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Evaluation of a Modified Water Cannon System to Control Small Iceberg Masses

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EVALUATION OF A
MODIFIED WATER CANNON SYSTEM
TO CONTROL SMALL ICEBERG MASSES

Gregory Warbanski
Erik Banke

HUSKY/BOW VALLEY EAST COAST PROJECT
St. John's, Newfoundland

Scientific Adviser: D. Strong

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Frontispiece: The water cannon mounted on the bow of the MV Placentia Bay

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

SUMMARY

Loss of valuable drilling time and concern for the safety of drilling operations on the Grand Banks of Newfoundland led to the investigation of improved techniques for controlling small ice masses, such as growlers, bergy bits, and small icebergs, which have been difficult to control by means of conventional towing and propeller-washing techniques.

The concept of using water cannon designed for offshore fire-fighting to increase the drift speed and to change the drift direction of small ice masses evolved during drilling operations off Labrador in the early 1980s (Anderson et al. 1986). An initial, short-term, but full-scale, evaluation program was conducted by British Petroleum and Husky/Bow Valley in 1985 using the MV Skandi Alfa. British Petroleum also used the MV Skandi Alfa for operational ice-management support during June to October 1985 at their Baie Verte J-57 well site, just north of the Grand Banks. The two, conventional, fire-fighting water cannon on the MV Skandi Alfa were mounted above the bridge and did not have a sufficiently fast response to compensate for vessel motion, a less than optimum arrangement for ice management purposes. Despite these shortcomings the evaluation program indicated that substantial control of small ice masses was achievable.

Based on the encouraging results, Husky/Bow Valley proceeded with procurement of a single-cannon system in November 1985 which was specifically designed for the ice application. It was felt that a single-cannon system intended specifically for changing the drift speeds and drift direction of small ice masses should incorporate water cannon motion compensation and placement of the cannon on the bow of the vessel.

This choice of location allows for a more favourable horizontal component for the water jet forces and allows the introduction of a safer working distance between the vessel bow and the iceberg. The ability to view the iceberg target during water cannon pushing operations is also improved.

To achieve continuous and consistent impacts of the water jet on iceberg sails, a high-powered, hydraulic, control system was incorporated as part of the motion compensation system for the single cannon. This feature facilitated almost instantaneous rotation of the cannon in response to commands from the control panel on the bridge.

The water cannon system installation work, a retrofit, commenced in February 1986 and was completed by 19 April 1986. The steps taken to improve the single water cannon therefore consisted of:

- mounting the water cannon on the bow of the MV Placentia Bay;
- installing a motion compensation system with a high-powered hydraulic control unit to compensate for vessel motion; and
- selecting the appropriate nozzle size to maximize the reaction force created by the water jet.

The Environmental Studies Research Funds (ESRF) was approached in November 1985 with a proposal to evaluate the modified system on the MV Placentia Bay. After system installation, initial sea trials of the water cannon system were conducted successfully outside St. John's Harbour on 19 April 1986 and immediately thereafter, water cannon evaluation operations commenced offshore.

Because of a shortage of icebergs in 1986, the test program was conducted in two phases. The initial phase started on 20 April 1986 and terminated on 21 May 1986. An interim report was prepared and submitted to ESRF in August 1986 covering the 26 push tests conducted during this test phase. A second phase was conducted during 1987 between March 11 and May 7.

A total of 54 push tests were conducted during the entire offshore test program. Other tests were conducted including:

- vessel positioning tests next to icebergs
- engine/pump tests with a range of nozzle diameters
- iceberg destruction tests
- vessel motion tests
- motion compensation evaluation tests

Push tests were conducted on icebergs ranging from 36 tonnes to 100,000 tonnes. Water cannon operations clearly demonstrated that changing drift speeds and changing drift directions is achievable with icebergs up to 60,000 tonnes (an iceberg this size would be a piece about 40 m long by 30 m wide by 16 m high or the size of an apartment building). Greater control can be exercised on smaller ice masses. Operations were carried out successfully in maximum combined seas to 7 m. In addition to changing drift speeds and drift directions, the water cannon demonstrated the ability to destroy small ice masses by thermal and mechanical interaction when sea temperatures were sufficiently high. This consideration could be important in achieving a greater degree of control of certain icebergs through the reduction of mass, at times of the year when water temperatures are high enough.

A clear demonstration of water cannon effectiveness in changing the drift direction of a small ice mass occurred on 15 May 1986 when berg 200 drifted towards the drilling unit Bow Drill 3 from the northeast. Berg 200, a small troublesome ice mass of 16,200 tonnes, defied earlier attempts to alter its drift course by conventional propeller-washing and towing methods. When the MV Placentia Bay commenced water cannon operations, the drift direction was successfully changed to a favourable southerly drift. This change in drift direction resulted in the Bow Drill 3 avoiding a shutdown situation. It is estimated that one full day of drilling time was saved during this single event.

Water cannon operations conducted offshore indicate that, as a result of placing the water cannon on the bow of the vessel and incorporating a high-powered hydraulic control unit in the motion compensation system, the single-cannon system on the MV Placentia Bay is very effective in controlling small ice masses up to about 60,000 tonnes. The modifications made to the system have resulted in a marked improvement in performance when compared to the conventional two-cannon system designed for fire-fighting on the MV Skandi Alfa and should therefore be of interest to oil industry operators drilling in iceberg-infested waters with a need for alternative methods of small ice mass management.

SOMMAIRE

À la suite du temps de forage perdu et des préoccupations exprimées au sujet de la sécurité des activités de forage sur les Grands Bancs de Terre-Neuve, on a cherché à améliorer les techniques de contrôle des petites masses de glace comme les bourguignons, fragments d'icebergs et petits icebergs, qui sont difficiles à contrôler au moyen des techniques traditionnelles de halage et de propulsion.

L'idée d'utiliser des canons à eau conçus pour lutter contre les incendies au large pour augmenter la vitesse de dérive et pour changer la direction de petites masses de glace est née au cours des forages effectués au large du Labrador au début des années 1980 (Anderson et al. 1986). Un premier programme d'évaluation à court terme mais complet a été réalisé par la British Petroleum et Husky/Bow Valley en 1985 en utilisant le MV Skandi Alfa. La British Petroleum a également utilisé le MV Skandi Alfa pour appuyer leurs activités de traitement des glaces de juin à octobre 1985 à leur puits J-57 de Baie Verte, juste au nord des Grands Bancs. Les deux canons à eau conventionnels du MV Skandi Alfa étaient montés au-dessus du pont et ne répondaient pas suffisamment vite pour compenser la vitesse du bateau, solution moins que satisfaisante pour le traitement des glaces. Malgré ces difficultés, le programme d'évaluation a montré que l'on pouvait arriver à contrôler notablement les petites masses de glace.

À partir de ces résultats encourageants, Husky/Bow Valley a acheté en novembre 1985, un système à canon unique conçu spécialement pour l'application à la glace. On a estimé qu'un seul canon spécialement destiné à changer la vitesse et la direction des petites masses de glace devrait prévoir une compensation du mouvement du canon à eau et la position du canon à l'avant du bateau.

Cet emplacement permet de lancer le jet d'eau de façon plus horizontale et d'introduire une distance de travail plus sécuritaire entre l'avant du bateau et l'iceberg. L'aptitude à voir la cible pendant l'opération est également améliorée.

Pour obtenir un impact continu et uniforme du jet d'eau sur l'iceberg, on a incorporé un système de contrôle associé au système de compensation du mouvement pour le canon unique. Ce dispositif a facilité presque instantanément la rotation du canon en réponse aux commandes du tableau de contrôle sur le pont.

Les travaux d'installation du système, une réadaptation, ont commencé en février 1986 et se sont terminés le 19 avril 1986. Les mesures prises pour améliorer le canon à eau étaient donc les suivantes :

- monter le canon à eau à l'avant du MV Placentia Bay;
- installer un système de compensation du mouvement avec une unité de contrôle hydraulique de grande puissance pour compenser le mouvement du bateau; et
- choisir la taille de gicleur appropriée pour maximiser la force de réaction créée par le jet d'eau.

En novembre 1985, on a demandé au Fonds de recherche pour les études sur l'environnement d'évaluer le système modifié du MV Placentia Bay. Après installation du système, on a fait avec succès des essais en mer au large du port de St. Jean, le 19 avril 1986, puis immédiatement après, on a commencé les opérations d'évaluation du canon à eau au large.

En raison du manque d'icebergs en 1986, les essais ont été réalisés en deux étapes. La première a commencé le 20 avril pour se terminer le 21 mai 1986. Un rapport d'étape présenté par FREE en août couvrait les 26 essais réalisés pendant cette étape. La deuxième a été réalisée en 1987 entre le 11 mars et le 7 mai.

On a effectué 54 essais au total pendant tout le programme. Il y a eu d'autres essais, notamment :

- des essais visant à placer le navire près des icebergs;
- des essais du moteur/pompe avec différents diamètres de gicleur;
- des essais de destruction des icebergs;
- des essais de mouvement du bateau;
- des essais d'évaluation de la compensation du mouvement.

Des essais ont été effectués sur des icebergs de 36 à 100 000 tonnes. Ils ont clairement montré que l'on peut modifier la vitesse et l'orientation de dérivation des icebergs pesant jusqu'à 60 000 tonnes (un iceberg de ce poids ferait environ 40 m de long par 30 m de large et 16 m de haut ou la taille d'un immeuble à appartements). Ce sont les masses de glace plus petites qui se contrôlent le mieux. Il y a des opérations réussies dans des maximums combinés (7 m) des vagues et de la houle. En plus de changer les vitesses et les directions, le canon à eau a montré qu'il pouvait détruire des petites masses de glace par une interaction thermale et mécanique lorsque la température de la mer est suffisamment élevée. Cela pourrait être important pour obtenir un degré élevé de contrôle de certains icebergs en réduisant la masse, pendant les saisons où la température de l'eau est assez élevée.

L'efficacité du canon à eau pour changer la direction d'une petite masse de glace a été démontrée clairement le 15 mai 1986, lorsque l'iceberg 200 a dérivé vers le lieu de forage Bow Drill 3 en provenance du nord-est. Iceberg 200, une masse glaciaire de 16 200 tonnes, avait déjà résisté aux tentatives de modifier sa course au moyen des méthodes traditionnelles = halage et propulsion. Après que le MV Placentia Bay ait utilisé le canon à eau, l'iceberg a modifié sa course vers le sud. Ce changement a évité au Bow Drill 3 d'interrompre ses activités. On estime qu'une journée de forage a ainsi été économisée.

Les opérations menées au large des côtes indiquent qu'en ayant placé le canon à eau à l'avant du bateau et en incorporant un dispositif de contrôle hydraulique à forte puissance dans le système de compensation du mouvement, le système de canon unique sur MV Placentia Bay est très efficace pour contrôler les petites masses glaciaires jusqu'à 60 000 tonnes. Les modifications apportées au système ont grandement amélioré la performance par rapport au système traditionnel à deux canons conçus pour éteindre les incendies du MV Skandi Alfa et s'avère donc intéressant pour les exploitants pétroliers qui forent dans des eaux infestées d'icebergs en leur offrant une autre méthode pour traiter les petites masses glaciaires.

INTRODUCTION

During their life-cycle, large icebergs slowly deteriorate and become smaller as a result of melting, erosion through wave-ice interaction, and calving. By the time they reach the growler stage they are often quite rounded and smooth. Because small ice masses such as growlers, bergy bits, and small icebergs can sometimes roll and overturn if unstable, they have often proven difficult to tow or deflect using conventional tow lines and tow nets.

The inadequate control of certain growlers and bergy bits has been of some concern to operators of drilling rigs on the Grand Banks where the presence of ice masses free-drifting in the vicinity of semi-submersible drilling units presents an economically unacceptable situation. Growlers and bergy bits have shut down drilling operations in the past, at times resulting in significant loss of drilling time. For example, in June 1985, a bergy bit that could not be controlled adequately by tow rope, tow net, or propeller-washing forced three drill rigs to cease drilling operations for several days. Results from a preliminary testing program with the MV Skandi Alfa in 1985 indicate that this bergy bit could easily have been diverted away from the rigs (and perhaps destroyed in the process) if a vessel equipped with water cannon had been available.

Many of the ice masses tracked by Husky/Bow Valley during the course of drilling on the Grand Banks have been of such small dimensions that their drift directions and drift speeds could have been changed substantially by application of the water cannon. During drilling of the Conquest K-09 well site between 12 November 1984 and 17 July 1985, 56 of the 102 observed ice masses displaced less than 50,000 tonnes and, therefore, could potentially have been controlled by a water cannon system.

Consideration for the safety of drilling operations and a necessity to reduce lost drilling time has led offshore operators to search for new methods for diverting small ice masses. Methods include a variety of nets, a sinking/floating towline combination, single-point attachment devices, and the water cannon.

Technology developed for fire-fighting offshore has great potential for the purpose of diverting small ice masses. This new concept was first tried offshore Labrador in 1982 when the MV Maersk Rider under contract to Petro Canada attempted a single push test on a small ice mass. The test results were never documented, but it was perceived at the time that water cannon could be effective in pushing small ice masses away from their free drift paths. The MV Maersk Rider was unfortunately transferred shortly thereafter to another drilling operation offshore Nova Scotia and departed iceberg waters.

During 1985, the supply vessel MV Skandi Alfa provided ice management support for drilling operations at the British Petroleum BP Beau et al Baie Verte J-57 drilling location, north of the Grand Banks. The MV Skandi Alfa was equipped with two, conventional, fire-fighting water cannon mounted above the wheel house. To test the feasibility of controlling small ice masses by water cannon, Husky/Bow Valley organized a full-scale evaluation program with British Petroleum. A short, full-scale, engineering evaluation program was conducted in August 1985.

Although the positions of the fire-fighting water cannon on the MV Skandi Alfa were less than ideal for the purpose of pushing icebergs, the results of that program conclusively demonstrated great potential for controlling small ice masses by water cannon. During drilling operations at Baie Verte J-57, it was estimated by BP that at least one million dollars worth of drilling time was saved as a result of water cannon operations.

Based on these encouraging preliminary results, Husky/Bow Valley and Husky Marine Services designed a water cannon system specifically for ice application and proceeded with procurement of components to be mounted on a Husky Marine vessel. To maximize the water cannon thrust (and thereby to attain the best control of ice mass drift speed and direction), it was felt that the water cannon should be mounted on the bow of the vessel closer to the ice target and lower than its previous bridge-top position, thereby improving the horizontal component of forces. It was concluded that compensation for vessel motion at the bow would be required to enable more consistent pointing of the water jet onto an iceberg target area. Moving the water cannon from above the wheel house to the bow area would also eliminate the obstruction to vision from the bridge created by the water jet and should significantly reduce the potential of spray from the water jet causing vessel-icing during operations in the colder months.

Retrofit work began early in February 1986 and by April 19 the entire water cannon system was installed and operational on the Husky Marine Services supply vessel, MV Placentia Bay. Sea trials were conducted outside St. John's harbour on April 19 and by April 29, Thune Eureka, the supplier of the water cannon system declared that the system met the required specifications.

A single water cannon with 3,600 m^3/h output capacity is mounted on the bow of the vessel. A 51-cm diameter fibreglass pipe delivers the sea-water from a centrifugal pump. The pump is mounted forward of the ship's port inboard main engine which provides 2,000 kW of power. The sea-water intake pipe and intake valve are located directly below the pump. A vessel motion sensor, a central computer, and a 44-kW hydraulic power supply comprises the motion compensation system. Manual joystick control and automatic motion compensation of the cannon is activated on a control panel situated on the vessel's bridge adjacent to the normal vessel controls.

An initial phase of the offshore engineering evaluation program was conducted during April and May 1986. Because of a shortage of icebergs the remainder of the test program was postponed until 1987. When icebergs returned to the Grand Banks in the spring of 1987, a second phase of the engineering evaluation program was conducted. The test program was to assess the performance of the improved water cannon system and to define operational limits imposed by high sea states, high winds, iceberg mass, and drift dynamics.

This report describes both phases of the offshore engineering evaluation program of the water cannon system conducted on the Grand Banks during the spring of 1986 and 1987 respectively. A total of 54 push tests were conducted on icebergs that ranged in size from 36 tonnes to 100,000 tonnes. Maximum combined seas of 7 m were experienced.

TEST EQUIPMEMT

WATER CANNON SYSTEM INSTALLATION

The water cannon evaluation program was conducted with the following equipment installed on the MV Placentia Bay:

- the water cannon system
- the positioning system
- the vessel motion sensor package
- additional test equipment.

The water cannon system consists of six integral components (Fig. 1):

- the water cannon mounted on the bow
- the piping system inside the vessel
- the sea chest for water intake
- the centrifugal pump
- the drive train
- the motion-compensation and water cannon control system.

Water Cannon on the Bow

The cannon (Model EF400 built by Thune Eureka of Norway) is mounted on a pedestal approximately 11 m above the water on the bow of the MV Placentia Bay and 3 m aft of the bow bumper (Figs. 2 & 3). Sea-water, provided by the centrifugal pump at high pressure and in volumes as large as 3,600 m^3/h, is ejected through the cannon nozzle (Fig. 4) at speeds up to 54 m/s.

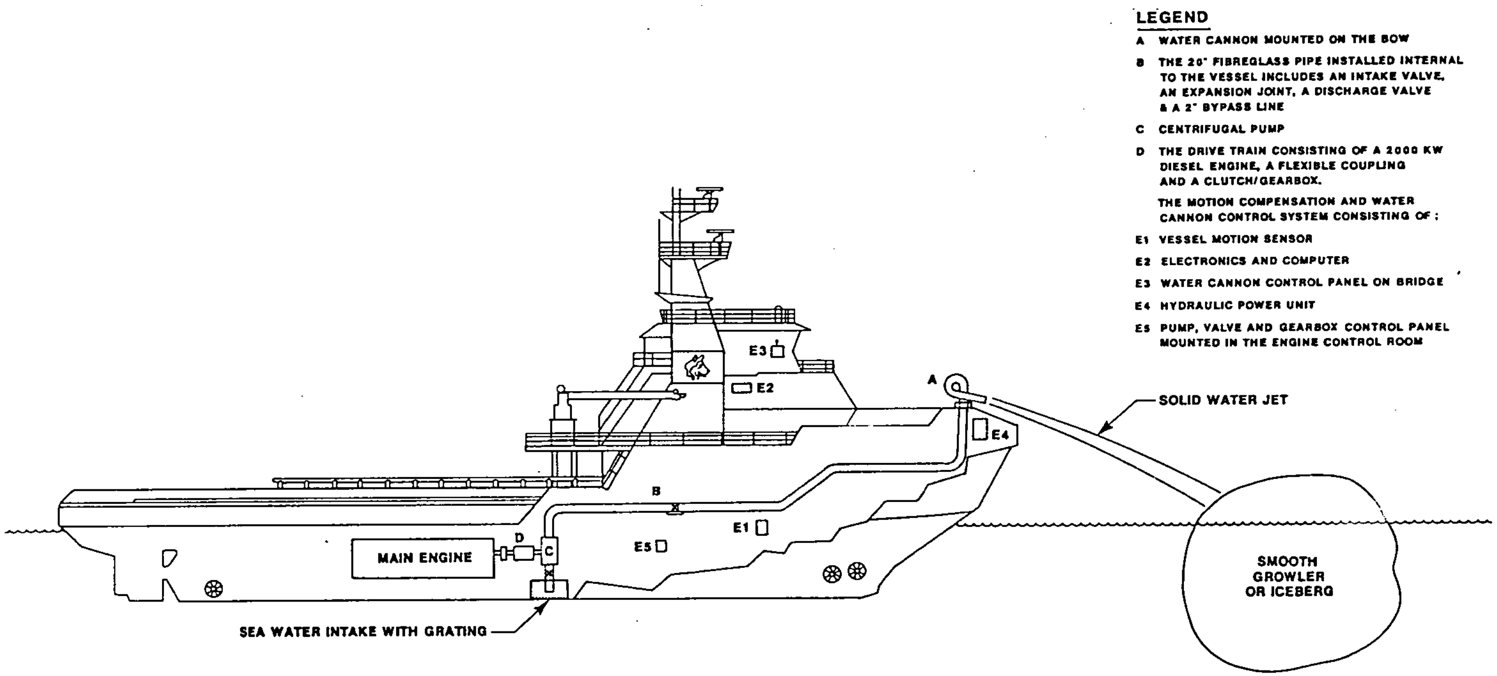


Figure 1. Husky marine vessel with water cannon (cutaway view).

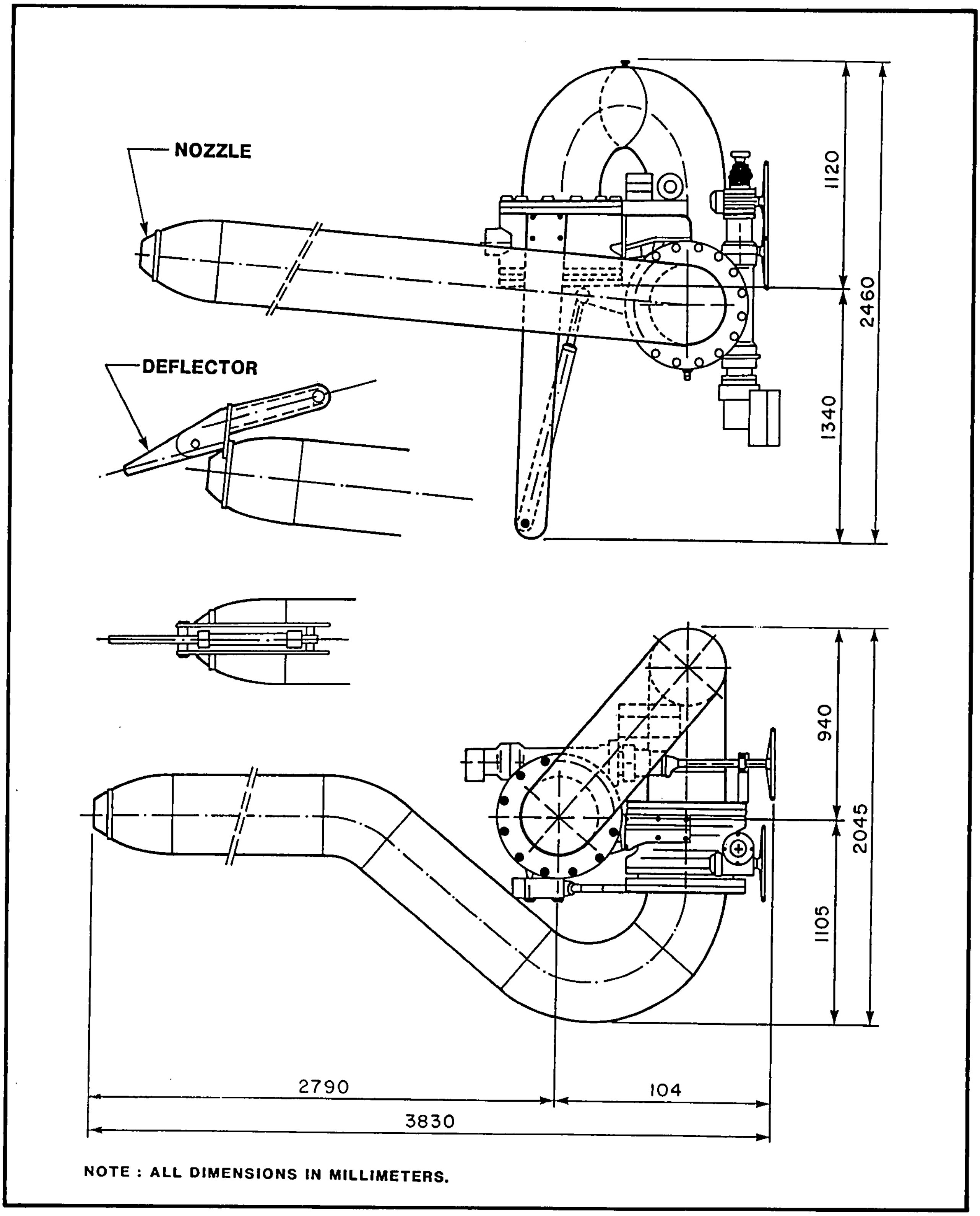


Figure 2. Water cannon Model EF400.

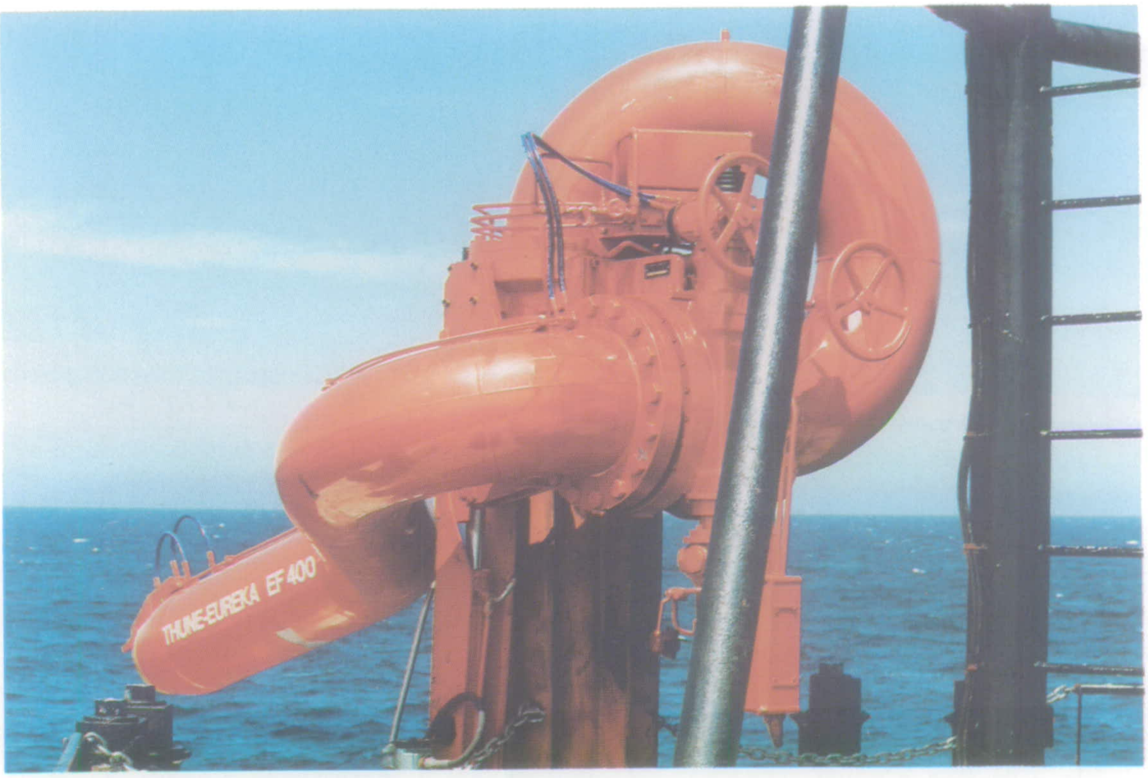


Figure 3. The 3,600-m^3/h capacity cannon mounted on the bow of the MV Placentia Bay.

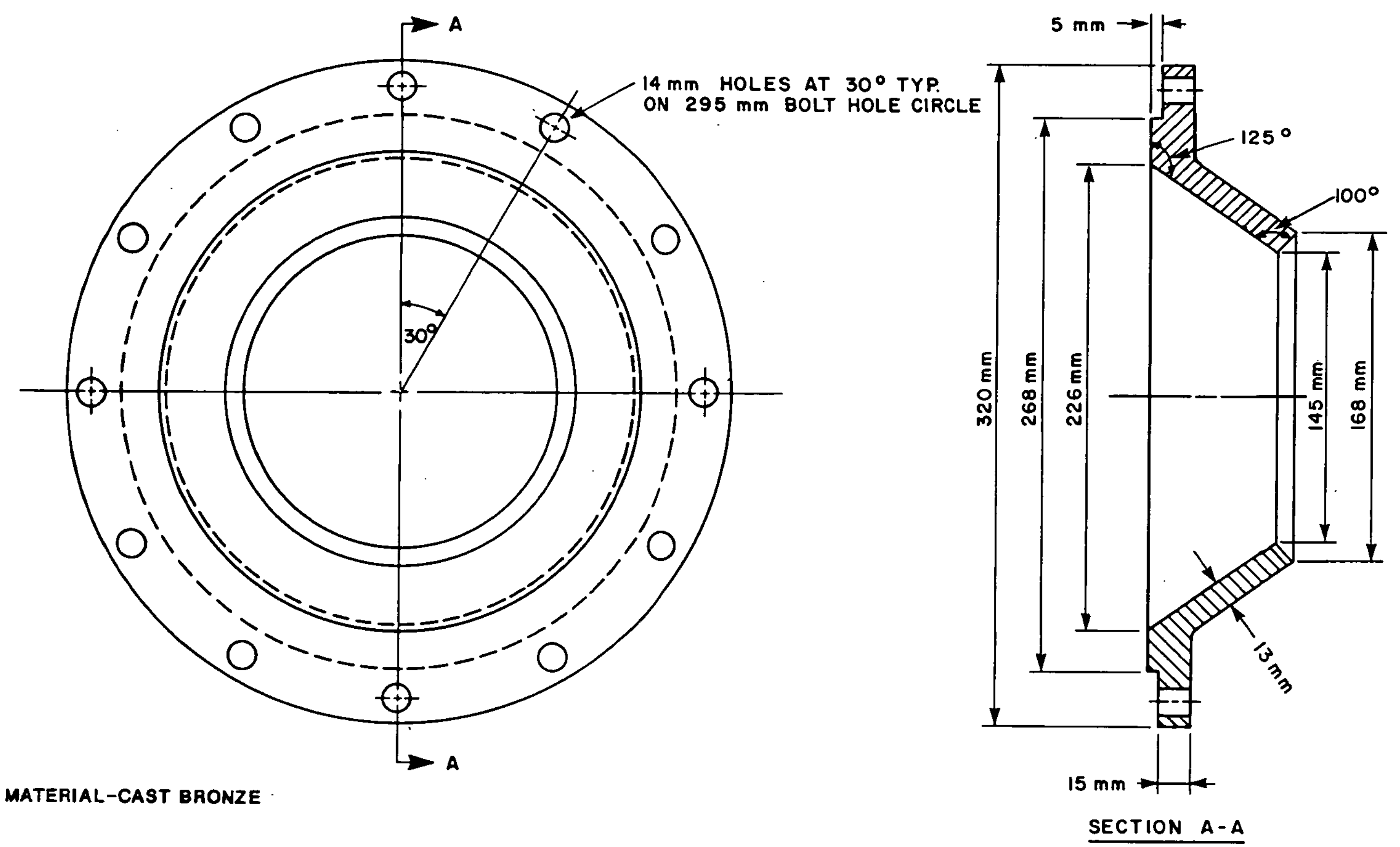


Figure 4. Thune Eureka water cannon nozzle.

The force of the water jet is approximately 5 tonnes. It is this force which, applied continuously to an iceberg, enables speed enhancement and direction control. A 145-mm diameter nozzle of cast bronze was also provided by Thune Eureka. This nozzle delivers sea-water at a rate of 3,100 m^3/h at an operating pressure of 18.5 bars. The purpose of this large nozzle was to maximize the jet reaction force for pushing icebergs. Thune Eureka also supplied a 100-mm diameter nozzle which operates at a pressure of 20 bars while delivering 1,600 m^3/h of sea-water. The intended use of this nozzle was to cut notches at the water line of icebergs in which a tow rope could be seated.

In addition to the two nozzles provided with the water cannon system, Husky/Bow Valley had three other nozzles. These nozzles were modified onboard the vessel so that engine/pump tests could be conducted with a range of nozzle diameters, including 100, 125, 130, 145, 152, and 165 mm, to select the nozzle diameter most compatible with the operation of the ship's MAK diesel engine. The desired operating parameters for the engine are 650 rpm and near 100% of the full power for the MAK diesel which is 2,000 kW.

For fire-fighting purposes, a hydraulic cylinder can be used to force a wedge-shaped deflector into the water jet at the exit side of the nozzle. This deflector alters the water jet from a solid stream to a highly diffused cloud of high-velocity mist. The deflector is activated by pressing a button on the joy stick on the water cannon control panel situated on the bridge.

