An Arctic Engineer's Story

1971 to 2006

by
Dan Masterson

To my wife Ginny and my sons,

Andrew, Greg, and Mark

Preface

In 1971, I just happened to be in the right place at the right time. I had just completed my PhD and was looking for work. I was told to contact Hans Kivisild who had just been given a contract from an oil company to investigate an engineering issue in the Arctic. This started my career in Arctic engineering, just when the second major exploration phase was beginning in the western Arctic, 123 years after Franklin started the first phase of exploration in the area. This recent phase was also filled with individuals who were going “where few had gone before,” but unlike the earlier explorers, these recent explorers were accompanied by regulators, scientists and engineers who wanted to ensure that the environment was protected and also to ensure that the operations were carried out in the safest and most cost-efficient manner. Between about 1970 to 1995, several oil companies and Arctic consulting companies turned Calgary into a world leader in Arctic technology. It was a time that one could have an idea, check it out in small scale, and within a year or so, use it in a full-scale operation. During the next 25 years, industry drilled many wells in the Arctic using the technologies described in this book. In 1995, the oil industry pulled out of the Arctic mainly due to lack of government incentives and poor drilling results. In 2016, both the Canadian and United States governments declared a moratorium on Arctic drilling. I retired in 2015, so I was fortunate that my career spanned the period of Beaufort Sea and Arctic Island exploration from start to end. Most of my work involved investigating pioneering ideas into the use of ice as a construction material for ice islands and ice platforms for exploratory drilling, and ice roads for moving the heavy equipment required by the oil and mining companies in the Arctic where there were no roads. The remainder of my work involved measuring the failure strength of ice to support the operational projects, and for use in ice interaction models to determine loads caused by both sea ice and glacial ice impacting structures. Most of this work has been written up over the years in a number of technical papers, which have been published in journals or presented in conferences by my colleagues and me. This book brings together this work into one place and presents it in a form that is of interest to engineers and non-engineers who have a keen interest in the Arctic. I also present anecdotal information of things that happened to me “behind the scenes” that have not been published anywhere else, but which, I feel, were interesting aspects of my career.

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Acknowledgements

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1. Introduction – The Genesis of Arctic Exploration

Interest in the Arctic Offshore was initially shown by explorers who sought a reliable route from east to west through the ice-covered waters of the region. This was the “Genesis” period of Arctic knowledge for Europeans. However, in the twentieth century mankind’s appetite for coal and oil and gas was growing rapidly. This growing demand, coupled with knowledge that the technology required, such as shipping, air transport, heavy mining and drilling equipment had been established, spurred activity. The logging industry in northern Ontario, Quebec and other cold regions of Canada contributed much needed knowledge, especially as regards the transport of heavy loads over floating ice covers.

The exploration history of the U.S. offshore oil and natural gas industry began in the Pacific Ocean more than 100 years ago. America’s offshore petroleum industry began in the late 19th century in the Pacific Ocean with drilling and production piers at Summerland, California. In 1896, as enterprising businessmen pursued California’s prolific Summerland oilfield all the way to the beach, the lure of offshore production enticed Henry L. Williams and his associates to build a pier 300 feet out into the Pacific, and mount a standard cable-tool rig on it. By 1897 this first offshore well was producing oil and 22 companies soon joined in the boom, constructing 14 more piers and over 400 wells within the next five years. The Summerland offshore field produced for 25 years – fuelling the growth of California’s economy.

Drilling platforms also appeared on lakes in Ohio and Louisiana. By the 1940s, technology was taking wells far into the Gulf of Mexico, but as recently as 1947, no company had ever risked drilling beyond the sight of land.

The Canadian petroleum industry arose in parallel with that of the United States. Because of Canada's unique geography, geology, resources and patterns of settlement, however, it developed in different ways. The evolution of the petroleum sector has been a key factor in the history of Canada, and helps illustrate how the country became quite distinct from her neighbour to the south.

Although the conventional oil and gas industry in western Canada is mature, the country's Arctic and offshore petroleum resources are mostly in early stages of exploration and development. Canada became a natural gas-producing giant in the late 1950’s and is second, after Russia, in exports; the country also is home to the world's largest natural gas liquids extraction facilities. The industry started constructing its vast pipeline networks in the 1950’s, thus beginning to develop domestic and international markets in a big way.

Despite billions of dollars of investment, its bitumen - especially within the Athabasca oil sands - is still only a partially exploited resource. By 2025 this and other unconventional oil resources - the northern and offshore frontiers and heavy crude oil resources in the West - could place Canada in the top ranks among the world's oil producing and exporting nations. In a 2004 reassessment of global resources, the United States' EIA put Canadian oil reserves second; only Saudi Arabia had greater proven reserves. In 2014, the EIA ranked Canada as third in World Oil Reserves at around 175 billion barrels, while Saudi was 2nd with around 268 billion barrels and Venezuela was ranked first with around 297 billion barrels of reserves.

Many stories surrounding the petroleum industry's early development are colourful. The gathering oil patch involved rugged adventurers, the occasional fraud, important innovations and, in the end, world-class success. Canadian petroleum production is now a vital part of the national economy and an essential element of world supply. Canada has become an energy giant.

In the early 1970’s when interest in the Arctic offshore was developing, engineers had little hard information and virtually no past operational experience from which they could evaluate the probability of success of future operations. Except for a few limited cases, we had no precedents to draw from. For example, we were forced to rely on theory for the bearing capacity and creep deflection of laterally loaded floating ice sheets. As you will see in later chapters, our guesses and assumptions, although somewhat conservative, were mostly correct.

With time, more and more exploration was accomplished, more testing was done and data on ice forces, creep deflection and ship transit and station keeping was accumulated and reported at numerous Arctic conferences in the US, Canada and other parts of the world. Compared to Genesis, we now had plenty of good data upon which to base design codes. And government and industry were fully behind this effort.

2. The Beginning of my Adventures into Arctic R and D

My adventure in the Arctic offshore, and onshore, started in late 1971 when I had just graduated from Queen's University at Kingston, Ontario, Canada. I had finished a Ph.D. on "The punching strength of reinforced concrete flat slabs" in the spring and had stayed around Queen's to write and publish two papers with my supervisor, Dr. Adrian E Long. I had been offered a position at FENCO, Foundation of Canada Engineering Company, by the head of their bridge department but had declined in order to publish the papers. Adrian had obtained funding for this effort and I wanted to take advantage of it. When the papers were finished and published, my wife Ginny (short for Virginia) took a month off in the fall of that year to do a tour of Europe. We carried a book titled "Europe on Five Dollars a Day" and most of the time it worked!

We returned to Kingston in late September of that year and I started searching for employment in Toronto. There was no point in trying Kingston as it was too small and the job situation there was very limited. Ginny had a good position at Kingston General Hospital as head nurse in the dialysis unit but I had to find work. The position in FENCO's bridge department was by now filled and I had to find something else. It was the middle of an economic downturn and gloom was everywhere. There was even an incidence of a person jumping out of an office window to his death. I met rejection after rejection from different engineering firms. Employment agencies were unhelpful and simply toyed with me on the phone. I finally went to see Ron Temple, head of the bridge department at FENCO and he directed me down the hall to Dr. Hans Kivisild who was an expert in river hydraulics and the effects thereon of ice cover and ice jams. He was doing some initial work for Home Oil, Shell Oil, Sun Oil, Imperial Oil and other companies who were evaluating ways of exploring for and transporting to market offshore oil and gas reserves in the Beaufort Sea and in the Queen Elizabeth Islands or Arctic Archipelago. The French oil companies, Aquitaine and Total, were particularly interested in drilling on the west side of the Arctic Archipelago to test the theory that the Prudhoe Bay field geology did extend along this area. It did but the drilling revealed that any petroleum reserves had long since drained away.

The Alaskan Prudhoe Bay Oilfield had been discovered in 1968 and a year later was shown by British Petroleum, who drilled a well 30 miles to the west of the discovery well, to be a 13-billion-barrel reservoir. Geology predicted that this large reservoir could extend eastward into Canada's Beaufort Sea. Prudhoe Bay was a totally land based reserve but the geology indicated that it should or would extend to the offshore and eastward. Thus, major oil and gas companies were interested in how this vast acreage might be economically explored and produced. Hans was in on the ground floor and he offered me a position as an engineer to do required calculations related to ice loads and ice effects on offshore installations, including islands, large structures and pipelines. So I was also being introduced to a new area where I could apply knowledge and experience from my university training and, as it turned out, from my experience gained from being raised on a farm in south western Ontario. The latter experience and knowledge turned out to be as valuable as the former, but more about that later.

Figure 1 Arctic Polar Region

Figure 2 Western Arctic Islands and US/Canadian Beaufort Seas

We did our first testing at Yellowknife in the early spring of 1972 and soon moved on to Tuktoyaktuk (or Tuk) where we were mobilized via helicopter to a test site approximately 50 miles offshore. We were ferried to the test site by a Sigorsky S-68 helicopter each day and ferried back at night. One afternoon a white-out occurred and the pilot informed us we would be staying on the ice with the helicopter for the night. It was -40 that night and the inside of the helicopter iced from breath moisture and became much like an icebox. It was warmer outside. Fortunately, Sun Oil had a small, heated building at the site to house recording instruments, so we could take turns going in there and get some hot soup or tea. We had a Herman Nelson oil fired heater but that was saved to warm the helicopter engine whenever the weather cleared enough to let us leave. Fortunately, the weather cleared the next morning and we were able to leave. We did have drums of jet fuel aboard and the pilot warned us not to smoke while we were sitting in the back of the helicopter during flight, or any other time! Now HSE procedures would not even allow us to fly in any aircraft carrying drums of fuel. We all got back to Tuk that day and had a nice warm supper in camp.

At the time there was only one phone in Tuk and calls to the south had to be booked. The following era of oil exploration in the Beaufort would change all of that. Old timers told me the same about Prudhoe Bay in the early days. There was one phone and one had to line up to make a call south. We made jokes about being in the ice testing lab at “Old Tuk U”.

The Testing

We were conducting compressive strength tests in pits dug in the ice using chain saws. These tests were regarded as equivalent to cylinder tests conducted in the laboratory. In fact, such tests were common in the fields of soil and rock mechanics so we had good precedent to go by. We were also conducting ice strength profiles through the ice using a Menard pressure meter, a hydraulic device which fitted down a 70-mm hole. By pumping hydraulic fluid into the flexible cylinder it expanded against the hole and gave a pressure-deformation curve. The problem with the device was that it was intended to test a much weaker material than ice and, in our attempts to fail the ice, we blew up the apparatus. High pressures in soil were low pressures in ice. Another set of tests were beam tests to attempt to get tensile/flexural strength. The first tests were tests on cantilever beams cut from the ice sheet. Three sides were cut free from the ice and the fourth was left attached. The problem with this test was, ice being a brittle material, the beam would break itself at the attached end before any load was applied. Later we tried “encastre – a word used by Dr Kivisild” beams where both ends were attached to the parent ice sheet. These tests were much more reliable but also much harder to interpret. The pit tests for compressive strength were definitely the easiest, most reliable and readily interpreted and yielded a lot of data on basic ice strength. My role in the tests was to assist with their execution and then to work with Hans Kivisild to interpret the results and to report them to the client. I do remember that Gary Rose came back with the results of an early set of tests recorded in a field book that had been dropped in a barrel of diesel fuel. I had to hold my nose while extracting the numbers from the book.

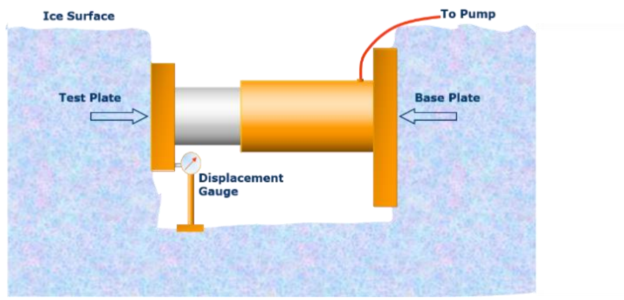

Figure 3 Ice Pit Test

But the results were all useable and revealed small scale ice strengths much in excess of those derived from lab tests and commonly thought to apply to naturally occurring ice. These principles would be carried through to much larger scale test and more sophisticated recording techniques in the future. At the time we were manually recording pressure and deformation readings from analogue dial gauges. And when our fingers got too cold we often missed a point of recording.

We drilled holes through the ice by hand or with a standard powered soils auger. We cut pits and beams with chain saws which froze solid from the cold air and water combination. Whenever we could, we avoided cutting through the ice as this meant seawater was brought up by the saw chain and working was miserable to impossible. Chain saws have drags behind the cutting teeth to remove wood cuttings. We found that for cutting ice it was best to file these drags off as the saw then cut much faster and more easily through the ice. Needless to say, the chain saws had a short life. We tried Pioneer and Homelite saws and then changed to Stihl saws. The Stihl were better but still had a short life. We would put the saws on the exhaust stack of the Herman Nelson heater to thaw them out or at least “unfreeze” them.

One lesson we quickly learned was if you were drilling holes in fresh water and there was an unfrozen layer of water near the surface, then this water would run into the hole and freeze instantly, resulting in a stuck auger which, without the aid of a steam hose, was impossible to retrieve. Similarly this happened in low salinity sea ice and in one instance we had to get a D4 Cat to yank the auger out of the ice. A stuck auger could take hours to retrieve. Eventually we used cheap grain auger as flights and, if the auger became stuck, it stayed stuck.

3. The Ice Road at James Bay

During the summer of 1972, a barge load of heavy construction equipment under tow to the James Bay hydroelectric project became grounded on a shoal at the mouth of the Fort George River, only a few miles from its intended destination. The towing contractor, Federal Commerce and Navigation Limited (FedNav), contracted FENCO to study the removal of the equipment by an ice road to shore. The total length of the road was approximately 1 mile and the ice was floating over this distance. The road was built by Sainte-Marie construction in late December 1972 and early January 1973. It was 30 m in width and 1.9 m thick. Small gasoline auger pumps were used to pump water onto the surface of the ice, so it could freeze in layers about 25 mm thick (1 inch).

Gary Rose was the field engineer and signed off on the road before it was used to transport the equipment. I was sent north with him to support the drilling and testing of the ice. Later FedNav would question the need for my presence at site and any billing related thereof. I did the calculations for required ice thickness and optimum road width before going north to the site. At site, Gary and I drilled holes and took cores to check ice thickness and ice quality. This was the site where we learned about the problems with surface water running down hole and freezing our auger. We did not have cheap, disposable auger flights at the time and thus had to retrieve the frozen-in auger using chain saws and lots of picking with bars. There was no steam hose. Sainte-Marie Construction had begun construction before our design was completed since they had built several floating ice roads across rivers in northern Quebec and Ontario. They were most cooperative and were good to work with. I learned a lot about ice construction techniques from them since they were very open with their knowledge and information.

This project was very political in that the purchaser of the equipment, a Quebec contractor, offered salvage value for the equipment at the barge. FedNav and Lloyd’s of London did not look favourably on this offer and undertook to deliver it to the contractor at their construction site for the stipulated selling price. One side was trying to show that it was damaged and only of salvage value and the other side was saying that it was delivered intact and new condition. Using the ice road enabled the shipper to deliver the equipment intact at the original sale price. Thus there was a lot of pressure to show that the ice road could perform, which it ultimately did. Gary was “under the microscope” when it was time to sign off on the road. I went for a walk on the road every time there were doubts and differing opinions and always felt good about the road. We monitored the deflections and any cracks most carefully, especially in the tidal crack zones near shore. In the meantime, St Marie Construction was using some of the lighter equipment, such as a grader and Cat, from the barge. When it came time to transfer the heavy ore crusher, we had built up our confidence and that of FedNav and Lloyd’s. The ore crusher came off without incident and the concept was proved and accepted. Later we did publish a paper on this project which appeared in the Canadian Geotechnical Journal in 1975. This project would lead to many others, including floating ice platforms for offshore drilling in the Arctic Islands for Panarctic Oils Ltd. and to offshore ice roads on the North Slope of Alaska.

4. Frozen Islands and Beaufort Sea Exploration in Canada

The very cold temperatures and long winters of the Arctic regions led to thoughts by Dr Kivisild and those working with him that islands could serve very well as cheap support structures for exploratory drilling support and possibly for production support in the Beaufort Sea and even in the Arctic Islands. The water depths of the Beaufort shelf are relatively shallow and would allow grounding with reasonable amounts of construction effort and material quantities. In the early to mid-1970's Imperial Oil, Sun Oil and the French oil companies were exploring or considering exploring for reserves in the shallow water (3 to 10m) water depths of the Beaufort. Gravel was being from YaYa lake on Richards Island in the Mackenzie Delta. This was a long haul to the offshore sites and the gravel source was limited in quantity. There had to be an easier and cheaper way to construct these islands.

The thinking was that the core of the island could be built of ice, a material produced by freezing the sea water at the site and grounding it. Ice alone would be problematic beyond the winter season since warm ambient temperatures would cause the core of the island to melt and wave action would quickly erode the perimeter. A solution was to construct the core out of ice and then to use gravel or dredged material to form the outer perimeter. Of course, the perimeter would require slope protection or it also would be quickly transported away by wave action. In addition, the ice core would have to have surface protection from solar radiation. This concept was investigated by FENCO for the French oil companies and, while theoretically possible, was found to be of little or no cost advantage over the hauled gravel or dredged material. A large expense associated with earth islands was the slope protection. However, the engineering performed on ice core islands did introduce us to a host of issues and force us to think through the problems, to understand the physics and to understand how possible solutions could work. This led to an understanding of thermal processes, refrigeration techniques (and costs, which were substantial) and of course coastal engineering and erosion. In the end the concept was not followed.

