Improving the Performance of Shallow Draft Tugs in Northern Canada

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ABSTRACT

Northern Transportation Company Limited, the primary provider of marine transportation services on the Mackenzie River system in Northern Canada, has embarked on a major refit program of their extremely shallow draft river and coastal tugs. The refit program of the company's 11 tugs operating in the Western Arctic region began in 2001 and continues today. The primary goal of the program has been to extend the life of the vessels and improve their performance by incorporating tested features learned through many years of operational experience while also introducing new technology. Severe operating conditions and shallow draft design constraints provide considerable challenges for the design of the vessels' tunnel stern hull form, propulsion system, and steering system. The performance improvements have been recorded through tests and trials as well as by the analysis of operational results after the completion of vessel modifications. Full-scale trial results of the maneuverability and bollard pull characteristics add to the understanding of these unique vessels.

KEY WORDS: shallow draft vessel; towboat; bollard pull; tunnel stern; nozzle; full-scale trials.

INTRODUCTION

Northern Transportation Company Limited (NTCL) operates the largest tug and barge fleet on the Mackenzie River system in Northern Canada. A major consideration for NTCL over the past several years has been determining whether to rebuild their existing vessels or to start a new-build program. The tug fleet is ageing with ages ranging from 32 to 50 years old. However, the hulls are in excellent shape for their age because they are in fresh water for a significant portion of their 4-month operational period each year. The remaining 8 months of each year the waters are ice-covered during the long, hard winter and the tugs are stored on dry land for maintenance and repair. The cold, dry conditions of the Canadian Arctic help to preserve the steel hulls. However, the original machinery is in need of replacement due to the escalating cost of maintenance and the increasing scarcity of spare parts. The older engines are also less fuel-efficient than modern diesels.

At the time these vessels were built there was much debate regarding the benefits of nozzle propulsion on such extremely shallow draft vessels. Some felt the nozzles would be ineffective given the relatively high speeds of the push tugs and the confined geometry of the deep tunnels. There was also considerable deliberation of twin screw versus triple or quadruple screw propulsion. Many of the captains swore by twin-screw boats while others were willing to give quadruple screw a chance. Consequently, a mixture of tugboats was built with open propellers, nozzles, twin screws, and quadruple screws. It was not until the Company was faced with the decision whether or not to invest money in the old tugs that they thoroughly analysed the performance of the various boats and came to realize that the nozzle boats significantly outperform their open-wheeled cousins. It was always known that the nozzle boats were the best pushing through the rapids on the Mackenzie River, or that they could get an extra knot of speed while pushing a full load of barges. However, it was not appreciated just how much more revenue-earning cargo could be carried or how much fuel expenses could be trimmed with the use of the nozzle boats until some operational analysis was completed. There was also considerable evidence that the quadruple screw boats were outperforming the twin screw boats on the River, but the twin screw boats held the advantage in rougher coastal conditions due to their slightly finer and narrower hull form.

BACKGROUND

Operations

Northern Transportation Company Limited owns and maintains a fleet of 12 river and coastal tugs, two Arctic Class supply vessels and 90 barges. The majority of these vessels operate in the Mackenzie River-Western Arctic region, based at NTCL's main receiving terminal in Hay River, Northwest Territories.

NTCL services an extremely large geographical area shown in Figure 1. The primary terminal for outbound cargo and all vessel maintenance is located at the inland port of Hay River, on Great Slave Lake in the Northwest Territories. Hay River is served by both rail and road connections from Alberta. Hay River is the southern terminus of the Mackenzie River navigation system and is more than 1,900 km from the Arctic coast of the Beaufort Sea. At the mouth of the River, the Western Arctic coastal area stretches from the Mackenzie Delta 750 nautical miles westward to Point Hope in Alaska and 1,000 nautical miles eastward to Taloyoak in Nunavut. The navigation season lasts for 4 ice-free months each year beginning in early June and ending in mid-October.

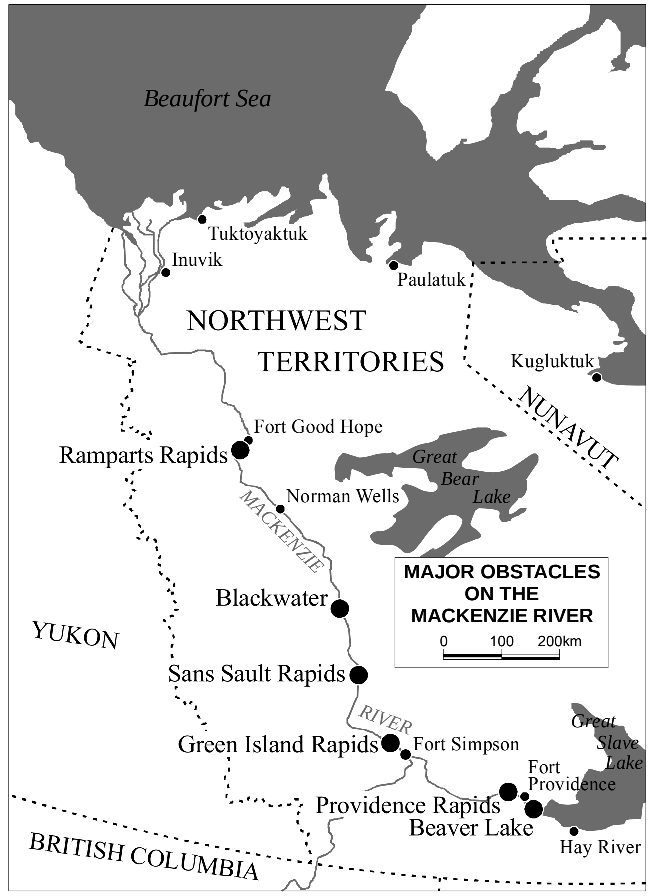

Figure 1. Mackenzie River; Western Arctic Region

High water on the Mackenzie River from spring run-off occurs from June to mid-July, followed by falling water levels which are dependent on rainwater amounts until freeze-up in mid October. The entire fleet is dedicated to river operations during high water levels and by August, three to four boats are transferred to the Arctic to fulfil coastal towing duties.

NTCL transports fuel, construction equipment, and general manufactured goods to the communities on the Mackenzie River and Western Arctic coast. Almost none of these communities have rail or road access. NTCL also ships supplies and heavy project cargo for the oil and gas industry to the Mackenzie Delta and nearby coastal areas. The heavy project cargo has included the 1,000 tonne drill rig shown in Figure 2 and the Badami production modules for a recent on-shore oil development by British Petroleum on the north slope of Alaska, shown in Figure 3.

Figure 2. Heavy Project Cargo Loaded on *1500* Series Barge

Figure 3. Oilfield Process and Accommodation Modules

The Mackenzie River is wide and deep in many areas, but there are significant navigation hazards including fast currents and very shallow water depth. The most significant hazards on the River are the Providence, Green Island, Sans Sault, and Ramparts Rapids. The transit through Providence Rapids has on average resulted in the most damage to equipment over the years. It is a narrow, twisty channel for navigation and currents in the channel range from 5 to 9 knots. The towboats are generally limited to relaying just two loaded barges at a time through this section going downstream, and three to four empty barges going upstream. The Sans Sault Rapids consist of boulder shallows with water depths between 1.2 and 2.4 metres. The current at Sans Sault is in the order of 3 to 4 knots. The Ramparts includes a drop over a rock ledge that extends over a distance of about 450 metres, through which current flows at 5 to 6 knots. The water depth over the ledge is as little as 1.8 to 2.4 metres at low water. The Ramparts also represent delay due to the necessity of relaying one or two barges at a time. The Ramparts become very challenging during a low water year and on occasion one of NTCL's best performing river boats will be stationed at the Ramparts just to shuttle barges while the other towboats work the rest of the River.

