Arctic Tanker Risk Analysis Project

Task 6
Casualty Potential and Risk Profile

prepared for

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STUDY TEAM

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10.1.0 INTRODUCTION AND BACKGROUND

The primary objectives of this phase were (1) to develop a casualty profile of the tanker route from Bent Horn to Montreal for the August 15 to September 30 season and (2) to arrive at an overall appreciation of the environmental risk along the route by combining the casualty and sensitivity results. The 28,000 DWT tanker the MV *Arctic*, which is owned by Canarctic Shipping Company Limited, uses this route to transport crude oil from the production well at Bent Horn on Cameron Island in the Canadian High Arctic. Casualties are defined here as those accidents which could potentially result in an oil spill of significant proportions.

Recent events have heightened public awareness and led to concerns for the protection of the environment from tankers and their operations. In the case of oil movements in Arctic waters these concerns are amplified by the perceived greater fragility of the natural environment. The goal of the casualty profile is to identify the most likely occurring hazards and compare these to the environmental sensitivities related to MV *Arctic* operations along the route during the summer navigation season. A risk profile combining casualty and sensitivity can then be used to assess risk management measures and then to produce a passage planning aid or other operational guide for the purposes of alerting the crew to particular hazards and thereby minimizing the risk of an oil spill.

The casualty profile is Task 6 of a multi-task project. Tasks 3 to 5 examined the environmental sensitivity of the route, defined accident types and possible effects, and provided data on the frequency of internal, external and natural hazards. The results of these tasks are combined here, after being compared for continuity, as well as modified to enable integration with other statistical sources.

In order to rank casualty potential, it was necessary to characterize the importance and likelihood of various hazards to a safe passage by the MV *Arctic*. This required the development of a methodology which would optimize the experience of the officers of the MV *Arctic* and recognize the limitations of existing Arctic data. The resulting Casualty Potential ranking system identified the most hazardous conditions for each route segment and provided a method of relative comparison. The Casualty Potential ranking system incorporates a methodology similar in concept to that used in the Sensitivity Ranking system (Task 3).

10.2.0 METHODOLOGY

This section describes the types of models or frameworks that have been employed in the past to assess the navigational risk along shipping routes. The information sources used in this study are then summarized followed by a description of the framework used here and definitions of terms.

Once the components of the Casualty Potential ranking system are defined, potentially hazardous tasks and systems termed "Sub-categories" are identified within three major causes of casualties (called simply "Categories"). The definition of what constitutes a hazard was based primarily on the previously cited information sources.

10.2.1 Choice of Model

Various Canadian studies of marine risk have employed methodologies which have used geographic data to describe relative navigational risk rather than use a world-wide database to estimate absolute accident probability. Therefore, the conventional concept of "risk = probability x severity of outcome" is often substituted by the concept of relative risk. Navigation risk indices dependent upon ship-miles and local geographic factors have been developed for Canadian waters on the east and west coasts (Fisheries and Oceans, 1976, 1978; and Cohen and Aylesworth, 1990). These studies experienced problems with the weighting of local factors. While this study attempts to overcome the arbitrary weighting of local factors through the definition of what constitutes a hazard (a hazard threshold), uncertainty is inherent in all analyses which attempt to integrate the qualitative techniques used to describe hazards.

A statistical approach was used by Consulting and Audit Canada (CAG) for the Canadian Coast Guard (1991) estimate marine risk in several Vessel Traffic Services zones in Canada. The methodology was based upon the assumption that causal factors and casualties can be related by a mathematical expression using multiple variables. Intuitively, a relationship does exist, but it may be difficult to describe in quantitative terms. Many other subtle factors will play a part in determining the final relationship.

Weighing the advantages and shortcomings of available approaches, a decision was made to rank and weight well-defined contributory factors as the basis for assessing relative casualty potential along the different route segments.

10.2.2 Data Sources

10.2.2.1 Reports of Task 3, 4 and 5

Task 3 Report: Definition of Environmental Sensitivity

Environmental sensitivity was determined for Route Segments 1 to 11 by a relative ranking system. Sensitivity can be related to the maximum conceivable environmental damage which would result from a marine spill along a particular segment of the route. The ranking system compared different areas on the extreme assumption that in every case, all of the shoreline within a particular segment is oiled. The relative comparison of environmental sensitivity in combination with the casualty potential is used here to estimate overall risk.

Task 4: Zurich Hazard Catalogue

The "Zurich" Hazard Analysis identified hazards of the MV *Arctic* route from the personal experience of a group of the ship's masters and chief engineers. A Hazard Catalogue was developed in order to list all the hazards identified, describe the cause of the hazard, the likelihood of the cause, the effect, and the significance of the effect. The results of this task were used to develop the sub-categories and to help determine the Assigned Value of each Sub-category. This was somewhat hampered by the inconsistency of terminology (cause, effect, casualty) between this and other tasks.