Because of the reaction forces from the water jet, 20% of full power (from the remaining three main engines not occupied with providing power to the centrifugal pump) is required during water cannon operations with icebergs to maintain a constant ship heading and position relative to the iceberg. Bow thrusters are instrumental in maintaining desired ship headings and position adjacent to an iceberg target.

The closest distance from the vessel that the water jet can strike the water surface is 16 m from the bow, or a horizontal distance of 19 m from the water cannon axis of rotation.

Visibility from the bridge is such that the water surface can be seen as close as 14 m from the bow (Fig. 5) therefore, the ice mass can be seen from the bridge even when the water cannon is pointed downward as far as possible below the horizontal. Operationally, the water cannon would be pointed down when destruction of an ice mass is in progress.

Usually the vessel is positioned during operations such that the ice mass is not directly ahead of the vessel but is situated off the port or starboard bow. This mode of operation is preferable because bow thrusters as well as the vessel propellers and the water cannon reaction forces can be used to back away from the ice mass in case rolling of the ice mass should occur. In addition, when the ice mass is situated adjacent to the port or starboard bow, it is easier to see from the bridge as the ice mass is less obscured by the impacting water and it is therefore easier to judge the actual distance to the berg.

The impact forces of the water jet on a target such as an iceberg, is equivalent to a small car (about 1 tonne) striking the berg every second at 54 m/s and coming to a virtual standstill. Because of the reaction force, the MV Placentia Bay would be pushed astern at about 3 knots, if propellers were not used to maintain a fixed position.

To ensure that the cannon cannot point at any part of the vessel and cause structural damage or injury to personnel, stops are installed to limit horizontal rotation to ±65 degrees, and in the vertical plane to 65 degrees above and 30 degrees below the horizontal. Movement of the cannon in azimuth and elevation is achieved by means of hydraulic-mechanical activators. Manual adjustment of initial pointing in the horizontal and vertical plane is available by means of two hand wheels on the cannon.

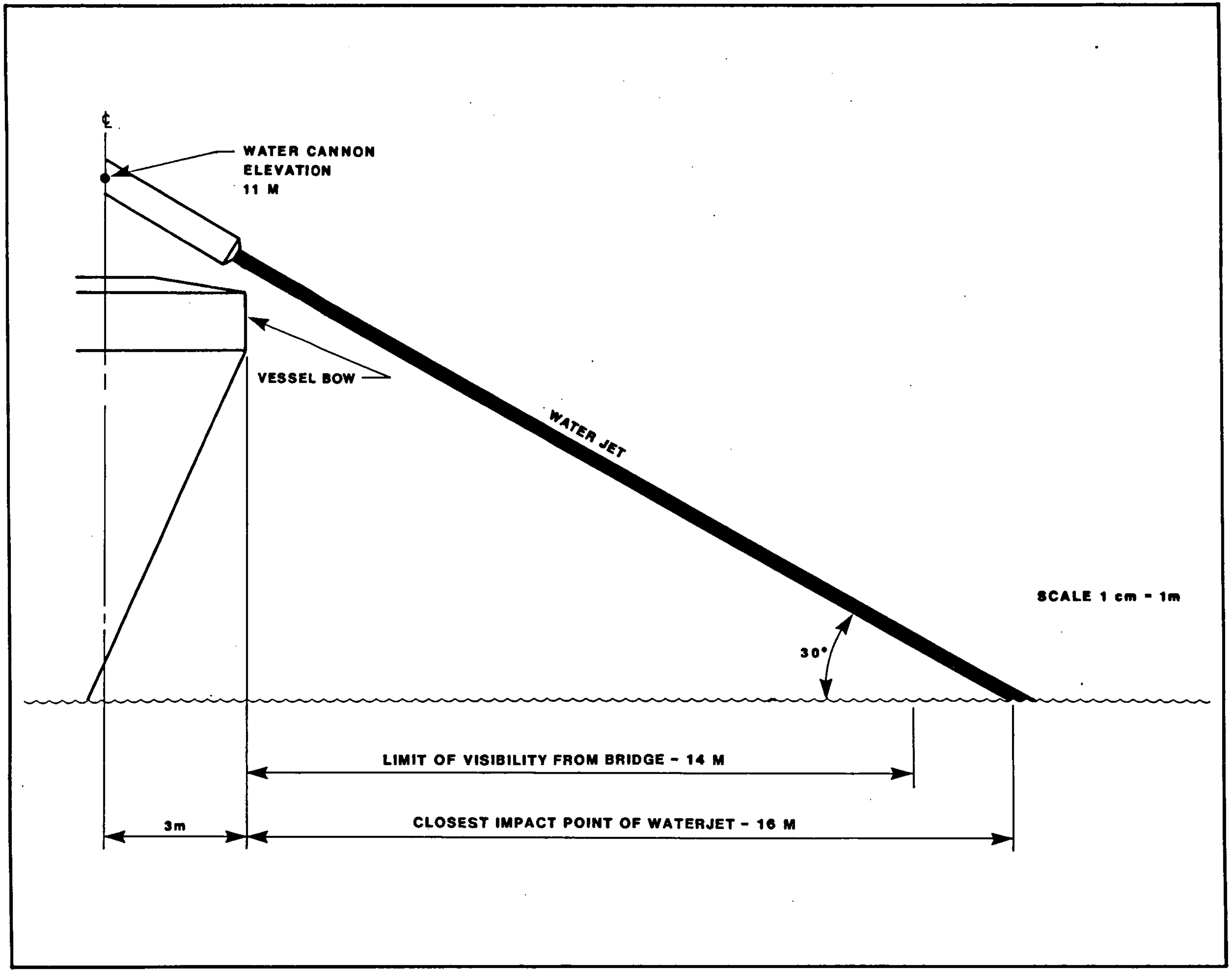


Figure 5. Water cannon on the bow of the MV Placentia Bay at the maximum downward-pointing position.

For protection against sea-water freezing inside the water cannon, electric heating is employed. Protective jackets have been installed to protect external components from freezing spray and from sea-water.

Interior Piping System

The pipe run connects the high-pressure side of the centrifugal pump to the water cannon (see Fig 1). The 51-cm inside-diameter pipe consists of fibreglass sections flanged to steel pipe stubs at each bulkhead penetration. The design pressure is 10 MPa for system operating pressures below 2 MPa. Thune Eureka estimates a pressure loss of 0.5 bars through the pipe.

The entire pipe run, which includes a discharge valve and a 5-cm bypass line, is installed inside the vessel to eliminate freezing problems. The discharge valve is situated at the vessel's main collision bulkhead at the forward end of the engine room. It exists for the purpose of maintaining the integrity of the collision bulkhead as well as providing a means of shutting off the flow of water to prevent flooding in case of pipe fracture. The valve is activated manually. The installation meets both Canadian Coast Guard and Lloyds of London ship classification specifications.

The 5-cm bypass line is installed to permit the piping system to be slowly filled with water prior to opening the discharge valve. This eliminates surge forces (water hammer) associated with water flowing through an empty pipe.

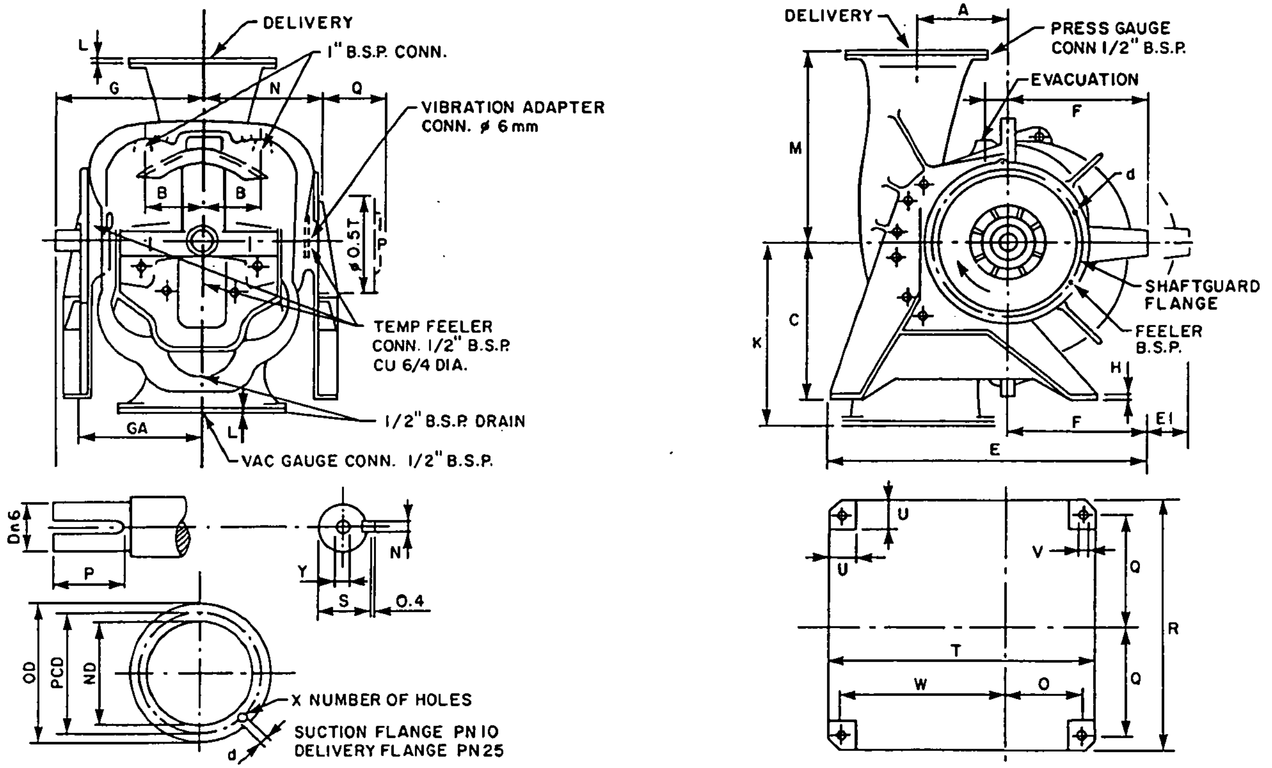
When full of water, the piping system contains in the order of 10 tonnes of sea-water, flowing at speeds up to 4.5 m/s. Fibreglass pipe was selected because of the relative ease of installation, and because of weight considerations as the fibreglass pipe is much lighter than steel pipe. The prefabricated fibreglass sections were tested to 1.5 times the working pressure by the manufacturer, ABCO Plastics Ltd. of Mahone Bay, Nova Scotia, prior to installation. Once installed, the piping system was pressured to 2 MPa, and viewed by Lloyds of London for certification purposes.

The suction side of the centrifugal pump includes a sea-water intake valve, an incoloy and stainless steel expansion joint, and a steel pipe stub penetrating the hull and extending into the seabay. The sea-water intake valve can be opened and closed manually and by push button on the control panel located in the engine control room (for pump, valve, and gearbox control). The seabay entrance contains a steel grate to prevent ingestion of debris and obstruction of the intake pipe.

When a system pressure drop occurs (because of a pipe fracture, for instance) the intake valve closes automatically and the clutch is automatically disengaged shutting down the centrifugal pump. This action prevents pumping sea-water into the vessel. The intake valve can also be closed and the clutch disengaged manually by the engine room crew.

Centrifugal Pump

The centrifugal pump, a Thune Eureka Model C 32BA (Fig. 6), has a pumping capacity of 3,600 m^3 of sea-water per hour, and an operating pressure of 16 to 20 bars. Typical suction pressure is -0.9 bars. Suction and delivery pressures are monitored on the control panel (for pump, valve, and gearbox) situated in the engine control room, and a pressure gauge is installed on both the high-pressure side of the pump, and on the low-pressure (suction) side. The high-pressure gauge indicates discharge pressures to 25 bars, and the suction-pressure gauge has a range of -1 bar to +1.5 bars. The centrifugal pump is located forward of main engine number 2, which is situated inboard on the port side. To provide positive suction at all times, the pump is placed below the vessel water-line. The main shaft of the pump is splined to the output shaft from the speed-increase gear box, which can transmit a maximum of 1,950 kW at 1,600 rpm. The pump performance curves are presented in Figure 7.



PUMP TYPE–SIZE	MAIN DIMENSIONS													BASE DIMENSIONS							WEIGHT KGS
	A	B	C	E	EI	F	G	GA	I	J	K	M	N	O	R	T	Q	U	H	V	W	
C32BA 14-18	315	230	560	1065	315	510	570	450	125	380	630	630	400	220	920	830	410	120	25	33	500	1070

PUMP TYPE–SIZE	SUCTION FLANGE						DELIVERY FLANGE						SHAFT GUARD FL.				SHAFT				
	ND	OD	PCD	d	x	L	ND	OD	PCD	d	x	L	OD	PCD	d	x	D	P	S	Z	Y
C32BA 14-18	450	615	565	26	20	34	350	555	490	33	16	38	450	410	14	8	85	150	90	24	M24

Figure 6. Centrifugal pump.

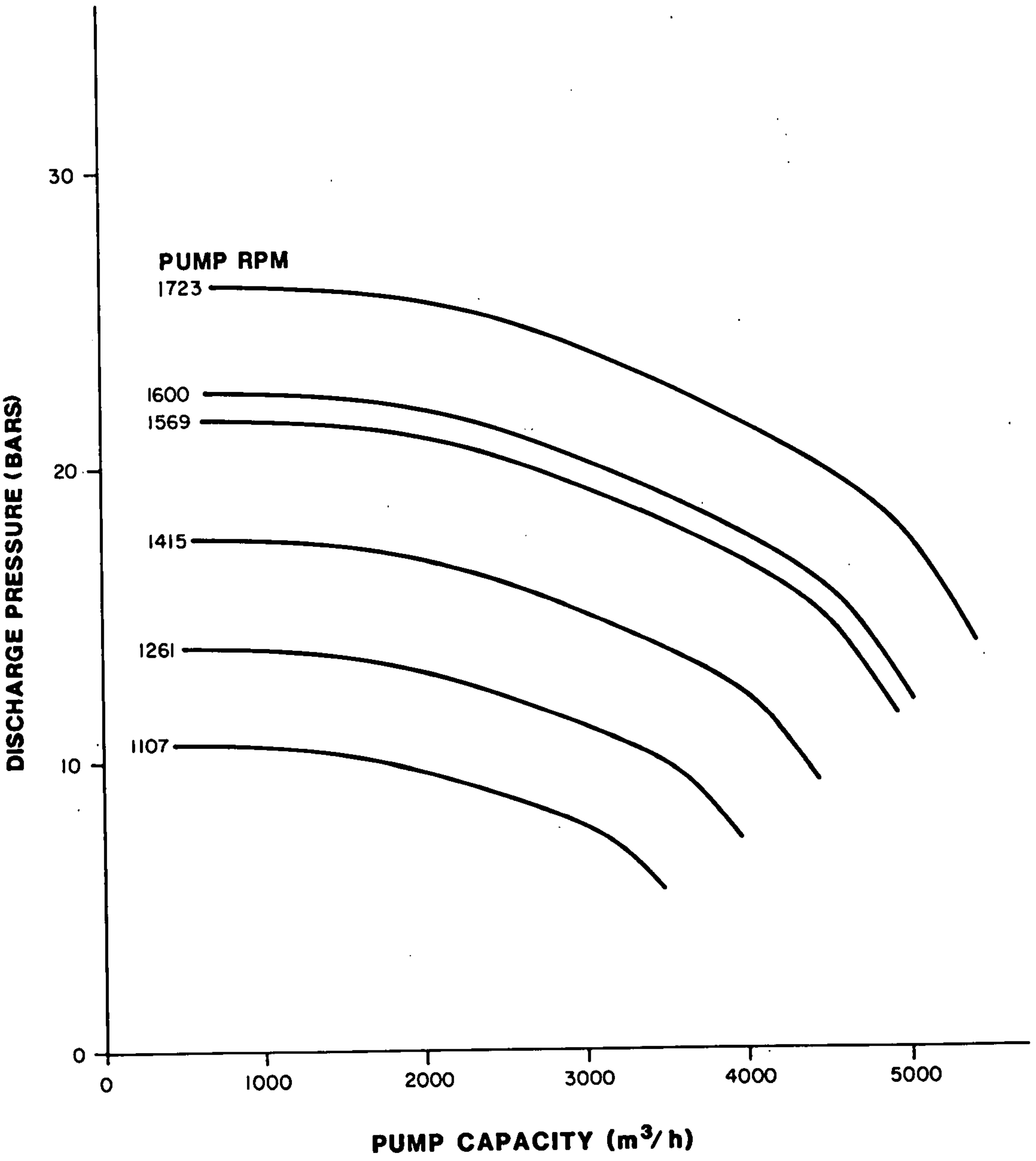


Figure 7. Centrifugal pump performance curves.

Drive Train

The power required to pump sea-water for directing small ice masses is supplied by one main engine on the inboard port side of the vessel. A full 2,000 kW of power is available at 650 rpm. A stub shaft connects the forward end of the engine drive shaft to a flexible coupling, which compensates for small misalignments along the shaft axis between the engine and the gearbox. The flexible coupling is connected to the input shaft of the Hytek/Tacke speed-increase gearbox, which also incorporates a multi-plate hydraulic clutch. The gear box increases the 650-rpm input from the engine to 1,600 rpm output, and has a continuous operating capacity of 1,950 kW. The high-speed output shaft connects directly into the centrifugal pump.

To activate the pump, the engine revolutions are reduced to 400 rpm and the clutch is engaged. Then the engine speed is increased gradually to 650 rpm at which full power is available for pumping.

The clutch is engaged and disengaged by push button on the control panel (for pump, valve, and gearbox control) located in the engine control room. In case of emergency, the clutch can be disengaged by pushing the "Clutch Emergency Release" button on the water cannon control panel, mounted on the bridge. A sudden pressure drop in the pipe will disengage the clutch automatically to prevent flooding of the vessel.

Motion Compensation and Water Cannon Control System

The function of the computer-controlled motion compensation system is to continually point the cannon (and water jet) at a preselected point target by compensating for vessel heave, pitch, roll, and yaw. Vessel heave, pitch, and roll information is provided by a motion sensor located amidships. Information on deviation of ship heading (yaw) from a preselected heading is provided by the ship's gyro compass.

Compensation for vessel translation is provided by activating bow thrusters and propellers such that the vessel position with respect to the iceberg is basically constant. In reality, the vessel is manoeuvred continually to hold position.

The motion compensation and water cannon control system consists of the following components (see Fig. 1):

The vessel motion sensor. This sensor is located 5.5 m directly above the keel, 6.0 m below the water cannon rotation axis, and horizontally 17.8 m aft of the cannon pedestal location. The motion sensor is mounted inside the forward bulk room, on the forward side of the aft bulk head. It includes a Datawell accelerometer to measure vessel heave and two inclinometers to measure vessel pitch and roll.

Motion at the water cannon is calculated (using solid-body translation methods) from the motion sensor location to the water cannon location. The calculations are performed by the system computer.

System computer. This unit is located in the electronics room immediately below the bridge. Midship motion information from the Datawell motion sensor, and information on vessel yaw (rotation about the vertical axis) taken from the Gyro compass are processed and translated to closely simulate motion at the water cannon location on the bow of the vessel. The simulated vessel motions at the water cannon are converted into proportional signals which control hydraulic valves to access the 44 kW of hydraulic power from the hydraulic power unit. This power is used to point the water cannon in the desired direction. The cycling frequency for computerized motion calculations and corresponding adjustments to the cannon pointing is 5 Hz.

Hydraulic cylinders on the cannon are activated in such a manner that the water jet will maintain a preselected target automatically when the stabilized mode of motion compensation is selected by the vessel's captain or system operator.

Water cannon control panel on the bridge. This panel (Fig. 8) is mounted on the bridge just above the ship's wheel for easy access by the captain. The main features of this panel are the joystick control for manual pointing of the water cannon, the stabilized mode settings for automatic motion compensated pointing of the cannon, a clutch emergency release control button, and power controls for the hydraulic power unit. In addition, a push-button control on the joystick activates the hydraulically controlled deflector that changes the solid water jet to a diffused jet suitable for fire-fighting.

Control commands flow from the control panel on the bridge to the system computer, which then transmits commands to the hydraulic system to activate the water cannon as desired.

Hydraulic power unit. Forty-four kilowatts of hydraulic power are available to change the angles of elevation and azimuth of the cannon at a rate of 20 degrees per second with a maximum acceleration of 50 degrees per second per second. The hydraulic power unit (Fig. 9) is situated forward on the deck immediately below the cannon, and uses the ship's electrical supply to power the hydraulic pumps. Hydraulic and mechanical power units (hydraulic cylinders) mounted on the cannon respond to commands to change the azimuth and elevation of the cannon as required.

Pump, valve, and gearbox control panel. The operating performance of the pump and gearbox is monitored on a control panel (Fig. 10), which is located in the engine control room. Pump suction and discharge pressures are displayed along with the status of the gearbox and clutch, and of the intake valve. Alarm lights indicate low lubrication-oil pressure, high lubrication-oil temperature, and low clutch-oil pressure. The clutch is engaged and disengaged from this panel, and the intake valve can be opened and closed from this panel by push button.

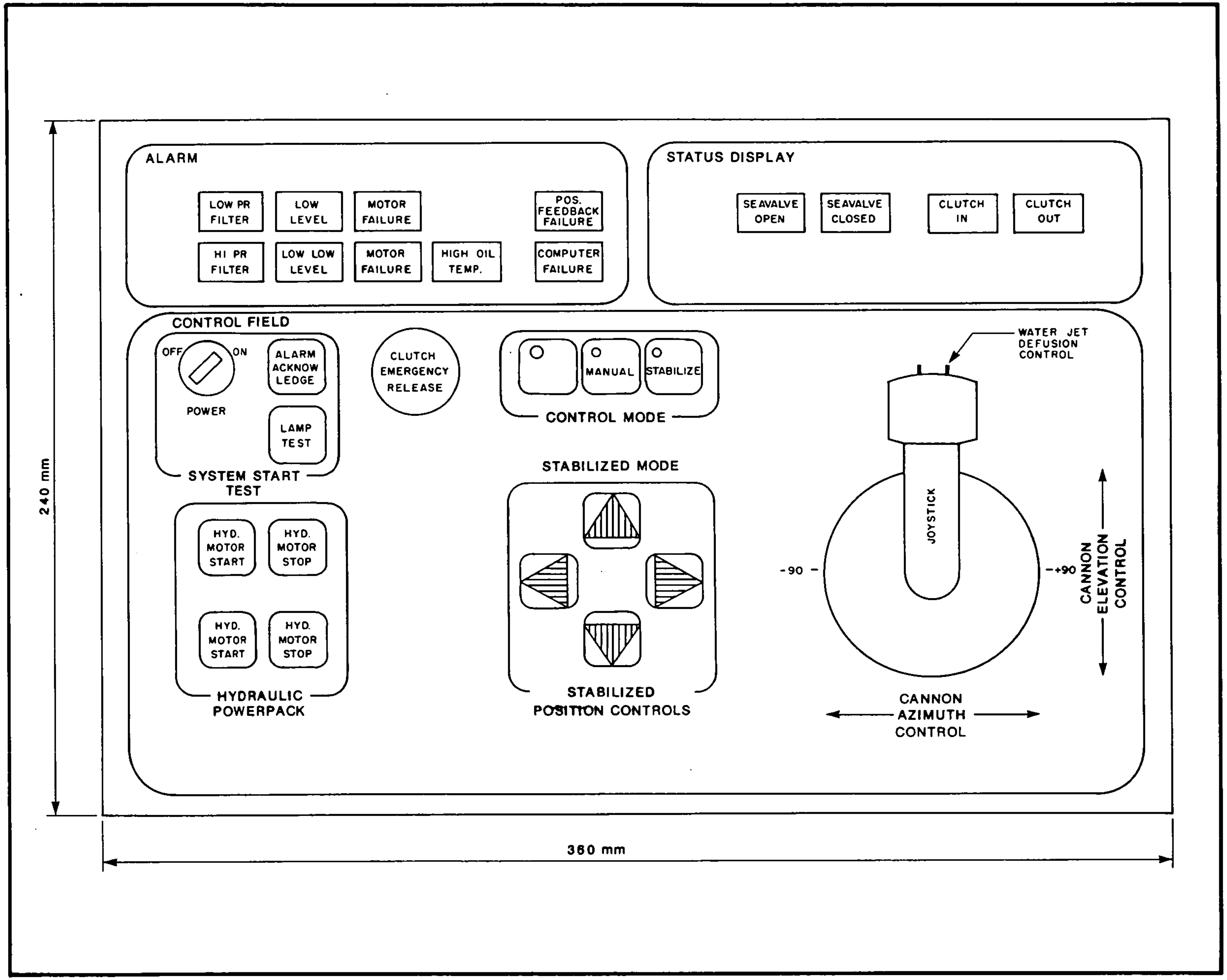


Figure 8. The water cannon control panel mounted on the bridge.

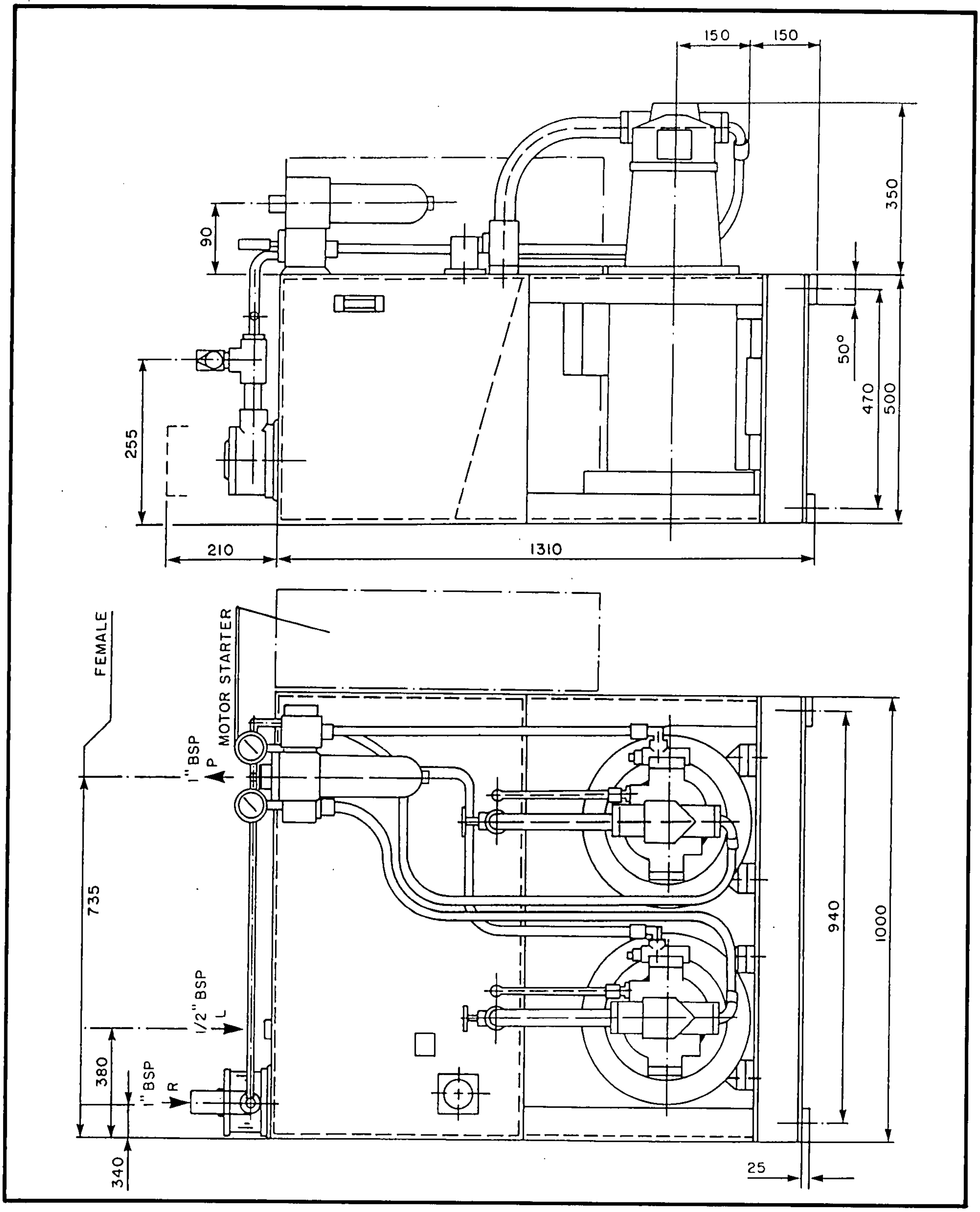


Figure 9. Hydraulic power unit.

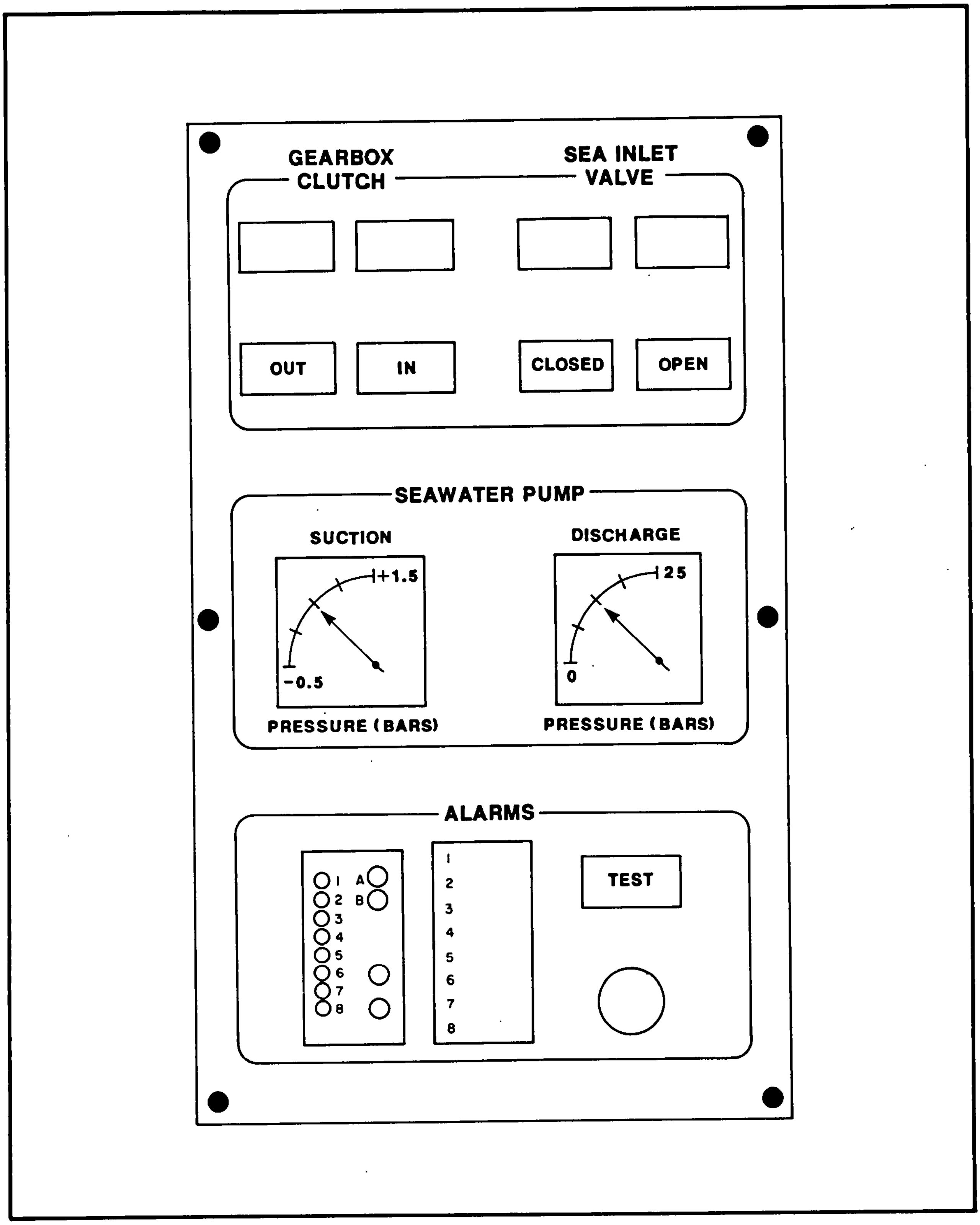


Figure 10. Control panel for the centrifugal pump, gearbox, and valves mounted in the engine control room.