The River Tugs typically push flotillas of six barges on the Mackenzie River. The barges are partially loaded due to draft constraints. The majority of cargo is shipped northbound with very little returning on the backhaul route upstream to Great Slave Lake. Bulk oil and dry deck cargos are consolidated at the River delta and barges are loaded to a deeper draft for coastal towing. The tugs typically tow three barges along the coast. The barges are essentially empty for their return trip upriver.

NTCL Fleet

The principal particulars for NTCL's Western Arctic tug fleet are shown in Table 1. The particulars for the barge fleet are given in Table 2. NTCL operates "River Tugs" and "Arctic Tugs".

The River Tugs primarily shuttle barge flotillas up and down the Mackenzie River. The River shallows restrict navigation to vessels with a draft of less than 1.7 metres (5.5 feet). A draft of less than 1.4 metres (4.5 feet) is preferred for navigation of the River throughout the entire season and to minimize the effects of squat on the flat bottomed tugs. Coastal traffic has increased over the years and now some of the River Tugs are occasionally used on coastal routes out of necessity. The River Tugs have not performed exceptionally well on the coast due to their extremely wide and shallow hull form.

The general arrangement of the River Tug ***Edgar Kotokak***, is shown in Figure 4. This boat is one of four sister vessels designed by Robert Allan Ltd. in the early 1970s. Two vessels were originally built with propeller nozzles (***Kelly Ovayuak*** and ***Jock McNiven***) and two without (***Edgar Kotokak*** and ***Henry Christoffersen***). The ***Edgar Kotokak*** was converted to nozzle propulsion during the winter of 2002/2003. The original main engines at 4 x 840 kW were replaced with more powerful ones at 4 x 1,045 kW during the same conversion.

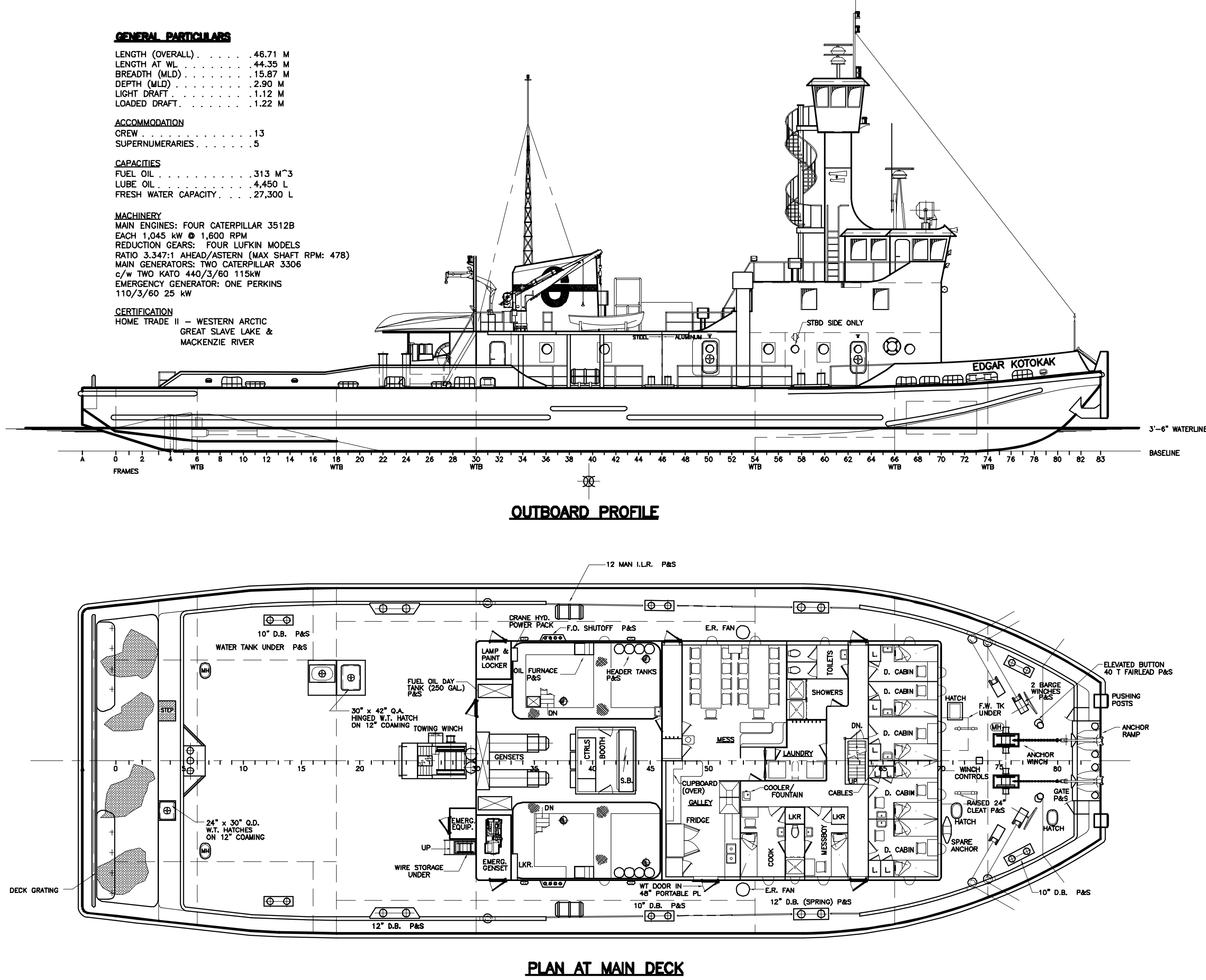

Figure 4. Shallow Draft Towboat *EDGAR KOTOKAK*

The Arctic Tugs tow barges along the Arctic coast and are subject to moderate sea states, generally not exceeding a significant wave height of 2.0 metres. The majority of Western Arctic ports are accessible to vessels up to 4.3 metre (14 foot) draft. However, some ports along the coast such as Paulatuk, Northwest Territories and Kugluktuk, Nunavut are very shallow and often only accessible by boats with draft less than 2.0 metres (6.5 feet). There is very little tide along the Arctic coast and water levels are often more influenced by wind direction. Arctic Tugs are occasionally stranded at Kugluktuk until an onshore wind brings water level back up again.

