.

If commercial oil fields are discovered, however, both areas are easily accessible and particularly suited to submarine transport year round. This has been proven already by a number of United States submarines, like "Archerfish", "Skate", "Seadragon", and "Queenfish" (McLaren, 1982).

GREENLAND

There is considerable interest in the Continental Shelf, which runs the entire length of east Greenland; it is one hundred to two hundred kilometers wide. The area from Scoresbysund to Kronprins Christian Land may consist of sediments identical to those off Norway's west coast (Taagholt, 1980). Aero-magnetic and seismic observations taken over large areas of the southeastern portion by the Danish government in 1979-1980 were positive, and deserving of further investigation (Taagholt, 1980). Denmark is considering drilling in the Greenland Sea (Gamble, 1979); but exploration is difficult due to the large number of icebergs. Some exploration has begun in northern Greenland which, because it is geologically related to the Arctic Islands, is thought to have some potential. The conditions for prospecting are particularly favorable there, for as Dr J. Taagholt (1980), Danish Scientific Liaison Officer for Greenland, points out, it has some of the largest ice-free area in Greenland, and though the summers are cold, they are long and very dry.

Attention has been focussed on Greenland's west coast continental shelf, thought favorable for petroleum deposits out to water depths of about five hundred meters (U.S. Central Intelligence Agency, 1978). When seismic surveys showed there was a sedimentary sequence underlying the shelf with large structures, Denmark awarded exploration licences for waters between 63° and 70° North latitude to six consortiums in 1975 (Ministry of Greenland, 1978). The first well, a wildcat, was drilled in two hundred meters of water in the Davis Strait in 1976 (U.S. Central Intelligence Agency, 1978). Companies such as Chevron, ARCO, and Mobil have subsequently drilled further wildcat wells from drill-ships (Geological Survey, Greenland, 1979; APOA, August, 1978). While there have been some indications of gas, results overall have been disappointing (Taagholt, 1981).

Dr Taagholt believes that when oil and gas are located, production itself will not be difficult. However, the matter of transporting the petroleum to refineries will be. Access to northern and eastern coasts is hampered by severe and variable ice conditions. On the western and southern coasts access is somewhat easier, because a relatively long summer permits it.

Over the past several decades, both conventional and nuclear submarines have demonstrated an ability to operate in Greenland's offshore waters, even in the presence of numerous icebergs (McLaren, 1982). If petroleum in commercial quantity is found, it is probable that its loading and transport from the northern and eastern coasts' production sites in particular, could best be accomplished by submarine.

CHAPTER V

PIPELINES AND ICE-BREAKER TANKERS: EXISTENT AND PROPOSED PETROLEUM TRANSPORT SYSTEMS

Long and expensive pipelines are currently favored by both government and industry for transporting oil and gas from the Arctic to southern refineries. The Trans-Alaska Pipeline has been in operation since 1977, and more and larger pipelines are planned for the future.

The Trans-Alaskan Pipeline

The Trans-Alaskan Pipeline is a 800 mile, 48-inch diameter pipeline which transports approximately 1.2 million barrels of oil from Prudhoe Bay to Valdez each day. Although planning for its construction began in 1968 following the discovery of oil at Prudhoe Bay (Polar Record, September, 1979), work on what was to be the largest privately funded construction effort in history did not begin until 1974. It wasn't until the Manhattan Project study group (see page 54) concluded that a pipeline was the safest and most efficient means for transporting this newly discovered oil, that companies joined to form the Alyeska Pipeline Service Company. Then, design and assembly of the pipeline began in earnest (British Petroleum, 1977).

The laying of the pipe was subject to expensive delays, as it could not proceed until a series of environmental and native land claim issues had been settled (Polar Record, 1977). Finally, on May 30, 1977, the last weld was completed; the first oil, which takes four and one-half days to travel the length of the pipe, was on its way to Valdez to be stored. Later, it was to be shipped to the United States at a set price of $4.91 per barrel. This price, established by the Interstate Commerce Commission, was about a quarter of the world price at that time (Polar Record, 1977). The Pipeline, with the exception of a few minor incidents, has been in operation ever since.

Although not yet a formal proposal, it has been suggested by some authorities that the spare capacity of the Trans-Alaskan Pipeline, some 800,000 barrels per day, should be used. It would require the construction of more pipeline as a branch to the main line to oil sources variously located off the northwest Alaskan coast (Bregha, 1979).

Polar Gas Project

Although this project has nothing to do with the transport of oil, it is a "mega-project" which proposes to use pipeline to transport petroleum. It is therefore included in this section. It is reasonable to assume that a successful laying of pipe for gas transport will contribute to the technology for the transport of oil along similar routes, including from the offshore areas. The proposed pipeline would run from sources in the Arctic Islands, the Mackenzie Delta, and the Canadian Beaufort Sea, to southern Canadian markets.

The Polar Gas Project, sponsored by a corporate consortium composed of Trans-Canada Pipelines, Pan Arctic Oils, Petro-Canada, Ontario Energy Corporation and Teneco of Canada (Polar Record, 1981), propose a "Y" pipeline up to 3,200 miles long (Oilweek, February 8, 1982). It would transport Arctic Island

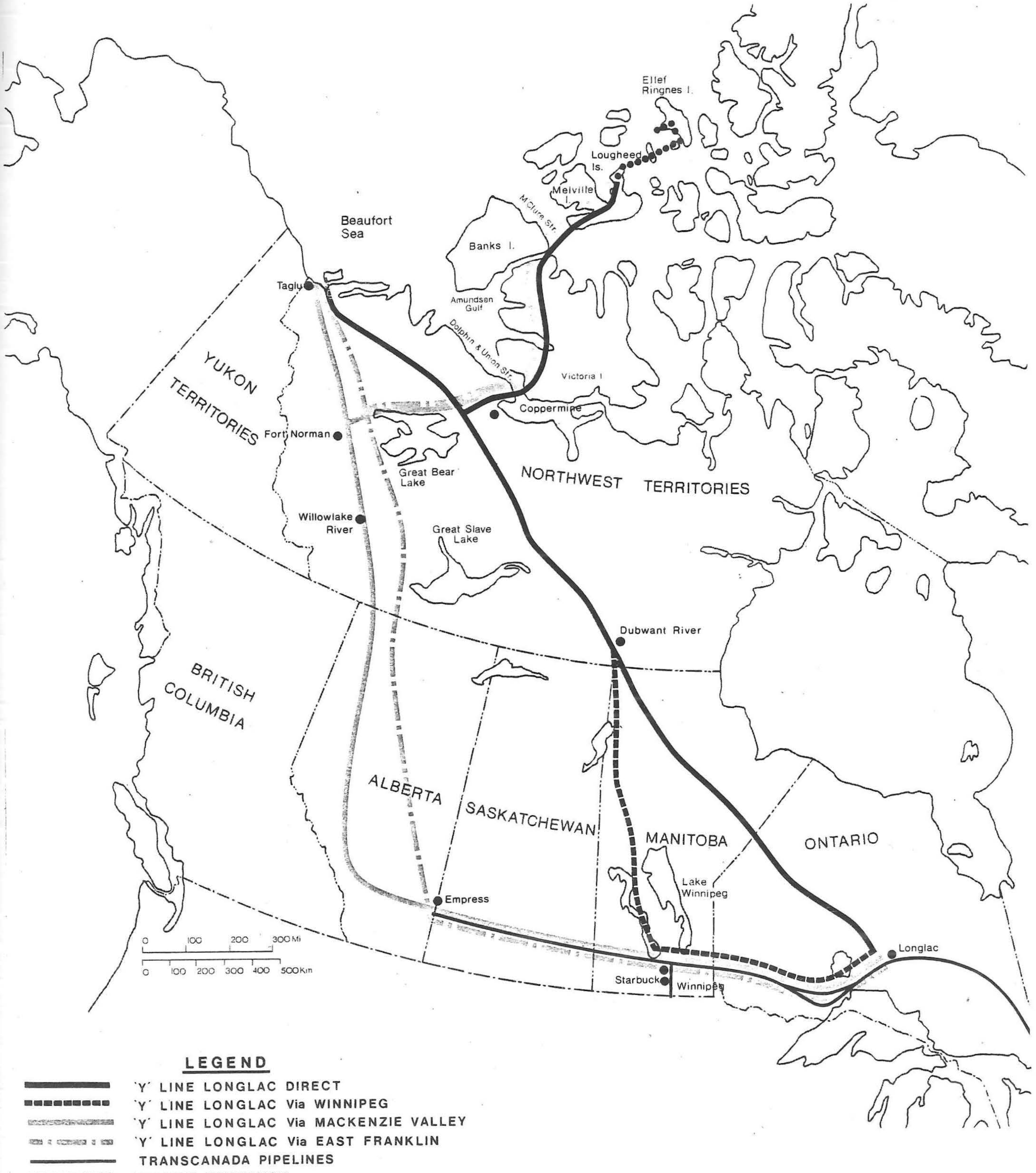
and Beaufort Sea gas to southern markets by the early 1990's, if things go according to plan (Urquahart, 1982b). The pipeline is expect to cost about $7 billion (in 1978 dollars), and deliver up to 93.5 million cubic meters of gas per day (Daks, 1981). According to Polar Gas, over $70 million has been spent already in developing the technology necessary for the construction, some of which will be underwater and in exceedingly difficult circumstances.

Several routing options are technologically feasible. The one most likely to be chosen originates from Drake Point, Melville Island and proceeds via the M'Clure Strait. It continues over Victoria Island and to the Canadian mainland via Dolphin Strait and Union Strait. A later extension would link the gas fields near Ellef Ringnes Island with the main line at Melville Island. See Figure 14 (Polar Gas Project, 1980).

Certainly one of the most formidable sections for construction will be across the M'Clure Strait, where the pipeline will be 122 kilometers long, and at depths to 503 meters. Because ice islands with drafts as much as 35 meters enter the Strait and scour the shallower portions, the pipeline will have to transit from land to deep water via tunnels buried up to 50 meters below the surface. Permafrost will also be a problem and as is the case for all pipelines, engineering will need to be virtually foolproof as technical failures during either construction or operation would be both difficult and costly to repair (Daks, 1981).

The Polar Gas Company is working on a revised application for submission to Canada's National Energy Board this year, 1982 (Oilweek, February 8, 1982). To date, none of their construction

Figure 14 Proposed Polar Gas Pipeline



(from Polar Gas Project, 1980)

plans have been subjected to review by any sort of regulatory agency, nor has there been an assessment of the potential environmental impact (Daks, 1981).

Alaskan Highway Pipeline

The greatest of the "mega-projects" planned for the next decade is the 5,500 mile Alaskan Highway Gas Pipeline. It is to carry natural gas from Prudhoe Bay and the Makenzie Delta to southern markets in the United States and Canada. In 1977, a joint agreement was signed by the two countries. Since then, however, plans have been delayed by a long deadlock in the United States Congress over matters of pricing and finance. It now appears to be stalled due to a lack of financial backers (Whitehorse Star, April 28, 29 and 30, 1982). At any rate, should it go forward, there are no plans to have it draw from Arctic offshore petroleum sources.

ICE-BREAKER TANKERS

Next to pipelines, ice-breaker tankers are presently considered the most likely means to be developed for transporting petroleum from the Arctic. While there are no such tankers yet in operation, a good deal of interest, effort, and money is being devoted to their development.

The Manhattan Project

The Manhattan Project was designed to determine the feasibility of transporting crude oil from the Alaskan North Slope to the United States eastern seaboard, using a standard tanker especially modified for Arctic voyages. Information from this experiment was then to be applied to the design and building of ice-breaker tankers suitable for year round operations in the Arctic. The project was sponsored by Humble Oil and other companies, and included a general assessment of the feasibility and cost-effectiveness of both tanker and pipeline systems.

The initial trials took place with the 115,000 ton, 43,000 shaft horsepower ship. She was fitted out with an ice bow, and given especial strenthening to meet the conditions ahead of her. Two voyages were conducted: one in the late summer and fall of 1969 after the ice-melt, and the other during the spring and early summer of 1970 when the ice was at its thickest (United States Department of Interior, 1972). The Canadian and United States governments assisted by providing ice-breakers, and ice reconnaissance and forecasting. The "Manhattan" was trapped in the M'Clure Strait en route to Prudhoe Bay on her first voyage. On the return route near Greenland, an iceberg fragment punched a twenty by thirty foot hole in one of her cargo tanks (Moreau, 1970). Nevertheless, she was able because of her tonnage, horsepower and protective features, <u>and</u> the assistance of three ice-breakers, to carry back a symbolic barrel of oil to the East Coast (U.S. Department of Interior, 1972). Although the second voyage, following a different route, was spoken of as successful, the commercial viability of this mode of transport was still apparently in doubt (British Petroleum, 1977).

In early 1970, Humble Oil awarded a contract to Newport News Shipbuilding to develop a class of 250,000 ton ice-breaker tankers, each capable of carrying between 1.5 and 1.7 million barrels of oil (Sater, 1971). In late 1970, however, Humble Oil decided to discontinue work on commercial tankers (Dosman, 1976).

In 1973, the United States Maritime Commission sponsored an Arctic Marine Commerce Workshop. The Arctic expert delegates, drawn from throughout the United States and Canada, expressed their strong belief that LNG ships should be employed in the Arctic, and recommended that the United States government purchase the Manhattan Project test data, which contained valuable information on powering performance and hull strength, and on torque overloads in the Arctic ice. They felt this information should be released to the maritime community (Arctic Institute of North America, 1973). There was apparently no response to this request.

Arctic Pilot Project

The idea of using ice-breaker tankers in the Canadian Arctic was revitalized when the Canadian government-owned corporation, Petro-Canada, formed a consortium with Dome, Melville Shipping, Ltd., Panarctic Oils, Ltd., and Trans-Canada Pipelines, to initiate an ice-breaker tanker project. This project was to test the economic and technical feasibility of producing natural gas from Arctic Island wells, of transporting it via a 160 kilometer buried pipeline to a terminal on Melville Island, then shipping it via ice-breaker tanker to a regassification plant in either Nova Scotia or Quebec. It was to operate on a year round basis, using Arctic Class VII ice-breaker tankers, capable of plowing continuously through seven-foot thick ice. The pilot phase of the $2.1 billion project, which is one-tenth full scale, calls for the construction and operation of two giant double-hulled

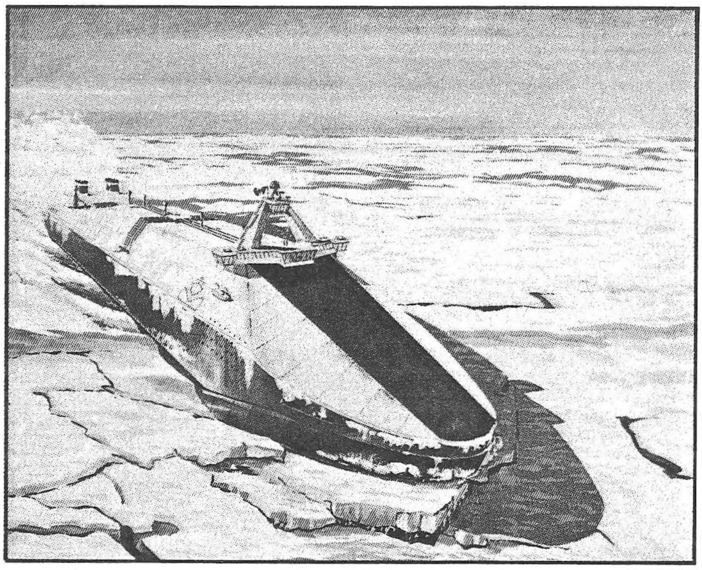
LNG carriers, 1,295 feet (375 meters) long, and 135,000 tons. Equipped with ice-cutting bows and keels, they are to make sixteen round trips annually (Giniger, 1982). See Figure 15.

Interestingly, the Arctic Pilot Project has seemed not to provoke the same degree of opposition as the Arctic Gas Line Proposal. Authorities consider the project likely to be approved, since it cleared a major regulatory hurdle in November, 1980 when the Federal Environmental Assessment and Review Panel found it to be environmentally acceptable, provided certain conditions were met (Canadian Arctic Resource Committee, 1980). The project subsequently bagan its hearings before National Energy Board in early February, 1982 (Urquahart, 1982a). According to the February 22, 1982 issue of Oilweek, plans are to begin shipping gas from eight production wells on the Borden Island-main pool, estimated reserves of 130 billion cubic meters, in the Drake Field. Estimated delivery is 1986.

