TP 12989E

Calibration of the Arctic Marine Transportation Simulation Model

Prepared for

TRANSPORTATION DEVELOPMENT CENTRE
SAFETY AND SECURITY
TRANSPORT CANADA

March 1997

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This report reflects the views of the authors and not necessarily those of the Transportation Development Centre.

Since the accepted nautical measures for speed and distance are knots (kn) and nautical miles (nmi) these units are used in this report.

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Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 12989E	2. Project No. 8918	3. Recipient's Catalogue No.
4. Title and Subtitle Calibration of the Arctic Marine Transportation Simulation Model		5. Publication Date March 1997
		6. Performing Organization Document No. 142071
7. Author(s) D.J. Lapp (Enfotec), Dr. A. Keinonen (AKAC Inc.), Dr. D.H. King (Sandwell Inc.)		8. Transport Canada File No. ZCD1460-361
9. Performing Organization Name and Address Sandwell Inc. Engineering and Construction Services Group 1190 Hornby Street Vancouver, B.C. V6Z 2H6		10. PWGSC File No. XSD-5-01971 11. PWGSC or Transport Canada Contract No. T8200-5-5555/01-XSD
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West 6th Floor Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final 14. Project Officer James D. Reid

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by Energy R&D and JIP (Joint Industry Project).
Related publication: User's Manual, Arctic Marine Transportation Model, Sept. 9, 1996.

16. Abstract

The Arctic Marine Transportation Model (AMTM) was calibrated using historical operational data for the M.V. Arctic, a 26 000 dead weight tonne, ice breaking, ore and bulk carrier. The AMTM is an animated simulation model for evaluating marine transportation systems. The model simulates vessel speed for varying sea states and ice conditions using detailed vessel performance algorithms which were the subject of this calibration project. A number of improvements were made to the vessel performance algorithms as a result of the study.

Predicted speeds in level ice in open water were within approximately 1.5 kn of the measured speeds. This level of accuracy is within the scatter in the measured area. In ice fields with less than 100 percent ice coverage, the predicted additional distance travelled to circumnavigate ice flows was in good agreement with the measured values. In ridged and rubbled ice, the historical data was not sufficiently precise to evaluate these aspects of the vessel performance algorithms. Predicted transit times for actual voyages were approximately 25 percent longer than the measured times as long as the vessel was able to maintain a speed of at least 3 kn. In more severe ice conditions, the historical ice data was not detailed enough to predict accurate vessel speeds.

17. Key Words Ships, ice breaking, ice, transportation, simulation, transit, model	18. Distribution Statement Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xii, 82, apps	23. Price —

CDT/TDC 79-005
Rev. 96

Canada

Transports Canada / Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada: TP 12989E

2. N° de l'étude: 8918

3. N° de catalogue du destinataire:

4. Titre et sous-titre: Calibration of the Arctic Marine Transportation Simulation Model

5. Date de la publication: Mars 1997

6. N° de document de l'organisme exécutant: 142071

7. Auteur(s): D.J. Lapp (Enfotec), Dr. A. Keinonen (AKAC Inc.), Dr. D.H. King (Sandwell Inc.)

8. N° de dossier - Transports Canada: ZCD1460-361

9. Nom et adresse de l'organisme exécutant:

Sandwell Inc.
Engineering and Construction Services Group
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Vancouver, B.C.
V6Z 2H6

10. N° de dossier - TPSGC: XSD-5-01971

11. N° de contrat - TPSGC ou Transports Canada: T8200-5-5555/01-XSD

12. Nom et adresse de l'organisme parrain:

Centre de développement des transports (CDT)
800, boul. René-Lévesque Ouest
6e étage
Montréal (Québec)
H3B 1X9

13. Genre de publication et période visée: Final

14. Agent de projet: James D. Reid

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Coparrainé par le R&D énergétiques et le JIP (Joint Industry Project).
Publication connexe : User's Manual, Arctic Marine Transportation Model, Sept. 9, 1996.

16. Résumé

Description des travaux de calage du Modèle de simulation de la navigation dans l'Arctique (AMTM pour Arctic Marine Transportation Model) à partir des données accumulées lors des nombreux voyages du N/M Arctic, un vraquier de cote arctique, de 26 000 tonnes de port en lourd. Ce modèle est un outil de simulation avec animation, utilisable pour les systèmes de transport maritime. Il permet de simuler l'avance d'un navire, à des allures de marche qui varient selon l'état de mer et les conditions glacielles. Il utilise pour cela des algorithmes de calcul détaillés, objet de la présente recherche sur le calage du modèle. Celle-ci a permis d'affiner ces algorithmes.

Les vitesses calculées dans des eaux libres de glaces ou dans des glaces d'épaisseur uniforme ont été égales aux vitesses mesurées, à 1,5 noeud près, écart situé dans les limites de dispersion observées pour les données tirées des expérimentations. Pour la navigation dans des champs de glace où la couverture est inférieure à 100 p. 100, les prévisions touchant les distances supplémentaires à couvrir pour contourner les floes ont donné une bonne approximation des distances réelles. Pour la simulation de la marche dans des champs de blocaille et des crêtes de pression, les données historiques disponibles n'étaient pas assez précises pour permettre d'apprécier l'adéquation des algorithmes utilisés pour simuler ces conditions. Les temps calculés par voyage ont été supérieurs aux temps réels par une marge d'environ 25 p. 100, chaque fois que le navire pouvait soutenir une allure d'au moins 3 noeuds. Dans des conditions glacielles extrêmes, la recherche a montré que la finesse du modèle a été poussée aussi loin que faire se pouvait, eu égard aux données historiques disponibles.

17. Mots clés: Navires, brise-glace, glaces, transports, simulation, marche, modèle

18. Diffusion: Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xii, 82, ann.	—

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Executive Summary

The Arctic Marine Transportation Model simulates vessel speed for varying sea states and ice conditions along a specified route. The model was prepared by Sandwell Inc. and by AKAC Inc. as a Joint Industry Project for a number of major oil companies.

The purpose of the present study was to calibrate the vessel performance algorithms using historical operational data for the M.V. Arctic, a 26 000 dead weight tonne, ice breaking ore and bulk oil carrier operated by Canarctic Shipping Company Ltd.

The study was carried out by three companies:

- **ENFOTEC Technical Services** compiled the historical operating data,
- **AKAC Inc.** calibrated the ice transit algorithm using the data, and
- **Sandwell Inc.** compared the performance of the simulation model to historical data for actual voyages of the M.V. Arctic.

The ice transit algorithm was found to be in good agreement with carefully measured data from M.V. Arctic trials performed in continuous level ice. Predicted speeds were within approximately ±1.5 kn of the measured speeds. This difference is within the scatter in the trials data.

The correlation between the model and the operational data proved to be much less satisfactory because of the difficulty in estimating ice conditions from a moving vessel. In addition, the ice conditions encountered in actual operation are much more complex than those encountered during ice trials. Many ice parameters such as ridges, rubble, pressure, snow cover, ice thickness, distribution, and ice coverage have a large effect on the average speed achieved by an ice breaker. To measure all of these quantities from a moving vessel with sufficient accuracy for detailed analysis proved to be problematic. Finally, the data had not been collected with the intent of calibrating a detailed transit model. Some of the inputs required for the model were either missing from the historical data, or had been given a different interpretation than the one used for the model. In either case, considerable interpretation was required to obtain the necessary input data for the model.

The correlation between the model and complete voyage segments also proved to be less satisfactory because of the limited accuracy of the voyage data. Voyages in thick ice where the vessel's speed was less than approximately 3 kn were particularly hard to model accurately because the vessel speed is predicted to at most ±1.5 kn by the present model. At low speed, this uncertainty is a large fraction of the average speed which leads to modelled transit time that is too long or too short by a factor of two or more. When the extreme portions of the voyages were excluded, the model transit time was in much better agreement with the model. In this case, the model transit time for each voyage was approximately 20-25 percent larger than the actual transit time.

Despite the above difficulties, a number of valuable results were obtained from the study:

- The transit model equation for circumnavigating ice flows was found to be in good agreement with the historical data.
- The model was modified in response to the historical data to allow for reduced effective ice thickness near the edges of ice flows.

- The model was modified to allow for an arbitrary distribution of ice thicknesses within a geographical region.
- The model was modified so that circumnavigation is done only when the ice is sufficiently thick for circumnavigation to increase average vessel speed.
- The model was modified so that the modelled ship avoids the thickest ice in a region whenever possible.

In addition to these specific improvements, the entire model was subjected to a high level of scrutiny in our efforts to identify the cause of any differences between the model and the operational data. At the conclusion of the study, the model's level of accuracy was as high as could be supported by the operational data.

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Sommaire

Le Modèle de simulation de la navigation dans l'Arctique (AMTM) est un outil qui permet de simuler l'avance d'un navire le long d'un itinéraire donné, à des allures qui varient selon l'état de mer et les conditions glacielles. Sandwell Inc. et AKAK Inc. ont élaboré conjointement ce modèle dans le cadre d'un projet réalisé pour un certain nombre de grandes pétrolières.

La présente recherche avait pour objet de caler les algorithmes de calcul des paramètres de simulation à partir des données accumulées lors des nombreux voyages du N/M Arctic, un vraquier de cote arctique, de 26 000 tonnes de port en lourd, appartenant à l'armateur Canarctic Shipping Company Ltd.

Elle a été entreprise par les trois sociétés suivantes :

- **ENFOTEC Technical Services** : compilation des données historiques;
- **AKAK Inc.** : calage de l'algorithme de calcul de la marche dans les glaces;
- **Sandwell Inc**. : comparaison des résultats de la simulation aux données historiques pour quelques-uns des voyages effectués par l'Arctic dans le passé.

L'algorithme de calcul de la marche dans les glaces a donné des résultats qui cadrent bien avec les mesures obtenues dans des glaces d'épaisseur uniforme lors des expérimentations effectuées à bord de l'Arctic. Les vitesses calculées ont été égales aux vitesses mesurées, à 1,5 noeud près, en plus ou en moins, écart situé dans les limites de dispersion observées pour les données tirées des expérimentations.

La corrélation entre la modélisation et la réalité a cependant été moins bonne que prévu, à cause de la difficulté à décrire les conditions glacielles à partir d'un navire en marche. En outre, les conditions glacielles rencontrées par un navire en service sont généralement plus complexes que celles des parcours d'essais dédiés. La vitesse moyenne affichée par un brise-glace est fortement influencée par la nature des glaces flottantes - crêtes, blocaille, etc. - et par d'autres paramètres tels que pression, épaisseur, distribution et couverture des glaces et enneigement. Mesurer ces paramètres à partir d'un navire en marche s'est révélé une tâche ardue. Dernière difficulté, les données historiques n'avaient pas été accumulées dans l'intention de servir au calage d'un modèle de simulation de la marche d'un navire dans les glaces. De sorte que certaines données nécessaires au modèle n'existaient pas dans les données historiques ou bien, si elles existaient, on leur avait donné une interprétation très différente de celle qu'il fallait pour le modèle. Quoi qu'il en soit, il a fallu beaucoup d'interprétation avant de pouvoir utiliser les données historiques pour le calage du modèle.

La corrélation entre la modélisation et la réalité des conditions entourant certains itinéraires a elle aussi souffert de l'imprécision de la description des conditions glacielles. Les marches dans des glaces épaisses qui font tomber la vitesse du navire au-dessous de 3 noeuds environ ont été particulièrement difficiles à modéliser du fait que l'erreur de calcul du modèle se situe entre plus ou moins 1,5 noeud. Aux faibles allures de marche, une telle erreur représente une fraction importante de la vitesse moyenne, et elle débouche sur des temps calculés qui sont ou trop longs ou trop courts par un facteur de deux ou plus. Lorsqu'on faisait abstraction des tronçons les plus ardus d'un itinéraire, les temps calculés se rapprochaient davantage des temps réels. Dans ces cas-là, les temps calculés par voyage ont été supérieurs aux temps réels par une marge d'environ 20 à 25 p. 100.

Malgré ces difficultés, des résultats intéressants ont été obtenus de la recherche, à savoir :

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- L'équation décrivant les distances supplémentaires à parcourir pour contourner les floes donne une bonne approximation des distances réelles.
- Le modèle a été affiné en tenant compte du fait que l'épaisseur des floes est toujours plus faible à leur périphérie.
- Le modèle a été affiné pour tenir compte d'une distribution non linéaire des épaisseurs des glaces à l'intérieur d'une région glaciaire donnée.
- Le modèle a été affiné de manière qu'un contournement n'est simulé que lorsque l'épaisseur des glaces est telle que cette décision débouchera sur un relèvement de la vitesse moyenne de marche.
- Le modèle a été affiné de manière que la simulation puisse éviter les parties où les glaces sont les plus épaisses.

Outre ces perfectionnements, le modèle a été vérifié avec soin dans le but d'expliquer tout écart entre modélisation et réalité. La recherche a montré que la finesse du modèle a été poussée aussi loin que faire se pouvait, eu égard aux données historiques disponibles.

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1. Introduction

1.1 Background

Arctic Marine Transportation Model

The Arctic Marine Transportation Model is an interactive, animated computer model for bulk cargo transportation systems using either icebreaking or open water type vessels. It can be used to optimize both the shipping and the terminal operations for these systems. The model simulates vessel performance for the varying sea states and ice regimes that are encountered along its route. The open water and ice transit algorithms used in the simulation model were created by AKAC Inc. based on the performance data for more than 20 icebreaking vessels.

The model was first developed in 1994, when Sandwell Inc. and AKAC Inc. were commissioned by BP Exploration, Exxon USA, and ARCO Alaska to simulate the transportation of liquefied natural gas (LNG) from Alaska to Japan in icebreaking LNG carriers. In late 1995, a Joint Industry Project (JIP) was formed to enhance and generalize this computer model. The JIP has been completed successfully and the model used for a number of different applications by individual JIP members. Two of these applications have involved further major extensions of the JIP model which are presently underway.

The sponsors of the JIP were Amoco Eurasia Petroleum Company, Arkhangelskgeoldobycha, BHP Petroleum (Exploration Inc.), Canada Steamship Lines, Chevron Petroleum Technology Company, Conoco Arctic Inc., Elf Neftegaz, Exxon Ventures (CIS) Inc., Mobil New Exploration and Producing Ventures, Neste OY, Norsk Hydro, Texaco Petroleum Development Company, and Timan Pechora Company.

M.V. Arctic

The M.V. Arctic is an icebreaking, 26 000 DWT, ore and bulk oil carrier owned and operated by Canarctic Shipping Company Ltd. The vessel operates in the Canadian Arctic over an extended shipping season that begins in May and finishes in early to mid-November. A five-year project was carried out during 1985 - 91 to monitor the ice conditions encountered by the M.V. Arctic and record them in a computerized data base.

1.2 Objective

In 1994/95, the Panel on Energy Research and Development (PERD) program 6C Transportation approved a project for the development of a computer model to simulate tanker transit performance on Arctic routes. The PERD objective was to provide the transportation of Arctic hydrocarbons resources to southern markets by improving the simulation capability in the design of Arctic marine transportation systems. The PERD objective was achieved in the present study by calibrating the existing Arctic Marine Transportation Model and by providing a non-exclusive licence for the model to the Transport Development Centre (TDC).

The purpose of the present study was to calibrate the Arctic Marine Transportation Simulation Model using historical operational data from the icebreaking cargo ship M.V. Arctic.

1.3 Project Team

The present study was carried out by a team of three companies:

- ENFOTEC Technical Services Inc. assembled the historical data for the M.V. Arctic,
- AKAC Inc. compared the ice transit algorithms used in the simulation model to the historical performance data for the M.V. Arctic, and
- Sandwell Inc. compared the performance of the simulation model to historical data for actual voyages of the M.V. Arctic.

Individual sections of this report were written by the appropriate authors: Section 2 by ENFOTEC, Section 3 by AKAC, and Sections 1 and 4 by Sandwell. Section 5, containing the conclusions of the study, was written by Sandwell based on the work by AKAC and Sandwell in Sections 3 and 4.

2. M.V. Arctic Data

2.1 Summary of Historical Data Utilized

The primary source of data utilized for the calibration effort was observations and data from a five-year program of environmental and ship performance data collection on the M.V. Arctic between 1983 and 1987, conducted by Norland Science and Engineering Ltd. under contract to Canarctic Shipping. The program involved placing observers on the vessel (and in later years some automated measuring technology) to monitor ship performance particulars as well as the ice and weather environment encountered by the M.V. Arctic for all of its inbound and outbound voyages above 60^{o} north latitude to the Canadian Arctic between 1983 and 1987. There were additional selected voyages following the end of the five-year program that used the same methodology and approach, and were carried out by personnel from Canarctic and Norland Science.

The data extracted from historical records was used for two purposes:

- Calibration of Model Algorithms
- Verification of Model Results

The data was extracted principally from the reports listed in the references. Other sources such as the ship's deck and engine logs were consulted and found to be either not readily available or of very limited use. Discussions with Dr. A. Keinonen (AKAC) were held concerning the types of data to be extracted to verify individual algorithms and for verification of the model results as a whole. Based on the notes provided by AKAC, categories of the data samples were prepared and listed in Table 2-1. The intention was to gather samples of these data for the two stated purposes up to the level of resources available to ENFOTEC for this work. A total of 11 samples were provided for calibration of individual algorithms and 4 samples for overall transit performance. These are discussed in more detail in Sections 2.3 and 2.4 and Appendix A.

Discussions took place between Sandwell, AKAC and ENFOTEC on the details and format of the data. The actual model input requirements for overall transit prediction were submitted to Sandwell and AKAC in spreadsheet format while samples from actual voyage logs were sent in their original form to AKAC.

Table 2-1 Categories of Samples for Model Algorithm Calibration and Model Verification

A. INDIVIDUAL ALGORITHMS

A1. Level ice speed continuous
Operational procedures applied
Shaft power levels
Ship speeds achieved
Ice thickness
Snow thickness
Air temperature
Ice salinity/temperature profile and/or cantilever beam strength

A2. Level ice speed ramming
Field size
Ramming cycle
Distance of ram acceleration
Power level used during backing and forward acceleration of ram
Time of reversal of direction of thrust
Impact speed with unbroken ice
Time of forward acceleration
Time of extraction time of backing
Time of change of direction of movement
Penetration time
Penetration distance
Level ice thickness
Snow thickness
Air temperature

A3. Ramming ridges
Ridge field size
Ridge ramming cycle
Distance of ram acceleration
Power level used during backing and forward acceleration of ram
Time of reversal of direction of thrust
Impact speed with unbroken ice
Time of forward acceleration
Time of extraction
Time of change of direction of movement
Penetration time
Penetration distance
Level ice thickness
Snow thickness
Ice salinity/temperature profile or measured value

A4. Circumnavigation of Ice
Amount of ice penetrated as a function of ice coverage
Amount of added distance due to circumnavigation of ice
Speed and/or power selection as a function of ice coverage, presence of multi-year ice, glacial ice as well as visibility

B. MODEL VALIDATION

B1. Transit speed validation
Power levels
Environment en route in zones
Input parameters to the model

B2 Ship speed in waves
Ship speed versus wave height, heading relative to waves
Criteria for voluntary speed loss and actual speed loss

2.1.1 Review of M.V. Arctic Vessel Performance and Trafficability Program

The five-year program began as a strictly observational program where observers recorded the ice and weather environment and ship performance using what systems were available on the bridge as well as their own observing experience. This data was recorded manually using data entry forms. Later this process was computerized on a PC through the development of a system known as the Ice Data Input, Analysis and Display System (IDIADS). This system provided the capability to enter observations on a PC HP Vectra computer installed on the bridge of the M.V. Arctic. The data was entered into a commercial PC-based database program for later compilation and analysis. Over the course of the program the early data in paper format was converted into electronic form and added to the growing database. The database program was called the Manager, one of the earliest of its kind on the market in 1985/86.

Over the years, the scope of data collection was expanded and became more refined and standardized. In later years, the IDIADS technology was further advanced through the development of an interface with ship propulsion instrumentation and some accelerometers installed at several locations in the vessel including the bow area.

IDIADS also facilitated the analysis of the ship performance and environmental data. As part of each year of the program, the data for the season was compiled and analyzed to determine such items as the spatial and temporal distribution of ice and weather conditions encountered by the vessel. The spatial and temporal relationships in these parameters were determined in relation to the performance of the M.V. Arctic. Every possible relationship between these data was investigated using the data base to establish regional and temporal trends. These historical records could then be used to predict the performance of the M.V. Arctic in the future.

Additional selected voyages were documented using IDIADS on an opportunity basis in the years following the end of the observation program at the end of the 1987 season. The additional voyages were documented using the same methods and procedures as developed during the five-year program, and such voyages were added to the IDIADS database. Regrettably the last voyage to use the IDIADS system was a trip to Deception Bay in March 1991. Since that time no further data collection efforts using this methodology have been undertaken.

The IDIADS system used a proprietary database program developed by Norland. The principals involved at Norland in the program have since departed, and there is no one in the company who can provide adequate support to this project or the compiled database. Moreover, the company that originally built the database program used by IDIADS (the Manager) has since ceased to exist, and the product is no longer supported. It uses a proprietary data structure that is not possible to access without considerable extra effort.

The historical data requires conversion to a modern PC database program, but with some of the data format in binary form, the conversion of this data is not easily accomplished. Therefore it was necessary in the time frame of this project to compile the required calibration data from hard copy records and past reports which reduced the number of examples that could be extracted in the required format for the available resources provided for the calibration effort.

2.2 Vessel Description

The M.V. Arctic is owned and operated by the Canarctic Shipping Company Limited. The ship is an icebreaking ore bulk oil carrier of 26 000 dead-weight. The M.V. Arctic is classed as an Arctic Class (AC) 3 (equivalent AC4) under the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR). Under the Lloyds Register of Shipping the vessel is classed as 1AS.

The vessel specifications are listed in Table 2-2. Figure 2-1 shows a diagram of the ship along its length as well as in plan view. The ship has an unusual length to beam ratio (approximately 9:1) that is more representative of oil tankers than traditional Arctic icebreaking vessels. The M.V. Arctic could be considered a 1/4 to 1/6 full scale model of a large Arctic Tanker envisaged for the transport of oil from Polar regions to southern markets.

A new bow design incorporating eight years of High Arctic experience was fitted to the M.V. Arctic in 1986. This resulted in a significant improvement in icebreaking performance. The vessel is capable of maintaining a continuous speed of 8 kn in first-year winter ice 1 m in thickness, and continuous forward motion can be maintained in 1.6 m ice thickness. Transit of ice in excess of 2 m thickness is achieved by continuous ramming. Since 1986, the vessel has successfully performed as a Class 4 vessel under CASPPR.

The addition of the new bow occurred during the middle of the observation program conducted between 1983 and 1987. The bow was fitted prior to the start of the 1986 season so that it is applicable for the last two-years of dedicated observation program as well as for the selected voyages of opportunity that were documented in later years.

2.2.1 Operating Procedures

The M.V. Arctic operates over an extended shipping season in the Canadian Arctic that begins in May and finishes in early to mid-November. Most voyages commence from a European port such as Antwerp, Belgium, and proceed to either the Nanisivik Mine on northern Baffin Island or the Cominco Polaris mine located on Little Cornwallis Island. Typically, the early and late season voyages go to Nanisivik while the voyages in the middle of the season proceed to Polaris. From 1986 to the present day, the M.V. Arctic completes one or two voyages each year to the Bent Horn oil terminal on Cameron Island to pick up an oil cargo for delivery to Montreal. These voyages are executed between mid-August and mid-September when ice conditions are generally easier. On voyages where heavy ice conditions are expected, the ship carries an ice master to relieve the Captain and allow the ship to maintain 24-hour operations.

The ship has sufficient ballast tanks to load to full icebreaking draft without cargo. On Arctic voyages the ship is always brought to that draft before crossing latitude 60^{o} north when the observation program started.