An interesting anecdote comes to mind. At the beginning Hans Kivisild called me into his office and, with a sheet of paper filled with equations and writing all over it including in the margins, explained his thinking and wanted me to continue the effort and to put it into a more organized form. I had great difficulty even understanding the thinking and his dealing with the differential buoyancy issues related to ice and soil as this structure was being built on the floating ice cover and gradually sunk to bottom. Dismayed at my difficulty grasping the concept, I took the sheet of calculations down to Gary Rose's office and asked for his help. He took a look at the sheet, crumpled it up and threw it in the waste basket, saying: "That will all change by tomorrow anyway"! We did retrieve the paper from the waste basket and I did perform a set of calculations, requiring many sheets of paper. I do wish I had kept that sheet for posterity. In retrospect, this "out of the box" thinking was our bread and butter and was not so much out of line with the thinking of others trying to devise methods of supporting exploration and production in these remote and difficult areas.

The history of Beaufort Sea operations is well documented and I will not repeat it here. Islands were built by hauling gravel and then by dredging sand from the seabed after sub cutting the surficial soft sediments. Slope protection was provided until it was realized that exploratory islands did not require it since they were seasonal or were two season and were large enough in plan to accommodate some erosion. Deeper water required the use of submerged berms with concrete or steel structures sitting on them to penetrate the waterline. Even deeper water required the use of floating structures and drill ships. Using drill ships in the ice infested waters of the Beaufort Sea was tricky and definitely a challenge. Nevertheless, Dome Petroleum and its subsidiary, Canadian Marine Drilling (CANMAR) and then Gulf Canada through its subsidiary BeauDrill did manage to drill several wells using floating, moored ships and other structures such as the Kulluk. These efforts were not cheap and the Petroleum Incentive Program instigated by the Canadian Federal Government made the effort possible.

It is incumbent to mention that on the Alaskan side offshore exploration was also proceeding in shallow water. There is no large river equivalent to the Mackenzie River there and thus much less sedimentation. The rivers come down from the Brooks Mountain range, flow seasonally at high discharge and deposit gravel near shore. This gravel is frozen but of good quality, and when mined provides a gravel with low fines content, which is good for island building. In addition, the offshore seabed is relatively competent and generally provides a good base for structures. Shell, British Petroleum and Exxon were pursuing this means of exploration and gravel was used for production island such as Endicott and Northstar by BP.

5. Arctic Islands Exploration

The Canadian federal government's eagerness to encourage Arctic Islands exploration, partly to assert Canadian sovereignty, led to the formation of Panarctic Oils Ltd. in 1968. This company consolidated the interests of as many as 75 companies and individuals with Arctic Islands land holdings plus the federal government as the major shareholder. As indicated in Figure 4, Panarctic drilled a large number of wells in the High Arctic. Unfortunately, they had one blowout, King Christian D-18, which blew wild for 91 days, and, after catching fire, was the source of an 80-metre (250 ft) column of flame. It was estimated that it was emitting as much as 200 million cubic feet (5,700,000 m^3*) of gas per day during the blowout.*

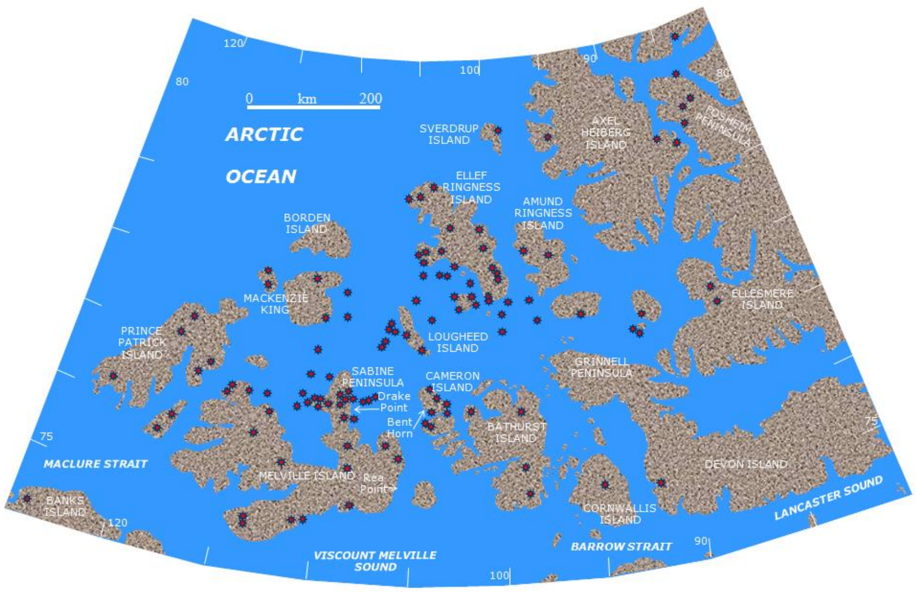

Figure 4 Canadian Arctic Islands and Wells Drilled

Drilling onshore revealed that the majority of reserves should lie offshore judging by the geology. Apparently, after the King Christian Island gas blowout, Panarctic had hauled the remains of the destroyed drilling rig onto the ice with the intent that in summer it would sink into the ocean. It didn't and the next winter it was still on the ice which had not melted that summer. Since Panarctic wanted to drill offshore anyway, the idea was born in the mind of Jim Strain, VP of exploration, that perhaps one could drill exploratory wells cheaply using the ice as a support. In the summer of 1972 Hans Kivisild was making sales call to various oil and gas companies and visited Strain. Strain asked about the possibility of drilling off the ice and Hans phoned me at our office in Toronto about the concept. I thought it was a crazy idea but he asked me to do some calculations anyway. I got some information on the layout and weight of the rig proposed to do the drilling and, using Timoshenko's Theory of Plates and Shells, which had a solution for laterally loaded plates on elastic foundations, came up with a required thickness of 12 ft or 3.5 m for the maximum ice thickness at the draw works, the heaviest load under the rig. I used an allowable maximum elastic bending stress of 50 psi or 350 MPa, a value used for the Fort George ice bridge and determined as a safe value by Dr

Lorne Gold of National Research Council of Canada (NRC). Long term deflection due to creep or time dependent deformation of the ice was also a concern as the rig had to remain above the waterline for the drilling period. To calculate this, Hans and I agreed to use an effective, long term elastic modulus of 1/100 the short short-term value. Deflection measurements taken during the Fort George equipment unloading had given us information on the short-term modulus value for large loads on thick ice. This value was lower than laboratory determined values.

Panarctic was not pleased to hear that such thickness was required since first year ice in the Arctic reaches a thickness of about 6 to 7 ft (1.8 to 2 m) in a winter season. Obtaining a thickness of almost double the natural growth would mean a lot of flooding. A saving grace in this was that only the central part of the platform needed to be this thick. It could be, and had to be, allowed to taper to the natural ice thickness at distance from the rig, similar to the floating ice roads discussed previously. A schematic and a photo of a rig on an ice platform are shown in Figure 5. Flooding of an ice platform with electric submersible pumps installed in insulated “wells” through the ice is shown in Figure 6 and flooding an airstrip with a hydraulic powered auger pump is shown in Figure 7.

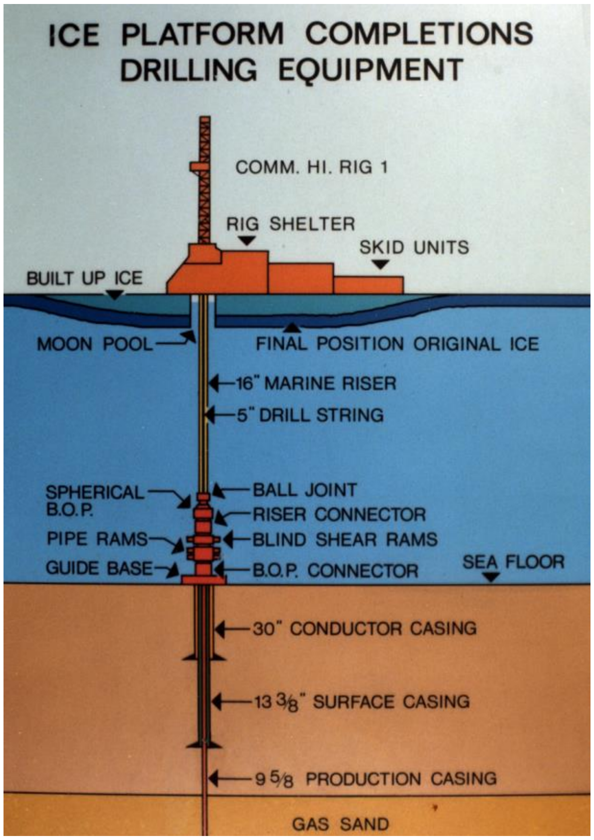

Figure 5 Land Rig on Ice Platform

Figure 6 Flooding a Floating Ice Platform with Electric Submersible Pumps

Figure 7 Flooding an airstrip with an hydraulic powered pump

Figure 8 Hecla N-52 L-R Ray Young, Dan Masterson, Manos Kazakopoulos

The final design thickness of the first ice platform in 1973, named Hecla N-52, was a negotiated maximum thickness with Panarctic's partner Tenneco and their consultant. As mentioned, our calculations had determined a maximum required thickness of 12 ft or 3.5 m to satisfy safety against breakthrough and loss of freeboard due to creep deflection. Remember that approximately 90 percent of floating ice is below water, so the thickened ice would have a freeboard, or above water dimension, of about 1.2 ft or less than half a meter.

Tenneco's consultant did a calculation, based on tank tests performed at Resolute Bay, that determined the maximum thickness would have to be higher and around 17 ft (5.2 m). Since Panarctic had already begun to build the platform, we knew that, with the equipment and resources available, this thickness could never be achieved. In addition, Tenneco's consultant specified that warm water should be used for the first one or two floods to ensure bonding to the existing sea ice. To this end a boiler was shipped to site and sea water pumped through it to heat the flood water. As it turned out the sea water pumped directly from under the sea ice cover already had ice crystals in it. Thus the boiler was simply supplying latent heat to melt the crystals and the temperature of the flood water was not raised even 1 degree. This effort was abandoned and the boiler was pulled off to the construction edge where the tubes froze and had to be repaired later. Flooding continued using gasoline powered auger pumps, the same pumps that had been used at Fort George earlier.

A compromise was made on the design ice thickness at 15 ft (4.5 m). It turned out that the data from the Resolute Bay tests was flawed and not applicable to the Hecla platform design. Failure had been determined from first crack in the ice, which occurred when the tanks were partially full. However, the tanks were filled to the top and there was only a change in slope of the load vs. deflection curve. With the tanks full, there was no breakthrough, no leakage of water from the base of the tanks, which was formed by the native ice sheet, and the freeboard was still positive. The tests did not produce a useable flexural strength of the ice. Lorne Gold's data was the only reliable reference. Increasing the required thickness from 12 ft to 15 ft decreased the maximum flexural stress from 50 psi to about 35 psi. The Hecla N-52 well was successfully drilled during the winter and spring of 1974. There were no failures and the freeboard remained positive. In later years the design allowable elastic stress was re-established at 50 psi and later at 70 psi or 500 kPa.

I should note the circumstances which surrounded getting access to this ice flexural strength data. I asked to see the data which justified a decreased allowable flexural stress and necessitated an increased ice thickness. Gordon Hood, chief engineer with Panarctic, asked me to come to Panarctic's office and he gave me the reports on the tank tests at Resolute Bay to read in the office. The data was apparently confidential, so I could not have a copy or remove the reports from their office. So I went into a closed room and read the reports, handing them back to Gordon after our session. As indicated previously, there was a first crack in the ice, after which the slope of the load-deflection curve decreased somewhat and then the tests were continued to "maximum load". Reading the report, I found that "maximum load" was the point where the tanks were full, not where any breakthrough or failure of the ice had occurred. At this point the ice was still intact with positive freeboard. I had previously completed 3 years testing reinforced concrete slabs for my Ph. D. and we always loaded the test slabs to about a quarter to a third of ultimate capacity BEFORE beginning the test. This ensured that the concrete was cracked, as it was designed to be since the steel reinforcement took the tensile stress. Testing a slab which had not been "worked in" would lead to anomalous results, high local stress concentrations, and was not acceptable practice. It followed that ice would be similar despite the re-bar in concrete. An ice sheet of uniform thickness, such as occurs at Resolute, would need to be "worked in" before a reliable test could be conducted. In addition, Real St Marie, the construction contractor for the Fort George ice road discussed previously, told me that he never trusted un-cracked ice but always used lighter equipment to "work it in" first. The initial cracking likely acted as stress reliever.

This working in was the first crack in the ice during the tank tests. It was not failure of the ice. I handed the report back to Gordon and indicated that my original design stood. He agreed and we went on to negotiate a final design thickness with Tenneco.

For subsequent ice platform construction projects, Denis Baudais of Panarctic designed and had built an electric submersible pump system mounted in insulated wells. These wells were frozen into the ice with the pumps inside them. As the ice thickness grew, the wells were heightened with extensions and the pumps placed higher. The pump discharge pipes were long enough to accommodate this extension. The pump wells were heat traced and the pumps were well below the bottom of the sea ice under surface to avoid intake of ice crystals now known to reside there.

The construction of the original ice platform had been an ordeal with the gasoline powered pumps, but the electric submersible pumps made the operation much more tractable and much easier to schedule and to progress ice build-up to the maximum allowed by prevailing weather conditions.

When Hecla N-52 had been drilled and tested, rig out began. The rig tower and draw works sat on a steel box-like substructure over the well, and the substructure sat on the ice. A hole in the ice about 12 ft square was cut through the ice and was lined with wood planking, allowing access to the seabed. While rig out was occurring, the rig mechanic summoned me over to the substructure and pointed out that the ice had been melted at the moonpool during drilling activity and that the wood plank liner was floating in the hole. The substructure was supported at the corners only with the main part of the beams spanning the melted region. This was not a safe or acceptable practise and in later projects, insulation was added to the liner and a system of tubing filled with circulating glycol was added to ensure that the ice around the moonpool remained frozen. In addition, steaming and rig floor or mat washing procedures were controlled to ensure that undermining of the ice foundation did not occur due to the influx of warm water. Furthermore, sea water from a remotely located pump near the back of the rig was continuously pumped into the moonpool to ensure that the water therein remained cold. Thermistor strings were also installed to check for any excessive warming of the ice. The sea ice was considered to be intact and capable of carrying load if its temperature was at or below -5 C. This criterion was used at the moonpool and also for the construction of the entire platform. For the remaining 37 wells drilled from ice platforms, undermining of the foundation ice beneath the substructure was never experienced in this area. However, at one water disposal well drilled through the ice and used to dispose of excess clean water from the rig, holes drilled near the well revealed that a large cone of ice had been melted around the well leaving only the ice freeboard next to the well. The disposal pipe had not been installed deeply enough below the bottom of the ice and the warm water circulated to the lower ice causing extensive melting. This was subsequently corrected by lengthening the water disposal pipe.

6. Frozen Mine Waste Wharf

Polaris zinc mine was an underground zinc mine on Little Cornwallis Island in the Canadian territory of Nunavut (Northwest Territories prior to Nunavut's official separation). The Polaris mine was located 1,120 kilometres (700 mi) north of the Arctic Circle, and 96 kilometres (60 mi) north of the community of Resolute. The Polaris mine closed in July 2002 following more than twenty years of zinc production

Location	Little Cornwallis Island Nunavut, NWT
Country	Canada
Coordinates	75*23'24"N 96*54;00"W
Production Products:	Lead and Zinc
Production	21,000,000 tonnes of ore
Financial Year	Life of mine
Opened	1981
Closed	2002
Owner	Cominco
Year of Acquistion	1964

Figure 9 Polaris Mine

In 1972, just after I joined FENCO, the company was hired by Cominco to look at the possibility of building a wharf at the mine site using frozen mine waste as the building material. Cominco was just establishing the mine site and wanted to ship out some ore that summer. Hans Kivisild and Ron McKay, a tireless and strong promoter of Arctic engineering and projects, came up with the idea of using the mine waste as a building material. Natural outcroppings of this material occurred near the site so the environmental issues were minimal.

In the early spring of that year I was sent to execute the project. Before going to the site via Resolute Bay, I had to go to Cominco's main office in Vancouver and sit with a young mining engineer to lay out the project. It was a simple project involving myself, a mine loader or scoop tram and a labourer. But the Cominco engineer insisted on drawing up a critical path diagram for it. When I got to site with this plan, the construction supervisor named Bob Tapper, told me to put it into the garbage. He had worked for Foundation Company of Canada, FENCO's parent, and had seen too many projects go awry using this method, or so he said anyway. To me a critical path procedure for two people and a loader was perhaps excessive.

When I arrived in Resolute, I was met by the pilot who would fly me to Cominco's site. He bundled me into a pickup truck and we went off to collect my helper. It turned out he was an Inuit and a resident of Resolute and was at the house of a friend drinking lots of alcohol. The pilot dragged him to the truck and then we loaded him on the plane for the flight. The pilot handed me a 2 x 4 and said if he got out of hand to use the 2 x 4. He was very peaceful during the flight and there was no need of force. The next morning the alcohol had worn off and we had breakfast together. He was most pleasant to talk to and to work with. I learned that he had built houses for the residents of Resolute using material left there by the United States Air Force. The materials were surplus, so he had been welcome to them. He was a very hard worker.

Our work was to cut the ice at the seaward face of the wharf, allowing the ice behind to sink as the mine waste was dumped on top of it. We could not cut through the ice as that would have resulted in our trench flooding and immediate stopping of the work. As it turned out the ice we left at the trench bottom was sufficient to transfer shear load and the ice loaded by the mine waste did not break free and immediately sink. Instead, the shear transfer resulted in a flexural crack forming in the ice further seaward. Eventually the seaward ice did break off in late spring, leaving the wharf face accessible.