POSITIONING SYSTEM

For determinations of speed increases and changes of drift direction associated with the application of the water cannon to small ice masses, accurate position fixes are required. At a typical drift speed of 0.6 knot, an iceberg traverses a distance of 1,200 m during 1 h. With a stated positional accuracy of 50 m, the distance measured would be 1,200 m ± 100 m, and the corresponding drift speed would be 0.6 knot ± 0.05 knot. This accuracy is considered sufficient for plotting changes in drift speeds and changes in drift direction for the associated ice masses.

To achieve the 50-m positional accuracy, McElhanney Offshore Surveys Ltd. of St. John's was retained to provide a senior offshore surveyor and the following equipment, which was installed on the bridge of the MV Placentia Bay (Fig. 11):

- one Internav Loran C model 408 operating in the RHO/RHO mode
- one Internav Loran C model 404 (back-up unit)
- one FTS frequency time standard
- one Magnavox dual-channel satellite receiver
- one Hewlett Packard 9826 computer
- one Okidata U82A microline printer
- one Electrohome colour monitor.

Computations of speed and drift were made by the Hewlett Packard computer using the McElhanney "NAVPAK" software. Drift of the Loran C system was checked periodically and accounted for in the position calculations. In addition to providing positioning services, McElhanney provided video coverage of water cannon operations.

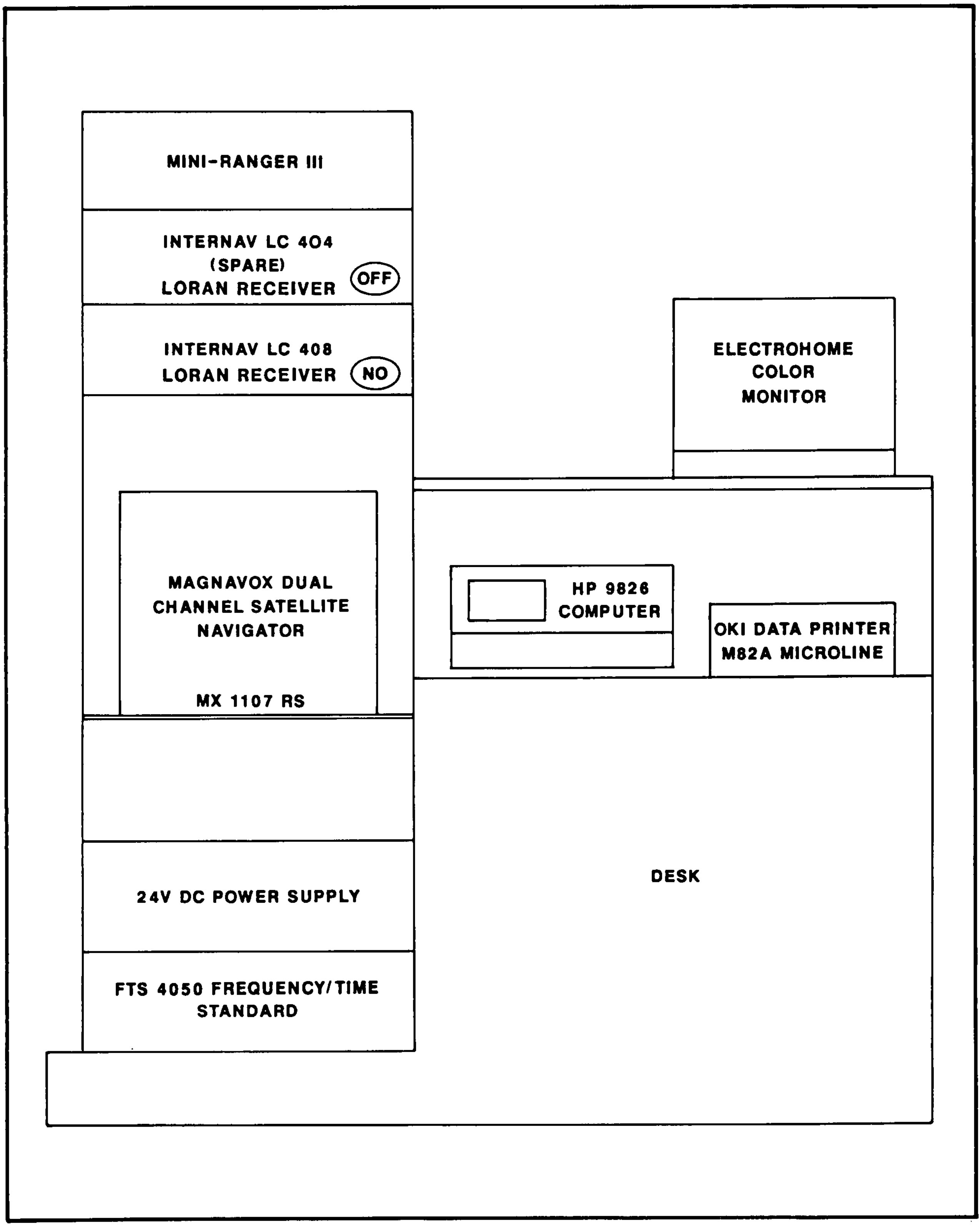


Figure 11. McElhanney positioning system installed on the bridge of the MV *Placentia Bay*.

INDEPENDENT MOTION SENSOR

A six-degree-of-freedom motion sensor, originally developed by the Centre for Cold Ocean Resources Engineering (C-CORE) at Memorial University of Newfoundland to monitor iceberg motion, was installed in the forepeak of the MV Placentia Bay.

Three servo-accelerometers were used to measure linear accelerations along orthogonal axes. To measure roll and pitch (angular rotation about the x and y axes respectively) two tilt gauges were installed. A solid-state compass was used to measure magnetic bearing.

The sensor cluster was installed about 60 cm aft of the water cannon base, and 30 cm below the deck plate on which the water cannon base is mounted. This location is 4.0 m above and 17.2 m forward of the location of the vessel motion sensor installed by Thune Eureka in the forward bulk room near midships. The six sensor outputs were filtered and multiplexed onto a single line, and were fed into a Hewlett Packard instrumentation recorder (Fig. 12). This arrangement allowed for about 1.5 h of data recording during the evaluation program.

The vessel motion information collected is relevant to the fine-tuning of the water cannon motion compensation system, and for determining vessel motion at any point in the vessel, through solid-body translation calculations.

The convention used in this study for the orientation of axes of motion appear in Figure 13. The linear accelerations AX, AY, and AZ are measured along the instantaneous position of the x, y, and z axes of the sensor cluster, hence their directions change with ship motion. The tilt meters are referenced to gravity, and measure the angles of the x and y axes with respect to vertical (TX, TY respectively). Thus values of TX less than 90° indicates the x axis is pointing upward; values of TX greater than 90° indicate the x axis is pointing downward. The compass measures the angle between magnetic North and the projection of the x axis in the horizontal plane.

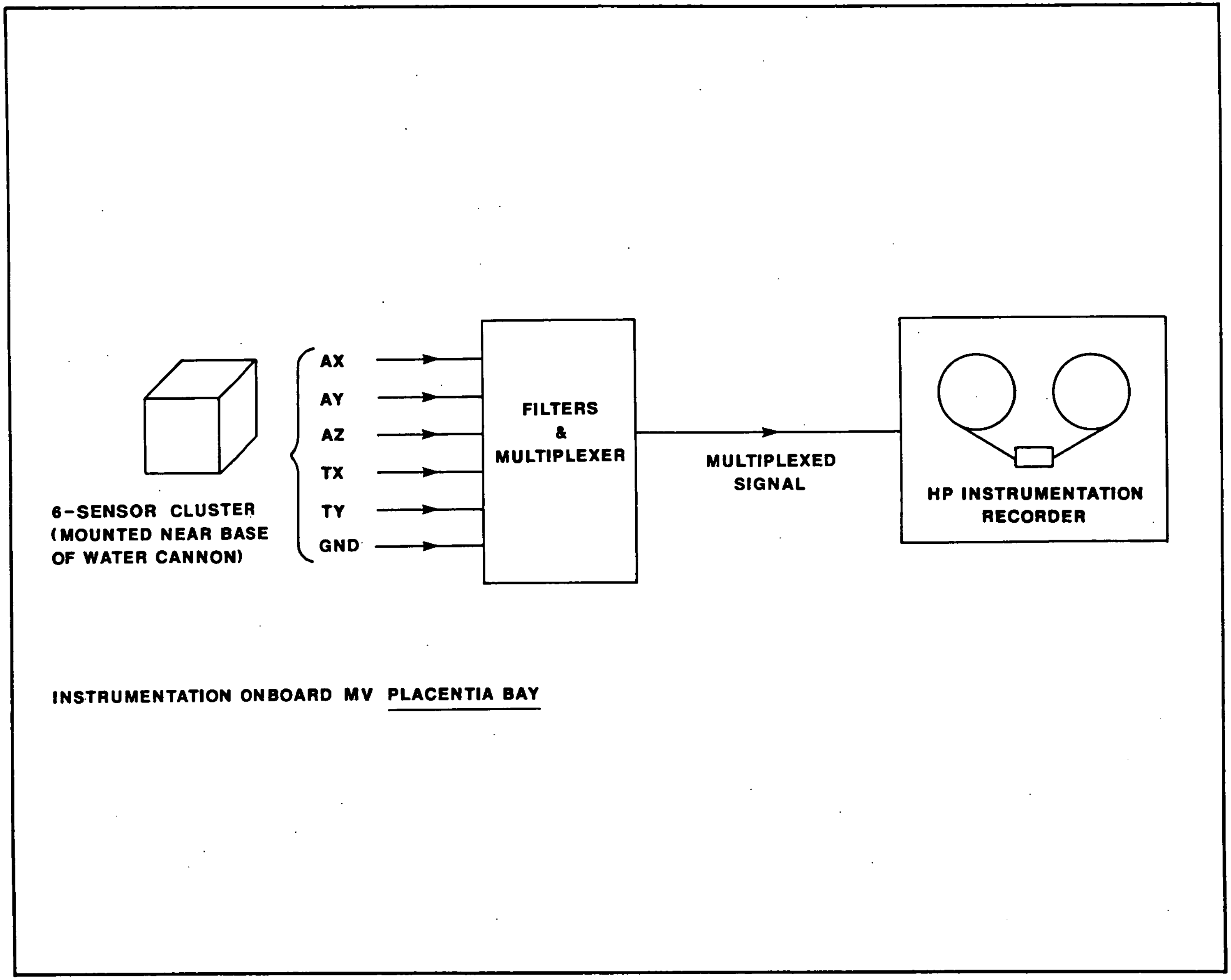


Figure 12. Independent motion measurement and data collection system.

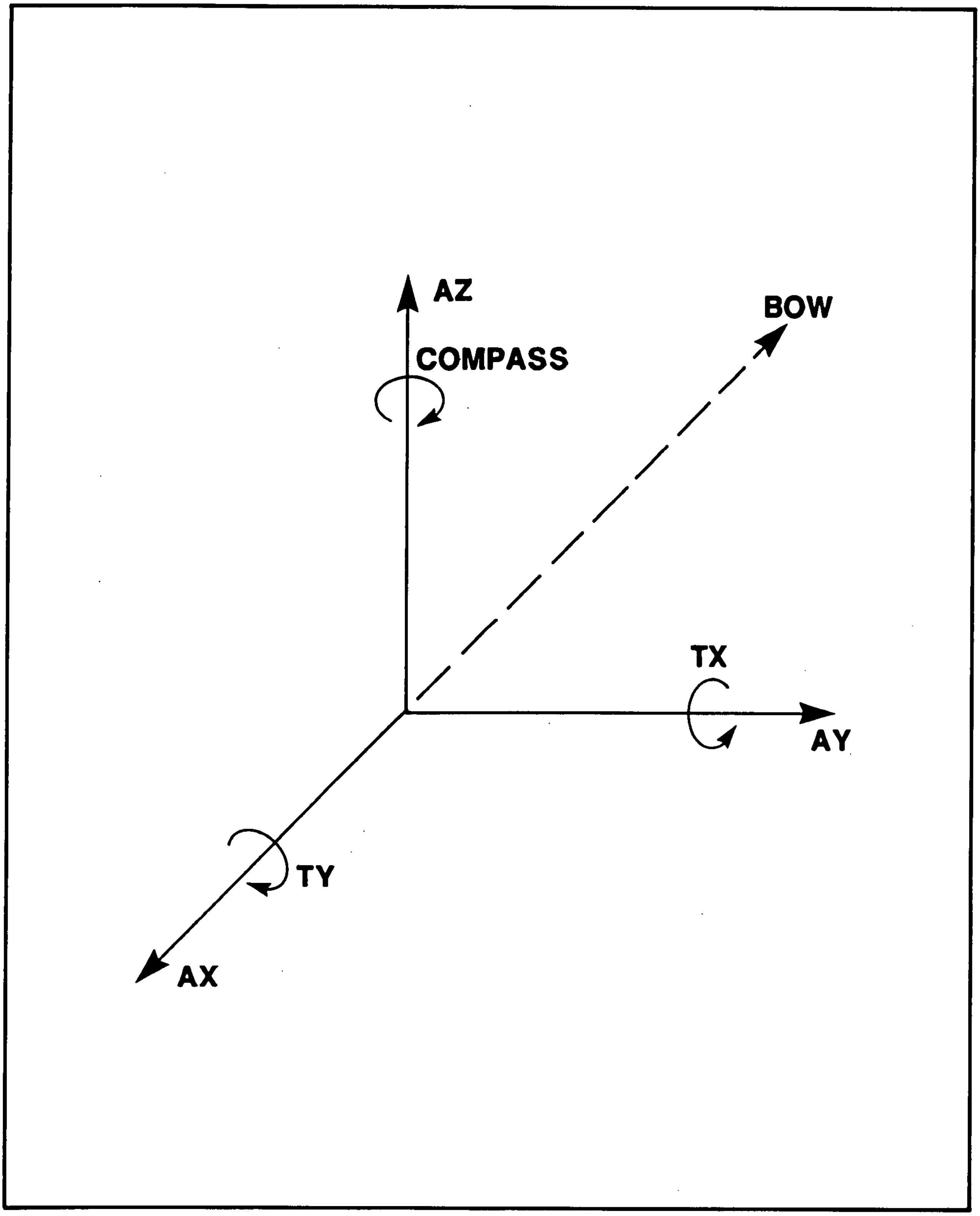


Figure 13. Convention for sensor axes of motion.

ADDITIONAL TEST EQUIPMENT

Additional test equipment required during the water cannon operational evaluation consisted of:

- one range finder
- one sextant
- assorted calculators and manuals
- various cameras for polaroid photographs, slides, and prints
- one VCR video camera.

METHODOLOGY AND PROCEDURES

Methodology and procedures for conducting the offshore test program with the modified water cannon system were developed primarily to permit evaluation of its capability to control small ice masses by changing their drift direction and increasing or decreasing their drift speed.

The methodology and procedures facilitated the collection of consistent test data, which in turn permitted the success of the modifications to be evaluated. This evaluation was accomplished by plotting the speed changes and the direction changes achieved by both the improved water cannon system on the MV Placentia Bay and the conventional, two-cannon, fire-fighting system on the MV Skandi Alfa on the same graphs to facilitate comparison.

Part of improving the performance of the modified water cannon system pertained to collecting vessel motion data (independent of the motion compensation system) at the water cannon location to assist in the fine-tuning of the motion compensation system. Procedures for both vessel motion data collection and engine/pump data collection were deemed useful and are therefore included although these aspects of water cannon operations were not part of the original test program proposal submitted to the Environmental Studies Research Funds.

Selecting the water cannon nozzle which permits the main engine to operate at the specified engine rpm, while generating the close-to-maximum water jet reaction force was another part of the optimization process.

TEST PROGRAM

The proposed test program is presented here for reference purposes.

Speed Enhancement as a Function of the Point of Application of the Water Jet. A series of push tests will be conducted on a range of ice masses to establish the optimum point of application of the water jet. The water jet can be applied a number of ways: directly onto the iceberg sail at some given height, onto the iceberg directly above the water line, or into the water near the water line.

The push test sequence will consist of one hour of free drift monitoring, followed by pushing the iceberg at sail height for one hour; then following another hour of free drift, the water cannon jet will be concentrated on the iceberg just above the water line. Another hour of free drift will be monitored, followed by one hour of concentrating the water jet on the water surface adjacent to the iceberg waterline. After three such test sequences, the speed enhancements achieved will be compared for the three methods and the optimum target point will be determined. Subsequent push tests will be conducted with the water jet applied to the optimum target area as defined by these tests.

Push Tests. Push tests will be conducted to assess the level of control of an ice mass which is represented by speed enhancement and the ability to change its direction using the water cannon.

Push tests will be conducted on a full range of iceberg masses from less than 1,000 tonnes to the greatest tonnage at which effective speed control and direction control reduces to zero. The upper limit of manageable iceberg mass is to be determined through the proposed test program.

Push tests will be conducted under the full range of sea state conditions available; the objective being to establish operational sea-state limits if possible, for operating the vessel and for conducting water cannon operations.

Push Test Directions. Push tests will be conducted in down drift, cross drift, and downwind directions, to establish the direction of push that provides maximum speed and direction control.

Ice Mass Destruction Tests. The rate of destruction of ice by the application of the water jet requires evaluation. The objective is to assess this technique for control of ice masses. For example, if a 1,500-tonne ice mass were intercepted within 15 h of drift from a rig, and the rate of destruction by thermal and mechanical interaction were 100 tonnes per hour, then the iceberg could have been destroyed before reaching the rig, quite apart from any speed control or direction control. Another application may be to reduce large icebergs (which are too large for speed control by water cannon) down to a size at which some control or speed enhancement becomes possible.

Destruction tests will be conducted by the application of the water cannon for a prolonged period (say 7-10 h for example). Iceberg mass will be estimated prior to commencement of the test and, after every 2-h test period, the rate of destruction in tonnes per hour will be estimated. The sea temperature will also be recorded.

Destruction testing will be conducted with a high-pressure/low-volume nozzle and with a low-pressure/high-volume nozzle to assess the destruction rate of each.

Destruction testing will be conducted on a small iceberg or bergy bit with the intent of totally destroying it. Bigger icebergs will also be partially destroyed to assess gain in speed enhancement.

As part of each destruction test (which also serves as a push test), speed and direction changes will be measured and plotted with respect to a diminishing mass, and compared to the free drift speed and direction of the ice mass which will be monitored for 1 h every 2 h.

Because the rate of destruction may be related to the consistency of applying the water jet to a precise point target position on the ice mass, the motion compensation characteristics of the cannon will be noted as a function of sea-state condition and vessel movement as determined by an accelerometer package.

Finally, destruction rates will be evaluated as an operational technique for management of small ice masses.

Maintaining the Water Jet Impact Position on Desired Point Targets. Tests to assess the consistency of maintaining the water jet impact position on a precise point target will be conducted as part of the push tests to evaluate the operational ability of the water cannon motion compensation package to compensate for vessel motion. These tests will be conducted over a range of distance between the vessel bow and the ice mass and for a variety of icebergs, because icebergs respond differently to wave action. Growlers follow wave motion closely whereas large bergs show less vertical motion. Therefore, maintaining consistency of the water jet impact point will be documented as a function of ice mass and sea state. Documentation will consist of obtaining video footage of the water jet meandering over selected icebergs and notation of visual observations.

To ascertain the ability of the water cannon motion compensation system to maintain a consistent target impact point, visual estimates of excursions or wander of the water jet impact position on the sails of icebergs will be made. By referencing the known sail height from the water line to the peak of the sail, the vertical displacement of impact position will be estimated. Video coverage will document the water jet excursion on the bergs.

For example, with a 10-m high vertical sail and a preselected target point 5 m above the water line, and a water jet excursion from the water line to the sail peak, the "target consistency" would be assessed as 10 m. If overshooting the peak of the sail or undershooting, the "target consistency" would be assessed as greater than 10 m.

Although this visual means of estimating "target consistency" is not highly accurate, it is regarded as being quantitatively satisfactory for the purpose of assessment. Target "impact consistency" is considered with respect to sea states and to the distance between the water cannon and the target ice mass.

Data from target consistency tests can be used to modify the motion compensation characteristics, such as rate of angular response, and to adjust the mode of vessel operation to minimize vessel motion as a function of push direction whether downwind, down-drift, or off the wind.

Propeller-Washing Tests with Vessel Movement Controlled. These tests are planned for the purpose of assessing a continuous propeller-washing technique for control of small ice masses. The loads imposed on the vessel by the wind, waves, currents, and the reaction force resulting from the water cannon will counteract or balance the propeller wash from the vessel in an attempt to allow continuous propeller-washing.

During the initial water cannon test program with the MV Skandi Alfa it was found that the propeller thrust required to balance the 8.8-tonne reaction force from the two water cannon with pumping capacity of 3,000 m^3/h each, was sufficient to produce a forward vessel speed of approximate 3.7 knots. How effective continuous propeller-washing might be in attaining speed and direction control of small ice masses, considering the thrust balance described above, will be assessed. Free drift velocity will be monitored prior to testing and the speed enhancement (if any) obtained by this technique will be measured.

WATER CANNON PUSH TEST PROCEDURES

Water cannon push test procedures included a number of sequential steps which allowed determination of first, a free drift vector for the ice mass prior to water cannon operations, secondly, drift resulting from water cannon applications, and finally, free drift after completion of the test (Fig. 14). To conduct a water cannon push test, the following steps were taken:

Step 1. Manoeuvre the vessel as close to the berg as is safe, noting ship heading so that the same heading can be used during subsequent positioning fixes to insure consistency.

Step 2. Take a positional fix noting time of fix.

Step 3. Take video film footage, still photographs, and slides of the ice mass.

Step 4. The vessel stands by the ice mass for 1 h to determine its free drift vector.

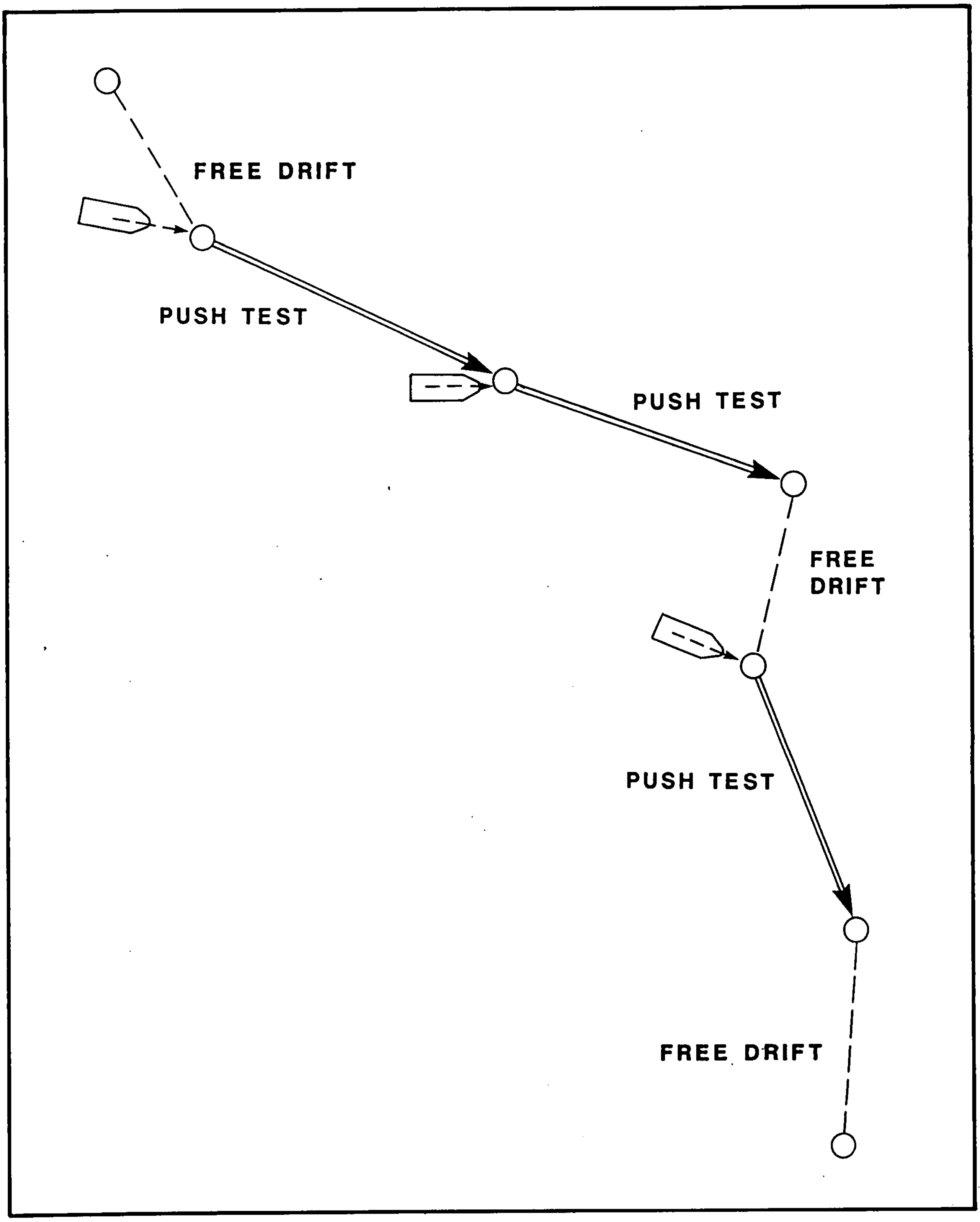


Figure 14. Typical push test procedures.

Step 5. Take polaroid photos, radar ranges, measurements with the range finder, and sextant angles to determine iceberg sail height, width, and length at the water line.

Step 6. Calculate above-water dimensions of iceberg and compute iceberg mass.

Step 7. After 1 h of free drift, proceed to the iceberg on the same heading as used during previous position determinations.

Step 8. When in the same position and heading relative to the iceberg, take a second positional fix noting time of fix.

Step 9. Calculate free drift speed and drift direction during the 1 h of free drift.

Step 10. Decision Point: Based on assessment of sea state, wind speed, and the iceberg free drift direction induced by winds and currents, decide what type of test to perform. For test purposes, selection of iceberg pushing direction can be downwind or down drift, crosswind, crossdrift, or against the wind or drift when low wind speeds prevail. The type of test dictates the ship heading assumed during the test.

In operational rig support situations there may not be a choice of push direction because of the necessity to prevent an ice mass from closing the distance to the rig.

Step 11. Decision Point: Select target for water jet. The target can be the sail of the iceberg at some preferred height above the water or at the water line. For small ice masses which move rapidly away when struck directly by the water jet, the decision may be to apply the water jet into the water adjacent to, or in front of, the ice mass so that the ice mass is driven by a surface current rather than direct impact forces. This latter method allows a smoother, continuous operation to be conducted rather than one involving the need to frequently reposition the vessel. During fog conditions, the target is often temporarily lost when the former method is used.

Step 12. Decision Point: Based on the size of the iceberg and knowledge of the shape of the iceberg keel, decide what distance to maintain between the bow of the vessel and the iceberg. For reasons of safety, a greater distance should be maintained with larger icebergs because rolling of the berg is a possibility and underwater keel sections may protrude further than expected during a rolling event. Growlers and bergy bits are much less likely to have protruding underwater keels and therefore a shorter distance can safely be maintained.

Step 13. Manoeuvre the vessel into position with the water cannon facing the iceberg and the vessel set on the preselected ship heading.

Step 14. Commence pump operations onboard the vessel according to the procedure specified.

Step 15. Take a positional fix for the ice mass and note time of fix at the start of pushing operations.

Step 16. Commence water cannon operations (Fig. 15) adjusting the water cannon to strike the chosen target area, and control the vessel position using thrusters and propellers to maintain the selected ship heading or push direction.

Step 17. Choose mode of water cannon control (joystick or stabilized/automatic mode).

Step 18. Continue pushing the ice mass for 1 h.

Figure 15. Water cannon operations with water jet striking the sail just at the water line.

Step 19. Document test proceedings with video, still photographs, and slides. Note significant events, such as loss of iceberg mass, and all relevant test parameters, such as wind and sea-state conditions, and the variation in impacting the ice mass at the desired impact point due to vessel motions.

Step 20. At the end of the 1-h push test, take a positional fix for the ice mass and note the time of the fix.

Step 21. Compute the speed-made-good and direction-made-good during the push test.

Step 22. Shut down the pump, according to procedures specified for shutdown of pumping operations.

Step 23. Move the vessel a short distance away from the ice mass.

Step 24. Take photographs and video footage of the ice mass after the test.

Step 25. Use sextant, radar, range finder, and polaroid photographs to estimate new berg dimensions and calculate new iceberg mass.

Step 26. At the end of 1 h of free drift the vessel returns to the berg assuming the same ship heading and same relative position.

Step 27. Take a positional fix and note time of fix.

Step 28. Compute the free-drift speed and direction during the 1 h following completion of the push test.

Step 29. Compare the free-drift conditions before and after the push test with the speed-made-good and direction-made-good during the test and plot the results.

CALCULATION OF CHANGES IN DRIFT SPEED AND DIRECTION

The rationale for acquiring the water cannon system lies with the requirement to control small ice masses by changing the free-drift speed and direction in such a way that the distance between the ice mass and the drill rig is increased. Therefore the control achieved by water cannon operations is measured by the actual change of drift direction and change of drift speed for the ice mass attributed to the application of the water jet. By comparing the speed-made-good and direction-made-good during water cannon operations with the free-drift speed and free-drift direction prior to and/or after water cannon applications, it is possible to obtain an index or measure of the operational control of small ice masses achieved by water cannon operations.

The following example illustrates the methodology:

a) Iceberg number 1, which measured 28.6 x 26.4 x 8.1 m and displaced 18,300 tonnes, drifted free at a rate of 0.19 knot towards 220°T between 0636 and 0813 on 27 April 1986. As shown in Figure 16, water cannon operations from 0834 to 0934 increased the drift speed to 0.74 knot and changed the drift direction 16° in a clockwise direction.

   In this case, the achieved speed enhancement and direction change is considered to be 0.55 knot speed enhancement (0.74 knot minus 0.19 knot) and 16° directional change, which is regarded as substantial control for this ice mass.

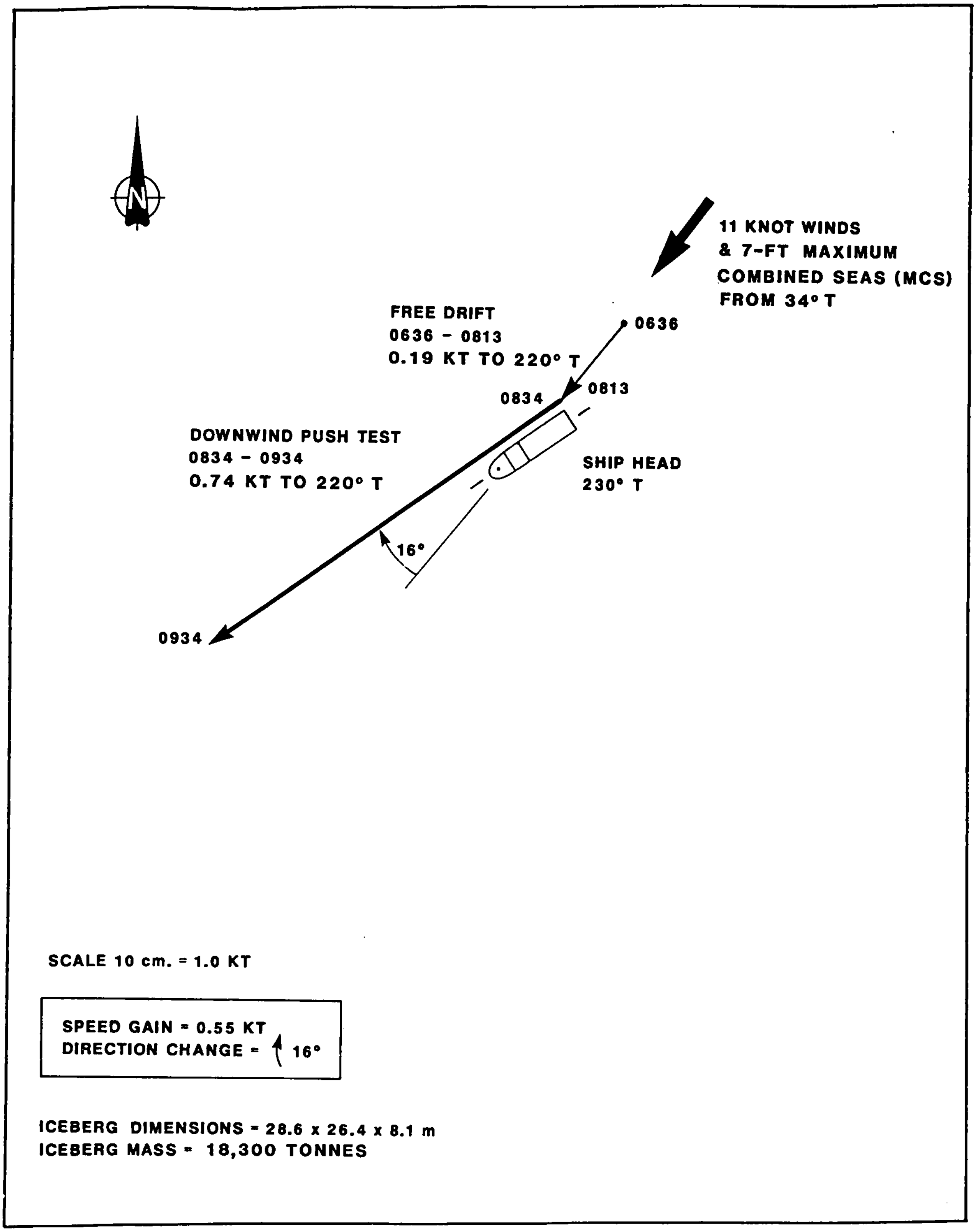


Figure 16. Sample push test for deriving speed gain and direction change due to water cannon operations.