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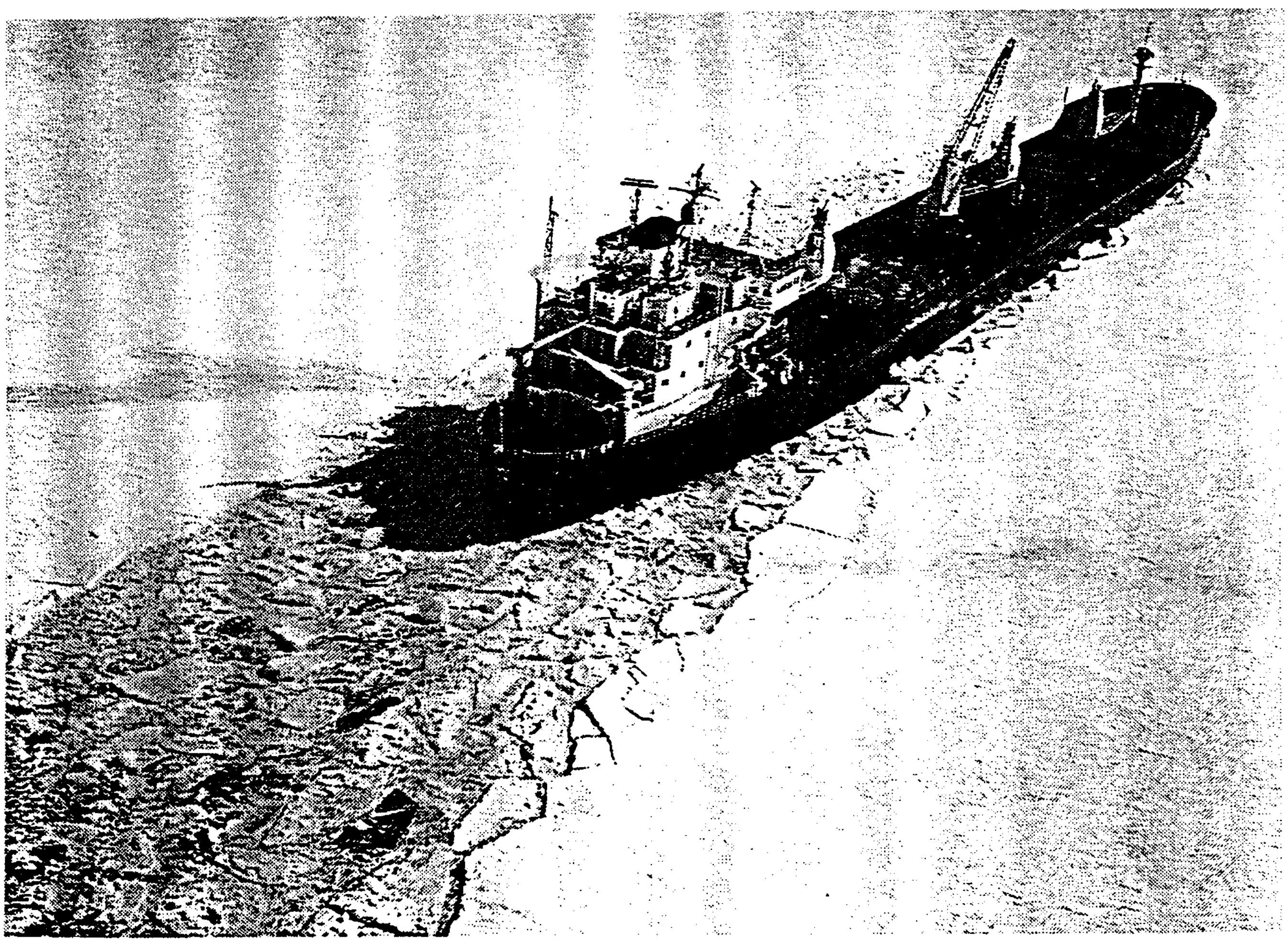
Table 2-2 Vessel Specifications

Vessel Name	Arctic
Vessel Type	Ore/Bulk/Oil Geared Carrier
LOA	220.82 m
Beam Extreme	22.932 m
DWT at summer draft	28 373.4 MT
DWT at ice draft	28 373.4 MT
Gross Tonnage	20 236
Net Tonnage	10 849
Summer draft	11.522 m
Moulded Depth	15.24 m
Number of holds/hatches	7
Slop Tank	1
Saddle Cargo Tank	1
Built - year	1978
- Country	Canada
- OBO conversion	1985
- Ice class upgrade	1986
- L.R. Hull Renovation	1995
Registry	Canada
Call Sign	VCLM
Ice Class	LR Ice Class 1A Super
Canadian Arctic Class	Class 3, with Class 4 (Equivalency)
Main Engine Power	14,770 BHP
Service Speed	15.0 kn
Average Fuel Oil Consumption	38 MT/day
Economical Speed	13.0 kn
Economical Fuel Oil Consumption	about 35 MT/day
Diesel Oil Consumption	about 3.0 MT/day
Ice Performance	
- 1 m thick First Year Ice	8 kn
- 1.6 m thick Ice	continuous forward motion
Grade of Fuel Oil	IFO 180 Cst
Grade of Diesel Oil	Marine Diesel
Tank Capacities	
- SBT	13 345 m^3
- tank 1 & 7	9 202 m^3
- fuel oil	1 881 m^3
- diesel oil	385 m^3
- dom. Water	306 m^3
Classification Society	Lloyd's Register
Owner	Canarctic Shipping Company Limited
Survey Status	In Class, 1SS Equivalency (March, 1995)
Main Engine	MAN14V/52/55A; 14 750 BHP @ 450 rpm
Steam Plant	2 (2200 & 3100 kg/hr)
Bunkering connections	1 P & S, 62 m aft of cargo manifold
Working load of derricks at manifold	16 MT
Working load of derricks on poop deck	2 MT
Hawser load - mooring	10 MT
Brake - mooring	20 MT

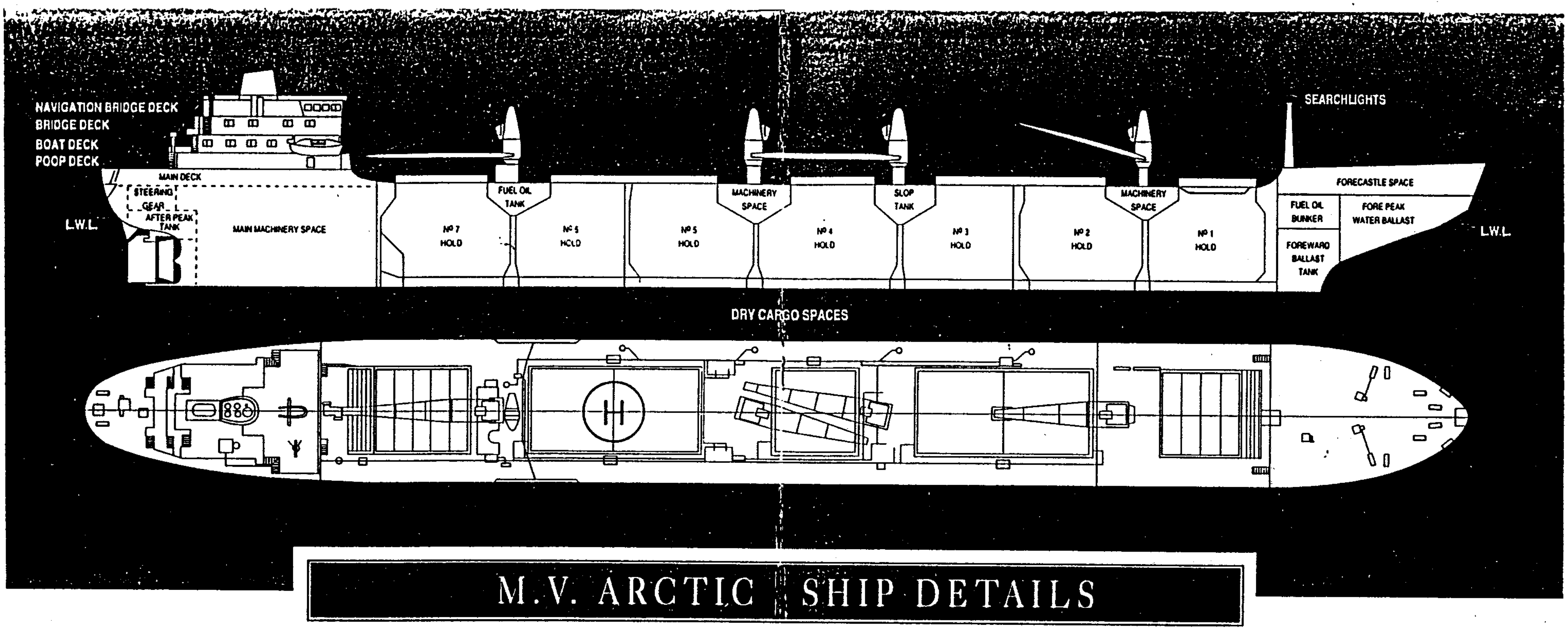
Table 2-2 Vessel Specifications (continued)

Hull Stress Monitoring	BMT model
Radio	2 M/F, H/F, VHF, GMDSS, Inmarsat A
Auto pilot	Sperry
Echo sounder	2 x Sperry
Radars	2 Sperry, 1 Decca, 1 Decca Arpa
Submerged log	Doppler
GPS	2
DECCA Navigator	1
IceNav® System	PC based shipboard ice navigation system
Oil Spill Containment Equipment	1 Steel Workboat (140 hp) 600 m Boom (Versatech Zoom Boom)



M.V. Arctic

Fig. 2-1 M.V. Arctic Plan



2.2.2 Synopsis of M.V. Arctic Voyages in Ice

The first voyage of the season to Nanisivik proceeds from Europe through eastern Baffin Bay following the lead along the west Greenland coast until it becomes necessary for the ship to break across northern Baffin Bay to reach Lancaster Sound. Depending on the location of the ice edge the ship must break through consolidated heavily ridged and rubbled ice in eastern Lancaster Sound or at the very least close pack ice conditions to the entrance to Admiralty Inlet. The M.V. Arctic must then break through about 60 miles of consolidated first-year winter ice at its maximum thickness which is in the order of 1.9 m. In most years the ice in Admiralty Inlet south of its junction with Lancaster Sound is smooth with few, if any ridges or rafting. It is a good representation of the ship's level icebreaking capabilities. Because of the maximum first year ice thickness in spring, the ship must ram through the ice to reach the Nanisivik docksite.

Voyages in the middle of the summer to Polaris are in open water to close pack ice conditions depending on the location and time of year. In some years the first voyage to Polaris occurs through consolidated ice conditions west of Resolute where the ice is in an early to advanced stage of decay prior to break-up. However, most years see the ice cover broken into open to close pack ice, mostly first-year decaying ice by the time M.V. Arctic completes its first voyage into Polaris.

The voyages to Bent Horn are conducted in highly variable ice conditions depending on the year. Conditions range from consolidated multi-year ice to open first-year pack ice between Resolute and Bent Horn. There is always the danger of heavy multi-year ice moving south through Byam Martin Channel which the ship has encountered in the past.

Ice conditions of the later season voyages to Polaris and Nanisivik after mid-September consist of newly forming ice mixed with multi-year ice that has survived the summer melt. These conditions are typically maximum at the eastern entrance to Lancaster Sound where multi-year ice from the north converges with ice moving east from Lancaster Sound. High concentrations of multi-year ice as well as ice pressure have combined in the past to best the M.V. Arctic for varying periods of time ranging from hours to a couple of days.

This summary indicates the wide variety of ice conditions that are typically encountered by the M.V. Arctic during its operating season and have required the vessel to adopt special operating procedures and advanced technologies to assist navigation in difficult conditions.

2.2.3 Ice Navigation Support

The extended shipping season means the vessel must operate in conditions of maximum ice thickness in spring, and darkness and worsening ice conditions in October and November. As well, the ship operates in areas where multi-year ice is present in significant quantities. These severe conditions have required the M.V. Arctic to develop and implement specialized ice navigation support systems. These systems include an enhanced cross-polarized marine radar that improves the detection of icebergs and multi-year ice hazards. The ship is equipped with a system known as IceNav which receives, stores and displays near-real time satellite and airborne remote sensing imagery and integrates it with ship specific systems such as GPS and GYRO.

During the years of the dedicated observation program in the mid-1980s, the M.V. Arctic was in the first stages of development of an Ice Navigation Support System. This system was known as SINSS (Shipboard Ice Navigation Support System) and consisted of first generation systems to receive satellite and airborne radar data. These were under active development during the latter years of the dedicated program (especially 1986 and 1987) as well as for subsequent years.

It is important to note that such systems and information were available to the ship for planning and executing vessel manoeuvres through moderate to difficult ice conditions. These systems relied on the availability of airborne radar data in particular. Most of the early voyages to Bent Horn had one or more radar images available to support navigation decision-making. The late season voyages almost always had one or more airborne radar flights providing tactical support. Therefore, ship's progress was definitely influenced by the availability of this data, and we believe reflect what will happen operationally in the operation of Arctic tankers in the future should they operate over an extended season.

2.2.4 Performance Measurements

Ship performance measurements for the M.V. Arctic have been conducted on several occasions over its history. The Bollard Pull tests from Long Loch Scotland in 1978 measured mean full power pull at 158.2 t.

In 1986, the M.V. Arctic was fitted with a new bow and this resulted in a significant change to the operation of the vessel in ice. In the report on the Vessel Performance and Trafficability of the M.V. Arctic for the 1986 season [1], it was noted that" . . . much more time was spent actively breaking ice for concentrations of 6 to 9 tenths during 1986. The increases are quire dramatic, on the order of 20 to 30 percent and may be indicative of increased confidence in the icebreaking capabilities of the vessel". For most concentrations where there was sufficient data, the Distance Made Good over the hour increased over the previous three years, especially in total ice concentrations between 6 and 8 tenths.

The performance of the M.V. Arctic fitted with the new bow was tested in the spring of 1986 in a series of tests in open water and ice covered waters. The trials were conducted prior to and during the first inbound voyage of the M.V. Arctic to Nanisivik in 1986 [2]. The ice trials were executed in Baffin Bay and Admiralty Inlet in different ice conditions.

The trials relevant to this project are summarized in Table 2-3.

Table 2-3 M.V. Arctic Performance Tests in Ice - Spring 1986

Location	Test Type	Ice Thickness (m)	Salinity	Ice Temperature (deg C)	Flexural Strength (K Pa)	Snow Cover (cm)	Results
Baffin Bay	Speed vs. Power Level First Year Ice [1]	1.10 m	6.0	-2.0	250	15-30	Figure 2-2
Strathcona Sound	Speed vs. Power Level First Year Ice	1.55 m	6.0	-2.0	400	15-20	Figure 2-2
Admiralty Inlet	Bollard Thrust in Ice	1.80 m	5.0	-4.0	400	15-30	Figure 2-3
	Level Ice Ramming	1.7-1.85 m	5.0	-4.0	400	15-30	Figure 2-4 and 2-5

Individual results of the tests are briefly described below.

Speed vs. Power - Level Ice

Two sets of tests were conducted - one in Baffin Bay and one in Strathcona Sound. The test sites represented two different ice thicknesses. Flexural strength of the first-year ice was higher in Strathcona Sound because the ice melt was less advanced. The ice conditions in Baffin Bay were not ideal as there was some ridging and rafting present in the ice.

The methodology involved setting power at a desired level and commencing measurement of ship speed when the vessel had reached a steady state. After several ship lengths the power was adjusted, and the procedure repeated until all the data points had been obtained. The results of the Baffin Bay and Strathcona Sound trials are presented in Figure 2-2.

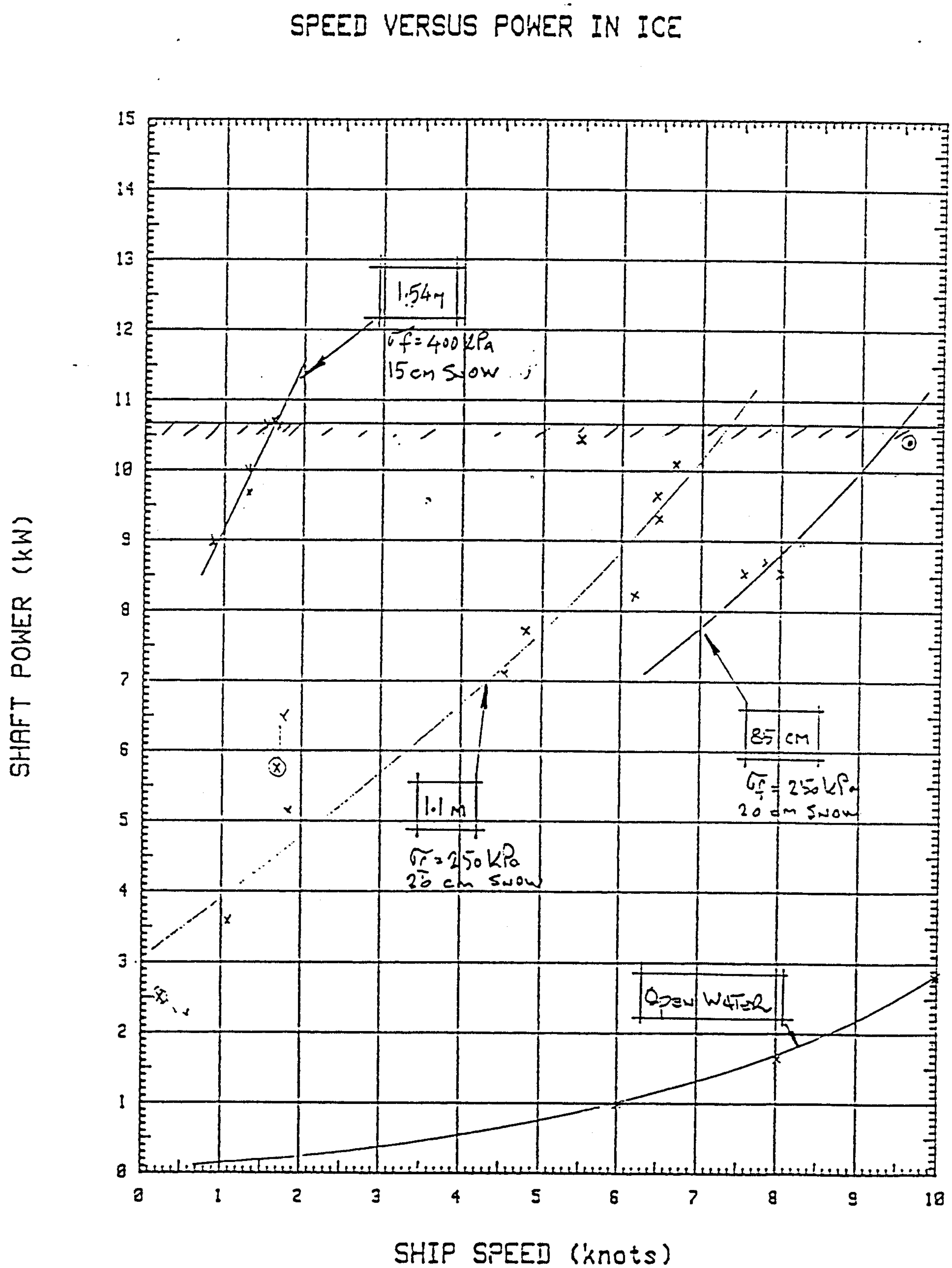
Bollard Thrust in Ice

This test was conducted in Admiralty Inlet on course for Strathcona Sound. The ship was stopped and the bow placed against the ice edge. With the ship at zero speed of advance the power was increased in steps up to full power, and the shaft power was measured at each step. The results of this test are presented in Figure 2-3.

Ramming in Level Ice

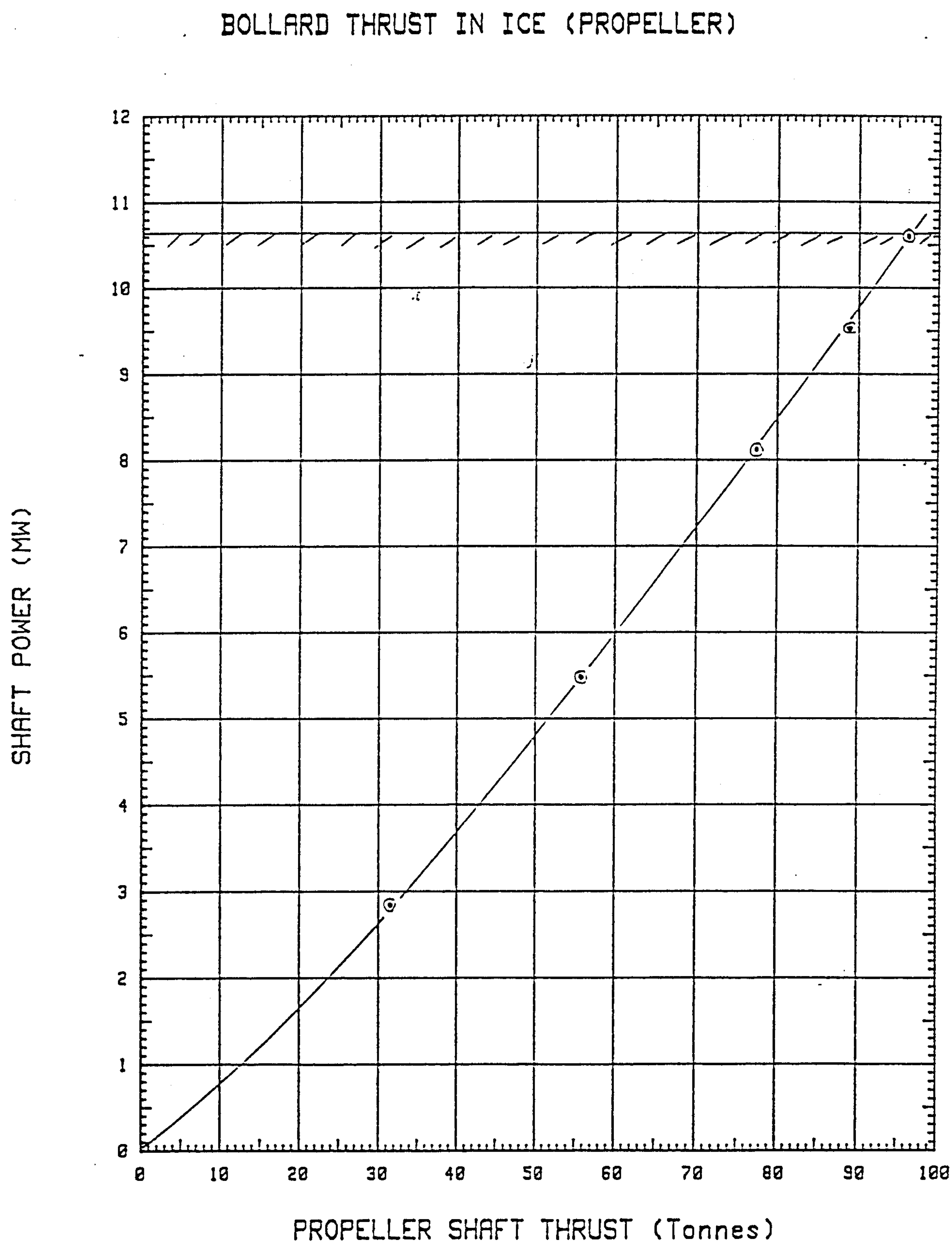
This test was executed in Admiralty Inlet where level first-year ice conditions were present. The test involved accelerating the ship from zero speed down a broken channel with rudder amidships and the combinator setting at full power until contact was made with the broken ice at the end of the channel. The combinator was maintained in that position until the ship came to a stop. It was then moved to 75 percent astern position and held there until the ship has reversed down the broken channel to a position that would allow the ram cycle to be repeated. The test produced a data set of over 150 rams. The results are plotted as average speed and penetration distance in Figures 2-4 and 2-5.

FIGURE 2-2
M.V. Arctic 1986 Performance Trials



* Some Rubble and Ridges

FIGURE 2-3
M.V. Arctic 1986 Performance Trials



MELVILLE SHIPPING LTD

FIGURE 2-4
M.V. Arctic 1986 Performance Trials

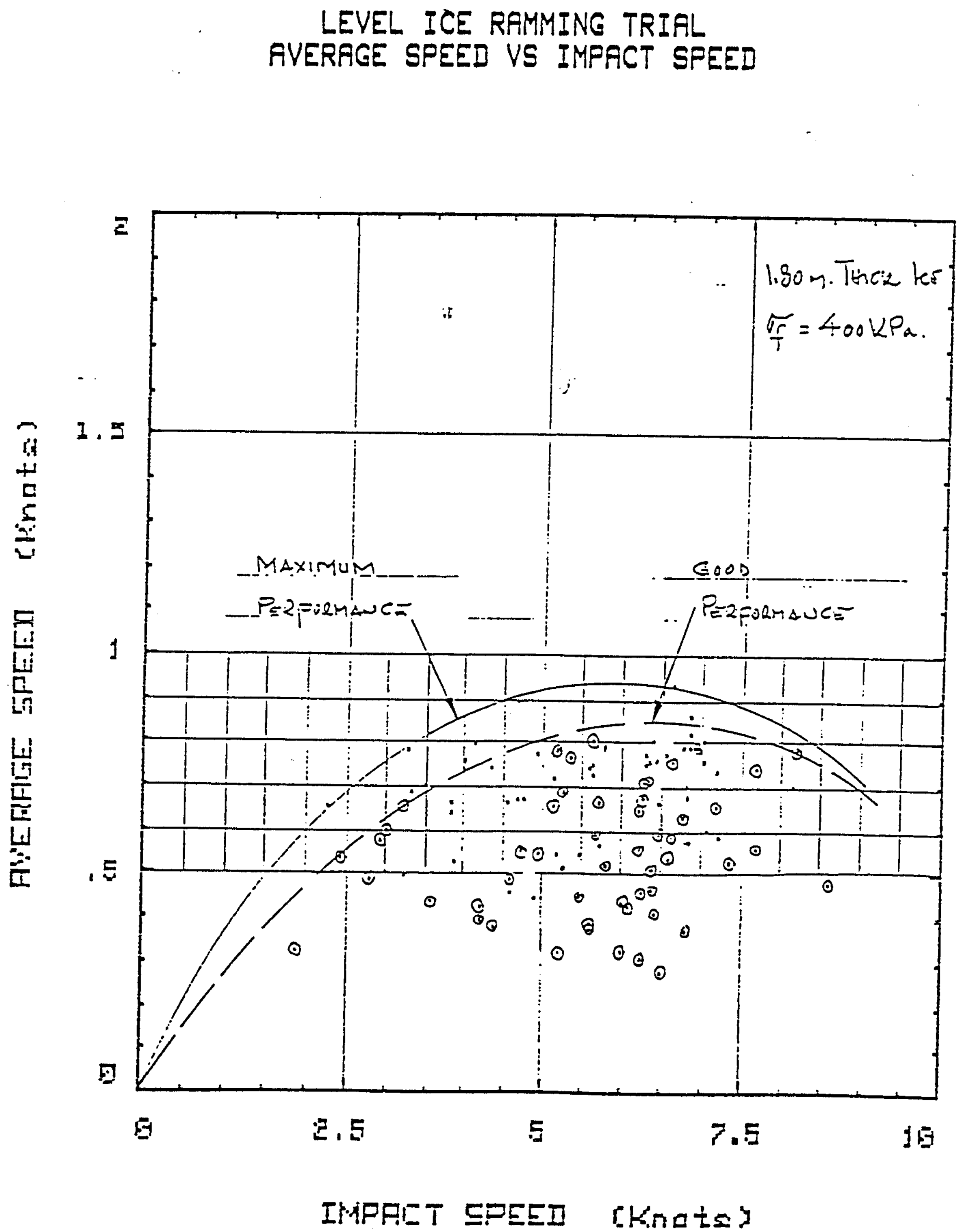
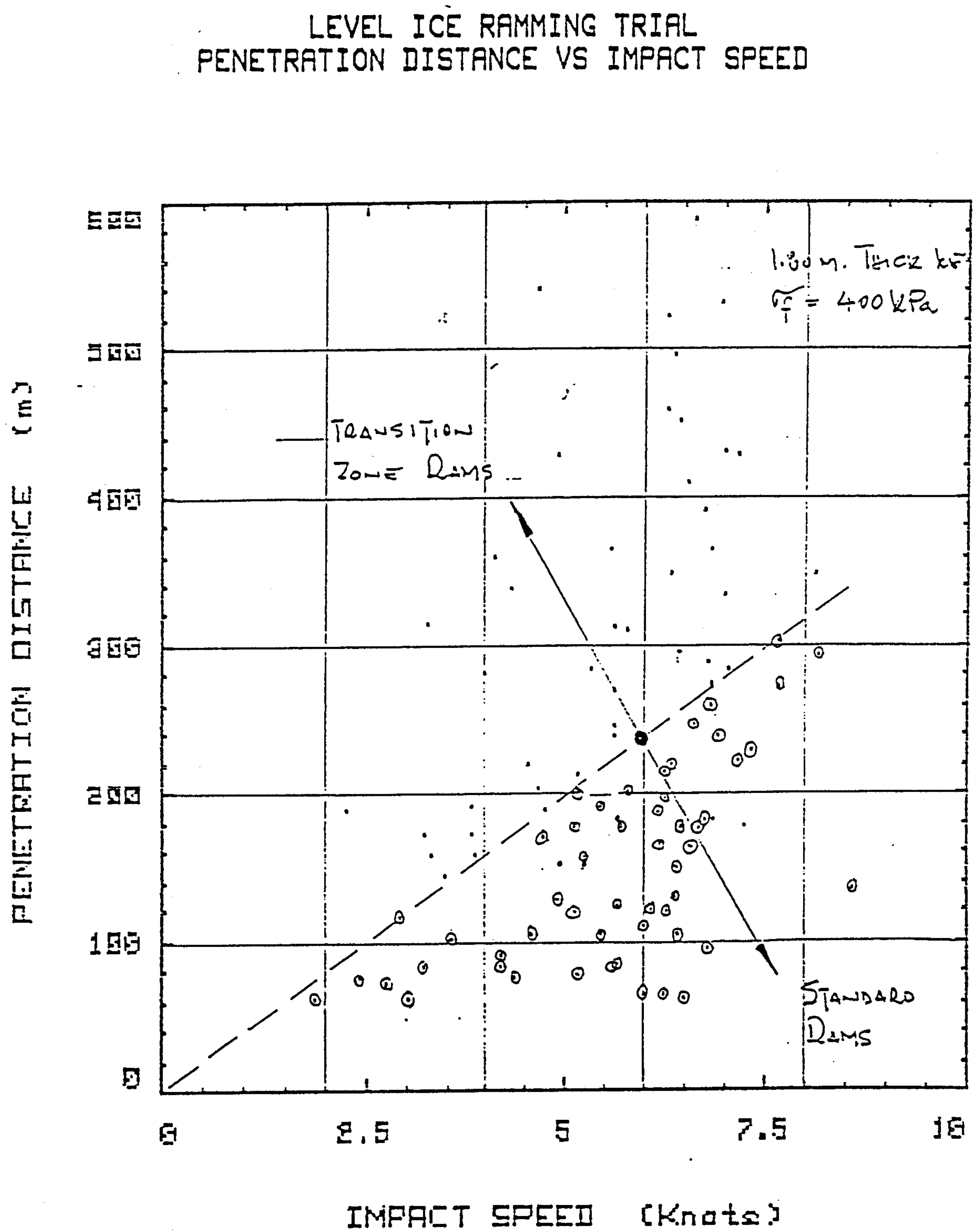


FIGURE 2-5
M.V. Arctic 1986 Performance Trials



2.3 Data Used for Model Algorithm Calibration

A total of eleven (11) samples were extracted from the historical database and hard copy records from past voyages of the M.V. Arctic for use in algorithm calibration. The following provides some of the data as well as additional commentary and documentation for each sample as appropriate. Further documentation for each sample is provided in Appendix A.