The face of the wharf was formed by using 8 x 8 posts and wire fence. The posts were frozen into the ice beneath the fill and the wire strung across them. This worked fine until breakup when floating ice, rushing through Crozier Strait at several knots, impacted the face and removed the posts and wire. However, the frozen fill stayed and resisted the ice and the frozen waste structure became a permanent fixture of that coastline. I did see an aerial photo a few years later and the wharf fill was visible.

At the time I was on the Cominco site, I was notified by the site supervisor that the RCMP wanted to see me in Resolute. I had no idea what this was about but agreed to see them on my way south. The site supervisor was of course concerned that he was harbouring a fugitive! I did see a RCMP officer at the airport and he informed me that Ron McKay had applied for a patent on a system for LNG offloading and that he had asked the RCMP to contact me and get me to sign a patent application right away. The officer and I agreed that the signing could wait until I returned south. Ron had overreacted. One had to remember that communications were sparse in 1972 and phone calls were a rare luxury. One could phone from Resolute Bay but this was a difficult process. Satellites were just being launched and communications from Canada's Arctic Islands was mainly via UHF radio.

Cominco had a very comfortable camp with very good food. While bunking there with the miners, I got to know a few of them. When the miners came in to camp from their underground work, they hung their wet clothes up in a tower located in the entrance mud room called “the dry”. Warm air was circulated upwards through this tower and their clothes dried. I noticed a pair of black long underwear hanging in the dry. It had been there several days and I was curious about its origin, especially where one would buy black long johns. A miner explained to me that they were not bought coloured black but were originally white. The miner had worn them for more than a year without washing them and when he left the site to go south he had left them in the dry.

7. Development of the Ice Borehole Jack

In 1974, we needed a tool to quickly measure the insitu engineering strength and stiffness properties of ice; properties needed by engineers to estimate ice forces on structures and ice load bearing capacity. Up to this time, the strength of ice could only be determined from ice cores, which were taken into a laboratory for testing. This was time consuming and the ice samples required extreme care to prevent melting and brine drainage. During operational field projects in particular, we needed a quick method of testing the strength of the ice. Also, the strength and stiffness of the ice sheet change with depth and thus it is necessary to have a measure of strength that includes variation with depth to provide a means of determining average or global strength properties. The tool that we developed measured the strength and stiffness at 0.3-0.5 m intervals vertically through the ice cover, and tests could be completed in about one hour.

The Menard pressure meter was the standard device for soils testing but was not strong enough for ice. The Goodman Jack (Goodman et al. 1968) was evaluated as an alternative. The Goodman Jack used hydraulic oil from a high-pressure pump and pistons to push opposing rectangular plates against the wall of a drilled hole. The body of the Goodman Jack and the face of the piston had the same curvature as the wall of the drilled hole. It operated at an internal pressure of 70 MPa, but because it had been developed for the testing of stiff rock, it did not have sufficient displacement to test the ultimate strength of ice.

Initial design considerations

Clearly there was a need for a device for the insitu testing of ice, and in 1974, Bill Graham and I decided to build such a tool that would determine ice strength and stiffness properties through the depth of an ice feature. The following were the main requirements for the borehole ice strength testing tool: It was sized to fit easily into a drilled hole about 150 mm (6 in) in diameter; It was built to be hydraulically operated and capable of exerting pressures of 70 MPa; It was built so the pistons driving the device were "stopped" and could not be pushed out of their sockets downhole at full travel of the piston; The end plate of the jack had to be capable of withstanding the full 70 MPa at full travel; Retraction of the piston(s) and load plate at the completion of a test had to occur through positive means, either through the action of a spring or two-way hydraulics, to ensure could be retrieved or moved further down the hole - Two-way hydraulics was used to achieve this; It was built to be light and portable; It was capable of measuring and recording pressure and displacement.

It was designed to be easily manufactured at a relatively low cost. Only high pressure hydraulic pumps were capable of developing the required pressures. Initial concepts tested included single, dual, and triple piston arrangements fitting 75, 115, and 150 mm holes with circular, elliptical, and square indentors. Unconfined compressive strength tests in pits cut into the surface of ice have been successfully conducted since 1971 using hydraulic rams and circular plates. Simple equipment, consisting of a hydraulic jack and pump, steel loading plates, and a mechanical displacement gauge were used to load the ice to ultimate strength over a circular area of 0.02 m^2 to obtain a pressure versus displacement curve, as demonstrated in Sinha (1991) and Masterson (1992, 1996). The rams had ample displacement to ensure that the ultimate strength of the ice was obtained. To increase the utility of this approach, the jack was adapted for placement into a drilled hole. The diameter of the hole needed to be sufficiently large to accommodate a tool that could develop enough displacement to ensure that the ultimate strength of the ice was reached in most cases. Since the pit tests demonstrated a single piston to be effective, this arrangement was adopted for the ice borehole jack, rather than using a multiple piston system. This was the basic specification for the borehole jack. Various materials were considered for the construction of the borehole jack. Factors considered in selecting a material included ease of machining, material strength, corrosion resistance, and durability. The materials evaluated included high strength marine red bronze, high strength steel, AISI (American Iron and Steel Institute) 316 stainless steel, and aluminum.

Because the jack was to be used in a salt water environment, the AISI 316 stainless steel was chosen. Also, stainless steel was readily available, economical, and has high strength. The design and construction of the original borehole jack was undertaken in mid-1974, funded by FENCO. The jack had a displacement of at least 50 mm and up to 150 mm, thus ensuring, from past experience with the surface pit tests (Kivisild 1975), that the ultimate strength of the ice would be attained during a test. The jack was designed to fit a 150 mm drilled hole. The exact stiffness and displacement of the ice at ultimate strength does depend on temperature and other basic physical properties of the ice, but this displacement was found to be adequate over a wide range of in situ ice properties. This design feature required the development and manufacture of new drilling equipment, since most equipment operating in the Arctic at the time drilled 90 or 100 mm holes. Subsequently, the standard CRREL (Cold Regions Research and Engineering Laboratory) (Rand and Mellor 1985) ice core barrel was enlarged from 100 to 150 mm in diameter, and this allowed laboratory uniaxial and tri-axial compression tests to be performed on ice cores taken from the same hole in which the borehole jack tests were performed (Iyer and Masterson 1991; Sinha 1991). This was a very desirable development, since field and laboratory tests could then be directly compared and the combined results reliably correlated. The jack was designed so that a pressure of at least 35 MPa could be applied to the ice, a value found to be sufficient for a wide variety of ice types, both fresh and saline.

This lightweight ice testing device has proven capable of measuring ice strength and stiffness properties and has been used by engineers and researchers in many parts of the arctic from its initial development in 1974 to the present. It has been accepted as a standard tool for the past 20 years for the verification of the basic mechanical requirements of floating airstrips and other similar structures.

Because of limited space, the theory of interpreting borehole jack data is not presented here and one is referred to Masterson (1992, 1996) for more details. Examples of data are also given in these references, along with comparisons of the results of borehole jack tests and laboratory tests.

8. Labrador

Exploration for oil and gas resources on the Labrador shelf started in 1971.

The Labrador Shelf of Newfoundland and Labrador was another prospective exploration province in the early period of eastern offshore exploration. First drilled in 1971, wells in the deeper waters were drilled from dynamically positioned drillships.

Icebergs calved from the glaciers off Greenland earned this stretch of water the unaffectionate nickname "Iceberg Alley." Icebergs drifting toward drilling equipment posed a unique hazard for the industry in that forbidding environment. But using a blend of cowboy and maritime technology, Labrador drillers handled the problem by lassoing the bergs with polypropylene ropes and steel hawsers, then towing them out of the way.

Worsening exploration economics and poor drilling results dampened the industry's enthusiasm for the area. Drilling stopped in the early 1980s, although it continued in the more southerly waters off Newfoundland.

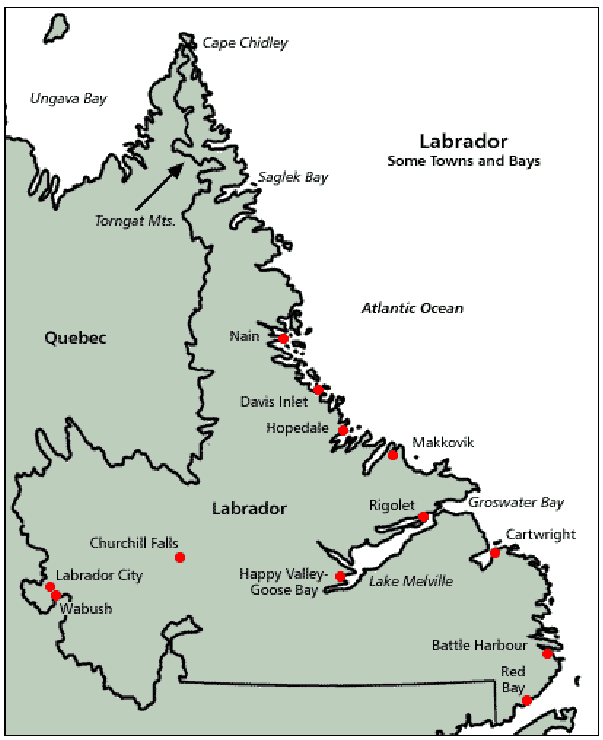

Figure 10 Labrador

In 1972, FENCO – the consulting arm of Foundation of Canada Ltd - sent Hans Kivisild and me to Calgary to open expand an existing office to concentrate on ice engineering and to service several oil companies working in the Arctic that now had head offices in Calgary. We moved in to the small office, expanded it and quickly hired another civil engineer, secretary, accountant, technicians, and additional engineers and scientists.

In 1975 Eastcan, a consortium of French and American oil and gas companies which was headed by Total, contracted FENCO to explore the pack ice offshore Labrador in the areas where the consortium had leases. This work involved flying from a land base via helicopter, as much as 100 nautical miles offshore, landing on the ice and drilling holes to determine ice thickness and performing insitu ice tests. The first expedition was conducted in March of 1975 and consisted of myself, Bill Graham and Jean Duval of Total. We flew ourselves and our equipment from Calgary through Montreal to St John's and then on to Cartwright, an abandoned DEW line site on the Labrador coast. The helicopters were mobilized from Newfoundland to Cartwright. Weather and logistic problems made this a challenging exercise, but we got to Cartwright and began our work.

Since the available helicopters were single engine, and since it was oil company policy not to fly offshore in single engine helicopters, two machines were used to go offshore and land on the ice. The idea was that if one helicopter broke down, the other could evacuate personnel. I remember that we wore floater suits that were not water proof. I asked the pilot about them, pointing out that we would die from hypothermia in the frigid north Atlantic waters. He agreed but said the suits made it easier to find the bodies and to settle insurance claims!

While preparing for the venture, I asked Jean Duval how thick the ice might be and how much auger we should bring. He said it was all first year ice and should be no thicker that about 4 ft or 1 m, considering the length of the season and temperatures of the region. I brought 3 times that length of auger to be sure and it turned out we needed all of that length to drill many of the holes. Jean had been correct regarding the thickness of ice growth, but the constant movement of the Labrador ice pack due to onshore wind and sea currents, ensured that the ice was very much deformed and rafted, a process where the ice overrides itself once or many times to become very thick. Visitors along on the expedition had expected thinner ice and were surprised at the ice thicknesses we found. Insitu strength tests revealed normal to lower than normal compressive strengths, certainly lower than the strengths found in the Beaufort Sea. The Labrador ice was warmer and exposed to continuous movement of the ice pack. It was much more ductile and its temperature was very near the freezing point throughout its thickness, a marked contrast to the ice of the Arctic Islands and the Beaufort Sea.

While performing our work out of Cartwright, we saw no icebergs, possibly because they were further offshore and could not penetrate the ice pack, or perhaps we were too early. In later years we did see a grounded berg and the pack ice was moving past it at a speed greater than 2 knots. This pack ice was breaking against the north side of the berg and forming a spectacular rubble pile as we watched. In 1975, on our last day of work, we landed on an ice floe which had a freeboard of at least 2m and whose surface was smooth and undulating, a marked contrast to the first-year ice surfaces we had been investigating. Bill and I started to drill this feature and found the drilling hard and very different from the first-year ice. We could not come close to drilling through to get a thickness reading. Coring met the same fate. We concluded we had landed on a multi-year ice floe or on a remnant of a tabular iceberg. Strength tests showed this floe had stronger and stiffer ice. Eastcan were not pleased about this discovery, as it showed that hidden within the first-year pack were thick multi-year floes or floes of glacial origin which were very menacing to offshore installations, especially permanent ones.

I should mention something about the positioning and navigation issues associated with working so far offshore on highly mobile pack ice. While we conducted our on-ice tests, which could take several hours, our position changed by several miles due to the constant and fairly rapid movement of the pack ice. We could easily move 20 to 50 miles while working. The pilots were very concerned about this and wanted to keep track of our position. GPS in those days was experimental and spotty, so our only reliable position information came from line-of-sight radio frequency contact. While we were on the ice, we had no line-of-sight contact with shore bases, so at regular intervals the helicopter(s) would take off and obtain sufficient altitude to achieve contact with shore, thus enabling establishment of a reasonably accurate position. We also had to keep a “weather eye” as the weather could change very quickly to fog, rain/snow and high wind. Our flight was strictly VFR or visual flight rules, which meant that we could not fly unless the pilots could see “ground”. If bad visibility developed, we were stuck offshore or would have to “hop” from visual patch to visual patch of ice in an attempt to get back to shore. Staying out on the Labrador pack for a night was out of the question, as an offshore wind could, and would, disperse the pack and send us out into the North Atlantic to perish. Fortunately, we were very conscious of the situation and listened to and followed the requirements of the pilots. Our shore base support was also very aware of the situation and waited anxiously for our communications. If they were not forthcoming, search and rescue would be initiated. Still, they would very likely be flying fixed wing so could not land so we would be spotted but helpless. And ships were slow and could not always get to us. Fortunately, our precautions worked and we were always able to return to base at the end of the day. Because of vulnerability to weather, we had many “layover” days when we could not work.

In subsequent years Eastcan contracted a twin-engine Puma helicopter which obviated the need to take two helicopters. Brian Wright of Gulf Canada, an Eastcan partner, had us try a camera mounted in the belly of this Puma to photograph the ice and to get better information on the ice formations in the pack. The Puma had a built-in hole in its belly which facilitated this and we thus got good information on the pack ice. Later a 9 x 9 inch Wild camera was used and excellent stereo pairs of photos were obtained. The on-ice investigations continued using the same helicopter.

Figure 11 Crew Testing Labrador Ice 1976 – Author is on the far left

During the tests off Labrador, we stayed in DEW Line (Defence Early Warning) camps. During the early cold war, radar observation sites were set up along the Arctic and eastern coasts of northern North America with the purpose of spotting Soviet Russia bombers or spy planes. The United States Air Force manned and operated the sites and by the 1970's they had been abandoned along the Labrador coast.

The Distant Early Warning Line, also known as the DEW Line or Early Warning Line, was a system of radar stations in the far northern Arctic region of Canada, with additional stations along the North Coast and Aleutian Islands of Alaska, in addition to the Faroe Islands, Greenland, and Iceland. It was set up to detect incoming Soviet bombers during the Cold War, and provide early warning of any sea-and-land invasion.

The DEW Line was operational from 1957 to the late 1980s and it was the northernmost and most capable of three radar lines in Canada and Alaska; the joint Canadian-US Pinetree Line ran from Newfoundland to Vancouver Island, and the Mid-Canada Line ran somewhat north of this.

Cartwright, Hopedale, Nain and Saglek were such sites along the Labrador coast. The first year of our investigations in 1975 we stayed at the Cartwright camp (actually part of the Pinetree line) and in subsequent years worked out of the others (all DEW line sites). Bell Telephone was the chief occupant of the abandoned camp and we were their paying guests. We were treated well while there but found the food to be awful. First quality foodstuffs were brought in but the "cook" managed to virtually destroy them during preparation for eating. We protested but were told that the situation would not change and that if we didn't like it we could leave. So we stuck it out for the approximately two week job.

The following year we worked out of Hopedale, farther north. We had our own cook or cooked our own food, I can't remember which. Since the facility had housed a large military crew and radar technicians, we had our pick of beds. When the site was abandoned by the USAF, they left many supplies, including large quantities of sheets, pillow cases, towels etc. Eastcan had all essentials working so we had regular showers. There was even an extensive library, with lots of Bibles I might add. The village of Hopedale was located at the water's edge and the base was much higher up. Two RCMP officers were stationed in the village, one of them with his wife and the other one alone. They often visited us to have conversation and to play cards. One night the senior officer gave me a pitch on the force, I think trying to get me to join. I was not interested.

I did find out that on Thursday the regular food and supplies flight came in from Goose Bay. Its cargo included an ample supply of liquor. We were apart from the village but apparently on Friday and Saturday night it was quite lively there. Hopedale was a racial mixture, containing Inuit, Cree and Europeans. Relations were not always smooth, especially when alcohol was added to the mix. The RCMP had their hands full on the weekends.

The investigations continued for 4 years, drilling of the ice for thickness and stereo photography by helicopter and then by fixed wing to get more and better information on the makeup and extent of the Labrador ice pack. The fixed wing aircraft enabled us to obtain information further afield since their range was much greater. By now they were flying IFR (instrument flight rating) and were not as constrained by weather. I continued to go out on expeditions for two more years and then left the field work to others on our team. Ken Anderson headed the effort.