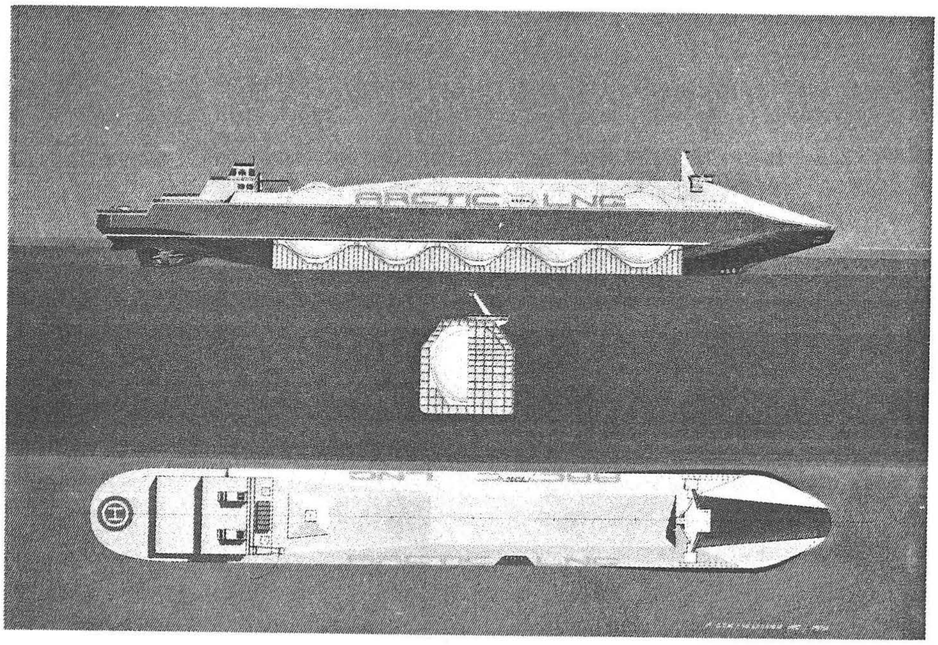
The Arctic Class X Tanker

Another tanker project is sponsored by Dome Petroleum. Dome is apparently quite far along in the design of a class of Arctic ice-breaker tanker which will be able to transport oil from the Beaufort Sea to world markets via the "Northwest Passage" year round (Brewer, 1982). These 1,280 feet (390 meters), 300,000 ton, double-hulled Arctic Class X ice-breaker tankers have a cargo capacity of 200,000 tons deadweight. With a conventional 150,000 shaft horsepower propulsion plant (double the power of the Soviet nuclear-powered "Arktika" which went to the North Pole in 1977 (Canadian Arctic Resources Committee, 1979a) designed

Figure 15 Arctic Pilot Project Ice-Breaker Tanker



Courtesy Arctic Pilot Project



Courtesy Arctic Pilot Project

Arctic LNG Carrier

(from APOA, spring/summer, 1982)

to drive it through ice ten feet thick at a speed of six knots and about twenty knots in the open ocean, they are scheduled to start operating as early as 1986 (Urquahart, 1982a).

Dome's project looks quite promising. Its technology is based upon design features which were tested in a prototype, the 3,642 ton ice-breaker "Canmar Kigoriak" built in 1979. It was the first ice-breaker to operate year round in Canadian Arctic waters. A second and smaller prototype, the "Robert LeMeur", is being built for Dome by Burrard Yarrows Corporation, Vancouver, and is scheduled for delivery in the summer of 1982. The new vessel has many features of the previous one, but will incorporate refinements suggested by the testing of its predecessor (Canada Government of the Northwest Territories, 1982).

The technology being developed by Dome might certainly be applied to the Arctic Pilot Project or even to building tankers to carry Arctic Island oil to world markets. As in the case with the ice-breaker LNG tanker envisioned by Petro-Canada, no final contract has been awarded for the ice-breaker oil tanker being developed by Dome.

Other Sponsors

The Canadian Coast Guard awarded a $6,000,000 contract for the design of a Class X ice-breaker in 1979, but no follow-up contracts have as yet been awarded. The proposed ice-breaker would assist ice-breaker tankers being developed by industry (Gamble, 1979).

In the United States the Maritime Administration commissioned a study of a transport system involving ten tankers, which would transport oil from Alaska's North Slope to the East Coast (Dosman, 1976). It has not gone beyond a reporting stage (Gamble, 1979).

CHAPTER VI

OBSTACLES TO THE DEVELOPMENT OF ARCTIC TRANSPORT SYSTEMS

The obstacles which face those who wish to establish a petroleum transport system in the High Arctic are not only physical; financial, political, and environmental impact problems must be overcome before construction can even begin. This chapter discusses these obstacles, and evaluates the relative impact on pipeline systems, ice-breaker tanker systems, and giant submarine tanker undertakings. The difficulty or ease with which each of these transport modes is able to overcome the hurdles as it proceeds toward development into a fully operational system, is discussed. In proportion with the locality of most of "the action", the examples given will be mainly Canadian. It does not mean that the development of the United States Arctic does not encounter equivalent difficulties; it does.

FINANCIAL OBSTACLES

The General Problem

The production of petroleum in the Arctic is not cheap; neither will its transport be. As mentioned earlier, the Canadian government and Canadian industry have already poured over $800 million into Arctic Island petroleum exploration alone and so far without a penny in return (Jones, 1981). While the United States and especially Canada seem determined to develop their Arctic petroleum resources as soon as possible (Daks, 1981), the accomplishments are still not adequate to meet the goal of self-sufficiency.

As Chapter IV has shown, much oil and gas have been found. The technology exists to discover it and in many cases, to produce it. But what is lacking, save for the Trans-Alaska Pipeline with its own geographical limitations, is a means of transporting Arctic petroleum to where it is needed. The development of transportation modes will be severely retarded if financial backing cannot be found. The recent predicament of the Alaska Highway Pipeline well illustrates this point (Whitehorse Star, April 28, 29 and 30, 1982). Finding the requisite capital is one of the challenges which must be faced.

It is somewhat ironical that the circumstances which make financial backers hesitant to invest in petroleum transportation systems would never have arisen had there been opportunity to do so earlier. The widespread recession, typified by inflation and high interest rates, shows no signs of abating (Newsweek, April 12, 1982). In part, the recession is seen to have been caused by the "secondary explosion" of oil prices in 1979 and 1980 (Bareau, 1982a; Financial Times, December 2, 1981). In response, conservation measures were taken by many nations, and since these were effective, there is now a surplus of oil and gas on the market (Vines, 1981). World financial authorities predict that as a result of the surplus, and the investments being made in the search for synthetic fuels (Huxley, 1982), there will be, and continue to be, a substantial lowering of oil prices (Bareau, 1982b). The net result is that although some authorities predict an eventual and perhaps dramatic rise in oil prices (International Herald Tribune, May 24, 1982), potential investors see no prospect of early returns on any long-term investment in the petroleum industry (Vines, 1981), and hence are reluctant to invest in what is now the most critical area of petroleum development: transport.

Therefore, it is necessary for petroleum transport systems proposed for the Arctic to appeal to potential financial backers. In order to to this the project must have a high probability of being successfully and quickly accomplished; a market must exist for the oil and gas which could be transported; the project must in general be cost-effective so that investors could expect an attractive and early return on their money.

Impact on Proposed Transport Systems

Using these criteria, the present proposals for new pipelines may encounter the most difficulty in being financed. Some authorities claim that pipelines are still the most economic method of transporting liquid and gases (Gorman, 1982), but recent examples and estimates indicate otherwise, especially when capital costs are included in the economic assessment. Pipelines are, historically and potentially, very prone to costly regulatory and technological delays (Robinson, 1980; Polar Gas Project, 1980). The Trans-Alaskan Pipeline was a prime example of this: it took nine years to construct, at a cost finally of $9.3 billion. This was approximately three times as long, and ten times as much as the original estimate (Foster, 1980).

? p50.
= 3 years.

The proposed Alaskan Highway Pipeline is another example. In 1977, the need for its construction was agreed to by both the United States and Canada (Arctic Institute of North America, 1982). Yet because of regulatory delays and inadequate financing, construction has not yet begun. The estimated cost of construction has gone up dramatically, from $10 billion in 1970, to an estimated $40 to $60 billion now (Whitehorse Star, April 30, 1982). Some experts predict that even if it is fully financed, it will not be completed by the estimated date of 1987. Further, some conjecture that it may never be completed (Nelson, 1982).

The prospects of the Polar Gas Project are even more open to conjecture; the estimated cost was $7 billion in 1978, and over $70 million have already been spent on developing the necessary technology (Polar Gas Project, 1980).

The financing prospects for ice-breaker tankers are perhaps even less promising than for pipelines, because this completely new system involves the development of much new and untried technology (Bregha, 1979). Also, if Canada adheres to her intention to establish an all-Canadian Arctic marine technology and shipbuilding industry, this will in itself be another mega-project for Canadian industry (Oilweek, March 1, 1982). Canada's desire to establish such an industry may well be less than her ability to do so; at present, Canada has no shipyards capable of building the proposed tankers, and any design and building in the near future will have to be done abroad (Giniger, 1982). It is estimated that the pilot phase alone of the Arctic Pilot Project will cost about $2.1 billion when its two ice-breaker LNG tankers are delivered in 1986 (Urquahart, 1982a).

Dome Petroleum's fleet of Class X giant ice-breaker tankers would require a sizeable chunk of the $90 billion Dome plans to invest in developing the Beaufort Sea (Lloyds' List, February 25, 1982). If either of the ships under consideration are built, they will be "by a large margin the most costly and complicated vessels ever built" (Captain T. Pullen, former commander of the Canadian ice-breaker "Labrador", quoted in Urquahart, 1982b). While the Canadian government will lend support to the ice-breaker tanker projects, the financial backing may still be insufficient.

Giant submarine tankers, whether proposed by General Dynamics or by others, will like ice-breaker tankers, require major new technological developments. This is true especially for the terminal facilities (U.S. Department of Interior, 1972; Nelson, 1982). It has been estimated that the capital cost will be in the order of $20 billion, which puts it in the same cost range as ice-breaker tanker and pipeline proposals. One can expect, therefore, that it may continue to experience the same difficulties in finding financial backers it has had to date (Robb, 1982). Because of the great expense of giant tankers and their associated logistical support systems, giant submarine tanker proposals will quite likely experience the same difficulty in obtaining sufficient financial backing.

Besides the enormous cost, there is another feature of General Dynamics' proposal which may cause hesitation amongst potential financial backers; it is that General Dynamics would be the builder. The proposal calls for construction of an entirely new class of submarine which might come up against the higher priority Trident and "Los Angeles" classes of submarine already commissioned by the United States Navy. These are way behind schedule, and their construction has been characterized by multiple problems. On April 1, 1981, the construction of the first Trident submarine, the "Ohio", awarded to General Dynamics in 1974, had fallen some thirty-two months behind schedule. Deliveries of the twenty-one

"Los Angeles" class submarines under construction at General Dynamics Electric Boat Division are running eighteen to twenty-four months behind schedule. The Secretary of the Navy, chastising General Dynamics for its failure to live up to contract, stated that "the performance to date [1981] of ... Electric Boat Division ... does not support its claims that it can handle new work" (Moore, 1981).

The submarine LNG tanker proposed by General Dynamics can be viewed as a "commercial Trident", privately funded and with all the problems associated with building a new complicated design, (perhaps five times as many because it is five times as large?). Moreover, the construction would have to be done without the priorities for the scheduling of material and manpower which the military submarine shipbuilding programs command. Thus it is unlikely that General Dynamics' submarine super-tanker could be built in a timely manner, both from the standpoint of the petroleum ready for transportation, and the investors' need for for a capital return in the near future.

POLITICAL OBSTACLES

The General Problem

Whatever transport method is chosen, it must pass through land and water which someone owns, has an interest in, or at least claims. These jurisdictional issues over the disposition and use of territory, whether the concerned party be local groups or national governments, must be resolved before any project can proceed. Aside from the jurisdictional issues, the course of national energy programs greatly influences how proposals for

Arctic petroleum transport will be received. Even when a proposal may have satisfied government regulatory requirements, the government itself may not have satisfied land claims and social impact issues raised by native groups. Hence the project will be further delayed as national policy is established on these issues, both in general and in particular.

Although Alaskan native claims were settled by a Congressional Act in 1971 (U.S. Office of Land Claims, 1978), the situation which greets developers is still confused and unpredictable. A mixture of objections raised by native local governments, native corporate groups, and municipal local governments has created an unsettled atmosphere, and resulted in a great number of legal actions. The North Slope Borough's efforts to regulate Beaufort Sea offshore development is a recent example (Arctic Coastal Zone Management Newsletter, 1979).

In Canada, native land claim and social impact issues remain for the most part unresolved. The Canadian government has never entered into any agreement or treaty in years past with its native peoples directly affected by Beaufort Sea and High Arctic petroleum development (Canada Office of Native Claims, 1978). The social issues include possible economic impact of any construction and operations in or through the area affected by the project. They also include the effects of intrusion by non-native workers and the overall impact on the community. Most authorities agree that such problems would be much less complex if land claims could be settled and the natives gain a reasonable degree of control over the future economic development of their ancestral territories (Canada Office of Native Claims, 1978;

Daks, 1981). Prime Minister Trudeau's statement at the first Constitutional Conference on April 28, 1980 well sums up the government's position:

> During the course of the 1970's, we changed our mind on aboriginal rights. With the help of your educational efforts and some judicial examination of the issue, the government accepted the concept of land rights accruing without treaties to the original inhabitants of this country. We begin negotiating land claims arising from these rights, acquired through the traditional use and occupancy of the land.
>
> (quoted in Canada Indian and Northern Affairs, 1981)

As a result, resolution of native land claim rights will have primacy over developmental plans (Canada Lands Directorate Environment, 1982). Hence the net effect will be that any project which might involve claims negotiation and settlement are at risk of being delayed, perhaps for years. The process may also be even further complicated by the amendment on native rights in Canada's new constitution (Whitehorse Star, April 22 and 26, 1982; Padgham, 1982). An example of the impact of this new emphasis on native claims is Judge Berger's recommendation for a ten year moratorium on development in the Mackenzie Valley while claims are settled. The government declined to accept this recommendation, but it influenced the withdrawal of the Arctic Gas Mackenzie Valley pipeline proposal.

In Canada the nationality of the major share holders of an initiating corporate consortium will make a difference to the political obstacles it will be necessary to overcome. The Geneva Convention on the Continental Shelf gave Canada in 1958 sovereign rights over the continental shelf in the Arctic; this extends to the exploration and exploitation of its resources. Therefore, foreign-owned companies and consortiums who intend to work there must incorporate in Canada and operate under Canadian permit and license; in so doing they expressly recognize Canada's sovereign rights (Dobell, 1976).

Canada claims sovereignty over all waters within the Canadian Archipelago including the "Northwest Passage" which must be used by all marine modes of transportation. The United States has taken the firm position that it is an international strait and that Canada's position constitutes a unilateral infringement of the freedom of the seas (McConchie and Reid, 1977; Pharand, 1981). It remains an issue for resolution at the Third Law of the Sea Conference. If resolved in Canada's favor, then non-Canadian ships and submarine takers will be subject to her jurisdiction, and restrictive acts such as her Shipping Act, which could require a licensing fee of one quarter of the market value of the ship (Lucas _et al_, 1978).

In any case, Canada in support of her own sovereignty position passed the Arctic Waters Pollution Prevention Act in 1970. Under the guise of concern with waste disposal, the Act allows Canada to regulate the design and operation of all shipping within her Arctic waters (_Canada Indian and Northern Affairs_, 1980a; Daks, 1981). Canada has also proposed, and the Law of the Sea Conference accepted and has written into its negotiating text, a provision which allows her to regulate the ice-covered areas of the Arctic seas (_Canada Arctic Coastal Zone Management Newsletter_, 1981). Moreover, if petroleum resource development continues in the Beaufort Sea, the matter of a seaward extension of the Yukon/Alaska boundary might become an issue between Canada and the United States (Dobell, 1976).