DETERMINATION OF ABOVE-WATER DIMENSIONS AND MASS OF ICEBERGS

Two methods were used to determine the above-water dimensions of icebergs; the polaroid photo and range technique and the sextant and range technique.

a) To determine iceberg sail dimensions by the polaroid photo and range technique, photographs of the iceberg are taken and the distance between the vessel and the iceberg in nautical miles is measured using either ship radar or an accurate range finder. The horizontal and vertical dimensions of the berg are measured from the photo (Fig. 17). The sail height and width are then calculated using

$$D = 17.02 \times R \times M$$

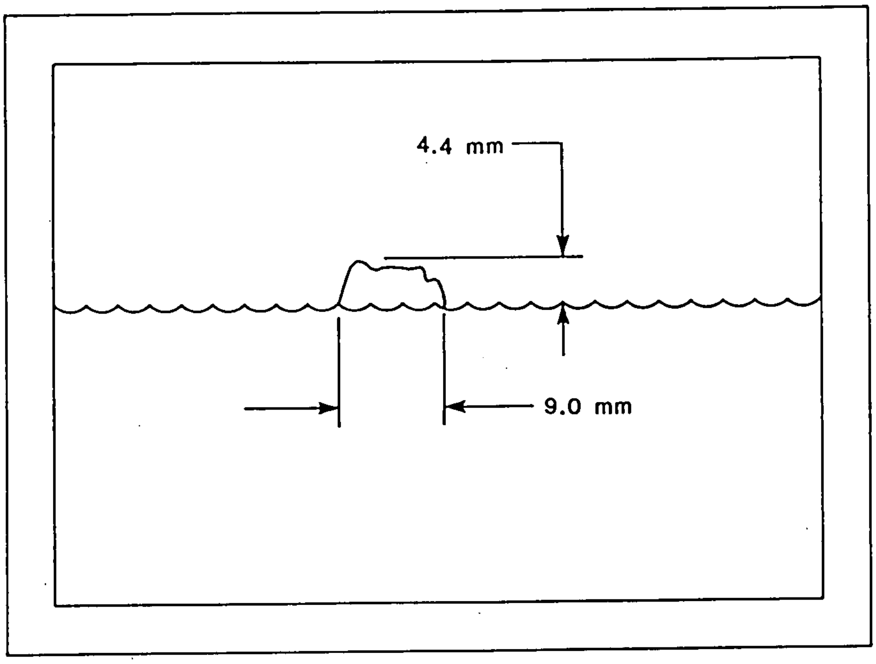
where: D = iceberg sail dimension in metres (height, width, or length)
R = range in nautical miles
M = height, width, or length measurement scaled from photograph (in millimetres).

This equation is provided by Kodak, the manufacturer of the polaroid camera and is based on the focal length of the camera lens (Sun - Polaroid 600 Land Camera - Autofocus 660).

b) A sextant is used to measure the vertical angle associated with sail height and the horizontal angle associated with the water line width or length. The ship radar is used to measure the range to the berg. To determine the iceberg sail height and width the following equation is used:

$$D = 0.54 \times A \times R$$

where: D = iceberg dimension in metres (sail height, width, or length)



POLAROID PHOTOGRAPH

Iceberg at a radar range of 0.31nm

Sail height = 17.02 x R x M
= 17.02 x 0.31 x 4.4
= 23 m

Horizontal width = 17.02 x R x M
= 17.02 x 0.31 x 9.0
= 48 m

Figure 17. Determining iceberg sail dimensions by Polaroid photographic technique.

A = vertical angle from the water line to the peak of the sail (in minutes of arc) or horizontal angle between left and right extremities of the berg at the water line

R = range from the vessel to the iceberg in nautical miles.

c) To estimate iceberg mass the formula proposed by the International Ice Patrol was used:

$$M = 3 \times L \times W \times H$$

where: M = mass of iceberg in tonnes
L = length in metres
W = width in metres
H = sail height in metres.

DATA COLLECTION AND ANALYSIS OF VESSEL MOTION

During selected periods of water cannon operations, the C-CORE technician onboard the vessel collected independent vessel motion data. The motion data in six degrees-of-freedom were collected on one channel of magnetic tape, and were displayed selectively on a single-track strip chart recorder. Recordings were generally made during water cannon operations. The C-CORE technician logged sea-state data and vessel heading information for each data collection period.

Selective analysis of the data was conducted by C-CORE using existing software. Vessel motion in six degrees-of-freedom was computed and plotted for a selected period associated with maximum sea states, and maximum vessel motion observed during the initial test phase during 1986.

Through processing of the magnetic tapes the sensor voltages were converted to physical units. The resulting three angular displacements and three linear accelerations (with gravitational component removed) constitute the six primary time-series records of the vessel motion at the sensor cluster location. To complete the description, differentiation and integration of the primary data can be performed at a later date to yield vessel displacement, velocity, and acceleration in each of the six degrees-of-freedom, as experienced at the sensor cluster location (essentially at the base of the water cannon). Figure 18 shows the data analysis system at C-CORE/Memorial University of Newfoundland.

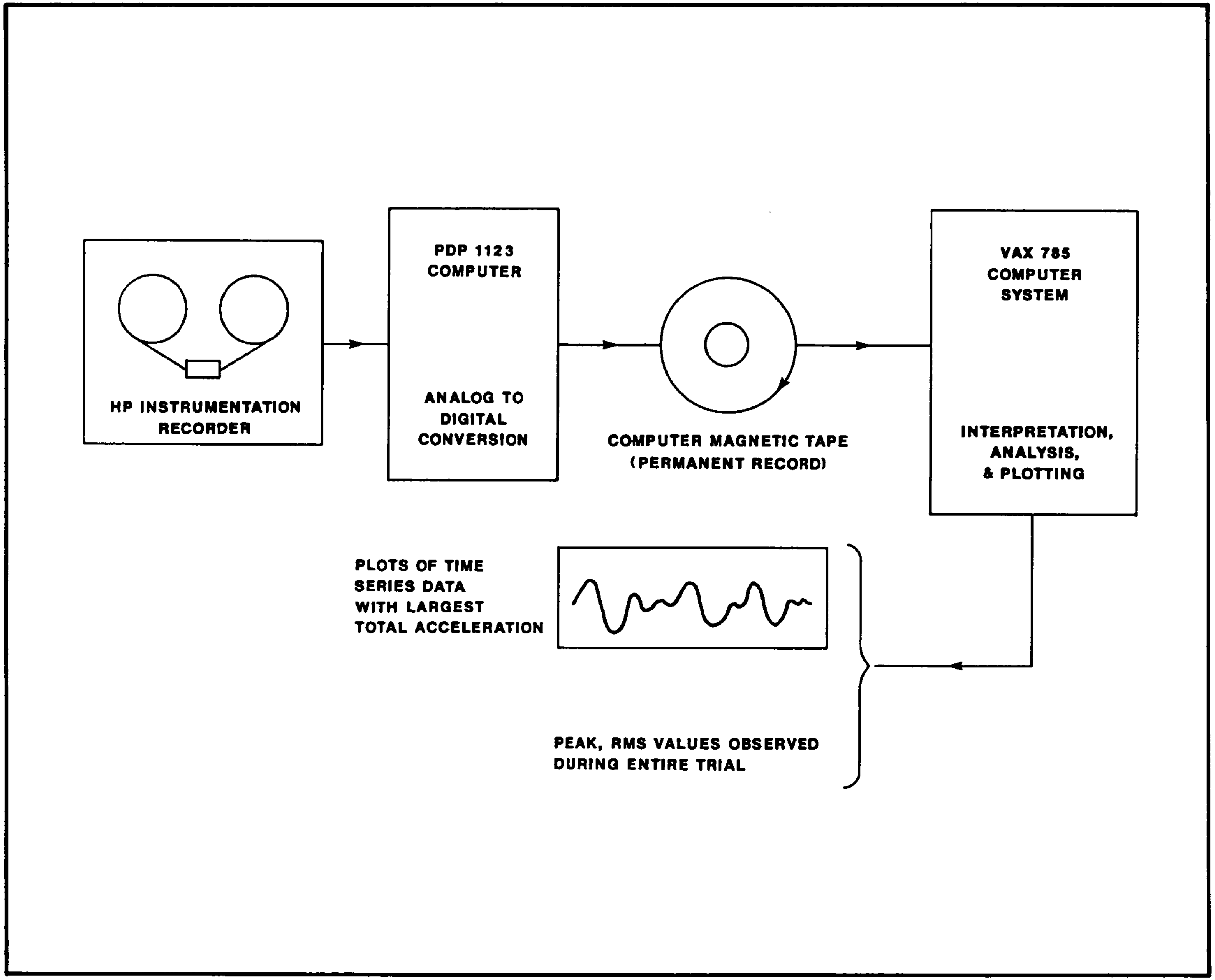


Figure 18. Motion data analysis system at C-Core/Memorial University of Newfoundland.

ESTABLISHING HIGH SEA-STATE OPERATIONAL PROCEDURES

A controlled series of tests was conducted to establish operational procedures for safely maintaining vessel position within effective water cannon range of a free-drifting iceberg in high wind and sea-state conditions and to actually conduct safe and effective water cannon operations under these conditions. The following tests were conducted:

- station-keeping at an iceberg with four main engines and three thrusters operating;
- station-keeping at an iceberg with four main engines and two bow thrusters operating;
- station-keeping at an iceberg with three main engines and two bow thrusters operating;
- station-keeping at an iceberg with three main engines and two bow thrusters operating (the preferred engine - thruster power configuration);
- station-keeping at an iceberg while rotating the vessel relative to the wind and wave direction with three main engines and two bow thrusters operating; and
- actual water cannon operations with three main engines, two bow thrusters and engine #2 providing power to the centrifugal pump.

SELECTION OF OPTIMUM NOZZLE DIAMETER

Thune Eureka, the supplier of the water cannon system estimated that using a 145-mm diameter nozzle on the water cannon would result in the maximum transfer of energy to the water jet which would result in the greatest possible water cannon reaction force (about 5 tonnes). A nozzle of 145-mm diameter was therefore provided by Thune Eureka with the water cannon system and was bolted to the discharge end of the cannon.

Water cannon operations commenced with the 145-mm diameter nozzle and it was observed that continuous pumping operations were not possible because of overloading of the engine as indicated by exhaust manifold temperatures in excess of 605°C (the maximum temperature recommended by the engine manufacturer). It was considered that conducting water cannon operations with a nozzle diameter less than 145 mm would permit continuous operation of the engine with exhaust manifold temperature below 605°C, while achieving near-maximum water cannon reaction force (F). To determine this nozzle diameter, a series of engine/pump tests was conducted with progressively larger nozzle diameter starting with a minimum diameter of 100 mm. Six different nozzle diameters were tested: 100 mm, 125 mm, 130 mm, 145 mm, 152 mm, and 165 mm. Some of these desired diameters were obtained using the lathe onboard the MV Placentia Bay.

Engine/pump tests were conducted for each of the six nozzle diameters with a range of engine speed varying from 400 rpm when clutching in, to 650 rpm at full engine speed. During each engine/pump test, the following parameters were monitored: time of test, engine rpm, fuel rack index, fuel consumption, and the pump discharge pressure. In addition, the chief engineer monitored the exhaust manifold temperature during each test, and the selection of the optimum nozzle diameter was based on continuous pumping with the largest nozzle without overloading the engine as indicated by an exhaust manifold temperature below 605° C. As a result of conducting the six engine/pump tests, an optimum nozzle diameter of 130 mm was selected. This diameter allowed continuous water cannon operations while achieving a 4.3-tonne reaction force which is close to the maximum water cannon reaction force of 4.8 tonnes associated with the 145-mm diameter nozzle.

After conducting the six engine/pump tests which resulted in selection of the 130-mm diameter nozzle as the optimum nozzle during 1986, it was discovered that the engine was not operating at peak efficiency. To restore the engine to its full 2000-kW power output, the engine was tuned. After tuning the engine, one further engine/pump test was conducted with the 145-mm diameter nozzle, during water cannon operations in 1987, as a result of which the maximum possible water cannon reaction force (4.8 tonnes) was achieved and continuous water cannon operations with the optimum 145-mm diameter nozzle became possible.

The results of the seven engine/pump tests conducted during water cannon operations during 1986 and 1987 appear in the following section in tabular form and include a plot of fuel consumption versus engine rpm for each of the six nozzle diameters. Pump discharge pressures are plotted against engine rpm for each nozzle diameter and serve as the basis for calculations of nozzle exit velocities and volume flow (Q) according to Bernoulli's equation for flow. For these calculations the nozzle pressure (P) is taken to be the measured pump discharge pressure minus 1 bar to account for the 10 m of elevation difference between the pump and the water cannon minus 0.5 bar to account for friction losses in the pipe (estimated by Thune Eureka).

Water cannon thrust or reaction force (F) is calculated according to the following equation provided by Thune Eureka.

$$F = 0.4 \times Q \times P^{0.5}$$

where: F is the thrust in tonnes

Q is the volume of water in cubic metres per hour

P is the nozzle pressure in bars.

The calculated values of the maximum water cannon reaction force for each of six nozzle diameters are presented in the section of results along with nozzle pressures based on the measured pump discharge pressures and the calculated values of exit velocities and flow volumes. The data are plotted and show the water cannon reaction force versus the cross-sectional area of the six nozzles, indicating a maximum reaction force associated with the optimum nozzle diameter.

RESULTS

The results of the water cannon evaluation program are described in the remainder of this report. Information on the ice masses subjected to water cannon operations and the observed performance of the water cannon is presented. A section is devoted to high sea-state operations and two examples of individual push tests are described. Supplementary information of interest to oil companies is presented in Appendix 1.

ICEBERG LOGS

A total of 26 ice masses were subjected to water cannon push tests during the offshore test program. These ice masses are listed according to mass in Table 1 but do not represent 26 separate icebergs. In some cases, the same iceberg was tested several times as the ice masses decreased because of natural deterioration and water cannon operations. For example, the 132,000-tonne ice mass shown in Table 1 is the same iceberg as the 100,000-tonne ice mass. The widths, lengths, and sail heights of the ice masses indicated in Table 1 were measured prior to commencing tests.

Testing for each ice mass did not always proceed immediately after size measurements were made and therefore the calculated ice mass associated with each test may be slightly less than the mass indicated in Table 1 owing to loss of mass from natural deterioration. It should be noted that some larger ice masses are listed in Table 2 along with the ice masses which were subjected to push tests. These larger ice masses, above 132,000 tonnes, were generally subjected to destruction tests or notch-cutting tests. Descriptions of icebergs follow MANICE (1980) nomenclature with respect to ice type and size.

TABLE 1

Ice masses subjected to push tests by the water cannon

Date of testing	Type of berg	Length x width x sail height (m)	Mass (tonnes)
86-05-06	Pinnacle	53 x 51 x 18	132,000
86-05-06	Pinnacle	45 x 45 x 17	100,000
87-04-18	Spherical	50 x 45 x 10	67,000
86-04-29	Dry dock	58 x 53 x 24*	65,000
87-04-18	Pinnacle	46 x 43 x 11	63,000
86-05-08	Wedge	44 x 41 x 9	47,600
87-04-20	Pinnacle	37 x 36 x 10	40,000
87-05-05	Dry dock	32 x 31 x 10	30,000
87-05-06	Blocky	34 x 25 x 10	24,700
87-05-02	Dry dock	31 x 29 x 9	24,300
86-04-23	Dry dock	29 x 26 x 8	18,300
87-04-30	Spherical	26 x 25 x 6	11,700
87-05-06	Blocky	34 x 32 x 4	11,400
87-05-01	Spherical	28 x 17 x 8	11,400
87-04-21	Blocky	32 x 28 x 4	10,700
87-04-15	Spherical	25 x 20 x 5	7,500
86-05-16	Bergy bit	16 x 14 x 5	3,360
86-05-16	Bergy bit	14 x 12 x 4	2,200
86-05-02	Bergy bit	20 x 15 x 2	1,800
86-05-18	Bergy bit	10 x 10 x 3	1,050
86-05-18	Bergy bit	9 x 9 x 3	730
87-03-31	Bergy bit	14 x 5 x 2	315
86-05-19	Bergy bit	7 x 6 x 1	125
87-03-19	Bergy bit	8 x 5 x 1	96
86-04-29	Bergy bit	7 x 5 x 0.5	50
87-03-28	Bergy bit	6 x 9 x 0.5	36

NOTE: Length, width, and sail height dimensions have been rounded off to the nearest metre.

* This ice mass had a single pinnacle which reached a height of 24 m above the water line.

EXAMPLES OF PUSH TESTS

The results of two water cannon push tests are presented. Each is described individually and the speed and direction change achieved during each test is derived. A drawing of the drift track is included for each test which shows vessel heading, wind and sea conditions, and indicates the speed gain and direction change (Figs. 19 and 20). Drift speed and direction vectors are plotted to show the drift rate in knots even though the period of free drift for the ice mass may not be exactly 1 h. Drift rates in knots are usually plotted at a scale of 10 cm = 1.0 knot or 5 cm = 1.0 knot. It should be noted that vectors are joined end to end as if there were no time lag between the end of the free drift period and commencing the test. Usually there was a time gap but because speed conditions are plotted (not positions) it is legitimate to join the vectors.

Water Cannon Test 1-5

In this downwind and cross-drift push test (see Fig. 19) the water jet was applied 40° off the free-drift direction of the iceberg. The free drift was 0.15 knot towards 320°T, and the vessel heading was 280°T. During the 1-h push test conducted with a 152-mm nozzle, the speed-made-good was 0.67 knot and the direction-made-good was 292°T. Thus, the application of the water cannon provided speed enhancement of 0.52 knot and 28° of counter-clockwise direction change. The distance to the berg was 50 m, and because only one bow thruster was available, some problems were experienced with maintaining position next to the berg. The stabilized mode was activated to compensate for vessel motions and the target impact consistency was 5-6 m.

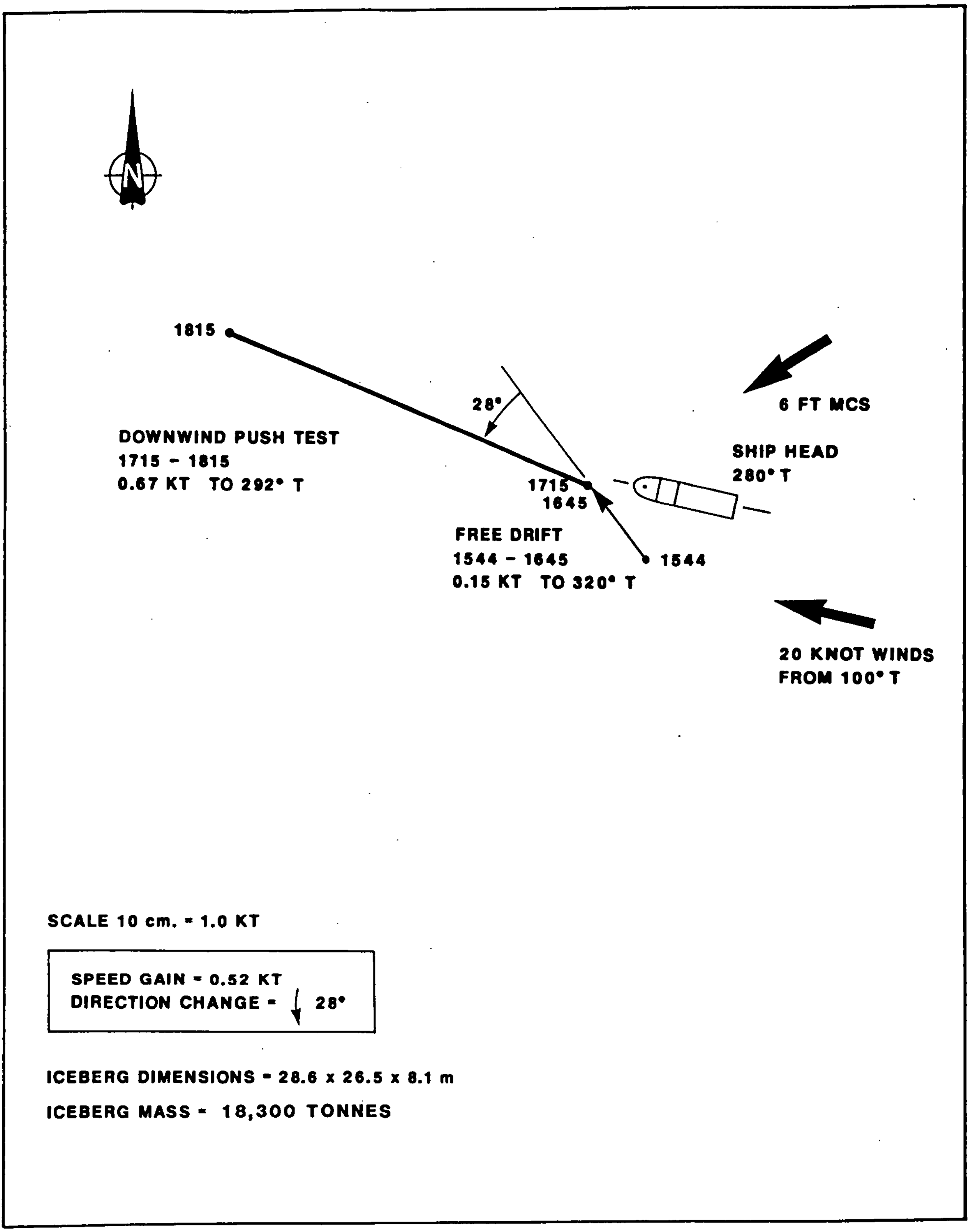


Figure 19. Downwind push test for an 18,300-tonne iceberg.

Water Cannon Test 8-1

Iceberg 8 free drifted (see Fig. 20) at 0.51 knot towards 229°T with no wind and only a 1-m swell recorded. This drift was clearly current-driven. The berg was closing on the drill-rig Bow Drill 3. It was decided to push the berg with a ship heading of 140°T which was almost perpendicular to its free-drift direction. The water jet was concentrated on the sail or at the water line and despite the necessity to "chase" the berg and reposition the vessel after each impact of the water jet on the ice, the speed-made-good was 1.43 knots towards 170°T. This constituted a speed gain of 0.92 knot and a direction change of 60° counter-clockwise. The water cannon was controlled manually by joystick with the distance to the berg being variable with a minimum of 30-40 m. The target was struck about 50% of the time. With more experience it was deemed possible to achieve much better impact consistency to maintain the water jet on the desired point target.

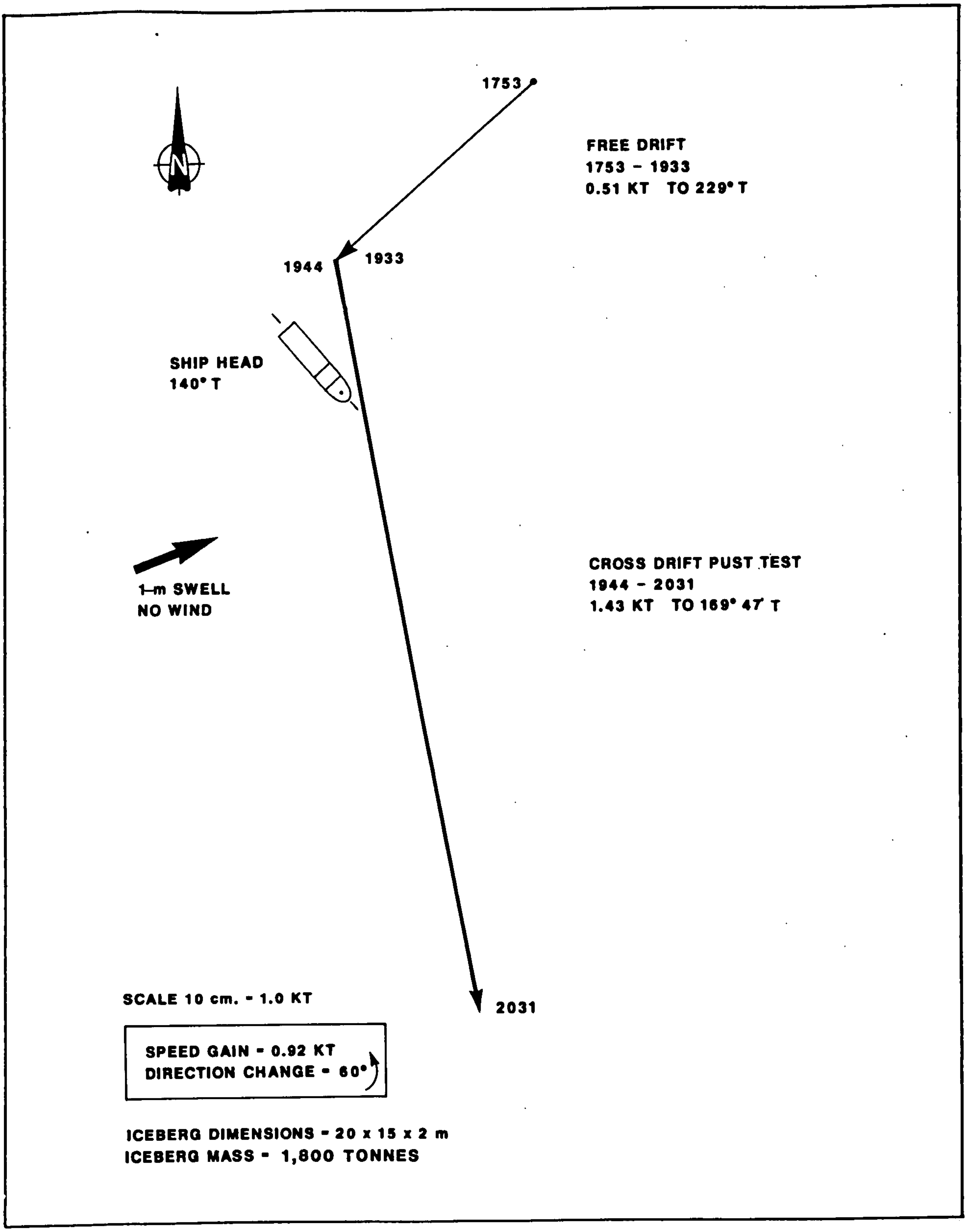


Figure 20. Cross-drift push test for an 1,800-tonne bergy bit.

SUMMARY OF PUSH TESTS

A summary of water cannon operations with icebergs as illustrated in the two examples, is presented in Table 2. Test results are divided into two main groups as follows:

1. Twenty-four down-drift push tests were conducted, designed to change the drift speed of small ice masses by pushing in a direction basically along, or close to, the free-drift direction. The difference between the free-drift direction and the ship's heading ranged from 0 to 46°. These data are tabulated in Table 3. In Figure 21 the speed gains achieved during the down-drift push tests are plotted as a function of iceberg mass. In addition, eight more data points are plotted. These represent speed gains associated with cross-drift push tests intended to change the drift direction. The eight data points are included because substantial speed gains were achieved in addition to the changes in drift direction.

   The speed gains achieved by the MV Skandi Alfa are also plotted in Figure 21 as a function of iceberg mass and are included to provide some basis for evaluating the increased effectiveness of the modified cannon system.

2. Twenty-seven cross-drift push tests were conducted, designed to change the drift direction of small ice masses by pushing with a ship heading well rotated from the free-drift direction. The angular differences ranged from 29° to 180°. The results are tabulated in Table 4 and in Figure 22. The achieved direction changes are plotted as a function of iceberg mass. The direction changes achieved by the MV Skandi Alfa are also plotted as a function of iceberg mass and are included to demonstrate the increased capacity of the modified water cannon in changing the drift direction of small ice masses.