2.3.1 Sample 1 - Ice Concentration vs. Ship Speed and Distance Made Good

Sample 1 includes summary tables taken from "Ice Regimes and Environmental Conditions encountered by the M.V. Arctic during the 1983 Shipping Season" as reported by Norland Science and Engineering Ltd. in March 1984. This report was one of the first attempts to study the influence of ice regimes on the transit time of the M.V. Arctic.

Sample Category Type:	A - Effect of Ice Concentration on Transit Speed
Date:	1983 Shipping Season - Old Bow
Position:	Baffin Bay through to Lancaster Sound
Power Available:	Full

The following nomenclature was used for the Sample 1 tables in Appendix A.

Ship Performance

SPD (Instantaneous speed, recorded on the hour)
DMG (Distance made good, hourly average of net distance travelled)

Total Ice Concentration Classes

BW (Bergy Water), TR (Trace), 1,2,3,4,5,6,7,8,9,10 (tenths total concentration)

Visibility Code	**Visibility Conditions**
1	Dark and fog at ≤ ¼ mile
2	Dark
3	Fog ≤ 1/8 mile
4	Fog ¼ - ½ mile
5	½ - 5 miles, fog possible
6	5+ miles

Ice Type Code	**Ice type**
M	≥ 3/10 MY included in regimes
A	Mostly Nilas and Grey
B	Mostly Grey-white and FY

Average Ice Salinity and Temperature by Voyage Number (estimated)

Voyage	First-Year Ice		Multi-Year Ice	
	Salinity (ppt)	Temperature (ºC)	Salinity (ppt)	Temperature (ºC)
1	6.0	-8.0	1.0	-10.0
2	3.0	-3.0	1.0	-8.0
3	2.5	-1.5	0.5	-6.0
4	7.5	-5.0	1.5	-8.0
5	7.0	-10.0	1.5	-10.0

The samples were analyzed by voyage number. In 1983, a voyage was considered to be both the inbound and outbound legs, and extended for all segments of the route above 60^{o} north latitude.

2.3.2 Sample 2 - Overall Transit Performance vs. Ice and Environmental Conditions

Sample #2 data was extracted from "M.V. Arctic Vessel Performance and Trafficability Program, 1987". These plots were produced from an overall analysis of trends in the data derived from the 1983-1987 database. These analyses use common ice conditions and other factors such as season, geographic location and visibility as they possibly relate to and influence ship performance. Virtually every possible combination of factors was tried in the analysis.

Sample Category Type: A - Individual Algorithms

The results of the following statistical analyses are presented in Appendix A.2.

1. Fuel Consumption vs. Ice Thickness
2. Shaft RPM and Shaft Power vs. Ice Thickness
3. Average Distance made Good (DMG) in Rough Ice defined by # of ridges/nmi
4. Average DMG and Fuel Consumption vs. Deterioration of Thick First-Year Ice
5. Average Fuel Consumption and DMG at Increasing Total Ice Concentrations
6. Average RPM and Shaft Power at Increasing Total Ice Concentrations
7. Average Fuel Consumption vs. First Year Floe size
8. Average Shaft Power vs. First Year Floe size
9. Average DMG vs. First Year Floe size
10. Percent Time Spent in Open Water vs. First Year Floe size
11. Average DMG vs. Visibility in Increasing Ice Concentrations
12. Average DMG vs. Sea State (6 000-7 200 N. 4 000-7 000 W.)
13. Average DMG in Increasing Old Concentrations
14. The Influence of Old Ice and the Surrounding Matrix on Average DMG and Fuel Consumption

2.3.3 Sample 3 - Continuous Speed in Level Ice

During the initial voyage to Nanisivik in June 1983, the ice observation and trafficability program included the measurement of ice properties in selected locations in Baffin Bay. A section of the voyage logs were analyzed to determine ship progress in level first-year ice conditions.

Sample Category Type: A1 Continuous Speed - Level Ice
Date 21/22nd June 1983
Voyage: Inbound voyage to Nanisivik

Description	Position #1	Position #2
Latitude/Longitude	74º 12’ N / 58º 59’ W	75º 21’ N / 62º 48’ W
Average Speed (kn)	4.5	5.9
Ice Thickness (cm)	90-113	118-128
Snow Cover (cm)	7-11	8-13
Ice Temperature	-1 °C	-1 °C
Ice Salinity (ppm)	5	5
Power Available (kW)	est. 9 500	est. 9 500
Elastic Yield Point (MPa)		1.2 (avg.)

The actual vessel performance and ice observation data sets are provided in Appendix A.

2.3.4 Sample 4 - Route Segment Analysis - Deception Bay Voyage March 1991

A vessel performance and trafficability program was conducted on the inbound voyage of the M.V. Arctic to Deception Bay, Northern Quebec in March 1991. The purpose of the voyage was to demonstrate year-round shipping access to the harbour using the M.V. Arctic. Norland Science and Engineering Ltd. carried out the observation program and the subsequent analysis of the data.

This data collection effort was the last one completed under this program. It represented the most advanced methodology for the collection and subsequent analysis of the data. We suggest this is the most complete and highest quality data of its kind to date.

The inbound route was subsequently subdivided into discrete segments representing common ice conditions over the time period and geographic distance travelled. Segments were also ended due to special events in the ice cover e.g., onset of ice pressure.

Sample Category Type: B1 Overall Transit Performance

2.3.5 Sample 5 - Continuous Speed in Level Ice - Baffin Bay Voyage 1 - May 1989

This sample presents the performance of the M.V. Arctic on her first 1989 voyage to Nanisivik through Baffin Bay. During this voyage ice properties were directly measured and these are presented in Appendix A. An extract from this voyage for level icebreaking is presented below.

Sample Category Type:	A1 Continuous Speed - Level Ice
Date:	06 May 1989
Voyage:	Brixham UK to Nanisivik, NWT
Position:	7049 N 5621 W
Duration:	1 hour
Ice Thickness:	91 to 108 cm
Snow Cover:	5 to 15 cm
Freeboard:	7 to 10 cm
Air Temperature:	-9.1° C
Snow/Ice Temperature:	-3.8° C
Ice Temperature:	-3.6° C
Distance made good:	3 mile
Power Available:	est. 8 000 kW

2.3.6 Sample 6 - Ramming at Limit in Level Ice with Rubble

This sample was extracted from the M.V. Arctic voyage into Deception bay in March 1991.

Sample Category Type:	A2 - Ramming at Limit in Level Ice with Rubble
Date:	10/11 March 1991
Voyage:	Winter Probe to Deception Bay, Quebec
Position:	6 054 N 6 205 Win Hudson Strait
Duration:	5 hours
Number of Rams:	19
Ice Thickness:	90 to 130 cm
Rubble Cover:	60 to 70 percent
Snow Cover:	20-30 cm
Snow/Ice Temperature:	-6.0° C
Ice Temperature:	-6.0° C
Ramming Cycle:	see “Event 109” - Appendix A
Distance made good:	1 mile
Power Available:	9 500 kW
Intermittent Pressure	

The ramming sequence employed by the ship was recorded in great detail. Event 109 from the observation log is a typical example of the method and progress made by the ship.

2.3.7 Sample 7 - Influence of Ice Information on Vessel Performance

Sample 7 presents an in-house analysis of the M.V. Arctic during the October 1986 voyage through Lancaster Sound. This data was taken from "Vessel Performance and Trafficability Study for the M.V. Arctic 1986 Trading Season". It includes maps showing actual routing of ARCTIC outbound through Lancaster Sound as compared to two optional routes that were studied using SAR imagery that was available at the time. A copy of the imagery is provided in Appendix A.7. Vessel performance for the two optional routes were estimated by analyzing the historical data to determine past ship performance in similar ice conditions as interpreted from the imagery.

Sample Category Type:	A4 - Circumnavigation of Ice
Date:	30 October 1986
Position:	Lancaster Sound

Part of the above study involved using the IDIADS to provide a comparison of vessel trafficability between encountered and avoided conditions, for a voyage segment supported by SAR imagery. The ice regime descriptions presented in the referenced Table 4-5 formed the basis of the IDIADS search. The actual data for the route taken was extracted first. The IDIADS database was then searched to find matching ice regimes which corresponded to the optional routes. The distance made good and fuel consumption are the output of this search.

2.3.8 Sample 8 - Circumnavigation of Ice with SAR Imagery

Sample 8 is from the first 1986 voyage to Bent Horn. The sample includes a map showing actual routing of ARCTIC inbound/outbound through Erskine Inlet. The following is an analysis of the route taken.

Sample Category Type:	A4 - Circumnavigation of Ice	
Date:	26-29 August 1986	
Position:	Erskine Inlet	
Straight Line Distance:	20.6 miles	
Distance Travelled:	22.5 miles	
Total Ice Coverage:	10 tenths	
	First Year	4-6 tenths (150 cm) -highly decayed with many melt ponds
	Old Ice	4-6 tenths (small to medium floes) -190-380 cm
Power Available:	10 000 kW	

Ship using SAR image and radar.

2.3.9 Sample 9 - Level Ice Performance Tests

Sample 9 presents the "ARCTIC" during performance testing in the Spring of 1986. The information was extracted from the following reports:

- "Level Ice Physical Properties in support of the M.V. Arctic Performance Trials in Baffin Bay and Admiralty Inlet May-June 1986", September 30, 1986.

- "Voyage Report - Performance Testing of the M.V. Arctic Spring 1986", June 30,1986.

This data set includes two separate variables related to ship performance. These are:

Sample (9a)

Sample Category Type: A1- Continuous Speed - Level Ice
Date: May - June 1986
Position: Admiralty Inlet

The attached figure for Shaft Power vs. Ship Speed for varying ice thicknesses and ice strengths is presented in Appendix A, Sample 9.

Sample (9b)

Sample Category Type: A2- Ramming a Ridge
Date: May - June 1986
Position: Admiralty Inlet

The attached sheets in Appendix A.9 describe a ridge ramming event at the western entrance to Strathcona Sound where there was a small ridge. Information on the ridge and the ice properties measured at the time of the test are included.

- Location of ridge along ship track and with respect to Admiralty Inlet.
- Ridge profile including ship's speed during penetration.
- Physical properties of ice in general in Admiralty Inlet including detailed description of ridge ice properties.
- Ice thickness along ship track showing ridge profile with respect to adjacent ice field.

The ship successfully rammed the ridge with no difficulty at a speed of 7 kn and then decelerated within 2 minutes to 1 knot and continued at that speed for another 3 minutes before coming to a complete stop. The vessel managed to penetrate a total of 248 m before coming to a halt (Melville Shipping Ltd., 1986).

From the ice properties collected, the ridge consisted of unconsolidated first year, grey-white ice blocks aligned along a narrow north-south axis.

2.3.10 Sample 10 - Circumnavigation of Ice in Lancaster Sound - November 1984

This sample is extracted from the last 1984 voyage to Nanisivik while the vessel was in Lancaster Sound. At this time of year, much of the voyage is conducted in darkness at these latitudes. This data was taken from an old SLAR image used during this voyage. It is presented as an attachment in Appendix A.10. Unfortunately the original image is of quite poor quality and thus did not reproduce as well as hoped.

Sample Category Type:	A4 - Circumnavigation of Ice	
Date:	9 November 1984	
Position:	73 N77 W (Lancaster Sound)	
Straight Line Distance:	22 miles	
Distance Travelled:	25 miles	
Total Ice Coverage:	9+ tenths	
	Grey	1-2 tenths
	Grey White	1-5 tenths
	First Year	4-9 tenths
	Old Ice	1-4 tenths (with first year hummocked around small to medium floes)

Note three (3) leads transversely crossing intended course
Actual ice penetrated as function of coverage: - 96 percent
Power Available: 8 000 kW
Visibility: Mostly darkness with some low sun with flat light.
Ship using SLAR image and radar.

2.3.11 Sample 11 - Circumnavigation of Ice in Baffin Bay - June 1984

This sample presents the “ARCTIC” on her 1984 maiden voyage to Nanisivik. This data was taken from an old SLAR image which was used during this voyage. It is presented as an attachment.

Sample Category Type:	A4 - Circumnavigation of Ice
Date:	10/11 June 1984
Position:	7 412 N 5 840 W to 7 448 N 5 948 W
Duration:	7 hours
Straight Line Distance:	46 miles
Distance Travelled:	61 miles
Ice:	First Year 4 to 9 tenths
	150 cm
Snow Cover:	2-20 cm
Air Temperature:	-2.0° C
Snow/Ice Temperature:	-3.0° C
Ice Temperature:	-3.5° C mean
Distance Icebreaking:	13.5 miles
Power Available:	10 365

2.4 Data Used for Model Verification

Four samples of data from historical voyages of M.V. Arctic were extracted for model verification purposes. These samples are provided in Appendix B in the form of spreadsheets. The data was extracted and reduced into a format that could be more readily used for model verification purposes. The following is a brief discussion of the voyages from which this data was compiled.

2.4.1 Voyage #1 - 1989 Spring Voyage from Brixham U.K. to Nanisivik

This voyage was selected as a representative example for M.V. Arctic operations in late winter ice conditions where ice properties are near their maximum values in terms of thickness and snow cover. This particular voyage was documented by Canarctic and Norland personnel for the inbound portion to Nanisivik, and included the direct measurement of ice and snow properties at selected locations. A map showing the actual voyage route through Baffin Bay into Nanisivik is provided in Figure 2-6. This map also shows the breakdown of specific voyage segments.

The Excel spreadsheets were submitted separately to Sandwell and AKAC for their work on model verification. Additional fields to the data set were provided and included: Position (latitude/longitude), speed, CMG (course made good), DMG (distance made good), shaft power, wave height, period and direction, snow/ice interface temperature, ice temperature and freeboard, salinity, snow cover and any additional comments.

To ensure correct interpretation of the data field inputs the following were taken into account:

- **Level ice thickness** - the thickness of the thickest, next thickest and third thickest ice types present according to their observed concentrations as reported by the ice observers. Covers up to the three thickest ice types but if less than three are present then only those are reported.

- **Ridging frequency** - the ridge frequency is the number of ridges per nautical mile for the three thickest ice types.

- **Background rubble** - The thickness represents the actual thickness of rubble as observed from the bridge plus the level ice thickness at its location. For example, a rubble ice thickness of 1.4 m at a location where ice thickness is 1 m represents a total rubble thickness of 2.4 m. It was not possible to measure the total thickness of rubble including its underwater depth so this is considered a minimum thickness which is likely greater than reported.

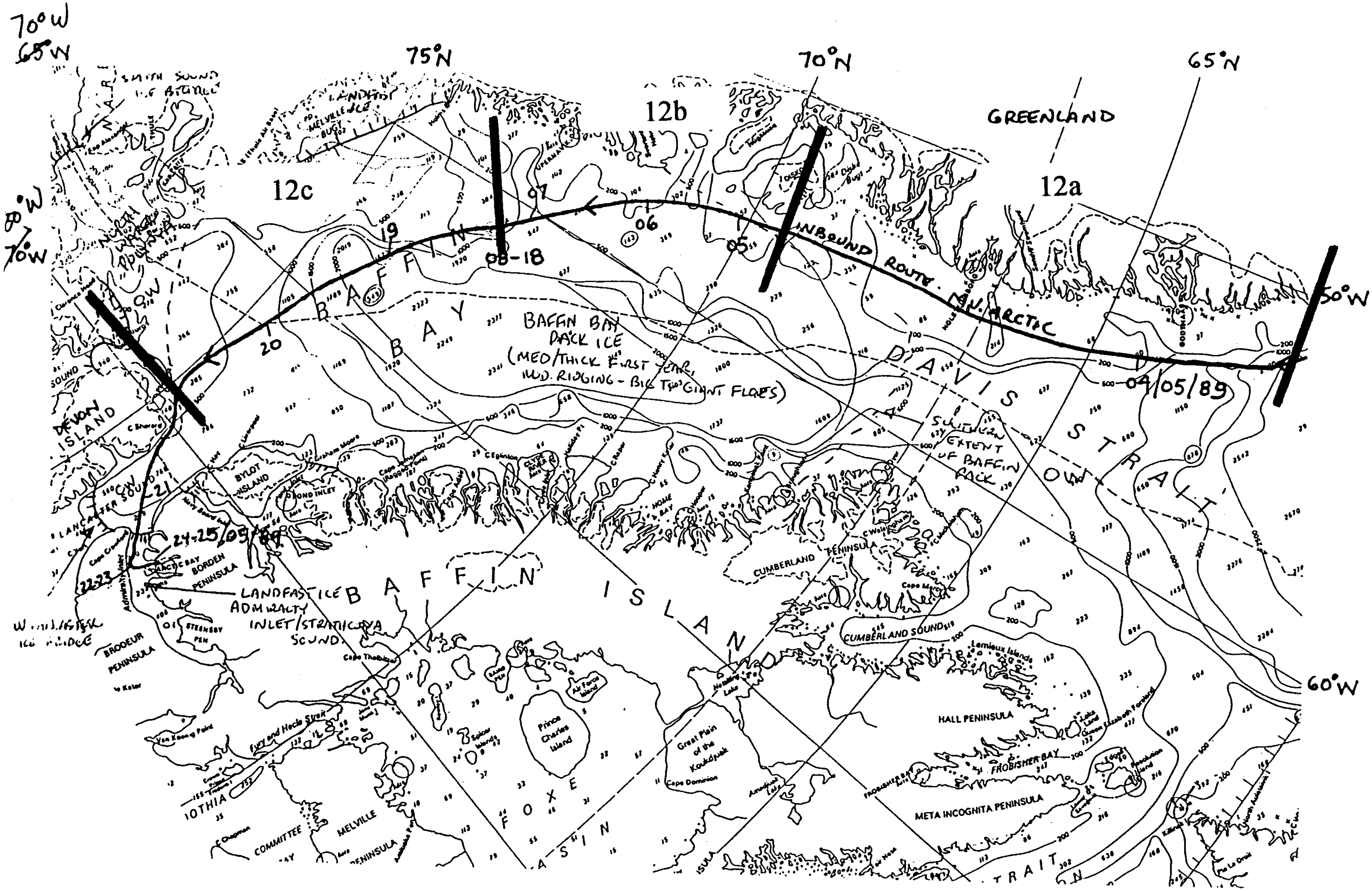


Figure 2-6 Inbound route of M.V. Arctic from Davis Strait to Strathcona Sound. (May 03-25, 1989)

2.4.2 Voyage #2 - Lancaster Sound/Admiralty Inlet Consolidated Ice

This voyage was conducted in the spring of 1987 with the M.V. Arctic fitted with the new bow. The inbound voyage through consolidated ice in Lancaster Sound and Admiralty was analyzed in detail by Norland. The results of this analysis are provided in Table 2.4. Figure 2-7 shows the SAR image of the consolidated ice cover. The planned and actual routes of the M.V. Arctic through this ice are presented as overlays to the image.

Table 2.4

MV ARCTIC Trafficability Summary
for Lancaster Sound and Admiralty Inlet
Spring 1987 Consolidated Ice

Route Segment	Time Period	Transit Distance (n.mi.)	Description / Features	Ridge Frequency (#/n.mi.)	Transit Time (hr:min)		Average Speed (n.mi./hr)		Fuel Consumption (kg/n.mi.)	
					Total	Ramming	Total	Ramming	Total	Ramming
Section "A"										
A.1	May31 0000– Jun 1 1305	5.0	MV ARCTIC breaks track first year only; no old ice no visible melt/decay	4.2	27:05	10:47	0.18	0.46	8288.	3300.
A.2	Jun 1 1305– Jun 3 1103	4.8	icebreaker escort leads first year only, thickness 210–250 cm little snow cover ram cycle= 12 min average	4.8	45:58	33:33	0.10	0.14	12966.	9464.
A.3	Jun 3 1103– Jun 4 0600	1.0	MV ARCTIC breaks track snow cover 0–100 cm 4–5/10 ridging, sail heights 200–250 cm	14.0	18:57	15:49	0.05	0.06	25751.	21493.
A.4	Jun 4 0600– Jun 4 1748	2.2	re-frozen lead ram cycle = 8 min average	1.4	11:48	11:04	0.19	0.20	8508.	7980.
A.5	Jun 4 1748– Jun 6 2202	3.5	trace old ice (ice cake)	5.1	52:12	41:04	0.07	0.09	24291.	19110.
Section "B"										
B.1-1	Jun 6 2202– Jun10 0100	4.6	2/10 old ice (big floe) measured: FY – 220 cm OI – 470 cm snow cover avg 100 cm 4/10 ridging, sail 300 cm ram cycle = 7 min average	5.9	74:58	54:36	0.06	0.08	–	–
B.1-2	Jun10 1200– Jun11 0200	1.1	3/10 old ice (small floe)	8.2	14:00	14:00	0.08	0.08	16361.	16361.
B.1-3	Jun11 1400– Jun13 0100	7.6	3/10 old ice (small floe)	3.0	35:00	20:10	0.22	0.38	7064.	4070.
Average for B.1:		13.3		4.4	123:58	88:46	0.11	0.15		

Table 2.4 (continued...)

MV ARCTIC Trafficability Summary
for Lancaster Sound and Admiralty Inlet
Spring 1987 Consolidated Ice

Route Segment	Time Period	Transit Distance (n.mi.)	Description / Features	Ridge Frequency (#/n.mi.)	Transit Time (hr:min) Total	Transit Time (hr:min) Ramming	Average Speed (n.mi./hr) Total	Average Speed (n.mi./hr) Ramming	Fuel Consumption (kg/n.mi.) Total	Fuel Consumption (kg/n.mi.) Ramming
B.2-1	Jun10 0100- Jun10 1200	2.7	2/10 old ice (med floe) following re-frozen lead	3.3	11:00	10:42	0.25	0.25	5931.	5797.
B.2-2	Jun11 0200- Jun11 1400	3.4	following re-frozen lead	0.9	12:00	8:25	0.28	0.40	5216.	3658.
B.2-3	Jun13 0100- Jun13 1300	3.4	following re-frozen lead	2.9	12:00	11:44	0.28	0.29	5840.	5710.
Average for B.2:		9.5		2.3	35:00	30:51	0.27	0.31		
B.3	Jun13 1300- Jun16 0300	6.3	trace old ice	7.0	62:00	47:54	0.10	0.13	15710.	12137.
Section "C"										
C.1	Jun16 0300- Jun19 0026	5.8	trace old ice 4/10 ridging 1/10 puddling	4.7	69:26	42:15	0.08	0.14	18863.	11478.
C.2	Jun19 0026- Jun20 0342	2.3	1/10 old ice	6.1	27:16	13:35	0.08	0.17	16608.	8279.
C.3	Jun20 0342- Jun27 0830	n/a	main engine repairs icebreaker ahead sunny and warm, melt accelerates	n/a	172:48	0:00	n/a	n/a	-	-
C.4	Jun27 0830- Jun28 0102	6.0	icebreaker leads difficult to follow turns in track	0.9	16:32	7:00	0.37	0.86	4290.	1820.
C.5	Jun28 0102- Jun28 0700	2.0	MV ARCTIC breaks track	2.0	5:58	5:58	0.34	0.34	5241.	5241.
Section "D"										
D.1	Jun28 0700- Jun30 2200	43.0	smooth first year only, estimate 180 cm snow cover 100 cm 4/10 puddling	0.1	63:00	61:15	0.68	0.70	2575.	2504.

Table 2.4 (continued...)