The boats must also be capable of transiting the Mackenzie River for maintenance at the Company's facility at Hay River. Consequently, the need to meet the 1.7 metre (5.5 foot) draft restriction on the Mackenzie River means that the Arctic Tugs are a compromise between a river and coastal vessel. The Arctic Tugs are designed to have a dual draft capability. They have the lightest possible operating draft between 1.4 metres (4.5 feet) and 1.7 metres (5.5 feet) for operations on the River and then are ballasted down to at least 2.0 metres (6.5 feet) for slightly better seakeeping performance on the coastal routes. The extreme shallow draft capability of the Arctic Tugs (i.e. less than 2.0 metres) has also worked to their advantage in the Arctic by allowing the vessels to move along the coast early in the season through the shallow water between the shore and the sea ice, which has grounded just offshore in slightly deeper water. NTCL has gained access to the Alaska North Slope using this method far earlier in the season than other vessels that are delayed until they are able to overcome ice conditions in the Bering Strait and Chukchi Sea coming from Southern Alaska.

Figure 5 shows the general arrangement of the Arctic Tug, ***Nunakput***. The ***Nunakput*** was designed and built by Allied Shipbuilders of North Vancouver, BC in 1969. The ***Nunakput*** has a river draft of 1.7 metres (5.5 feet) and a coastal draft of 2.0 metres (6.5 feet). The tug was originally built with open screw propulsion, but was fitted with nozzles during the winter of 2000/2001. Figure 6 shows the general arrangement of the ***1500*** series barges, which are the real workhorses of the NTCL fleet. These combination barges carrying high-flashpoint petroleum products in the tanks and containerized and break-bulk cargo on deck. These barges are operated with a draft of 1.4 metres (4.5 feet) for river work and then loaded down to a maximum of 2.1 metres (6'-8") along the coast.