Impact on Proposed Transport Systems

What is perhaps striking about the political obstacles is that the questions to be settled may have only marginal connection with the subject affected, in this case, petroleum transportation. It is obvious that native land claims are concerned with Arctic transport systems to the extent that they are land-based. Thus pipelines for example are highly vulnerable, as are tanker systems which require large land terminals. It can be expected that Dome's ice-breaker tanker, the Polar Gas Project, and any new addition to the proposed Norman Wells Pipeline Extension may encounter difficulties. The Arctic Pilot Project and submarine transport proposals, because they do not so impose upon the land, might seem to be less affected. They will, however, have some social and economic impact on native people who are concerned with disturbance to the sea-based hunting and fishing economy. It is also obvious that if Canada chooses to exercise her sovereignty over Arctic waters and to regulate activity there, marine modes are highly vulnerable to hindrances from that source, _if_ the regulations are adversary.

In summary, it would be fair to say that not all transport modes are equally susceptible to a particular type of political/legal/regulatory obstacles; but for each mode, potential regulatory/legal obstructions exist. The extent to which they will be applied is not altogether predictable.

ENVIRONMENTAL IMPACT OBSTACLES

The General Problem

The science of environmental impact assessment is a new one, and theory and methodology are still evolving. The kinds of knowledge that would be most helpful, for instance in the biological sciences, are not always developed and available. As a result, the process of impact assessment tends to be both long and tentative, with the final opinion relying on a degree of subjective judgement (Page, 1981). The problem of building a transport system that minimizes environmental pollution and disturbance is a technical one. The problem of getting a proposal through various review and regulatory stages is a political/processual one. Thus the extent to which a project is delayed or requires change on behalf of safeguarding the environment is a function of the nature of the technology proposed, and of the regulatory process.

When the Alaskan Beaufort, Chukchi, and Bering Seas petroleum fields are ready for a transport system, corporate consortiums will have to deal with the United States Federal National Environmental Act (NEPA), and the supporting regulatory process. Considered by some authorities to be reasonably effective (Lang, 1979), NEPA has to date been characterized by lengthy bureaucratic delays, and expensive court challenges by environmental groups (Franson and Lucas, 1978; Page, 1981).

In the Canadian review process, a Canadian owned or incorporated company or group of companies that plans to export Canadian oil, as the first step has to make application for license to the National Energy Board (NEB). Applicants must submit an assessment of the probable environmental impact, including a description of the existing environment, and a statement of measures which will be taken to minimize impact (Franson and Lucas, 1978). A sequence of preliminary and final hearings then follows.

Since impact assessments of sufficient detail have not always been demanded or provided under this arrangement, and since NEB approval of the project has occurred even before the submission of an assessment, a non-statutory Federal Environment Assessment and Review Procedure was established in 1974-1975 by Cabinet directive. It presently appears to apply only to those extra-governmental organizations undertaking projects which are sponsored by a federal department or agency. Thus it would apply to Dome, Petro-Canada, Panarctic, and most of the other companies mentioned, as all are partially government owned. In any case, as all projects require approval of one or more of the Federal government departments - either DIAND for land or Environment for license, every project can expect to be referred to FEARO and and its process of guidelines, Environmental Impact Statements, public hearings, etc. The proposing consortium will have to submit an Initial Environmental Evaluation (IEE) <u>if</u> it believes that its project has the potential to "cause adverse environmental consequences". Then, unless the proposing consortium further determines <u>on its own</u> that its project will have "significant environmental consequences", it is free to proceed with project planning, using to best advantage the information gathered during the IEE (Franson and Lucas, 1977).

It can be expected that environmentalists and potentially affected native groups, already sensitized to major oil spill and pollution problems, will become intervenors in the route to approval.

Only the Arctic Pilot Project, of the projects discussed in this thesis, has actually begun this lengthy review process. Its EARP was established in 1977, and it commenced its NEB hearings this past February, 1982 (Urquahart, 1982a). The Polar Gas Project is expected to submit its application some time later this year.

Impact on Proposed Transport Systems

Experts predict that the Arctic Pilot Project has a good chance of speedy approval because liquified natural gas is considered environmentally less hazardous than oil. Also, the Project is relatively small-scale, with just two ships (Page, 1981). The author believes, however, that it will encounter a major stumbling block if it delays too long in submitting its EIS. Knowledgeable environmentalists and native groups are rapidly awakening to the fact that the communications and the mating habits of marine mammals such as the Bowhead whale could be seriously affected by the high radiated noise level from ice-breaker tankers as they crush through the heavy ice, and as heavy propellers churn through the water (Eaton, 1982). The concerns for high acoustic noise levels, particularly below 100 Hz, by Danish and other delegates at a recent Workshop on Underwater Noise and Marine Mammals conducted by the Arctic Pilot Project were justified (Peterson, 1981). If absolute sound pressure level readings were measured by a suitably equipped and calibrated platform, the truth of the matter would be evident in short order. Some preliminary experiments at sea with just merchant ships or average-size tankers will be quite revealing. The author therefore predicts that both the Arctic Pilot Project and Dome's proposed ice-breaker tanker fleet could encounter serious difficulties in gaining approval because of the high radiated noise levels from their tankers.

The Greenland government is already on record as being strongly opposed to the Arctic Pilot Project (Whitehorse Star, March 2, 1982), and is joined by Canada's Inuit Tapirisat (Beer, 1982). They sense that among other major concerns, the noise level will have a profound impact on marine life, and that generally the marine environment will be considerably disturbed.

Generally speaking neither pipelines nor tankers can be said to have an exemplary record in regard to oil spills and pollution. One has only to recall the gigantic spills of the "Torrey Canyon", the "Amoco Cadiz", or the "Kurdistan" (Livingston, 1981); or to read the April 9, 1982 issue of News/North in which its energy columnist notes that there was a total of some forty-five pipeline failures in 1980 in Canada alone. They spilled some 8,511 cubic meters of oil into the surrounding environment.

How long would it take to locate and repair, and contain the oil from a pipeline leak under the ice-covered Beaufort Sea, or under the M'Clure Strait, or from an ice-breaker tanker in the "Northwest Passage" during the winter months? The fact is that the state of the art for dealing with oil spills even on the open sea or on land is inadequate and unsatisfactory (Page, 1981). An oilspill under ice in the Beaufort Sea, in the Arctic Islands, the "Northwest Passage", Baffin Bay or the Davis Strait, would be a very serious matter, and very difficult to repair and clean up. These things must be considered:

1. Floating ice provides a barrier to the location, repair and clean-up of the oil spill. Severe weather does also.
2. Access difficulties may cause delay in getting containment and other necessary equipment to the scene.
3. Much remains to be learned about Arctic currents; and therefore, the spread and travel of oil from a spill at a given location is uncertain.

4. Cold water hinders the natural breakdown of hydrocarbons.
(Page, 1981; Wadhams, 1981a)

And what of submarine tankers and oilspills? The high degree of engineering quality control which has ensured watertight integrity in submarines already built by shipyards such as Vickers Barrow, Howaldtwerke Kiel, Newport News and Mitsubishi are evidence of safe construction directly transferable to submarine tankers. The probabilities of inadvertent leaks is judged to be extremely low.

In any case, whatever the probability of environmental damage by any proposed transportation mode, the regulatory process promises to be lengthy, beset by contention between developers and environmentalists and native groups. The final decision on whether a project, especially a mega-project, is given the go-ahead or not will likely be made at a very high governmental level.

PHYSICAL OBSTACLES

The General Problem

The physical environment of the Arctic presents any potential developer with a host of technological challenges. How well and economically a proposed transport technology will overcome these obstacles is, of course, the critical factor in the decision of which method(s) to develop. Depending upon the transport technology under consideration, ice, snow, permafrost, extreme cold and the other conditions which make construction and operation in the Arctic difficult and hazardous, present different obstacles and challenges. How they affect each transport mode is discussed in the following sections.

Pipelines

The laying of pipelines requires a great deal of work on site in the Arctic itself, whereas tankers and submarines can be constructed in more agreeable climates. Many pipeline components can be manufactured outside the region, but they must be assembled on location. Darkness, low temperatures, high winds, and "white out" conditions make work difficult if not impossible. The extreme cold causes welding and fabrication problems, such as hydrogen embrittlement and sulphide cracking (Oilweek, January 25, 1982). Within the basic permafrost zone, serious technical problems concerning pipeline integrity exist for both oil and gas lines. They pose difficult geothermal questions as decisions are made on how to control melting and thaw settlement in permafrost, or frost heaving, and design suitable safe structures (Page, 1981; and others). It should be noted that the lack of a credible solution to the frost heave problem on a gas line contributed to the final withdrawal of the Arctic Gas Pipeline application (Daks, 1981). Even on land, pipeline technology has a long way to go before these problems are genuinely solved, and zero defects pipeline can be economically manufactured and operated.

The problems are compounded when the proposed route of the pipeline requires construction through and under seawater and ice. The proposed Polar Gas Pipeline could have the most difficulties in this regard. The necessary technology for the safe and successful in-water construction of pipeline crossing various marine channels in the Canadian Archipelago, and particularly, in the M'Clure Strait, will have to be developed. There are constant threats of severe damage, particularly at the sea/shore transitions, by ice-scouring from heavy pressure ridges, and chunks of ice islands with keels of more than thirty meters. They are present in the Beaufort Sea, and they also enter M'Clure Strait. A great deal of research remains to be done in order to determine both the sources of these ice islands and pressure ridges, and their migratory routes and maximum keel depths (Page, 1981).

Ice scour will probably be the most critical problem in the Beaufort Sea also (<u>Oilweek</u>, January 25, 1982). The constant presence of grounded pressure ridge keels, particularly in the "Shear Zone" at the edges of the moving pack ice is characterized by very heavy pressure ridges (Wadhams, 1980); it results in tremendous pressures on the sea bottom for nine months of the year. Gouging and scouring have been noted in depths up to sixty meters, although they generally average between one-half and one meter deep; on the outer shelf, gouges have been observed as much as five and one-half meters deep (Dinter and Grantz, 1981). Very little technical data is available on other important characteristics like currents, ice thickness and movements, and bathymetry of the Beaufort Sea, the Arctic Islands channels, and the "Northwest Passage". What is known, however, is that conditions are unusually severe. Preliminary research indicates that protection for pipelines will be required out to depths of forty-five meters in some places (Kaustinen, 1980). It has been suggested that enclosing or burying the pipeline in a special tunnel cut into the bottom of the sea may be the best solution (Page, 1981). It should not be forgotten that permafrost will also have to be dealt with beneath the sea in both the Arctic Islands and the Beaufort Sea

(Pounder, 1981). On the surface, the constant presence and pressure of ice on pipe-laying barges and on the pipe strings themselves as they are being put into the water, will not be without difficulty.

Ice-Breaker Tankers

The Soviet ice-breakers, "Sibir" and "Arktika" have demonstrated to the world that routes can be forged through heavy polar ice and even to the North Pole, during the months of May through August (Armstrong, 1979). In the North American Arctic, Dome Petroleum's new prototype ice-breaker, the "Canmar Kigoriak" recently demonstrated a capability to operate in Canadian Arctic waters on a year-round basis (Brewer, 1982).

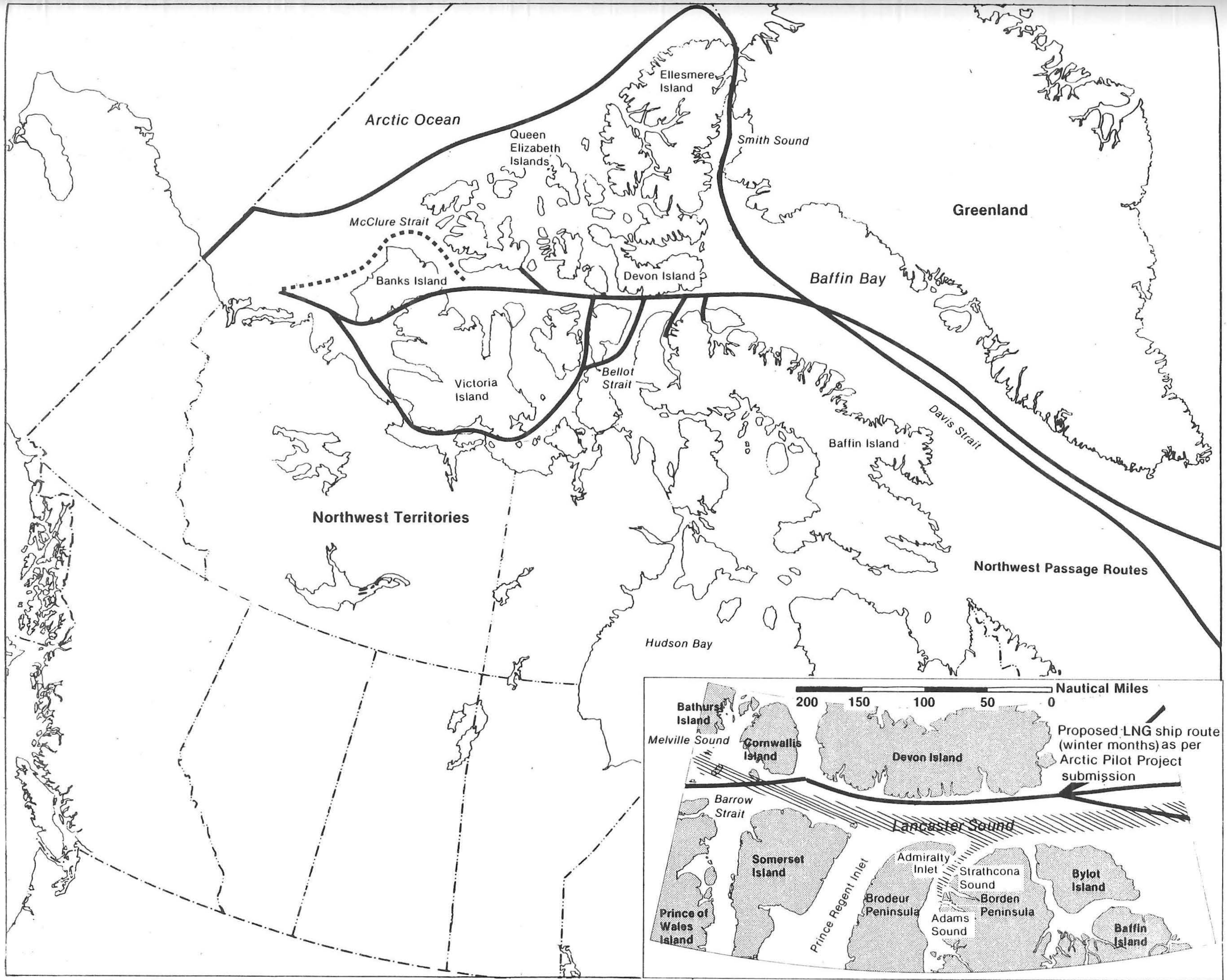
Despite these recent successes, those contemplating Arctic marine transport should not forget the "Manhattan's" difficulties. Also, it should be recalled that one of Canada's newest ice-breakers, the 28,000 ton "M.V. Arctic" was severely damaged as a result of collision with a small iceberg, a "growler", in 1978 (Pullen, 1981). Finally, a review of an article on shipping losses caused by ice, based on Lloyd's Register of Shipping Casualty Returns from 1890 to 1977, is illuminating: it lists some 253 merchant ships of all nationalities which have been lost as a result of collision with, or of being trapped and crushed within, the ice. Sizes ranged from 100 tons to the "Titanic", 46,329 tons. Of the ice-caused losses, over 70 have been in the North American Arctic (Polar Record, 1979).

It is not hard to understand why many marine experts wonder whether the requisite shipbuilding technology can ever be developed to ensure the reliable operation year round of ice-breaker tankers as proposed by the Arctic Pilot Project and Dome Petroleum. While some authorities doubt, others have concluded that the recent knowledge and experience gained by Finnish and other shipbuilders in Arctic-like environments such as the Gulf of Bothnia, indicate "the ship design technology and this operational reliability are now available" (Peters, 1978).

The successful use of ice-breaker tankers through the "Northwest Passage" and in other Arctic waters will depend not just on their technological characteristics; the state of the surrounding water (ice) will make a difference. Thickness of level ice, distribution, and size, depth and frequency of pressure ridges, the amount and thickness of multi-year depth of snow cover, ice strength and pressure within the pack, and the limits of open water areas will all be determinant in the ice-breaker's accomplishments (Peters, 1978). The ice-breaker tanker's ultimate ability to overcome the resistance posed by these factors and still be able to proceed safely at an economical speed will be the final proof. In any case, the fact remains that at the present time, feasibility of year-round navigation as far west in the "Northwest Passage" as Melville Island and the M'Clure Strait by any type of surface vessel, remains to be proved. See Figure 16.