MV ARCTIC Trafficability Summary
for Lancaster Sound and Admiralty Inlet
Spring 1987 Consolidated Ice

Route Segment	Time Period	Transit Distance (n.mi.)	Description / Features	Ridge Frequency (#/n.mi.)	Transit Time (hr:min)		Average Speed (n.mi./hr)		Fuel Consumption (kg/n.mi.)	
					Total	Ramming	Total	Ramming	Total	Ramming
Section "E"										
E.1	Jun30 2200- Jul 1 0308	5.0		0.2	5:08	5:08	0.97	0.97	1738.	1738.
E.2	Jul 1 0308- Jul 1 0941	9.0	speed reduced for preferred arrival	0.4	6:33	6:33	1.37	1.37	1068.	1068.

Source: Norland (1987)

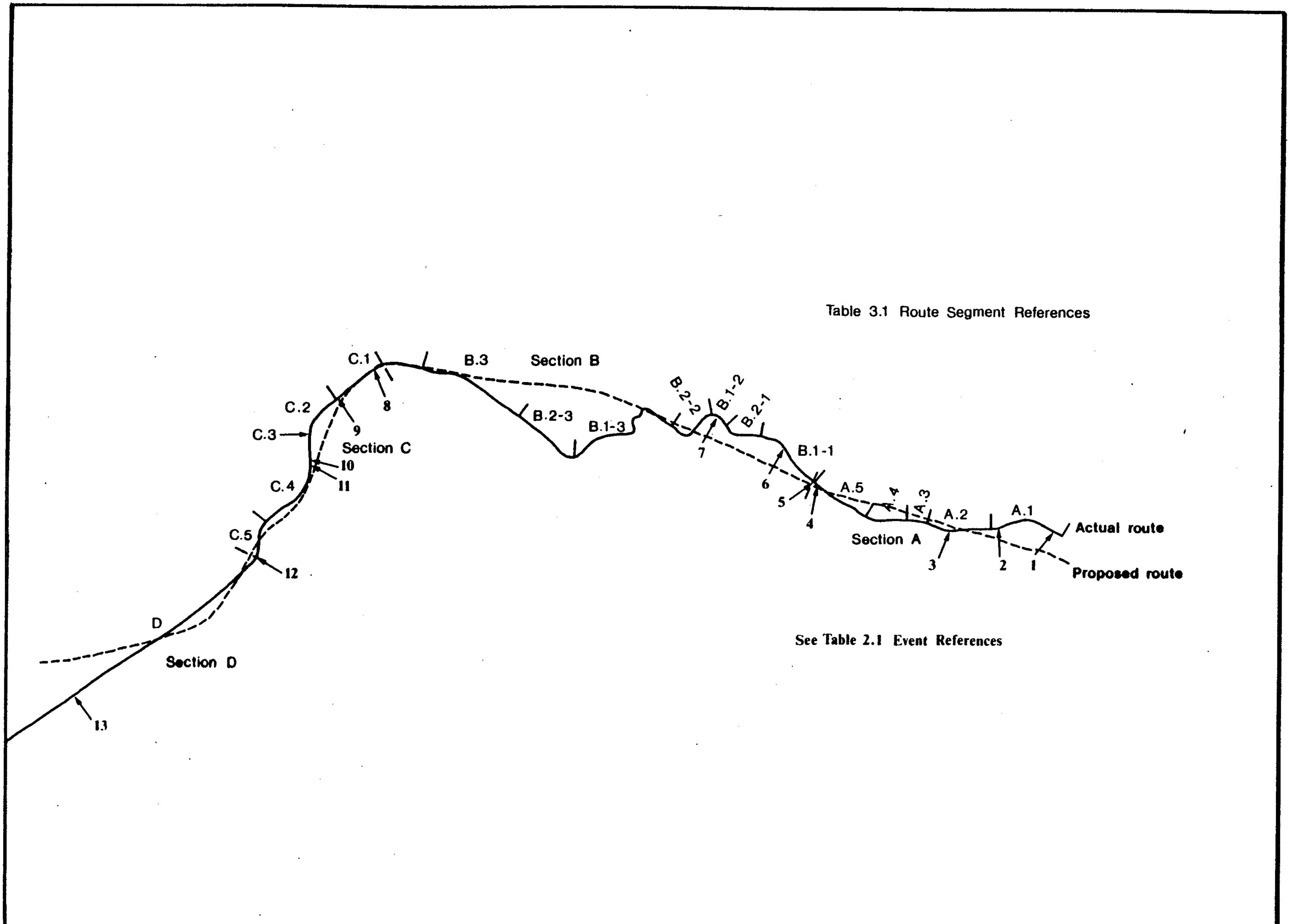


Figure 2-7 M.V. Arctic Consolidated Ice Transit
Lancaster Sound and Admiralty Inlet Spring 1987

2.4.3 Voyage #3 - Late Season Voyage to Nanisivik

In November 1988, the M.V. Arctic sailed to Nanisivik for its last voyage of the season. Norland Science, in conjunction with Canarctic, conducted a verification study of the proposed Ice Regime Shipping System for Canadian Coast Guard Northern Branch. The route travelled by the vessel is presented in Figure 2-8. The map also shows the geographic location where zones of common ice regimes were defined as well as segments of the route. These were various attempts to define ice regimes at varying scales of observation.

This project afforded the opportunity to collect additional vessel performance and trafficability data to add to the IDIADS data base. This data was subsequently reviewed and analyzed for the purpose of Model Verification, and the results are presented in Table 2.5.

Table 2.5

Calibration of Arctic Marine Transportation Model - Sample 13
November 1988 Voyage to Nanisivik

	TIME		COVER		LEVEL ICE THICKNESS					RIDGING FREQUENCY			BACKGROUND RUBBLE		
MONTH	DAY	HOUR	C	H1	H1	H2	H2	H3	H3	N1	N2	N3	DELTA H	DELTA H	DELTA H
				(m)	%C	(m)	%C	(m)	%C	(nm)	(nm)	(nm)	(m)	(m)	(m)
ZONE 4-1	DISTANCE 775 MILES					AVERAGE SPEED 13 KNOTS									
11	8	1700													
	TO		0	0	0	0	0	0	0	0	0	0	0	0	0
11	9	0000													
	TO		0	0	0	0	0	0	0	0	0	0	0	0	0
11	9	0700													
	TO		0	0	0	0	0	0	0	0	0	0	0	0	0
11	9	1000													
	TO		BERGS	0	0	0	0	0	0	0	0	0	0	0	0
11	9	1700													
	TO		0	0	0	0	0	0	0	0	0	0	0	0	0
11	10	0100													
	TO		BERGS	0	0	0	0	0	0	0	0	0	0	0	0
11	10	0900													
	TO		95	0.1	95	0	0	0	0	0	0	0	0	0	0
11	10	1400													
	TO		90	0.1	90	0	0	0	0	0	0	0	0	0	0
11	11	0000													
	TO		95	0.15	45	0.1	50	0	0	0	0	0	0	0	0
11	11	0200													
	TO		95	0.15	65	0.1	30	0	0	0	0	0	0	0	0
11	11	0800													
ZONE 4-2	DISTANCE 132 MILES					AVERAGE SPEED 14.0 KNOTS									
11	11	0800													
	TO		95	0.25	15	0.15	40	0.1	40	0	0	0	0	0	0
11	11	1200													
ZONE 4-3	DISTANCE 83 MILES					AVERAGE SPEED 14 KNOTS									
11	11	1200													
	TO		95	0.25	70	0.15	20	0.1	5	0	0	0	0	0	0
11	11	1700													
ZONE 4-4	DISTANCE 58 MILES					AVERAGE SPEED 10.2 KNOTS									
11	11	1800													
	TO		95	0.5	80	0.25	10	0.1	5	2	0	0	0	0	0
11	11	2000													
	TO		95	0.5	60	0.25	35	0	0	2	0	0	0.5	0	0
11	12	0000													
ZONE 4-5	DISTANCE 40 MILES					AVERAGE SPEED 8.7 KNOTS									
11	12	0000													
	TO		95	0.5	70	0.1	25	0	0	4	0	0	0	0	0
11	12	0300													
ZONE 4-6	DISTANCE 12 MILES					AVERAGE SPEED 10.5 KNOTS									
11	12	0300													
	TO		95	3	10	0.5	65	0.25	5	0	3	0	0	0	0
11	12	0500													
ZONE 4-7	DISTANCE 23 MILES					AVERAGE SPEED 7 KNOTS									
11	12	0500													
	TO		95	0.5	85	0.1	10	0	0	9	0	0	0.1	0	0
11	12	0700													
	TO		95	0.5	50	0.15	40	0.1	5	8	0	0	0.1	0	0
11	12	0800													
ZONE 4-8	DISTANCE 29 MILES					AVERAGE SPEED 13.5 KNOTS									
11	12	0800													
	TO		90	0.25	10	0.15	50	0.1	30	0	0	0	0	0	0
11	12	0900													
	TO		95	0.6	20	0.15	30	0.1	50	0	0	0	0	0	0
11	12	1000													
ZONE 4-9	DISTANCE 31 MILES					AVERAGE SPEED 12 KNOTS									
11	12	1000													
	TO		95	0.5	80	0.25	15	0	0	0	0	0	0	0	0
11	12	1200													
	TO		100	0.5	100	0	0	0	0	8	0	0	0	0	0
11	12	1300													

Table 2.5 (continued...)

Calibration of Arctic Marine Transportation Model - Sample 13
November 1988 Voyage to Nanisivik

LEADS			RUBBLE FIELDS			PRESSURE					WAVES			SHAFT
FREQ	F	DUR (h)	FREQ	SIZE (nm)	DUR (h)	FREQ P1	DUR P1 (h)	FREQ P2	DUR P2 (h)	T (deg C)	HEIGHT (m)	PERIOD SECS	DIRECTION	POWER (kw)
0	0	0	0	0	0	0	0	0	0	-2	4	5	AHEAD	4700
0	0	0	0	0	0	0	0	0	0	-4	4	5	PORT BOW	8100
0	0	0	0	0	0	0	0	0	0	-5	2	4	PORT BOW	8000
0	0	0	0	0	0	0	0	0	0	-5	1.5	3.5	PORT BOW	7900
0	0	0	0	0	0	0	0	0	0	-8	2	5	PORT BOW	7100
0	0	0	0	0	0	0	0	0	0	-10	1.5	5	PORT BOW	6900
0	0	0	0	0	0	0	0	0	0	-12	0	0	0	7100
0	0	0	0	0	0	0	0	0	0	-14	0	0	0	7250
0	0	0	0	0	0	0	0	0	0	-16	0	0	0	7500
0	0	0	0	0	0	0	0	0	0	-17	0	0	0	9300
0	0	0	0	0	0	0	0	0	0	-19.5	0	0	0	9450
0	0	0	0	0	0	0	0	0	0	-20	0	0	0	9750
0	0	0	0	0	0	0	0	0	0	-22	0	0	0	9700
0	0	0	0	0	0	0	0	0	0	-23	0	0		8500
0	0	0	0	0	0	0	0	0	0	-24	0	0	0	10000
0	0	0	0	0	0	100	2	0	0	-25	0	0	0	9400
0	0	0	0	0	0	100	1	0	0	-25	0	0	0	9600
0	0	0	0	0	0	0	0	0	0	-23.5	0	0	0	9900
0	0	0	0	0	0	0	0	0	0	-24.5	0	0	0	9500
0	0	0	0	0	0	0	0	0	0	-25	0	0	0	9100
0	0	0	0	0	0	0	0	0	0	-27.5	0	0	0	9600
0	0	0	0	0	0	0	0	0	0	-30	0	0	0	9950

Figure 2-8: Inbound Transit
Davis Strait and Baffin Bay
November 8 - 11, 1988

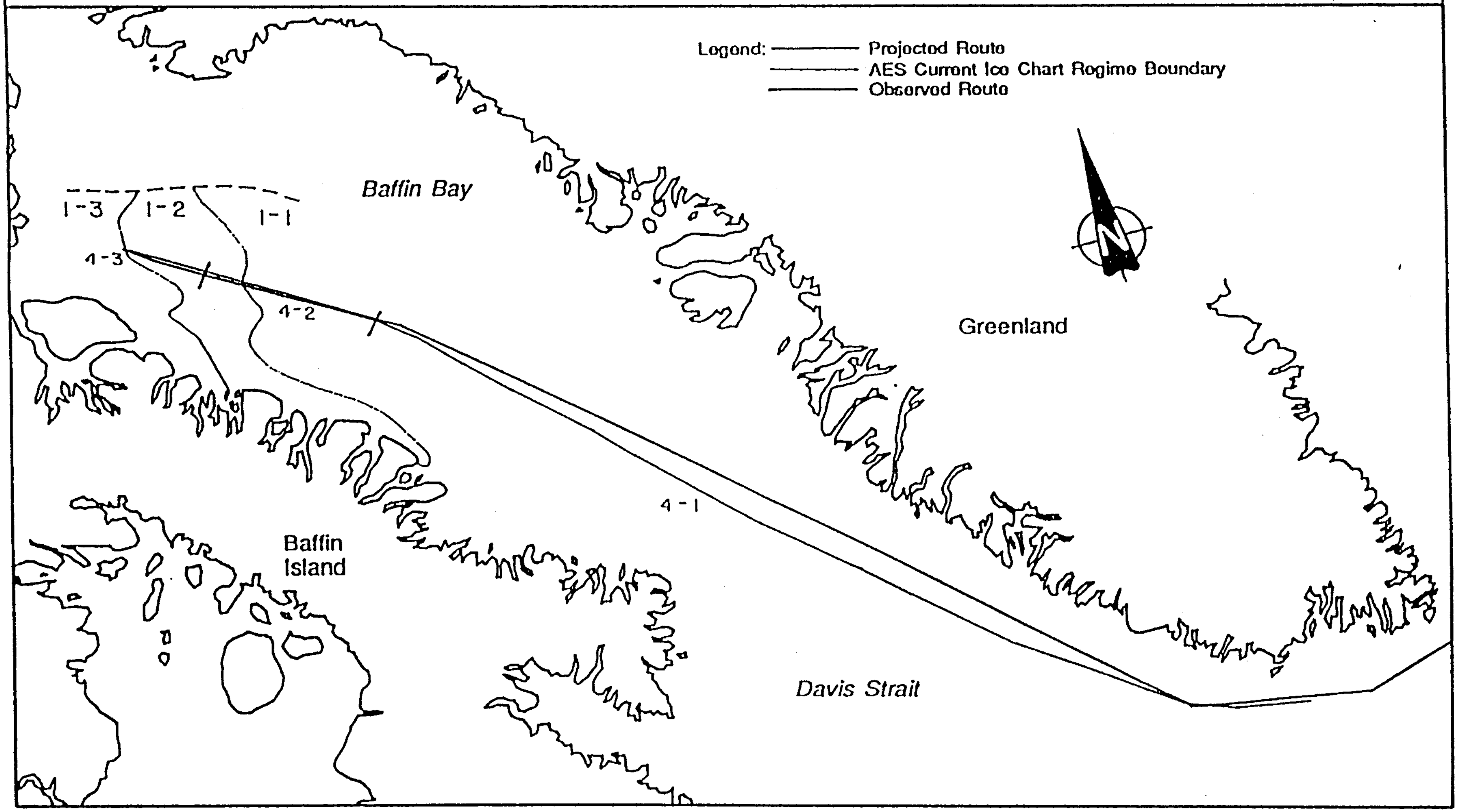
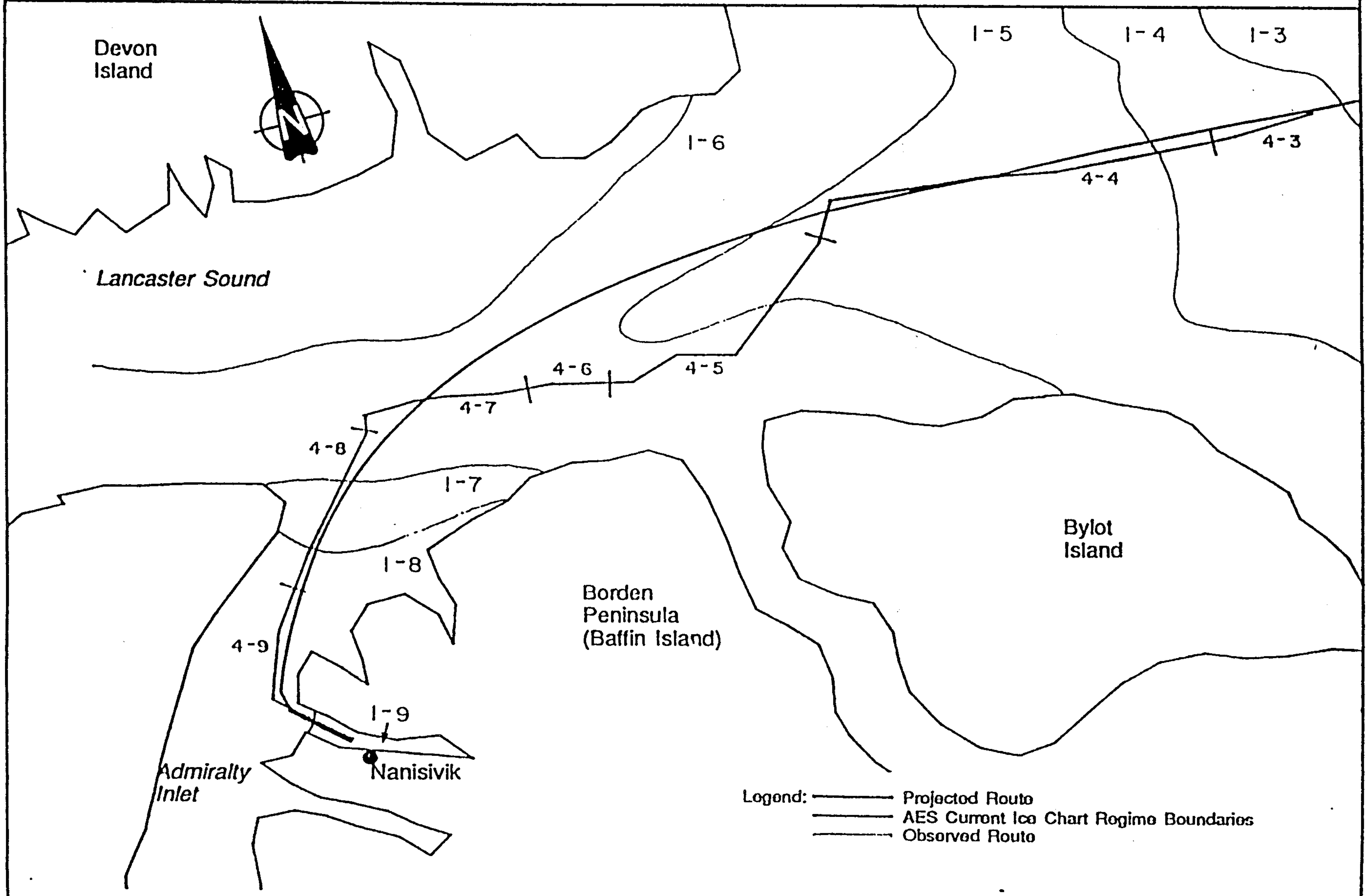


Figure 2-8 (continued...) Inbound Transit: First Projection and Observed Routes
Lancaster Sound and Admiralty Inlet
November 11-12, 1988



2.4.4 Voyage #4 - Voyage to Deception Bay

The M.V. Arctic voyage to Deception Bay was selected for model verification purposes as well as for the calibration of individual algorithms. The same voyage and data set reported in Section 2.3, Sample 4 and in Appendix A, Sample 4.

3. Validation of Ice Transit Algorithms

3.1 Background

The transit simulation model which is being validated here is presented in [7]. The main ship performance algorithms, beyond what is reported in [7] were developed and reported in [8,9].

The purpose of current project is to validate the algorithms used, based on full scale operational data over the years with M.V. Arctic in its numerous transits into the Arctic. This ship has been the most extensively evaluated Arctic vessel performing commercial transits into the Canadian Arctic.

The basis for validation of the ship performance calculation algorithms, which are used in the transit simulation model, is extensive observations of the ice covered and ocean environment, and the ship operation in that environment.

This type of validation will give added confidence to the user of the Arctic transit simulation model, and the correspondence between the individual algorithms used, and the actual transit performance of the ship.

The original ship performance calculation formulas have already taken into account all the full scale trials data of M.V. Arctic specifically in level ice and in manoeuvring in ice. Thus the remaining individual formulas which need validation are the following:

- circumnavigation distance in partial ice cover
- penetration of various categories of ice in a mixed ice regime
- ramming performance
- limiting performance, getting stuck
- performance in ice pressure (if suitable data available)
- speed loss in waves

The skill of the ship's Master can have a significant impact on the performance of an icebreaker, especially when the vessel is operating near the limit of its capabilities. Throughout the study, we have assumed that the Master circumnavigated the most severe ice whenever possible and displayed a typical level of skill in handling the vessel when ramming.

3.2 Approach Used

3.2.1 Interpretation of Recorded Ice Conditions Data

The comparison of a transit model with actual ship performance can be done in two distinct ways:

- Taking the environmental general data from the transit area and converting to a transit ice and environmental profile, along the ship route actually taken.

- Taking the specific ice data and performance of the ship in a real transit. This ice data is now specifically the data of ice that the ship penetrated.

Any mixing of general environmental data and the specific ice profile that the ship transited, will cause difficulty in performing a specific validation between the transit model and the simulation model. Unfortunately, the distinction between average ice conditions and the ice actually penetrated has not be maintained during the data collection.

The end user of the transit model would typically input environmental data which is applicable to the geographic region and intended route (not input specific ice profiles which the ship transited). One of the most complex parts of the transit model is the transformation from the general ice conditions for a zone to the specific ice conditions penetrated by a vessel. This transformation is described as “circumnavigation” in this report.

When a ship navigates for the purpose of transit it would typically try to avoid ice as much as possible and find the easier ice conditions, which it penetrates. This leads to the ship actually “seeing” an easier subset of ice conditions than the general ones are. In the case of the M.V. Arctic the ice sensing systems, and associated navigation techniques to intelligently avoid ice and find thinner ice conditions to penetrate represent the latest development in ice navigation. It can be stated that a validation of a transit model against M.V. Arctic data represents a reasonable expectation of a future ship transit, which assumes use of intelligent navigation around ice and through thinnest ice.

The documentation of ice conditions for the M.V. Arctic transits is mainly at a visual observation level during ship transit. The data that was collected on board the vessel is the sole source which can be used within current validation scope. It can be assumed that the overall ice conditions in the general region could have been more severe than the subset of data which was reported during M.V. Arctic transits.

The documentation of ship transit through a variety of ice conditions, is a very demanding and complicated task. Documenting general ship progress, and use of power, as well as documenting the navigation route are standard practices, and can be done without too many complications. The complication however is, in how the ice data, and to a degree the other environmental data is documented during the transit. As observing on a continuous basis what the ship penetrates is a labour intensive effort, and is not standardized for the purpose of transit analysis, the data collection does not address systematically all of the important parameters, which considerably influence the transit performance. It is not useful to document just the general ice conditions, which are already known as input data for the navigation purposes. Ideally, for a transit model evaluation, accurate documentation of the exact ice conditions which the ship penetrated would be required. This includes parameters such as amounts of various types of ice penetrated, the proportion of the transit which the ship used leads, closeness of free ice edge, which gives a considerable reduction of ice resistance, as well as count of ridges penetrated, their sizes, extent of background rubble penetrated, etc. Operational documentation of the number of rams and their effectiveness would also be an integral part of transit documentation for validation of ship transit performance.

When looking at the data that has been collected on board M.V. Arctic during ship transits, it is clear that there has not been a specifically identified intent of documenting the data for current type of transit model and its algorithm evaluation. The data reported lacks much details and some key parameters, in those areas where the influence of such parameter would have been major, in terms of transit performance. An example of this is the actual number and thickness of ridges and rubble penetrated. The other parameter is the relief in ice resistance through breaking the edges of ice floes only. This is expected to take place much of the time in ice coverage of 9+ tenths and less. The data displayed a large scatter when evaluated internally, due to the lack of detailed documentation of these key parameters.

The current validation process does not have another general environmental data set in the region of transit as input. Developing such a data set on the basis of AES ice charts, and other input information available to M.V. Arctic operators, would be a major task which could not be considered within the scope of the project.

It was assumed in the validation that the data documented on the ship represented the general ice conditions in the region of transit. The assumption was conservative, as the general overall ice data has been more difficult than the ice data assumed here. The ice that the ship navigates is expected to be an easier subset of the general ice data condition, due to circumnavigation of more severe ice conditions.

3.2.2 Data Completeness and Consistency

The current validation represents a comparison between the ice conditions as documented from the ship during transit against the calculated ship speed. Representativeness of ice conditions of the whole ice regime in the navigation region still needs to be addressed.

The task of validation of a mathematical algorithm based simulation model, using data that is considerably older than the mathematical models, and which has not specifically been collected for the purpose of such validation turned out to be a challenging task. Early inspection of the M.V. Arctic transit data suggested that the specifics of the data were not sufficient to provide a detailed validation of all algorithms.

The level of validation which was adopted was determined by the input data itself. The main objective was to match the transit model calculated transit times with those which the ship actually experienced. The scatter and inaccuracy within the data determined the level of accuracy in this type of validation. While it was recognized that the M.V. Arctic transit data represented good quality documentation, the interpretation of the data for transit modelling was beyond the scope of application intended for the data when it was collected. This limitation resulted in many gaps in the data for transit modelling.

The validation of individual algorithms was essential in assessing which algorithms might be best modified to adapt the simulation to the way that actual transit is performed. This was done in by isolating data which showed the specific influence an algorithm expressed. The process was repeated in order to achieve the greatest degree of accuracy and completeness

3.2.3 Validation of Individual Algorithms

Without the validation of individual algorithms, an overall validation does not indicate the source of any differences between an actual transit and a simulated one. An overall validation would only show the actual overall progress differences between the ship and the simulation through the same environment.

An individual algorithm-based comparison is required in order to make a rational assessment of similarities and differences between actual transit operations and the simulated ones. Thus when there is a clear difference between actual transit speed and the simulated one, it is possible to evaluate the reasons. The reasons would typically fall into three categories:

- inaccuracy or incompleteness of the actual transit data (environment, operational performance, actual ice penetrated, etc.)
- inaccuracy of the algorithms
- inconsistency in the logic followed by the transit simulation

Assessment of the cause of an unacceptably large difference between the actual transit and simulated transit is of key importance in identifying and modifying the component which caused the inaccuracy.

This report addresses the interpretation of and required complementary parameter inclusion for actual transit data.

The report also compares individual algorithms and actual ship transits, isolating when possible, the influence of each algorithm and making direct comparisons.