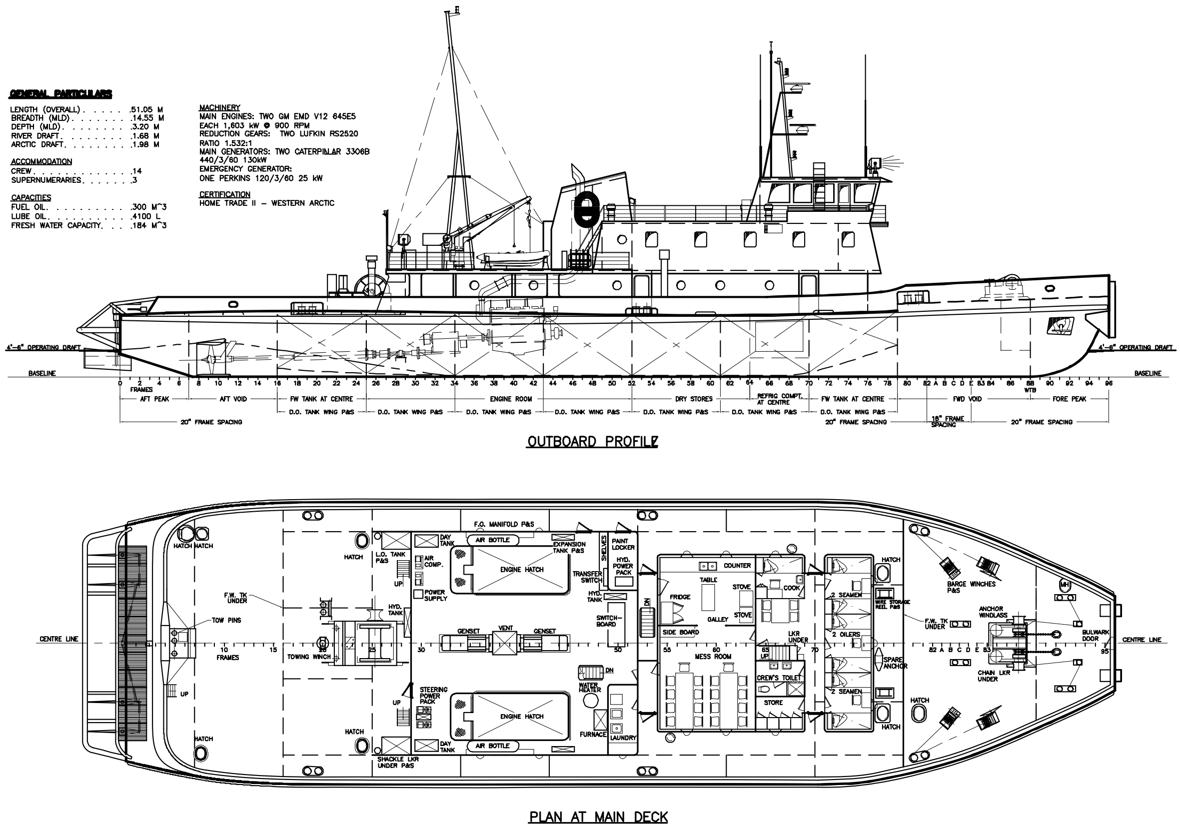

Figure 5. Shallow Draft Towboat *NUNAKPUT*

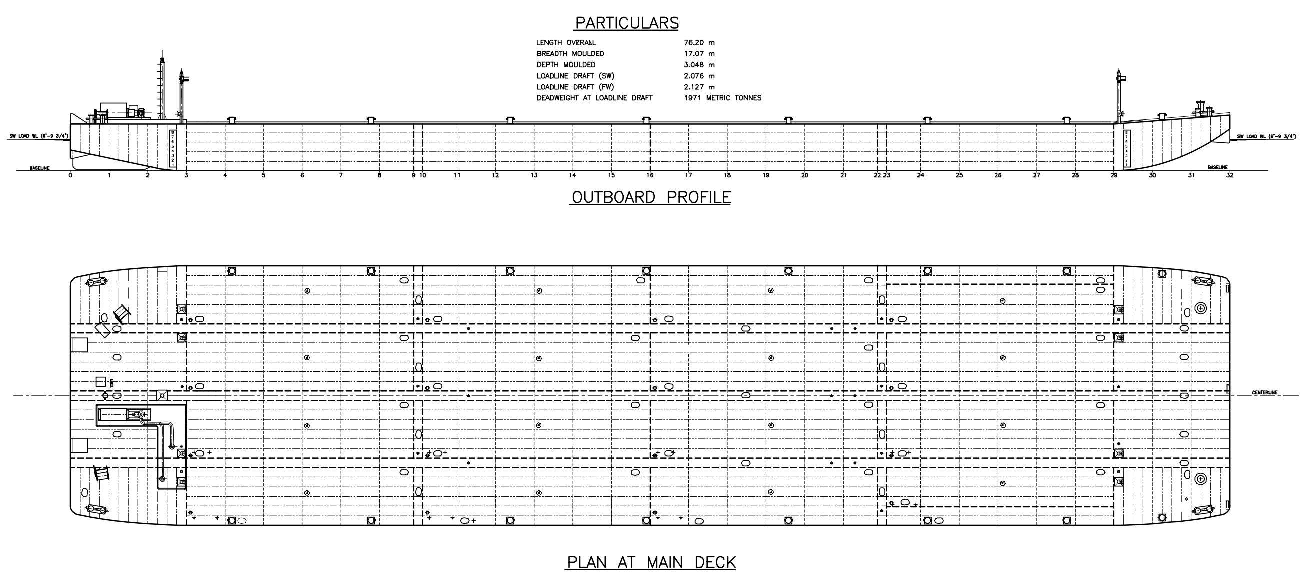

Figure 6. *1500A* Series Combination Oil/Deck Barge

Table 1. NTCL Tug Fleet; Western Arctic

Vessel Name	Type	Build Year	Length (m)	Breadth (m)	River Draft (m)	Power (kW)	No. of Shafts	N (nozzle) O (open)
Nunakput	Arctic	1969	51.1	14.6	1.68	3,207	2	N[1]
Pisurayak Kootook	Arctic	1969	48.8	12.2	1.83	3,207	2	N[2]
Kitikmeot	Arctic	1969	48.8	12.2	1.83	3,207	2	N[3]
Vic Ingraham	River	1971	47.1	15.2	1.14	3,356	4	N
Henry Christoffersen	River	1974	46.7	15.9	1.14	3,356	4	O
Edgar Kotokak	River	1974	46.7	15.9	1.14	4,176[4]	4	N[3]
Kelly Ovayuak	River	1974	45.2	15.9	1.14	4,176	4	N
Jock McNiven	River	1974	45.2	15.9	1.14	3,356	4	N
Arctic Kugaluk	River	1973	30.9	11.6	1.40	1,678[4]	2	N
N.T. Marjory	River	1956[5]	24.7	9.0	1.07	820	2	N[1]
Sans Sault	River	1965	23.7	7.3	1.14	925[4]	2	O

[1] Nozzles added in 2001
[2] Nozzles added in 2002
[3] Nozzles added in 2003
[4] Vessel re-powered in 2003
[5] Extensively rebuilt in 1973 and re-powered in 2001

Table 2. NTCL Barge Fleet; Western Arctic

Barge Series	Qty	Type	Length (m)	Breadth (m)	Depth (m)	Light Draft (m)	River Draft (m)	River DWT (tonnes)	Maximum Draft (m)	Maximum DWT (tonnes)
1500	28	Deck/Bulk	76.2	17.1	2.90	0.53	1.52	1,300	2.15	2,190
1050	1	Deck/Bulk	65.9	14.9	3.05	0.56	1.52	960	2.20	1,730
1030	3	Bulk	61.0	14.6	2.95	0.38	1.52	1,010	2.00	1,270
1000	24	Deck/Bulk	61.0	15.2	2.29	0.46	1.52	990	1.80	1,005
820	2	Deck/Bulk	53.4	15.2	2.36	0.36	1.52	885	1.70	1,020
800	11	Deck/Bulk	48.8	14.6	2.95	0.38	1.52	810	1.90	930
750	3	Deck/Bulk	59.24	12.2	2.0	0.37	1.52	825	1.60	849
700	2	24 Man Camp	47.3	13.7	2.16	0.81	1.52	–	1.52	–
600	16	Deck/Bulk	45.7	10.7	2.03	0.36	1.52	560	1.60	607

SHALLOW DRAFT DESIGN CONSIDERATIONS AND ANALYSIS OF THE NTCL FLEET

Tunnel Stern

A well-designed tunnel stern should help to ensure the good performance of a shallow draft tugboat. Smooth water flow entering and exiting the propeller enhances efficiency and performance. Some guidelines for tunnel design have been published, but these are largely based on deeper draft vessels operating in Europe, Russia, and the USA. There is some guidance for extremely shallow draft tug design provided by Allan (1971) in his paper concerning the design and build of the ***Vic Ingraham***, which was the prototype for the four River Tugs of the ***Henry Christoffersen*** Class. Figure 7 derived from Bogdanov (1974) provides some recommended values for the geometry of a tunnel stern vessel.

Table 3 provides a comparison of various elements of tunnel design for the NTCL Arctic Tugs and River Towboats along with recommended values from Bogdanov (1974). The tunnel entrance slope (θ) is probably the most important design criterion. A low angle and radiused entrance helps to ensure that the water flows smoothly along the crown of the tunnel as it accelerates towards the propeller. However, this comes at the sacrifice of hull buoyancy that is much needed to maintain minimum draft. The tunnel entrances of the NTCL tugs are well proportioned and probably could have afforded to be at an even steeper angle. The crown of the NTCL river towboat tunnels is quite high relative to its draft, but this is mostly out of necessity to provide an extremely shallow draft vessel with high power. A smaller diameter propeller, which leads to a smaller tunnel, could have been chosen to alleviate this concern, but this would have led to higher propeller loading which is probably a greater evil than a deep tunnel. Transom immersion of the NTCL vessels is greater than the recommended range based on Russian experience. The immersed transom prevents ventilation of the propellers when reversing and also provides protection from floating debris and ice when moving astern. A slightly higher transom may have improved the hydrodynamic efficiency of the vessels, but operational concerns overruled in this case.

Propellers

The draft restriction for shallow river tugs forces the naval architect to select a propeller diameter that is considerably less than the optimal value, while the operator demands the highest thrust possible to provide better control of large barge trains on the river. Mackenzie River service also demands high blade strength requirements to withstand contact and smaller than optimal sized blades to allow river debris to pass through the propeller disc, especially for nozzle propellers. The end result is extremely high propeller loading, shaft rpm, and propeller tip speed. Table 4 shows propeller loading (shaft power/disc area) for various river and ocean-going tugs operating in the USA, Europe, and Mackenzie River. The propeller loading on NTCL's twin-screw Arctic Tugs is remarkably higher than any of the other vessels listed.

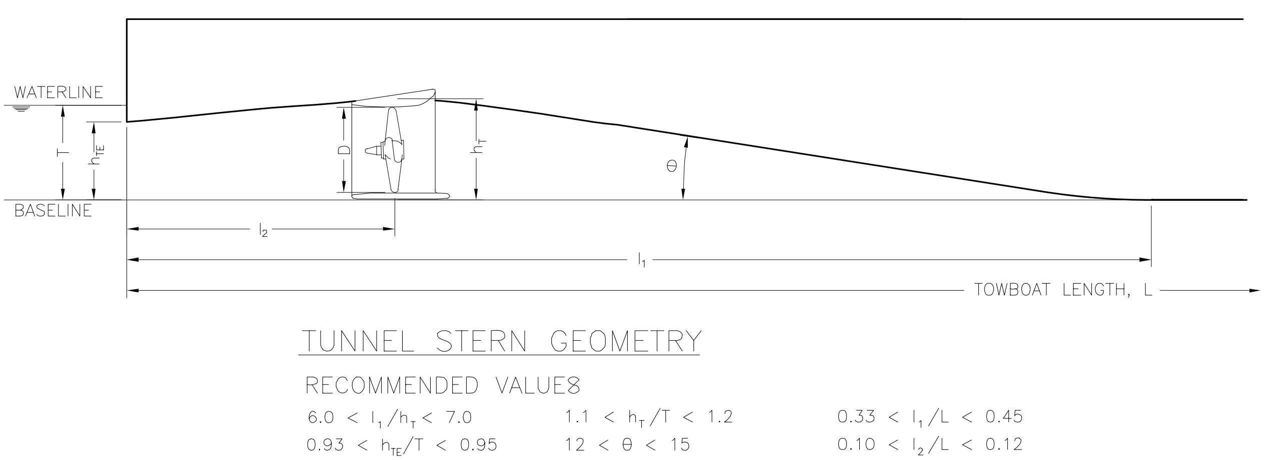

Figure 7. Tunnel Stern Geometry

Table 3. Comparison of Selected Tunnel Design Parameters

Tunnel Design Parameter	Recommended Value[1]	NTCL River Towboats (*Edgar Kotokak*, etc.)	NTCL Arctic Tug[2] (*Nunakput*)
θ	12° to 15°	12°	9°
h_T/T	1.1 to 1.2	1.40	1.07
h_{TE}/T	0.93 to 0.97	0.88	0.82

[1] From Bogdanov (1974)
[2] The tunnel design parameters for the ***Nunakput*** are evaluated at a river draft of 1.68 metres

Heavy propeller loading leads to cavitation, which can cause progressive breakdown in the flow across the propeller blade and a subsequent loss of thrust. Cavitation also produces noise, vibration, and erosion of the propeller blades, struts, and rudders. Cavitation phenomenon is worsened in vessels where the flow of water into the propeller disc is not uniform creating large wake variations. The deep tunnels of the Arctic Tugs partially restrict the flow of the water into the propellers especially in shallow water.