I do remember that on a trip from Goose Bay to the coast we became weathered in at Makkovik on the Labrador coast. We were flying a single engine Otter plane and the fog came in on us. The pilot was literally flying with his map on his knee and simply could not continue further, so we landed at Makkovik and were billeted for the night at local homes. I was billeted in a home with one bed and a family of about 5 people. Supper was whatever could be grabbed off the kitchen table and I was given the bed for the night. I don't know where everyone else slept. There were only two rooms in the house, maybe three. I had been informed that the compensation for the lodging was $50, which I paid in the morning. We were most grateful for the hospitality of the local people as the alternative was a cold, miserable night in the Otter. The people I billeted with were friendly but very quiet. I was tired as we had travelled from Calgary through Montreal to Goose Bay that day and then tried to reach Hopedale the same day. By the time we landed at Makkovik I did not require conversation and was ready to eat something and go to bed. Maybe the locals saw this.

Return flights from Goose Bay through Montreal to Calgary were also interesting. After the first expedition, I returned with Jean Duval. In Montreal we were about to board the Air Canada flight. Being a consultant, I had an economy seat while he had first class. He would not hear of me flying economy so purchased a first-class seat for me. This was my first time flying first class and I was astounded at the food and drinks available, all part of the airfare. We had cocktails before dinner, wine with dinner and fillet mignon as a main course. The plates were china and the cutlery silver. I was used to plastic cutlery and plates with the usual pre-prepared airline fare. We did of course have some time in Montreal to explore the sights and to visit a couple of bars.

On another trip to Calgary after an expedition onto the ice, Air Canada was very late leaving Goose Bay. In compensation they offered us a free drink. I was about to order something when Brian Wright, whom I was travelling with, advised me to order a Rusty Nail. This drink consists of a normal amount of scotch and the same amount of Grand Marnier. He explained that the free drink could thus become two drinks under the guise of one. Air Canada delivered the Rusty Nails without hesitation. The Rusty Nail was very good and I like them to this day.

9. Ship Expedition off Labrador and Davis Strait

In 1978 Imperial Oil contracted FENCO to conduct current measurements and ice tests offshore Labrador and in part of Davis Strait. The expedition was conducted from a Newfoundland sealing ship named the Lady Johnson II. This ship had been Christened the Polar Bjorn at launch and was about 100 ft length over all (LOA) and had a narrow beam. We boarded in early December of 1978 in St. John's and sailed up the Newfoundland coast and into the Labrador pack ice. The captain, Harrison Johnson, was a seasoned sailor in these waters, having brought a first load of supplies to the USAF base at Thule Greenland during the cold war early years. He was a true Newfoundlander with a thick out port accent that I could not penetrate. One evening he told a joke which I got and after that I found him understandable.

The Lady Johnson II had a narrow beam and rolled 11 degrees from centre even in St John's harbour. Until I got my sea legs, and stomach, I was on a diet of sea biscuits and tea. Once we entered the Labrador ice pack we had little motion due to the damping of waves by the ice. Since the Labrador pack is directly exposed to the North Atlantic, waves do propagate into the ice, breaking it into floes and forcing it to rise and fall with considerable amplitude. At times we had undulations of the ice of 6 to 10 ft. Our oceanographer, Laurie Davidson, had his hands full trying to get current profiles in this environment. Ken Anderson and I did disembark onto the ice when there was a swell in the pack on one occasion. It was an experience to see the gunwales of the ship one moment below your line of sight and well above the next moment. The Imperial Oil representative wisely called us quickly back onto the ship. We did encounter ice with minimal swell on other occasions and were able to conduct some ice sampling and strength tests.

At one point, a strong wind blew onshore, compressing the pack, and we became stuck. The captain was not overly concerned and decided we should remain motionless for a day or two until the wind shifted and the ice pack loosened. So there we sat for about two days. This was not a popular decision with some of the people. First there was worry that the hull would crush but an inspection of the hull framing and plating indicated enough strength to resist the first-year pack. She was not an icebreaker but had a good hull. Then there was worry that we would be stuck there for Christmas. Some wanted the captain to attempt moving, even in small amounts, just to ensure that we did not get permanently frozen in. Harrison did not think this to be necessary, and we whiled away the time updating our data sorting and playing cards. There was also a good supply of rum and scotch on board. And sure enough the wind did switch, loosening the pack and we were on our way again. Harrison was correct to wait it out instead of thrashing about trying to get free. We were never stuck again.

Captain Harrison sailed inside the Labrador ice pack all the way northwest along the coast and into western Davis Strait. We performed our ice tests and obtained some more current meter profiles. A visiting Dutch captain on board who had skippered VLCC's (very large crude carriers) criticized Harrison as being merely a coastal sailor and not able to sail in open water.

However, on our return from Davis Strait, we sailed directly over 60 degrees north and 60 degrees west (60-60) which was definitely covered by open water. We recovered a previously deployed current meter at this site and sailed directly for the Newfoundland coast. That night there was a storm with high wind and waves with ice mixed in. We woke up in the morning and the ship superstructure was coated with several inches to feet of ice. In addition ice blocks were piled on the deck, thrown there by the waves. Every crew hand was out using wooden mallets with long handles to knock the ice accretion from the superstructure. The ice made us top heavy and put the ship in imminent danger of capsizing due to a significant alteration of the centre of gravity, a very dangerous situation and one which has capsized ships in the past. The Dutch captain never said anything again about Captain Harrison's sailing ability.

Figure 12 Sealing Vessel in Labrador Pack - 1978

On our last night out off the Newfoundland coast, the weather and sea were dead calm. The ship's owner, Harrison's brother, had provided us with rum and scotch on a daily basis. We did not imbibe during the voyage since we had work to do. However, we would arrive at St John's harbour the next day, so we partied. I awoke in my cabin the next morning and found all drawers had been dumped onto the floor. The ceiling was the floor and vice versa. I had a bad headache and felt nauseated. I went out on deck and we were in 30 ft seas which were washing over the upper deck I was on. So I got soaking wet. I needed to see the horizon so went to the bridge where there was of course a view and protection from the seas. Harrison chewed tobacco and he had a plastic ice cream bucket nailed to the wall beside his "wheel" which he used as a spittoon. He had run out of tobacco so he had a deck hand beside him peeling the wrapper off cigarettes, so he could chew that tobacco. My stomach would not tolerate this, so I left the bridge and braved the deck and sea spray. Needless to say, none of us bothered with breakfast. Near noon we arrived at the entrance to St John's harbour (The Narrows). The seas were still high and we were bobbing around like a cork. Captain Harrison lined up the ship and then said “now” and we shot through the narrow opening and were still. St John’s deserves its reputation as a safe harbour. I looked back, and beyond The Narrows was a wall of water. My knees were shaking and my stomach was regaining composure. One of the crew said he had seen the rough seas of the north Atlantic make “grown men cry” and now I could see why.

Weather of course was of primary interest to Harrison and his crew while we were at sea. There was a first-generation GPS system on board which was the size of a suitcase, and the captain used it to its fullest extent for navigation. He also checked with any shore stations for the latest weather reports and position. Charts were of course available. But his primary weather tool was his “glass”. This was a glass barometer which was mounted on a wall in the ship’s passageways. The captain would tap his glass and then take a reading. He would then go on deck and take human sensory readings. He once pronounced that in 12 hours it would storm for 12 hours, and it did. There were no ice charts but there was radar on the bridge which showed the edge of the pack ice and showed icebergs as bright spots.

Along the Newfoundland coast heading north we sailed through a Russian fishing fleet which stretched from horizon to horizon. There was at least one factory ship to which trawlers brought their catch. This made Harrison livid and he said he should “shoot a shot across their bow”. He did not but did complain about the lack of protection the Canadian government gave to Newfoundland fishing. He said Newfoundland should join the United States and get real protection from the US Coast Guard. A local radio station in St John’s was CJON. He called it Canada Jumped On Newfoundland. On our way north, I looked to port and saw a long, high coastline. I asked him where we were and he replied that I was looking at the Newfoundland coast. “Some people calls that God’s country” he said.

10. Alaska

Our work in Alaska began through British Petroleum (BP) in 1975 when Roger Herrera phoned me and asked if we could advise BP on the feasibility of unloading production modules from grounded barges over the ice to West Dock. Hans Kivisild and I flew to San Francisco to meet with BP personnel and to lay out a plan for some work.

History of Prudhoe Bay Operations and West Dock

Prudhoe Bay Oil Field is a large oil field on Alaska's North Slope. It is the largest oil field in both the United States and in North America, covering 213,543 acres (86,418 ha) and originally containing approximately 25 billion barrels (4.0×10^9 m^3) of oil. The amount of recoverable oil in the field is more than double that of the next largest field in the United States, the East Texas oil field. The field is operated by BP; partners are ExxonMobil and ConocoPhillips Alaska.

Commercial oil exploration started in Prudhoe Bay area in the 1960s and the field was discovered on March 12, 1968, by Humble Oil (which later became part of Exxon) and Atlantic Richfield Company (ARCO), with the well Prudhoe Bay State #1. ARCO was the operating partner. Drilling sites for the discovery and confirmation wells were staked by geologist Marvin Mangus. BP was among the companies that had been active in the region, and BP was able to establish itself as a major player in the western part of the Prudhoe field. [1] The field was initially operated as two separate developments, the BP Western Operating Area and the ARCO Eastern Operating Area. Upon acquisition of ARCO by BP and sale of ARCO Alaska assets to Phillips Petroleum in 2000, the two operating areas were consolidated and BP became the sole operator of the field. In 1974 the State of Alaska's Division of Geological & Geophysical Surveys estimated that the field held 10 billion barrels (1.6×10^9 m3) of oil and 26 trillion cubic feet (740×10^9 m3) of natural gas. Production did not begin until June 20, 1977 when the Alaska Pipeline was completed.

Following our San Francisco meeting with Sohio-BP, I flew to Anchorage and on to Prudhoe Bay. I should mention that BP at the time had partnered with Standard Oil of Ohio, an arrangement necessary for BP to circumvent currency laws of the UK at the time whereby there were strict limitations on the amount of capital that British companies could remove from the country. So our client was Sohio-BP, even though the people we dealt with were BP employees.

Prudhoe Bay was in a stage of infrastructure development, and large production modules pre-fabricated in the lower 48 states were being shipped by barge to the North Slope of Alaska (Prudhoe Bay).

Figure 13 Barge with Modules

The barges were 400 ft long with a 100 ft beam and 25 ft draft. A typical barge loaded with modules is shown in Figure 13. Figure 14 shows loaded barges at West Dock in 1976.

Figure 14 Sealift 1976

From “Tours of Arctic Alaska” - Photo donated by Bev Bullcook

The voyage from the west US coast to Prudhoe Bay was through the Bering Strait and then east into the Chukchi and Beaufort Seas (Figure 15). The Polar ice pack is often close to the Alaskan coast, much closer than it is to the Canadian coast of the Beaufort Sea, especially the Mackenzie Delta region. This is seen in Figure 16. Thus, once the barges left Wainwright and approached Barrow, they were vulnerable to blockage by pack ice, which could be quite thick even in late summer. This occasionally caused delays in arrival of the barges and the modules at West Dock.

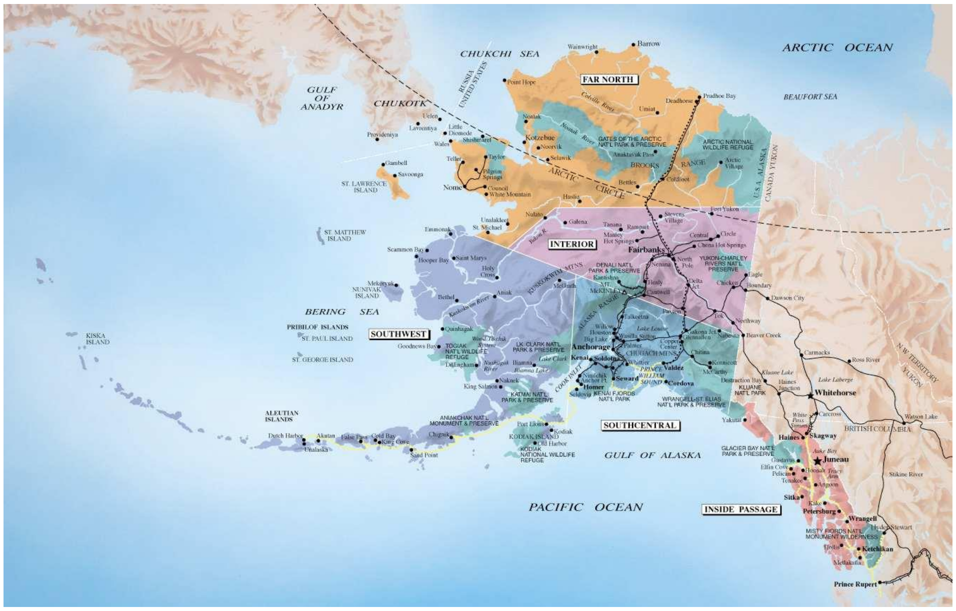

Figure 15 Alaska Map

Figure 16 1975 summer ice conditions in Bering Strait, North Slope Alaska, and Canadian Beaufort Sea. Note blockage of coastal route around Pt Barrow.

In the summer of 1975 a “pinch” occurred and the barges had to wait it out at Wainwright. By the time they rounded Barrow and reached Prudhoe Bay, it was fall and the first-year sea ice had started to form. They could only get to within about one mile of the end of West Dock as it ended then. ARCO (Atlantic Richfield Company) and BP had barges and modules stuck in the ocean and no apparent way to get the modules to shore. The pace of construction demanded that the modules get to shore that year. BP was interested to know if the modules could be unloaded over the ice by first flooding and grounding it. My calculations indicated it was possible using ice platform flooding techniques IF the seabed material was stiff enough to support the ice and keep the bending stresses within acceptable limits. We also needed the first-year ice thickness or we would never reach the bottom.

I went to site and was met by Jeff Stoner of BP. He was to drive me to West Dock as I would never make it alone. Pipelining and construction activity were proceeding at a furious pace and the main road (called the spine road) and its offshoots were often plugged with large 1000-ton modules being moved on crawlers or by large drills drilling holes in the permafrost for vertical support members (VSM) to support the gathering lines leading to pump station one (PS-1) at the head of the Trans-Alaska Pipeline System (TAPS). Jeff had to phone ahead to see which routes might be open. We would try one and wiggle our way around the equipment, or else he would have to try another. Under normal circumstances one could fly to Deadhorse, the Prudhoe airport and main operations centre, rent a pickup and drive to your location. ARCO and BP had check points with guards but they could easily be passed with a valid driver's licence, even an Alberta licence.

I got to the site and drilled a profile of ice thickness holes from the end of West Dock out to the barges. The ice was about 5 ft. thick and thus we had to build about 10 to 15 additional ft. to ground the ice. I then needed to determine the strength and stiffness properties of the underlying soil. I had no proper soils testing or sampling equipment, so BP got me a piece of steel pipe about 1.5 inches diameter and long enough to reach seabed and to penetrate it. I lowered the pipe to seabed through holes drilled in the ice and then drove it about 1.5 to 2 ft. into the bottom. The pipe was then retrieved and the soil stuck inside the pipe was extruded. I then flew to Anchorage where I met with Harding and Lawson who took the samples and did basic water content, density and shear strength tests. FENCO was also able to determine the soil subgrade modulus from the driving history I had recorded. The bottom was stiff enough to support the ice, certainly orders of magnitude stiffer than a water base. We reported to BP that it would be feasible to bring their modules off over grounded ice.

An engineer from ARCO phoned me and objected to our recommendation to BP. He said the modules were not designed to travel in the cold over ice. I replied that I had just returned from Prudhoe and that there were many modules moving over the gravel roads in temperatures which were at least – 20 F or – 25 C. Since they were mounted on crawlers I could not see what difference moving over the ice would make. And in subsequent years we moved both modules and heavy drill rig components over the ice with no problem. Our recommendation stood. BP was our client and we had made a recommendation based on sound engineering and past experience. Remember that by this time Panarctic was landing Hercules C-130 aircraft on the ice and hauling large rig components to floating ice platforms much further offshore.

Then I received a phone call from BP's purchasing agent in San Francisco saying to stop all work, the project was over. I learned later that West Dock was extended out to the grounded barges, a gravel extension. BP's share of the cost was very likely calibrated to the cost of a grounded ice road, certainly much less than paying for half of a gravel extension.

Frozen gravel is plentiful on Alaska's north slope. The rivers flowing from the Brook's Range mountains are fast flowing and seasonal, very much in contrast to the Mackenzie River in Canada. The Mackenzie is a large, slow flowing river and carries a heavy silt load which it deposits offshore in the Beaufort Sea. Good gravel sources are rare on much of the Canadian side and the seabed is soft in many places. Gravel was used to construct roads on the Alaska North Slope and the spine road runs 30 miles from Deadhorse to the west field. It is 5 ft. thick to prevent the permafrost from thawing in summer. Pads were built to support production equipment and operations. Many millions of cubic yards of gravel were hauled to develop this large oilfield.

BP had just built a new operations centre and living quarters. It was (and still is) a beautiful facility complete with swimming pool, tennis court, running track etc. It was commonly called the BP Hilton. I was billeted in Construction Camp 1 (CC1), the first camp of a string along the TAPS pipeline. It was more conventional but was still very nice. The rooms were large and well-appointed and single occupancy, something I was not used to in the Canadian Arctic. I walked into the large mess, in mid-afternoon, and I could have prime rib, freshly cooked, to any taste, raw to well done. There was plenty of other food stuff, including a wide assortment of desserts.

Circling the building complex were at least fifty full crew cab pickup trucks. Their engines were all shut off and their block heaters were plugged into 110-volt electricity. I was used to the rule that if you used an internal combustion engine in the winter in the Arctic you never shut it off because you could not start it again. It was very cold at Prudhoe, but these pickups could be silent due to the electric plug-ins which hung from a "bull rail", a series of vertical posts with cross members between them. Camps and facilities in most of the Canadian Arctic could not supply enough electricity to power such an undertaking. But Prudhoe was a large, permanent, producing oilfield and thus generated sufficient cash to fund such infrastructure. I must have been like Dick Wittington on his first visit to London, except in this case at Prudhoe, the streets really were "paved with gold".