3.3 Interpretation and Evaluation of M.V. Arctic Transit Data

3.3.1 M.V. Arctic Specifications

Input data to the simulation model for the M.V. Arctic are summarized in the following table.

Table 3-1 Model Input Data for M.V. Arctic

Parameter	Value	Units	Comments
Displacement	38,000	tonnes	
Length	211.9	m	Length at the water line.
Beam	22.9	m	Beam extreme, from Table 2-2.
Draft	11.0	m	
Installed Power	11.0	MWatts	14,770 BHP from Table 2-2.
% Max Continuous Power	96%		10.6 MWatts max. continuous power used in trials (from Figure2-2).
Propeller Type	nozzle		
Hull Type	older icebreaking form		This choice for hull-type affects only the wave resistance.
Hull Shape	rounded		A chimed hull is not used.
Buttock Angle	20.5	degrees	
Flare Angle	54.8	degrees	
Lubrication Coefficient	0.0		Hull lubrication, although installed, was assumed to be unused.
Hull Coating Coefficient	1.0		Inerta coated hull.

3.3.2 M.V. Arctic Trials Data

The M.V. Arctic trials data was used extensively during the original development [7,8] of the following algorithms:

- level ice resistance
- open water resistance
- thrust
- turning in ice
- ridge resistance
- channel resistance

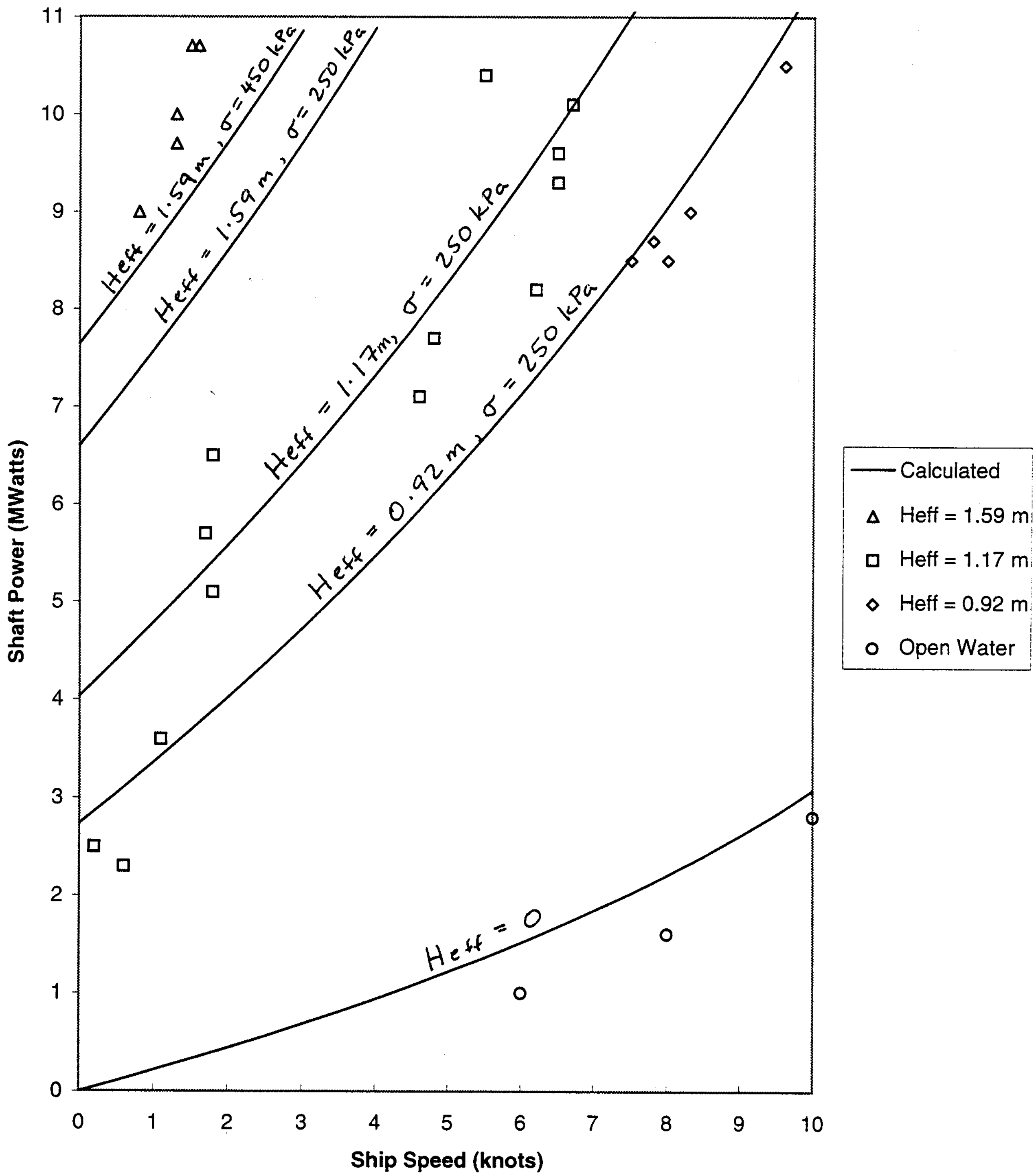
The performance calculation algorithms in level ice and open water were compared to the trials data (from Figure 2-2) in Figure 3-1. The algorithms were in good agreement with the trials data, within less than about 1.5 kn. This agreement was within the scatter in the trials data; therefore, no further calibration is required for these two algorithms.

The M.V. Arctic transit data was specifically extracted from a vast data base of recorded transit operations with that ship, during over ten years of operations, from a variety of specifically extracted data samples and reports from the operations of M.V. Arctic, which can be found in the Appendices.

The data collected was considered extensive and unique. It was collected mainly for the purposes of operational and ice regime system evaluation for Arctic regulations. There was no expressed original intent of collecting the data for the purpose of validating a transit simulation model, for which it is being currently applied.

It is important to recognize that the algorithms that are used for transit performance calculation had been developed based on a considerable amount of full scale ships trials data, where accurate ship performance in at least level ice is measured and documented. In particular, M.V. Arctic trials data in open water and in level ice, as well as ramming and turning had been used to the develop the open water, level ice, and ramming performance algorithms. Given this historical development of the algorithms, one would expect that the present transit data would be in rough agreement with the trials data, and hence would be in agreement with the level ice algorithm. Comparisons of this kind were used to determine the internal consistency of the recorded ice conditions and ship speeds.

Figure 3-1
Level Ice and Open Water Trials



3.3.3 Data Consistency

The purpose of this section is to set the scope of expectation for the evaluation inspecting the internal accuracy of the M.V. Arctic transit data.

The first assessment is that of scatter within the data. This is represented by comparing individual data points one on one, where the ice conditions or performance were similar, and comparing the compatibility of various pieces of data.

Table 3-2 shows some selected couples of data, where large scatter is found between nominally identical conditions or performance. The following examples can be seen in this comparison:

- Sample 1z versus 1ag. In apparently very similar conditions, in 1.6 m thick ice the ship moves in sample 1ag only $1/7^{th}$ of the speed of that in sample 1z. This is despite 20 percent higher power in sample 1ag. Both samples had a short pressure event.

- Sample 1p versus 4-15. The ship moved in identical level ice thickness and coverage in seemingly identical conditions, except for low pressure lasting part of the time in 4-15, only $1/20^{th}$ of the speed in sample 4-15 in comparison to 1p. The power used in 4-15 was also over 30 percent higher than in 1p. This comparison, together with the earlier ones, illustrates that the uncertainty of the data makes it difficult to judge for example of influence of ice pressure. In this case the superficially visible difference is the pressure, but the real influence of pressure cannot be assessed due to the uncertainty in the data.

- Sample 1r versus 1s the ship moved in 2.6 m thick ice nearly as fast as in 0.9 m thick ice, with more ridges and otherwise nearly identical conditions. According to calculations, in sample 1r the ship should have moved less than $1/10^{th}$ of reported speed in conditions as they were documented.

- Sample 1w versus 1ac. In 1ac, in 1.6 m thick ice with 7 ridges per nautical mile and background rubble of 1.27 m, and part time pressure, the ship moves more than 5 times faster than in sample 1w with same ice thickness with 6 ridges per nautical mile and no background rubble, and no pressure. The power is close to 20 percent higher in the latter, but according to modal application of any kind the ship should have been faster in sample 1w.

- Sample 2b versus 2i. Here the ship moved four times faster in sample 2b which had identical ice thickness with 2i, and over 20 percent lower power, as well as pressure and 4.8 ridges (2b) against 1 ridges per nautical mile (2i). In 2b there was also pressure present, whereas none was there in 2i.

Table3-2 MV Arctic Internal Scatter

Sample 1: 3-20 May 1989, Sample 2: 31 May - 1 July 1987, Sample 4: 3-18 March 1991

	95% Coverage									100% Coverage				
Data Segment	1z	1ag		1p	4-15		1r	1s		1w	1ac		2b	2i
Speed (knots)	2.75	0.37		6.25	0.35		1.38	1.82		0.15	0.86		0.23	0.06
Power (kilowatts)	7727	9500		6917	9406		9199	9956		8000	9500		7042	9085
Ice Concentrations														
H1 (m)	0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00
%H1	0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00
H2 (m)	1.60	1.60		0.91	0.90		2.60	0.90		1.60	1.60		1.20	1.20
%H2	0.89	0.89		1.00	1.00		1.00	0.89		1.00	1.00		1.00	1.00
H3 (m)	0.15	0.30		0.00	0.00		0.00	0.15		0.00	0.00		0.00	0.00
%H3	0.11	0.11		0.00	0.00		0.00	0.11		0.00	0.00		0.00	0.00
Ridging (/nm)	3.00	1.00		4.00	0.00		5.00	4.00		6.00	7.00		4.80	1.00
Background Rubble														
deltaH1 (m)	0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00
deltaH2 (m)	1.10	1.10		1.11	1.12		0.00	0.00		0.00	1.27		1.20	0.00
deltaH3 (m)	0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00
Rubble Fields														
Frequency	0.00	0.00		0.00	0.30		0.00	0.00		0.00	0.00		0.00	0.00
Duration (hours)	0.00	0.00		0.00	2.50		0.00	0.00		0.00	0.00		0.00	0.00
Leads														
Frequency	0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00
Duration (hours)	0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00
Pressure														
Frequency P1	1.00	0.00		0.00	1.00		0.00	0.00		0.00	1.00		0.00	0.00
Duration P1 (hours)	0.20	0.00		0.00	6.00		0.00	0.00		0.00	0.20		0.00	0.00
Frequency P2	0.00	1.00		0.00	0.00		0.00	0.00		0.00	0.00		1.00	0.00
Duration P2 (hours)	0.00	0.10		0.00	0.00		0.00	0.00		0.00	0.00		1.00	0.00
Tot. Duration of Event (hours)	2.00	3.00		11.00	12.58		13.00	16.00		22.00	5.00		13.00	17.00
Snow (cm)	10.00	8.00		8.00	15.00		8.00	8.00		11.00	14.00		0.00	0.00

The following is a summary of the samples of the M.V. Arctic for internal scatter comparison:

Ship transit data which is collected visually and not for the specific purpose of validation of transit algorithms, tends to be approximate and direction giving in nature. There is a considerable scatter in ship performance data even when such performance is measured as accurately as possible within the scientific means for performing ship trials. The added uncertainty about the accuracy of the data and its representativeness of the actual conditions penetrated is not known. However, through review of the internal scatter of the data it can be assessed that visually observed data has resulted in a large amount of scatter.

The level of detail in observed transit data is not sufficient to make a detailed assessment and evaluation of transit model algorithms. The best use of data is achieved by selective comparison with overall performance, as well as for specifically extracted data against calculated data, evaluating one algorithm at a time. As it is not possible to be certain of the accuracy of individual data points, in terms of completeness and accurate representation of the penetrated ice profile, an overall average comparison, accepting a very large scatter is the most logical and best level of comparison.

3.4 Validation of Individual Algorithms

3.4.1 General Comparison of Actual and Calculated Speed

Appendix C shows the development of analysis and comparison of the M.V. Arctic transit data against the Arctic transit model algorithms calculated performance. The sample of transit which is used for this comparison is based on a wide representation. Sample 12 of M.V. Arctic data includes a full range of both open water and ice conditions, where the ship has transited solid thin and thick ice, circumnavigated ice, proceeding in a continuous as well as ramming mode of operation.

Figure C-1 shows the comparison between the calculated transit speed and the actual transit speed for each of the legs of the transit sample. The spreadsheet for this calculation is in Appendix C. In Figure C-1 the transit speed is plotted, showing actual transit speed on the x-axis and the calculated ship speed on the y-axis.

It can be seen that there is a very large scatter embedded into the comparison from point to point. This behaviour was expected based on the internal M.V. Arctic data evaluation. There is not enough accuracy and not all key parameters are recorded for the transit, to make an accurate validation feasible. However, it is possible to see in Figure C-1 that the average speed that the ship actually had and the calculated speed correlate fairly well. The calculated speed is on average somewhat lower than the actual speed. Especially in the presence of background rubble it appears that the ship outperforms the mathematical calculated speed. This is assessed to be likely due to the ability of the ship to avoid penetration of a significant portion of the background rubble. The model assumes penetration of background rubble in direct proportion to the area covered by background rubble. There also could be the possibility of reducing the severity of the background rubble input data. It is possible that the rubble data recorded may have been more severe than the actual background rubble. The performance equivalency of rubble in comparison to level ice is also potentially conservative. However, there is not accurate enough data to support any specific conclusion in this respect, or to justify a modification to currently used algorithms.

Transit calculation algorithms did not take into account ice floes seize, in ice covers less than 100 percent. In real life, an icebreaking vessel will seek the leads in such coverage, as well as break mainly only the edges of ice floes, when penetrating ice from the lead. Thus an additional coefficient is introduced into the algorithms for transit speed calculation, which give a well justified relief for the ship resistance in high ice concentrations below 100 percent. A coefficient of 0.8 was found by trial and error to give the best agreement with the data.

It is recommended that current approach and algorithms be used as they are, including the above coefficient of 0.8 for effective ice thickness in 9+ tenths of ice cover or less.

It is also recommended that the background rubble penetration used in current approach may be conservative. However, current validation does not suggest a specific coefficient for reduction of such rubble, or circumnavigation of the background rubble.

3.4.2 Distance of Circumnavigation

The M.V. Arctic data contained four specific examples of circumnavigation, which each were selected, interpreted and documented by ENFOTEC. The analysis and comparison of the circumnavigation distance is shown in Appendix B.

The circumnavigation algorithm contained two parts in the transit simulation model:

- Added distance of transit due to circumnavigation.
- Proportions of various types of ice penetrated when circumnavigating.

The circumnavigation distance algorithm is compared against M.V. Arctic data in Table 3-3.

Table 3-3 Circumnavigation Factor

Data Source	Ice Coverage	**Circumnavigation Factor**	
		M.V. Arctic Data	Transit Model
Sample 11	0.65	1.33	1.33
Sample 7	0.90	1.20	1.18
Sample 8	0.95	1.09	1.14
Sample 10	0.96	1.14	1.13

In Figure 3-2, the distance of transit is plotted against ice coverage. The distance is expressed in proportion to the short route distance, which would be achievable without any circumnavigation. Actual distance transited relative to the short distance is shown in Figure 3-2.

It can be seen that the algorithm used in the transit simulation repeats the actual circumnavigation distance with remarkable accuracy. It is important to note that in real life there should be a dependency between circumnavigation distance on the geographic regions, the ice regime penetrated, and the scale of presentation.

The data which is reported on transit of ship does not contain information of the actual ice conditions penetrated in such a fashion that it could be meaningfully used for validation. The best validation for this is made through overall comparison between the simulated and actual speed. This gives the practical match between the transit data and the simulation model.

The algorithm used for circumnavigation, is recommended to be used for a general application.

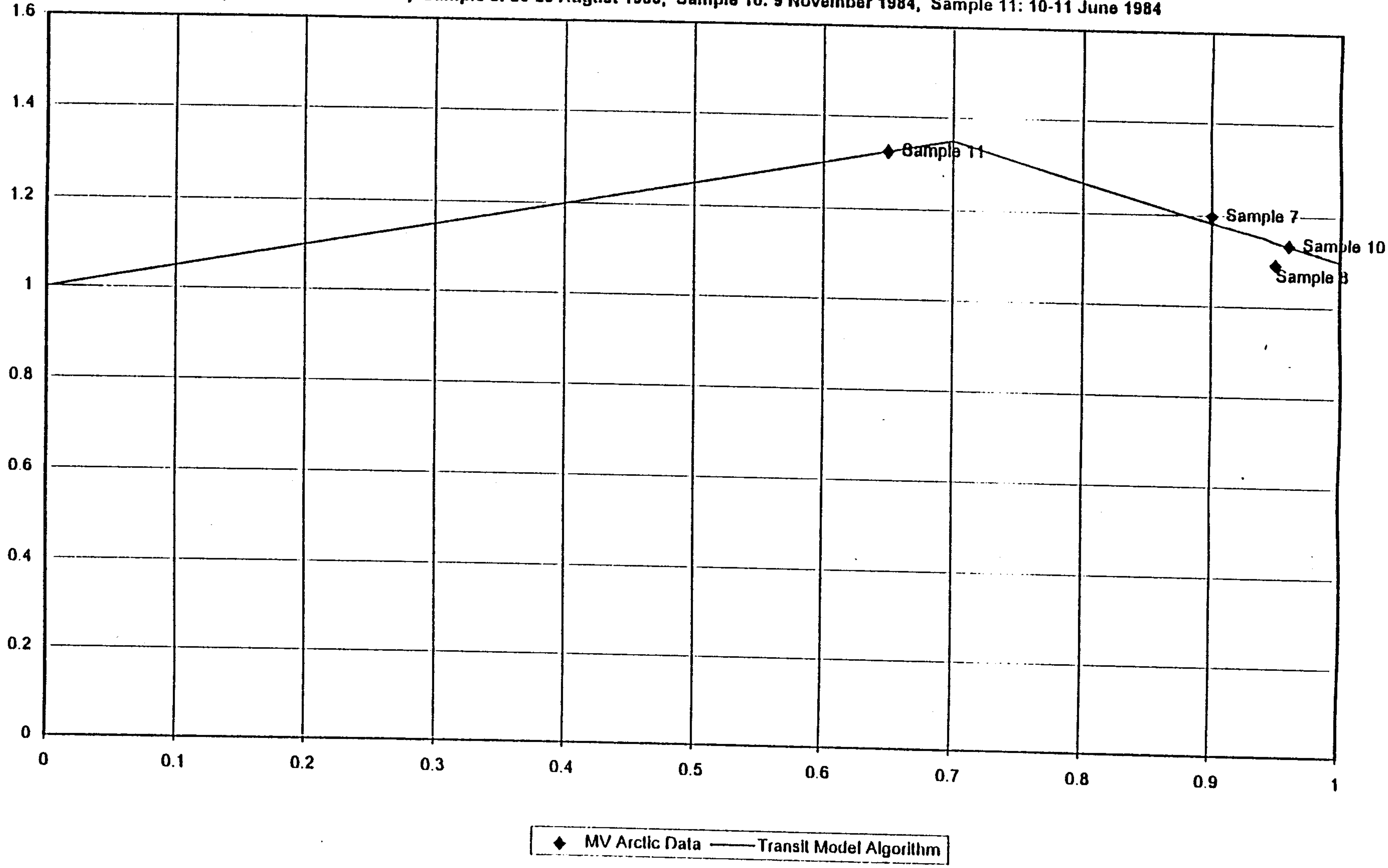
3.4.3 Maximum Speed during Circumnavigation

The M.V. Arctic uses a maximum speed of 8 kn when circumnavigating thick ice or when using a lead. This is an approximate speed as general input from operator. The limiting speed is a user input in the simulation. A maximum speed of 8 kn in high ice concentrations has been used throughout in current validation.

It is recommended that a speed limit be used in the presence of thick ice. This limit should be established for each ship, as the reasons for lower speed for smaller ships may be related to ship motions, whereas for larger vessels it is likely to be limited by the strength of the vessel, which may not be sufficient for unlimited operational speeds. It should also be noted that there are vessels which are strong enough to be operated at unlimited speed in the presence of multi-year ice. An example is the Russian nuclear icebreakers, which use high power and speed as the way to negotiate their way to the North Pole at the average speed well in excess of 10 kn.

Figure 3-2 - MV Arctic Circumnavigation Comparisons

Sample 7: 30 October 1986, Sample 8: 26-29 August 1986, Sample 10: 9 November 1984, Sample 11: 10-11 June 1984



3.4.4 Limiting Performance

Appendix D reports the limiting performance analysis. Figure D-4 shows a comparison between calculated ship performance and the actual performance when the ship has been mainly ramming. Inaccuracy in the data and scatter made this comparison complicated. It seems that the documentation of ridges and rubble with reasonable accuracy using visual techniques, and the lack of any existing standard of documenting them, makes it challenging to make a reasonable assessment of the transit model algorithms. However, there was one clear case of ramming in level ice which could be considered more accurate than most of the rest of the data. This data point agrees with the calculated performance of M.V. Arctic, using the formula presented in [7].

It is recommended that the algorithm in [7] be used for determination of performance limit in thick ice beyond the thickness where the ship performance is below 1 m/s.

3.4.5 Loss of Speed in Waves

Appendix E summarizes the data in open water and waves. Figure E-5 shows the calculated speed versus power, the actual ship speed at each power level where speed had been recorded during the transit.

The waves were relatively small, and thus it can be concluded from this comparison that scatter of observed operational data likely overshadows the actual comparison more than anything else.

It is recommended that the algorithm in [7] be used for the transit calculation.

3.5 Summary

Development of the level ice and ridged ice resistance, open water resistance and thrust calculation algorithms are based, amongst over 20 other vessels, on all M.V. Arctic trials data, and are in good agreement with it, within less than 10 percent. Thus the validation which follows deals purely with the operational performance aspects, and the overall performance in transiting mixed ice regimes.

The validation performed was based on incomplete and inaccurate data sets, which were not collected for the purpose of transit model validation. The overall purpose of the transit validation has taken place on a respective global scale, on which it is possible to ensure that overall transit performance of the M.V. Arctic is assessed against the transit simulation algorithms.

The specific results from this validation which give valuable input into transit simulation model and performance calculation algorithm development, are:

- Overall comparison between transit of ship and transit simulation algorithm based estimates are in good agreement. The area where least agreement is found is in thick ice where ramming occurs. This is considered likely to be due to insufficient and inaccurate documentation of the actual transit of the vessel through such thick ice conditions.

- Circumnavigation distance is in good agreement with the recorded data.

- Reduction of ice coverage from 10/10ths to 9+ /10ths generally improves the performance more than the original performance calculation algorithms suggested. This performance improvement is thought to be caused by the fact that the ship effectively breaks edges of ice floes with a free ice edge effect, in the process of circumnavigation. This results a lowered ice resistance. This was matched by introducing a coefficient for effective ice thickness in the presence of total ice coverage less than 10/10ths, of 0.8.

- The ship circumnavigation of thick rubble and the thickness of rubble appear to considerably influence the performance of the ship, and cause considerable scatter within the M.V. Arctic data and in the comparisons between data and the algorithms. They need to be more accurately documented, in order to establish a consistent interpretation of the transit ice conditions and circumnavigation of rubble.

- Occasionally the M.V. Arctic appeared to penetrate thicker ice than the indicated ice conditions would suggest. Possibility of thick ice avoidance is not a standard and same every time. This causes considerable scatter and uncertainty in detailed evaluation of ship performance algorithms. This is expected to be due to local ice concentrations, which may be higher than the average ice conditions indicated in the transit logs.

- Further improvements of algorithms/transit model requires specific data collection. This requires definitions of new parameters of ice and ship navigation beyond any existing standards recordings. The historical data lacks some of the parameters and the accuracy required for more accurate validation.

- The most important additional information required from ship voyages is:

    - the actual ice conditions that the ship penetrates, and
    - the regional ice and environmental data for same region.

    These ice conditions are different because the ship's captain will circumnavigate the worst regions of ice.

4. Simulation Model Verification

4.1 Interpretation of Voyage Input Data

Three voyages of the M.V. Arctic were used to validate the modelled ship performance to historical data. The voyages are labeled Sample #1, Sample #3, and Sample #4 and are described in Section 2.4. Sample #2 was not used for validation because the data for this voyage involved a number of long delays for engine maintenance which could not be isolated sufficiently from the transit data to make the validation meaningful.

Each voyage was divided into a number of geographical zones for input to the model with each zone representing one or more data records. For the purposes of the simulation model, the ice conditions within a zone are assumed to be uniform. Therefore, zones were chosen for the M.V. Arctic voyages so that the variations in recorded conditions within a zone were minimized. The observed variations recorded along the route within a zone were assumed to be random fluctuations about the average conditions. These fluctuations are taken into account by the percentage of ice coverage and by the distribution of ice thicknesses.

Assumed in the process of dividing the ship's route into zones is that the variation in the ice conditions along the route was caused primarily by changes in the ship's position rather than by a change in ice conditions with time. With the exception of leads and pressure, the ice conditions within each zone were assumed to be constant for the duration of the test run. Leads and of pressure events within a zone were modelled as periodic processes with a calculated average duration and average time between events.

The process of averaging the ice conditions within a zone required some care to ensure that the average values were physically meaningful. For example, average ice thickness was calculated as a weighted average using (distance travelled) * (ice coverage) as the weight. The following scheme was used to perform the weighted averages:

Ice Conditions Parameter	Weight used to Calculate Average
Ice thickness	(distance travelled)*(ice coverage)
Ice coverage	(distance travelled)
Ridge frequency	(distance travelled)
Ridge height	(distance travelled)*(ridge frequency)
Background rubble	(distance travelled)
Frequency of leads, pressure	(elapsed time)
Duration of leads, pressure	(elapsed time)*(frequency)
Fraction of route in leads	(distance travelled)
Ice temperature	(distance travelled)

4.2 Improvements to the Marine Transit Model

The Arctic Marine Transit Model required a number of improvements in order to work with historical ice conditions as opposed to theoretical values. Although these improvements are not strictly part of the validation assignment, their need was first recognized as a result of this work. Subsequent transportation projects using the simulation model have benefited from these improvements.

Improvements were made to the following aspects of the model:

Ice Thickness Distribution

In the original version of the model, the ice coverage in a zone was divided into thick ice, medium ice, and thin ice. “Thick ice” was taken as the thickest 20 percent of the ice converge, “medium ice” was taken as the next 60 percent thickest ice, and “thin ice” was taken as the thinnest 20 percent. A representative thickness was then chosen for each ice thickness band. With measured ice data, it was impossible to work within this idealized framework. The concept of an ice thickness distribution represented by thick, medium and thin ice was retained; however, the percentage coverage for each thickness was made part of the ice input data for each zone.