The heavy loading of the propellers on the twin screw Arctic Tugs is the primary reason these boats do not perform as well on the River as the quadruple screw River Tugs. In general, the propellers of the Mackenzie River fleet are designed to operate at cavitation levels far in excess of conventionally accepted practice. However, the propellers and rudders have not suffered too badly from cavitation-induced damage. This may be because they tend to require repair or replacement due to contact or erosion before cavitation becomes a concern.

Nozzles

Some naval architects and operators have in the past felt that nozzle propulsion on river towboats is not beneficial. The argument has been made that in order for a nozzle to be effective it has to have water flowing past the entire 360° of the outside surface and there has to be adequate clearance between the outside of a nozzle and the hull. In the case of shallow draft vessels, this theory has meant that a nozzle propeller had to have a smaller diameter than an open propeller in order to fit the nozzle within the confined geometry of a tunnel stern. The comparison was then made between a small diameter nozzle propeller versus a larger diameter open propeller. Model tests and analysis of this scenario showed very little to no benefit for the nozzle option.

Three of the vessels built for NTCL's Mackenzie River fleet back in the early 1970s were originally fitted with nozzles at the time of their construction. However, these nozzles were not installed so that the outside diameter of the nozzle was clear of the tunnel sides, but instead were imbedded into the tunnel structure so that the top of the nozzle at the leading edge was in line with the tunnel crown as shown in Figure 7. Two nozzles were fit into a single tunnel with the adjacent sides of the nozzles connected together for structural support and the other sides of the nozzles imbedded into the tunnel sides. The outside of the nozzle at the bottom was flattened so that the nozzle would not extend below the baseline of the vessel thereby minimizing the risk of contact with the river bottom (the same design method was used in the recent refits as can be seen in Figure 10). Two sister vessels were built with open propellers of the same diameter. Thirty years of experience has shown that the nozzle boats significantly outperform the open propeller vessels despite the compromises that had to be made to fit an equivalent diameter nozzle propeller into the same tunnel stern. The most important factor for extremely shallow draft vessels with high propeller loading is to fit the maximum nozzle propeller diameter possible. Sacrificing nozzle shape to achieve this is well worth the effort.

Another concern of some propulsion designers and operators is that nozzles lose their thrust advantage as vessel speed increases. A standard nozzle may perform significantly better than an open propeller at bollard conditions but loses this advantage at higher speeds. The crossover of the two thrust curves is at around 7 to 8 knots when considering a conventional 19A or Kort nozzle. Gruzling (2004) has shown that the "High Efficiency" nozzle produced by NautiCAN Research & Development, which does not compromise efficiency for ease of construction, maintains its advantage over open propellers throughout the entire speed range. The popular nozzle models 19A, 22, 24, and 37 originally developed by MARIN have, from a structural point of view, a simple shape with straight line profile at the outer diameter and an axial cylindrical section for part of the inside diameter. This makes construction more economical but sacrifices performance especially when compared to a nozzle profile based on a true NACA aerofoil section, which has curved surfaces on both the inner and outer diameters.

It is now understood that nozzles offer significantly better performance characteristics and fuel efficiency than open propellers despite the restrictive geometry of a shallow draft tunnel stern vessel or the relatively high speed of a river towboat. NTCL have also found that the nozzle offers protection to the propellers from bottom contact. However, this is somewhat offset by increased ingestion of river debris into the propeller disc of the nozzle. Nonetheless, NTCL have found that the performance advantages far outweigh the few operational difficulties. This is especially true with rising fuel costs.

Rudders

River tugs in charge of large barge trains require the most effective control surfaces possible. However, shallow water, riverbanks, and cavitating propellers create considerable design challenges for efficient rudder design.

NTCL approached this problem in two different ways when they built their existing fleet many years ago. Some of the boats have large transom-mounted rudders while others have much smaller rudders positioned in the tunnels immediately behind the propellers.

The rudders mounted on the transom have the advantage of lots of space available for a large surface area and are also conveniently located for maintenance and repair as can be seen in Figure 8. The ease of maintenance was the primary reason that this location was chosen. Unfortunately, the transom is also the location most exposed to contact with the riverbank when pushing a barge train around a sharp bend. Consequently, these rudders have experienced lots of damage and two to three rudders per boat are damaged or lost each season. In extreme cases, the boats have limped back to homeport with only one of eight rudders still intact. Turbulent, cavitating flow past the rudders on the open-wheeled boats has also led to considerable vibration related maintenance requirements.

In contrast, the nozzle boats were built with smaller rudders tucked up in the tunnel immediately behind the propeller as can be seen in Figure 10. These vessels do not manoeuvre quite as well as the other vessels at very low speeds because of restricted flow past the rudders, but on the other hand rarely experience damage in their protected position. Only one of the 16 rudders on the two River Tugs with this configuration has been lost over the last 30 years. The manoeuvrability of the two different rudder arrangements is reported to be similar at higher speeds when there is ample flow past the nozzle rudders.

Figure 8. Transom Mounted Rudders

Table 4. Propeller Loading

Vessel	Power (kW)	Shaft Speed (rpm)	Propeller Diameter (mm)	No. of Blades	Propeller Material	Propeller Disc Area (m^2)	BAR	Power / Disc Area (kW/m^2)	Tip Speed (m/s)
Shallow Draft River Towboats:									
NTCL Arctic Tugs: (***Nunakput***, ***Kitikmeot***, etc.)	2 x 1603	585	1524	4	SS316	2.32	0.95	690	46.7
NTCL River Towboats: ***Edgar Kotokak***	4 x 1044	478	1473	4	SS316	2.17	1.05	481	36.9
NTCL River Towboat: ***Vic Ingraham***	4 x 839	479	1422	4	SS316	2.02	0.80	415	35.7
NTCL River Towboats: ***Kelly Ovayuak*** & ***Jock McNiven***	4 x 839	424	1422	4	SS316	2.02	1.05	415	31.6
NTCL River Towboats: ***Henry Christofferson***	4 x 839	424	1422	4	SS316	2.02	0.80	415	31.6
Wiking	3 x 1342	—	2057	—	—	4.23	—	317	—
Mark Easton	2 x 2088	—	2743	—	—	7.53	—	277	—
H. Bloch	3 x 1193	—	2057	—	—	4.23	—	282	—
Alois Luhr	2 x 2461	200	2997	—	—	8.98	—	274	31.4
Mannesmann IV	3 x 1119	253	2057	—	—	4.23	—	264	27.3
Rio Sauce	2 x 358	385	1448	—	—	2.10	—	171	29.2
Deep Draft Ocean-Going Tugs:									
Captain Cook	2 x 839	245	2134	—	Ni-Al-Br	4.55	—	184	27.4
Jervis Crown	2 x 984	216	2286	—	Ni-Al-Br	5.23	—	188	25.9

REFIT PROGRAM

Table 1 shows that there is considerable variety amongst NTCL's tug fleet. The performance and duties of each boat varies significantly as well. Priorities were assigned to each vessel.