Analysis currently being completed by the author for the Office of Naval Research indicates that a high frequency of deep draft ridges could be a major problem. The analysis is of mid-channel under-ice profiles taken by United States nuclear submarines in the far west area of the "Northwest Passage" during February and August, 1960. In addition, recent environmental background reports prepared on the "Northwest Passage" for the Canadian

Figure 16 Northwest Passage Routes



Northwest Passage Routes

(from Canada Indian and Northern Affairs, 1980)

Minister of Indian and Northern Affairs (1980) and the Ministry of Transport, indicate that documented observations of ice characteristics and distribution are only available for the months of May through November. Very little is known about ice in the more severe conditions typical of the remainder of the year (Canada Indian and Northern Affairs, 1980; Norcor, 1978). The reports are, however, consistent in their observations that there is always a heavy consolidation of ice in the Barrow Strait and there is a heavy concentration of icebergs, ranging in size from 5,000 to 5,000,000 tons, which develops in the eastern entrance of the "Northwest Passage" during the months of July through October as a result of migration from Baffin Bay.

These hazards to ice-breaker tankers are further compounded by the fact that the months of July and August are characterized by heavy rainfall and fog, and in October, by the year's heaviest snow falls (Canada Indian and Northern Affairs, 1980). Moreover, high sea states and the longer periods of darkness and low visibility which characterize late fall, winter, and early spring in Baffin Bay and the Davis Strait, add even further to the general dangers of ice-breaker tanker operations in these areas. Significantly, a senior Canadian Coast Guard spokesman at NEB hearings in November, 1981, revealed that the average and maximum wave heights and sea states off the coast of Labrador were "a couple of times higher" than Arctic Pilot Project estimates, and that "actual ice conditions were more severe" (quoted in Oilweek, November 2, 1981).

The sum total of all these hazards to ice-breaker tanker traffic sheds doubt on their viability as a means of transporting petroleum from the High Arctic. Furthermore, the greatest challenge for this form of marine transport might not even be the design of the ship; the design and construction of deepwater moorings and/or terminals might be an even greater task. They must be capable of withstanding the dynamic pressures of the pack ice, and be in sufficiently deep waters to permit round-the-clock, year-round, mooring, loading of oil, and processing of dirty ballast waters - all this, in an extremely harsh environment (Canadian Arctic Resources Committee, 1979a).

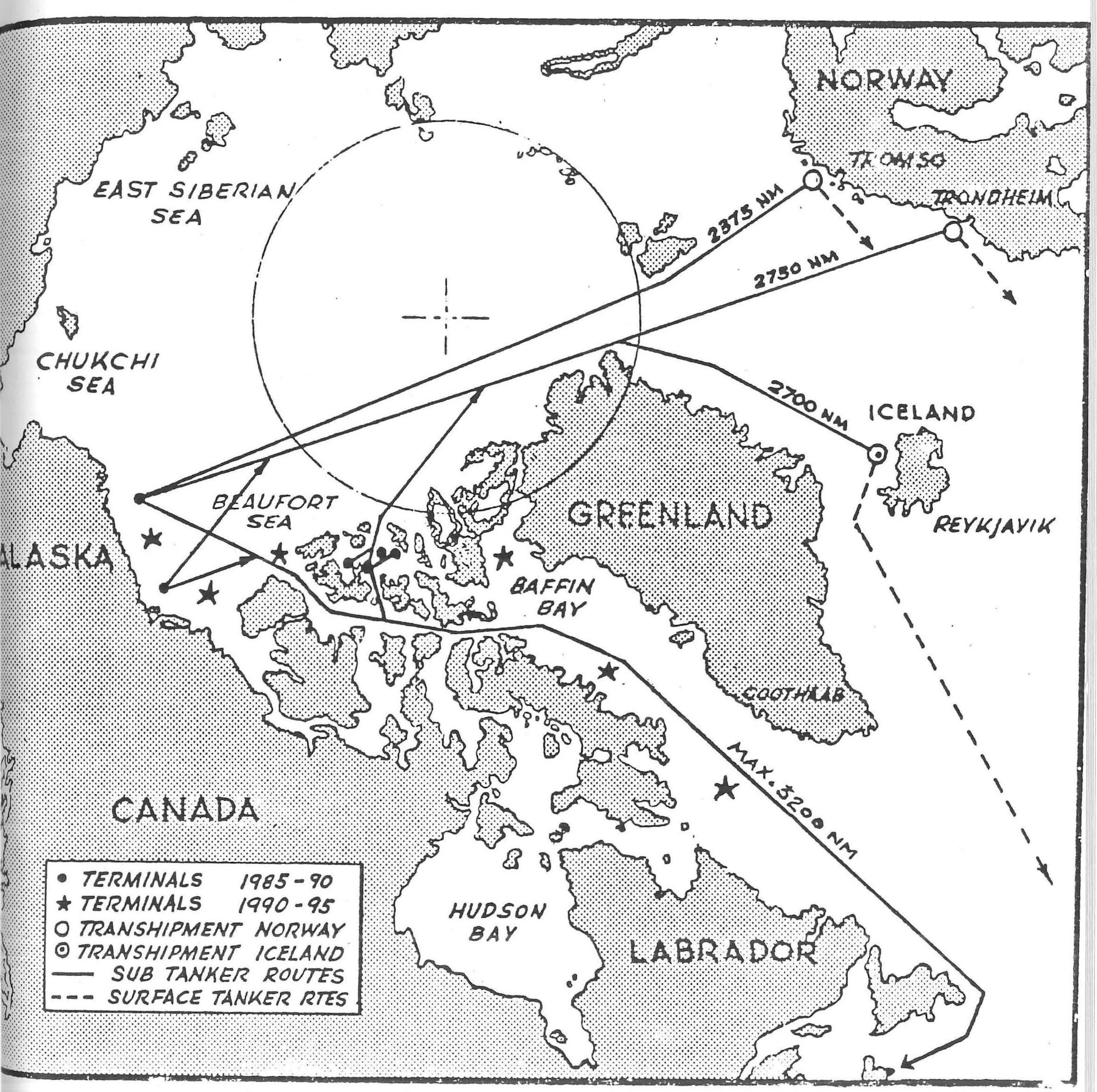
The Giant Submarine Tanker

In common with the large ice-breaker tankers, the giant submarine tanker requires massive terminal facilities, and will face the same technological challenges. But the submarine tanker of any size, because it is sub-marine, escapes other problems which confront ice-breaker tankers. As Admiral I. Galantin of the United States Navy noted:

> A fully laden tanker ploughing a rough sea is virtually a submarine constrained to the surface for the sake of the top hamper on its few remaining feet of freeboard. It requires little imagination and very simple engineering to go all the way in putting the ship underwater and producing a simpler, more efficient hull, one which can escape the stresses of surface operation and which can maintain a higher economic speed.
>
> (Galantin, 1958)

Submarine tankers would be operating beneath and clear of icebergs and ice fragments, and would not be in constant contact or collision with them or the pack ice. Aside from the fact that it obviously makes progress much easier, it also reduces to the minimum the chances of ice penetrating oil tanks or carriers.

Figure 17 Arctic Submarine Shipping Routes



(after Veliotis and Reitz,
1981a)

Below the surface, high seas and inclement weather do not matter. Neither are they affected by surface visibility.

The submarine super-tanker may, however, lose some of the advantages that existing submarines have in an Arctic environment, due to its great size. It is the opinion of several experts that "large submarine tankers would be limited severely in both lateral and vertical movements in the Beaufort Sea and among the Arctic Islands" (US Department of Interior, 1972; and others). They are probably too large to respond rapidly and safely to sudden and/or unexpected changes in the location and depths of deep draft ice. In addition, they would be much too big to be able to surface in the average size open lead or polynya. Thus route options are reduced, and emergencies which require surfacing could not always be responded to in a timely manner. In fact, the size of proposed submarine super-tankers is so great that one must question whether it should be built at all, for serious maneuverability and ship-handling problems seem sure to result. If they ever proved suitable for Arctic petroleum transport, they would have to be limited to deeper offshore areas that might contain commercial size deposits, or if the construction of deep water loading terminals became technically and economically feasible.

CHAPTER VII

THE ARCTIC SUBMARINE AND SUBMERGED TOW SYSTEM

The author proposes that an Arctic petroleum transport system made up of small (of a size already proven in Arctic operations), powerful, conventionally-powered submarines towing hydrodynamically shaped cargo carriers may best meet the petroleum industry's near-term needs, for at least six months of the year initially and year round eventually.

Such a submarine tow transport system (STTS) is not a completely new idea. The concept which involved standard military submarines towing small cargo carriers was successfully tested by the Germans towards the end of WW II (Rossler, 1981). In 1958 a Dracone Company engineering handout suggested towing their product, a flexible neoprene impregnated container, by submarine. The idea is mentioned from time to time in periodicals such as the U.S. Naval Institute Proceedings (Ruhe, 1970), and the Naval Research Reviews of June, 1973. Finally, U.S. Navy submarines have towed sizeable communication buoys since the early 1970's (Naval Research Reviews, July, 1974). Aside from the Dracone handout, the idea has not appeared or been circulated in private industry.

Assuming that the petroleum industry or a corporate consortium is seriously interested in transporting oil from individual production wells in the High Arctic, for example, to potential markets before the end of the decade, a prototype of the envisioned submarine system which would do just that can be realized and in operation within three or four years (IKL, 1982). This submarine would be capable of carrying internally or in towed shapes, at least 20,000 barrels of oil. It could be accomplished at considerably less risk and at a fraction of the cost of any other proposed transport modes.

Such a submarine and tow system would not require the availability of one of the world's few very large shipyards. It could be designed and built by a wide, and hence cost-competitive, range of already experienced conventional submarine designers and shipbuilders. It could, for instance, be constructed in a Canadian shipyard employing the design and shipbuilding experience of such well-known companies as Ingenieurkontor Lübeck (IKL). The cost would be between $100 and $150 million with follow-on production models, depending on number, costing less per copy.*

BASELINE CHARACTERISTICS

The baseline or prototype submarine would have the following capabilities:

1. Capable of towing two (later four or more) cargo carriers in Arctic waters with an initial capacity of at least 10,000 barrels of oil each, at sustained submerged speeds of 8 kts (later 12), at a maximum operating depth of 600 feet.
2. Capable of safely navigating within the harsh environmental conditions characteristic of the Beaufort Sea, the Canadian Archipelago, Baffin Bay, Davis Strait and Greenland Sea and of conducting sustained submerged operations and routinely

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* Information from West German submarine design and fabrication experts. See also Lübecker Nachrichten, 25 May 1982, concerning price of $198 million quoted to the United States Navy for a similar size military submarine.

breaking through thin ice in these waters; initially from early May to late October, ultimately year-round when suitable fuel cell or nuclear propulsion plants become available for later production model submarines.

3. Capable of maneuvering to and receiving oil at production loading sites and of later transferring the tow or discharging oil at open ocean transfer points for subsequent transfer to ocean tugs, floating storage tanks or standard tankers or of proceeding on to refinery locations in Norway, southern Greenland, southern Canada or southern Alaska.
4. Capable of snorkel transit operations, including quick recharge of battery while hovering or proceeding at slow speed in open polynyas and leads.
5. Capable of surface operations.
6. Capable of contact/obstacle detection, rough classification and avoidance while surfaced or submerged.
7. Capable of oceanographic, bathymetric and seismic survey work (when not transporting oil) and of gathering area specific information for not only its own future operations but also for such things as environmental impact assessments. It could even be used to assist in under-ice oil spill containment and pollution reduction operations.

SPECIFICATIONS FOR PROTOTYPE AND EARLY PRODUCTION MODEL

The preliminary specifications for prototype and early production model submarines and tows are as follows:

(Optimum based on submarine purpose and state of art technology*)

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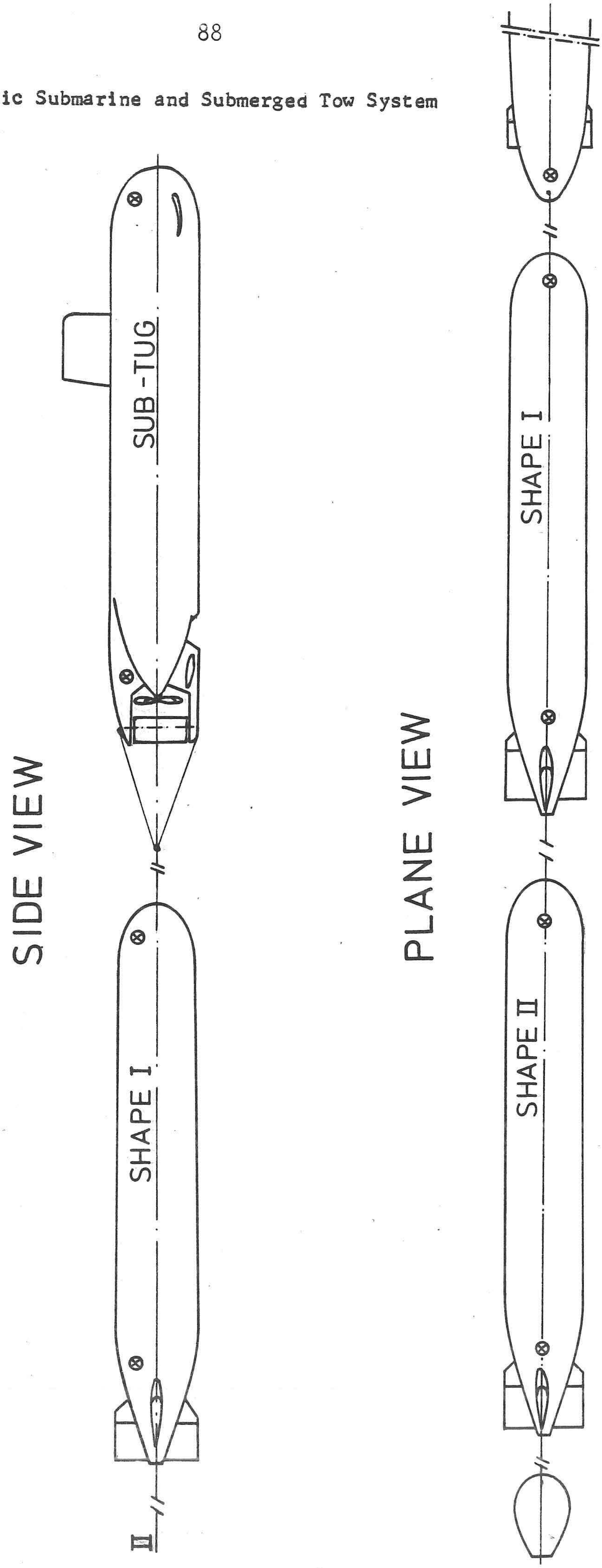
* Based on discussions with Professor Gabler and Dr Abels of Ingenieurkontor Lübeck (designers of IKL type 206, 207, 208, 209, and 1500 class conventional submarines) (See Figure 18).

Figure 18. The Arctic Submarine and Submerged Tow System



Basic Dimensions

Submarine-Tug

Length overall	226 ft (68.7 m)
Beam (pressure hull inner diameter)	25.65 ft (7.82 m)
Height overall (keel to top of sail)	47.6 ft (14.52 m)
Surface displacement (diving trim)	2200 long tons
Submerged displacement	2775 long tons
Fuel capacity	220 tons
Crew	20

Towed Shapes (two, each containing at least 10,000 barrels of oil)

Length overall	About 150 ft (45.7 m)
Diameter	About 20 ft (6.1 m)
Submerged displacement	About 1400 long tons

Propulsion Plant Data*

Four high speed Diesel engines

Type:	Motoren- und Turbinen-Union GmbH (MTU) 12V652
Output:	4 x 950 KW at 1400 RPM

Four AC generators

Output:	4 x 870 KW

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* Production models to use fuel cells for propulsion power after 1986 when they become available on the commercial market (Rossler, 1981; Moore, 1981; Gabler and Abels, 1982), and eventually nuclear power propulsion plans where commercially feasible and politically acceptable

Main battery (8 lead acid batteries,
120 cells each)

Type: Wilhelm Hagen 45SP13K

Weight (including connectors): 750 metric tons

Two DC propulsion motors

Maximum output: 8320.5KW total

One 5-bladed damped, low RPM propeller

Maximum output: 8020.9 KW

Operational Performance (with 2 towed bodies)

Snorkel range at 10 kts: 12,000 nm (19,300 km)

Submerged cruising ranges
(initial total battery capacity of 100% discharging to 20%):*

Speed	Duration	Range
2 kts	334.62 hrs	669.2 nm (1,077 km)
4 kts	141.77 hrs	567.1 nm (913 km)
6 kts	52.71 hrs	316.3 nm (509 km)
8 kts	25.03 hrs	200.2 nm (322 km)
10 kts	12.86 hrs	128.6 nm (207 km)
12 kts	7.10 hrs	85.2 nm (137 km)
15 kts	3.12 hrs	46.8 nm (75 km)

* Based on unpublished analysis conducted for author on IKL's Digital VAX/VMS Computer on 25-26 May 1982

?