Task 5.1 Report: Natural Hazards

Glacial and sea ice data was obtained through Canarctic's IDIADS database. The database consists of 30,000 observations made primarily from the MV *Arctic* between 1983 and 1987. Mean, maximum, and minimum concentrations of all ice classes were used in Task 6 to determine frequencies of total ice and multi-year above various concentration levels (e.g. multi-year ice _ 7/10). The number of glacial ice pieces (icebergs, bergy bits, and growlers) per nmi. was used to predict the frequency of growlers per nmi.

Task 5.2 Report: Internal Hazards

The records of the Planned Maintenance System database and the Second Engineer's Workbook were provided. Each entry in the Planned Maintenance System listed the type of breakdown, its cause level and effect, but the causes were not attributed to environmental or operating factors. The Second Engineer's Handbook was similar in type of data presented. This reliability information provided an estimate of the relative incidence of equipment breakdown.

Task 5.3 Report: Definition and Quantification of External Hazards

The report describes the potential failure rate of three types of navigation systems: positioning systems, high frequency (HF) communications, and information systems (ice and weather). The failure rates derived are used directly as a contributing factor to human performance during navigation. Also discussed in the report was the casualty potential related to the use of escorts during the first stages of the Bent Horn route. It was concluded that escorts in the context of MV *Arctic* operations consist only of short term assistance while maneuvering in heavy ice and do not constitute a significant hazard (compared with traditional escorts of low Ice Class ships).

Task 5.4 Report: Human Performance

Bridge operations of the MV *Arctic* were analyzed for relationships to human performance. Tasks imposing high demands were identified. As well, factors increasing overall demands and demands of specific tasks were identified. The results were used in Task 6 to determine contributing factors, their hazard levels, and the hazard frequency. Specifically, data for fatigue and frequency of bridge communications was derived from the report (produced by Humansystems Incorporated).

10.2.2.2 Other Primary Data Sources

It was considered more appropriate to utilize a much larger climate database for the MV *Arctic* route than the IDIADS data summarized in the Task 5.1 report. Marine data collected from vessels of opportunity and archived by the Atmospheric Environment

Service was obtained for the months of August and September. The data was organized into marine areas representing each route segment (or groups of segments where the segments were short). Wave heights, visibility, wind speeds, and wind chill frequencies were obtained from this data source. The data covers various periods depending on the area, but each area was represented by a minimum of 17 years of observations (A.E.S., 1992).

The presence of other commercial traffic and fishing vessels constitutes a collision hazard. Historic records of traffic volumes and casualty data were obtained to contribute to the analysis of causal factors. The Canadian Marine Casualty Information System (MCIS) database of the Transportation Safety Board of Canada, (containing over 4,000 records of casualties involving vessels over 5,000 GRT) was used to provide casualty data for the risk analysis. Within the MCIS database, this study made particular use of the 535 casualty records for vessels of over 5,000 GRT operating in the Gulf of St. Lawrence.

Traffic data were obtained from the Canadian Coast Guard Nordreg database and from the Canadian Coast Guard 1991 VTS Update Study. Traffic data from the Montreal and Quebec VTS zones was also used to determine the percentage of annual traffic that transits the Gulf of St. Lawrence during the study period. Data sources are summarized in Table 10.

Table 10 Other Primary Data Sources

Climatic and Oceanographic Data	Atmospheric Environment Service
Vessel Traffic Data	Canadian Coast Guard, and Consulting and Audit Canada
Casualty Data	MCIS database, Transportation Safety Board of Canada

10.2.3 Casualty Potential Framework

A methodology was developed using casualty categories, sub-categories, assigned values, and exposure indices. Given a specific marine transportation route and divisions of the route into segments, the casualty potential for each segment is determined as follows:

- marine casualty causes are divided into three groups: Human Performance, Equipment Failure, and Undetectable Ice. These groups are given the title of **Categories**

- **Sub-categories** are identified and grouped under the three categories

- factors contributing to casualties within each sub-category are identified and frequencies (temporal or spatial) of each factor are summed to provide an **Exposure Index** (EI) for each sub-category (e.g., proportion of the route segment comprised of a narrow channel).