It was quickly decided that the cost of a significant modification to the tunnel stern shape of any of the vessels could not be justified at this stage of their lives. The benefits were considered marginal while the cost would be considerable. Similarly, alteration or introduction of an additional shaftline was not considered feasible.

The lowest technical and financial risk was to fit nozzles to the open screw boats as a first step in their modernization. It was well understood that the nozzle boats in the fleet outperformed the open propeller vessels. This was demonstrated during the pre-refit bollard pull trials of the ***Nunakput***, ***Henry Christoffersen***, and ***Kelly Ovayuak*** in 2000 described in the next section. Economic analysis showed that fitting nozzles to the open screw boats would quickly pay for itself in just a few years.

The first boat to be modified for NTCL's refit program was the Arctic Tug, ***Nunakput***. The ***Nunakput*** was originally designed to be an identical sister ship to the other two Arctic Tugs, ***Pisurayak Kootook*** and ***Kitkimeot***, but was increased in size during construction in 1969 in an effort to make it float at a lighter draft than its sisters. The lighter draft has meant that the ***Nunakput*** has been used more on the River than the other two Arctic Tugs**.** River work requires a tug with high bollard pull capability and good manoeuvrability in order to manage barge flotillas in strong river currents and around tight bends. Thus the addition of a nozzle to the ***Nunakput*** would provide the greatest immediate benefit to the company by enhancing fleet productivity on the River.

NautiCAN nozzles were fitted to the ***Nunakput*** and ***N.T. Marjory*** during the spring of 2001. The vessels performed so well that the same conversion was done to the ***Pisurayak Kootook*** and ***Kitkimeot*** in 2002 and 2003, respectively.

Buoyed by the success of the nozzle modifications, NTCL pushed on to a much more extensive refit of another vessel in its fleet, the ***Edgar Kotokak***, in the spring of 2003. The quadruple screw ***Edgar Kotokak*** was built in 1974 with open propellers and eight large rudders mounted on the transom. The rudders were connected together with a conventional tie-bar arrangement operated by a single steering gear mechanism so that all rudders, port and starboard, turned in unison to the same angle. The boat was powered by four Caterpillar V16 D399 diesel engines each developing 839 kW at 1,225 rpm. The tunnel stern is shown in Figure 9 prior to the refit.

It was decided to fit four new nozzles that each came as a combined package complete with triple high-lift rudders and steering gear pre-mounted. The total installed power was increased by 25% with the installation of new Caterpillar 3512B diesel engines rated for 1,045 kW at 1,600 rpm. New Lufkin reduction gears were installed increasing shaft speed from 424 rpm to 478 rpm in order to accommodate the increased power through the existing shafting. Propeller diameter was actually increased from 1,422 mm to 1,473 mm even with the addition of the nozzle. The propulsion system post refit is shown in Figure 10.

Figure 9. *Edgar Kotokak* Before Refit

Figure 10. *Edgar Kotokak* after Refit with NautiCAN Nozzles

The new steering gear set-up that came with the nozzles allowed independent control of starboard and port rudder systems which was believed would provide much better control and higher turning moment on the tug and barge flotilla. The towboat captain would now be able to turn the rudders on one side hard over with the propellers providing forward thrust while the rudders on the opposite side remain parallel to the centreline and the propellers are reversed. Keeping the rudders at 0° on the reversing side would prevent the rudders from blocking the water flow to the propellers as used to be the case in the old arrangement. This would allow the towboat to provide a much greater turning moment on a barge flotilla than before.

FULL-SCALE TRIALS

A series of bollard pull trials were performed which compared performance both before and after the refit of some of the vessels. Sea trials were performed on the quadruple screw river tug, ***Edgar Kotokak***, to test its speed and manoeuvrability.

Bollard Pull

Bollard pull trials were performed on three separate occasions near NTCL's synchrolift repair facility on the Hay River. The trials were arranged as shown in Figure 11

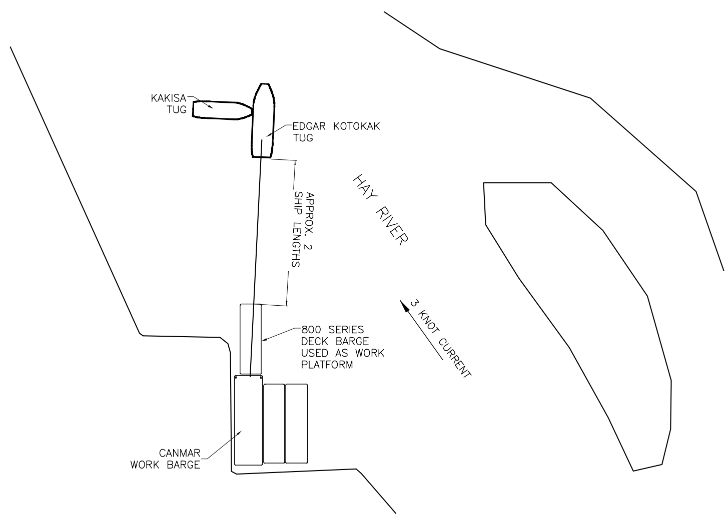

Figure 11. Bollard Pull Trials Arrangement at Hay River, NT

The vessels were positioned near the middle of the channel where the water is the deepest at approximately 3.5 metres. The vessel drafts varied from 1.1 to 1.6 metres. There was generally a light current of 2 to 3 knots flowing in the River. The effect on the tension in the towline was estimated and a correction to the final bollard pull value was made. The correction applied due to river current was always less than 1.0% of the bollard pull measurement so it was felt that its accuracy did not have a big impact on the final result. All vessels were tested in the same fashion so at least the results show a good relative comparison of their performance even if the absolute value has some margin of error.

A vessel's bollard pull, or thrust at zero speed of advance, is really the only practical and economical measurement of propeller thrust that can be made in a commercial setting. However, it is still a good performance indicator because thrust at near zero speed is very important for river tow-boats in their effort to control large barge flotillas heading downriver. Figure 12 shows the results of the bollard pull trials.