Depth:

Maximum Operating: 600 ft (966 m)

Collapse: 1,200 ft (1,930 m)

Electronic

In general, maximum economical application of space and weight-saving technology to equipments, cabling and connectors.

Navigation:	Periscopes (2) Radar Satellite High Latitude gyro Inertial Loran/Omega Fathometers (2) Passive sonar (for acoustic sea lane/channel marker detection and piloting) (Damon, 1972)
Ice avoidance:	Active frequency modulated sonar
Polynya location and sizing, Ice thickness:	Vertical active acoustic "profiler", dual upward side scan sonars
Contact/obstacle detection, classification avoidance:	Passive sonar Radar Periscopes
Communications:	HF VHF UHF Underwater telephone
Special Configuration Modes:	Seismic survey Bathymetric survey Oceanographic Survey Environmental monitoring and data collection

Other

Ship (course and depth) control:	Standard electric hydraulic to ensure maximum reliability, maneuverability and redundancy
Ballast control:	High pressure air, diesel exhaust, electropneumatic control
Tow control:	Kevlar sheathed nylon core for tow; fibre optic cable insert for transmission of tow control signals and monitoring (i.e. depth, maneuvering, ballast, reverse thrust, emergency under ice "anchor" release, etc.) (Swenson, 1980; *Naval Research Reviews*, 1972; Taylor, 1973; IKL, 1982)
Secondary propulsion	Vertical and lateral maneuvering thrusters for submarine and each towed shape. "Drag" thruster for towline, attached by cable to last shape (Block, 1982)
Atmosphere control	Standard conventional submarine sufficient for submerged endurance capabilities
Crew escape "sphere"	Room for all crew members (2.5 m diameter) (Gabler, 1975; IKL, 1981)

Recent "state of the art" technology can be applied during design and construction, if economically feasible, in order to make further gains in submerged speed and endurance for given electrical propulsion plant capabilities. (Representative substantiating references as indicated).

A. Toward Weight Reduction

1. Pressure hull, "sail", control surfaces, high pressure bottles:

   Prototype/early production:

   (a) Hull to be of HY 80 or H.T.S. and of smallest size possible (Gabler, 1982)

   (b) Reduction of maximum operating depth to minimum required for safe under-ice navigation (thus reducing hull thickness and weight)

   Later Production consider use of following materials (if economically feasible):

   (a) Use of titanium or aluminum alloys (Naval Research Reviews, 1972; Reem, 1975; Moore, 1981)

   (b) Use of organic and metallic matrix composition materials (Hettche, 1978; Wynne, 1980)

   (c) Use of Glass Reinforced Plastic (GRP) (Forbes, 1982)

   (d) Acrylic

2. Outer hull, mast fairings:

   (a) Fibreglass (Naval Research Reviews, 1972)

3. Major machinery and electronic equipment:

   (a) Reduction of quantity through duality of purpose.

   (b) Use of fibreoptics, coaxial cables and multiplexing for signal transmission (Naval Research Reviews, 1972-78; Taylor, 1973; IKL, 1982)

(c) Maximum use of microchip, bubble memory, and digital micro processor technology (Moore, 1981; Büttner, 1973)

(d) Use of multiple high flux density permanent magnets to reduce electrical losses and thus permit reduction in size of DC propulsion motors. (IKL, 1982)

(e) Battery lightest weight/highest capacity combination
Use battery for stability ballast. (Gabler, 1978)
Consider external mounting outside pressure hull.

(f) Maximum reliable automation and space remote monitoring to further reduce hull and crew size. (Abels, 1978)

(g) Use of lightweight materials to maximum extent possible consistent with long-term safety, reliable operation, ballasting and ship's stability requirements.

4. Towed shape

(a) Neutrally buoyant.

(b) Manufactured of strong but light weight materials.

(c) Internally exposed to sea pressure through collection/expansion tank system (avoids needs for a "pressure hull").

(d) Necessary control and monitoring components to be miniaturized and encapsulated.

B. Toward Vehicle Drag Reduction

Overall objective to reduce skin friction by maximizing extent of laminar flow over hull form. This will delay onset of turbulence, and reduce net force in astern direction due to pressure distribution over hull (Goodson, 1974; Griffiths and Field, 1973; IKL, 1982).

1. Submarine and tow hulls, control surfaces:

Prototype

(a) Optimum shape for minimum drag. (Gabler, 1982)

(b) Maximum economical smoothness, through removal of defects and discontinuities.

Later production

(a) Polymer coatings

(b) Polymer ejection

(c) Suction slot in boundary layer with stern jet/discharge

(d) Skin heating

2. Minimum number of hull projections (control surfaces, masts, antennas, etc.)

   (a) Hydrodynamically shaped or fairings for those necessary (IKL, 1982)

C. Efficient Use of Power

(a) Use of high flux density permanent magnets in electrical motors and generators to reduce electrical losses (IKL, 1982)

(b) High speed diesel/generator/high capacity battery combination such that battery can be quickly recharged (less than an hour) during snorkel operations of opportunity (i.e. open polynyas, leads). (Gabler, 1982)

(c) Latest high capacity battery features; tubular cells, parallel power extraction from individual cells, internal resistance reduction, maximum specific power. (Abels, 1978; Kruger, 1973)

(d) Use of snorkel transit when sea ice conditions permit.

In conclusion, the author proposes the building of a fleet of small powerful submarines, and petroleum carriers which can be towed submerged. The proposed prototype or near-term system requires only the application of suitable available "state of art" technology to produce a very competitive and environmentally acceptable alternative to existent Arctic Petroleum Transport systems and proposals. It will also enable the petroleum industry to begin more quickly realizing a financial return on their already substantial investiments in the Arctic.

CHAPTER VIII

ADVANTAGES OF THE ARCTIC SUBMARINE AND SUBMERGED TOW SYSTEM

It should be emphasized that the basic characteristics, including operational capabilities, will be very similar no matter whether the proposed Arctic transport submarine is conventionally or nuclear powered. In Chapters I and II, mention was made in the marginal and fringe areas of the Arctic voyages by the conventional submarines of Germany, Russia, the United States and Great Britain. The USS "Trigger", for example, penetrated ninety-seven kilometers under the pack ice in 1957 (Anderson, 1959), and during the past two decades, there have been cruises under the ice by British conventional submarines, such as the "Amphon", "Finback", and "Oracle" (Polar Record, 1962; Wadhams, 1972).

With existing technology, the conventionally powered prototype submarine transport proposed by the author could operate submerged for over two days at six knots, or for over five days at four knots. This is without needing to recharge batteries or replenish the atmosphere. Installation of fuel cells in production models of the same submarine during the next five years, and eventually nuclear power, will increase submerged endurance at these and higher speeds dramatically (Gabler, 1982). Neither are in the author's opinion however, necessary for immediate, successful operation during the period May through October.

The "normal" size of the proposed submarine will allow it to maneuver, as others before it have, in all types of water depths, including those as shallow as forty meters, like the shallow and/or restricted waters of the Bering Strait, the Chukchi Sea, the Beaufort Sea, and within the Canadian Archipelago. It can confidently choose its routes beneath the ice, and has many more manuevering options than the proposed giant submarine tanker, because it can surface and submerge as needed in smaller areas of open water. Once submerged, it can maneuver in narrower, shallower channels. The vessels of the system will have the existing high quality of engineering and construction that is requisite for present-day submarines. Hence accidents and failures due to material inadequacy or mediocre engineering are far less likely to occur than with other kinds of new ships.

Should the proposed Arctic transport submarine be nuclear-powered eventually, environmentalists and others should be reassured by the fact that the United States, Great Britain, and France have built and operated such submarines for over two decades without a single incident.

Its Merits in Regard to Overcoming Financial Obstacles

The Arctic submarine proposal has been developed so that the financially unattractive aspects of the other projects and proposals are avoided or minimized. Specifically:

1. It is not a "mega-project". It does not require enormous investments to have it undertaken. A prototype could be built for between $100 and $150 million, with production models costing less.
2. The nature of the system will allow it to be built incrementally, and to function almost as soon as the first submarine and tows are operative. Because of this, and because it requires a much lower threshold volume of oil than do the other alternatives for it to be economically viable, it will be able to earn money almost immediately. Too, it can grow as the petroleum industry's needs dictate.

3. Because it relies upon proven technologies, it can be expected that delays due to technical problems will be minimized; and if they do occur, they will be less costly, in scale with the rest of the project.
4. It is not restricted in its usefulness to petroleum transport or for that matter, even to transport. It can be used for other purposes, such as seismic and oceanographic surveys.
5. Finally, by achieving early operational status, it will be able to reap the full benefit of government tax credits (Vines, 1981).

These are surely advantages in competing for financing under present conditions.

Its Merits in Regard to Overcoming Political and Environmental Impact Obstacles

The proposal makes no special claim to being able to speed what appear to be inherently slow-moving review and regulatory processes; or to stabilize the vagaries of national energy policy. Like other proposals, it may be either victim or benefactor. The Arctic submarine and tow system is, however, categorically excluded from some of the issues that other alternatives must face: for instance, land claims. Of all the transport technologies discussed, the Arctic submarine makes by far the least demand on land. Thus it is exempt from native land claim per se.

It may be argued that it is not exempt from native "social impact" issues, for it may be seen to infringe upon marine-based economies. If it is challenged on that account, it will fare much better than the alternatives. Unlike ice-breakers, submarines do not disturb the ice or the people who cross it, and by inference, the marine life that would be unsettled by such disturbance.

As for noise, because this type of submarine's very survival during wartime depended and depends on blending in with the ambient sea state and operating with a minimum of radiated noise, very effective noise reduction and sound quieting technology has been developed; it has been applied by submarine shipbuilding yards for years. Thus interference with the communications and breeding of marine mammals, and consequent interference with native economies, is most unlikely. In short, it is a technology of minimum environmental disturbance.

Its Merits in Regard to Overcoming Physical Obstacles

The Arctic submarine does not have to overcome obstructing ice and harsh weather: it avoids them. Permafrost likewise is no problem. What then, might be problematic for successful operation of a submarine in Arctic waters? Experienced submariners would answer: the need to come to the surface for routine or emergency purposes, in spite of environmental conditions. The environmental characteristic of ice-covered areas which makes surfacing possible is the presence of polynyas, leads, or thin ice "skylights". Without these, surfacing is not usually conducted.

Need one be overly concerned about the possible absence or insufficiency of openings in the waters where the Arctic transport submarine would operate? The author believes not. The pack ice in these areas has, generally speaking, no consistent thickness. The constant fracturing, diverging and compacting of the ice pack which occurs due to various combinations of currents, tidal fluctuations, winds and upwellings, continuously create areas of open water or very thin ice (Sater, 1979; Stirling and Cleator, 1981).

Although their number and size vary with season and location, experience with their frequency of occurrence indicates that a conventionally powered submarine of adequate submerged endurance capacity, and equipped with a pair of upward side-scanning sonars, would be able to locate a spot in which to surface.

The observations of many submariners and oceanographers well acquainted with Arctic waters will confirm these conditions (Wittman, 1966; Steele, 1962; Calvert, 1959; and others). The author's own experience has indicated that at least one polynya suitable for surfacing can be found approximately every five miles.

The USS "Seadragon" encountered over 350 polynyas or leads of widths 100 meters or greater during her historic late August 1960 first submerged transit through Viscount Melville Sound and the M'Clure Strait en route the central Beaufort Sea (Steele, 1960). The investigations and analysis by Dr P. Wadhams of under-ice characteristics in the Beaufort Sea, the Greenland Sea and the Arctic Ocean, though not specifically addressing the the frequency of open water and thin ice areas from the author's standpoint, provide further confirmation (Wadhams; 1971, 1977, 1978, 1979, 1980 and 1981). For example, in the southern Beaufort Sea, polynyas or leads of 100 meters width or greater were encountered on an average of once every twenty-four kilometers during April 1976 (Wadhams and Horne, 1980) and once every eight kilometers off north-east Greenland in October 1976 (Wadhams, 1981). The work of Dr C. Swithinbank (1972) in the Arctic Ocean, and that of L. LeSchack (1977, 1980) in the Beaufort Sea is also supportive of the author's observations on the frequency of open water.

In addition, analysis of submarine under-ice profiles of Baffin Bay in February and the M'Clure Strait in February and August, currently being conducted by the author for the United States Office of Naval Research provide even further confirmation. For example, statistical analysis reveals a great number of polynyas and leads in Baffin Bay and indicates that polynyas or leads of widths greater than 100 meters will be encountered on an average of once every 9.5 kilometers on both sides of the M'Clure Strait in February even though average ice thickness ranges between 4 and 7 meters (McLaren and others, 1982b). (See Figure 19).

Finally, recent information on the distribution of polynyas in the Canadian Arctic indicates the presence of permanent navigable leads in Lancaster Sound and the eastern entrance to the Northwest Passage and the entrance to the M'Clure Strait during most months of the year (Stirling and Cleator, 1981). (See Figure 20).

Although more observations - certainly those from satellites will be of value - and geographically specific analysis during all months of the year are desirable for all proposed operating areas, it is the author's strong belief that open water and/or thin ice are sufficiently frequent as to pose no obstacle to the safe, efficient operation of an Arctic transport submarine by an experienced crew.