Circumnavigation in Thin Ice

Circumnavigation is useful only when the ice is thick enough that the ship is slowed significantly. A shortcoming of the original model that quickly became apparent when analyzing the M.V. Arctic data was that the modelled ship was being slowed by circumnavigation around thin ice that could easily break at its cruising speed. The model was modified so that circumnavigation is performed only when it increases the ship’s average speed along its intended route.

Avoidance of Thick Ice

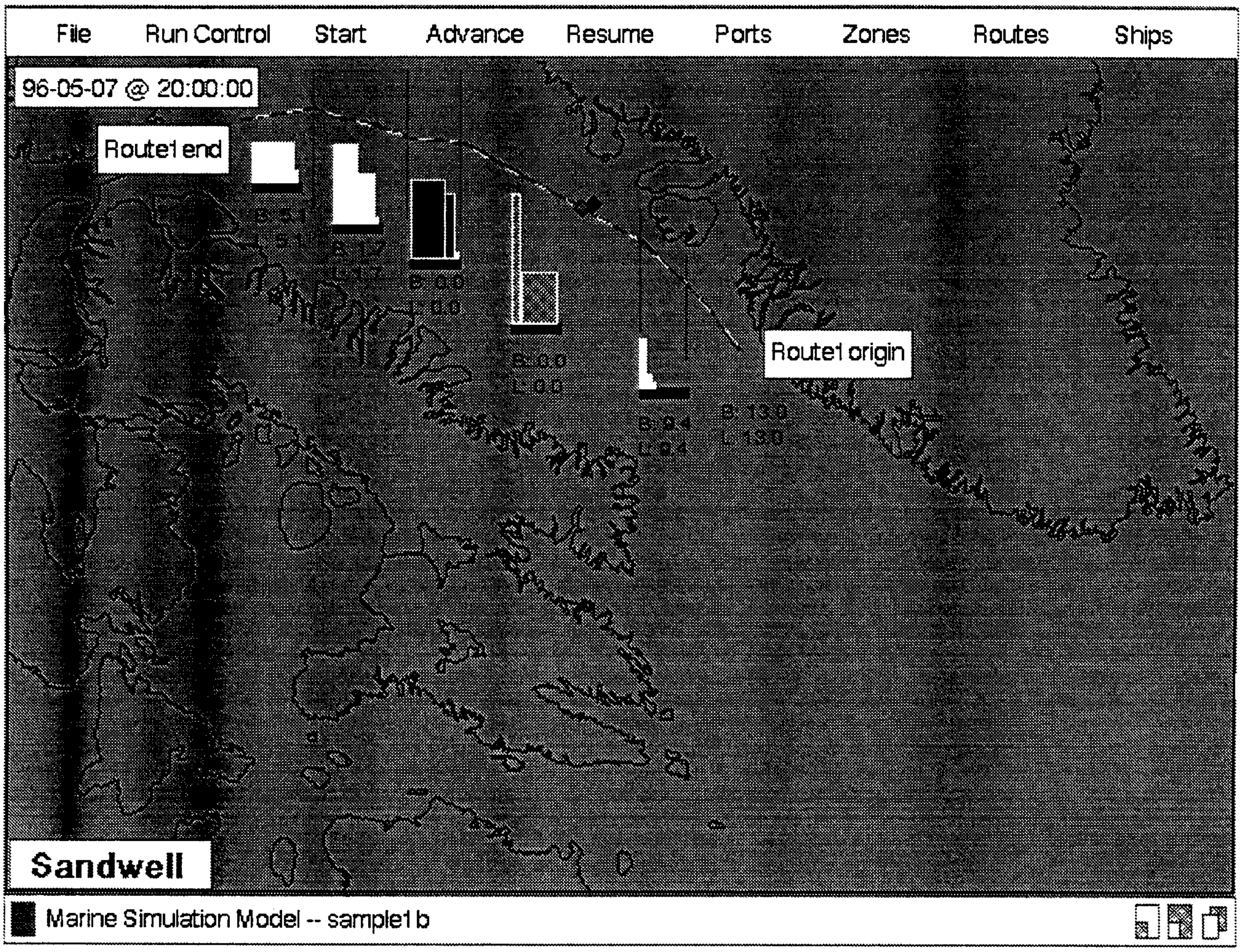
In the original version of the model, the vessel was assumed to penetrate ice in each of the three ice thickness bands in proportion to their individual coverages. This assumption was acceptable as long as the ship was able to maintain a reasonable speed in the thickest ice. In a number of the M.V. Arctic’s voyages, ice is encountered that is much thicker than 1.6 m, its maximum thickness for continuous ice-breaking. However, the thick ice covered only a relatively small fraction of the zone and could be avoided easily by circumnavigation. However, the modelled ship was stopped altogether because it tried to penetrate the thick ice. To correct this problem, the simulation model was modified so that circumnavigation was attempted separately around the ice in each thickness band. This feature allows the modelled ship to select the optimum route through the modelled ice field.

4.3 Simulation Model Results

4.3.1 Sample Voyage #1

The simulation model for Voyage #1 is shown in Figure 4-1.

Figure 4-1 Simulation Model for Voyage #1



The M.V. Arctic's route is shown as a dashed line on the computer screen starting at the icon labeled "Route 1 origin" and ending at the icon labeled "Route 1 end". The position of the M.V. Arctic at any time during the simulation run is shown by the small diamond-shaped object. The green diamond represents the position of the actual ship based on the vessel records, while the red diamond represents the position of the modelled ship. The map which forms the model's background shows the southern end of Greenland and the Baffin Island region. The same background map was used for each voyage.

Simulated time is shown digitally in the upper left-hand corner of the display using the notation year-month-day @ hour; minute; second. For modelling convenience, the year for the voyage was displayed as 1996 whereas the actual voyage was in 1989. The displayed month, day, and hour are shown correctly for the historical data.

The route for this voyage was divided into six geographical zones based on the actual ice conditions encountered during the voyage. The zone boundaries along the route are indicated by the short lines across the route.

The small bar gauge-like icons near each zone show the ice thickness and percentage coverage for each of the three modelled ice thickness classes for the zone. The bar's height represents the ice thickness, while the bar's width shows the fraction of coverage for each ice thickness. A shaded bar indicates that the zone is experiencing an ice pressure event. Solid red indicates high ice pressure, while a shaded red indicates medium ice pressure. Solid red and shaded red are shown as dark grey and hatched light grey respectively in the black-and-white image in Figure 4-1.

The numbers labeled "B" and "L" along the route are used to display the modelled ship's speed in kn for the ice conditions in each zone. The labels "B" and "L" are used to distinguish between loaded and ballasted speed, which are the same for the calibration exercise.

Simulation Results

The historical ice conditions data within each zone and the average values for the zones are shown in Table 4-1. The ice conditions input data for the simulation model are shown in Table 4-2. Some of the ice transit model calculations are shown in Table 4-3. The simulated progress of the modelled ship through the ice is compared to the actual ship in Figure 4-2 and in Table 4-4.

The simulation model results are compared to the recorded values on a zone-by-zone basis in the following paragraphs. In this discussion the concept of "effective ice thickness" is used to describe the recorded ice conditions. This quantity is model dependent, but is nevertheless a valuable way to compare the ice conditions in one zone to another. Effective ice thickness is defined by the equation:

Effective Ice Thickness = (level ice thickness) + (effective thickness of background rubble and snow)
+ (effective thickness of ridges)

See the User Manual for the simulation model for a complete description of the terms in this equation.

Zone 1. Zone 1 has no ice coverage so the ship's speed is determined by the captain's choice of safe cruising speed rather than by the ship's capability. The M.V. Arctic's economical cruising speed is specified as 13.0 kn in Table 2-2 so this was entered as an input to the simulation model. The recorded average speed for the zone was 11.1 kn.

Zone 2. The ice coverage for this zone is 31 percent. At this coverage, all the ice can be avoided by circumnavigation. The ship's average speed along it course is reduced from its cruising speed in ice by additional distance travelled due to circumnavigation. The modelled cruising speed in ice of 10 kn was reduced by circumnavigation to an average of 9.5 kn along the route, in reasonable agreement with the recorded average speed of 8.5 kn.

Zone 3. This zone had 94 percent ice coverage which is high enough that ice must be penetrated ice for nearly the entire route through the zone. Of this coverage 20 percent was in 2.6 m ice while 77 percent was in 1.0 m ice. The modelled ship was able to avoid all of the 2.6 m ice by circumnavigating though the 1.0 m ice. The effective ice thickness in this zone is increased by approximately 0.8 m in the medium thickness ice by background rubble and snow. It is further increased by approximately 0.2 m by ridging, bringing the total effective thickness to 2.0 m in the medium thickness ice. In addition, there were medium pressure events for 25 percent of the time in this zone which increased the effective ice thickness by a factor of 1.35. Under these conditions the modelled ship is forced to spend much of its time ramming and can manage only 1.3 kn. This speed is in reasonable agreement with the recorded average speed of 2.8 kn for this zone.

Zone 4. In this zone the effective ice thickness for the thickest ice (72 percent coverage) was approximately 1.6 + 0.6 + 0.0 = 2.2 m and in the medium thickness ice (22 percent coverage) was approximately 1.3 + 0.6 + 0.0 = 1.9 m. Medium and high pressure events further increased the effective ice thickness for a total of 20 percent of the time in this zone. These conditions appeared to be similar to those for Zone 3 and resulted in the modelled ship travelling at the same speed as that zone, i.e., 1.3 kn. However, the historical data indicates that the M.V. Arctic became stuck part way through this zone, and was able to manage an average speed of 0.1 kn. Although the difference in these speeds is only 1.2 kn, the percentage difference is huge and results in very different transit times: 233 hours for the M.V. Arctic versus only 28 hours for the model. This mismatch is clearly visible in Figure 4-2.

Zone 5. In this zone the thickest ice (52 percent coverage) had an effective thickness of approximately 1.6 + 1.2 + 0.2 = 3.0 m while the medium thickness ice (41 percent coverage) had an effective thickness of approximately 1.0 + 0.9 + 0.0 = 1.9 m. Medium and high pressure events increased the effective ice thickness for 29 percent of the time in this zone. A lead opened up for 16 percent of the time in this zone. The thickest ice was avoided by circumnavigation, therefore the modelled ship spent most of its time penetrating the medium thickness ice at an average speed of 2.4 kn, in exact agreement with the recorded value.

Zone 6. The ice in this zone consisted almost entirely (91 percent coverage) of medium thickness ice whose effective thickness was approximately 0.8 + 0.8 + 0.0 = 1.6 m. The average speed in this ice was 3.0 kn. Because the remaining had negligible thickness, the effective total ice coverage was 91 percent * 92 percent = 84 percent. This allowed the ship to circumnavigate 57 percent of the ice, increasing its average speed to 5.1 kn. The recorded speed for the ship, however, was only 1.3 kn, much less than the modelled value.

Summary

The model agreed with the recorded ship speed for Sample #1 with a typical accuracy of +/- 1.5 kn in ice conditions. In most of the zones, this correlation was sufficient to predict reasonably accurate transit times. However, in ice whose effective thickness was greater than 1.9 m, the ship speed was less than the uncertainty in the model which resulted in highly inaccurate transit times.

Table 4-1 Sample #1 - Zone Averages

	Time				Time	Dist.	Level Ice Concentrations (%)							Level Ice Thickness			Ridging				Background Rubble (m)						Leads			Pressure				
							Total	% of total area			% of ice cover						Ridge frequency			Ridge	Thickness			Eqiv. Level Ice Thickness						Medium		High		
	Year	Mon.	Day	Time (h)	in Seg. (h)	in Seg. (nmi)	Cover	in H1	in H2	in H3	in H1	in H2	in H3	H1 (m)	H2 (m)	H3 (m)	N1 (/nmi)	N2 (/nmi)	N3 (/nmi)	Height (m)	H1 (m)	H2 (m)	H3 (m)	Del. H1 (m)	Del. H2 (m)	Del. H3 (m)	Freq.	F	Dur. (h)	Freq.	Dur. (h)	Freq.	Dur. (h)	Temp. (C)
Zone 1	89	5	3	18	5	112.5	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	1
	89	5	3	23	5	29.4	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-3
	89	5	4	4	8	115.6	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-4
	89	5	4	12	4	55.7	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-4
	89	5	4	16	7	68.2	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-5
	89	5	4	23	13	95.7	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-4
	89	5	5	12	3	24.2	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-5
					45	501.3	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0				0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-3
Zone 2	89	5	5	15	2	12.7	10%	10%	0%	0%	100%	0%	0%	0.90	0.00	0.00	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-2
	89	5	5	17	2	19.6	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-4
	89	5	5	19	1	6.9	10%	10%	0%	0%	100%	0%	0%	0.90	0.00	0.00	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-4
	89	5	5	20	2	15.0	20%	20%	0%	0%	100%	0%	0%	0.90	0.00	0.00	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-4
	89	5	5	22	2	25.4	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-4
	89	5	6	0	4	44.9	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-3
	89	5	6	4	5	52.8	20%	20%	0%	0%	100%	0%	0%	0.90	0.00	0.00	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.01	0.01	0.01	100%	100%	5.0	0%	0.0	0%	0.0	-3
	89	5	6	9	11	68.7	90%	25%	45%	20%	28%	50%	22%	1.10	0.30	0.15	5.0	0.0	0.0	7.0	1.0	0.5	0.0	0.90	0.34	0.02	0%	0%	0.0	0%	0.0	0%	0.0	-9
					29	246.0	31%	13%	13%	6%	42%	40%	18%	1.01	0.30	0.15	2.6	0.0	0.0	7.0				0.48	0.34	0.02	17%	100%	5.0	0%	0.0	0%	0.0	-4
Zone 3	89	5	6	20	16	76.0	95%	0%	95%	0%	0%	100%	0%	0.00	0.91	0.00	0.0	4.0	0.0	7.0	0.0	2.0	0.0	0.03	1.13	0.03	0%	0%	0.0	0%	0.0	0%	0.0	-9
	89	5	7	12	13	18.0	95%	0%	80%	15%	0%	84%	16%	0.00	1.40	0.10	0.0	4.0	0.0	7.0	0.0	0.0	0.0	0.03	0.03	0.03	0%	0%	0.0	100%	13.0	0%	0.0	-9
	89	5	8	1	16	29.1	95%	95%	0%	0%	100%	0%	0%	2.60	0.00	0.00	5.0	0.0	0.0	7.0	0.0	0.0	0.0	0.03	0.03	0.03	0%	0%	0.0	0%	0.0	0%	0.0	-5
	89	5	8	17	6	16.7	95%	0%	85%	10%	0%	89%	11%	0.00	0.90	0.15	0.0	4.0	0.0	7.0	0.0	0.0	0.0	0.03	0.03	0.03	0%	0%	0.0	0%	0.0	0%	0.0	-8
	89	5	8	23	2	8.8	80%	0%	80%	0%	0%	100%	0%	0.00	1.60	0.00	0.0	5.0	0.0	7.0	0.0	0.0	0.0	0.03	0.03	0.03	0%	0%	0.0	0%	0.0	0%	0.0	-11
					53	148.6	94%	19%	73%	3%	20%	77%	3%	2.60	1.02	0.12	5.0	4.1	0.0	7.0				0.03	0.77	0.03	0%	0%	0.0	25%	13.0	0%	0.0	-8
Zone 4	89	5	9	1	16	5.5	95%	95%	0%	0%	100%	0%	0%	1.60	0.00	0.00	4.0	0.0	0.0	7.0	0.0	0.0	0.0	0.03	0.03	0.03	0%	0%	0.0	0%	0.0	100%	16.0	-9
	89	5	9	17	22	3.3	95%	0%	85%	10%	0%	89%	11%	0.00	1.30	0.10	0.0	4.0	0.0	7.0	0.0	0.0	0.0	0.04	0.04	0.04	0%	0%	0.0	0%	0.0	100%	22.0	-11
	89	5	10	15	63	-6.6	100%	100%	0%	0%	100%	0%	0%	1.60	0.00	0.00	6.0	0.0	0.0	7.0	0.0	0.0	0.0	0.04	0.04	0.04	0%	0%	0.0	0%	0.0	0%	0.0	-11
	89	5	13	6	120	-2.2	95%	85%	0%	10%	89%	0%	11%	1.60	0.00	0.10	3.0	0.0	0.0	7.0	0.0	0.0	0.0	0.04	0.04	0.04	0%	0%	0.0	0%	0.0	0%	0.0	-10
	89	5	18	6	2	5.5	95%	0%	90%	5%	0%	95%	5%	0.00	1.30	0.10	0.0	0.0	0.0	7.0	0.0	0.7	0.0	0.03	0.91	0.03	10%	100%	0.2	0%	0.0	0%	0.0	-7
	89	5	18	8	10	14.2	95%	85%	0%	10%	89%	0%	11%	1.60	0.00	0.15	3.0	0.0	0.0	7.0	0.9	0.0	0.0	1.13	0.03	0.03	0%	0%	0.0	100%	10.0	0%	0.0	-12
					233	19.7	96%	69%	21%	6%	72%	22%	6%	1.60	1.30	0.13	4.0	1.4	0.0	7.0				0.55	0.59	0.03	0%	100%	0.2	4%	10.0	16%	38.0	-10
Zone 5	89	5	18	18	5	8.7	95%	0%	90%	5%	0%	95%	5%	0.00	1.17	0.10	0.0	3.0	0.0	7.0	0.0	0.9	0.0	0.05	0.93	0.05	0%	0%	0.0	0%	0.0	0%	0.0	-7
	89	5	18	23	5	4.3	95%	0%	85%	10%	0%	89%	11%	0.00	0.90	0.30	0.0	3.0	0.0	7.0	0.0	1.1	0.1	0.04	0.86	0.22	10%	100%	0.5	0%	0.0	0%	0.0	-10
	89	5	19	4	6	18.3	100%	100%	0%	0%	100%	0%	0%	1.60	0.00	0.00	7.0	0.0	0.0	7.0	1.4	0.0	0.0	1.31	0.05	0.05	0%	0%	0.0	100%	6.0	0%	0.0	-13
	89	5	19	10	4	17.1	90%	0%	80%	10%	0%	89%	11%	0.00	0.90	0.10	0.0	0.0	0.0	7.0	0.0	1.1	0.0	0.03	0.84	0.03	45%	100%	1.8	0%	0.0	0%	0.0	-9
	89	5	19	14	2	10.7	90%	80%	0%	10%	89%	0%	11%	1.60	0.00	0.10	2.0	0.0	0.0	7.0	0.9	0.0	0.0	1.13	0.03	0.03	100%	100%	2.0	0%	0.0	0%	0.0	-8
	89	5	19	16	3	1.1	90%	85%	0%	5%	94%	0%	6%	1.60	0.00	0.10	4.0	0.0	0.0	7.0	0.9	0.0	0.0	1.13	0.03	0.03	0%	0%	0.0	0%	0.0	0%	0.0	-8
	89	5	19	19	2	4.3	95%	85%	0%	10%	89%	0%	11%	1.60	0.00	0.30	1.0	0.0	0.0	7.0	0.9	0.0	0.1	1.13	0.03	0.21	0%	0%	0.0	0%	0.0	100%	2.0	-5
					27	64.5	94%	49%	39%	6%	52%	41%	7%	1.60	0.98	0.14	4.9	1.4	0.0	7.0				1.24	0.87	0.07	16%	100%	1.4	22%	6.0	7%	2.0	-9
Zone 6	89	5	19	21	8	14.7	90%	0%	80%	10%	0%	89%	11%	0.00	0.75	0.30	0.0	1.0	0.0	7.0	0.0	1.0	0.1	0.02	0.73	0.20	0%	0%	0.0	0%	0.0	0%	0.0	-2
	89	5	20	5	8	6.3	95%	0%	90%	5%	0%	95%	5%	0.00	0.90	0.10	0.0	1.0	0.0	7.0	0.0	1.2	0.0	0.03	0.88	0.03	0%	0%	0.0	0%	0.0	0%	0.0	-6
	89	5	20	13	0	0.0	95%	0%	90%	5%	0%	95%	5%	0.00	0.72	0.10	0.0	11.0	0.0	7.0	0.0	1.8	0.0	0.04	1.00	0.04	0%	0%	0.0	100%	0.2	0%	0.0	-3
					16	21.0	92%	0%	83%	9%	0%	91%	9%	0.00	0.80	0.26	0.0	1.0	0.0	7.0				0.00	0.77	0.17	0%	0%	0.0	0%	0.0	0%	0.0	-3

Table 4-2 Sample #1 - Zone Input Data

	Ice Concentration				Level Ice Thickness			Ridging				Background Rubble			Leads			Pressure				
	Total	fraction of ice cover						Ridge frequency			Ridge	Effective Level Ice Thickness						Medium		High		
	Cover	in H1	in H2	in H3	H1 (m)	H2 (m)	H3 (m)	N1 (/nmi)	N2 (/nmi)	N3 (/nmi)	Height (m)	Delta H1 (m)	Delta H2 (m)	Delta H3 (m)	Freq	F	Dur (h)	Freq.	Dur. (h)	Freq.	Dur. (h)	Temp. (deg C)
Zone 1	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-3
Zone 2	31%	42%	40%	18%	1.01	0.30	0.15	2.6	0.0	0.0	7.0	0.48	0.34	0.02	17%	100%	5.0	0%	0.0	0%	0.0	-4
Zone 3	94%	20%	77%	3%	2.60	1.02	0.12	5.0	4.1	0.0	7.0	0.03	0.77	0.03	0%	0%	0.0	25%	13.0	0%	0.0	-8
Zone 4	96%	72%	22%	6%	1.60	1.30	0.13	4.0	1.4	0.0	7.0	0.55	0.59	0.03	0%	100%	0.2	4%	10.0	16%	38.0	-10
Zone 5	94%	52%	41%	7%	1.60	0.98	0.14	4.9	1.4	0.0	7.0	1.24	0.87	0.07	16%	100%	1.4	22%	6.0	7%	2.0	-9
Zone 6	92%	0%	91%	9%	0.00	0.80	0.26	0.0	1.0	0.0	7.0	0.00	0.77	0.17	0%	0%	0.0	0%	0.0	0%	0.0	-3

Table 4-3 Sample #1 - Contributions to Modelled Vessel Speed

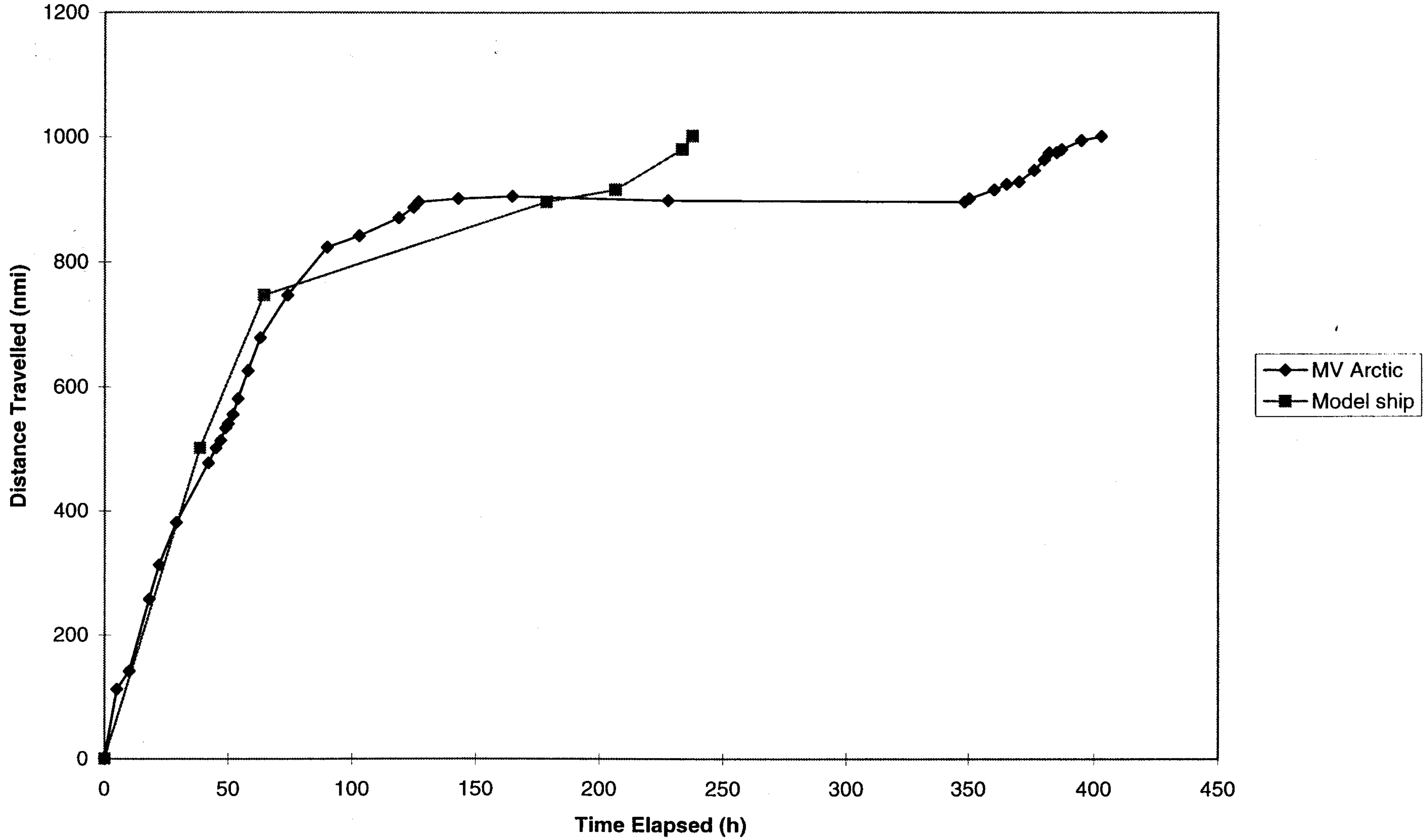
			Ice Thickness Band			
			H1	H2	H3	no ice
Zone 1	Effective Ice Thickness, Heff	(m)	na	na	na	0.00
	Percent of Zone Area	(%)	na	na	na	100%
	Percent of Distance Travelled	(%)	na	na	na	100%
	Vessel Speed	(kn)	na	na	na	13.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	13.0			
Zone 2	Effective Ice Thickness, Heff	(m)	1.58	0.64	0.17	0.00
	Percent of Zone Area	(%)	13%	13%	6%	22%
	Percent of Distance Travelled	(%)	0%	14%	6%	79%
	Vessel Speed	(kn)	3.0	10.0	10.0	10.0
	Circumnavigation Factor		1.066			
	Average Speed along Intended Route	(kn)	9.4			
Zone 3	Effective Ice Thickness, Heff	(m)	2.80	1.90	0.20	0.00
	Percent of Zone Area	(%)	19%	73%	3%	5%
	Percent of Distance Travelled	(%)	0%	71%	10%	20%
	Vessel Speed	(kn)	0.0	1.1	10.0	10.0
	Circumnavigation Factor		1.280			
	Average Speed along Intended Route	(kn)	1.7			
Zone 4	Effective Ice Thickness, Heff	(m)	2.30	2.00	0.20	0.00
	Percent of Zone Area	(%)	69%	21%	6%	4%
	Percent of Distance Travelled	(%)	0%	66%	20%	14%
	Vessel Speed	(kn)	0.2	1.0	10.0	10.0
	Circumnavigation Factor		1.590			
	Average Speed along Intended Route	(kn)	1.3			
Zone 5	Effective Ice Thickness, Heff	(m)	3.00	1.90	0.20	0.00
	Percent of Zone Area	(%)	49%	39%	6%	6%
	Percent of Distance Travelled	(%)	0%	59%	21%	19%
	Vessel Speed	(kn)	0.0	1.2	10.0	10.0
	Circumnavigation Factor		1.500			
	Average Speed along Intended Route	(kn)	1.7			
Zone 6	Effective Ice Thickness, Heff	(m)	na	1.60	0.40	0.00
	Percent of Zone Area	(%)	na	83%	9%	8%
	Percent of Distance Travelled	(%)	na	43%	28%	28%
	Vessel Speed	(kn)	na	3.0	10.0	10.0
	Circumnavigation Factor		1.240			
	Average Speed along Intended Route	(kn)	5.1			