Construction Camp 1 was a big edifice, not a mobile trailer camp as I had been used to. So I slept well Saturday night even though Sunday morning there was ample evidence there had been lots of partying and boozing going on, especially in the bathrooms. There were also church services in different areas of the camp being led by preachers of one sort or another. Was repentance taking place?

It was common knowledge that there was so much equipment at Prudhoe and on the TAPS right-of-way that trucks and Cats would turn up in the lower 48 in the possession of whomever. The construction camps originally had ringer washing machines and the union employees threw them out in the snow and demanded automatic machines. A German Canadian filled me in on some of the more interesting happenings.

11. POAC '75

The preceding summer, Hans Kivisild and I had attended a conference in Fairbanks: - Port and Ocean Engineering Under Arctic Conditions (POAC'75). Ginny and I flew to Anchorage and then on to Fairbanks from Edmonton. On arriving in Anchorage, we were confronted by an armed guard sitting on an elevated chair, holding a shotgun. He had a pistol on his belt and I spotted another weapon stuck into the top of one boot. Such was the volume of pipeline workers and rig roughnecks that things apparently got rough and such caution was required. In Fairbanks we were greeted by Dr. Bill Sackinger of the University of Alaska at Fairbanks (UAF). We were billeted in the university residence which was comfortable enough and were treated very well. Bill was in very good spirits. There was a reception the first evening and there were tables piled high with Alaska king crab, smoked salmon and shrimp. We had never seen so much crab in one place at one time. There was also plenty of beer and wine to drink.

During the days there, we of course attended presentations and Hans gave one on our insitu ice testing methods. We also toured downtown Fairbanks and found that there were two or three prostitutes on most street corners and a pimp to watch over them. The prostitutes were forward and accosted the men eagerly. I walked with Ginny so was not bothered. Soon we had a group of men walking with us so that the prostitutes left them alone. Hotel rooms were at a premium and men were being charged exorbitant fees to sleep in the hallways.

Hans and I attended an invited talk one evening delivered by Douglas Fairbanks Jr. His topic was shipment of North Slope natural gas to market, and he was adamant that any pipeline should not go through Canada. Pierre Trudeau was prime minister at the time and his relationship with the US was not always smooth. Bill Sackinger asked us if we were offended by this talk. Frankly, we were not. But we would have enjoyed any work emanating from the construction of a pipeline through Alaska and Canada to the lower 48. I did work on such a project in the early 1980's, the Alaska Gas Pipeline.

During the conference, Bill made an announcement to the attendees that the sealift to Prudhoe Bay had been delayed at Wainwright due to heavy pack ice at Barrow. It was unlikely that the barges would make it to West Dock before freeze-up. And they didn't, as we have previously discussed. Our attendance at the 3rd POAC conference had given us a heads up on future developments.

12. Sohio and North Slope Ice Roads

In 1978 Richard Goff and Bob Potter of Sohio-BP contacted me and asked if we could assist with an ice road with a dual purpose. A three-mile section of the floating portion of the ice road would be used to haul gravel from shore to an island construction site called Niakuk 3 where an exploration well was to be drilled. The remaining section, about 6 miles in length, carried on to a barrier island called Reindeer Island. This section of the road was definitely floating, and drilling rig components were to be hauled over so that drilling of an exploration well could be carried out on that natural island. The traffic on the first three miles of road was heavy, and we later recorded heavily loaded gravel trucks (168 tonnes or 300,000 lbs.) passing a given point every three minutes. A 320 tonnes (700,000 lbs.) rig load, including the substructure and draw works and tower, was moved from the island to shore at the end of drilling. This was the largest recorded load transported over a floating ice road.

The road entered onto the sea ice on the east side of Prudhoe Bay, a distance of several miles from West Dock which was discussed earlier. Once the design was complete, various North Slope contractors were engaged to perform the flooding. Crowley All Terrain Company (CATCO) was the prime contractor since they owned and operated the Rolligons, large balloon tired vehicles which were initially developed by Bechtel Corporation, originally for use in Saudi Arabia, and were used extensively to haul drilling rigs, fuel and other supplies (Figure 17).

Figure 17 Large Rolligon

The large low-pressure tires of the Rolligon made them effective on soft terrain and vulnerable permafrost and offshore they would float if they broke through the ice. Pumps were mounted on the Rolligons, and on other tracked vehicles of various types, and flooding of the road began. The pumps employed were low pressure centrifugal suction pumps. A hose was used to access water through a hole drilled through the ice. The suction side of these pumps was very susceptible to freezing and they proved to be ineffective for road building. Archimedes auger pumps were commonly used in Canada for this type of work and were far more reliable. CATCO (Bill Kuper) asked for information on how this worked and I gave Bill a sketch.

Figure 18 “Baby” Rolligon with Drilling Auger and Auger Pump

CATCO was quick to pick up on this method and the following summer they had “baby Rolligons” outfitted with a drill and auger pump, as shown in Figure 18. This system worked very well for road construction and was used for years after. In the Canadian Arctic flooding in the Mackenzie Delta had been achieved for Imperial Oil by simply drilling a hole through the ice and then turning the drill auger in the hole, thus upwelling water onto the ice surface. Panarctic’s contractor built auger units which were hydraulically powered for flooding. Such a unit is shown pumping water in Figure 7. A few of these units were also purchased by CATCO for use on the Alaska North Slope but the Rolligons were the preferred choice long term.

Following the successful Reindeer Island ice road, flooded ice roads in the nearshore region of the North Slope became common to achieve the ice thickness required for gravel and rig hauling. Other operators, such as Shell and Exxon were quick to utilize the method. Other engineering companies were also quick to use the floating ice road design methods now established and proven.

13. National Research Council of Canada(NRC)

It seems appropriate at this point to mention the support and expertise of NRC in reviewing, vetting and permitting floating ice structures such as the Panarctic ice platforms and various ice roads. The support of Lorne Gold and Bob Frederking was necessary for satisfying objections to the design principles and associated assumptions. In 1974 NRC people came to the Hecla N-52 site to verify and assist with establishing the strength of the ice forming the floating platform. They even provided instrumentation in the form of river stage recorders which were very useful in continuous monitoring of ice freeboard and tidal motion. They had no direct involvement in the Alaska ice roads, but did organize ice road workshops where we were able to publish our work in the resulting proceedings and to discuss design and construction methods with people who were also involved with ice roads in other locations. Eventually NRC would support the inclusion of this knowledge in Arctic codes such as the CSA Offshore Structures code, the ISO Offshore Structures standard and the API Arctic standard. Over the past 40 years this group, initially under the Division of Building Research, has been a constant technical presence and source of support.

14. Exploration Using Grounded Ice Islands

Exploration for oil and gas in the shallower waters of the Beaufort Sea had been supported using dredged islands in the Canadian side and hauled gravel islands on the Alaska side. The Mackenzie River sediments are very extensive on the Canadian side while there is no gravel close to shore. Any available gravel is located quite far from shore and is limited in supply. Thus the operators on the Canadian side opted to contract foreign dredges from the Netherlands to dredge sand to form islands. Imperial Oil was the first major user of this methodology. Sun Oil drilled early wells using hauled gravel islands as Imperial had done. On the Alaska side Sohio was an early user of gravel islands, followed by ARCO and Shell. All of the earth islands were in water depths of about 6 m maximum except for Issungnak in Canada at a water depth of 18.6 m and Mukluk in Alaska at a water depth of 14.6 m.

The use of hauled gravel and dredged islands was very much limited to shallower water depths since the volumes of material required to build them increases as the cube of the water depth. So an earth island in 10 m or water vs. one in 1 m of water requires 1000 times the amount of material. Methods of circumventing this were devised by terminating the earth fill berm below water and using a concrete or steel structure to penetrate the water surface. Thus Dome/Gulf drilled a well called Tarsuit in 20 m water depth. Four concrete caissons were placed on a submerged berm then the middle of the caissons filled with sand to form the drilling support surface and provide resistance against ice loads. Gulf drilled several wells at greater water depths (27 m) by placing a steel structure called Molikpaq on a submerged sand berm. The Molikpaq was floated to the well site, and set down onto the berm by flooding its tanks with water. The inside of the Molikpaq was filled with 150,000 tons of sand to resist the ice loads. When the well was completed, the Molikpaq's tanks were emptied and the caisson floated to a new location. Dome did something similar using a converted super tanker called the Single Steel Drilling Caisson (SSDC). This vessel was floated over a berm and set down by filling the vessel with water. On completion of the well, the water was removed and the SSDC towed to a new location. Dome subsequently constructed a large "Mat" that was attached to the base of the SSDC, so that it could drill in deeper water depths without the need of a costly sand berm. Imperial Oil also developed a Caisson Retained Island (CRI) system to drill from submerged berms. This was a circle of steel caissons that was set down onto a berm and filled inside with sand to resist the ice loads and as a surface for the drilling operations. On completion of the well, the circle of caissons was separated at one point and towed in a line to a new location. At the new location, the caissons were reconnected to form a circle, cables were post tensioned to make the circle of caissons rigid, and then the caissons were set down on a new berm.

With all of these accomplishments, there were two issues that remained key in the use of the technology. One was the cost of the installations and the other was the environmental issue. Hauled and dredged islands and berms required the excavation and dumping of large quantities of material which remained long after the exploratory well had been plugged and abandoned. There were, and are, environmental and navigation concerns about this residue, although the islands and berms were constructed of naturally occurring material from the local area. The costs were relatively high compared to the costs Panarctic was incurring with its ice platform wells.

In 1977 Union Oil of California drilled an offshore shallow water well in Alaska in 3 m of water using grounded ice as the drilling base. The natural ice was flooded until it grounded, and the well was drilled from the ice surface. In 1978 Exxon conducted experiments in ice building off the east dock near BP's Niakuk 3 wellsite. They first tried a standard field irrigation system with all of the piping and nozzles. This proved to be unworkable and unmanageable in the cold Arctic environment. As a plan B they brought in a large 200 psi pump from Anchorage, fitted a fire nozzle to it and sprayed water onto the test island. This worked and they built a lot of ice quickly - more than 1 m per day. The pump had no flow lines exposed to the cold temperatures, except the discharge nozzle and this did not freeze, because of the pressure. We had learned years earlier that intake lines with their suction were vulnerable and that is where freezing occurred.

The following year Exxon decided to build another test island using a large spray pump, and they wanted to set up a joint venture where Sohio-BP would pay part of the cost. Sohio-BP were cautious about joining, fearing that the test would cost millions and possible prove little. I had switched companies and was with Geotech by this time. Bob Potter of Sohio-BP gave me a copy of Exxon's project report from the first test island and asked me to review it. Clearly from the records the spraying worked and produced substantial vertical and lateral build-up of ice, i.e. it froze lots of good ice in a hurry.

I compared the spraying to theory from carburation of fuels in an engine. By forcing a fluid through an orifice, it was atomized and re-formed from a continuous stream of water into a mixture of water droplets and air. The drops were necessary for ignition of fuel in an engine cylinder and were very helpful in accelerating the freezing rate of water. I recommended that Sohio-BP participate.

Sohio and Partners constructed two experimental spray ice islands in the winters of 1983-1984 and 1984-1985. Construction technique, spray technology, and design concerns with limitations were investigated thoroughly.

During the winter of 1983-1984, Sohio constructed a test grounded ice island in 41 ft. (12.5m) of water in the Canadian Beaufort Sea. A "rubble generator" was towed to a site north of McKinley Bay in October of 1983. Rubble, or mounds of broken ice, form when an ice sheet moves against an immovable obstacle, causing it to principally break in flexure, and to pile and ground out around the structure. The thin, new ice of the Beaufort Sea is normally highly mobile in early winter and thus large amounts of grounded ice rubble can be generated. Spraying on top of this rubble serves to surcharge it thus giving the rubble stability against horizontal ice forces. As well, the spraying cements the top portion of the loose rubble, making it less likely that the ice structure formed will be eroded by ice motion.

The bow from Dome Petroleum's SSDC was chosen as the rubble generator with some modifications. It was equipped with a platform and two fire monitors powered by 100 hp (75 kW) pumps to spray sea water into the air and form the spray ice. The original objective was to construct an ice structure by first generating rubble and then by spraying to consolidate this rubble. The ice did not move as was anticipated because of an early freeze-up, resulting in negligible rubble. Thus the island was constructed by spraying alone.

The below water portion of the ice structure was constructed from December 03, 1983 to January 17,1984, and the above water portion of the island was constructed in 5 days (January 19-24, 1984) using the icebreaker Kigoriak which had a large water cannon mounted on its deck. This pump operated at the same pressure as the 100 hp (75 kW) pumps and had approximately 7 times the capacity.

The main emphasis of the following 1985 test was to measure in situ strength characteristics of the spray ice with close attention to the submerged saturated spray ice below the sea level. The experimental island constructed was located approximately 12 mi (19km) offshore Prudhoe Bay, beyond the barrier islands in 30 ft. (9 m) water depth. The diameter was 350 ft. (107 m), and it was principally constructed using two large pumps with each being mounted on a skid with its driver, fuel tank, generator, controls and spray monitor. The skid was then enclosed to protect the equipment and personnel from the cold and wind-blown spray ice, and each pump at the discharge was equipped with a monitor and a nozzle to form the water spray. The pumps had a pump rate of 3600 gpm (14400 l/min) and 1000 gpm (4000 l/min) and were both diesel driven. Being mounted on skids, they were easily moved from location to location depending on the wind direction so that total coverage of the island with spray ice was repeatedly achieved on a regular basis. At each location the monitors directed the spray from side to side and also controlled the angle of elevation.

Several different nozzles were used to determine their effectiveness under differing conditions. It was found that a nozzle producing a wide spray pattern was not as effective as that producing a straight stream as it was much more sensitive to prevailing wind disturbance. An effect was observed at wind speeds as low as 10 km/hr, and at 20 km/hr the effect became very significant. With wind variations, it was found necessary to continually move the pumps around the island periphery so as to maintain a steady spraying operation by keeping the pumps upwind of the area to be sprayed. Spraying was periodically halted to allow consolidation and freezing. It was found that one hour of spraying followed by two hours of consolidation and freezing was the optimum pattern for achieving maximum build-up of good quality spray ice.

During construction a survey grid was set up to record ice thickness build-up by securing tubes into the sea ice and extending them as build-up occurred. Three thermistor strings recorded the temperature profile to seabed, and thin wall flat jacks were installed both vertically and horizontally. The vertical flat jacks were later pressurized with fluid and pressure versus volume change data were obtained. The horizontal flat jacks measured vertical deformations.

The main testing program was performed after the island was completed and comprised of cone penetration tests at fifteen locations, several borehole pressure-meter tests in three holes, the collection of samples from the three boreholes for laboratory testing, and the installation of slope indicators to record horizontal movement with Sondex tubes to record settlement of the island.

The samples were tested triaxially in a temperature controlled laboratory under differing confining pressures both drained and undrained. The saturated ice, being very sensitive to temperature change, was tested at the North Slope to minimize temperature and sample disturbance. The island was also probed to seabed extensively to check seabed contact. Also, all surface settlement, movement and temperatures were recorded regularly until the island melted in July.

The tests positively concluded that islands made from spray ice in water depths up to about 40 ft. (12m) in the Beaufort Sea were, and are, practical for exploration drilling, and likely could be extended to deeper water with improved technology and proper conditions. Construction and drilling must occur during the winter season as the island melts during the following summer. The ice islands definitely are a seasonal exploratory tool and not meant for year-round production.

Spray Ice Island Wells

Amoco MARS (1986)

Amoco Petroleum was a partner with Sohio in the second test island at Prudhoe Bay. At the end of the project, Amoco announced that they intended to use the spray ice technology the following year to drill a well on the North Slope.

Before proceeding to a description of this project and others following, I need to relay some of the people aspects of ice islands and their test programs. In the mid 1980’s the oil patch was slowing down and people employed therein were seeking a soft landing so to speak. Also, the concept of building exploratory islands out of a cheap commodity like sprayed sea water had an appeal. Whether they had built anything out of ice before and put a load on it or not, lots of people became experts in designing, testing and building ice structures. “Ice is nice” as one engineer at Gulf Canada put it, a marked departure from the attitude that it was a nuisance material menacing offshore structures and ships. Spraying added a dimension of excitement and interest in how such an operation could be conducted and recorded. The resulting material bore semblance to many geotechnical materials. Was it a purely frictional material, cohesive or Mohr-Coulomb? It certainly exhibited few of the characteristics of natural sea ice, especially below the waterline. It was very porous as shown by falling head permeability tests. The ice below waterline was in full communication with the sea and a hole drilled to seabed filled with water to the ocean waterline with no delay. And what was this spraying about and why did you need 200 psi pumps rather than the usual 50 psi? What nozzles were the best, how long between spray applications, what did you do about wind etc.? Needless to say, there were many ideas and theories, and all had to be tried.

Comparisons to snow making were rampant, even though that procedure had virtually nothing to do with spray ice. We could not place an oil drilling rig on ski slope snow. The strength and stiffness or creep (time dependent deformation) properties were most unsuitable. Since atomization and drop formation and size were important, it quickly became apparent to me that surfactants (soap), which reduced surface tension and thus drop size, would be of advantage. But could we convince the environmental regulators to permit such activity? All of these considerations and the attendant excitement caused one construction supervisor to coin the phrase "scientesticals". Contractors saw money in owning the equipment and building islands, engineers saw projects which applied standard technology in somewhat different ways and thus an edge on getting projects to design and then quality control. Scientists saw opportunity to be the first to test a unique material and to publish the results. Ideas on spray nozzle configuration and shape, angle of the nozzle to vertical, horizontal sweep angle, optimum drop size and of course the right strength envelope describing and quantifying the resulting material were everywhere and profuse. Exxon patented the spray ice island concept, apparently more as a defence measure than out of the belief that they could make a lot of money out of the concept or its practice.