USS SARGO and USS SEADRAGON 1960 surveys of M'Clure Strait

Figure 19

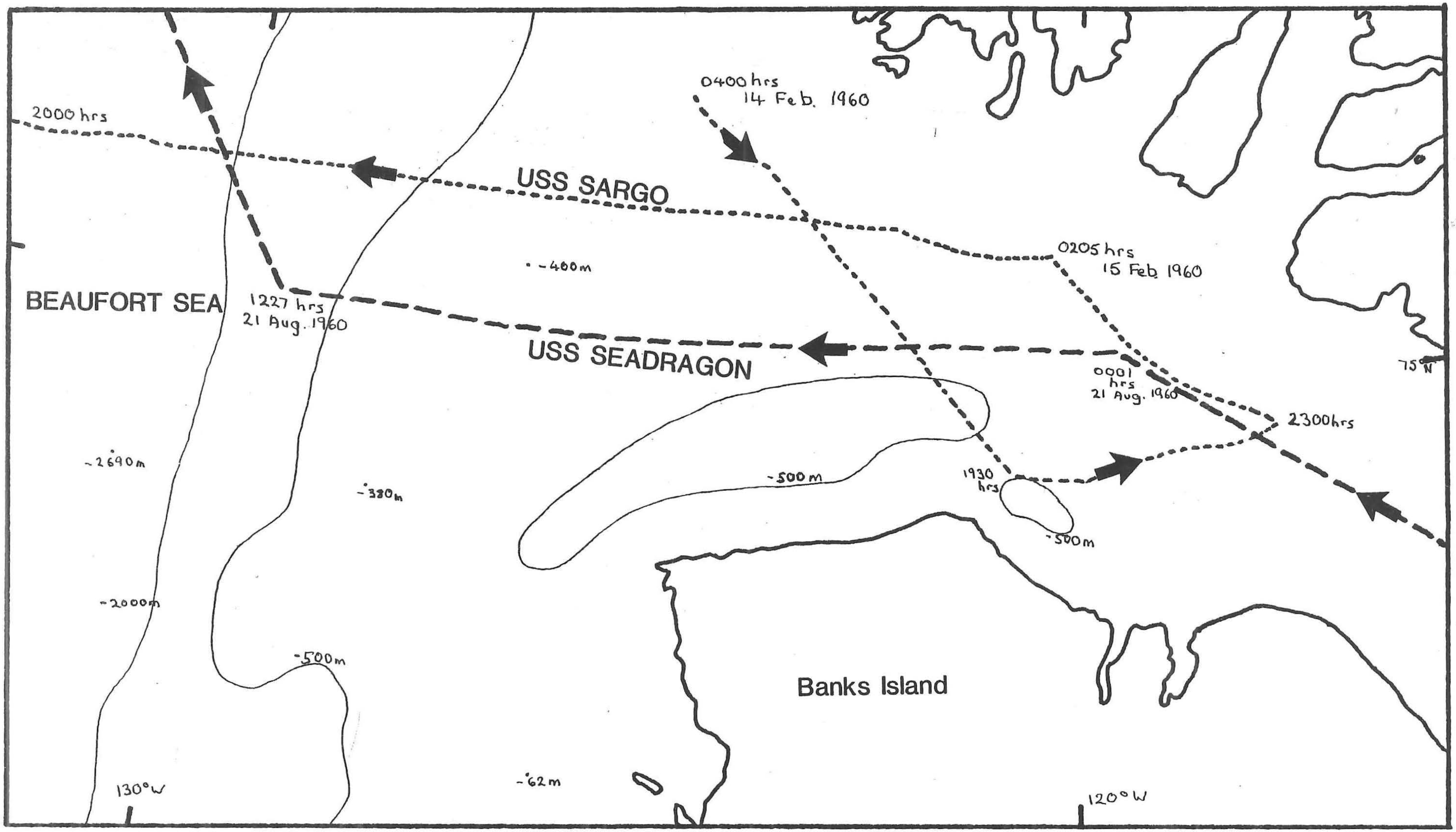
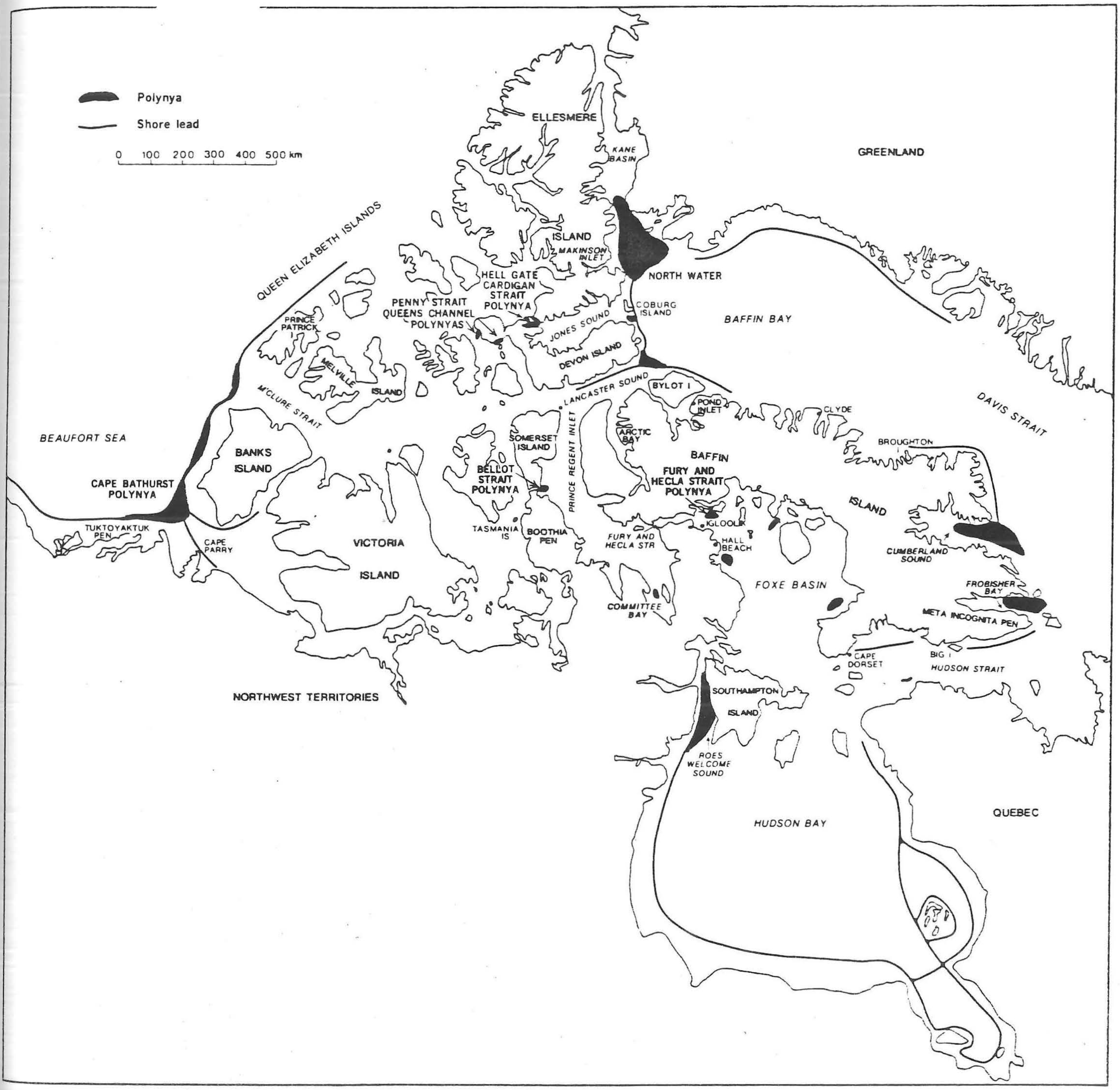


Figure 20 Map of the Canadian Arctic, showing distribution of recurring polynyas and leads



(after Stirling and Cleator, 1981)

CHAPTER IX

CONCLUSION

It is hoped by the author that the foregoing has convinced the reader that:

1. Submarines can operate successfully year round in Arctic waters.
2. There is considerable "produceable" oil and gas in the Arctic, much of which is offshore.
3. The existent and usually proposed modes of transport for this petroleum - pipelines, ice-breaker tankers and the submarine super-tankers - are of questionable suitability, and their development is highly problematic.
4. The Arctic submarine and tow system proposed by the author is both a feasible, and a desirable, interim or near-term alternative.

To review the reasons why this is so:

1. The Arctic submarine and tow system is not a "mega-project". Its capital costs, and hence, financial risk, will be considerably less than in the case of other Arctic Transport systems.
2. The system can be incrementally developed, financed and placed into service. Thus it can be better controlled, and would be more responsive to the changing needs of government and industry than a "mega-project".
3. The system's small-scale individual components and conventional power plant, and the use of only "off the shelf" proven technology will ensure that it can be rapidly and uneventfully designed, constructed and delivered by any experienced submarine shipbuilder - unlike a "mega-project".
4. The system should not require extensive and expensive "feasibility" studies. It is essentially a proven concept which can be immediately carried forth through the leadership and management of a small, knowledgeable and highly experienced (rather than high powered) "tiger team".
5. There should be much less to contend with in the way of environmental impact issues because there will not be noise pollution problems and both the probability and scale of an oil spill would be considerably less because of the inherently high degree of engineering and overall quality control which characterize submarine construction.

6. The system, including the prototype, will be versatile unlike a "mega-project" alternative because it can be used for other purposes such as seismic, oceanographic, and environmental impact surveys.

7. Because an "Arctic" submarine system already has an essentially proven capability for safe and reliable operations in the High Arctic, it will not require the development of new or additional technology to enable it to "fight" and successfully "overcome" the physical environment (i.e. like pipelines and ice-breaker tankers). It will, rather, be able to naturally and successfully adapt to and blend in with its natural habitat - the sea. Hence, the prospects of routine or catastrophic damage are considerably less as will be its life cycle costs. It will accordingly also be better able to adhere to schedules.

8. The system will not require a proven commercial-sized field before it will be economically viable. It can be put to work almost immediately after delivery to transport oil from individual production wells to which its smaller size will permit greater access, to market. Hence it will more quickly "earn its keep".

9. The system will not require the elaborate shipping control, search and rescue, emergency assistance or logistics systems which "mega-project" marine transport systems will require.

10. The system will require and can assist in the development of terminal and production loading facilities on a much smaller scale and cost than what would be required for a "mega-project".

11. The prototype system could be made compatible with and be used in further development/refinement of such underwater production systems as Shell and Esso's new underwater manifold center (Joseph, 1981) and Panarctic's Drake F-76 subsea flowline bundle (Pallister, 1981).

12. Although prototype/early production "Arctic submarines" will be powered by high capacity conventional power plants, later production models can be nuclear powered if oil price and market make this economically viable.

13. The system can not only serve as a forerunner: it will also be able to complement other transport alternatives as High Arctic petroleum fields enter full commercial production.

Despite these many advantages, the author foresees hesitancy on the part of government and industry in going forward with such a project. This hesitancy may well be based upon other than rational grounds. Submarines, let alone submarines under ice, are beyond most people's comprehension of what constitutes reasonable, safe and straightforward transportation. That "visibility", for instance, given today's technology, can be better under water than on top does not occur to most people. Neither does the notion that below the Arctic ice exists a far more unobstructed passage than can ever be laboriously carved out by ice-breakers.

Although a great number of submarines, both conventional and nuclear, have been built and used by the world's nations, secrecy and silence have characterized the treatment of their technological characteristics and their operational capabilities. Thus, lack of a real appreciation and general working knowledge of submarines may bring the verdict of "high risk" to the author's proposal, even though it is perhaps the safest, surest mode of Arctic petroleum transport of any.

E.F. Roots of Environment Canada summed up the situation well when he said:

> The development of a marine transportation system in the Arctic is a problem whose dimensions are set by the environment ... If we succeed in adapting not only our technology, but also our modern management practices and policies, to the Arctic environment, we may be able to take full advantage of the unique assets of the Northern environment. (Roots, 1979)

To this, the author would add the expansion of vision and the consequent adaptation which this would bring in decision-making.

References

ABELS, F. 1973. The effect of marine technology on design and development of submarines. Schiff und Hafen, No.9/1973 (Engish translation of special issue to mark the 60th birthday of Professor Gabler), p.8-11.

ABELS, F. 1979. New developments in German submarine design. Intec '78 Conference Proceedings. Geneva, Interavia.

ABELS, F. 1982. Discussions with author at IKL, Lübeck on 25 May 1982.

ALASKA INDUSTRY. 1979. Alaska OCS can expect action. Alaska Industry. October 1979, p.35 and 47.

ALASKA CONSTRUCTION AND OIL. 1982. Drill report. Alaska Construction and Oil. April 1982, p.70 and 72.

ANDERSON, W.R. 1959. Nautilus-90-North. London, Hodder and Stoughton.

ARCTIC COASTAL ZONE MANAGEMENT NEWSLETTER. 1979. Borough moves to regulate offshore. The Arctic Coastal Zone Management Newsletter, No.19, April 1979, p.4.

ARCTIC INSTITUTE OF NORTH AMERICA. 1973. Arctic Marine Commerce AIRLIE House Workshop, Warrentown, Virginia, 26-28 February 1973. Washington, D.C., The Arctic Institute of North America.

ARCTIC PETROLEUM OPERATORS ASSOCIATION. 1978. Canadians highlight Arctic Petroleum development. A.P.O.A. Review, Vol.1, No.4, November 1978, p.3.

ARCTIC PETROLEUM OPERATORS ASSOCIATION. 1979. Beaufort Sea activities. A.P.O.A. Review, Vol.2, No.2, July 1979, p.2-3.

ARCTIC PETROLEUM OPERATORS ASSOCIATION. 1979. Active summer of Arctic exploration in Beaufort Sea and South Davis Strait. A.P.O.A. Review, Vol.2, No.3, November 1979, p.2.

ARCTIC PETROLEUM OPERATORS ASSOCIATION. 1980. Active summer program proceeds in Arctic. A.P.O.A. Review, Vol.3, No.2, August 1980, p.3.

ARCTIC PETROLEUM OPERATORS ASSOCIATION. 1981a. Beaufort Sea production: The plan. A.P.O.A. Review, Vol.4, No.3, December 1981, p.4.

ARCTIC PETROLEUM OPERATORS ASSOCIATION. 1981b. Pan Arctic expands operations in the Arctic islands. A.P.O.A. Review, Vol.4, No.3, December 1981, p.10.

ARCTIC PETROLEUM OPERATORS ASSOCIATION. 1982. Dome keeps up the pace. A.P.O.A. Review, Vol.5, No.1, Spring/summer 1982, p.4-6.

ARMSTRONG, T. 1979. Soviet capabilities in Arctic marine transport. In: *Marine transportation and High Arctic development: policy framework and priorities Symposium Proceedings 21-23 March 1979, Montebello, Quebec*. Ottawa, Canadian Arctic Resources Committee.

BABBITT, F.G. 1970. A submarine for the Tsar. *U.S. Naval Institute Proceedings*, April 1970, Vol.96, Number 4/806, p.47-55.

BAREAU, P. 1982a. The economic scene. *Journal of the Institute of Bankers*, Vol.103, Part 1, February 1982, p.14.

BAREAU, P. 1982b. The economic scene. *Journal of the Institute of Bankers*, Vol.103, Part 2, April 1982, p.48.

BEER, M. 1982. International trouble for the APP. *News/North*, Friday, March 12, 1982, p.A5 and A15.

BERGER, T.R. 1977. *Northern Frontier Northern Homeland the report of the MacKenzie Valley pipeline inquiry: volume two*. Ottawa, Minister of Supply and Services.

BLAIR, C.H. 1959. Arctic submarine material. *U.S. Naval Institute Proceedings*, September 1959, Vol.85, No.9, p.39-45.

BLOCK, W. 1982. Discussions with author at IKL, Lübeck on 25 and 26 May, 1982.

BREGHA, F. 1979. Petroleum development in Northern Alaska. *Marine transportation and High Arctic development: policy framework and priorities Symposium Proceedings 21-23 March 1979 Montebello, Quebec*. Ottawa, Canadian Arctic Resource Committee, p.223-251.

BREWER, J. 1982. Dome perfects its new breed of Arctic Tanker. *Lloyd's List*, 25 February 1982.

BRITISH PETROLEUM. 1977. *Our Industry Petroleum*. London, British Petroleum Company Ltd.

BRITISH PETROLEUM. 1982. *Annual Report and Accounts 1981*. London, Metcalfe Caldwell.

BRODY, H. 1975. *The people's land; Eskimos and whites in the eastern Arctic*. Harmondsworth, Middlesex, Penguin Books Ltd.

BUTLER, J. 1982a. YTG pressed for land claim information. *The Whitehorse Star*, Vol.82, No.69, Thursday, April 8, 1982, p.3.

BUTLER, J. 1982b. Pearson pushes land in key PC convention. *The Whitehorse Star*, Vol.82, No.80, Monday, April 26, 1982, p.1-3.

BÜTTNER, G. 1973. Position and development possibilities of electronic equipment on submarines with conventional propulsion. *Schiff und Hafen*, No.9/1973, p.12-15.

BUXTON, J. 1982. Italians finalize agreement on Soviet gas. Financial Times, 29 January 1982.

CALVERT, J. 1961. Surface at the Pole. London, Hutchinson and Co.

CANADA. ENERGY, MINES AND RESOURCES. 1977. Oil and natural gas resources of Canada, 1976, Report EP77-1. Ottawa, Minister of Supply and Service.

CANADA. OFFICE OF NATIVE CLAIMS DEPARTMENT OF INDIAN AFFAIRS AND NORTHERN DEVELOPMENT. 1978. Opinion paper native claims: Policy, processes and perspectives. In: KEITH, R. and WRIGHT, J. 1978, ed. Northern Transitions Volume II Second National Workshop on people, resources and the environment North of 60°. Ottawa, Canadian Arctic Resources Committee, p.284-93.

CANADA. INDIAN AND NORTHERN AFFAIRS. 1980a. Lancaster Sound regional study jurisdiction and legislative background report V. Ottawa, Ministry of Indian Affairs and Northern Development.

CANADA. INDIAN AND NORTHERN AFFAIRS. 1980b. Non-renewable resources and transport of the Lancaster Sound region background report IV. Ottawa, Minister of Indian Affairs and Northern Development.

CANADA. INDIAN AND NORTHERN AFFAIRS. 1980c. Selected physical characteristics background report I Lancaster Sound regional study. Ottawa, Ministry of Indian Affairs.

CANADA. INDIAN AND NORTHERN AFFAIRS. 1982. Lancaster Sound regional study. Newsletter/Bulletin, No.5, March 1982, p.1.

CANADA, INDIAN AFFAIRS AND NORTHERN DEVELOPMENT. 1982. 1981 Annual Report Government of the Northwest Territories. Yellowknife, Department of Information Government of the Northwest Territories.

CANADA. LANDS DIRECTORATE ENVIRONMENT. 1982. Towards a final settlement. Land, Vol.3, No.1, p.21.