Table 4-4 Sample #1 - Comparison of Actual to Modelled Ship Speed

Geographic Zones			MV Arctic			Model Ship		
	Distance in zone (nmi)	Cumulative distance (nmi)	Time in zone (h)	Cumulative time (h)	Average speed (kn)	Time in zone (h)	Cumulative time (h)	Average speed (kn)
		0		0			0	
Zone 1	501.3	501.3	45	45	11.1	39	39	13.0
Zone 2	246.0	747.3	29	74	8.5	26	64	9.5
Zone 3	148.6	895.9	53	127	2.8	114	179	1.3
Zone 4	37.3	915.6	233	360	0.1	28	207	1.3
Zone 5	64.5	980.1	27	387	2.4	27	234	2.4
Zone 6	21.0	1001.1	16	403	1.3	4	238	5.1
Overall	1001.1		403		2.5	238		4.2
Ratio of Model to Actual						0.59		1.70

Overall, excluding Zones 4 and 6	960.4		154		6.2	206		4.7
Ratio of Model to Actual						1.34		0.75

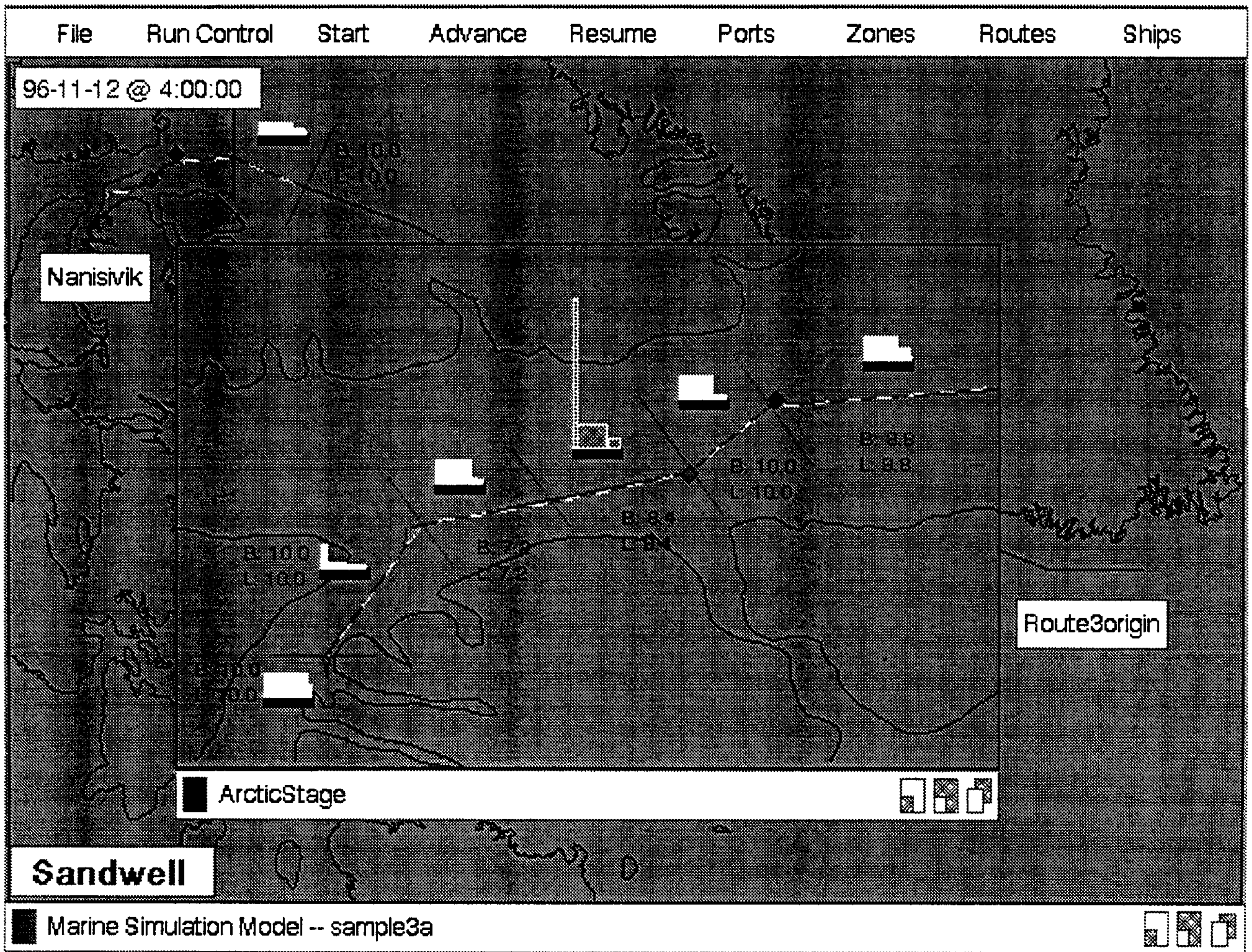
Figure 4-2 Sample #1 - Distance Travelled vs. Time Elapsed



4.3.2 Sample Voyage #3

The simulation model for Voyage #3 is shown in Figure 4-2.

Figure 4-3 Simulation Model for Voyage #3



See Section 4.2.1 for a description of the objects in the simulation model. This version of the model differs from the others in that an inset is included which shows an enlargement of the last portion of the route. The route was divided into seven geographical zones numbered 3 through 9. Zones 1 and 2 were ignored in this analysis because these were primarily in open water and because it was unclear how to interpret the data for Zone 2.

Simulation Results

The historical ice conditions data within each zone and the average values for the zones are shown in Table 4-5. The ice conditions input data for the simulation model are shown in Table 4-6. Some of the ice transit model calculations are shown in Table 4-7. The simulated progress of the modelled ship through the ice is compared to the actual ship in Figure 4-4 and in Table 4-8.

The simulation model results are compared to the recorded values on a zone-by-zone basis in the following paragraphs. The quantity “effective ice thickness” is described in Section 4.2.1.

Zone 3. Although Zone 3 had 95 percent ice coverage, the maximum ice thickness was only 0.3 m. This ice is thin enough that the M.V. Arctic can easily maintain its cruising speed. The recorded average speed was 13.8 kn, which is its economical open water cruising speed. The simulation model used an assumed safe cruising speed in ice of 10.0 kn. Since this value was a direct input to the transit model, any agreement or lack of agreement is not significant.

Zone 4. In this zone, the effective thickness of the thickest ice was 0.8 m covering 70 percent * 95 * = 0.67 percent of the zone. The remaining ice had negligible thickness. Although it was possible for the model to circumnavigate all of the thickest ice, it was faster to travel in a straight line, resulting in an average modelled speed of 8.8 kn for the zone. This speed is slightly less than the 10 knot maximum cruising speed specified for ice. The recorded speed of 9.7 kn was slightly higher than the modelled value.

Zone 5. The ice conditions in this zone are somewhat less severe than those in Zone 4, resulting in a higher modelled transit speed of 10.0 kn, the maximum speed allowed in ice. The recorded speed was 13.3 kn indicating that the M.V. Arctic is permitted to operate faster in ice than we had assumed.

Zone 6. This is the first zone in this sample with ice conditions severe enough to have an effect on ship speed that can be compared to the model. Medium pressure was experienced which increased the effective ice thickness in the zone to 4.1 m in the thickness ice (10 percent of the area) and to 0.8 m in the medium thickness ice (60 percent of the area). The thickness of the thinnest ice was negligible. Circumnavigation permitted the modelled ship to avoid the thickest ice (which was too thick to penetrate at all), while a speed of 8.4 knot could be maintained through the medium thickness ice. After allowing for the open water portion of the voyage, the modelled average speed was 8.4 kn. The recorded speed for the M.V. Arctic was 6.0 kn, somewhat less than this value. Some of this difference is likely to be the caused by the uncertainty in estimating ice pressure since this was a significant factor in the zone. Note that ice pressure is quantified in the modelled by only three possible values: none, medium, and high.

Zone 7. This zone consist of 0.5 m ice with frequent ridges covering 73 percent of the zone area. The remainder of the zone is either open water or ice of negligible thickness. Medium pressure is specified for 67 percent of the time in this zone. The resulting effective ice thickness was 1.0 m (exclusive of pressure) in which a modelled speed of 5.6 kn could be maintained. Most but not all of this ice was circumnavigated, resulting in an average speed of 6.5 kn. The recorded speed was slightly higher at 7.7 kn. This zone was a good test of the circumnavigation algorithm which was responsible for most of the reduction in average speed.

Zone 8, 9 The thickest ice in these zones was 0.5 m which can be penetrated by the M.V. Arctic at its cruising speed for ice. The value entered to the model for this speed was 10.0 kn, while the recorded values were 14.5 kn in Zone 8 and 10.3 kn in Zone 9.

Table 4-5 Sample #3 - Zone Averages

	Time: Year	Time: Mon.	Time: Day	Time: Time (h)	Time in Seg. (h)	Dist. in Seg. (nmi)	Total Cover	Level Ice Concentrations (%): % of total area in H1	% of total area in H2	% of total area in H3	% of ice cover in H1	% of ice cover in H2	% of ice cover in H3	Level Ice Thickness: H1 (m)	H2 (m)	H3 (m)	Ridging: Ridge frequency N1 (/nmi)	N2 (/nmi)	N3 (/nmi)	Ridge Height (m)	Background Rubble: Thickness H1 (m)	H2 (m)	H3 (m)	Equiv. Level Ice Thickness Del. H1 (m)	Del. H2 (m)	Del. H3 (m)	Leads: Freq.	F	Dur. (h)	Pressure: Meduim Freq.	Dur. (h)	High Freq.	Dur. (h)	Temp. (C)
Zone 3	88	11	11	12	6		95%	70%	20%	5%	74%	21%	5%	0.25	0.15	0.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-20
					6	83	95%	70%	20%	5%	74%	21%	5%	0.25	0.15	0.10	0.0	0.0	0.0	0.0				0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-20
Zone 4	88	11	11	18	2		95%	80%	10%	5%	84%	11%	5%	0.50	0.25	0.10	2.0	0.0	0.0	6.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-22
	88	11	11	20	4		95%	60%	35%	0%	63%	37%	0%	0.50	0.25	0.00	2.0	0.0	0.0	6.0	0.5	0.0	0.0	0.42	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-23
					6	58	95%	67%	27%	2%	70%	28%	2%	0.50	0.25	0.10	2.0	0.0	0.0	6.0				0.25	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-23
Zone 5	88	11	12	0	3		95%	0%	70%	25%	0%	74%	26%	0.00	0.50	0.10	0.0	4.0	0.0	6.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-24
					3	40	95%	0%	70%	25%	0%	74%	26%	0.00	0.50	0.10	0.0	4.0	0.0	6.0				0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-24
Zone 6	88	11	12	3	2		95%	10%	60%	25%	11%	63%	26%	3.00	0.50	0.20	0.0	3.0	0.0	6.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	100%	2.0	0%	0.0	-25
					2	12	95%	10%	60%	25%	11%	63%	26%	3.00	0.50	0.20	0.0	3.0	0.0	6.0				0.00	0.00	0.00	0%	0%	0.0	100%	2.0	0%	0.0	-25
Zone 7	88	11	12	5	2		95%	85%	0%	10%	89%	0%	11%	0.50	0.00	0.10	9.0	0.0	0.0	6.0	0.1	0.0	0.0	0.28	0.00	0.00	0%	0%	0.0	100%	1.0	0%	0.0	-25
	88	11	12	7	1		95%	50%	40%	5%	53%	42%	5%	0.50	0.15	0.10	8.0	0.0	0.0	6.0	0.1	0.0	0.0	0.28	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-24
					3	23	95%	73%	13%	8%	77%	14%	9%	0.50	0.15	0.10	8.8	0.0	0.0	6.0				0.28	0.00	0.00	0%	0%	0.0	67%	0.7	0%	0.0	-25
Zone 8	88	11	12	8	1		90%	10%	50%	30%	11%	56%	33%	0.25	0.15	0.10	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-25
	88	11	12	9	1		95%	20%	30%	45%	21%	32%	47%	0.60	0.15	0.10	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-25
					2	29	93%	15%	40%	38%	16%	43%	41%	0.48	0.15	0.10	0.0	0.0	0.0	5.0				0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-25
Zone 9	88	11	12	10	2		95%	0%	80%	15%	0%	84%	16%	0.00	0.50	0.25	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-28
	88	11	12	12	1		100%	0%	100%	0%	0%	100%	0%	0.00	0.50	0.00	0.0	8.0	0.0	6.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-30
	88	11	12	13	0		0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	0
					3	31	97%	0%	87%	10%	0%	90%	10%	0.00	0.50	0.25	0.0	3.1	0.0	6.0				0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-28

Table 4-6 Sample #3 - Zone Input Data

	Ice Coverage				Level Ice Thickness			Ridging				Background Rubble			Leads			Pressure				
	Total Cover	Fraction of Ice Cover						Ridge frequency			Ridge	Effective Level Ice Thickness						Medium		High		
		in H1 %C	in H2 %C	in H3 %C	H1 (m)	H2 (m)	H3 (m)	N1 (/nmi)	N2 (/nmi)	N3 (/nmi)	Height (m)	Delta H1 (m)	Delta H2 (m)	Delta h3 (m)	Freq	F	Dur (h)	Freq.	Dur. (h)	Freq.	Dur. (h)	Temp. (deg C)
Zone 3	95%	74%	21%	5%	0.25	0.15	0.10	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-20
Zone 4	95%	70%	28%	2%	0.50	0.25	0.10	2.0	0.0	0.0	6.0	0.25	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-23
Zone 5	95%	0%	74%	26%	0.00	0.50	0.10	0.0	4.0	0.0	6.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-24
Zone 6	95%	11%	63%	26%	3.00	0.50	0.20	0.0	3.0	0.0	6.0	0.00	0.00	0.00	0%	0%	0.0	100%	2.0	0%	0.0	-25
Zone 7	95%	77%	14%	9%	0.50	0.15	0.10	8.8	0.0	0.0	6.0	0.28	0.00	0.00	0%	0%	0.0	67%	0.7	0%	0.0	-25
Zone 8	93%	16%	43%	41%	0.48	0.15	0.10	0.0	0.0	0.0	5.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-25
Zone 9	97%	0%	90%	10%	0.00	0.50	0.25	0.0	3.1	0.0	6.0	0.00	0.00	0.00	0%	0%	0.0	0%	0.0	0%	0.0	-28

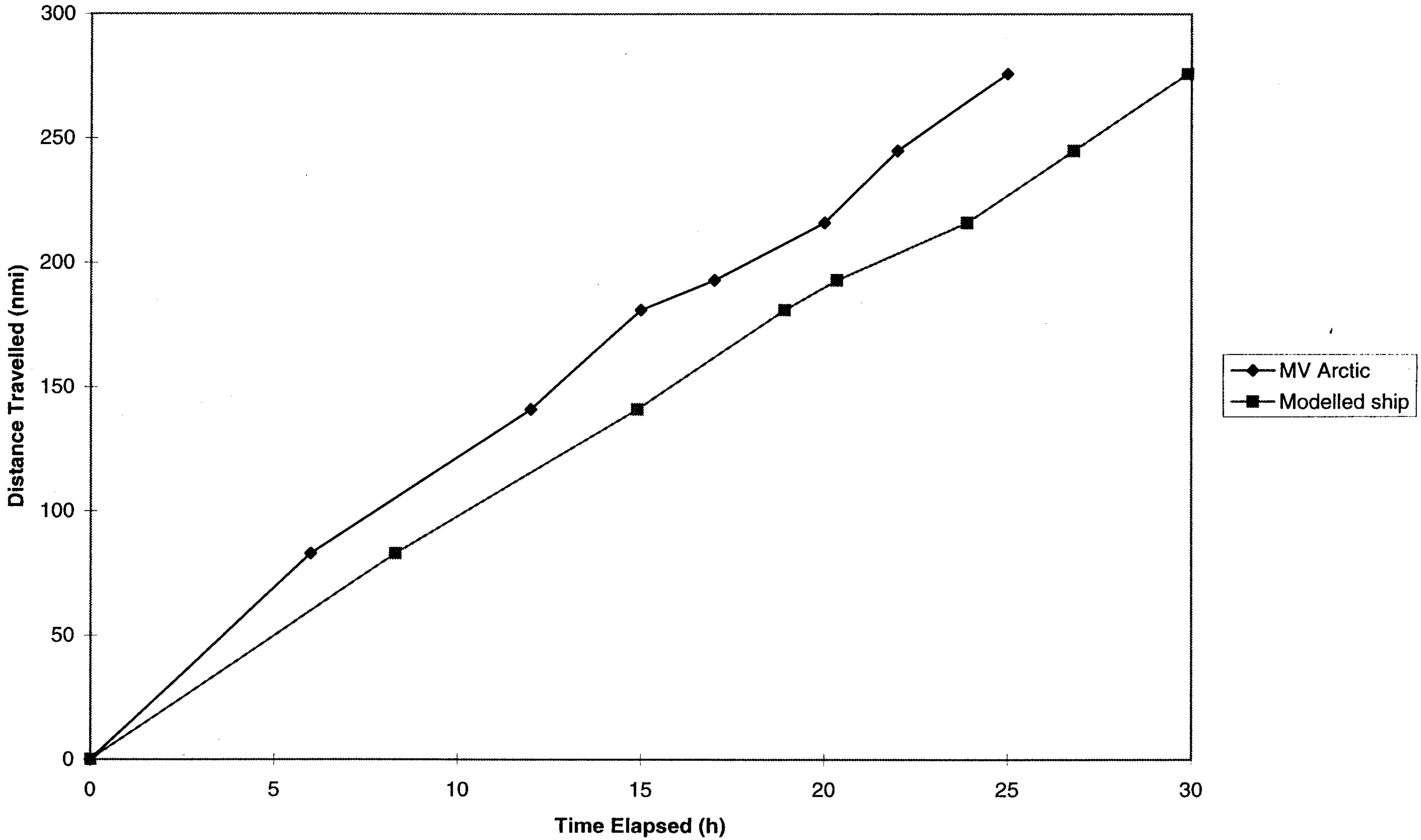
Table 4-7 Sample #3 - Contributions to Modelled Vessel Speed

			Ice Thickness Band			
			H1	H2	H3	no ice
Zone 3	Effective Ice Thickness, Heff	(m)	0.25	0.15	0.10	0.00
	Percent of Zone Area	(%)	70%	20%	5%	5%
	Percent of Distance Travelled	(%)	70%	20%	5%	5%
	Vessel Speed	(kn)	10.0	10.0	10.0	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	10			
Zone 4	Effective Ice Thickness, Heff	(m)	0.81	0.25	0.10	0.00
	Percent of Zone Area	(%)	67%	27%	2%	5%
	Percent of Distance Travelled	(%)	67%	27%	2%	5%
	Vessel Speed	(kn)	8.3	10.0	10.0	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	8.8			
Zone 5	Effective Ice Thickness, Heff	(m)	na	0.61	0.10	0.00
	Percent of Zone Area	(%)	na	70%	25%	5%
	Percent of Distance Travelled	(%)	na	70%	25%	5%
	Vessel Speed	(kn)	na	10.0	10.0	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	10			
Zone 6	Effective Ice Thickness, Heff	(m)	4.05	0.79	0.27	0.00
	Percent of Zone Area	(%)	10%	60%	25%	5%
	Percent of Distance Travelled	(%)	0%	67%	28%	6%
	Vessel Speed	(kn)	0.0	8.3	10.0	10.0
	Circumnavigation Factor		1.052			
	Average Speed along Intended Route	(kn)	8.4			
Zone 7	Effective Ice Thickness, Heff	(m)	1.03	0.15	0.10	0.00
	Percent of Zone Area	(%)	73%	13%	8%	6%
	Percent of Distance Travelled	(%)	11%	44%	28%	17%
	Vessel Speed	(kn)	5.6	10.0	10.0	10.0
	Circumnavigation Factor		1.322			
	Average Speed along Intended Route	(kn)	7.2			
Zone 8	Effective Ice Thickness, Heff	(m)	0.48	0.15	0.10	0.00
	Percent of Zone Area	(%)	15%	40%	38%	8%
	Percent of Distance Travelled	(%)	15%	40%	37%	8%
	Vessel Speed	(kn)	10.0	10.0	10.0	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	10.0			
Zone 9	Effective Ice Thickness, Heff	(m)	na	0.58	0.25	0.00
	Percent of Zone Area	(%)	na	87%	10%	3%
	Percent of Distance Travelled	(%)	na	87%	10%	3%
	Vessel Speed	(kn)	na	10.0	10.0	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	10.0			

Table 4-8 Sample #3 - Comparison of Actual to Modelled Ship Speed

Geographic Zones			MV Arctic			Model Ship		
	Distance in seg (nmi)	Cumulative distance (nmi)	Time in zone (h)	Cumulative time (h)	Average Speed (kn)	Time in zone (h)	Cumulative time (h)	Average Speed (kn)
		0		0			0	
Zone 3	83	83	6	6	13.8	8	8	10.0
Zone 4	58	141	6	12	9.7	7	15	8.8
Zone 5	40	181	3	15	13.3	4	19	10.0
Zone 6	12	193	2	17	6.0	1	20	8.4
Zone 7	23	216	3	20	7.7	4	24	6.5
Zone 8	29	245	2	22	14.5	3	27	10.0
Zone 9	31	276	3	25	10.3	3	30	10.0
Overall	276		25		11.0	30		9.2
Ratio of Model to Actual						1.20		0.84

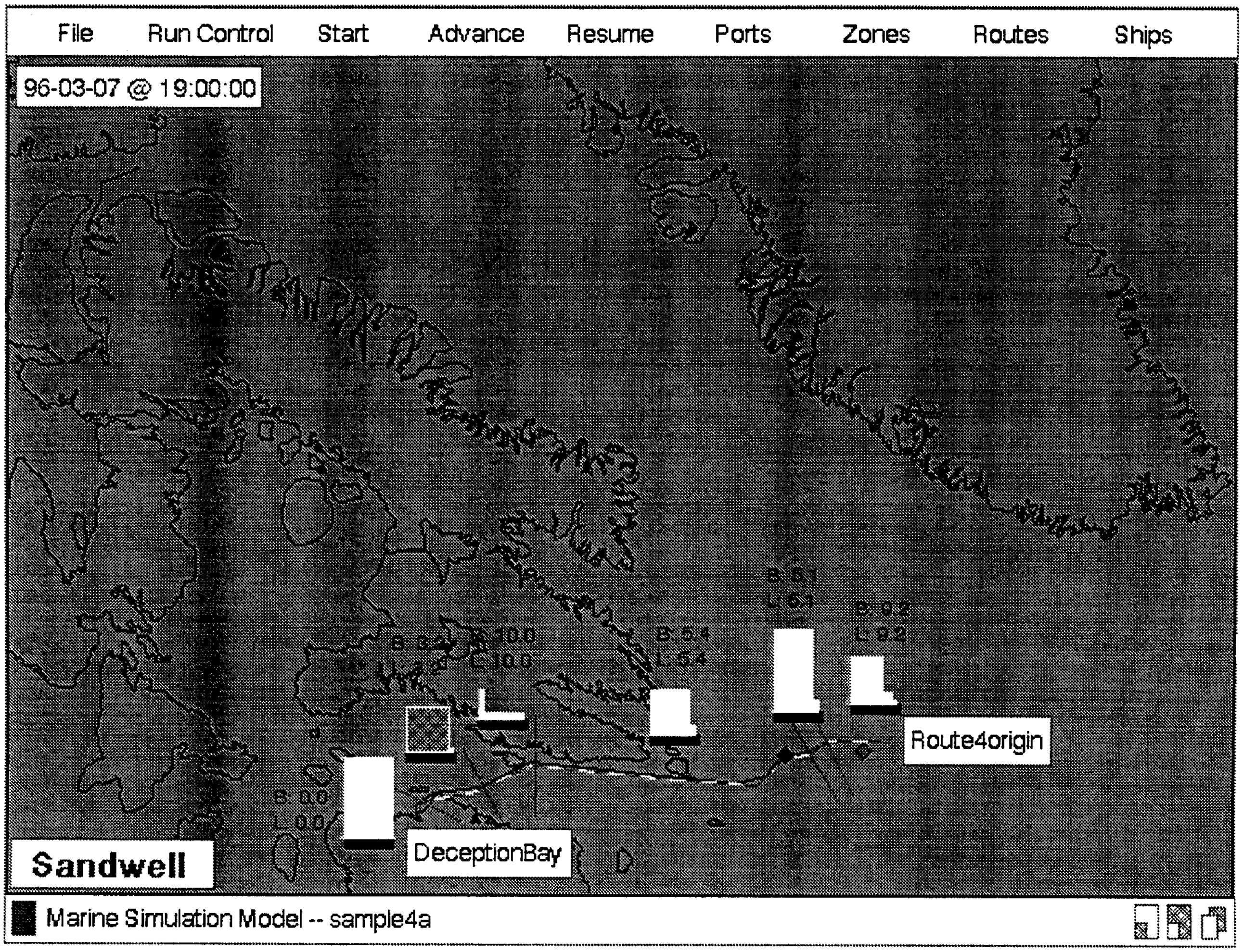
Figure 4-4 Sample #3 - Distance Travelled vs. Time Elapsed



4.3.3 Sample Voyage #4

The simulation model for Voyage #4 is shown in Figure 4-3.