My little group, used to building ice platforms and roads, was swamped with over lookers and second guessers. And experienced construction workers were supervised and directed as never before. It may have been understandable in the advent of a new application of an old technology but it was surprising and at times unnerving.

Against this background Amoco announced the MARS well. It was most gratifying to have a major company use the spray island technology for their exploration on the west side of the North Slope of Alaska. Over the summer plans were made for the winter construction with the design and building of 5000 gpm, 200 psi skid mounted units driven by 600 hp Cat diesel engines. The pumps were designed by a US company and manufactured in Germany. They had to be built as there was not a lot of demand for such high capacity pumps working at such a high discharge pressure. We at Geotech figured that the total skid weight should be around 45,000 lbs. which would allow the contractor CATCO to start construction when the ice reached a thickness of around 30 inches. The frame of the skids was constructed of low temperature steel flown in from the UK, an unnecessary measure as nobody in the Arctic built steel skids of low temperature steel. The skids were constructed in Houston and wound up weighing 80,000 lbs. each. Thus about 40 inches of ice was required to take them to site and once there they frequently broke through the recently deposited spray ice and nearly tipped over.

Once the core of the ice island was grounded, holes were established around the perimeter on floating ice from which water could be pumped. The large pumps were then capable of reaching the centre of the island which was about 300 m in diameter.

Figure 19 Spraying Ice at MARS on left and Completed Island on right

We at Geotech had designed the pumping system and had designed the island dimensions for stability against lateral ice forces, using accepted Alaska pressures and loads. However, during the design approval process, Amoco decided to award the final design and approval negotiations to EBA engineering. We were allowed to attend meetings, but the final design report was issued by EBA. In addition, the QC/QA during construction and commissioning of the island was awarded to Golder Engineering and we were asked to leave the site. We had worked hard to develop this technology and now we were being excluded. It was not a pleasant experience. We had designed ice structures for Sohio and for Panarctic and had good experience with what was required. For instance, the moonpool design by EBA consisted of a timber box constructed of heavy 8 in. x 8 in. cross section timbers. The finished structure was extremely heavy and most difficult to install. Thinner 4 inch thick timber would have sufficed and offered ample safety against any later ice pressures. We had advised installation of thermistors and cooling tubes at the moonpool since it was well known that melting would occur. These were refused. Later I received a call during drilling of the well that CATCO had drilled ice thickness holes and had found no ice underneath the rig below waterline. Drilling activity had melted it all and the ice above waterline had formed an arch bridge to transfer the vertical rig loads laterally to the non-melted surrounding ice. Not an ideal situation. The well was finished on schedule without further incident but there was good opportunity for a failure in bearing capacity. The extra heavy timbers of the moonpool offered no advantage or assistance in this case as they were sitting in water with no ice lateral pressures to resist.

Esso Angasak (1987)

Imperial Oil Ltd (IOL) in Canada decided the following winter to drill an exploratory well from an ice island with its partners. The well was in 5.4 m water depth. IOL asked Geotech to contribute expertise to the well and one or two of our people were at site. Geotech also built four 200 psi, 3000 gpm pump skids for the construction. These units weighed about 12,000 lbs and could be mobilized on about 15 to 20 inches of ice thickness and they did not break through the spray ice crust. The original pumps were cooled with sea water and had no radiators. This proved to not be a practical and workable solution for spraying sea water in the Arctic and subsequently the pumps were modified to include radiators. The engines were Detroit Diesel and the pumps were Worthington, US pumps built in Germany.

Chevron Karluk (1989)

Chevron decided to drill an exploratory well in 6.4 m water depth at Prudhoe Bay Alaska in 1988. CATCO and Geotech had formed a joint venture to offer design and construction of spray ice islands as a fixed price package. CATCO owned the equipment and Geotech provided the engineering. Steve Pederson of Crowley, owner of CATCO, and Arne Matiisen of Geotech were instrumental in establishing and marketing of this JV. We had interesting sales trips to Houston, New Orleans and California to explore potential projects. These were years when oil prices had hit $10 per bbl. and it was difficult to find enthusiasm for exploratory drilling. However, Chevron did want to determine if the Karluk location had potential or not. If not then they could walk away from the lease but if it held promise, then there would be intense negotiations with the North Slope Borough and the Alaska Whaling Commission, a powerful group which had stood off the global effort to stop all whaling years earlier since the local people depended on whaling for food.

This was the year that Geotech's Arctic engineering group was sold to Sandwell Engineering (called Sandwell Swan Wooster at the time). So we moved from a small start-up company to a relatively large engineering company. Swan Wooster had designed the Esso CRI, the Tarsuit concrete caissons and the Gulf Molikpaq structure so we fit nicely into their structure. I reported to John Bruce who had been the principal engineer on the projects.

Chevron agreed to negotiate an island with the JV, which we named I.C.E. for Ice Construction and Engineering and which Bill Kuper of CATCO nicknamed Instant Cash Erosion. We finally negotiated a contract with Chevron and the island was permitted with the Alaska State Government and with the federal Minerals Management Service, a part of the US Department of the Interior. MMS (now called BOEM or Bureau of Offshore Energy Management) took a keen interest in the project and were most cooperative during the design review and permitting. The island lay partly in Alaska State waters and partly in federal waters, thus the joint jurisdiction.

By this time CATCO had cut away a lot of the surplus steel in the MARS skids and their weight was reduced to around 50,000 lbs. Also, the pumps were changed from a submersible pump to Worthington 200 psi suction centrifugal pumps. The suction end had always been a problem for freezing but this was overcome by covering the suction pipe with an insulated box. The suction pipe was adjacent to the main pump skid and thus quite short, making this a relatively easy task to accomplish. Thus the pump skids were much more manageable and could be transported on about 32 inches of floating ice. This made a big difference to timing and project schedule. Also, they were far less likely to break through the spray ice crust while work proceeded on the island construction.

The main conclusions drawn from Karluk are listed below (Masterson et al, 1990)

1. *Construction of the island was completed on schedule in a safe and efficient manner.*
2. *Island design and construction costs were within budget.*
3. *Two pumps were modified to reduce their weight to less than one half the original. These units were easier to move around the island and construction efficiency was increased.*
4. *Verification testing after construction revealed that the island met or exceeded all design specifications*
5. *Instrumentation for monitoring the horizontal and vertical movement of the island during drilling was successfully installed. There was no excessive movement.*
6. *Cooled brine was circulated in the annulus between the conductor pipe and the surface casing to maintain ice integrity.*
7. *Placing the rig on mats underlain by insulation, along with good practice with heat and water on the rig floor, prevented ice melting under the rig.*
8. *Monitoring during drilling showed that the island performance met or exceeded design requirements.*

Esso Nipterk P-32 (1989)

In 1989 Imperial Oil or Esso decided to use a spray ice island to drill an exploratory well in 6.6 m water depth. Geotech was contracted to build two more 200 psi, 3000 gpm pump units for this project. This time the units had radiators for cooling instead of sea water cooling, and they worked. These units had the same engines but were better constructed, being more powerful and more reliable. Also, these units had automated swivels for horizontal control of the nozzle sweep, eliminating the need for a full-time operator stationed in the pump unit.

The seabed at Nipterk had a soft surficial layer of sediment which was several meters thick. There was much concern during the design of the island whether this layer would have sufficient shear strength to resist the horizontal ice loads expected. However, Esso's experience with past dredged islands had shown that the soft layer was compressed and/or displaced during construction with the result that the shear strength at the ice/soil interface was adequate for the development of the required lateral resistance. The principle design, end of construction (EOC) and actual island parameters are listed in Table 1, taken from Weaver and Poplin, 1987.

Table 1   Nipterk Technical Summary (Weaver and Poplin, 1997)

Parameter	Design assumption	EOC verification	Actual Performance
Grounded diameter (m)	360	320	—
Freeboard (m)	2.5 to 4	3.73 to 4.15	—
Above-water unit weight (kN/m^3)	7	5.8	—
Underwater unit weight (kN/m^3)	-1.0	-0.9	—
Min. soil strength (kPa)	5	12	8
Adhesion factor (kN/m^3)	0.85	0.95	—
Max. ice load (MN/m)	0.76	1.58	1.53
Creep settlement rate (m/month)	0.14	< 0.14	0.05

The island performed well and the exploratory well was drilled successfully.

Pioneer Natural Resources (Ivik , Natchiq, Oooguruk - 2003)

The introduction to a paper by Masterson et al, 2004 states the following regarding this project.

Pioneer Natural Resources drilled three exploratory oil wells from grounded ice islands during the winter of 2003 in 3m (10 ft.) of water in Harrison Bay Alaska, located west of Prudhoe Bay in the southern Beaufort Sea. The islands were built using sprayed ice for the main bulk of the material and were finished using ice chips mined from the local near shore sea ice. As well, 32 km (20 miles) of grounded ice road was constructed using ice chips. The road was used to transport two drilling rigs to the islands, one rig weighing 680 tonnes (1,500,000 lbs.) and the other 1140 tonnes (2,500,000 lbs.). Drilling from the first island started in mid-February 2003 and all drilling was completed by end March 2003. Ice build-up rates, chip haul rates, ice strength and density and seabed subgrade modulus were measured to substantiate the engineering assumptions made during design of the islands and roads. The ice islands and surrounding pack ice were monitored for movement during drilling using DGPS. Vertical settlement of the islands was also monitored. Extensive monitoring of the rig moves over the ice roads was conducted, where minor breakthroughs were encountered for the heavier rig.

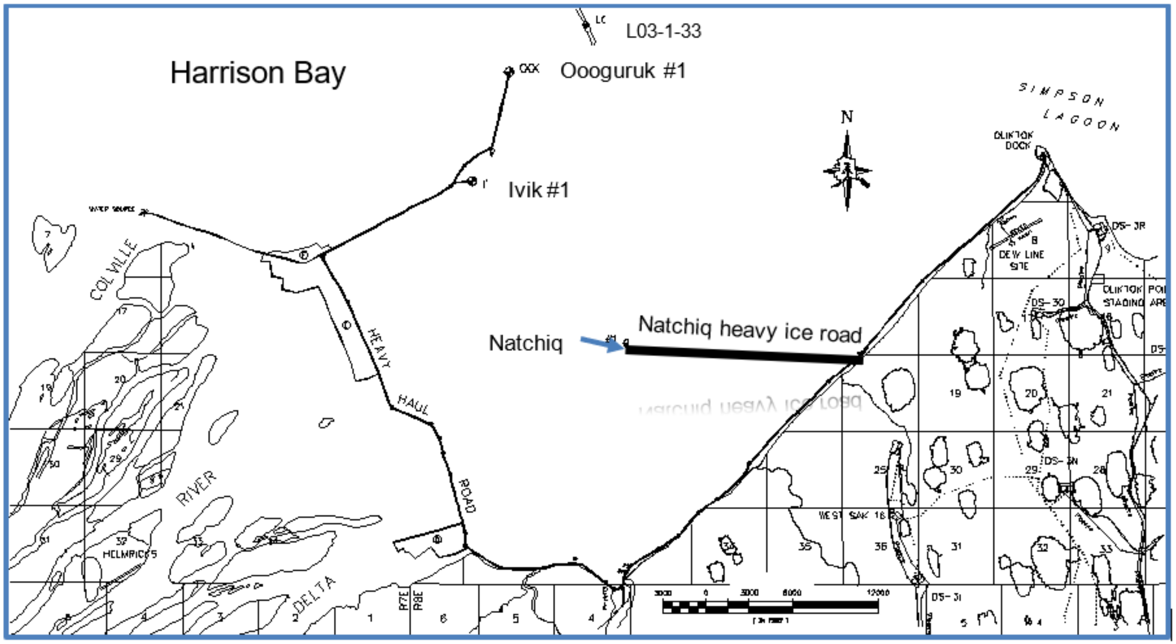

Figure 20 Location of Pioneer Wells

15. Pond Inlet Iceberg Tests

Background and Business Issues

The most significant and difficult work that GEOTECH successfully undertook was the execution of the Medium Scale ice crushing strength tests at Pond Inlet NWT in 1984 (Masterson et al, 1992). But before launching into a technical description of this project, some background is necessary. First, who was this GEOTECH? Geotech's original name was ttiGeotechnical Resources Ltd., a company started in Calgary by Terra Tek, Inc. of Salt Lake City Utah. Terra Tek was(is?) a high-tech company who performed sophisticated rock testing for the Nevada Nuclear test site. The blasts of the tests subjected the rock to extremely high temperatures and pressures, and Terra Tek's sophisticated lab in Salt Lake was equipped to provide meaningful rock properties at these conditions. The temperatures and pressures to which the rock was subjected took the rock well beyond its elastic limits and even beyond its normal plastic limits. The rock became similar to molten steel at temperatures of several thousand degrees Fahrenheit. In order to perform sensible analysis of the rock under these conditions, reliable physical properties were required. Terra Tek was able to achieve the required results.

From this initial requirement, Terra Tek was able to perform insitu and laboratory tests on rock which were of interest to the oil and gas industry. One of their major achievements was the successful measurement of rock stress using oilfield packers and applying pressure to the rock in the "packed off" region until the rock fractured. The oil industry knew that rock formations they encountered in their reservoirs contained stresses far exceeding the stress due to the rock overburden. This stress affected their "fracking" of reservoirs, a practice common in the business to increase the flow of product from the reservoir to the well bore. The market for this kind of expertise and measurement was potentially strong in Canada, and thus Terra Tek set up GEOTECH. The "tti" prefix was meant to signify Terra Tek International. A modest operation was established in Calgary in about 1980. Initial staff were recent Ph.D. graduates William F. Bawden and Brian Conlin.

Around this time, Sid Green and Jim Strain of Dome Petroleum, put together a deal whereby Dome would own 40 percent of GEOTECH and would in turn derive benefits at relatively low cost from GEOTECH's and Terra Tek's research. Besides the rock mechanics and related core analysis, Sid was interested in expanding into Arctic engineering. In 1980/81, I was looking to change employers. I had been offered positions by oil and gas companies but did not see this as the best option at the time. I had known Jim Strain when he was vice president of operations at Panarctic. We had a mutual respect for each other and I became acquainted with Terra Tek and GEOTECH. Finally, an offer was made and I accepted. I liked the look of Terra Tek and their approach to geotechnical and rock engineering. My Ph.D. background in concrete structures enabled me to appreciate where they were coming from. I also enjoyed working with Will Bawden who had a strong geotechnical and rock mechanics background.

The work I was doing for Panarctic and Sohio/BP and other companies interested them, and I went to work for GEOTECH in 1981.

I was immediately thrust into a world of management and finance, dealing with a board of directors etc. Engineering, or geotechnical engineering, was a key part of the picture but many things were added on. Sales, client relations and new and continuing business had always been important, but now they and the “bottom line” were paramount. I was criticized for being too involved in the technical details and not taking a more detached and business-like view of the projects we did. It was especially important to look long range and to anticipate business trends as best possible.

This task was made infinitely more complex and difficult with Dome as a significant owner. Dome had its own Arctic group, Canadian Marine Drilling Limited, CANMAR, of which I was well aware. We had worked on projects for years, not always with great satisfaction for either party. I had good friends and former employees in CANMAR and respected their abilities. CANMAR was not easy to work for or with and had an aggressive, superior attitude which could and did make for tense relationships. Once I joined GEOTECH the tension increased considerably as we were competitors within the same envelope. I knew from my consulting experience that this situation was often counter-productive and could lead to the ruination of one or both of the parties involved. In this case one competitor owned the other and it was clear who would be ruined first. It was a tough go.

Discussions Leading to Ice Strength Tests at Pond Inlet

With this ongoing situation in mind, I will describe the beginning and evolution of the Pond Inlet Ice Crushing tests conducted at Pond Inlet NWT Canada in the spring of 1984. Mobil Oil was leader of the Hibernia Design and Management Group designing production facilities for the Hibernia field located on the Grand Banks of Newfoundland. They needed ice pressure vs area data to better define the ice pressures used to design large gravity base structures capable of resisting impacts by icebergs. The series of tests to supply the design information was devised by Don Nevel of Mobil Research and Development at the time. Don had previously worked for CRREL (the Cold Regions Research and Engineering Laboratory) which was part of the US Army Corps of Engineers. Don had been interested in the ice strength tests being conducted by Imperial Oil in Canada and I had met him in the Arctic during one of those test programs. Don is an accomplished and internationally recognized ice engineer/researcher and has published signature papers on many ice related engineering topics. I remember that at our first meeting in the 1970’s he was quite interested in the strength tests we were conducting in pits dug in the ice (see Figure 3).

In August of 1983 I met Don and his boss George Vance at Mobil’s office in Dallas. I went to Don’s house that evening and we discussed tests that he wanted to perform on ice crushing strength. He wanted to use a rigid steel indentor whose surface was not flat but had a curvature. He wanted to servo control the tests and was interested in what experts such as Terra Tek might have to contribute to establishing this control, if it were at all possible. Don and George indicated that they wanted to issue a turnkey contract and that they would work closely with the chosen contractor. George thought the tests might cost $1 million.

I flew the next day to Salt Lake City and met with Sid Green and other Terra Tek people such as Chris Johnson to explore how such tests might be servo controlled. Chris and the crew concluded that night that it could be done and Chris agreed to come to Calgary in early September. Chris did provide more information, especially on data acquisition during the tests.

Sid Green in the meantime talked with Don and Don revealed that he was favourable towards our team. Subsequently GEOTECH sent a proposal for the tests to Mobil in Dallas. Larry Owen of Terra Tek became involved, as did Mike Derr, both contributing to the servo control and data acquisition. On October 3, 1983 Don and I discussed the test program again and revised the cost estimate. On October 12, 1983 Don advised me that GEOTECH/Terra Tek had the contract with Mobil for the test program. Next we had to find a venue for the tests.