TABLE 2
Summary of water cannon push test data

Day-Month 1986	Berg test	Berg size length x width x sail height (m)	Iceberg mass (tonnes)	Free drift		Induced drift		Speed change (kts)	Direction change (°T)	Ship heading (°T)	Type of test Type of nozzle	Vessel to berg (m)	Wind		MCS** (m)	Waves impact vessel on	Target impact consistency (m)	Point of impact objective
				Speed (kts)	Dir. (°T)	Speed (kts)	Dir. (°T)						Speed (kts)	Dir. (°T)				
23-04	1-1	28.6 x 26.4 x 8.1	18,300	0.6	318	0.77	344	0.17	26	318	Down-drift P.T.* 145-mm nozzle	70-80	10	240	2	Port beam	N/A	Iceberg sail
27-04	1-2	28.6 x 26.4 x 8.1	18,300	0.19	220	0.74	236	0.55	16	230	Downwind P.T. 165-mm nozzle	40-50	11	034	1	Stern	8	Sail
27-04	1-3	28.6 x 26.4 x 8.1	18,300	0.09	309	0.57	284	0.48	25	250	Downwind P.T. 152-mm nozzle	40-50	20	070	1	Stern	5	Sail
27-04	1-4	28.6 x 26.4 x 8.1	18,300	0.20	239	0.54	249	0.34	10	240	Downwind P.T. 152-mm nozzle	40-50	20	060	1	Stern	5	Sail and water line
27-04	1-5	28.6 x 26.4 x 8.1	18,300	0.15	320	0.67	292	0.52	28	280	Downwind P.T. 152-mm nozzle	50	20	100	2	Stern	5-6	Sail and water line
29-04	5-1	58 x 53 x 24	65,000	0.82	101	0.95	120	0.13	0	070	Cross-drift P.T. 152-mm nozzle	60-70	30	233	2	Stern	4-5	Sail (jet horizontal against highest sail)
29-04	5-1	58 x 53 x 24	65,000	0.50	145	0.94	155	0.12	0	125	Downwind P.T. 152-mm nozzle	60-70	30	233	2	Port beam		
29-04	5-2	58 x 53 x 24	65,000	0.62 0.56	167 204	0.75	193	0.17	0	175	Downwind P.T. 152-mm nozzle	40	14	000	2	Stern	4	Sail
29-04	5-3	58 x 53 x 24	65,000	0.56 0.51	170 191	0.63	186	0.10	5	115	Cross-drift P.T. 152-mm nozzle	50	20	010	2	On port side 70° off port stern	4-5	Sail

TABLE 2 (Cont'd)

Day-Month 1986	Berg test	Berg size length x width x sail height (m)	Iceberg mass (tonnes)	Free drift		Induced drift		Speed change (kts)	Direction change (°T)	Ship heading (°T)	Type of test Type of nozzle	Vessel to berg (m)	Wind		MCS (m)	Waves impact vessel on	Target impact consistency m (Dia)	Point of impact objective
				Speed (kts)	Dir. (°T)	Speed (kts)	Dir. (°T)						Speed (kts)	Dir. (°T)				
29-04	6-1	7 x 5 x 1/2	50	0.80	147	1.50	149	0.70	2	140	Down-drift P.T. 152-mm nozzle	Var (chasing ice mass)	25	233	2	Stern	Variable	On sail and in water
02-05	8-1	20 x 15 x 2	1,800	0.51	229	1.43	170	0.92	59	140	Cross-drift P.T. 152-mm nozzle	Var (chasing ice mass)	0	000	1	Star-board beam	Variable	On sail, at water line and in water
05-05	7-1	80 x 57 x 20.6	281,000	0.12	310	0.15	306	0	0	300	Destruction 152-mm nozzle	50-60	20	045	2	Stern	Variable	Sail at water line
06-05	7-2	53 x 51 x 17.7	132,000	0.65 1.32	23 54	0.93	25	0	0	0	Downwind P.T.				4	Stern	6-7 m Manual mode	Sail
06-05	7-3	45 x 45 x 16.5	100,000	1.32 1.42	54 64	1.52 1.63	56 63	0.16 0.24	2	355	Destruction and Cross-drift P.T.	50-60	35	200	4	Port side stern	6-7 6-7	Sail just above water line
06-05	7-4	45 x 45 x 16.5	100,000	1.42	64	Test Aborted Due to Berg Rolling				38	Destruction test 100-mm nozzle	60	40	220	6	Stern	Highly variable	Sail
08-05	7-5	44 x 41 x 8.8	47,600	0.93	216	1.06	215	0.13	0	225	Down-drift P.T.	50-60	35	020	5	Starboard beam 25° off starboard stern	12-15	Water-line
08-05	7-6	44 x 41 x 8.8	47,600	0.92	210	0.70 0.66	190 184	-0.12 0.05	20 13	90 90	Cross-drift P.T.	60-70 60-70	35 35	010 010	6	On port beam	12	
08-05	7-7	44 x 41 x 8.8	47,600	0.60 0.75	187 195	0.74	185	0.07	10	90	Cross-drift P.T.	70	35	010	6	On port beam	9 Manual mode	On sail at water line
08-05	7-8	44 x 41 x 8.8	47,600	0.92 0.83	190 196	0.77	186	-0.10	7	90	Cross-drift P.T.	60-70	35-40	010	6	On port beam	Variable	

TABLE 2 (Cont'd)

Day-Month 1986	Berg test	Berg size length x width x sail height (m)	Iceberg mass (tonnes)	Free drift		Induced drift		Speed change (kts)	Direction change (°T)	Ship heading (°T)	Type of test Type of nozzle	Vessel to berg (m)	Wind		MCS (m)	Waves Impact Vessel On	Target Impact Consistency (m)	Point of Impact Objective
				Speed (kts)	Dir. (°T)	Speed (kts)	Dir. (°T)						Speed (kts)	Dir. (°T)				
16-05	18-1	16.3 x 14 x 5.0	3,360	0.69	164	1.3	170	0.61	6	130	Distance test	70-80	26	280	2	Starboard stern	Variable	Into water
16-05	18-2	16.3 x 14 x 5.0	3,360	1.0	181	1.5	180	0.5	1	130	Medium distance test	50-60	26	280	2	Starboard stern	Variable	Into water
16-05	18-3	14 x 12 x 4.3	2,200			1.6	170	0.6	11	150	Distance test Destruction test	30-40	20	270	2	Starboard stern	Variable	Into water
16-05	18-4	14 x 12 x 4.3	2,200	1.2	182	2.1	190	0.9	8	150-170	Cross-drift P.T Destruction test	40-50	20	270	2	Starboard side	2-3 Manually	Sail
16-05	18-5	10 x 10 x 3.5	1,050	0.8	173	1.9 1.3	166 170	0.7 0.5	16 3	90 90	Cross-drift P.T.	50	15 15	270 270	2	Stern	Highly variable	Sail
16-05	18-6	9 x 9 x 3 9 x 8 x 3 Final	730 650	0.9	183	1.0	176	0.2	3	100	Destruction test	25-30	15-20	330	2	Port side		Sail
19-05	20-1	7 x 6 x 1	125	0.3	80	0.6	8	0.3	72	000	Cross-drift P.T.	60-70	25	210	1	Port side off stern	Objective easily maintained	Into water
19-05	20-2	7 x 6 x 1	125	0.2	19	0.7	16	0.5	3	000	Cross-drift P.T.	40-50	25	210	1	Port side off stern	Tendency to overrun berg at this dist.	Into water
19-05	20-3	7 x 6 x 1	125	0.2	19	0.9	2	0.7	17	350	Down-drift P.T.	50-60	25	210	1	Port side off stern	Objective easily maintained	Into water

TABLE 2 (Cont'd)

Day-Month 1987	Berg test	Berg size length x width x sail height (m)	Iceberg mass (tonnes)	Free drift Speed (kts)	Free drift Dir. (°T)	Induced drift Speed (kts)	Induced drift Dir. (°T)	Speed change (kts)	Direction change (°T)	Ship heading (°T)	Type of test	Vessel to berg (m)	Wind Speed (kts)	Wind Dir. (°T)	MCS (m)	Waves Impact Vessel On	Target Impact Consistency (m)	Point of Impact Objective
19-03	2-1	8 x 5 x 0.8	90	0.80	316	1.20	014	0.40	58	032	Cross-drift P.T.	50	15-20	140	4	Beam	-	Water
19-03	2-2	8 x 5 x 0.8	90	0.64	310	1.34	304	0.70	6	315	Down-drift P.T.	10-70	15-20	140	4	Stern	-	Water
28-03	4-1	6 x 4 x 0.5	36	0.59	321	1.19	026	0.60	65	050	Cross-drift P.T.	50	20-25	150	3	Beam	-	Water
28-03	4-2	6 x 4 x 0.5	36	0.56	335	1.64	334	1.08	0	320	Down-drift P.T.	50	20-25	150	3	Stern	-	Water
31-03	5-1	14 x 5 x 1.5	315	0.24	206	0.94	046	1.18	160	026	Stop-drift P.T.***	50	0	-	4	Bow	-	Water
31-03	5-2	14 x 5 x 1.5	315	0.30	251	0.95	340	0.65	89	340	Cross-drift P.T.	50	0	-	4	Beam	-	Water
15-04	4-1	25 x 20 x 5	7,500	0.40	005	0.79	057	0.39	52	090	Cross-drift P.T.	50	20-25	140	1	Bow	-	Water
15-04	4-2	25 x 20 x 5	7,500	0.24	025	0.67	068	0.44	43	100	Cross-drift P.T.	Var	20-25	140	1	Bow	-	Water
18-04	5-2	50 x 45 x 10	67,000	0.54	115	0.40	103	-0.14	12	020	Cross-drift P.T.	50	20	230	2	Stern	-	Water
18-04	5-3	46 x 43 x 10.5	63,000	0.44	123	0.35	113	-0.09	10	030	Cross-drift P.T.	50-70	20	230	2	Stern	-	Water
18-04	5-5	46 x 43 x 10.5	63,000	0.43	113	0.52	123	0.09	10	113	Down-drift P.T.	60	25	230	1	Beam	-	Water
20-04	6-1	37 x 36 x 10	40,000	1.04	113	1.24	121	0.20	8	115	Down-drift P.T.	70	25	310	3	Stern	-	Water
20-04	6-2	37 x 36 x 10	40,000	1.23	119	1.44	137	0.14	18	210	Cross-drift P.T.	70	25	330	4	Beam	-	Water
21-04	7-2	32 x 28 x 4	10,700	0.80	100	1.14	093	0.34	7	050	Down-drift P.T.	50	30	225	3	Stern	-	Water

TABLE 2 (Cont'd)

Day-Month 1987	Berg test	Berg size length x width x sail height (m)	Iceberg mass (tonnes)	Free drift		Induced drift		Speed change (kts)	Direction change (°T)	Ship heading (°T)	Type of test	Vessel to berg (m)	Wind		MCS (m)	Waves Impact Vessel On	Target Impact Consistency (m)	Point of Impact Objective
				Speed (kts)	Dir. (°T)	Speed (kts)	Dir. (°T)						Speed (kts)	Dir. (°T)				
22-04	7-3	32 x 28 x 4	10,700	0.72	063	1.00	065	0.28	2	065	Down-drift P.T.	50	30	245	7	Stern	-	Water
30-04	3-1	26 x 25 x 6	11,700	0.60	243	0.75	287	0.15	44	020	Cross-drift P.T.	Var	30	180	6	Stern	-	Water
01-05	4-1	28 x 17 x 8	11,400	0.45	271	0.50	299	0.05	28	330	Cross-drift P.T.	70	30	180	7	Stern	-	Water
01-05	4-2	28 x 17 x 8	11,400	1.06	356	1.32	015	0.26	19	000	Down-drift P.T.	Var	35	180	5	Stern	-	Water
02-05	8-1	31 x 29 x 9	24,300	0.26	076	0.31	049	0.05	27	050	Cross-drift P.T.	50	20	200	4	Stern	-	Sail
02-05	8-2	31 x 29 x 9	24,600	0.20	018	0.60	024	0.40	6	025	Down-drift P.T.	50	20	180	4	Stern	-	Sail
05-05	9-1	32 x 31 x 10	30,000	0.30	116	0.44	097	0.14	19	085	Cross-drift P.T.	60	15	240	1	Stern	-	Sail
05-05	9-2	32 x 31 x 10	30,000	0.20	019	0.27	046	0.00	27	085	Cross-drift P.T.	60	15	240	1	Stern	-	Water
05-05	9-3	32 x 31 x 10	30,000	0.30	019	0.77	025	0.47	6	025	Down-drift P.T.	60	15	240	1	Stern	-	Sail
05-05	9-4	32 x 31 x 10	30,000	0.40	035	0.06	317	0.34	78	215	Stop-drift P.T.	60	15	240	0	-	-	Sail
06-05	10-1	34 x 25 x 9.7	24,700	0.41	242	0.78	260	0.37	18	250	Down-drift P.T.	60	10	245	0	-	-	Sail
06-05	10-2	34 x 25 x 9.7	24,700	0.28	265	0.51	270	0.23	5	260	Down-drift P.T.	60	0	-	0	-	-	Water
06-05	10-3	34 x 32 x 3.5	11,400	0.18	315	0.50	304	0.32	9	315	Down-drift P.T.	35	0	-	0	-	-	Sail
06-05	10-4	34 x 32 x 3.5	11,400	0.10	315	0.31	013	0.20	58	025	Cross-drift P.T.	30	0	-	0	-	-	Sail

* P.T. = Push test

** MCS = Maximum Combined Seas

*** Stop-drift P.T. is a push test attempting to stop the drift of an ice mass by pushing in the direction opposite to its free drift.

NOTE: Target impact consistency is shown only for those tests when the automatic motion compensation system was used to compensate for vessel motion.

TABLE 3

Results of 24 down-drift push tests designed to increase drift speed of icebergs

Test number	Free-drift speed (kts)	Induced-drift speed (kts)	Speed gain (kts)	Iceberg mass (tonnes)
5-5	0.43	0.52	0.09	67,500
5-2	0.62	0.75	0.13	65,000
7-5	0.93	1.06	0.13	47,600
6-1	1.04	1.24	0.20	40,000
9-3	0.30	0.77	0.47	30,000
9-4	0.06	0.40	0.34	30,000
10-1	0.41	0.78	0.37	24,700
10-2	0.28	0.51	0.23	24,700
8-2	0.20	0.60	0.40	24,300
1-1	0.60	0.77	0.17	18,300
1-2	0.19	0.74	0.55	18,300
1-4	0.20	0.54	0.34	18,300
10-3	0.18	0.50	0.32	11,400
4-2	1.06	1.32	0.26	11,400
7-2	0.80	1.14	0.34	10,700
7-3	0.72	1.00	0.28	10,700
18-1	0.69	1.30	0.61	3,360
18-2	1.00	1.50	0.50	2,200
18-3	1.00	1.60	0.60	2,200
18-4	1.20	2.10	0.90	2,200
20-2	0.20	0.70	0.50	125
2-2	0.64	1.34	0.70	96
6-1	0.80	1.50	0.70	50
4-2	0.56	1.64	1.08	36

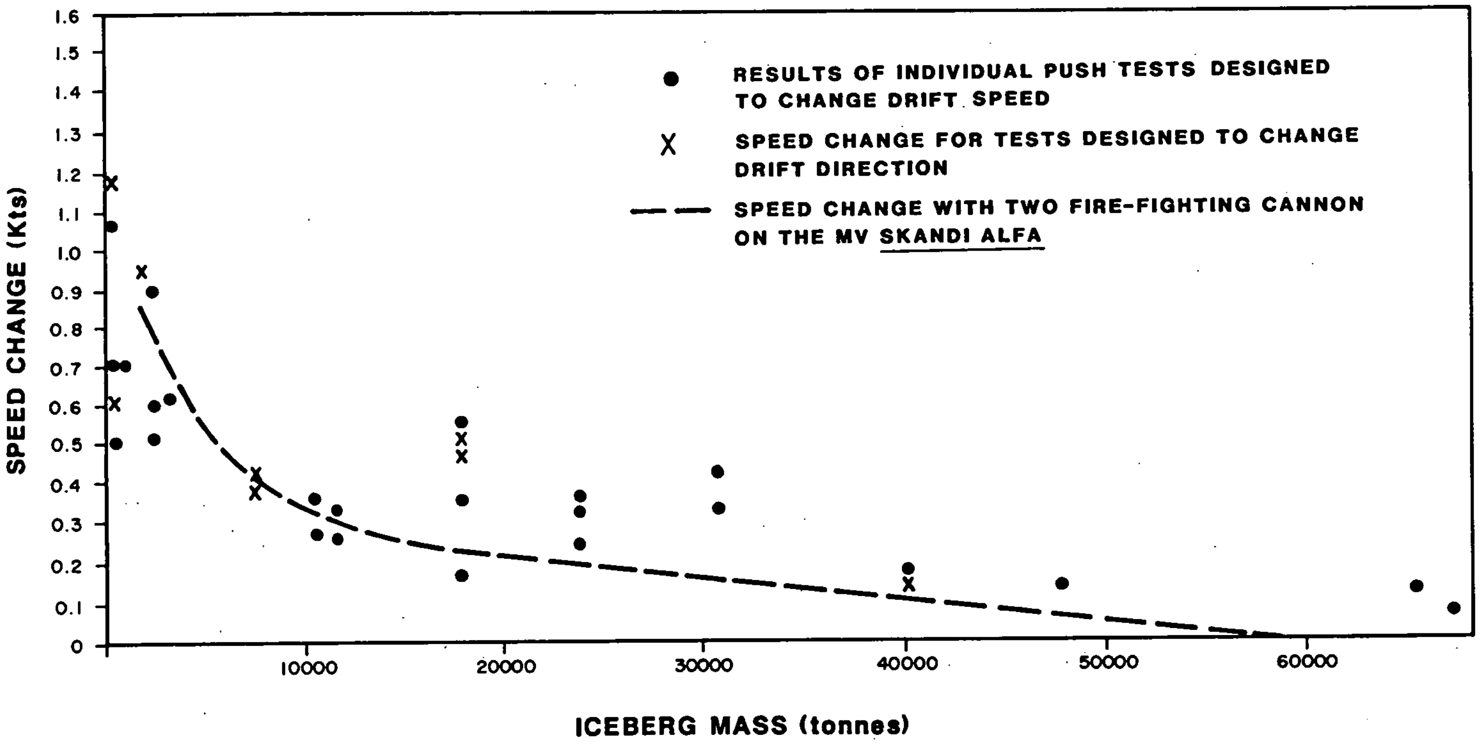


Figure 21. Speed changes achieved by the optimized water cannon as a function of iceberg mass.

TABLE 4

Results of 27 cross-drift push tests designed to change drift direction of icebergs

Test number	Free-drift direction (°T)	Ship head (°T)	Achieved direction change (°)	Achieved speed gain (kts)	Iceberg mass (tonnes)
7-3	054	355	0	0.16	100,000
5-2	115	020	12	0.00	67,500
5-1	101	070	0	0.13	65,000
5-3	169	115	5	0.10	65,000
5-3	120	030	10	0.00	63,000
7-6	210	090	20	0.12	47,600
7-6	197	090	13	0.05	47,600
7-7	187	090	10	0.07	47,600
7-8	190	090	7	0.10	47,600
6-2	119	210	18	0.14	40,000 (P)
9-1	144	085	19	0.13	30,000
9-2	019	085	28	0.00	30,000
8-1	170	050	27	0.00	24,300
1-3	309	250	25	0.48	18,300 (P)
1-5	320	280	28	0.52	18,300 (P)
3-1	243	020	44	0.15	11,700
4-1	271	330	53	0.05	11,400
10-4	290	025	58	0.20	11,400
4-1	005	090	52	0.39	7,500 (P)
4-2	025	100	43	0.43	7,500 (P)
8-1	229	140	60	0.92	1,800 (P)
18-5	182	090	16	0.70	1,050
5-1	206	026	160	1.18	315 (P)
5-2	258	340	90	0.61	315 (P)
20-1	080	000	72	0.30	125
2-1	316	032	58	0.40	96
4-1	321	050	65	0.60	36

NOTE: (P) denotes that the speed gain is plotted in Fig. 21.

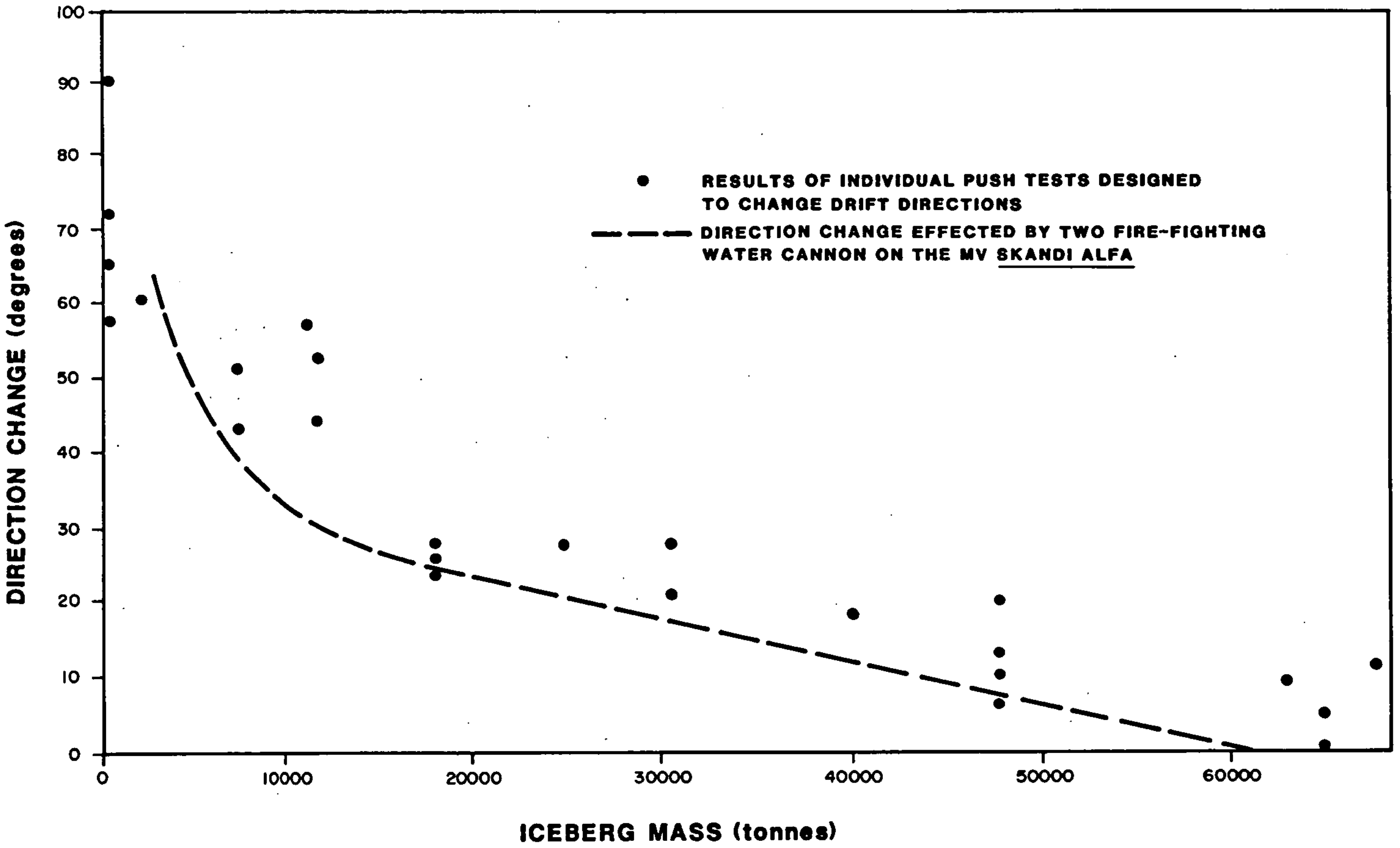


Figure 22. Direction changes achieved by the optimized water cannon as a function of iceberg mass.

MAINTAINING THE WATER JET IMPACT ON A DESIRED TARGET POINT

The ability to maintain a consistent target point of impact for the water jet on the iceberg was observed visually with reference to the measured iceberg sail height. A total of ten reliable estimates of the water jet excursion from the desired point targets were collected and are presented in Table 5.

In most cases of estimating "target impact consistency", the stabilized (motion compensated) mode of water cannon control was used. When the vessel bow (and the water cannon) rises in response to a rising wave, the water cannon should respond by rotating downwards automatically when the stabilized mode of water cannon control is activated. Likewise, when the vessel bow (and the water cannon) drops into a wave trough, the water cannon should rotate upwards to maintain a consistent impact target point.

It was observed initially that a phase lag existed in the motion compensation system response (attributed to a software problem) resulting in the water jet either overshooting the iceberg target or undershooting into the water in front of the iceberg. The problem was not related to forcing of the water cannon by hydraulic power because it was observed that the water cannon azimuth and elevation could be altered virtually instantaneously by joystick control. The rate of rotation is 20°/s and the acceleration is 50°/s.s with the application of up to 44 kW of hydraulic power. The cycling time of the computer system sending water cannon pointing instructions to the hydraulic servo system is 0.2 s.

TABLE 5

Estimates of sea state and corresponding target impact consistency*

Estimated sea state MCS (m)	Estimated range of target impact* (m)	Vessel to target distance (m)	Test number	Mode of control system
1.5	5	40-50	1-3	AUTOMATED
1.5	5	40-50	1-4	AUTOMATED
2.0	5-6	50	1-5	AUTOMATED
2.0	8	40-50	1-2	AUTOMATED
2.0	10	60-70	5-1	AUTOMATED
2.0	4	50	5-2	AUTOMATED
2.0	4-5	50	5-3	AUTOMATED
3-4	6-7	50-60	7-1	MANUAL
4-5	12-15	50-60	7-5	AUTOMATED
6	9	70	7-7	MANUAL

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* "Target impact consistency" is the range over which the water jet impact wanders in the vertical plane because of vessel motion when aimed at a desired target point. The range of wander is reduced by the automatic motion compensation system.

VESSEL MOTION AT THE WATER CANNON

Measurements of vessel motion in six degrees-of-freedom at the water cannon location were made by C-Core personnel. A total of 18 h 36 min worth of vessel motion data were collected and are summarized in Table 6. Most of the independent vessel motion measurements were made at relatively low sea states as indicated in the table. During the 1986 phase, measurements were made while the vessel responded to 6-m maximum combined seas on the beam of the vessel. During the 1987 phase of the test program, measurements of vessel motion were made in maximum combined seas of 7 m while conducting water cannon operations with following seas.

In addition to the vessel motion measurements made while conducting water cannon operations, several opportunities were taken to measure vessel motion with the vessel heading into maximum combined seas of 7 m and 10 m at a speed of 1 knot. These opportunities occurred while the vessel was on standby at the drilling unit Bow Drill 3. On another occasion, vessel motion measurements were made while steaming into 6-m maximum combined seas at a speed of 1.5 knots and on yet another occasion, vessel motion measurements were made while the vessel steamed at 10 knots with 4- to 5-m maximum combined seas on the starboard beam.

The data were analysed selectively by C-Core using software developed for analysis of motion of small ice masses due to sea state. The raw signals are first digitized and then processed on the VAX mainframe computer located at Memorial University in St. John's. All data are stored at C-Core in digital format for future reference and further analysis.

Data analysis for water cannon Test 7-7 conducted with 40-knot winds and 6-m maximum combined seas has been completed by C-Core. This test represents the maximum, or worst-case, vessel motion experienced during the 1986 phase of the water cannon test program. The motion in six degrees-of-freedom is presented in Figures 23 to 28. These figures are plots of three angular displacements and three linear accelerations (with gravity removed) for the 90-s segment which contains the largest instantaneous total acceleration seen during Test 7-7.

Vessel acceleration along the vertical axis (heave) is presented in Figure 23 and indicates a maximum of 3.05 m/s.s and a period of 8 s. By comparison, acceleration along the x axis (surge) reaches a maximum of 0.40 m/s.s (Fig. 24) and along the y axis (sway) accelerations reached 0.72 m/s.s (Fig. 25). These accelerations agree qualitatively with expected ship motion where heave is greater than surge and sway.

The maximum vessel pitch was 8.2° (Fig. 26) and vessel roll (which limited the vessel operations with 6-m maximum combined seas impacting almost broadside) is presented in Figure 27 as 26.2° on either side of vertical.

In rotation, Figure 28 shows the compass rotation (yaw) varying from 28° to 88° and back, in approximately 8 s. This yaw is attributed to the 6-m maximum combined seas that impacted the vessel almost broadside during the event.

These results give an indication of the extreme vessel motion characteristics experienced during the initial phase of the water cannon test program. Average values of the above vessel motions for water cannon Test 7-7 are considerably less than the maximum values recorded.

TABLE 6

Summary of vessel motion measurements

Date	Test number	Time period	Duration	Maximum combined seas(m)
1986				
April 23	1-1	19:30-20:51	1 h 21:35 min	2
April 27	1-2	08:38-10:08	1 h 30 min	1
April 27	1-3	11:51-12:51	39:15 min	1
April 27	1-5	16:59-18:16	1 h 17:40 min	2
April 29	5-1	09:04-10:40	1 h 36 min	2
April 29	5-2	15:25-16:54	1 h 29 min	2
May 6	7-2	07:21-08:51	1 h 30 min	4
May 6	7-3	11:19-12:49	1 h 30 min	4
May 6	7-4	14:52-15:17	25:05 min	5
May 8	7-5	07:48-08:58	1 h 10 min	5
May 8	7-6	10:03-11:33	1 h 30 min	6
May 8	7-7	13:49-15:03	1 h 14 min	6
1987				
March 13	*	10:00-10:16	16 min	7
March 13	*	12:41-12:56	15 min	10
March 18	18-1	11:30-11:47	17 min	4
March 18	18-2	14:28-14:47	20 min	4
March 18	18-3	15:39-16:04	25 min	4
April 19	**	13:06-13:29	23 min	6
April 19	5-6	18:16-18:41	25 min	5
April 19	***	19:22-19:42	20 min	4 to 5
April 20	6-2	15:49-16:05	16 min	3
April 22	7-3	10:12-10:38	26 min	7
		TOTAL	18 h 36 min	

* The vessel was heading at 1 knot into 7 to 10-m maximum combined seas.

** The vessel was heading into 6-m maximum combined seas at 1.5 knots.

*** The vessel was steaming at 10 knots with 4- to 5-m maximum combined seas on the starboard beam.

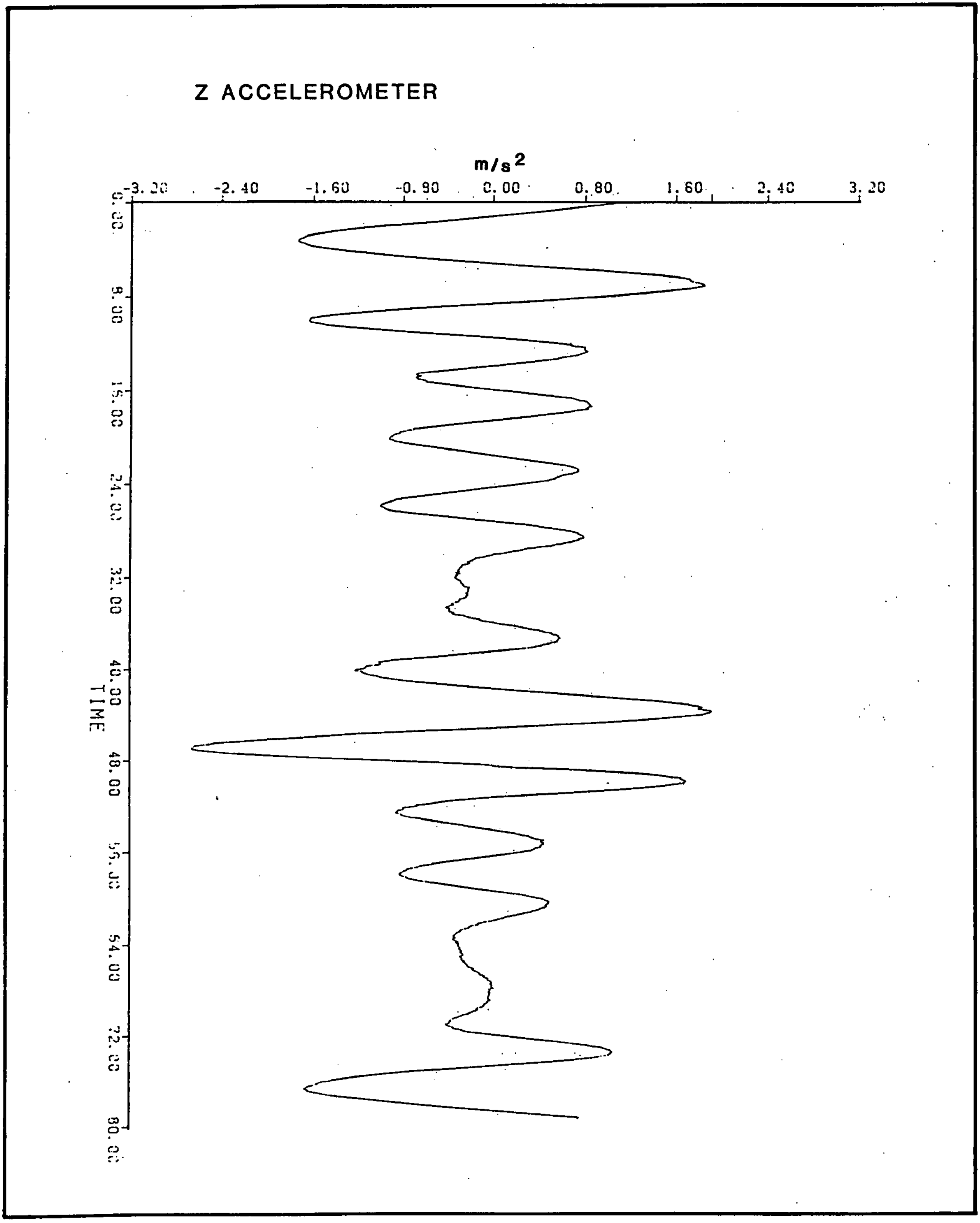


Figure 23. Worst-case vessel heave with 6-m seas on port beam.