Figure 4-5 Simulation Model for Voyage #4



See Section 4.2.1 for a description of the objects in the simulation model. The route was divided into six geographical zones.

Simulation Results

The historical ice conditions data within each zone and the average values for the zones are shown in Table 4-9. The ice conditions input data for the simulation model are shown in Table 4-10. Some of the ice transit model calculations are shown in Table 4-11. The simulated progress of the modelled ship through the ice is compared to the actual ship in Figure 4-6 and in Table 4-12.

The simulation model results are compared to the recorded values on a zone-by-zone basis in the following paragraphs. The quantity "effective ice thickness" is described in Section 4.2.1.

Zone 1. Zone 1 had 66 percent coverage of approximately 1.0 m thick ice with the remainder containing either open water or ice that was thin enough that the ship is not slowed. The 1.0 m ice coverage was just low enough that it could have been circumnavigated completely, but this would have slowed the ship more that simply penetrating all of the thicker ice. The average speed modelled for the zone was 9.2 kn compared to a much slower measured speed of 1.2 kn. It is not clear why the M.V. Arctic's speed was so slow in this zone since the trials data in Figure 2-2 indicate that it can travel much faster under the recorded ice conditions.

Zone 2. Zone 2 contained ice whose effective thickness was 1.7 m and which covered 80 percent of the area. This coverage is high enough that the ice could not be circumnavigated completely. After circumnavigation, 34 percent of the route was spent penetrating this ice at a modelled speed of 2.6 kn, with the remainder of the route travelled at the 10 knot maximum speed in ice. After allowing for the effects of leads (43 percent of the time), the modelled average speed for zone was 7.4 kn. The measured speed for the zone was only 3.3 kn, much slower than the modelled speed. The measured speed suggests that the vessel was not able to circumnavigate any of the thick ice in this zone.

Zone 3. Zone 3 contained ice whose average effective thickness was 1.5 m and which covered 81 percent of the area. Similar to Zone 2, most of this ice was circumnavigated by the modelled ship. After allowing for leads (13 percent of the time) and medium pressure events (13 percent of the time), the modelled average speed for the zone was 5.5 kn. The measured speed however was only 2.2 kn. Most of this difference in speeds is the result of the second and third records for this zone (see Table 4-9) during which only 5.2 nmi were attained during 58 hours of operation. The second record shows medium pressure for 25 percent of the time while the third record shows large amounts of background rubble which contributed 1.2 m to the effective thickness. These conditions were severe enough apparently to force the M.V. Arctic to ram for extended periods.

Zone 4. The thickest ice in Zone 4 had an effective thickness of only 0.7 m which is thin enough that the modelled ship can maintain its 10 knot maximum speed in ice. The measured speed however was only 5.8 kn for this zone. There is no indication in the recorded ice data why the vessel should have travelled so slowly in relatively thin ice.

Zone 5. Zone 5 contained ice whose effective thickness was 1.2 m and whose coverage was 86 percent of the area. In addition, medium pressure events occurred for 44 percent of the time in this zone. With these inputs, the modelled average speed was 3.8 kn compared to a recorded speed of 2.1 kn.

Zone 6. Zone 6 was entirely covered by 1.6 m ice along with considerable amounts of background rubble which increased the effective ice thickness to 3.8 m. This thickness exceeds the modelled icebreaking capability of the vessel, resulting in zero speed. The zone was completed eventually only because a lead occurred for 2 percent of the time in the zone. The modelled average speed for the zone was 0.3 kn compared to a recorded speed of 0.1 kn.

Sandwell

Summary

There was poor agreement between the modelled and recorded speeds for this voyage. Some of this difference appears to be due to incomplete ice conditions data or to maintenance activities that were not reported. This seems to be the case in Zones 1 and 4 where the recorded speed for the M.V. Arctic was much less than that warranted by the recorded ice conditions. In Zone 2, the slower recorded speed for the vessel may have been caused by conditions that made circumnavigation impossible in that instance.

Table 4-9 Sample #4 - Zone Averages

	Time: Year	Time: Mon.	Time: Day	Time: Time (h)	Time in Seg. (h)	Dist. in Seg. (nmi)	Level Ice Concentrations (%): Total Cover	% of toal area: in H1	% of toal area: in H2	% of toal area: in H3	% of total cover: in H1	% of total cover: in H2	% of total cover: in H3	Level Ice Thickness: H1 (m)	H2 (m)	H3 (m)	Ridging: Ridge frequency: N1 (/nmi)	N2 (/nmi)	N3 (/nmi)	Ridge Height (m)	Background Rubble (m): Thickness: H1	Thickness: H2	Thickness: H3	Eqiv. Level Ice Thickness: Del. H1 (m)	Del. H2 (m)	Del. H3 (m)	Leads: Freq.	F	Dur. (h)	Pressure: Medium: Freq.	Medium: Dur. (h)	High: Freq.	High: Dur. (h)	Temp. (C)
Zone 1	91	3	7	4	3	11.5	90%	60%	20%	10%	67%	22%	11%	0.95	0.25	0.05	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.02	0.02	0.02	6%	100%	0.2	0%	0.0	0%	0.0	-2
	91	3	7	7	20	16.2	95%	70%	15%	10%	74%	16%	11%	0.95	0.25	0.10	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.02	0.02	0.02	12%	100%	2.4	0%	0.0	0%	0.0	-3
					23	27.7	93%	66%	17%	10%	71%	18%	11%	0.95	0.25	0.08	0.0	0.0	0.0	0.00				0.02	0.02	0.02	11%	100%	1.3	0%	0.0	0%	0.0	-2
Zone 2	91	3	8	3	3	9.8	90%	0%	80%	10%	0%	89%	11%	0.00	1.67	0.25	0.0	1.0	0.0	8.0	0.00	0.00	0.00	0.01	0.01	0.01	43%	100%	1.3	0%	0.0	0%	0.0	-3
					3	9.8	90%	0%	80%	10%	0%	89%	11%	0.00	1.67	0.25	0.0	1.0	0.0	8.0				0.01	0.01	0.01	43%	100%	1.3	0%	0.0	0%	0.0	-3
Zone 3	91	3	8	6	11	39.0	90%	80%	10%	0%	89%	11%	0%	0.95	0.25	0.00	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.02	0.02	0.02	13%	100%	1.4	0%	0.0	0%	0.0	0
	91	3	8	17	45	5.2	95%	70%	25%	0%	74%	26%	0%	0.95	0.25	0.00	0.2	0.0	0.0	7.0	0.00	0.00	0.00	0.02	0.02	0.02	10%	100%	4.5	25%	11.3	0%	0.0	-1
	91	3	10	14	13	0.0	90%	50%	20%	20%	56%	22%	22%	0.95	0.25	0.10	2.0	0.0	0.0	7.0	2.25	0.00	0.00	1.24	0.02	0.02	15%	100%	2.0	0%	0.0	0%	0.0	-11
	91	3	11	3	15	25.1	95%	85%	10%	0%	89%	11%	0%	0.95	0.25	0.00	4.0	0.0	0.0	7.0	1.30	0.00	0.00	0.96	0.05	0.05	0%	0%	0.0	8%	1.2	0%	0.0	-8
	91	3	11	18	16	24.5	90%	80%	10%	0%	89%	11%	0%	0.95	0.40	0.00	1.2	0.0	0.0	7.0	1.25	0.00	0.00	0.91	0.02	0.02	7%	100%	1.1	0%	0.0	0%	0.0	-11
	91	3	12	10	20	76.1	95%	75%	10%	10%	79%	11%	11%	0.95	0.25	0.10	0.9	0.0	0.0	7.0	1.50	0.00	0.00	1.04	0.07	0.07	15%	100%	3.0	0%	0.0	0%	0.0	-14
	91	3	13	6	11	22.1	95%	75%	10%	10%	79%	11%	11%	0.95	0.15	0.00	0.2	0.0	0.0	7.0	1.50	0.00	0.00	1.03	0.05	0.05	29%	100%	3.2	50%	5.5	0%	0.0	-17
	91	3	13	17	9	114.9	95%	85%	10%	0%	89%	11%	0%	0.90	0.10	0.10	0.3	0.0	0.0	7.0	0.00	0.00	0.00	0.05	0.05	0.05	29%	100%	2.6	0%	0.0	0%	0.0	-16
					140	306.9	94%	81%	10%	3%	86%	11%	3%	0.93	0.20	0.08	0.8	0.0	0.0	7.0				0.49	0.05	0.06	13%	92%	2.3	13%	6.0	0%	0.0	-12
Zone 4	91	3	14	2	10	58.0	90%	10%	80%	0%	11%	89%	0%	0.60	0.15	0.00	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.05	0.05	0.05	10%	100%	0.9	0%	0.0	0%	0.0	-16
					10	58.0	90%	10%	80%	0%	11%	89%	0%	0.60	0.15	0.00	0.0	0.0	0.0	0.0				0.05	0.05	0.05	10%	100%	0.9	0%	0.0	0%	0.0	-16
Zone 5	91	3	14	12	9	35.8	95%	0%	80%	15%	0%	84%	16%	0.00	0.90	0.10	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.05	0.05	0.05	46%	100%	4.1	0%	0.0	0%	0.0	-19
	91	3	14	21	3	4.4	95%	0%	85%	10%	0%	89%	11%	0.00	0.90	0.10	0.0	0.0	0.0	0.0	0.00	1.50	0.00	0.05	1.00	0.05	18%	100%	0.5	0%	0.0	0%	0.0	-15
	91	3	14	24	12	10.4	95%	0%	95%	0%	0%	100%	0%	0.00	0.90	0.00	0.0	0.0	0.0	0.0	0.00	2.00	0.00	0.05	1.17	0.05	0%	0%	0.0	100%	12.0	0%	0.0	-9
	91	3	15	12	8	15.9	95%	0%	95%	0%	0%	100%	0%	0.00	0.90	0.00	0.0	0.3	0.0	7.0	0.00	0.00	0.00	0.05	0.05	0.05	0%	0%	0.0	25%	2.0	0%	0.0	-9
					32	66.5	95%	0%	86%	9%	0%	91%	9%	0.00	0.90	0.10	0.0	0.1	0.0	7.0				0.00	0.30	0.05	15%	100%	2.3	44%	14.0	0%	0.0	-15
Zone 6	91	3	15	20	22	0.8	95%	0%	95%	0%	0%	100%	0%	0.00	1.70	0.00	0.0	0.0	0.0	0.0	0.00	2.00	0.00	0.05	1.57	0.05	5%	100%	1.1	0%	0.0	0%	0.0	-10
	91	3	16	18	48	8.0	100%	0%	100%	0%	0%	100%	0%	0.00	1.60	0.00	0.0	9.0	0.0	8.0	0.00	2.00	0.00	0.33	1.80	0.33	0%	0%	0.0	0%	0.0	0%	0.0	-13
	91	3	18	18	0	0.0	100%	0%	100%	0%	0%	100%	0%	0.00	1.40	0.00	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.05	0.05	0.05	0%	0%	0.0	0%	0.0	0%	0.0	-15
					70	8.8	100%	0%	100%	0%	0%	100%	0%	0.00	1.61	0.00	0.0	8.2	0.0	8.0				0.00	1.78	0.00	2%	100%	1.1	0%	0.0	0%	0.0	-13

Table 4-10 Sample #4 - Zone Input Data

	Ice Coverage				Level Ice Thickness			Ridging				Background Rubble			Leads			Pressure				
	Total	fraction of ice cover						Ridge frequency			Ridge	Effective Level Ice Thickness						Meduim		High		
	Cover	in H1	in H2	in H3	H1 (m)	H2 (m)	H3 (m)	N1 (/nmi)	N2 (/nmi)	N3 (/nmi)	Height (m)	Delta H1 (m)	Delta H2 (m)	Delta H3 (m)	Freq	F	Dur (h)	Freq.	Dur. (h)	Freq.	Dur. (h)	Temp. (deg C)
Zone 1	93%	71%	18%	11%	0.95	0.25	0.08	0.0	0.0	0.0	0.0	0.02	0.02	0.02	11%	100%	1.3	0%	0.0	0%	0.0	-2
Zone 2	90%	0%	89%	11%	0.00	1.67	0.25	0.0	1.0	0.0	8.0	0.01	0.01	0.01	43%	100%	1.3	0%	0.0	0%	0.0	-3
Zone 3	94%	86%	11%	3%	0.93	0.20	0.08	0.8	0.0	0.0	7.0	0.49	0.05	0.06	13%	92%	2.3	13%	6.0	0%	0.0	-12
Zone 4	90%	11%	89%	0%	0.60	0.15	0.00	0.0	0.0	0.0	0.0	0.05	0.05	0.05	10%	100%	0.9	0%	0.0	0%	0.0	-16
Zone 5	95%	0%	91%	9%	0.00	0.90	0.10	0.0	0.1	0.0	7.0	0.00	0.30	0.05	15%	100%	2.3	44%	14.0	0%	0.0	-15
Zone 6	100%	0%	100%	0%	0.00	1.61	0.00	0.0	8.2	0.0	8.0	0.00	1.78	0.00	2%	100%	1.1	0%	0.0	0%	0.0	-13

Table 4-11 Sample #4 - Contributions to Modelled Vessel Speed

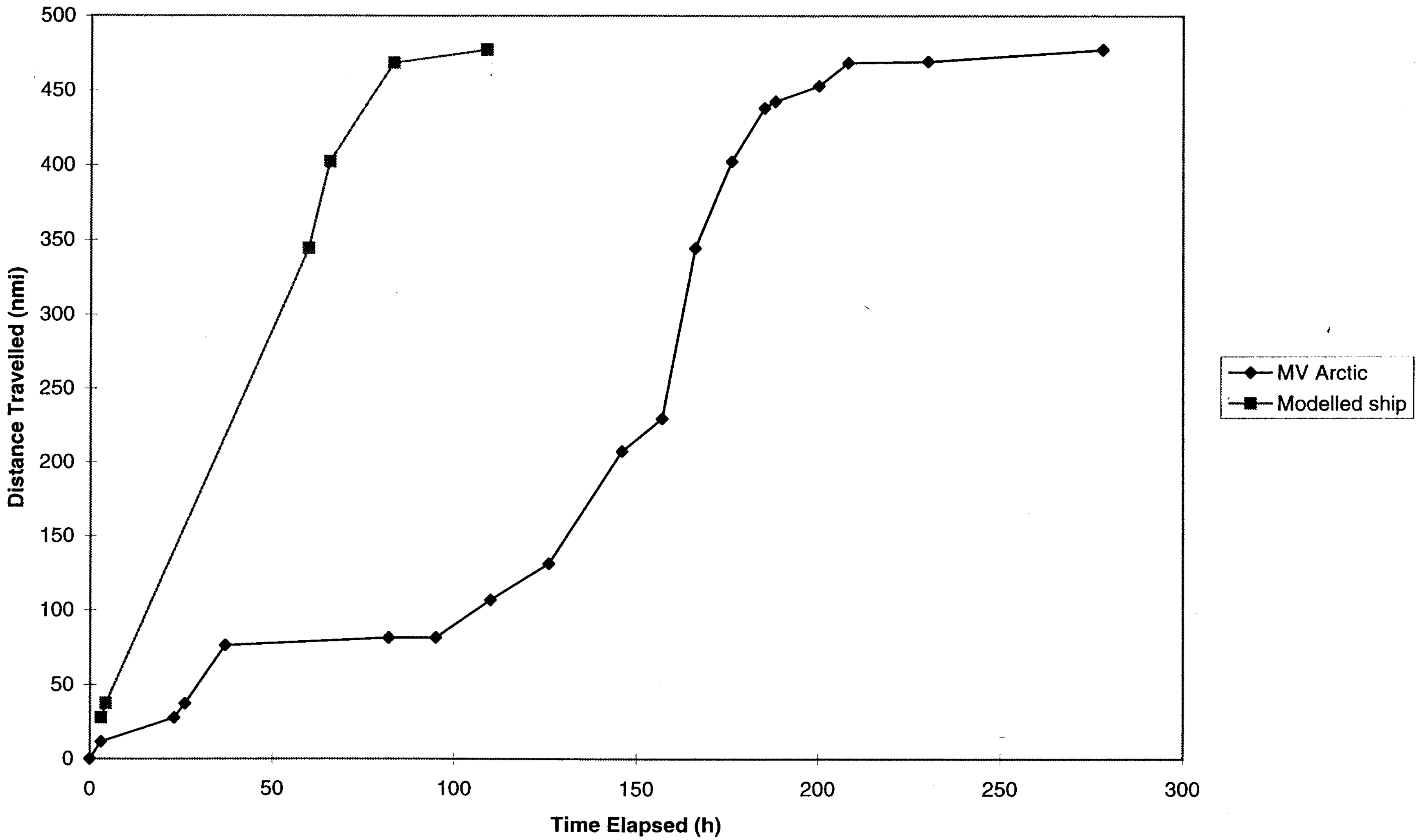
			Ice Thickness Band			
			H1	H2	H3	no ice
Zone 1	Effective Ice Thickness, Heff	(m)	0.97	0.27	0.10	0.00
	Percent of Zone Area	(%)	66%	17%	10%	7%
	Percent of Distance Travelled	(%)	66%	17%	10%	7%
	Vessel Speed	(kn)	8.8	10.0	10.0	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	9.2			
Zone 2	Effective Ice Thickness, Heff	(m)	na	1.73	0.26	0.00
	Percent of Zone Area	(%)	na	80%	10%	10%
	Percent of Distance Travelled	(%)	na	34%	33%	33%
	Vessel Speed	(kn)	na	2.6	10.0	10.0
	Circumnavigation Factor		1.266			
	Average Speed along Intended Route	(kn)	5.1			
Zone 3	Effective Ice Thickness, Heff	(m)	1.45	0.25	0.14	0.00
	Percent of Zone Area	(%)	81%	10%	3%	6%
	Percent of Distance Travelled	(%)	36%	34%	9%	20%
	Vessel Speed	(kn)	3.0	10.0	10.0	10.0
	Circumnavigation Factor		1.260			
	Average Speed along Intended Route	(kn)	5.4			
Zone 4	Effective Ice Thickness, Heff	(m)	0.65	0.20	na	0.00
	Percent of Zone Area	(%)	10%	80%	na	10%
	Percent of Distance Travelled	(%)	10%	80%	na	10%
	Vessel Speed	(kn)	10.0	10.0	10.0	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	10.0			
Zone 5	Effective Ice Thickness, Heff	(m)	na	1.20	0.15	0.00
	Percent of Zone Area	(%)	na	86%	9%	5%
	Percent of Distance Travelled	(%)	na	55%	29%	17%
	Vessel Speed	(kn)	na	4.9	10.0	10.0
	Circumnavigation Factor		1.213			
	Average Speed along Intended Route	(kn)	6.1			
Zone 6	Effective Ice Thickness, Heff	(m)	na	3.80	na	0.00
	Percent of Zone Area	(%)	na	100%	0%	0%
	Percent of Distance Travelled	(%)	na	100%	0%	0%
	Vessel Speed	(kn)	na	0.0	na	10.0
	Circumnavigation Factor		1.000			
	Average Speed along Intended Route	(kn)	0.0			

Table 4-12 Sample #4 - Comparison of Actual to Modelled Ship Speed

Geographic Zones			MV Arctic			Model Ship		
	Distance in zone (nmi)	Cumulative distance (nmi)	Time in zone (h)	Cumulative time (h)	Average speed (kn)	Time in zone (h)	Cumulative time (h)	Average speed (kn)
Zone 1	27.7	27.7	23	23	1.2	3	3	9.2
Zone 2	9.8	37.5	3	26	3.3	1	4	7.4
Zone 3	306.9	344.4	140	166	2.2	56	60	5.5
Zone 4	58	402.4	10	176	5.8	6	66	10.0
Zone 5	66.5	468.9	32	208	2.1	18	83	3.8
Zone 6	8.8	477.7	70	278	0.1	26	109	0.3
Overall	477.7		278		1.7	109		4.4
Ratio of Model to Actual						0.39		2.56

Overall, excluding Zones 1 and 6	441.2		185		2.4	80		5.5
Ratio of Model to Actual						0.43		2.31

Figure 4-6 Sample #4 - Distance Travelled vs. Time Elapsed



5. Summary and Conclusions

The simulation model and its ice transit algorithms were tested against three types of historical data for the M.V. Arctic:

- ice trials results
- operational data
- complete voyages segments

The following paragraphs describe the results for each data type:

Ice Trials Data

The ice transit algorithms were found to be in good agreement with the trials data. This data tested the model's ability to predict vessel speed in continuous level ice that is free from ridges and rubble. Under these conditions, the model's predicted speed was within approximately +/-1.5 kn of the measured speeds. This difference is within the scatter in the trials data.

Operational Data

The correlation between the model and the operational data proved to be much less satisfactory because of the difficulty in estimating ice conditions from a moving vessel. In addition, the ice conditions encountered in actual operation are much more complex than those encountered during ice trials. Many ice parameters such as ridges, rubble, pressure, snow cover, ice thickness distribution, and ice coverage have a large effect on the average speed achieved by an icebreaker. To measure all of these quantities from a moving vessel with sufficient accuracy for detailed analysis proved to be problematic. Finally, the data had not been collected with the intent of calibrating a detailed transit model. Some of the inputs required for the model were either missing from the historical data, or had been given a different interpretation than the one used for the model. In ether case, considerable interpretation was required to obtain the necessary input data for the model.

Despite the above difficulties, a number of valuable results were obtained from the operational data:

- Circumnavigation Distance. The circumnavigation distance equation used by the model was found to be in good agreement with the operational data.

- Ice Flow Edges. A new component was added to the model to reduce the effective ice thickness by a factor of 0.8 for ice coverage less than 100 percent. This factor represents the reduction of ice resistance offered by the edge of a discrete ice flow compared to a continuous ice surface.

- Background Rubble. The penetration of background rubble may offer somewhat more resistance than used in the present model. Although, the data was not accurate enough to adjust the model, this aspect of the model has been highlighted as an area for future work.

- Fraction of Ice Penetrated. Under some circumstances, the M.V. Arctic appears to penetrate thicker ice more frequently than the simulation model. The relationship between ice coverage and the amount of ice penetrated is an area which should be investigated further.

Complete Voyage Segments

The correlation between the model and complete voyage segments also proved to be less satisfactory because of the limited accuracy of the voyage data. Voyages in thick ice where the vessel's speed was less than approximately 3 kn were particularly hard to model accurately because the vessel speed is predicted to at most +/-1.5 kn by the present model. At low speed, this uncertainty is a large fraction of the average speed which leads to modelled transit time that are too long or too short by a factor of 2 or more. In particular, when a vessel becomes stuck, it is impossible for any model to predict the exact point at which the vessel becomes stuck or how long it will remain stuck in the ice.

When the extreme portions of the voyages (speeds less than 2 kn) were excluded, the model transit time was in much better agreement with the model. When this was done for voyages 1 and 3, the modelled transit time was in the range 20 - 35% longer than the actual time. For voyage 4, however, the correlation was still very poor.

Model Improvements

Several improvements were made to the simulation model as the result of the calibration project:

Ice thickness distribution. Provision was made to accommodate more realistic distributions of ice thickness.

Circumnavigation in thin ice. The model logic was modified so that circumnavigation is done only if it increases the ship's average speed. Circumnavigation of thin ice is counter-productive because it forces the ship to travel a longer distance, decreasing its average speed.

Avoidance of thick ice. The circumnavigation algorithm was modified so that the modelled ship avoids the thickest ice in the zone whenever possible. Formerly, the modelled ship penetrated ice in each of the three ice thickness bands in proportion to their frequency of occurrence in the zone, ignoring the possibility of circumnavigation. With the old algorithm, a small amount of very thick ice would cause the ship to become stuck even though this ice could have been avoided.

Unfortunately, because of the large amount of internal scatter in the recorded transit data, it was not possible to isolate and modify individual areas of the model, such as ridge penetration, to improve the correlation between the model and the data.

Applicability of the Model for Feasibility Studies

The model has been shown to be accurate to +/- 1.5 kn in level ice, given known ice conditions. This level of accuracy is sufficient for most applications. In more complex ice conditions involving ridges, snow, rubble, etc. one would expect a somewhat greater level of uncertainty. The present study was not able to determine the value for this more general level of uncertainty.

The accuracy of the ice conditions themselves are the greatest source of uncertainty in the prediction of vessel speed for a feasibility study. In the present study, the IDIADS data was found to have a relatively large amount of uncertainty, largely because of interpretational difficulties. For a feasibility study, the analyst typically has average monthly ice thicknesses plus satellite images to determine likely vessel routes, the presence of leads, and the amount of ridging. This data should be sufficiently accurate for a feasibility study, but without a direct comparison, we cannot say exactly how accurate it might be. It would be valuable to perform a study that compared estimated ice conditions from this type of data to actual vessel transit times.

For any feasibility study, it is important to note that the predicted transit time for a vessel becomes much more uncertain at slower vessel speeds. At low speed, the propeller thrust is only slightly greater than the ice resistance, therefore small differences in ice conditions or calculated resistance can cause large percentage differences in vessel speed and transit time.

Summary

The comparison of the simulation model to transit data for an actual icebreaker proved to be a valuable exercise despite the difficulties encountered. A number of important improvements were made to the model as the result of the study and the entire model was subjected to a high level of scrutiny in our efforts to identify the cause of any differences between the model and the operational data. At the conclusion of this study, the model's level of accuracy is as high as can be supported by the operational data.

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APPENDIX A
Additional Documentation for Model Algorithm Calibration

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX B
Data Used for Model Calibration

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX C
M.V. Arctic, General Ice Transit in Mixed Ice Conditions

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX D
M.V. Arctic, Limiting Performance

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX E
M.V. Arctic, Performance in Waves

(Not available in electronic format/
Non disponible en format électronique)