CANADIAN ARCTIC RESOURCES COMMITTEE. 1979a. Marine transportation and High Arctic development: Policy framework and priorities Symposium Proceedings Montebello, Quebec, 21-23 March 1979. Ottawa, Canadian Arctic Resources Committee.

CANADIAN ARCTIC RESOURCES COMMITTEE. 1979b. Lancaster Sound area to be studied, study of the "Northwest Sea Route" is next stage. Arctic Seas Bulletin, Vol.1, No.7, September 1979, p.1-2.

COURTNEY, J.L. 1977. Arctic resource transportation: present system and future development. In: AMARIA, P.J. and others, ed. Arctic Systems. New York and London, Plenum Press.

CREWE, P.R. and HARDY, D.J. 1962. The submarine ore carrier. Paper presented at meeting of the Royal Institute of Naval Architects, 28 March 1962.

DAKS, G. 1981. *A choice of futures: politics in the Canadian North*. Ontario, Methuen.

DANENHOWER, S. 1931. The Arctic submarine "Nautilus". In: WILKINS, H., 1931. *Under the North Pole*. New York, Brewer, Warren and Putnam Incorporated, p.235-73.

DAMON, M.H. 1972. SANS, Ships acoustic navigation system. *Journal of the Institute of Navigation*, Vol.19, No.1, Spring 1972, p.15-17.

DENMARK. THE GEOLOGICAL SURVEY OF GREENLAND. 1979. *Well data summary sheets, wells drilled 1976-1977*. Copenhagen, Geological Survey of Greenland.

DENMARK. THE MINISTRY FOR GREENLAND. 1978. *Exploratory drilling offshore West Greenland*, Copenhagen, Ministry for Greenland.

DEY, B. 1981. Shipping routes, ice cover and year-round navigation in Canadian Arctic. *Polar Record*, Vol.20, No.129, p.549-59.

DINTER, D. and GRANTZ, A. 1980. Constraints of geological processes on petroleum development in the western Beaufort Sea. In: *Petroleum and the marine environment PetroMar 80*. London, Graham and Trotman Ltd., p.285-98.

DOBELL, P.C. 1976. The policy dimension. In: DOSMAN, E.J., *ed*. 1976. *The Arctic in question*. Toronto, Oxford University Press.

DODSWORTH, T. 1982. Paris and Kremlin agree on gas pipeline contract. *Financial Times*, 25 January 1982.

DRACONE DEVELOPMENTS LIMITED. 1958. *A new method of transport*. (Business brochure), Cambridge, Heffer and Sons Ltd.

DUNBAR, M.J. 1980. *Marine transportation and high Arctic development: A bibliography*. Ottawa, Canadian Arctic Resources Committee.

DUNLOP LIMITED GRG DIVISION. 1977. *The answer to bulk liquid transport problems* ... Dunlop Dracones (Business brochure). Lancashire, Dunlop Limited.

EATON, B. 1982. New group seeks planning on Beaufort development. *The Whitehorse Star*, Vol.82, No.69, Thursday, April 8, 1982, p.10.

EDELSACK, E. 1975. Superconductivity: An emerging technology. *Naval Research Reviews*, March 1975, Vol.XXVIII, No.3, p.1-10.

ENGINEERING. 1958. Collapsible oil barges undergo sea trials. *Engineering*, October 3, 1958.

EVERS, K. 1972. *Ingenieurkonton Lübeck Prof. Dipl.-Ing. Ulrich Gabler* (Business brochure), Lübeck, Ingenieurkontor.

FISHER, A. 1981. Tanker fleets being run down to cut redundant vessels. Financial Times, Wednesday, December 2, 1981, p.VIII.

FORBES, B. 1982. Slingsby Engineering, discussions with author during February 1982.

FOSTER, P. 1980. The blue-eyed sheiks, the Canadian oil establishment. Toronto, Totem Books.

FRANSON, R.T. and LUCAS, A.R. 1976 (corrected to 1980). Canadian environmental law volume 1. Scarborough, Butterworth and Company (Canada) Limited.

GABLER, U. 1978. New generation of conventional submarines. Paper presented at Europort '78 (Naval construction and equipment conference), Amsterdam, 14 November 1978.

GABLER, U. 1982. Discussions with author at IKL, Lübeck, 25 May 1982.

GALANTIN, I. 1958. The future of nuclear-powered submarines. U.S. Naval Institute Proceedings, Vol.84, No.6, p.33.

GAMBLE, D.J. 1979. The scope and implications of Arctic offshore drilling. Arctic Sea Bulletin, Vol.1, No.2, April 1979, p.1-3.

GENERAL DYNAMICS. 1970. Advertisement. U.S. Naval Institute Proceedings, Vol.96, Number 6/808, June 1970.

GEOGRAPHICAL JOURNAL. 1901. A new plan for reaching the North Pole. Geographical Journal, Vol.17, No.4, p.435.

GINIGER, H. 1982. Project to ship gas from Arctic nears approval in Canada. The New York Times, Saturday, February 13, 1982.

GOODSON, R. 1974. Optimization procedures for drag reduction. Naval Research Reviews, Vol.XXVIII, No.7, July 1974, p.11-19.

GORDON, J. 1954. Under the Arctic ice. Ships and the sea, January 1954.

GORMAN, J. 1982. Energy issues. News/North, Friday, April 9, 1982, p.A13.

GORLATOV, S. and GAKKEL', Ya. 1965. A significant event in the history of navigation. Problems of the Arctic and Antarctic, Issue 20, 1965, p.84-91. (Translation of Znamenatel'neye subytiye i isterii more' plavaniya, Vypusk 20, 1965).

GRIFFITH, J. and FIELD, D. 1973. Fluorinated network polymers. Naval Research Reviews, Vol.XXVI, No.12, December 1973, p.15-25.

HARGREAVES, I. 1981. Arctic gas-by-submarine plan. Financial Times, Thursday, November 19, 1981.

HARRISON, G.R. 1979. The need for Arctic-oriented R and D in the Canadian Arctic. In: Marine transportation and High Arctic development: policy framework and priorities Symposium Proceedings 21-23 March 1979, Montebello, Quebec. Ottawa, Canadian Arctic Resources Committee.

HETTCHE, L.R. 1978. Naval structural materials: requirements, issues and opportunities. Naval Research Reviews, Vol.XXXI, No.6, June 1978, p.19-24.

HUXLEY, J. 1981. It's the Jugger-Nautilus. The Sunday Times, November 29, 1981.

HUXLEY, J. 1982. Synthetic fuels plans drop in the 'agony gap'. The Sunday Times, May 9, 1982, p.54.

IMPERIAL OIL LIMITED. 1982. Annual Report 1981. Toronto, Imperial Oil Limited.

INGENIEURKONTOR LÜBECK (IKL). 1981. Gabler Submarines and Submersibles. Lübeck, Ingenieurkontor.

INGENIEURKONTOR LÜBECK (IKL). 1982. Discussions by author with various engineers, 24-26 May 1982.

ITTINUAR, P. 1981. Inuit participation in politics. In: ZASLOV, M., ed. A century of Canada's Arctic islands 1880-1980. Ottawa, The Royal Society of Canada, p.291-98.

JOHANSSON, B.M. 1972. Oy Wartsila AB, polar shipbuilders. Polar Record, Vol.16, No.100, p.24-40.

JONES, G.H. 1981. Economic development - oil and gas. In: ZASLOW, M., ed. A century of Canada's Arctic islands 1880-1980. Ottawa, The Royal Society of Canada, p.221-30.

JOSEPH, J. 1981. Production systems prepared for very deep water. Financial Times, Wednesday, December 2, 1981, p.VII.

KAUSTINEN, O.M. 1980. Feasibility of constructing marine pipeline crossings in the Arctic. In: EUROCEAN. 1980. Petroleum and the marine environment PETROMAR 80. London, Graham and Trotman Limited, p.193-216.

KAYSER, P. 1973. Experience with the high speed diesel engines in submarines. Schiff und Hafen, No.9/1973. (English translation of special issue to mark the 60th birthday of Professor Gabler), p.12-15.

KINTNER, E.E. 1959. How we developed the Nautilus machinery. The New Scientist, March 26, 1959, p.694-98.

KORNING, P. 1982. Pipeline death rattle. The Whitehorse Star, Vol.82, No.84, Friday, April 30, 1982, p.16.

KRUGER, P. 1973. The influence of submarine construction on oceanographic vehicles and equipment. *Schiff und Hafen*, No.9/1973 (English translation of special issue to mark the 60th birthday of Professor Gabler), p.24-26.

KRONHOLM, W. 1981. Sub could mine natural gas, General Dynamics proposes. *San Diego Evening Tribune*, November 10, 1981.

LAKE, S. 1931. The development of the under ice submarine. In: WILKINS, H., 1931. *Under the North Pole*. New York, Brewer, Warren and Putnam Incorporated, p.203-32.

LANG, R. 1979. Environmental impact assessment: reform or rhetoric? In: LEISS, W., 1979. *Ecology versus Politics in Canada*. Toronto, University of Toronto Press, p.233-55.

LeSCHACK, L. and CHANGE, D. 1977. *Arctic Under-ice Roughness, a Technical Report for the Office of Naval Research*. Silverspring, Development and Resources Transportation Company.

LeSCHACK, L. 1980. *Correlation of Under-ice Roughness with Satellite and Airborne Thermal Infrared Data, a Technical Report prepared for the Office of Naval Research Arctic Program*. Silverspring, LeSchack Associates, Limited.

LINBERGH, K. and PROVORSE, B. 1977. *The Trans-Alaska Pipeline Volume III Emerging Alaska*. Seattle, Scribe Publishing Company.

LIPPMAN, T.W. 1981. Submerged tanker idea floated. *International Herald Tribune*, Thursday, October 29, 1981, p.13.

LIVINGSTON, J. 1981. *Arctic Oil the Destruction of The North?* Toronto, Totem Books.

LÜBECKER NACHRICHTEN. 1982. Amerika zeigt interesse an u-booten aus Lübeck. *Lübecker Nachrichten*, 25 May 1982.

LUCAS, A.R. and others. 1979. Regulation of High Arctic development. In: *Marine Transportation and High Arctic development: policy framework and priorities Symposium Proceedings 21-23 March 1979, Montebello, Quebec*. Ottawa, Canadian Arctic Resources Committee.

LYON, W.K. 1959. *The polar submarine and navigation of the Arctic Research Report 88*. San Diego, U.S. Navy Electronics Laboratory.

LYON, W.K. 1963. The submarine and the Arctic Ocean. *Polar Record*, Vol.11, No.75, p.699-705.

MALCOLM, A.H. 1982. Pioneers of Polaris mine Arctic's lode. *The New York Times*, Monday, March 22, 1982, p.D1 and D4.

MARKHAM, W.F. 1981. *Ice Atlas Canadian Arctic Waterways*. Quebec, Canadian Government Publishing Centre.

MASTERSON, D. and WATTS, J. 1979. Completion of an offshore well in the Canadian Arctic Islands. Paper presented at the 11th Offshore Technology Conference, Houston, Texas, 30 April-3 May 1979.

MATHIESEN, T. 1954. Svalbard in the changing Arctic. Oslo, Glydendal Norsk Forlag.

McCARTNEY, R. 1982. Oil glut's legacy: a weaker OPEC. International Herald Tribune, Monday, May 24, 1982, p.7.

McCASLIN, J. 1972. What they've found in the Arctic. The Oil and Gas Journal, October 1972.

McCONCHIE, R. and REID, R. 1977. Canadian foreign policy and international straits. In: JOHNSON, B. and ZARCHER, M. 1977. Canadian Foreign Policy and the Law of the Sea. Vancouver, University of British Columbia Press.

McLAREN, A.S. 1981. Under the ice in submarines. U.S. Naval Institute Proceedings, Vol.107/7/941, July 1981, p.105-09.

McLAREN, A.S. 1982a. Exploration under the Arctic ice. Explorers Journal, March 1982, p.34-39.

McLAREN, A.S., WADHAMS, P. and WEINTRAUB, R. 1982b. An analysis of ice profiles from Baffin Bay and the Northwest Passage. Technical Report to U.S. Office of Naval Research Arctic Program (in press).

McWETHY, R. 1958. Significance of the Nautilus Polar cruise. U.S. Naval Institute Proceedings, Vol.84, No.5, May 1958, p.32-35.

MEISLER, S. 1979. Arctic oil drillers shrug off the hazards of 'enemy ice'. The Providence Sunday Journal, November 25, 1979, p.A28.

MENELEY, R.A. 1976. Exploration Prospects in the Canadian Arctic Islands. Calgary, Panarctic Oils Limited.

MILES, P. and WRIGHT, N. 1978. An outline of mineral extraction in the Arctic. Polar Record, Vol.19, No.118, p.24, 26, 32-33.

MOORE, J., ed. 1976. Jane's Pocket Book 8 Submarine Development. London, MacDonald and Jane's Publishers Limited.

MOORE, J., ed. 1981. Jane's Fighting Ships. London and New York, Jane's Publishing Company Limited.

MOREAU, J.W. 1970. Problems and developments in Arctic Alaska transportation. U.S. Naval Institute Proceedings, Vol.96, No.5/807, May 1970, p.98-119.

MORTON, N. 1980. The politics of non-renewable resource development in Greenland, North Norway and Svalbard. Polar Record, Vo.20, No.126, p.215-30.

NELSON, R. 1982. The ice above the giant below. Popular Mechanics, March 1982, p.116.

NEWS/NORTH. 1982. Lobby groups form anti-Beaufort coalition. News/North, Friday, March 5, 1982, p.A3.

NEWSWEEK. 1981. Submarine supertanker. Newsweek, November 30, 1981, p.88.

NEWSWEEK. 1982. Oil: a Saudi ultimatum. Newsweek, April 12, 1982, p.48-49.

NEW YORK TIMES. 1931a. Nautilus damaged in dive under ice. The New York Times, Sunday, September 6, 1931.

NEW YORK TIMES. 1931b. The Nautilus returns. The New York Times, Tuesday, September 8, 1931.

NEW YORK TIMES. 1931c. Nautilus expected at Bergen today. The New York Times, Sunday, September 20, 1931.

NEW YORK TIMES. 1931d. Calls Nautilus a wreck. The New York Times, Friday, September 25, 1931.

NORCOR ENGINEERING AND RESEARCH LIMITED. 1978. A Study of Ice Conditions along Shipping Routes in the Arctic Archipelago. N.p.

NORMAN, P. 1981. West Germany signs huge piped gas deal with Russia. The Times, November 21, 1981.

NORTHSLOPE BOROUGH. 1978. Dome/Canmar blowout in MacKenzie Bay. The Arctic Coastal Zone Management Newsletter. Issue No.13, August 1978, p.1.

OILWEEK. 1981a. Frontier exploration alive, drilling heads for count-down. Oilweek, Vol.32, No.45, December 14, 1981, p.28.

OILWEEK. 1981b. Submarine tanker design developed for the Arctic. Oilweek, December 14, 1981, p.38-44.

OILWEEK. 1981c. Oil self sufficiency by the end of the century. Oilweek, Vol.32, No.45, December 14, 1981, p.60-62.

OILWEEK. 1981d. Beaufort sea drilling moves to year round operation. Oilweek, Vol.32, No.46, December 21, 1981, p.6.

OILWEEK. 1982a. New era for oil and gas development in the North. Oilweek, Vol.32, No.50, January 18, 1982, p.2.

OILWEEK. 1982b. Increased natural gas sale. Oilweek, Vol.32, No.50, January 18, 1982, p.12.

OILWEEK. 1982c. Panarctic spuds two Sverdrup Basin tests. Oilweek, Vol.32, No.51, January 25, 1982, p.6.

OILWEEK. 1982d. Arctic regions call for special engineering. Oilweek, Vol.32, No.51, January 25, 1982, p.42.

OILWEEK. 1982e. Polar Bear Pass may be opened for exploration. Oilweek, Vol.33, No.2, February 15, 1982, p.5.

OILWEEK. 1982f. Frontier exploration in the spotlight. Oilweek, Vol.33, No.2, 1982, p.36-37.

OILWEEK. 1982g. Canada loses favor for oil and gas investors. Oilweek, Vol.33, No.3, February 22, 1982, p.36.

OILWEEK. 1982h. Drake Point field must be utilized. Oilweek, Vol.33, No.3, 1982, p.45.

OILWEEK. 1982i. Drake Point utilization clarified. Oilweek, Vol.33, No.6, March 15, 1982, p.9.