On October 18 Jacque Benoit, Walt Spring and I met in Ottawa with NRC's Hydrology Institute to discuss testing in glaciers. Simon Ommaney and Stephen Jones advised that the western Canadian glaciers were too warm, having temperatures very close to 0^{o} C. There would be significant pressure melting. They advised us to go to the Arctic but Walt and Jacque wanted to investigate western glaciers anyway, obviously because of the potential to reduce logistic costs. Ken Croasdale proposed going into the Rocky Mountains. Fritz Kerner at Polar Continental Shelf said that the Arctic glaciers had core temperatures of -15 to -20^{o} C. And Cape Sherard on Devon Island had an existing Petro Canada camp. Mobil still wanted to investigate the temperate glaciers first before committing to the Arctic. I did agree since the logistic costs could be much lower in the right location. The Rocky Mountains are mostly federal parkland and thus there would be great difficulty getting a permit to test there, if one could get a permit at all. I started looking at British Columbia locations outside parkland and getting what temperature information was available. Don was keen to keep looking and favoured investigating the Stewart BC glaciers. He was interested in coming along.

George Vance first indicated that he wanted a report from us favouring an Arctic location for the tests, but after talking with Don he modified the approach and said he wanted an impartial report. So I was off to Stewart BC on October 26, 1983. I visited the Salmon Glacier via helicopter with Garnet Dawson. I cored the ice and found it to be clear and crystalline, not snow ice. Its temperature was 0^{o} C. The following day we attempted more sampling via helicopter on the Salmon but were stopped by weather. So some sampling was done at the Bear glacier 15 minutes' drive away. I checked one more glacier south of Haines Junction and returned to Vancouver.

On October 31 we learned that there were grounded iceberg fragments at Pond Inlet NWT. Since Mobil and the Hibernia group had established relations through their operations, and with the introduction of George Koenig to the project, a person very familiar with the area and its people, Pond Inlet was picked as the test location. Accommodation was available in the village and the inhabitants were able and willing to assist with the project.

By the end of November, we were seriously into the planning and necessary analysis of the tests. Arfon Jones of Terra Tek, senior partner to Sid Green, did a fracture analysis to determine the spacing required between tests. His work would later prove very useful. George Koenig helped us sort out how to perform the tests on the bergs. We would mine our way into the bergs from the surrounding solidly frozen ice cover of Pond Inlet using simple methods. Nothing we had not done before, just at a larger scale. And there was good, experienced labour available in Pond Inlet.

In early January I met with Don Nevel in Dallas. We reviewed past tests conducted for Gulf and Mobil's previous drop ball tests, (small scale high velocity impact tests conducted for the Hibernia group) and after several hours of work and deliberation concluded that we needed 4 tunnels, 5 tests per tunnel. Arfon's theoretical work had been most helpful in this deliberation. Previously, Joe Kenny at GEOTECH had strongly advised me that we would have to be very careful with the engineering of the test equipment. We were, and it paid off. Joe was responsible for the design of the indentors and supports while Peter Thuerig was responsible for the actuator and accumulator design. They did an excellent job.

Details of the equipment and project are presented in Section 17. I provide considerable details of these tests, which many readers may not find too interesting. However, I feel that this was one of the most interesting and important projects that I had the pleasure of managing and working on.

During the project, I was still continually occupied with the issues related to our Dome ownership, trying to work with Canmar (on spray ice projects in the Beaufort) and answering to a nervous board of directors, thus I could not spend the time I wished or should have on the project. This affected the overall management and cost control of the design, procurement, manufacture and final testing of the test equipment. As an example, we had hired an accountant who had audit experience only and was not familiar with tracking the committed costs of an ongoing project. Thus, if he did not have an invoice in hand, there was no cost. However, the invoiced costs amounted to just over half of the total invoiced plus committed costs. I was caught out by Jacque Benoit who pointed out the discrepancy to me too late. Jacque had to go to Hibernia management and request more money. Luckily, he was able to get more. From this point on we kept a log of all purchase orders (committed costs) as well as tracking invoiced costs.

16. Pond Inlet Indentor Tests: Equipment Design and Test Results

Hydraulic System

The components of the high pressure hydraulic system included the actuators, accumulators and system components such as valves, hoses, manifolds and fittings. The design philosophy was to ensure a minimum weight design consistent with safety. The guide lines set down for design of the hydraulic system are summarized below.

Accumulator

The design provided for the following:

a) Minimum theoretical burst pressure for shell and end plates = 4 x design pressure.

b) Minimum theoretical yield pressure for total accumulator assembly = 2 x design pressure.

Each accumulator was subjected to a static pressure test of 1.6 x design pressure to ensure compliance with the design philosophy.

Actuator

The design provisions for the actuators are set as follows:

a) Minimum theoretical burst pressure for shell and end plates = 4 x design pressure.

b) Minimum theoretical yield pressure for total actuator assembly = 1.8 x design pressure.

c) Offset eccentricity of load on the actuator rod at maximum loading up to 3°.

Each actuator was subjected to a static pressure test of 1.5 x design pressure.

The actuators were also tested under load in a shop test program.

High Pressure System Components Design

All valves, hoses, manifolds and fittings were designed such that maximum burst pressure = 4 x design pressure and these components were tested under a static pressure of 1.6 x design pressure.

In the above, design pressure is understood to be the operating pressure of the equipment when used by qualified and experienced personnel familiar with the equipment design and operation. The test program required an operating pressure of 35 MPa.

Materials for Hydraulic Vessels

An ASTM A 106 seamless Grade B steel pipe, with a minimum yield strength of 291 MPa and a minimum tensile strength of 414 MPa was adequate for the cylindrical confining chambers of the actuator. The actuator end cap and piston were made from 6061 T6 aluminum 150 mm thick plates. The stroke of the piston, necessary to meet test specifications, was 300 mm. The piston rod (4140 steel) was proportioned to satisfy axial load requirements. In addition, the piston was designed to avoid yielding for a maximum offset, at full load, of 3°. Molythane seals adequate for pressures in excess of 35 MPa were specified for both the accumulators and actuators.

The manifolds, which interfaced the servo control valve with the actuators, were produced from 6061 T6 aluminum blocks. The manifolds and their connection were designed for an operating pressure of 35 MPa. Hydraulic valves, filters, connections and hoses were factory rated for an operating pressure of 35 MPa.

Integrated Hydraulic System Design

The accumulators, manifolded together, stored the hydraulic pressure necessary to activate the four actuators. The hydraulic oil was distributed to the four servo valves via a ball valve, a distribution manifold and four 40 mm diameter hydraulic hoses. The pilot valve line, which controls the servo-valve, was charged by a separate accumulator at 21 MPa. Filters capable of filtering to 3 microns at 35 MPa and flow rates up to 600 L/min were also provided on the pilot and major hydraulic line to ensure dirt fragments did not interfere with the servo controller.

Figure 21 shows the assembled test equipment in the yard in Calgary and the equipment being tested prior to shipment.

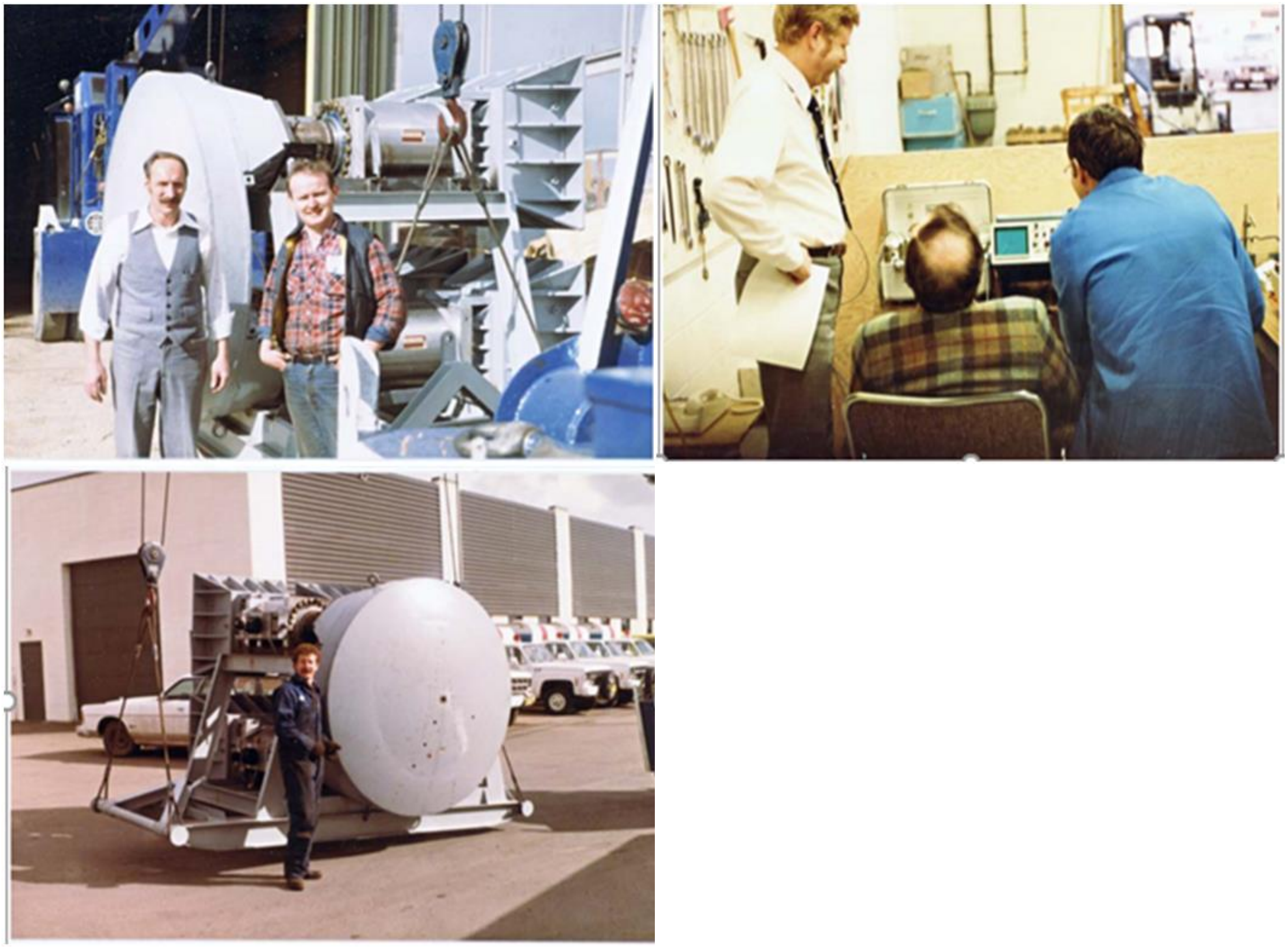

Figure 21 Shop Testing of Assembled Indenter Equipment in Calgary

Servo Control System

Closed loop or feedback control is a method in which the system output is fed back for comparison with the input, for the purpose of reducing any difference between input command and output response. Closed loop control offers the advantages of increased linearity and high performance. Furthermore, because the command signal typically takes the term of a time varying voltage, the ability to automate or test using complex profiles is inherent to the system. However, the system must be carefully designed to avoid instability.

The various transducers, actuators, amplifiers and coupling mechanisms constitute what is commonly called a servo-loop. This servo-loop permits servo control of one process variable. For safety and operational reasons, the actual controlled variable was displacement. A stationary mount for the feedback transducer (displacement potentiometer) relative to the ice was necessary if the desired displacement profile was to be achieved. The displacement profile was chosen to be a quarter-sine curve. It had an initial velocity of 100 mm/s at the wall surface and decreased to zero after travelling a distance into the ice determined by the indentor size.

Design of the servo-loop involved selection and/or design of the various components which made up the system to achieve desired performance.

For most servo systems, the servo valve is the limiting component. The main considerations for the servo valve were: it had to be a high response flow control type, be rated at 900 L/min and operate at 35 MPa. The selected valve was a Moog model D079B-211 three stage unit with a high performance AD76 pilot valve. A mating servo controller was selected from Moog's product line which would drive the servo valve. A 2 kHz excitation option was specified for the LVDT (linearly variable differential transformer) because of the fast response required.

Data Acquisition System

The data acquisition system consisted of the transducers and associated instrumentation required to collect data pertinent to the program and store the data on a media which could be transported to Calgary for later analysis. The test program required measuring indentor loads, pressures along the indentor face and indentor position. An estimate of the highest frequency component expected in the data was required in order to select transducers, signal conditioners, and sampling rates. Previous tests with flat jacks (Iyer and Masterson, 1991) and small indentors showed pressure pulses with rise times approaching one millisecond. A bandwidth of DC to 10 kHz was selected as being sufficient to faithfully record the expected signals.

A Honeywell Model 101 FM recorder was used with 14 intermediate band record and playback amplifier cards. A separate voice record and playback channel was used to notate the tape. Record speed was 60 inches/sec which provided a DC to 40 kHz bandwidth with the intermediate amplifiers. The load was monitored by a load cell in series with each actuator and the displacement by potentiometers referenced to the floor of the tunnel.

Tunnel Excavation and Wall Milling

Prior to the tunnel excavation operations, both plastic and brittle failure mechanisms in very thick ice subjected to loading by spherical indentors were analysed.

The results from this analysis led to the following criteria:

a) The minimum spacing between tunnels or between a tunnel and an iceberg side should be equal to 5 times the diameter of the largest indentor (5 x 2 m = 10 m)

b) The minimum distance between impact tests within a tunnel should be equal to 2 times the diameter of the indentor used for the test or of the adjacent test indentor, whichever was greater

c) Considering that in all tunnels the smallest indentor (0.02 m^2) tests should be performed near the entrance of the tunnel, these tests should be located a minimum of 1.5 m from the tunnel entrance.

While these criteria determined an average tunnel depth of 15 m, the physical dimensions of the apparatus and clearances for manoeuvrability determined an average tunnel porthole size of 3 m x 3 m.

Once the tunnel excavation method was established, the equipment, manpower and accommodation requirements for the tunnelling operations were determined. In early April 1984, personnel from Calgary were mobilized, along with miscellaneous support equipment, to Pond Inlet. The tunnels were excavated by cutting the ice into blocks using air driven chain saws. The blocks were fragmented and removed from the tunnel. Care was taken to keep the tunnel walls parallel and the tunnel floor as flat as possible. Approximately 3 m of tunnel could be excavated each day. Once the tunnel was finished, the floor was flooded with fresh water, which froze leaving a level floor surface.

The tunnel walls were hand chiselled to rough dimensions. Once this operation was completed, a wall milling apparatus was used to finish the wall surface. The apparatus consisted of a circular saw sliding along a wooden frame attached to the wall of the tunnel. By mid-April the four tunnels were excavated, three weeks ahead of schedule, and the ice landing strip was completed. 17 blocks of ice from the iceberg, comprising a total volume of 4 m^3, were also sent to Calgary for properties tests.

Figure 22 shows a view of the Tunnels from Sea Level at the Start of Excavation , and Figure 23 shows an aerial view of the iceberg and 4 tunnels during the tests.

Figure 22 Excavating a tunnel, and a view of 3 of the tunnels from sea level

Figure 23 Aerial View of Iceberg and the 4 Test Tunnels during the tests

Figure 24 shows the test equipment in a tunnel. Following the tests, we cut the ice away on each side of the interaction zone to show the shape of the ice failure zone; this is shown on the right in the figure below.

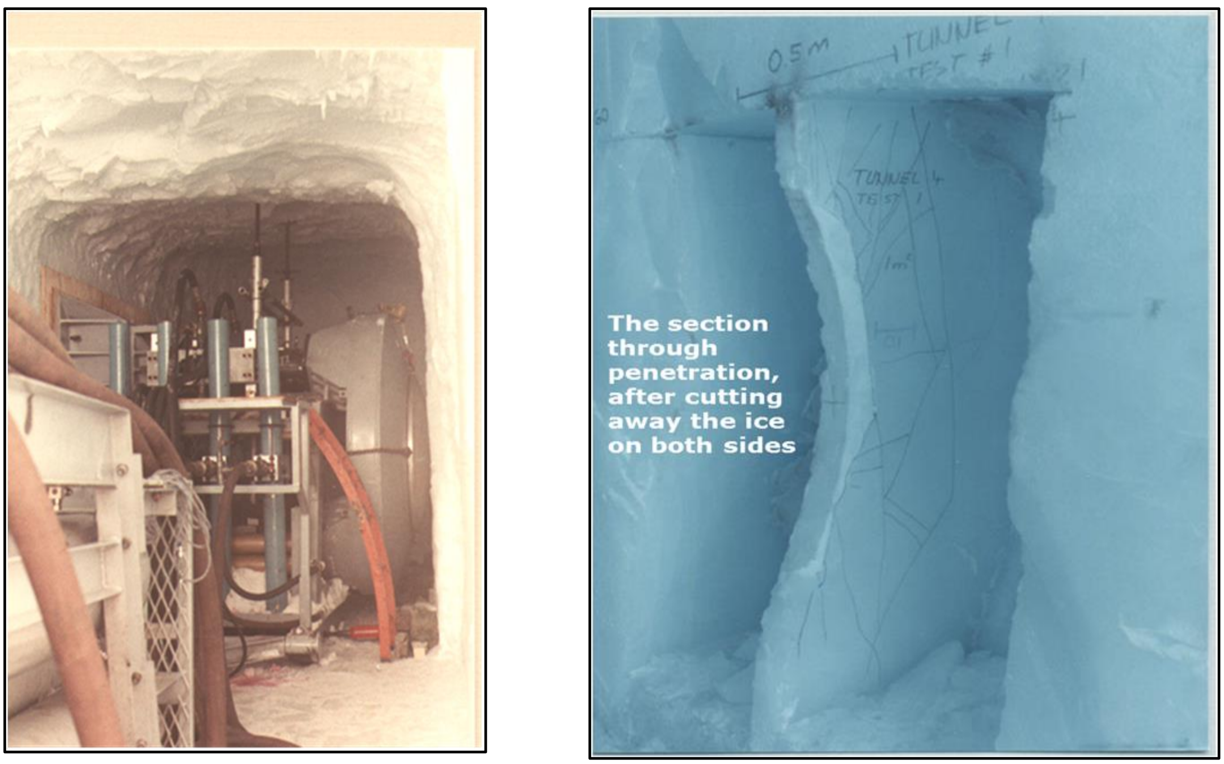

Figure 24 Equipment in test tunnel and section through tested ice showing shape of ice indentation

Field Tests and Test Procedure

Over 30,000 kg of test apparatus and equipment was trucked to Hay River and then flown to Pond Inlet by Hercules C-130 aircraft. As the quad accumulator system was stripped of all housing prior to leaving Calgary, once on site the system had to be reassembled. Table 2 presents the test schedule, including the test date, tunnel number, test number and size of indentor used for each test.