These were the first bollard pull trials ever performed on these vessels so the results finally confirmed what had long been common knowledge among the towboat captains, but never proven and quantified. The nozzle boats significantly outperform the vessels with open propellers. The best comparison is made between the quadruple-screw sister vessels in three different configurations:

Henry Christoffersen
Open Propeller 26.5 tonnes @ 3,356 kW

Kelly Ovayuak
Modified 19A Nozzle 38.7 tonnes @ 3,356 kW

Edgar Kotokak (interpolated)
NautiCAN Nozzle 41.0 tonnes @ 3,356 kW

The ***Edgar Kotokak*** with nozzles developed 55% more bollard pull than its sister vessel with open propellers at equivalent power levels. The nozzle advantage is surprisingly large given that the general literature and model tests have argued a smaller difference between nozzle and open propeller. However, some of the research and model tests that have investigated this issue have compared open propellers and nozzle propellers of different diameters. The conventional argument when comparing the performance of a given hull with and without nozzles has been that the nozzle propeller diameter must be made smaller to provide adequate clearance between the outer diameter of the nozzle and the hull as explained earlier.

Sea Trials

Sea trials of the ***Edgar Kotokak*** were performed in June of 2003 and consisted of turning circles, Kempf zig-zags, and crash stop tests. NTCL had invested a significant amount of money in refitting the vessel with new engines, propellers, nozzles, and steering system so they wished to document the performance of the vessel as well as provide a benchmark for future refits and new vessels.

Three turning circles were completed successfully, two at 20° rudder angle and one at maximum (43°) rudder angle. Run No. 1 was conducted while pushing a laden ***800*** Series barge (see Table 2), while the other two runs were done with the vessel free running. GPS coordinates were measured using a GPS monitor. The turning circle results are summarized in Table 5.

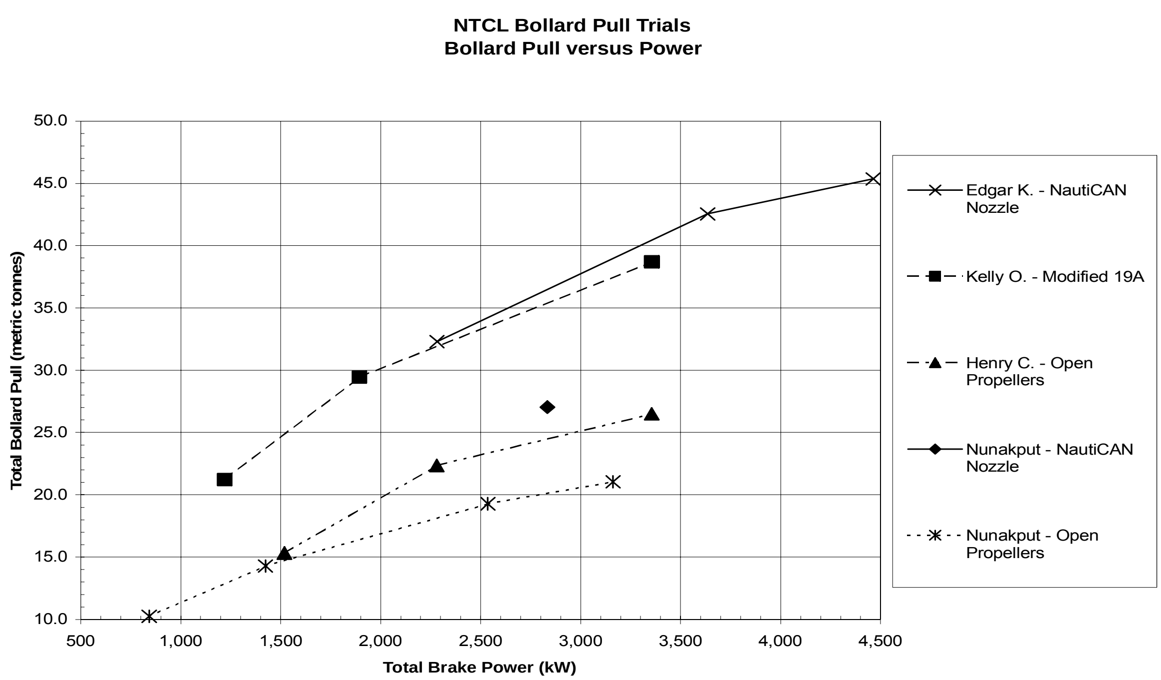

Figure 12. Bollard Pull Trial Results

A series of Kempf zig-zags were completed for a 20° rudder angle. Different combinations of engine speed and barge configuration were used for each test run. Time and GPS measurements were recorded manually at key points along each path. The results of the Kempf zig-zags are summarized in Table 6. Figure 13 shows a typical plot of vessel heading versus time for the Kempf zig-zag test.

The manoeuvring tests illustrate the vessel handles very well as can be seen by the turning circle diameter of just 2.0 ship lengths while travelling ahead at essentially full speed (12.4 knots) and employing maximum rudder angle of 43°. The zig-zag tests show the tug is very responsive to rudder executions even when pushing a barge. The tug and barge combination was able to veer off 20° from its original course within 25 seconds of initial rudder execution while advancing only 111 metres or 1.2 ship lengths (based on overall length of tug and barge).

Table 5. Turning Circle Data

Run. No	Condition	Speed (knots) Start / Finish	Elapsed Time(s)	Average Diameter (m)	
				(m)	Ship Lengths
1	1,600 rpm, 20° rudder, with barge	11.4 / 11.0	252	431	4.5 [1]
2	1,300 rpm, 20° rudder, free running	12.4 / 10.4	159	284	6.1
3	1,300 rpm, 43° rudder, free running	12.4 / 5.5	95	92	2.0

1 The ship length includes the barge. Total combined length = 95.4 metres

Table 6. Kempf Zig-Zag Data

Run No.	Condition	Speed (knots) Start / Finish	Overshoot (degrees)	Execute Time(s) [1]	Advance to Second Execute [2] (m)
1	1,000 rpm engine speed, free running	10.9 / 9.0	9	14	70
2	850 rpm engine speed, free running	9.0 / 8.4	7	ND[3]	ND
3	850 rpm engine speed, with barge	7.3 / 7.3	7	33	133
4	1,000 rpm engine speed, with barge	9.1 / 8.4	7	25	111

[1] Execute time = time between the initial rudder execution and when the yaw angle first reaches 20° from the initial heading.
[2] Advance to second execute = forward distance the vessel travels until the yaw angle first reaches 20° from the initial heading.
[3] ND = No Data

Table 7. Crash-Stop Trial Results

Trial	Time to Come to Full Stop(s)	Time to Begin Reversing after Full Stop(s)
June 14, 2003 (first attempt)	20	6
June 14, 2003 (second attempt)	27	Not recorded
July 4, 1973[1]	33	Not recorded

[1] Completed by Burrard Dry Dock Company Limited at English Bay, Vancouver, BC.