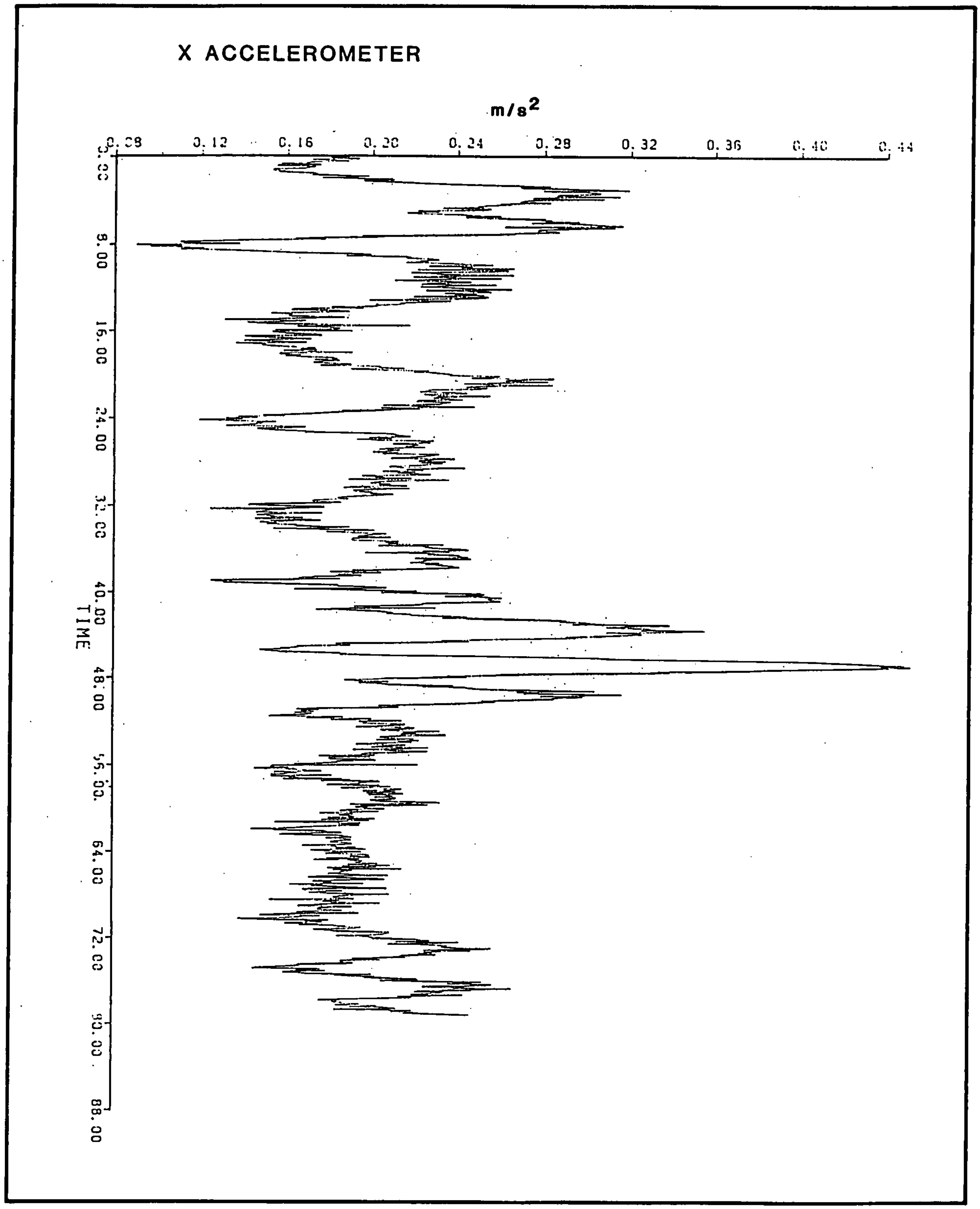


Figure 24. Worst-case vessel surge with 6-m seas on port beam.

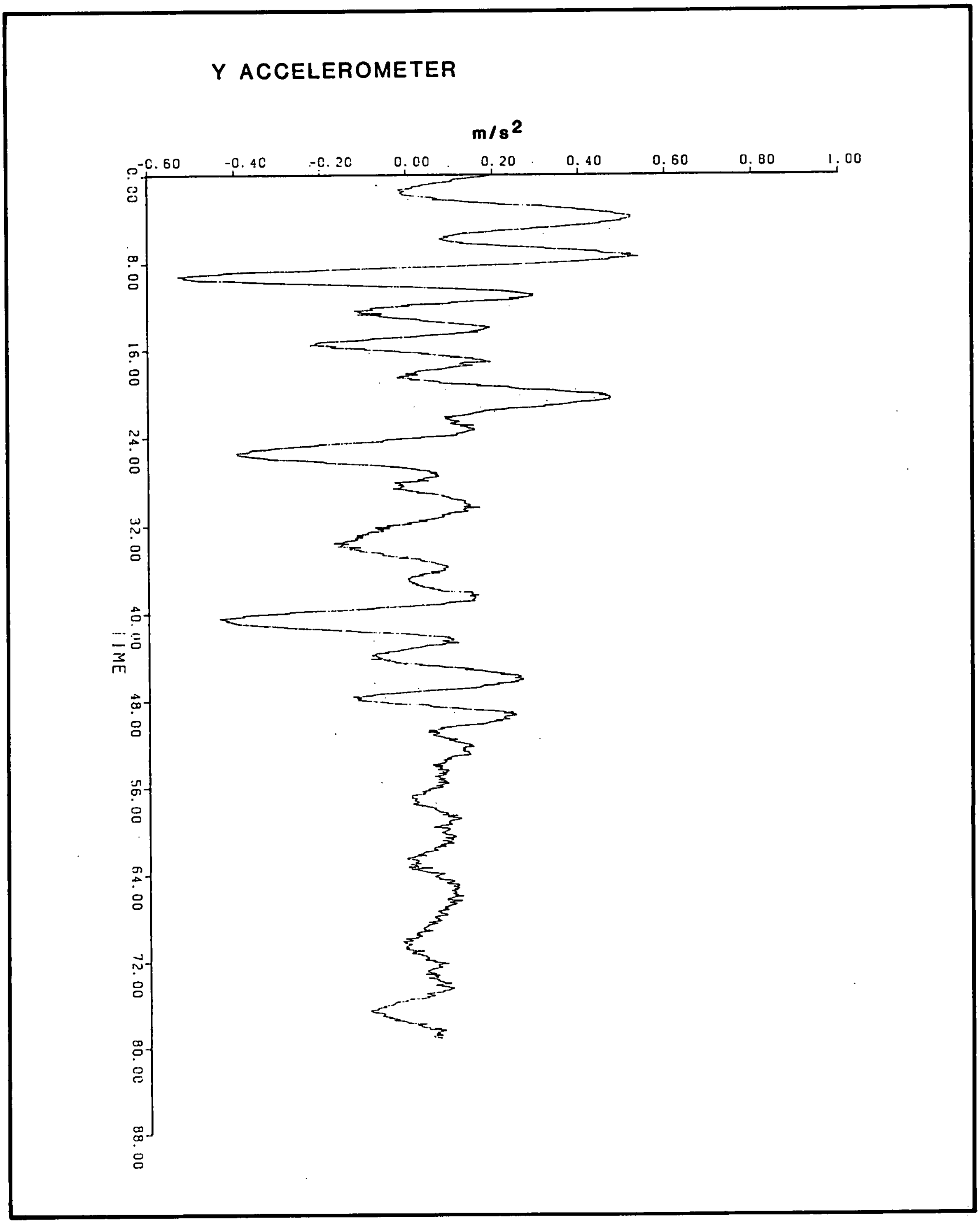


Figure 25. Worst-case vessel sway with 6-m seas on port beam.

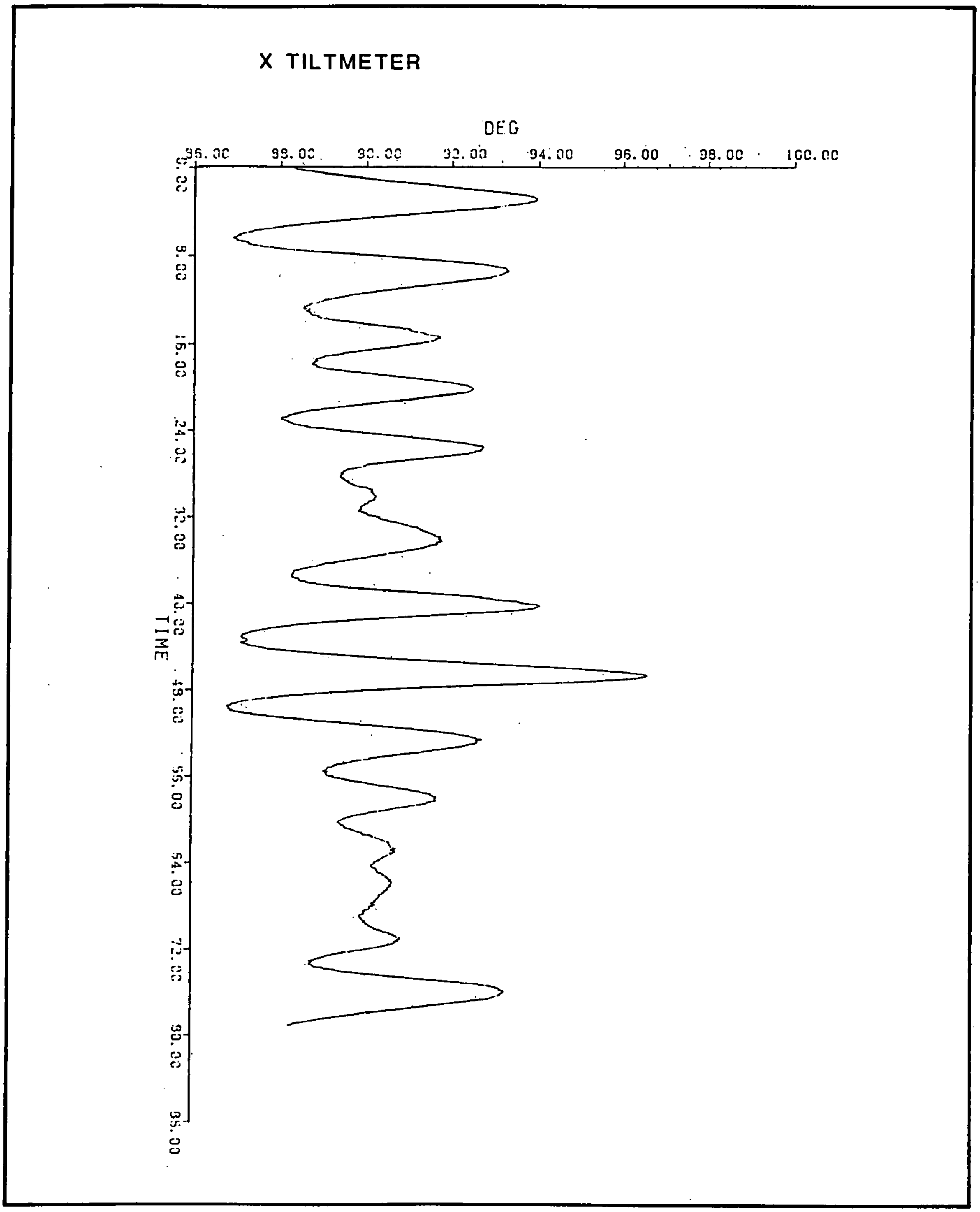


Figure 26. Worst-case vessel pitch with 6-m seas on port beam.

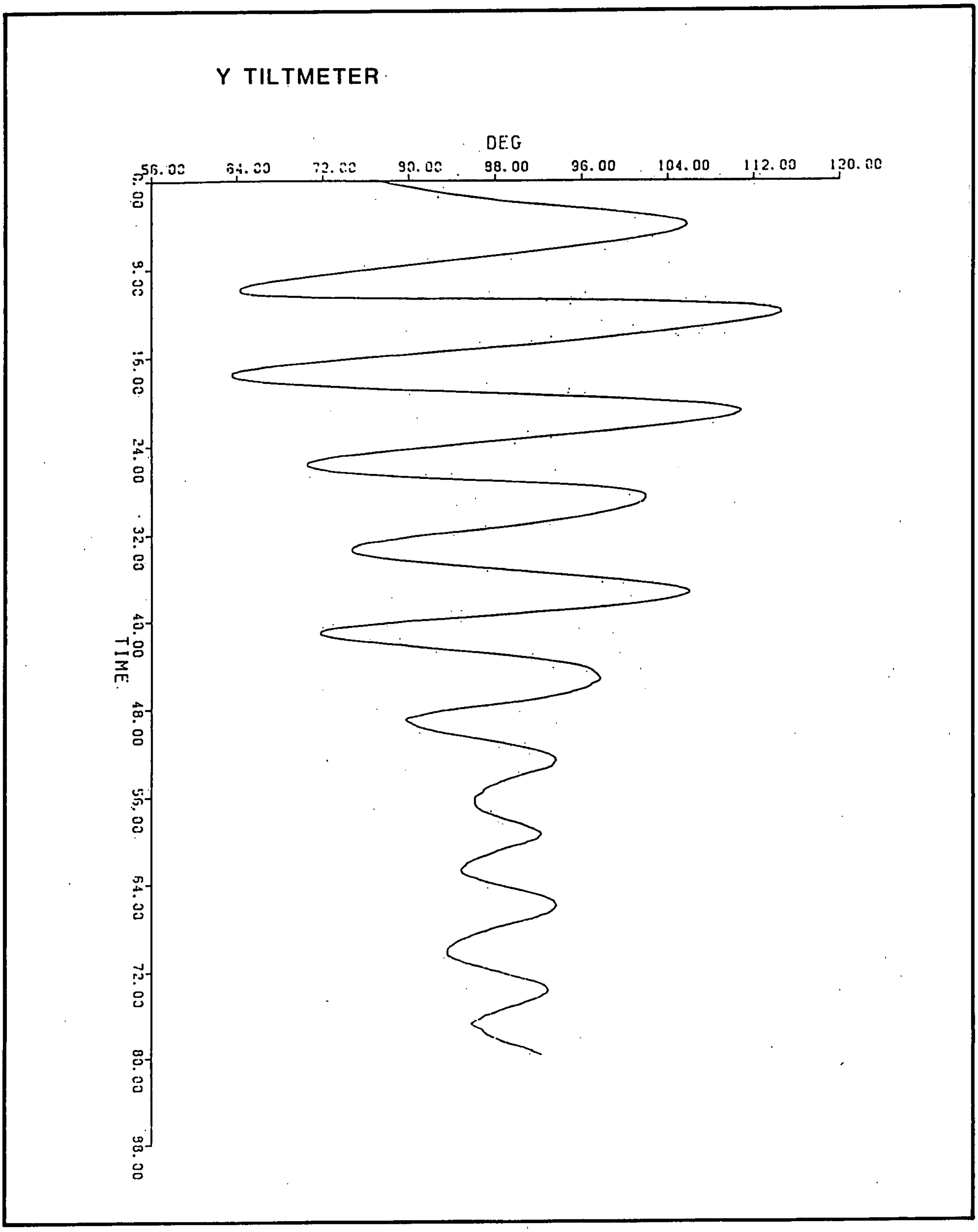


Figure 27. Worst-case vessel roll with 6-m seas on port beam.

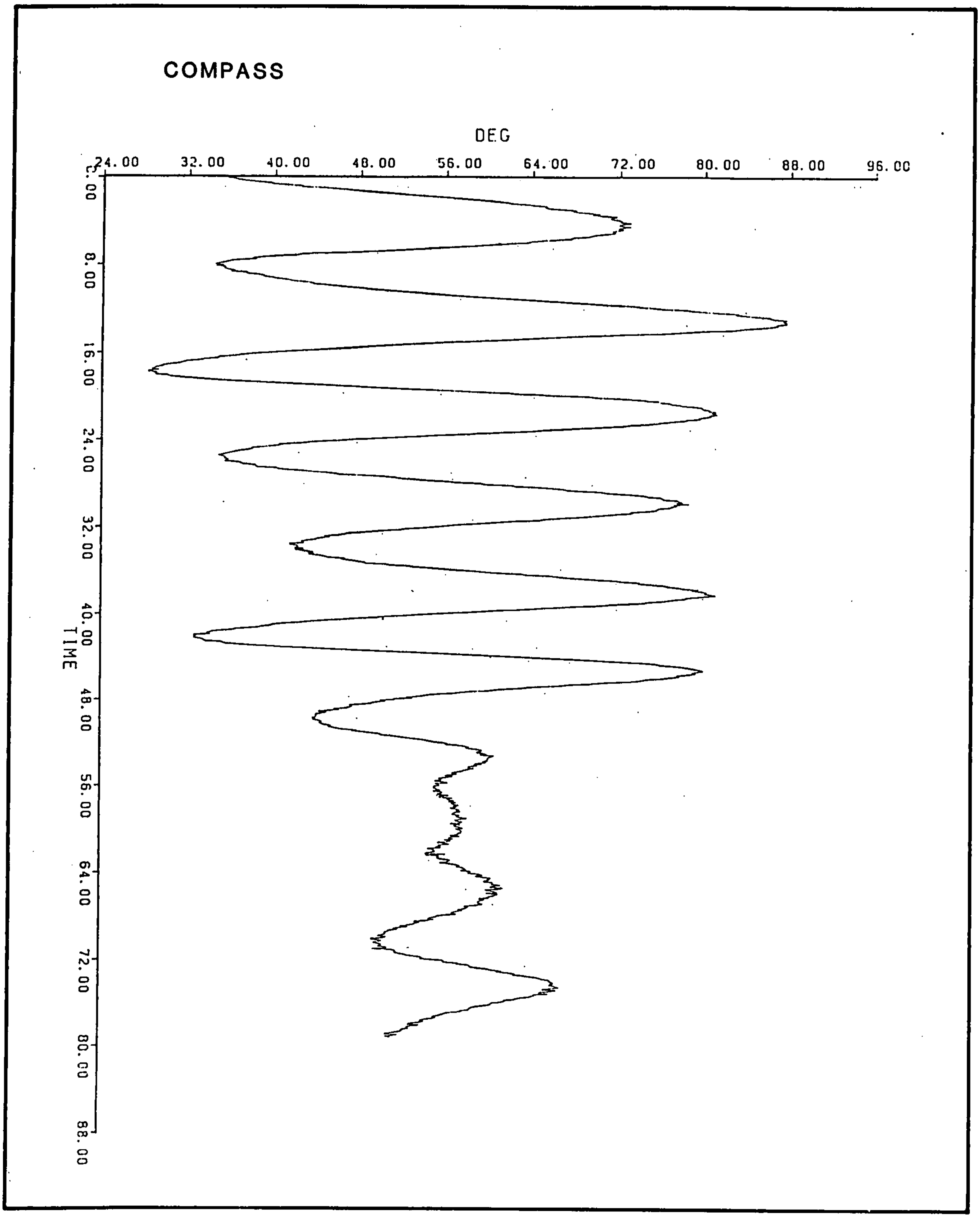


Figure 28. Worst-case vessel yaw with 6-m seas on port beam.

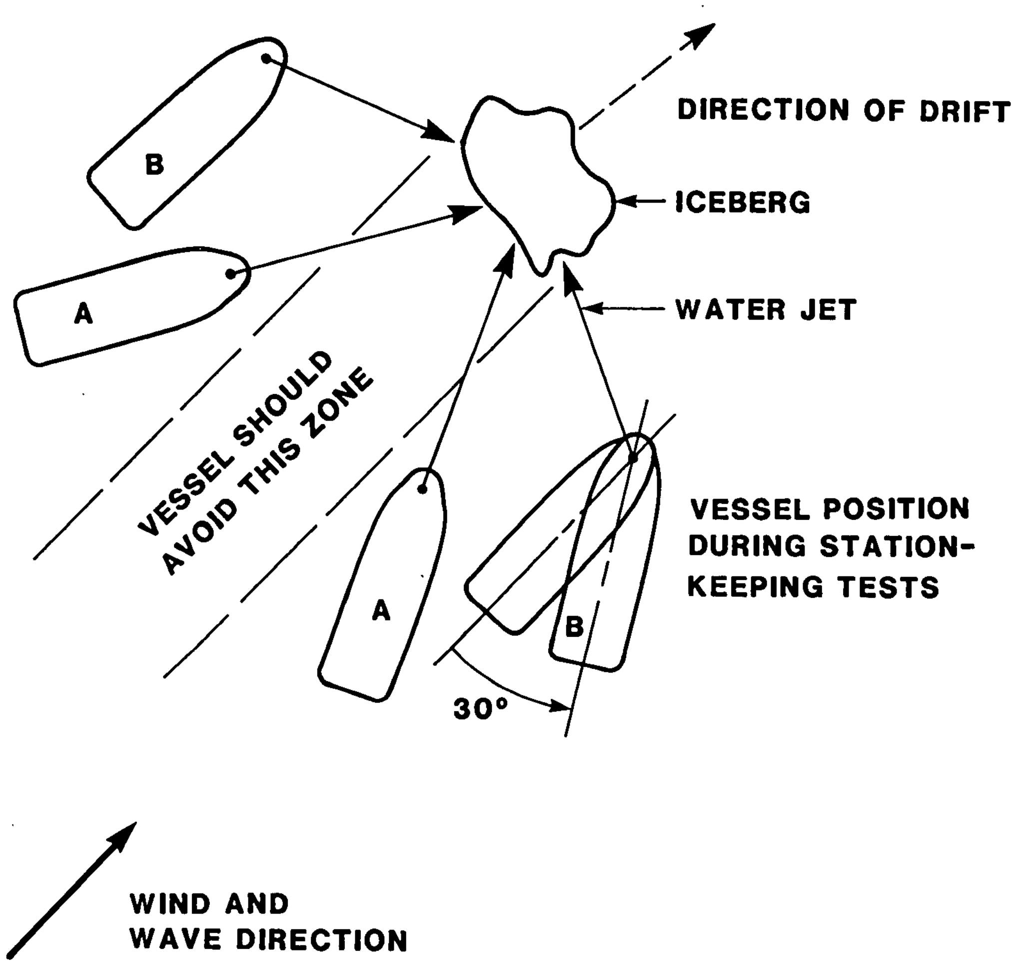
HIGH SEA-STATE OPERATIONS

The zone directly upwind of an iceberg (or any other floating or fixed object) is an undesirable place for a vessel to be situated at high sea state and high wind conditions. Failure of the ship's propulsion system or a sudden deterioration in visibility and weather might result in a collision with the iceberg (or object) because the ship might drift at a higher speed than the iceberg because of its large above-water surface area and limited keel depth. For this reason, the vessel avoided this zone during high sea-state operations. Six station-keeping or positioning tests were conducted with the vessel positioned about 60 m from an iceberg (Fig. 29). In this position, the vessel was able to drift clear of the iceberg if an engine failure were to occur.

Test 1 Station-keeping test at an iceberg with four engines and three thrusters. During this test, the four main engines provided propulsion and power to operate two bow thrusters and one stern thruster. The water cannon was not in operation.

The iceberg was drifting towards 063°T at a speed of 0.7 knot. The vessel heading was 050°T. Maximum combined seas (MCS) of 7 m and 35-knot winds originated from 230°T and impacted directly on the stern of the vessel. The vessel was controlled by joystick. No difficulties were experienced in holding position about 60 m laterally removed from the iceberg.

Test 2 Station-keeping test at an iceberg with four main engines and two bow thrusters. During this test, full power from the four main engines was available for propulsion and operation of the two bow thrusters. Again the water cannon was not in operation. No difficulties were experienced in holding position while 6- to 7-m maximum combined seas and 35- to 40-knot winds impacted directly on the vessel stern.



A VESSEL POSITIONS FOR INCREASING DRIFT SPEED OF AN ICEBERG
B VESSEL POSITIONS FOR CHANGING DRIFT DIRECTION OF AN ICEBERG

* 30 DEG. IS THE OPERATIONAL LIMIT OF VESSEL ROTATION FROM THE WIND DIRECTION AND/OR WAVE DIRECTION

Figure 29. Vessel/iceberg postions for safe ship-handling during water cannon operations at high sea states.

Test 3 <u>Station-keeping at an iceberg with three main engines and two bow thrusters</u>. During this test, the two main engines (#3 and #4 on the starboard side) were used for propulsion. Main engine #1 on the port side was used to power the two forward thrusters and to provide propulsion. Main engine #2 on the port side was declutched from the port-side propeller and from the water cannon pump. The vessel was controlled by joystick. No difficulties were experienced in holding station next to an iceberg while 7-m maximum combined seas and 35-knot winds impacted the vessel stern.

Test 4 <u>Station-keeping at an iceberg with three main engines and two bow thrusters</u>. This test was conducted with the two starboard main engines providing propulsion and power for two bow thrusters. On the port side, main engine #1 provided propulsion whereas main engine #2 was declutched from the port shaft and from the centrifugal pump to simulate engine configuration during water cannon operations. This test was identical to Test 3 except for the fact that power for the two bow thrusters was provided by the starboard main engines.

The operating arrangement of propulsion and thrusters used during Test 4 effectively balanced the available power on the port and starboard propellers and maximized the power available to the thrusters. This combination increased the vessel's ability to counterbalance winds and waves by the propellers while providing maximum ability to follow a drifting iceberg laterally as it is deflected by the water cannon.

With this arrangement, no difficulties were experienced in holding position next to an iceberg while 7-m maximum combined seas and 35-knot winds impacted directly on the stern of the vessel and on the iceberg which was drifting at a speed of 0.72 knot.

Tests 1 to 4 demonstrated safe station-keeping with 7-m MCS and 35-knot winds. Test 4 demonstrated that the best power balance between propulsion and thrusters involves running the two forward thrusters from the two starboard main engines (#3 and #4) while deriving propulsion from main engines #1, #3, and #4. Engine #2 is then free to drive the centrifugal pump providing water to the water cannon.

Test 5 Station-keeping at an iceberg while rotating the vessel relative to the wind and wave direction. This test was conducted to determine vessel handling limitations in high sea states and thus water cannon operational limitations. During this test, the vessel gradually changed heading to test drift and roll limitations under the prevailing environmental conditions. Propulsion was provided by one port engine and the two starboard engines which also provided power to operate the two bow thrusters. Engine #2 was declutched.

When winds and waves strike the vessel directly on the stern, the drift of the vessel resulting from winds and waves is easily counterbalanced by the ships propellers working in reverse. When winds and waves strike the vessel on the beam as the vessel rotates off the wind and sea direction, the drift speed of the vessel is increased, and thrusters must be used to prevent the vessel from drifting faster than the iceberg. This situation represents one limitation to broadside water cannon operations in high sea-state conditions. Another limitation is the high degree of roll of the vessel when operating with waves impacting the beam of the vessel.

Initially during the test, the vessel heading was 058°T with winds and waves impacted directly on the stern. The vessel was rotated gradually to a heading of 043°T and joystick control was used to maintain position while drifting with iceberg number 10 at a rate of 0.72 knot. No problem was experienced with this situation. When the vessel heading was changed to 033°T which was 25° off the wind, position keeping was still possible but the vessel roll reached 15°. When the vessel was rotated about 33° from the wind and wave direction, the vessel roll increased to 20°. Although it was then still possible to hold position next to the iceberg, it was the Captain's opinion that vessel roll in the 7-m seas was the limiting operational factor in this broadside situation. In this case, excessive vessel rolling made water cannon operations impossible before the vessel was pushed off location at the iceberg by the wind and wave forces.

The Captain considered that safe operations would limit the vessel position to 30° or less off the wind and wave direction to reduce vessel roll to acceptable levels.

Test 6 Water cannon operations with an iceberg in 7-m MCS and 30-knot winds. This test was conducted with engine #2 driving the centrifugal pump to provide water to the water cannon while engines #1, #3, and #4 provided propulsion. Power for the two bow thrusters was derived from the thruster generator driven by engines #3 and #4 on the starboard side.

Test 6 was conducted on 22 April 1987 with iceberg number 10 drifting at 0.72 knot towards 063°T. The vessel was positioned so that the iceberg was 60 m off the port bow with a vessel heading of 065°T. The water cannon was pointed towards the iceberg having been rotated 15° to 25° counter-clockwise. The 7-m combined seas and winds of 30 knots impacted directly on the vessel stern. This situation resulted in excellent vessel operations with a minimum of vessel roll. The drift speed of the 10,700-tonne iceberg was increased to 1.0 knot by application of the water cannon. No difficulty whatsoever was experienced during this test. It is therefore considered to be a good demonstration that water cannon operations can be conducted safely under at least 7-m maximum combined seas and 30-knot wind conditions.

OPTIMUM NOZZLE DIAMETER FOR PUSHING SMALL ICE MASSES

The data collected during the six engine/pump tests in the 1986 phase of the test program are presented in Tables 7 to 12 for nozzle diameters of 100, 125, 130, 145, 152, and 165 mm respectively. The data consist of: time of the test, engine speed ranging from 400 to 650 rpm, fuel rack index, fuel consumption, and the discharge pressure from the centrifugal pump associated with each nozzle diameter and with each rpm setting of the engine.

As a result of conducting the engine/pump tests, it was determined that the exhaust temperatures of the engine were excessive for continuous pumping operations with any nozzle greater than 130-mm in diameter. A 130-mm nozzle was then used during the remainder of the test program in 1986.

The fuel consumption of the engine was monitored by the fuel-rack index where a setting of 35 represents 100% of the maximum possible flow rate which is approximately 500 L/h. Readings taken at each rpm setting during each test are plotted in Figure 30. Although fuel consumption by itself is not a governing factor in selecting the optimum nozzle diameter, there is a requirement to operate efficiently. It is evident in Figure 30 that the larger the nozzle, the greater is the fuel consumption. For example, with a 100-mm diameter nozzle, 380 L/h of fuel is consumed each hour. With a 130-mm nozzle, 470 L/h are consumed. For larger-diameter nozzles, fuel consumption of approximately 500 L/h is experienced at rpm from 600 to 620.

TABLE 7

Pump and engine data with 100-mm nozzle, 6 May 1986

Local time	Engine rpm	Fuel rack index	Fuel consumption (%)	Fuel consumed (L/h)	Discharge pump (bars)
1442	400	14.0	40	162	6.0
1450	500	19.0	54	207	11.0
1457	520	20.0	57	220	12.3
1504	540	21.0	60	237	13.2
1508	560	22.0	63	249	14.3
1513	580	23.0	66	278	15.5
1518	600	24.0	69	300	16.8
1524	620	25.5	73	320	18.0
1530	640	27.0	77	365	19.0
1535	650	28.0	80	380	20.0

TABLE 8

Pump and engine data with 125-mm nozzle, 27 April 1986

Local time	Engine rpm	Fuel rack index	Fuel consumption (%)	Fuel consumed (L/h)	Discharge pump (bars)
1445	400	11.0	46	177	6.0
1450	500	21.0	60	241	11.8
1455	520	22.0	63	252	12.0
1500	540	24.0	69	274	13.0
1505	560	25.0	71	300	14.0
1510	580	27.0	77	332	15.0
1515	600	29.0	83	362	16.0
1520	620	30.0	86	407	17.2
1525	640	31.0	89	454	18.5
1535	650	32.0	91	454	19.0

TABLE 9

Pump and engine data with 130-mm nozzle, 13 June 1986

Local time	Engine rpm	Fuel rack index	Fuel consumption (%)	Fuel consumed (L/h)	Discharge pump (bars)
1300	500	21.0	60	246	11.8
1305	520	22.5	64	254	12.5
1310	540	24.0	69	280	13.4
1315	560	25.5	73	312	14.4
1320	580	27.0	77	338	15.5
1325	600	29.0	83	365	16.6
1330	620	30.0	86	416	17.5
1335	640	32.0	91	464	18.8
1340	645	33.0	94	470	18.9

TABLE 10

Pump and engine data with 145-mm nozzle, 21 April 1986

Local time	Engine rpm	Fuel rack index	Fuel consumption (%)	Fuel consumed (L/h)	Discharge pump (bars)
1115	400	17	48.6	166	5.3
1120	420	19	54.0	178	5.8
1123	440	20	57.1	208	6.7
1125	460	21	60.0	231	7.6
1127	480	22	62.9	237	8.7
1130	500	23	65.7	250	9.5
1135	520	25	71.4	284	10.7
1140	540	27	77.0	341	11.6
1147	560	28	80.0	397	12.7
1152	580	30	83.7	423	13.1
1157	600	31	88.6	441	14.7
1935	610	32	91.4	448	15.7
1945	620	34	97.1	496	16.4

TABLE 11

Pump and engine data with 152-mm nozzle, 27 April 1986

Local time	Engine rpm	Fuel rack index	Fuel consumption (%)	Fuel consumed (L/h)	Discharge pump (bars)
1145	500	24	68.6	271	8.5
1150	520	26	74.3	285	9.7
1155	540	28	80.0	312	10.7
1200	560	29	82.8	363	11.5
1205	580	31	88.6	412	12.5
1210	600	33	94.3	468	13.7
1215	615	35	100	507	14.7

TABLE 12

Pump and engine data with 165-mm nozzle, 27 April 1986

Local time	Engine rpm	Fuel rack index	Fuel consumption (%)	Fuel consumed (L/h)	Discharge pump (bars)
0810	500	25	71.0	271	8.0
0815	520	27	77.0	313	9.0
0821	540	29	83.0	392	10.0
0827	560	31	89.0	426	10.7
0835	580	32	91.4	463	11.5
0839	600	35	100	496	12.5

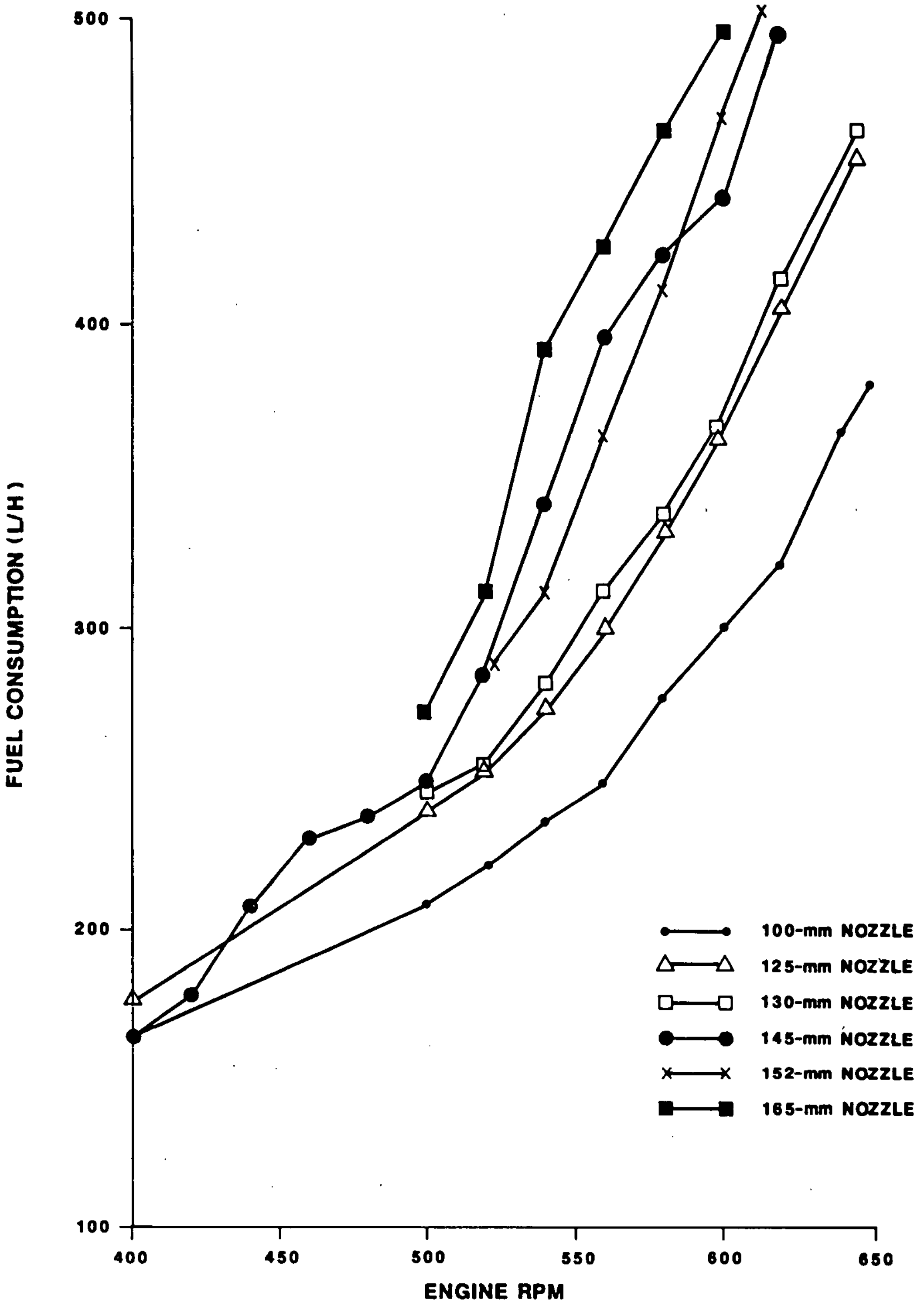


Figure 30. Engine fuel consumption vs engine rpm for nozzle Diameter of 100, 125, 130, 145, 152, and 165-mm.