- **Assigned Values** (AV's), are determined for each sub-category in order to indicate the relative potential for a significant marine casualty (e.g., hull penetration) which could lead to an oil spill

- **Priority Indices** (PI's) are defined as the Exposure Indices multiplied by the Assigned Values

The Casualty Potential of a specific route segment is determined by calculating the Priority Index (product of the Exposure Index and the Assigned Value) for each sub-category, summing these values within each category and then summing overall. For example, using the three categories of Human Performance, Equipment Failure, and Undetectable Ice, the Casualty Potential (CP) would be calculated as follows:

$$CP = \Sigma\, PI_{HP} + \Sigma PI_{EF} + \Sigma PI_{UI}$$

$$= \Sigma\, EI_{HP} \times AV_{HP} + \Sigma\, EI_{EF} \times AV_{EF} + \Sigma\, EI_{UI} \times AV_{UI}$$

where the subscripts have the following meaning:

HP = Human Performance

EF = Equipment Failure

UI = Undetectable Ice

and PI = Priority Index

EI = Exposure Index (derived from the sum of contributing factors for each sub-category)

AV = Assigned Value of a sub-category

The definitions of Category, Sub-category, Exposure Index, Assigned Value, and Priority Index are described in more detail in Sections 2.3.1 to 2.3.4.

While the derivation of Casualty Potential is a critical part of the overall risk profile (when combined with the ranking of environmental sensitivity), it is the highlighting of important causal factors along the route that will aid in the prevention of casualties (just as knowledge of the locations of sensitive coastal areas aids in the mitigation of potential impacts). This highlighting is accomplished in Section 3.2 by the provision of graphs which compare the importance of the causal factors leading to casualties and high sensitivities.

10.2.3.1 Categories and Sub-categories

The Casualty Potential ranking scheme is composed of three major categories (generic causes of marine casualties). The distinct causes are human performance problems, equipment failures, and undetectable ice. These categories describe the casualty types of any marine transportation route and could be applied to any route world wide (the undetectable ice category would be dropped for routes not crossing ice-infested waters).

Most sub-categories fall under the category of human performance, since most casualties have their source in sub-optimal performance of the crew. The second and third categories represent possible sources of casualties that, at least in their immediate nature, are independent of human performance (e.g., engine failure, impact with a piece of snow-covered multi-year ice embedded in first-year ice). Equipment failure and undetectable hazards represent certain non-human risks that are always present in marine and Arctic transportation. Undetectable ice was considered a separate category because of the inability of existing sensor equipment to consistently detect some ice hazards.

Sub-categories are specific groupings of contributing causes within the three main Categories. Their identification and measurement is crucial to the relative ranking of Casualty Potential and the subsequent application of this study to the development of a passage planning aid or risk management guide. The sub-categories are route and vessel specific and cannot be directly transferred from one route analysis to another route. Sub-categories for the MV *Arctic* route from Bent Horn are described in detail in sections 2.4 through 2.6.

10.2.3.2 Exposure Index

The Exposure Index is a time or position dependent expression of a combination of factors which have been shown to influence the safety of ship operations. For example, the sub-category of ship-handling would have an exposure index comprised of wind speed, wave height, current speed, channel restrictions, presence of sea ice or icebergs, communication errors, and fatigue. The Exposure Index allows a comparison between route segments of the importance of factors contributing to the sub-categories.

For each sub-category on a particular route segment, the Exposure Index is equal to the sum of the frequency of occurrence of each contributing factor. For example, if a sub-category of machinery operations had contributing factors of waves heights ≥ 3 m and wind chill ≥1500 W/m^2, and a particular route segment had 15% frequency of wave heights ≥ 3 m and 8% frequency of wind chill ≥1500 W/m^2, the Exposure Index would be 0.15 + 0.08 or 0.23.

This additive approach simplifies the relationships between the variables chosen to model the exposure of a vessel to a hazard. A complete statistical expression of all dependent variables is not feasible within the scope of this study (or even possible with the available databases used here). The additive approach is conservative because it would result in a higher estimate of casualty potential that the multiplication of the fractional values for each variable (as would be done if all of the variables were completely dependent).

In some cases the sum of the contributing factors is multiplied by a set of conditions which serve to aggravate the factors. For instance, fatigue of the bridge watchkeepers may aggravate their sub-optimal collision avoidance performance when they are exposed to poor visibility, high traffic volumes, and external navigation failure.

10.2.3.3 Assigned Value

The Assigned Value is a subjective weighting factor which is applied to the Exposure Index of each Sub-category. This value is a collective expression of the relative likelihood of a sub-category resulting in a significant casualty (typically associated with extensive hull damage). Assigned Values are determined by ranking sub-categories within a category. The sub-category having the highest likelihood of resulting in a casualty is given an Assigned Value of 10 and the remainder are ranked accordingly. For instance if an error in ship-handling was deemed to be the most likely error to result in a casualty it would be given an Assigned Value of 10. If an error in collision avoidance was only half as likely to result in a casualty, its Assigned Value would be 5.

10.2.3.4 Priority Index

A Priority Index is calculated for each sub-category on each route segment. It is the product of the Exposure Index and the Sub-category Assigned Value. For each route segment, the Priority Indices are summed to provide the Casualty Potential. Figure 4 depicts the calculation of the Priority Index.