Table 2 Schedule of Tests

TUNNEL No.	TEST DATE	TEST NO	TEST CATEGORY
1	84-05-02	1	0.02 m^2
1	34-05-04	2	0.10 m^2
1	84-05-06	3	0.10 m^2
1	84-05-13	4	1.00 m^2
1	84-05-14	5	3.00 m^2
2	84-05-10	1	0.5 m^2
2	84-05-10	2	0.5 m^2
2	84-05-17	3	0.1 m^2
2	85-05-17	4	0.02 m^2
2	84-05-19	5	1.00 m^2
3	84-05-15	1	1.0 m^2
3	84-05-16	2	3.0 m^2
3	84-05-18	3	0.5 m^2
3	84-05-18	4	0.5 m^2
3	84-05-19	5	0.02 m^2
4	84-05-21	1	1.00 m^2
4	84-05-21	2	3.00 m^2
4	84-05-22	3	3.00 m^2
4	84-05-22	4	0.10 m^2
		5	0.10 m^2

Potentiometer Mounts

The displacement potentiometers, which provide the feedback outputs, directly affect the servo performance. Feedback errors could be produced from a number of sources including: mechanical misalignment; non-stationary mounts resulting from sticky wipers on the potentiometers or ice induced shocks; and rotation or pivoting of the actuator piston to which the wiper was connected. Potentiometer mounts were improved to minimize feedback errors.

Servo-system Interaction

Whenever two or more servo systems are coupled, the perturbations caused by one or both can lead to instabilities in either loop. This interaction was predicted early on, but the system had enough mechanical compliance to avoid this.

Loop Stability

To achieve stability at all points on the operating curve, the loop gain had to be set for worst case conditions, which occurred at full extension of the piston. This limited response time at fully retracted piston position.

Discussion of Force versus Time Curves and System Performance

The sawtooth imposed on the force time curve was not anticipated in 1984. This aspect of the load time curve is discussed in the following. The magnitude of the drop in force from peak to consecutive low in some of the sawtooth curves was considerable, being close to 50 percent of the maximum indentor force during the test. This phenomenon is similar to that observed during dynamic global loading of Gulf’s Molikpaq structure (Jefferies and Wright, 1988). Thus this rise and fall of the force on a regular basis is of interest, especially if the values at the peaks are influenced by the ice-structure system (as they well may be in the case of the Molikpaq). The major causes of the sawtooth waveform could be due to improper tuning of the servo control system, mechanical linkages, system stiffness, or progressive load build-up and failure in the ice.

Test 2-1 (Tunnel 2 Test 1), a single actuator, 0.5 m^2 test, was conducted with no servo control. The same sawtooth effect was observed with a frequency of 27 Hz, very similar to that of the other tests. Apparently, no tuning of the servo system would have changed this behaviour. As well, tests conducted on ice using flat jacks showed a similar force versus time response (Iyer and Masterson, 1991). Thus one must conclude that the force versus time response observed was largely ice induced. During the load drop evidenced by the sawtooth effect, the indentor velocity can be approximately 0.75 m/s which is a factor of 5 greater than the servo systems response capabilities. At this point the system is not under servo control until the indentor encounters resistance from further full contact with the ice, slowing its speed of advance. The servo controller is then able to respond and ensure that the next load build-up occurs at the prescribed velocity. The cycle is then repeated.

The response of the system was checked, as mentioned previously, with a series of sinusoidal displacement tests under no load at Pond Inlet. The single actuator was stepped out 10 mm, stepped back 20 mm and then brought to the null position. This was done at different rates and the response frequency of the system was found to be about 3 Hz. From the 10 mm pulse tests, the maximum velocity or "slew" rate of the actuator was found to be about 150 mm/sec. This value is the amplitude of the velocity function above. Thus, for this servo system

$$wA = 150$$

where w = frequency

A = amplitude

The slew rate limit system response is a function of the displacement amplitude.

If A is 10 mm, w is 15 sec^{-1} and the response frequency is 2.4 Hz, close to 3 Hz as measured at Pond Inlet. If A is 1 mm, the response frequency is 23.8 Hz. This is of the same order as the sawtooth frequencies noted on the force versus time curves where displacements between peaks on the curve are of the order of 1 mm. Thus, it could be concluded that the sawtooth effect was system induced. However, waveforms around 10 Hz were noted which are thus not slew rate limited.

The tests were in displacement control and a relatively smooth global displacement versus time response was sought and obtained. During the impact, force built to a point where fracture on a fairly large scale was initiated in the ice. The force required to propagate fractures and to subsequently extrude crushed ice around the indentor was lower than previously required. At the same time though, new ice was being contacted. Photographs of ice sections through the impacted area confirmed the above phenomenon. Moreover, it was noted that crack penetration due to impact was relatively shallow. There did not appear to be a general tendency to develop major cracks or fractures which could result in large scale flaking, although this occasionally did happen. Large scale flaking or spalling caused the 3 m^2 indentor to be lifted from its mounts during Test 3-2. Tests conducted with the servo control valve fully open (i.e. no servo control) showed the same sawtooth effect, confirming that the servo control system could not have been the cause of this phenomenon.

Secondly, the system stiffness could affect the shape of the force versus time curve. A soft system would interact with the ice breaking mechanism and may affect the force values obtained. Because tunnel dimensions could not in all cases be exact, plywood shims had to be used between the actuator base plate and the tunnel wall. At times, as many as 21 sheets of 19 mm (3/4 inch) thick plywood were used to shim tests. It was thought that this practice might soften the system and compromise the data obtained. Two tests, Test 4-4, a 0.1 m^2 test and Test 2-6, a 1 m^2 test, were conducted with no plywood shims. Test 4-4 gave an irregular sawtooth force vs. time function and Test 2-6 gave a regular sawtooth function. Thus it can be concluded that plywood shims were not a significant factor influencing the ice failure.

Subsequent detailed analysis of the effects of system stiffness and elastic stiffness of the ice indicate that the system is not a major contributor to the sawtooth form of the load vs. time curves. The fact that the sawtooth behaviour increases in amplitude as the test size increases and as the penetration increases within a test is interesting. This may be due to a change in the mechanisms of failure in the ice as the scale of the test increases. It may also indicate less surface effects in the larger tests since indentation is greater in this case.

Equipment Design

The design of the servo controlled hydraulically powered ice indentor system may be divided into four distinct systems; structural, hydraulic, servo control and data acquisition. Each is described independently.

The philosophy for the design of the impact simulation apparatus was to produce a test system that:

a) would withstand the anticipated impact load,

b) would have minimum weight and dimensions for ease of transportation,

c) would require minimum field assembly,

d) would be sufficiently robust to be field repairable in the event of certain failure modes,

e) would be sufficiently versatile for future applications.

Structural Systems – Indentors

Five spherical indentor plates, each with a specified radius of curvature and maximum area of contact were required for the tests. For descriptive purposes, the indentor plates are distinguished in terms of their nominal maximum areas of contact and ranged from 0.02 to 3 m^2. To reduce transportation and logistics costs all plates were of minimum weight design. Close attention to the design of the 3 m^2 indentor plate was essential to controlling weight. To design the indentor plates involved establishing the ice pressures which would act on the plate. Based on other experience (Iyer, 1983, Schwarz, 1974, Iyer and Masterson, 1987 and 1991), bounds for the design pressure were determined. For the smaller indentors, higher pressures were anticipated. This was not a serious design problem, because it was possible to carry the loads economically in direct bearing from the ice via the plates to the actuators. The 0.1m^2, 0.2m^2 and 0.5m^2 indentor plates were machined from aluminum blocks and mounted on a single actuator.

Figure 25 shows a cross section through the 3 m^2 indentor plate and shows, conceptually, its connection to one of the four hydraulic systems that were used. The indentor plate consisted of a central spherical membrane which reacted against a tension ring beam. The actuators are connected such that they react against the ring-beam. Two load conditions were considered in the final design of the plate. The first case was a load on the central portion of the plate (pressure = 10 MPa) which describes conditions in the initial stages of a test. The second load case was uniform pressure over the entire plate (7 MPa) and described the loading condition at full penetration in the closing stages of the test. It was also decided to minimize material safety factors when considering failures controlled by yielding. With appropriate support these failures could be quickly corrected. Failures, which would have jeopardized the test program, such as global plate buckling were designed against by using appropriately conservative material safety factors. Connection details of the plates to the actuators were designed according to the same philosophy.

The existing supporting system for the 3 m^2 indentor was employed for the 1 m^2 indentor plate. A circular aluminum block, 150 mm in thickness, was pressed to a radius of curvature equal to 2.3 m. This would allow the back face of the aluminum block to fit the 3 m^2 indentor plate.

Figure 24 above shows a photograph of the 3 m^2 assembly placed in the tunnel. Each actuator was provided with a back plate which distributed the load from the actuator to the wall of the tunnel during a test.

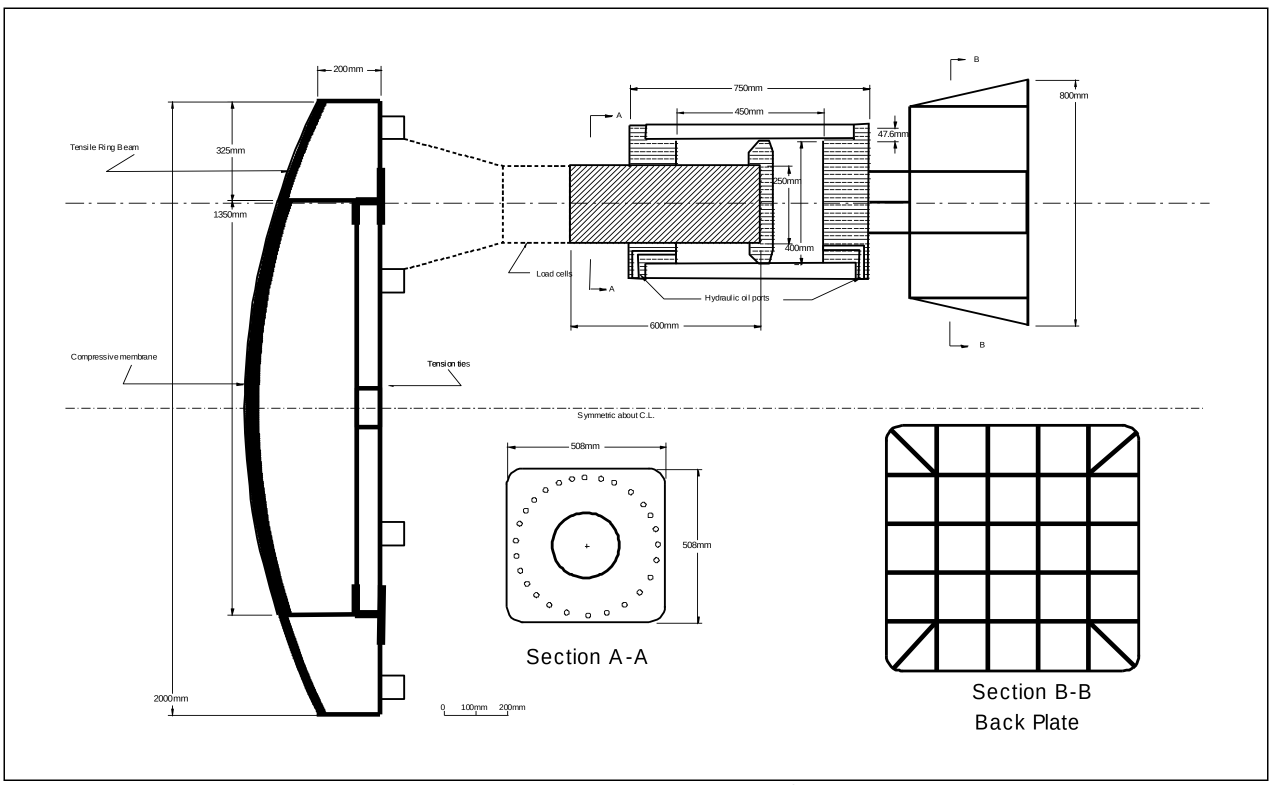

Figure 25 Cross Section of 3 m^2 Indentor

Experimental Test Conclusion

The impact simulation tests confirmed that interaction pressure decreases with increasing contact area.

Most of the test results conform to the following functional relationship:

$$q = k\, a_c^m$$

where:

q	=	Pressure
k	=	Constant
a_c	=	Area of contact
m	<	1

However, in certain tests the pressure did not decrease monotonically with increased area of contact. This could be explained by the fact that the actual area of contact with the ice is different than the theoretical area of contact. Because of the brittle and uneven nature of the ice failure in front of the indentor, this discrepancy is understandable. Large chunks of ice were observed to be dislodged from the immediate test area during some of the tests. An examination of the test videos confirmed this.

A comparison of the test results from indentors of different sizes and curvatures shows that, as the indentor curvature increases, the pressure for the same contact area decreases or pressure decreases as the curvature (l/R) increases.

17. Closure (To Be or Not to Be)

The preceding sections have described some of the work, the risk, and the associated difficulties encountered while accumulating useful ice crushing pressure and load bearing data and experience related to ice impacting offshore structures and load capacity of floating ice. The tests were conducted at large scale, rendering the data obtained directly useful for design. No longer did we have to scale up small scale laboratory test results using theory.

The work done from the 1970's to the 2000's was accomplished by pioneers who took established engineering knowledge and applied it to ice in new and unique ways. And they took it one step further and used it in practical applications in the most difficult of surroundings. While this work was done for oil and gas exploration and for various reasons may not be used in the near future to aid in the development of those resources, the testing, the calculations, the understanding, the parameters and the implementation of it are universal in their applications.

In a world where the ownership and use of arctic areas are currently being disputed by many governments, any technology that aids humans to manage and safely work in these harsh environments is a bonus. I am proud of the work that those acknowledged in this book have done. Their work will go on and on and be used by generations of engineers, contractors and environmentalists to make the Arctic a liveable area.

None of this work was easy. It was necessary to balance human safety, environmental concerns, production costs, political interest, corporate ideals with people skills to work for decades in a harsh world to become successful managing ice in a way that would set the standard for the future. Those involved gave their all to accomplish immense tasks despite the odds. While this book details their work on several fronts, some of those accomplishments in summary are included in the following subsections.

Exploration and examination techniques (the example projects given in the book describe these).

New exploration models developed from the old.

Extensive testing was carried out on sea ice, pack ice, and icebergs.

New methods of sampling were improvised that give excellent samples to test.

Major cutting in to the sides of ice structures were done to allow engineers to examine, test and sample ice.

Testing procedures

Existing testing procedures borrowed from soils, concrete and steel were tried and successfully modified to fit the new material, ice.

This involved extensive use of machinists, welders and hydraulics specialists to develop the innovative testing equipment described in this book – that can be and will be used again and again.

The Borehole Jack is a prime example. We know of examples where it is being replicated now, over 40 years since it was first developed.

Documentation in this book and in work files gives good evidence of the practicality of the methods devised, which can be used on any project.

Empirical equations and calculations developed

While previously developed equations for stress, strain and failure of materials were readily available, these research and construction projects allowed those to be modified and adapted to specific ice conditions. This work has resulted in national codes of practice specifying the requirements for safe and successful structures.

With these, like many applications in engineering, practical experience and a sixth sense about structural properties was needed.

Practical applications proven by years of on-site work and construction.

Empirical calculations from newly devised test methods were proven time and time again with the construction of runways, camp situation and drilling platforms.

Successful construction of underwater pipelines working from sea ice gave extensive data on how to accomplish these without disruption to the environment, deterioration of ice, etc.

Grounded ice islands and floating ice platforms located over deep waters (500+ m) can be created to carry immense loadings for the duration of the winter and everything cleaned and removed prior to spring breakup. These methods save millions of dollars in exploration costs wherever they can be applied.

Successful runway construction on floating ice that carried as many as 80 to 100 successful landings of Hercules aircraft bringing in equipment and supplies.

New techniques for constructing ice roads for transportation (e.g. spraying with high pressure pumps)

The development of safe and environmentally secure construction techniques as described in the book.

While some may say that these projects were detrimental to the environment, every precaution known at the time was taken to ensure sites were developed clean and left clean.

Many of the tests, construction projects give a perfect account of the durability of ice and its usefulness for human needs without damaging the environment.

The methods developed to determine ice strength and durability can easily be extracted to confirm ice reaction to long term warm or cold trends.

Proven technologies accompanied by dozens of research papers (many conferences were held, each producing a proceedings containing the technical papers presented resulting in national and international standards, e.g. ISOPE 19906).

Papers were written and published in various public archives that detail the work undertaken, test methods developed and results given.

Some of these are listed here for reference.

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