PUMP DISCHARGE PRESSURES AS A FUNCTION OF NOZZLE DIAMETER

Pump discharge pressures were monitored during each engine pump test at each incremental rpm setting. The pressures were measured by a pressure gauge located on the discharge side of the pump. These data (see Tables 7 to 12), plotted in Figure 31 against engine rpm for each nozzle diameter, indicate an increase in pump discharge pressure with smaller-diameter nozzles with 19 to 20 bars being achieved. With large nozzles, the pump discharge pressures reduce to as low as 12.5 bars with a 165-mm nozzle.

These pump discharge pressures serve as the basis for calculations of nozzle exit velocities and volume flow according to Bernoulli's equation for flow. The nozzle pressure (P) is taken to be the measured pump discharge pressure listed in Tables 7 to 12 minus 1 bar to account for the 10 m of elevation difference between the pump and the water cannon minus 0.5 bar to account for friction losses in the pipe (estimated by Thune Eureka).

Water cannon thrust or reaction force (F) is calculated according to the following equation provided by Thune Eureka:

$$F = 0.4 \times Q \times P^{0.5}$$

where: F is the thrust in tonnes
Q is the volume of water in cubic metres per hour
P is the nozzle pressure in bars.

For each of the six tested nozzle diameters, the calculated values of the maximum nozzle pressures (P), the maximum flow rates (Q), and the maximum water cannon reaction forces (F) are presented in Table 13.

The calculated jet reaction force is plotted in Figure 32 as a function of the cross-sectional area of the nozzle. It is clear that the maximum reaction force is 4.8 tonnes and that this is associated with a 145-mm diameter nozzle operating with a nozzle pressure of 14.9 bars and a flow volume of 3,124 m^3/h.

After conducting the six engine/pump tests, which resulted in the selection of the 130-m diameter nozzle as the optimum nozzle during 1986, it was discovered that the engine was not operating at peak efficiency because of a fuel injector problem. During the test program in 1987, the injector problem was resolved and it then became possible to pump water through the 145-mm diameter nozzle continuously without encountering excessively high temperatures in the engine exhaust manifold.

An additional engine/pump test conducted with the 145-mm diameter nozzle demonstrated that the maximum possible reaction force of 4.8 tonnes was achieved while fuel consumption decreased by 5%. The results of the engine pump test with the engine properly tuned are presented in Table 14. The improvements in fuel consumption and reaction force are presented in Table 15.

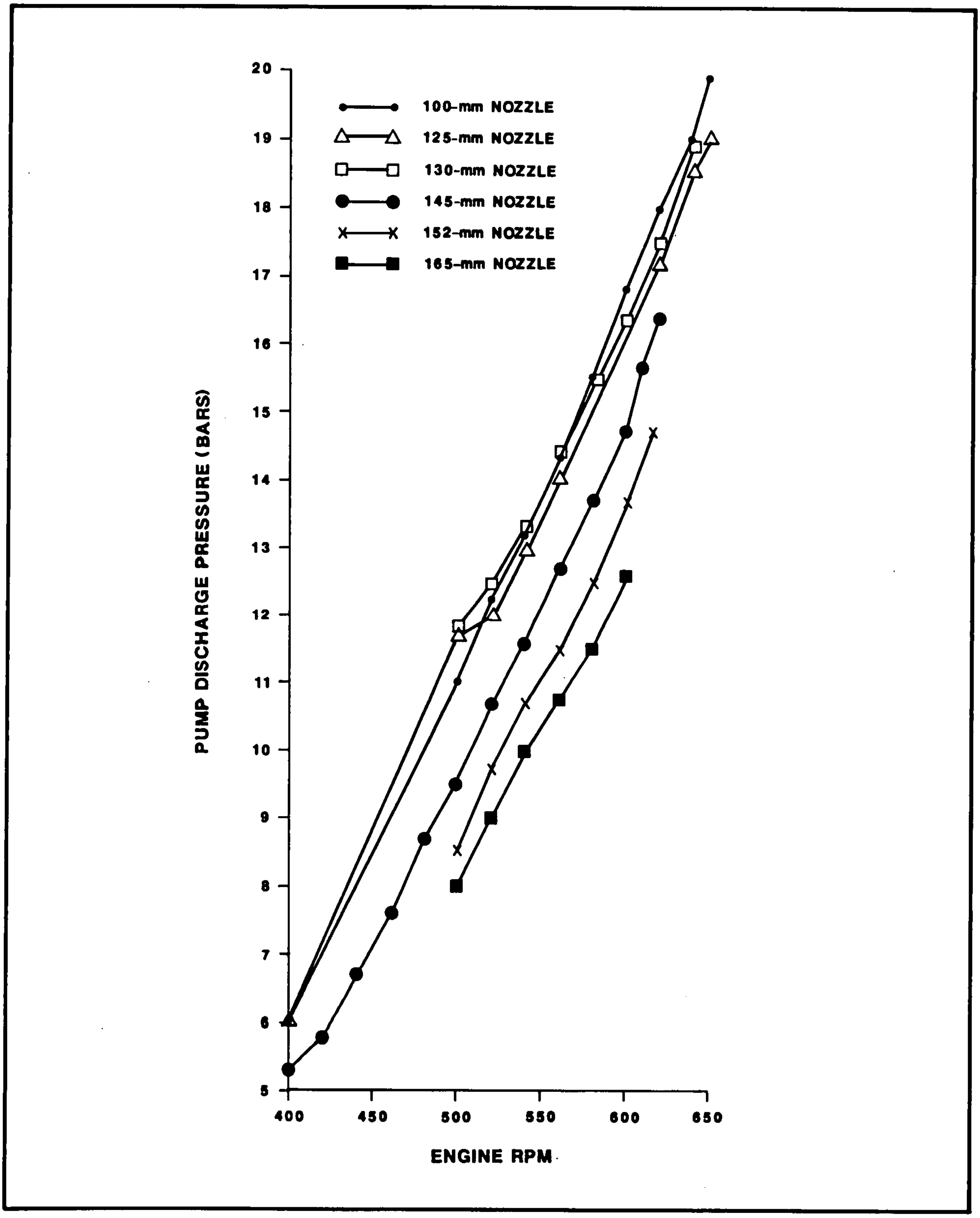


Figure 31. Pump discharge pressure vs engine rpm for nozzle diameters of 100, 125, 130, 145, 152, and 165-mm.

TABLE 13

Flow rates and reaction forces associated with six different nozzle diameters

Cross-sectional area of nozzle (m^2)	Nozzle diameter (mm)	Nozzle exit speed (m/s)	(Q) Flow rate (m^3/h)	(P) Nozzle pressure (bars)	(F) Reaction force (tonnes)
0.00785	100	58.4	1650	18.5	2.8
0.0123	125	56.8	2515	17.5	4.2
0.0133	130	56.7	2715	17.4	4.5
0.0165	145	52.6	3124	14.9	4.8
0.0181	152	49.5	3225	13.2	4.7
0.0214	165	45.2	3482	11.0	4.6

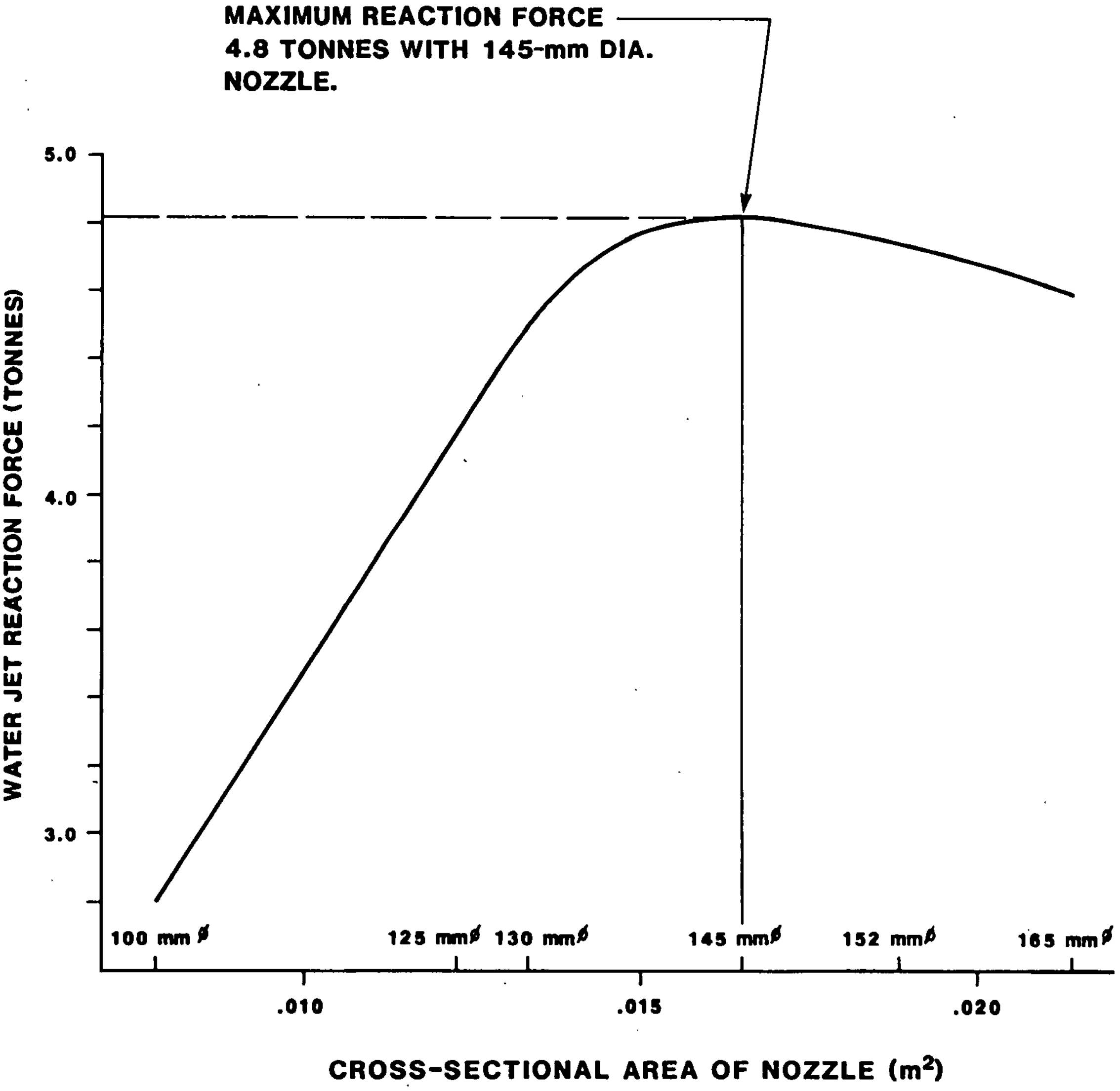


Figure 32. Water jet reaction force versus nozzle cross-sectional area.

TABLE 14

Pump and engine data, after engine tuning, with 145-mm nozzle diameter

Engine rpm	Fuel rack index	Fuel consumption (%)	Fuel consumed (L/h)	Discharge pump (bars)
520	22	63.0	306	11.0
540	25	71.0	336	12.0
560	27	77.0	358	13.0
580	30	73.0	385	13.5
600	31	89.0	400	14.0
620	33	94.0	447	14.5

Note: A fuel rack index of 35 is 100% fuel consumption.

TABLE 15

Fuel consumption and reaction force for 130-mm and 145-mm nozzle diameters

Parameter	Optimum 130-mm nozzle prior to engine tuning	Optimum 145-mm nozzle after engine tuning	Improvements
Fuel consumption (L/h)	470	447	5% fuel reduction
Reaction force (tonnes)	4.5	4.8	6.7% increase

DESTRUCTION OF ICE MASSES BY THE WATER CANNON

During water cannon operations with iceberg number 18, an attempt was made to assess the effect of the water cannon on the rate of destruction of ice masses. Destruction of small ice masses usually occurs in one of three ways: 1) chunks of ice are blasted off or eroded by the impact of the water jet; 2) thermal interaction occurs, which results in gradual melting of the ice at the surface in the area of impact; and 3) on occasions when icebergs roll, there is a resultant loss of mass by calving of small growlers.

Iceberg number 18 was intercepted by the MV Placentia Bay on 14 May 1986 at 1420, and measured by radar and sextant technique to be 27 m x 20 m at the water-line, with a sail height of 10 m. The calculated mass was 16,200 tonnes. The water jet was applied for a period of 25.33 h, and followed by free drift and natural deterioration for a period of 17.5 h. On May 16 at 0800, berg 18 measured 16 m x 14 m x 5 m and displaced 3,360 tonnes.

After 7 h of water cannon operations and 13.5 h of natural deterioration on May 16, berg 18 measured 9 m x 8 m x 3 m, and displaced 650 tonnes. Table 16 shows the sail dimensions of berg 18, and the displacement during water cannon operations on May 15 and 16.

The approximate rate of ice mass loss or destruction resulting from the combined effects of water cannon operations and natural deterioration processes are plotted as a function of ice mass (Fig. 33). Clearly the rate of ice mass loss of berg 18 was substantial when the mass was 16,200 tonnes. The loss rate was about 800 tonnes per hour.

When berg 18 was reduced to a mass of 3,360 tonnes, the rate of destruction was in the order of 300 tonnes of ice per hour and a lesser rate of about 100 tonnes of ice per hour prevailed when the mass was 1,050 tonnes.

It was possible to derive the rate of reduction due solely to natural deterioration processes during one period only. Between 1530 on May 15 and 0900 on May 16, (a period of 17.5 h) berg 18 deteriorated from 9,000 tonnes to 3,360 tonnes. The natural rate of destruction was therefore about 300 tonnes of ice per hour in this mass range. This result implies that for the 8.75 h of water cannon operations on May 15 (Table 16), the loss of ice mass attributed solely to the water jet interaction was about 500 tonnes of ice per hour.

TABLE 16

Sail dimensions and masses of iceberg number 18

May	Local time	Activity	Sail size (m)	Calc. mass (tonnes)	Mass* lost (tonnes)
15	0645		27x20x10	16,200	
		8.75 h of water cannon operations 8.75 h of natural deterioration			
15	1530		20x15x10	9,000	7200
		17.5 h of natural deterioration			
16	0900		16x14x5	3,360	5640
		2 h of water cannon operations 4 h of natural deterioration			
16	1300		14x12x4.3	2,200	1160
		2 h of water cannon operations 3 h of natural deterioration			
16	1600		10x10x3.5	1,050	1150
		2 h of water cannon operations 2.5 h of natural deterioration			
16	1830		9x9x3	750	300
		1 h of water cannon operations 2 h of natural deterioration			
16	2030		9x8x3	650	100

* Note the decrease in the loss of mass as the iceberg size decreases.

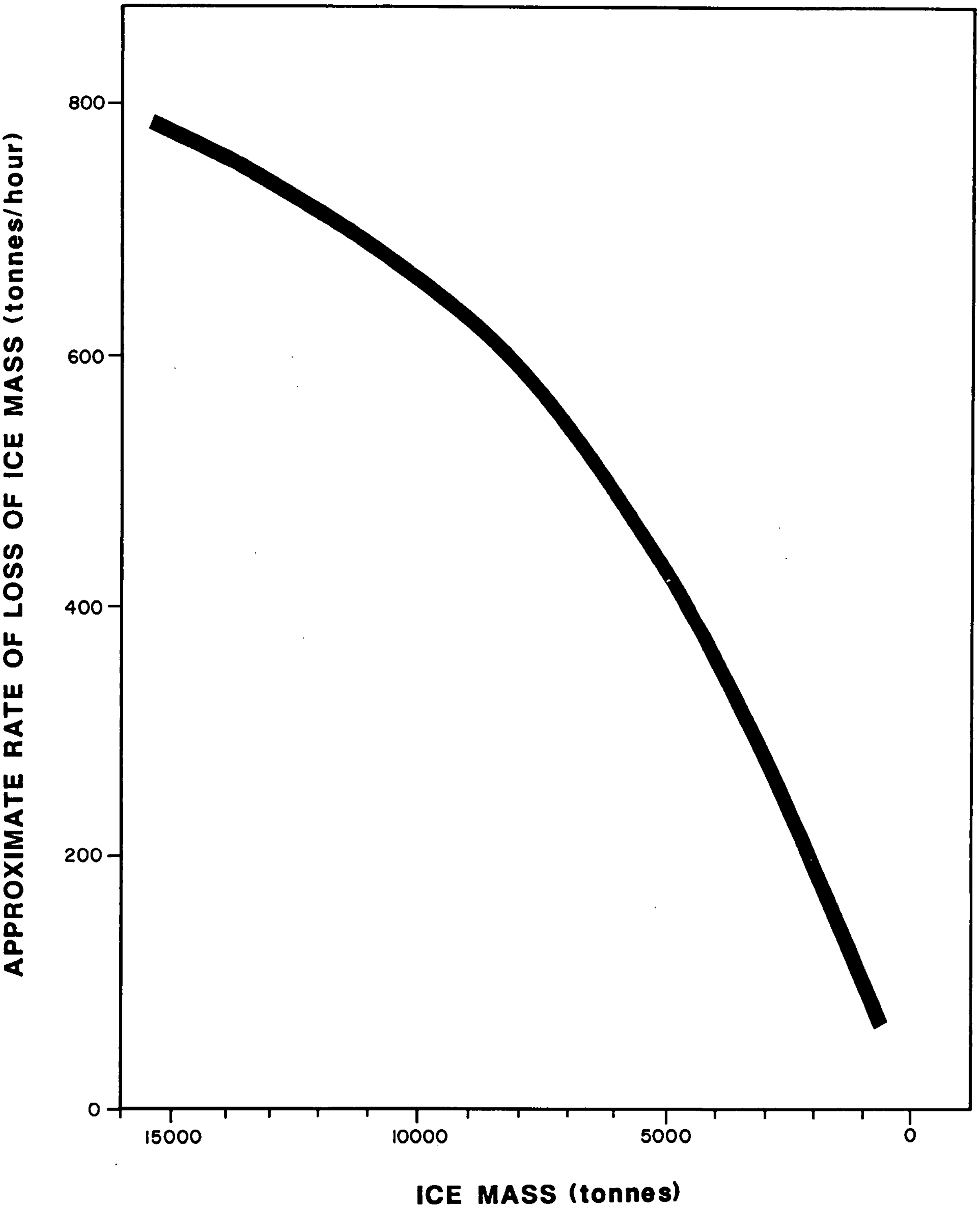


Figure 33. Approximate rate of ice mass loss from berg 18 by water cannon and natural deterioration as a function of diminishing ice mass.

DISCUSSION

WATER CANNON SYSTEM OPTIMIZATION

After conducting water cannon tests with the MV Skandi Alfa during August, 1985, it was perceived that greater control of small ice masses could be achieved by placing the water cannon further forward and at a lower elevation (i.e., on the bow of a vessel). This positioning could potentially reduce the distance between the water cannon and ice mass targets or allow for better safety margins for vessel to iceberg distance, but primarily it contributes to a greater horizontal component of the water jet force. Mounting the cannon above the wheel house creates an obstruction to vision from the bridge windows during water cannon operations, as well as potential for icing of the vessels bow area because of freezing spray from the water jet during winter wind conditions. It was thought that a bow-mounted cannon would remedy these problems to some extent.

The water cannon on the MV Skandi Alfa were controlled by manual joystick with no means available for compensating the cannon pointing for vessel motion. Because of the slow response of the cannon to the operator controls, overshooting and undershooting of iceberg sails occurred regularly, resulting in reduced control of the ice masses. Vessel motion compensation was regarded as a necessity and was recommended as a component of the modified water cannon system. The motion-compensated water cannon mounted on the bow of the MV Placentia Bay constitutes an improved version of the water cannon system for the purpose of controlling small ice masses.

The success of the modifications is evaluated by comparing:

1) The superior speed gains achieved during pushing of ice masses by the improved water cannon system with those achieved by the two-cannon fire-fighting system on the MV Skandi Alfa (see Fig. 21).

In Figure 21 it is evident that maximum speed gains are achieved with small ice masses and that with greater ice masses, the speed gains decrease. The upper limit of controllable mass is taken to be about 60,000 tonnes. The maximum achieved speed gain was 1.18 knots which was accomplished during a push test designed to reverse the drift direction of a 315-tonne bergy bit. The somewhat reduced performance associated with ice masses of 10,000 to 12,000 tonnes are attributed to application of the water jet onto the sea surface. The reason for applying the water jet onto the water in most of these cases was the limited visibility in darkness, rain, and fog which prevented the vessel from approaching sufficiently close to the ice masses to apply the water jet directly onto the sail. Considerations for vessel safety have top priority. It is estimated that speed gains of ice masses of 10,000 to 12,000 tonnes should be in the order of 0.6 to 0.8 knot by applying the water jet directly onto the sails of such ice masses.

In Figure 21, the speed gains achieved by the two-cannon fire fighting system on the MV Skandi Alfa are indicated by the dashed line. Evidently, for most of the ice masses, the speed gains achieved by the improved water cannon system are significantly higher than those achieved by the MV Skandi Alfa, except for some cases at the low end of the mass range. This exception is thought to be due to the greater ability to steer smaller ice masses using two cannon. Better "steering ability" implies that less time is spent repositioning the vessel as the smaller ice mass drifts rapidly away after being struck directly by the water jets.

During push tests directed perpendicular to the free-drift direction of berg 7 (mass of 47,600 tonnes), it was noted that a decrease in the drift speed occurred whereas the drift direction was changed by as much as 20°. Although this change did not constitute an increase in the drift speed, slowing down the rate of drift towards a drill rig may be a desirable ice management strategy. For example, reducing the drift speed of a small ice mass advancing towards a drill rig may keep the particular ice mass outside the ice response zone calling for drilling operations shutdown procedures, until such time that favourable winds and current permit water cannon operations to divert the ice mass away from the drill rig.

2) The greater direction change of small ice masses achieved by the modified water cannon system with the direction changes achieved by the two-cannon fire-fighting system on the MV Skandi Alfa (see Fig. 22).

It is readily apparent that the single cannon system on the MV Placentia Bay is significantly more effective than the two fire-fighting water cannon on the MV Skandi Alfa in effecting drift direction changes for small ice masses. The upper limit of ice mass which can be directed by the MV Placentia Bay water cannon is considered to be about 60,000 tonnes, although small directional changes were associated with greater ice masses.

Judging by the spread in the data points for the same iceberg mass, a wide range of drift direction changes can be selected and are achievable, depending on the vessel heading selected relative to the free-drift direction. Pushing in a direction perpendicular to the free-drift direction results in maximum direction change. Pushing in a down-drift direction can result in no change in drift direction, while achieving a significant speed change. Achieving a speed increase only, without changing the free-drift direction would be satisfactory when the free-drift direction is already favourable with respect to a drill rig location, when there is a requirement to move a small ice mass around the drill rig.

Although the 4.8-tonne reaction force of the single modified water cannon system is less than the 8.8-tonne reaction force of the two-cannon fire-fighting system on the MV Skandi Alfa, the single cannon provides greater speed gain and more directional control of small ice masses (see Figs. 21 and 22). The improved performance is attributed to the modifications to the water cannon system. Although the greater horizontal component of the water cannon reaction force no doubt contributes to the improved performance of the modified cannon, it is thought that the primary reason is that the high power hydraulic power unit and the sensitivity of the system controls permitted near continuous application of the water jet onto the sail or onto the water surface in front of ice masses. The 44-kW hydraulic power available to activate the water cannon permitted rapid cannon rotations which reduced overshooting and undershooting of iceberg sails to perhaps 5% or less of the time. By comparison, the control system on the MV Skandi Alfa was unable to rotate the two-cannon fire-fighting system to compensate for vessel motion. As a result, overshooting or undershooting occurred up to 50% of the time on various occasions. Overshooting a sail is a total loss of deflection force whereas undershooting into the water makes a contribution to the speed gain albeit a reduced one, when compared to water application directly onto the sail.

It was perceived that moving the single water cannon to the bow of the vessel would improve visibility and reduce spray and icing on the bow of the vessel. This change in cannon placement did in fact result in improved visibility during water cannon operations relative to the visibility from the bridge of the MV Skandi Alfa.

Likewise, the spray and potential icing problem associated with water cannon operations on the MV Skandi Alfa were virtually eliminated by placing the water cannon on the bow of the MV Placentia Bay. The modified water cannon system is therefore judged to be successful in improving visibility and greatly reducing spray and icing potential.

POINT OF APPLICATION FOR THE WATER JET

One objective of the test program was to determine the effectiveness of increasing the drift speed of small ice masses by applying the water jet in different ways. The impact of the water jet onto the sea surface accelerates a mass of sea-water, creating a surface current that pushes a small ice mass to increase its drift speed. Not only does accelerating a mass of sea-water require energy but a current of finite speed is achievable. Thus, if the maximum current speed achievable was 1.0 knot, then the upper limit of the achievable speed change for the ice mass would also be 1.0 knot. The effectiveness of this technique was evaluated by comparing the speed gains with those achieved by impacting the water jet directly on the sail of the same iceberg under similar wind, current, and drift conditions.

As an example, an ice mass of 2,200 tonnes (berg 18) was first pushed by applying the water jet onto the water surface (test 18-3) and then by direct application of the water jet onto the sail (test 18-4). The vessel heading was essentially the same during both tests and wind and wave conditions were similar. By applying the water jet directly onto the sail of berg 18, the speed change was 0.9 knot. By comparison, applying the water jet onto the sea surface resulted in a speed change of only 0.6 knot. Despite the necessity to "chase" the berg and to reposition the vessel after impacts by the water jet on the sail of this small ice mass, clearly striking the sail resulted in a greater speed change (0.9 versus 0.6 knot).

Repositioning the vessel after impacts by the water jet on the smaller ice masses is tiresome for the vessel bridge crew. The preferred mode of operation is to apply the water jet directly onto the sea surface and to control the drift direction in a more continuous and consistent process. There is then less requirement to reposition the vessel.

It is believed that only small ice masses in the order of a few thousand tonnes can be controlled effectively by a surface current generated by the water cannon. The reason must lie with the losses encountered in overcoming inertia and friction associated with accelerating a mass of surface water to generate the driving current.

To illustrate the point, an iceberg of 24,700 tonnes was pushed by the water jet impacting directly on the sail and by applying the water jet onto the sea surface next to the berg. The application of the water jet on the sail resulted in a speed gain of 0.37 knot whereas the drift of the berg was increased by only 0.23 knot by applying the water jet onto the sea surface.

Attempts were also made to apply the water jet consistently and continuously at the waterline of icebergs for purposes of assessing speed gains achieved by this mode of application. It was virtually impossible to apply the water jet directly at the water line in a consistent and continuous mode because of vessel motion which resulted in alternative impacts of the water jet onto the sea surface and onto the sail. It is therefore not possible to make definitive statements about the effectiveness of pushing at the water line.

Attempts were made to push small ice masses by continuous propeller-washing with the water cannon pumping in the opposite direction, where the propeller thrust was controlled to balance the reaction force of the water cannon and the wind loading on the vessel. This exercise proved futile. It is considered that the continuous propeller-washing technique offers no advantages for management of small ice masses, probably because the current generated by the propellers in this balanced mode is so very slow.

One set of vessel-to-target distance tests was conducted with berg 18. The water jet was pointed to impact onto the sea surface. In tests 18-1, 18-2, and 18-3 the distance from the bow to the berg was 70-80 m, 50-60 m, and 30-40 m respectively. Based on the results (which are summarized in Table 2), distance does not appear to be an important parameter within the range of distance selected. The associated speed changes were 0.61, 0.5 and 0.6 knot respectively. Distances less than 30 m are not favoured because of safety reasons, and the fact that the horizontal component of the water jet force is decreased. Because of the system geometry, the percent of the total force which appears as a horizontal force component varies with distance as follows: 70-m, 98.8%, 60-m, 98.4%, 50-m, 97.7%, 40-m, 96.4%, 30-m, 93.9%, 20-m, 87.6% and 16-m, 82.4%. Accordingly the longer distances are preferred.

WATER CANNON MOTION COMPENSATION SYSTEM

The necessity for an automated system to adjust the cannon for vessel motion depends largely on the planned duration of operation. Short-term control of the water cannon by joystick on the bridge is effective in achieving consistent target impact (i.e., continuously impacting the iceberg sail) once the operator becomes accustomed to the response of the water cannon to the joystick control.

In the manual mode of operation, the captain controls the vessel's heading and position adjacent to the iceberg by using one joystick and controls the water cannon azimuth and elevation by activating another joystick on the water cannon control panel. Other functions on the bridge require additional crew. Fatigue sets in after a few hours of manual operations. For long-term water cannon operations, motion compensation is regarded as a necessity, not only to achieve better target impact consistency, (which translates into more effective control of small ice masses), but also to ensure that the captain's attention can be focused on the vessel keeping station adjacent to the ice mass.