OILWEEK. 1982j. Esso planning Atkinson test in the Delta area. Oilweek, Vol.33, No.9, April 5, 1982, p.77.

OILWEEK. 1982k. Tarsiut could lead Beaufort Sea development. Oilweek, Vol.33, No.10, April 12, 1982, p.24.

O'TOOLE, T. 1980. Two seas off Alaska may hold large reserves of oil. Washington Post, January 27, 1980.

PADGHAM, M. 1982. Land claims, administrative competence main CYI issues. The Whitehorse Star, Vol.82, No.81, Tuesday, April 27, 1982, p.1.

PAGE, R. 1981. The High Arctic: environmental concerns, government controls and economic development. In: ZASLOW, M., ed. 1981. A Century of Canada's Islands 1880-1980. Ottawa, The Royal Society of Canada, p.231-44.

PALLISTER, J. 1981. Meeting the Arctic challenge. APOA Review, Vol.4, No.1, May 1981, p.9-17.

PANARCTIC OILS LIMITED. 1981a. VIP Information Binder (Received by author during September 1981 trip to Panarctic facilities in the Arctic Islands).

PANARCTIC OILS LIMITED. 1981b. Thirteenth Annual Report 1980. Calgary, Panarctic Oils Limited.

PETERS, S.S. 1978. Arctic gas from the High Arctic Islands via the marine mode. In: KEITH, R. and WRIGHT, J., ed. 1978. Northern Transistions Volume II. Ottawa, Canadian Arctic Resources Committee.

PETERSON, M., ed. 1981. The Question of Sound from Icebreaker Operations. The Proceedings of a Workshop February 23-24, 1981, Toronto, Canada. Calgary, Arctic Pilot Project Petro-Canada.

PETRO-CANADA. 1980. Arctic Pilot Project. Calgary, Petro-Canada.

PETRO-CANADA. 1981a. This is Canada's National Oil Company. Calgary, Petro-Canada.

PETRO-CANADA. 1981b. Oil search underway off Labrador. The Explorer, Vol.5, No.7, July 1981, p.1.

PHARAND, D. 1973. The Law of the Sea of the Arctic with Special Reference to Canada. Ottawa, University of Ottawa Press.

PHARAND, D. 1981. Canada's jurisdiction in the Arctic. In: ZASLOW, M., ed. 1981. A Century of Canada's Arctic Islands 1880-1980. Ottawa, The Royal Society of Canada, p.111-30.

PIMLOTT, D. and others. 1976. Oil under the ice. Ottawa, Canadian Arctic Resources Committee.

POLAR GAS PROJECT. 1980. The Polar Gas Pipeline: Update 1980. Toronto, Polar Gas Project.

POLAR RECORD. 1962. British submarines in Arctic trials, 1961. Polar Record, Vol.11, No.75, p.89.

POLAR RECORD. 1977. Completion of the Trans-Alaska Pipeline. Polar Record, Vol.18, No.117, September 1977, p.613-14.

POLAR RECORD. 1979. Shipping losses caused by ice, 1890-1977. Polar Record, Vol.19, No.121, 1979, p.343-62.

POLAR RECORD. 1981a. First Canadian Arctic gas sale. Polar Record, Vol.20, No.127, p.380.

POLAR RECORD. 1981b. The Polar Gas Project. Polar Record, Vol.20, No.129, September, p.520.

POST, A. 1976. Superconducting machinery for ship propulsion. Naval Research Reviews, November 1976, Vol.XXIX, No.11, p.22-29.

POUNDER, E.R. 1981. Ice, snow and permafrost research. In: ZASLOW, M., ed. 1981. A Century of Canada's Arctic Islands 1880-1980. Ottawa, The Royal Society of Canada, p.163-70.

PRESTON, A. 1975. Submarines the History and Evolution of Underwater Fighting Vessels. London, Octopus Books Limited.

PULLEN, T.C. 1981. The development of Arctic ships. In: ZASLOW, M., ed. 1981. A Century of Canada's Arctic Islands 1880-1980. Ottawa, The Royal Society of Canada, p.153-62.

REEM, G. 1975. New tools for Alvin. *Naval Research Reviews,* Vol.XXVIII, No.12, December 1975, p.20-28.

RICHARDS, W.E. 1979. The solution to Canada's oil and gas needs - the Arctic. *Arctic Seas Bulletin*, Vol.1, No.5, July 1979, p.1.

ROBB, D. 1982. Submarine tankers proposed for Arctic LNG transport. *Sea Technology*, February 1982, p.23-25.

ROBINSON, J.B. 1980. Policy, pipelines, and public participation: the National Energy Board's Northern Pipeline Hearings. In: DWIVEDI, O.P., *ed.* 1980. *Resources and the Environment: Policy Perspectives for Canada*. Toronto, McClelland and Stewart.

ROOTS, E.F. 1979. Environmental aspects of Arctic marine transportation and development. In: *Marine Transportation and High Arctic development: policy framework and priorities Symposium Proceedings 21-23 March 1979, Montebello, Quebec*. Ottawa, Canadian Arctic Resources Committee, p.69-92.

ROSSLER, E. 1981. *The U-Boat, the evolution and technical history of the German submarines*. Translated by Harold Erenberg. London, Arms and Armour Press.

ROWLEY, G. 1981. Northern Canada today. In: ZASLOW, M., *ed.* 1981. *A Century of Canada's Arctic Islands 1880-1980*. Ottawa, The Royal Society of Canada, p.291-98.

RUHE, W.J. 1970. Seapower in the seventies. *U.S. Naval Institute Proceedings,* Vol.96, No.4/806, April 1970, p.27.

SATER, J.E., *coord*. 1969. *The Arctic Basin, Revised Edition*. Washington, D.C., The Arctic Institute of North America.

SATER, J.E. and others. 1971. *Arctic Environment and Resources*. Washington, D.C., The Arctic Institute of North America.

STEELE, G. 1960. Commanding Officer's narrative of USS Seadragon (SSN 584) Northwest Passage (Section C of unpublished voyage report).

STEELE, G. 1962. *Seadragon, Northwest under the ice*. New York, E.P. Dutton.

STEFANSSON, V. 1922. *The Northwest Course of Empire*. New York, Harcourt, Brace and Company.

STEFANSSON, V. 1931. The history of the idea. In: WILKINS, H. 1931. *Under the North Pole*. New York, Brewer and Warren Incorporated.

STEFANSSON, V. 1960. *Northwest to Fortune*. London, George Allen and Unwin Limited.

STIRLING, I. and CLEATOR, H., ed. 1981. Polynyas in the Canadian Arctic. Occasional Paper Number 45, Canadian Wildlife Service. Ottawa, Minister of Environment, Canadian Wildlife Service.

SWENSON, R. 1980. Kevlar. Naval Research Reviews, Vol.XXXII, No.4, Summer 1980, p.36-40.

SWITHINBANK, C. 1972. Arctic pack ice from below. In: KARLSSON, T., ed. 1972. Sea Ice: Proceedings of an International Conference, Reykjavik, Iceland, May 10-13, 1971. Reykjavik, National Research Council, p.246-54.

TAAGHOLT, J. 1980. Northern waters: resource endowments. In: SCRIVENER, D., ed. 1980. Northern Waters: Resources and Security Issues Cooloquium Center for Defense Studies, University of Aberdeen, 17-19 September 1980.

TAAGHOLT, J. 1981. Greenland--seen from a historic and security political point of view. (Unpublished manuscript in author's possession).

TAYLOR, H. 1973. Fibreoptics communications. Naval Research Reviews, Vol.XXVI, No.1, January 1973, p.21, 26.

TAYLOR, P.K. and MONTGOMERY, J.B. 1977. Arctic Submarine Tanker System. Paper presented at the 9th Annual Offshore Technology Conference, Houston, Texas, 2-5 May 1977.

THE OIL AND GAS JOURNAL. 1972. Imperial's drilling island - so far, so good. The Oil and Gas Journal, October 23, 1972.

THORE'N, R. 1963. Navigation Systems and Aids to Navigation for Nuclear Fleet Ballistic Missile Submarines and Viewpoints on Conventional Submarines Operating Under Ice, App. to FOA 3 Report A 556. Stockholm, Research Institute of National Swedish Defense.

TRUITT, J. 1970. Moving Alaska's oil by submarine tanker. Navy, Vol.75, No.3, March 1970, p.80-81.

TURNER, W. 1979. $1 billion bid on Beaufort Sea leases: sale also introduces profit sharing. New York Times, December 12, 1979.

UNITED STATES OF AMERICA. CENTRAL INTELLIGENCE AGENCY. 1978. Polar Regions Atlas. Washington, D.C., Central Intelligence Agency.

UNITED STATES OF AMERICA. DEPARTMENT OF INTERIOR. 1971. An Analysis of the Economic and Security Aspects of the Trans-Alaska Pipeline Volume II Supporting Analyses. Washington, D.C., U.S. Government Printing Office.

UNITED STATES OF AMERICA. DEPARTMENT OF INTERIOR. 1972. Final Environmental Impact Proposed Trans-Alaska Pipeline Volume II Introduction and Summary. Washington, D.C., U.S. Government Printing Office.

UNITED STATES OF AMERICA. DEPARTMENT OF INTERIOR. 1972. Final Environmental Impact Statement Proposed Trans-Alaska Pipeline Volume 5 Alternatives to the Proposed Action. Washington, D.C., U.S. Government Printing Office, p.74-77.

UNITED STATES OF AMERICA. NAVY HYDROGRAPHIC OFFICE. 1950. Manual of Ice Seamanship H.O. Pub. No.551. Washington, D.C., U.S. Navy Hydrographic Office.

UNITED STATES OF AMERICA. OFFICE OF NAVAL INTELLIGENCE. 1951. German U-Boats in the Arctic. Office of Naval Intelligence Review, Vol.VI, Parts I-V.

UNITED STATES OF AMERICA. OFFICE OF NAVAL RESEARCH. 1972a. Office of Naval Research's deep submersible given a titanium pressure sphere. Naval Research Reviews, Vol.XXV, No.1, January 1972, p.25.

UNITED STATES OF AMERICA. OFFICE OF NAVAL RESEARCH. 1972b. Unmanned Arctic research submersible successfully tested by Navy. Naval Research Reviews, Vol.XXV, No.9, September 1972.

UNITED STATES OF AMERICA. OFFICE OF NAVAL RESEARCH. 1972c. DSRV-2. Naval Research Reviews, Vol.XXV, No.10, October 1972, p.32.

UNITED STATES OF AMERICA. OFFICE OF NAVAL RESEARCH. 1973a. NRL developing high speed processor computer. Naval Research Reviews, Vol.XXVI, No.3, p.21.

UNITED STATES OF AMERICA. OFFICE OF NAVAL RESEARCH. 1973b. Research at the Naval Undersea Center. Naval Research Reviews, Vol.XXVI, No.7, p.4, 10, 12-14.

UNITED STATES OF AMERICA. OFFICE OF NAVAL RESEARCH. 1973c. Reinforced concrete may be used as the basic hull material for limited depth submersibles. Naval Research Reviews, Vol.XXVI, No.7, p.17-18.

UNITED STATES OF AMERICA. OFFICE OF NAVAL RESEARCH. 1974. Buoy integrated antenna submarine program (BIAS). Naval Research Reviews, Vol.XXVII, No.7, p.19.

URQUAHART, J. 1982a. Canada to open hearings on pilot project of $2.1 billion to ship LNG for Arctic. Wall Street Journal, February 2, 1982.

URQUAHART, J. 1982b. Northward Ho! Canada's mining firms turn to Arctic Islands, site of rich resources. Wall Street Journal, February 5, 1982, p.1, 16.

VELIOTIS, P. and REITZ, S. 1981a. A Submarine LNG Tanker Concept for the Arctic. Groton, General Dynamics Corporation.

VELIOTIS, P. and REITZ, S. 1981b. U.S. in submarine tanker plan for Arctic LNG. Lloyd's List, Monday, October 19, 1981, p.4.

VINES, S. 1981. Oil giants start massive investment to stay on top. The Observer, October 18, 1981, p.18.

WADHAMS, P. 1971. British Submarine work in the Arctic, 1971. Polar Record, Vol.15, No.99, 1971, p.923.

WADHAMS, P. 1976. Oil and gas in the Beaufort Sea. Polar Record, Vol.18, No.114, 1976, p.237-50.

WADHAMS, P. 1977. A Joint Topside-Bottomside Remote Sensing Experiment on Arctic Sea Ice. Paper presented to the 4th Canadian Symposium on Remote Sensing, Quebec City, May 1977.

WADHAMS, P. and HORNE, R. 1978. An analysis of ice profiles obtained by submarine sonar in the AIDJEX area of the Beaufort Sea, Scott Polar Research Institute Technical Report 78-1. Cambridge, Scott Polar Research Institute.

WADHAMS, P. and others. 1979. Transects by submarine of the East Greenland Polar Front. Deep Sea Research, Vol.26A, p.1311-27.

WADHAMS, P. and HORNE, R.J. 1980. An analysis of ice profiles obtained by submarine sonar in the Beaufort Sea. Journal of Glaciology, Vol.25, No.93, p.401-24.

WADHAMS, P. 1981a. Oil and ice in the Beaufort Sea - the physical effects of a hypothetical blowout. In: Petroleum and the Marine Environment PETROMAR 80. London, Graham and Trotman Limited, p.299.

WADHAMS, P. 1981b. Sea-ice topography of the Arctic Ocean in the region 70°W to 25°E. Philosophical Transactions of the Royal Society of London, Vol.302, No.1464, p.45-85.

WADHAMS, P. 1981c. The ice cover in the Greenland and Norwegian Seas. Reviews of Geophysics and Space Physics, Vol.19, No.3, p.345-93.

WALLACE, H.N. 1981. Geographical explorations to 1880. In: ZASLOW, M., ed. 1981. A Century of Canada's Arctic Islands 1880-1980. Ottawa, The Royal Society of Canada, p.31.

WEAVER, K.F. 1981. America's thirst for imported oil our energy predicament. In: ENERGY A Special Report in the Public Interest, Facing up to the Problem, Getting Down to Solutions. Washington, D.C., National Geographic Society, p.2-22.

WERNER, H. 1981. Deep Sea Program. Technologies International Document T.I. III/81, November 1981, N.p.

WILKINS, H. 1931. Under the North Pole. New York; Brewer, Warren and Putnam Incorporated.

WITTMANN, W. and SCHULE, J. 1966. Comments on the mass budget of Arctic pack ice. In: RAND CORPORATION. 1966. Proceedings of the Symposium on the Arctic Heat Budget and Atmospheric Circulation. Santa Monica, Rand Corporation.

WHITEHORSE STAR. 1981. Oil for Canada from the Beaufort Sea, how soon? The Whitehorse Star, Thursday, October 8, 1981, p.8-9.

WHITEHORSE STAR. 1982a. Greenland opposes Arctic transport plan. The Whitehorse Star, March 2, 1982, p.5.

WHITEHORSE STAR. 1982b. Stabilization unlikely oil glut forcing prices down ... The Whitehorse Star, Friday, March 12, 1982, p.11.

WHITEHORSE STAR. 1982c. Colonial link severed as Constitution signed. The Whitehorse Star, Vol.82, No.75, Monday, April 19, 1982, p.5.

WHITEHORSE STAR. 1982d. Huge Arctic gas deal signed. The Whitehorse Star, Vol.82, No.76, Tuesday, April 20, 1982, p.6.

WHITEHORSE STAR. 1982e. More pipeline woes seen. The Whitehorse Star, Vol.82, No.80, Monday, April 26, 1982, p.4.

WHITEHORSE STAR. 1982f. Natives want 2/3 more to have constitutional status. The Whitehorse Star, Vol.82, No.80, Monday, April 26, 1982, p.6.

WHITEHORSE STAR. 1982g. No more pipeline aid - Haig. The Whitehorse Star, Vol.82, No.82, Wednesday, April 28, 1982, p.1.

WHITEHORSE STAR. 1982h. Pipeline problems blamed on oil Co.'s. The Whitehorse Star, Vol.82, No.83, Thursday, April 29, 1982, p.1.

WHITEHORSE STAR. 1982i. Serious $ problems for p'line-Sharp. The Whitehorse Star, Vol.82, No.84, Friday, April 30, 1982, p.4.

WYNNE, K. 1980. Improved processing matrix method for high strength polymers. Naval Research Reviews, Vol.XXXII, No.4, Summer 1980, p.36.