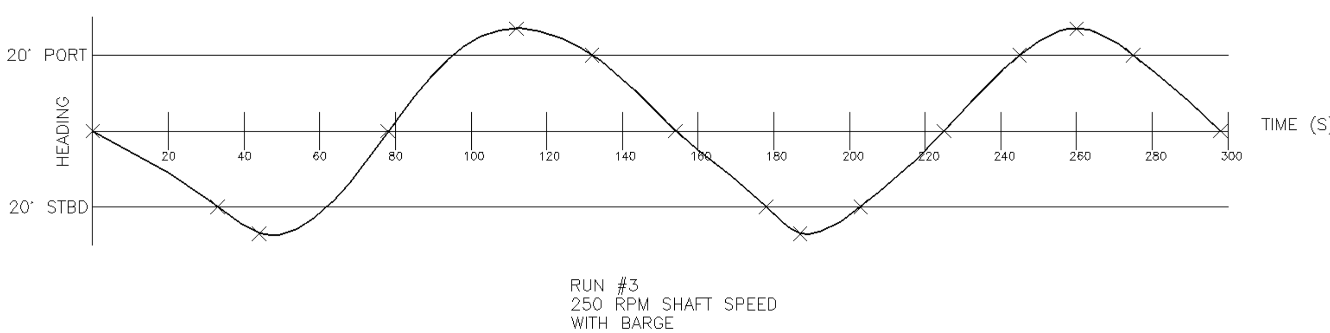

Figure 13. Kempf Zig-Zag Manoeuvre

Two crash-stop trials were attempted at full speed ahead, approximately 14 knots. The results of the crash stop trials are summarized in Table 7.

The maximum speed attained while pushing the barge was 12.8 knots, and this was primarily limited by the bow wave of the barge riding up onto the deck of the barge.

IN-SERVICE PERFORMANCE

The nozzle refits have proven to be very successful. Bollard pull trials have shown that the thrust at zero speed has increased by up to 55% over open propellers at the same power level. The nozzle manufacturer claims that the nozzle maintains an advantage over the open propeller for speeds up to 10 knots. This has proven to be true in service as the tugs have been able to complete a round trip on the River three days sooner than before. Also, the ***Edgar Kotokak*** has been able to handle three more barges on the southbound (upriver) portion of the trip. The nozzle vessels have noticed a 1-knot drop in top speed when running light without barges, but this is of little concern since these boats are moving barges nearly 100% of the time.

It has been difficult to analyze the voyage data for the NTCL vessels operating on the River. The make-up of the tow changes during the course of a typical river trip as cargo is loaded and unloaded along the way. In contrast, the Arctic voyages are generally more consistent as it often involves hauling cargo between two ports only.

Analysis of several voyages along the Arctic coast is shown in Table 8. The barges are always towed along the coast in either a close-coupled arrangement when weather allows or spaced further apart using conventional deep sea towing gear. The tow conditions vary considerably from trip to trip. A coastal voyage could experience calm water, heavy wind and seas, dense fog, or even broken ice as an example. Consequently, the resistance of the tug and its tow varies considerably as well depending on the make-up and total displacement of the tow, weather conditions, and ice conditions.

In an effort to equalize the differences, the voyages have been compared by calculating the vessel's fuel efficiency, defined as:

Fuel Efficiency = Fuel Consumption/Transportation Efficiency

where,

Transportation Efficiency = tow DWT x speed

The variation in calculated values for Fuel Efficiency as shown in Table 8 is attributed to different weather and ice conditions. It can be seen that the average Fuel Efficiency of the ***Nunakput*** improved from 2.06 to 1.81 litres/tonne* knots while the ***Edgar Kotokak*** improved from 2.33 to 1.84 litres/tonne*knots as a result of the nozzle refit. This is a 12% and 21% improvement for the ***Nunakput*** and the ***Edgar Kotokak***, respectively. The ***Edgar Kotokak*** also showed a very impressive best performance of 1.26 litres/ tonne*knots for the 665-nautical mile trip between Tuktoyaktuk, Northwest Territories and Cambridge Bay, Nunavut in August, 2005. The quadruple-screw ***Edgar Kotokak*** really shines under calm conditions, but can still labour in heavy seas even after the refit, especially when compared to the narrower twin-screw ***Nunakput***. The ***Nunakput*** may have a less efficient propulsion system due to its high propeller loading, but its hull form is certainly better suited to rougher sea conditions, which at times can be the overriding factor.

Another benefit of the refit to the ***Edgar Kotokak*** is the new triple rudder system installed behind each nozzle with independent steering port and starboard. The new steering system has substantially improved manoeuvrability, which is so important especially when traveling downstream with loaded barges. Anecdotal evidence has shown that manoeuvrability has improved remarkably, translating into improved productivity. The tow needs to get split up at four spots when going down river to go through rapids. To split up the tow, they have to stop and tie off some of the barges and to do that they have to turn 180° upstream first. All the other boats, including the ***Jock McNiven*** and the ***Kelly Ovayuak***, will start setting up to spin the tow 0.5 to 0.25 mile before the tie-up depending on the tow and current conditions at the location. The tug and tow are now much more responsive with the triple rudder system. The first time they were operating the recently refitted ***Edgar Kotokak***, one crew went to turn the tow a quarter mile before the tie-up, as was the usual procedure, and they finished turning a quarter mile before the tie-up!

CONCLUSIONS

NTCL has initiated a successful refit program. They have installed modern machinery and equipment while also incorporating some new technology to improve the performance and economy of their fleet. Post-refit trials have shown improved bollard pull and in service they have proven to be more productive and fuel-efficient. Sea trials have been performed to obtain valuable baseline data on manoeuvrability, which will provide a benchmark for future refits of other vessels in their fleet as well as for shallow draft vessel design in general.

The experimentation, full-scale trials, and analysis of these unique vessels, which are at the extreme end of shallow draft operations and power densities, have provided valuable data to allow for further refinements of new vessels of this type.

Table 8. Voyage Data; Arctic Coastal Routes

Vessel Name	Barges	DWT (tonnes)	Trip Duration (h)	Voyage Distance (N.M.)	Average Vessel Speed (knots)	Voyage Fuel Consumptn (litres)	Fuel Efficiency [litres/(Displ.*speed] (litres/tonne*kts)
Nunakput (O)	NT1509	1,911	116	665	5.73	62,820	1.92
	NT1519	1,901					
	NT1528	1,901					
	Total	5,713					
Nunakput (O)	NT1504	1,482	115	665	5.78	63,641	2.21
	NT1514	1,501					
	NT1525	2,001					
	Total	4,984					
Nunakput (N)	NT1509	2,156	121	665	5.50	49,801	1.70
	NT1514	1,268					
	NT1521	1,899					
	Total	5,323					
Nunakput (N)	NT1509	1,943	157	665	4.24	48,839	1.91
	NT1513	1,999					
	NT1528	2,086					
	Total	6,028					
Edgar Kotokak (O)	NT1522	1,401	91.5	523	5.72	57,961	2.33
	NT1523	1,751					
	NT1526	1,201					
	Total	4,353					
Edgar Kotokak (N)	NT1507	961	77	523	6.79	42,778	1.69
	NT1511	1,414					
	NT1523	1,341					
	Total	3,716					
Edgar Kotokak (N)	NT1511	1,148	74.75	523	7.00	34,545	2.03
	NT1515	1,286					
	Total	2,434					
Edgar Kotokak (N)	NT1506	1,124	76	665	8.75	45,990	1.26
	NT1508	1,896					
	NT1526	1,161					
	Total	4,181					
Edgar Kotokak (N)	NT1505	1,712	145	964	6.65	90,960	2.36
	NT1520	1,985					
	NT1527	2,094					
	Total	5,791					

Key: (O) = Open Propeller pre Refit, (N) = Nozzle Propulsion post Refit

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