In the stabilized mode, the captain controls the vessel by joystick and makes occasional adjustments to the water cannon azimuth and elevation by pushing the stabilized position control buttons. This requires only one person at the controls and leads to safer water cannon operations.

Stabilized Mode

Compensating the water cannon for motion of the vessel bow requires measurements of the vessel motion at some point within the hull. Ideally, measurements of vessel heave, pitch, and roll should be made at the water cannon. Unfortunately, the motion sensors are sensitive to vibrations which are severe at the bow of a vessel. Therefore the motion sensor is mounted near the centre of the vessel, well removed from vibrations at the bow.

To simulate the motion of the water cannon at the bow by measurements of vessel motion at another location, solid-body translation of motion is required. Accuracy of determinations are directly related to the accuracy associated with measuring the horizontal and vertical distance between the two planes of rotation of the water cannon and the position of the sensor system, in this case on the bulkhead in the forward drilling mud storage room near midships.

During the test program it was noted that a phase lag of 1.5 to 2 s was associated with the response of the water cannon in pitch and heave. A rise of the vessel bow should result in the water cannon rotating downwards to maintain target consistency. Likewise the water cannon should respond to a drop of the bow by rotating upwards. The apparent phase lag was manifested in the water cannon rotating upwards as the vessel approached its position of greatest elevation and in its position of lowest elevation, the water cannon rotated downwards when the response was out of phase.

To ensure that heave, pitch, and roll at the water cannon is simulated precisely when measurements of vessel motion are taken at another point within the hull (and to check the solid-body translation calculation), the translated motion values from the computer should be compared with outputs from an independent sensor system measuring motion at the water cannon. Signal magnitude and phase should be closely matched for each motion parameter (heave, pitch, and roll). If a phase lag exists or the motion magnitudes are different, there is potentially a problem with the midship motion sensor signals or with the translation computations.

If solid-body translation signals for each motion parameter match the signals generated by the independent motion sensor system at the water cannon, one can have confidence that the midship motion sensor translation values generated by the system computer are correct in magnitude and phase. In the event then, that the water cannon does not respond satisfactorily to the heave, pitch, and roll at the bow, the problem must then lie with the hydraulic system.

During part of this study, the motion compensation system suffered from a software error, which manifested itself in a phase lag resulting in the water cannon overshooting and undershooting the iceberg target. Because of the phase lag, target "impact consistency" was poorer than expected. In general terms, a target "impact consistency" of approximately 8 to 10 m in automatic motion compensation mode was associated with 3-m maximum combined seas, depending on the orientation of the vessel with respect to the wave direction.

Because of the phase lag, manual control was much more effective in achieving target "impact consistency" than was automatic motion compensation. For example, with 6-m maximum combined seas, target "impact consistency" with manual joystick control was estimated at 9 m. By comparison, the excursion of the target impact point in the automated mode was estimated at 10 to 15 m. Clearly the motion compensation system needs improvement. The most recent software change that has been made by

Thune-Eureka is expected to remove or greatly reduce the phase lag observed during the latter part of the test program.

Fine-tuning of the motion compensation system could be achieved by incorporating a potentiometer for the purpose of adjusting the response for each motion parameter, and by sequentially adjusting each parameter individually while the other motion parameters are set to zero. This capability should be designed as part of the water cannon control panel on the bridge of the vessel or by adding a computer monitor and keyboard to the system so that adjustments to the motion translation algorithms can be made in real-time using system software.

VESSEL CONTROL DURING WATER CANNON OPERATIONS

When winds and waves strike the beam of a vessel, one of the results is a wind-driven drift. Unless thruster and propellers are able to counterbalance the large wind and wave loadings and to maintain the same drift speed as an iceberg, water cannon operations cannot be conducted. Such wind-driven drift therefore imposes one limitation on water cannon operations. Excess vessel rolling represents another limitation. The upper limits for water cannon operations was found to be 40-knot winds and 5- to 6-m maximum combined seas when winds and waves impacted the beam of the MV Placentia Bay.

Refinement of techniques for maintaining position at a drifting iceberg resulted in safe and effective water cannon operations in 7-m maximum combined seas and 30-knot winds. No difficulty was experienced with the winds and waves impacting the stern of the vessel and it is the opinion of Captain L. Lacey that in this mode of vessel positioning, water cannon operations can in fact be conducted safely in sea states greater than 7-m maximum combined seas and wind speeds in excess of 30 knots. The authors concur with this conclusion. The sea-state limits of safe and effective water cannon operations have in fact not been reached during this test program.

Speed gain does not appear to be significantly compromised by high sea state. During the down-drift push test 7-3 on 22 April 1987, the speed gain of the 10,700-tonne iceberg was 0.28 knot in conditions of 30-knot winds and 7-m maximum combined seas. This performance was effectively the same as that achieved with 5-m maximum combined seas on 1 May 1987 with an ice mass of 11,400 tonnes (see Table 2, test 4-2), and was slightly less than the 0.32-knot speed gain of test 10-3 (see Table 2) on 6 May 1987, when the water jet was applied to the sail of an 11,400-tonne iceberg in calm seas.

This observation is surprising because in high sea state small ice masses have been observed to disappear under the sea surface from time to time. Thus, the water jet impacts onto the sea surface part of the time and onto the sail as the iceberg reappears. One would expect loss of impact force as a result.

With high wind speed conditions beyond 35 or 45 knots it is expected that the water jet will be diffused to sufficient extent to reduce the effectiveness of the water cannon operations.

SELECTION OF NOZZLE FOR MAXIMUM WATER JET REACTION FORCE

The water cannon system included a 145-mm nozzle that was matched by Thune-Eureka to the 2000-kW engine output to produce the maximum reaction force. Thune-Eureka calculated a 5-tonne reaction force from this nozzle based on full power being available to drive the centrifugal pump.

When the water cannon system was first operated with the 145-mm nozzle mounted on the cannon it was discovered that the engine exhaust temperature became excessive and continuous operation was not feasible. For this reason a series of engine/pump tests was conducted with progressively greater nozzle diameters, starting from a diameter of 100 mm in a effort to find the optimum size.

The nozzle diameter which would provide the greatest water cannon reaction force and at the same time would permit the engine to operate at full power in a continuous mode without excessive exhaust temperatures was the objective.

By manufacturing progressively larger nozzles and conducting engine/pump tests, a diameter of 130 mm was found to be optimum. The water cannon reaction force for this nozzle was calculated as 4.5 tonnes, which was considered to be close enough to the 5 tonne reaction force computed by Thune-Eureka.

The fact that the full water cannon reaction force was not achieved was initially attributed to pressure losses in the pipe system. However, after the test program in 1986, further investigation indicated that the engine was not delivering full power and after engine tuning, a further engine/pump test was conducted with the 145-mm diameter nozzle. The test indicated that improvements in the performance of the engine allowed full-power generation. Continuous pumping operation was now possible with the 145-mm diameter nozzle without experiencing engine overheating. The result was that the reaction force was increased to 4.8 tonnes from the 4.5 tonnes achieved with the 130-mm nozzle and the fuel consumption was reduced by 5% when the larger nozzle was used after engine tuning.

It is considered that achieving the maximum water cannon reaction force is an important step in the optimization process. It is concluded that to achieve maximum effectiveness of the water cannon system on the MV Placentia Bay, a 145-mm diameter nozzle should be used.

DESTRUCTION OF AN ICE MASS BY WATER CANNON

On May 15, 8.75 h of water cannon operations and natural deterioration reduced berg 18 from 16,200 tonnes to 9,000 tonnes. The measured destruction was 820 tonnes per hour which implies an estimated rate of destruction due solely to the water cannon of about 500 tonnes of ice per hour (see Fig. 33).

Further destruction testing between 1530 on May 15 and 0900 on May 16 resulted in berg 18 losing 5,640 tonnes of mass in 17.5 h indicating a reduction rate of approximately 322 tonnes per hour. This occurred after 25.3 h of previous water cannon operations which may have had an effect on the natural rate of destruction afterwards; due possibly to thermal stresses associated with removing the outer layers of warmer and weaker ice, exposing the colder layers to the sea-water temperature of 2.5°C.

By analysing these two cases it appears that the rate of destruction decreases as the ice mass itself diminishes. This finding is supported by yet another test on May 16, in which 2 h of water cannon operation and 4 h of natural deterioration reduced berg 18 from 3,360 to 2,200 tonnes, a reduction of 580 tonnes per hour. Clearly the higher rate of ice mass loss seen on May 15 is not applicable to this smaller ice mass, because only a mass of 1,160 tonnes of ice was lost the following day.

During yet another test on May 16 from 1600 to 1830, a further 2 h of water cannon operations and 2.5 h of natural deterioration reduced berg 18 by a further 300 tonnes, which suggests a combined rate of destruction of 150 tonnes per hour.

It is concluded that the rate of ice mass destruction is a function of the mass (or surface area) of the icebergs. A combined rate of destruction of 800 tonnes of ice per hour was associated with reducing berg 18 from 16,200 to 9,000 tonnes; and only 150 tonnes per hour associated with reducing the mass of berg 18 from 1,050 to 750 tonnes, which represent the highest and lowest rates (see Fig. 33).

Concerning the rate of destruction of ice mass by water cannon only, it is possible that up to 500 tonnes of ice were destroyed per hour initially. It is impossible, however, to separate the water cannon effect from natural deterioration effects on berg 18 when the ice mass was small.

Overall, berg 18 was reduced from 16,200 tonnes to 650 tonnes in a matter of 38 h for an average rate of destruction by the water cannon (including natural deterioration) of about 400 tonnes of ice per hour.

The implication of destroying ice mass, thus gaining greater control of drift speed and direction, therefore should be considered in ice management situations when sea-water temperatures are sufficiently high.

It should be noted that the rate of destruction was significant for a small ice mass and a water temperature of 2.5° C. During water cannon operations with sea-water at 0°C, it was observed that little ice mass reduction occurred. Presumably with higher sea-surface temperatures, the rates of natural deterioration and ice mass reduction by water cannon will be even greater than those indicated for a sea-surface temperature of 2.5°C.

Mean sea surface temperature data from Environment Canada - Marine Statistics (MAST) Computer Program - Marine Climatological Summaries indicate that from January to April mean temperatures are below 1°C. For the months of May to December inclusive, mean temperatures are above 3°C with a maximum of 12.8°C in August. The frequency of small ice masses is greatest in the months of May and June on the Grand Banks when sea-water temperatures are high enough to be effective in ice mass destruction.

POTENTIAL FOR MULTIPLE-CANNON SYSTEMS

Having demonstrated that small ice masses are indeed amenable to management by a single water cannon, it is logical to consider multiple-cannon systems with two to four cannon as such systems are now in use for fire-fighting purposes. Before proceeding along these lines it should be noted that the force required to double a given speed gain is four times greater than the force applied to achieve the initial speed gain. Accordingly doubling the number of cannon (from one to two for instance) will result in a speed gain of $2^{0.5}$ of the speed gain achieved by one cannon. If the speed gain for a small ice mass were 0.5 knot, two cannon would be needed to increase the speed gain to 0.7 knot. Clearly power requirements must be considered for multiple-cannon systems.

Merely doubling the number of water cannon has serious implications for the power requirements and configuration of a vessel as follows:

- the amount of power (number of engines) required for pumping operations increases by a factor of two which would reduce the power available for station-keeping at icebergs;

- thruster requirements would increase to compensate for the increased reaction force generated by the cannon, which would further reduce the power available for station-keeping;

- more hydraulic power would be required to allow control of two cannon, which would place additional loading on the generators;

- the control and motion compensation system would become more complex if separate controls for each cannon were implemented;

- a larger diameter pipe or an additional pipe of the same diameter would be required to carry sea-water to the cannon, and the additional weight of pipe and water might influence stability of the vessel;

- a larger intake pipe and a larger seabay or an additional intake pipe and seabay of similar size would be required; and

- extra fuel tanks might be required if long-term water cannon operations were contemplated.

There are likely other important items to consider when contemplating multiple-cannon systems. Considering these limitations and the power available on present-day supply vessels used by the oil industry, the potential for multiple-cannon systems for control of small ice masses is probably limited to two cannon, although it is recognized that four-cannon systems exist for fire-fighting.

CONCLUSIONS

The primary conclusion drawn from the water cannon test program is that the single cannon mounted on the bow of the MV Placentia Bay is undoubtedly an effective tool for controlling small ice masses up to about 60,000 tonnes.

When compared with the performance of the two-cannon fire-fighting system on the MV Skandi Alfa, the single cannon not only has a greater capacity for changing the drift direction of small ice masses but also its capacity for increasing the drift speeds is greater. For example, the maximum speed gain achieved by the MV Skandi Alfa for an 18,000-tonne mass was 0.22 knot. For the same sized iceberg, a maximum speed gain of 0.55 knot was achieved by the single cannon on the MV Placentia Bay. This improvement is considered to be substantial and it is concluded that the overall "optimization" steps taken have been worthwhile.

The improved speed gains and direction changes achieved by the modified water cannon are attributed to three main aspects of the "optimization" process:

1) The powerful hydraulic power unit and sensitive control system which facilitated almost instantaneous rotational responses of the water cannon to commands from the control panel on the bridge. This response resulted in effectively impacting the sails of icebergs with an estimated 95% consistency with little overshooting or undershooting.

2) The greater horizontal component of the water jet as a result of the water cannon position on the bow, and the better focus of the water jet beam due to nozzle selection.

3) Placing the water cannon on the bow definitely improved visibility of ice masses during water cannon operations, relative to the visibility from the bridge of the MV Skandi Alfa where the two overhead water jets obscured vision.

With the development of improved techniques for vessel station-keeping at icebergs under conditions of high wind speeds and high sea-state conditions, safe and effective water cannon operations with at least 7-m maximum combined seas and 30-knot winds have been achieved. It is concluded that water cannon operations can be successfully conducted under even more severe wind and wave conditions.

Additional conclusions drawn from observations during water cannon operations are:

2) The greatest degree of control of small ice masses is attained by applying the water jet onto the sails from a distance of 60 to 70 m.

3) Maximum speed gain is achieved by pushing in the direction of free drift.

4) Maximum direction changes can be achieved by pushing perpendicular to the free-drift direction.

5) Smaller ice masses below 3,000 tonnes can be controlled more easily by a surface current generated by applying the water jet into the sea adjacent to the ice mass.

6) Station-keeping at a drifting iceberg with winds and waves impacting the vessel stern can safely be done when the vessel is positioned off to the port or starboard of an iceberg.

7) To avoid excess rolling of the vessel and to prevent drifting faster than the ice mass, the heading of the vessel should be no more than 30° removed from the direction of winds and waves. This position keeps the wind and seas impacting more on the vessel's stern than on its beam.

8) A motion compensation system should be considered if long-duration water cannon operations are planned.

9) For short-duration operations, joystick control of the cannon is perfectly adequate.

10) Maximum reaction force of 4.8 tonnes for the single water cannon was achieved with a 145-mm diameter nozzle.

11) Water cannon operations can be conducted in conditions of at least 30-knot winds and 7-m maximum combined seas. The upper limits of safe and effective water cannon operations in high winds and high sea state were not experienced during the water cannon test program because of a lack of opportunity under more extreme wind and sea-state conditions.

12) Optimum or peak engine performance is a necessity both to maximize the water cannon reaction forces and to conserve fuel.

13) An accurate positioning system is important for determining speed gains and direction changes achieved during short-term tests but a standard shipborne Loran-C positioning system is sufficient for long-duration water cannon operations, such as those required for diverting a small ice mass past a drill rig.

14) Training of the bridge crew is essential to achieve safer and effective water cannon operations especially in positioning the vessel adjacent to icebergs in high sea-state conditions.

15) A positive approach by the bridge crew is essential towards achieving effective water cannon operations.

16) Under the wind and sea-state conditions experienced during the offshore test program, icing of the water cannon was not a problem and did not interfere with water cannon operations.

17) Spray generated by the water cannon did not cause icing of the vessel, because the wind carried the spray downwind and away from the vessel.

18) A portable water cannon control panel on the bridge would facilitate improved visibility as it could be used from the best vantage point on the bridge.

19) Access to the motion compensation system and its software to permit adjustment of individual motion parameters is necessary to improve automatic motion compensation of the water cannon.

RECOMMENDATIONS

The following recommendations are based on observations from the water cannon test program:

1) For high sea-state operations, position the vessel 60 to 70 m off the port or starboard side of an iceberg to permit drifting clear in case of engine malfunction. Positioning a vessel directly upwind of an iceberg should be avoided to reduce the potential for a collision.

2) Training of the bridge crew, especially in station-keeping a vessel adjacent to an iceberg, should be considered prior to commencing water cannon operations.

3) A portable joystick control panel for the cannon should be considered, which would facilitate improved visibility during water cannon operations from the port or starboard sides of the bridge.

4) Automatic declutching and closing of the intake valve in case of a sudden pressure drop in the system must be part of any water cannon system for safety reasons.

5). Design of future water cannon systems should include serious consideration of the balance of power for propulsion, thrusters, and the pumps. Placing the water cannon on the bow to improve water cannon effectiveness and visibility from the bridge should also be considered.

6) A motion compensation system is considered to be essential for long-term operations and should therefore be considered seriously.

7) Future motion compensation systems should incorporate:
   - full access to all computer software;
   - ability to evaluate each motion parameter independently by setting other parameters equal to zero through the software; and
   - interactive adjustment of motion compensation response to individual parameters through software index adjustment or manual adjustment of trim potentiometer or other such adjustment device.

8) If considering use of two- to four-cannon systems, particular attention should be paid to:
   - extra power requirements
   - extra thrust requirements
   - additional control systems
   - additional pipe and vessel stability implications
   - additional fuel requirements.

9) Hydraulic, mechanical, and electrical controls on the water cannon should be protected from direct wave impacts.

10) Water cannon systems should be operated periodically to ensure system function and to prevent a build-up of rust and marine growth in the centrifugal pump and the intake pipe and valve.

11) The use of fibreglass pipe should be considered in a retrofit situation, because of the greater ease of installing low-weight fibreglass relative to steel pipe.

12) All up-to-date system manuals and schematics must be secured from the manufacturers and suppliers of system components. This requirement should be included at the system specification or contract stage.

13) Local servicing for the water cannon system components should be organized at an early stage of any retrofit. Special training should be considered if necessary.

14) Further analysis of the vessel motion data collected and archived at C-Core is recommended.

15) Further water cannon operations should be conducted in maximum combined seas in excess of 7 m and winds in excess of 35 knots when the opportunity arises, to determine more definitive operational limits.

16) Fire-fighting certifications should be kept in mind when planning the installation of water cannon systems.

APPENDIX 1

ITEMS OF SPECIFIC INTEREST TO OIL COMPANIES

The items included in this appendix are considered to be of interest to oil companies contemplating the use of water cannon for management of small ice masses:

- fire-fighting certification
- List of suppliers and contractors
- Position of the water cannon control panel on the bridge of a vessel
- Vessel operational procedures when pushing small ice masses
- Procedures for commencement and shutdown of pumping operations on the MV Placentia Bay.

FIRE-FIGHTING CERTIFICATION

Lloyds of London and Det norske Veritas requires two water cannon for certification to Fi-Fi One standard, the reason being that one cannon is to be available to fight fires and the second cannon can be used to provide a mist curtain while personnel evacuation takes place.

Due to the fact that only one water cannon is mounted on the MV Placentia Bay and considering the classification requirements, Lloyds have agreed to add a "notation" of class stating that the vessel has fire fighting capability with pumping capacity in excess of Fi-Fi One (1) but with only one (1) water cannon. Addition of one more water cannon would permit full Fi-Fi One certification which requires a minimum of 2400 m^3/h sea-water pumping capacity, two water cannon, a length of throw of 120 m for the water jet, and a height of throw of 45 m (Table A-1). The water cannon on the MV Placentia Bay has a length of throw of 210 m and a height of throw of 60 m which exceeds the specified values for Fi-Fi One.

TABLE A-1

Water monitor system capacities

Class notation	I	II		III
No. of monitors	2	3	4	4
Capacity of monitors in m^3/h	1200	2400	1800	2400
No of pumps	1-2	2-4		2-4
Total pump capacity in m^3/h	2400	7200		9600
Length of throw in m*	120	150		150
Height of throw in m**	45	70		70
Fuel oil capacity in hours***	24	96		96

* Measured horizontally from the monitor outlet to the mean impact area

** Measured vertically from sea level to the highest point of trajectory elevation at a horizontal distance at least 70 m from the nearest part of the vessel

*** Capacity for continuous operation of all monitors to be included in the total capacity of the vessel's fuel oil tanks

Source: Det norske Veritas. 1984
Rules for classification of steel ships, Part 5 Ch. 7 Sec. 5

LIST OF SUPPLIERS AND CONTRACTORS

Equipment and services were provided by the following contractors:

<u>Thune Eureka</u> P.O. Box 38, N-3401 Lier, Norway Telephone: 03-850400 Telex: 18608	the cannon, pump, clutch & gearbox, motion compensation system, control panels and midships motion sensors.
<u>ABCO Plastics Ltd.</u> Mahone Bay, Nova Scotia Telephone: (902) 624-8383	20" fibreglass pipe and fittings
<u>Colda Engineering Ltd.</u> St. John's, Newfoundland Telephone: (709) 722-1315	installation of the pipe and drive train
<u>Newfoundland Marine Design Ltd.</u> St. John's, Newfoundland Telephone: (709) 722-2270	design and specifications for vessel retrofit of water cannon system
<u>McElhanney Surveys Ltd.</u> St. John's, Newfoundland Telephone: (709) 726-4252	navigation/positioning equipment and video coverage
<u>Newfoundland Dockyard</u> St. John's, Newfoundland Telephone: (709) 737-7800	installation of seabay, hatchway
<u>Husky Marine Services</u> St. John's, Newfoundland Telephone: (709) 722-8050	management of all contract work and procurements

<u>E. Banke Consulting</u> Bedford, Nova Scotia Telephone: (902) 835-9274	co-ordination of the water cannon test program offshore, data analysis and preparation of reports
<u>Centre for Cold Ocean Resources Engineering</u> Memorial University of Newfoundland St. John's, Newfoundland Telephone: (709) 737-8354	independent motion sensors and recording equipment, software and analysis
<u>Electro Mechanical Services Ltd.</u> St. John's, Newfoundland Telephone: (709) 364-6724	system wiring, hydraulic installations

POSITION OF THE WATER CANNON CONTROL PANEL ON THE BRIDGE OF A VESSEL

On the bridge of the MV Placentia Bay, the control panel for the water cannon is mounted along the longitudinal axis of the vessel directly aft of the water cannon and about 3 m above. The main advantage of this location is that the vessel and the water cannon can be controlled by one person, usually the vessel captain or the first mate.

If the water cannon control panel is removed from the vessel control position, water cannon operations in the manual/joystick mode require two operators; one to control the vessel and one to control the water cannon at the remote control panel.

From the longitudinal axis position, an ice mass and the water jet impact area are easily visible when the vessel is situated such that the ice mass is off the port or starboard bow. However, for pushing an ice mass directly ahead of the vessel, visibility is limited from a point directly aft of the water cannon. To improve visibility and safety during such operations, the water cannon should be controllable from the port or starboard side of the bridge. This implies either a fixed control panel on the port or starboard side or a portable control panel. Considering the fact that the control panel on the MV Placentia Bay is connected to the rest of the water cannon system by eight substantial shielded cables, it is obvious that one stationary/fixed control panel is essential.

Based on observations, it is considered that safer and more effective water cannon operations may result when a combination of control panels is used. The combination should consist of one hardwired panel installed adjacent to the vessel controls and one portable panel containing a joystick and being connected to the fixed panel by an umbilical cord.

VESSEL OPERATIONAL PROCEDURES WHEN PUSHING SMALL ICE MASSES

When changing the direction and speed of very small ice masses, it is important to avoid directing the water jet onto the ice mass. If an impact occurs the ice mass will be diverted starboard or port and fracturing may occur.

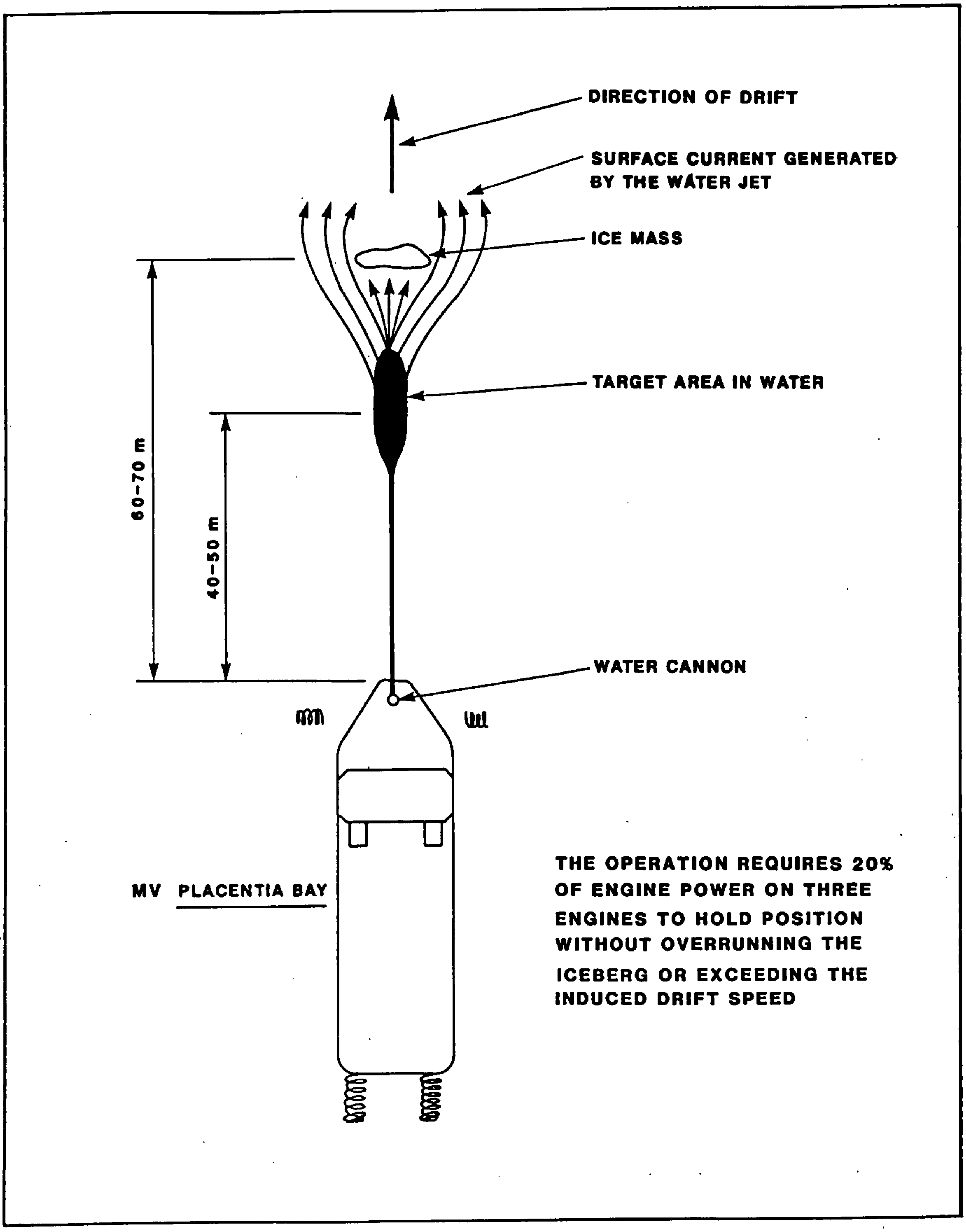
When time is of no great concern, the preferred mode of operation is to maintain a distance of about 60 m between the bow and the ice mass and set the cannon to apply the water jet into the water in front of the berg (Fig. A-1). The high speed water jet generates a surface current which is effective in increasing the drift speed and controlling the drift direction of small ice masses, up to about 3,000 tonnes.

The advantages of this technique are that:

- "chasing" the target iceberg is not required to reposition the vessel;
- the crew suffers less fatigue; and
- the probability of fracturing the ice mass is greatly reduced should this not be desired.

Experience indicates that 20% of propellor pitch is normally required to hold position and maintain the constant distance to the berg without overrunning the ice mass under normal environmental conditions.

When it is important to move a small ice mass past a drill rig in the shortest possible time, greater speed changes and direction changes can be achieved by applying the water jet directly onto the sail of the ice mass.



THE OPERATION REQUIRES 20% OF ENGINE POWER ON THREE ENGINES TO HOLD POSITION WITHOUT OVERRUNNING THE ICEBERG OR EXCEEDING THE INDUCED DRIFT SPEED

Figure A-1. Vessel/iceberg position for pushing ice masses of less than 3,000 tonnes by applying the water jet onto the sea surface.

PROCEDURES FOR COMMENCEMENT AND SHUTDOWN OF PUMPING OPERATIONS ON THE MV PLACENTIA BAY

When a decision is made to commence water cannon operations, the following step-by-step procedure may be used as a guide. On the bridge, the captain or system operator:

- ensures the drain valve on the water cannon is closed;
- ensures that the water cannon clamp down device on the bow is released, the safety chain is removed, and that the water cannon is free to move;
- ensures that the joystick control for water cannon pointing is in the same direction as the water cannon itself to avoid instantaneous water cannon motion upon startup;
- turns control panel key to "on" position;
- ensures the two hydraulic control motors are in manual mode;
- starts the two hydraulic control motors by pushing motor start control on panel;
- tests that cannon moves by joystick control before pumping water;
- requests that engine room staff engage clutch to commence pumping operations;
- advises chief engineer when water is flowing; and
- when full water flow is obtained, moves vessel to position near iceberg.

In the engine room, the chief engineer upon request for water from the bridge to begin pumping water:

- checks hydraulic fluid level at water cannon hydraulic power package;
- ensures intake valve is open;
- ensures discharge valve is closed;
- ensures by-pass valve is open;
- engages clutch at engine idle speed;
- awaits notification from bridge that the water is flowing;
- opens discharge valve slowly;
- brings engine revolutions up slowly to running speed of 650 rpm; and
- advises bridge that pumping operations are at full power.

When the system is running, the chief engineer:

- maintains clutch, pump, and pressure watch (and records).

When the system is running, the captain:

- selects desired target point on or near iceberg (on sail, in water, or at water line);
- selects mode of water cannon control (manual or stabilized); and
- selects direction of push based on free-drift direction of the ice masses relative to the drill rig and its ice response zones.

During system shutdown, the captain:

- switches to manual water cannon control mode;
- points the water cannon down to drain water;
- advises engine room to shut down;
- before water stops running, rotates water cannon into lock down position;
- shuts down hydraulic pumps;
- locks water cannon into its cradle resting position; and
- opens drain valve on water cannon.

During system shutdown, the chief engineer:

- reduces engine revolutions to idle speed;
- declutches to disengage the centrifugal pump;
- shuts discharge valve when pump stops; and
- shuts intake valve.

End of procedure.

REFERENCES

Allsop, T. 1985. Cannonization: of ice tested. East Coast Offshore Magazine, 5(4):18-20.

Anderson, K.G., D. McDonald, P. Mitten, S. Nicholls, and D. Tait. 1986. Management of small ice masses. Environmental Studies Revolving Fund Report No. 042. Ottawa. 183 pp.

Banke, E., and G. Warbanski. 1986. Test program to evaluate an optimized water cannon system to control small ice masses. (Unpublished Interim ESRF Report)

Det norske Veritas. 1984. Rules for Classification of Steel Ships. Det norske Veritas.

Det norske Veritas. 1983. Fire Fighting. Det norske Veritas. 8 pp.

Environment Canada. 1980. MANICE: Manual of ice reporting. Atmospheric Environment Service. 97 pp.

Environment Canada. 1985. Marine Statistics (MAST) Software Program: Marine Climatological Summaries. Atmospheric Environment Service, Canadian Climate Centre.

Husky/Bow Valley East Coast Project. 1986. New water cannon herds growlers. Offshore Resources Magazine, 4(2):8-9.

McCabe, Charles. 1986. Ice masses moved by water cannons. Ocean Industry Magazine, April, 1986. p. 294-295.

REFERENCES (Cont'd.)

Warbanski, G., and E. Banke. 1985. Evaluation of shipborne fire-fighting water cannons for the purpose of pushing icebergs, bergy bits and growlers. Husky/Bow Valley East Coast Project Technical Paper, September 1985 (unpublished manuscript), 130 pp.