10.2.4 Identification of Sub-categories for the MV *Arctic*

Tables 2.2 through 2.4 list significant Sub-categories within the three categories, as well as the Assigned Values used to determine the Casualty Potential for each route segment.

Sub-categories were determined from an evaluation of the Zurich Hazard Analysis, Task 5 reports, and the MCIS database. Each Sub-category grouped related causes of casualties together. Types of causes are listed in detail in Appendix E. One or more sources provided support to the inclusion of each Sub-category.

In order to provide the tools necessary to minimize the most significant risks of the MV *Arctic* operations from Bent Horn to Montreal, it was decided to focus on operations which could result in a spill of significant proportions such as the rupture of at least one cargo tank. Therefore, operations and tasks which could have critical or catastrophic consequences were designated as sub-categories. Operations such as oil transfer (unlikely to cause a spill of significant size) were not designated as sub-categories.

The precise wording of operational tasks or equipment failure groups described in each information source varied, but it was similar enough to enable a comparison of the sources and development of the sub-categories. For example, the Task 5.4 report did not have a "ship-handling" task, but did highlight the task "maintaining course" as critical to the safety of the ship. Similarly, the Zurich group did not identify the task of ship-handling at Montreal, Bent Horn or along the route, but it did identify the hazard of a "ship moving off berth - Bent Horn" with an effect rating of negligible. Maintaining course would include controlling the ship's course and speed, in other words ship-handling or conning.

Figure 4 Flow Chart of the Priority Index Calculation (using the Ship Handling Sub-category as an example)

10.2.5 Derivation of Assigned Values

Assigned Values were chosen to reflect the best information available from the MCIS database, the Zurich Hazard Catalogue, Task 5 reports and other sources. The use of combined sources was chosen since probabilities of cause and effect could otherwise not be determined without heavy reliance on the statistical manipulation of a casualty database such as Casmain or MCIS (both which comprise mostly non-Arctic geographic data).

In general, the ranking schemes used in Task 5 and the Zurich Hazard Analysis varied in terminology, but provided essentially the same qualitative information. The Zurich Hazard Analysis ranked hazard effects as negligible, marginal, critical or catastrophic in terms of the magnitude of spill that was possible given the occurrence of a type casualty. For example, "catastrophic" would involve a major spill resulting from the breaching of two or more tanks. Similarly, "negligible" was associated with a minor spill that might result from a hose breakage. The Task 5.4 report ranked tasks in terms of their importance to the "safety of the ship" on scale from 0 (no importance) to 9 (critical). This scheme is closely focused on ship safety and the risk of a casualty (a comparable ranking was achieved from the MCIS database). Tasks which the bridge officers ranked as 7 or greater were described as "very important" (Buck and Webb, 1992). The derivation of the relative proportions ascribed to the MCIS database is discussed in Appendix E.

A second problem in deriving absolute weightings of cause and effect became apparent in the Task 5 reports. The ranking schemes chosen by the various sub-tasks were relative (not absolute), and different definitions of cause and effect prevailed. For example, Task 5.4 defined the importance of human performance tasks on a scale which considered the safety of the ship. In other words, a relative indication of perceived casualty severity was provided which may or may not include consideration of the potential consequences of a casualty. Similarly, analysis of the MCIS database provided the frequency of occurrence of casualties and related statistics, not consequences. The Zurich Workshop results also indicated the relative importance of a hazard in terms of its potential effect. In that report, effect included severity of damage to the ship and or a potential spill. Therefore, the estimation of absolute cause and effect probabilities from the output of Task 5 were not attempted.

Given the qualitative nature of the rankings and definitions provided in source reports and databases, the Assigned Values are subjective weights intended only to proportion the type activities responsible for a serious casualty within each category. Tables 2-2 to 2-4 show the derivation of Assigned Values for each Category. An inspection of these tables reveals a close correspondence between the descriptive and numerical rankings of the subtasks and the assigned values with the exception of the Zurich group rating of negligible for ship-handling. This peculiarity is due to the rating of the ship moving off of her station at Bent Horn. The task of handling a ship at Montreal which could result in a striking was not evaluated.

Table 11 Human Performance Assigned Values

Sub-category	Relative Importance			Assigned Value
	Task 5.4 (Task Importance)	Zurich (Effect Category)	MCIS *	
Ship-handling	Very Important	Negligible	.50	10
Navigation	Very Important	Catastrophic	.19	8
Collision Avoidance	Very Important	Critical	.11	5
Machinery Operations	--	Critical	.20	4
Fueling Operations	--	Negligible	--	0

*Proportion of MCIS casualties with a contribution from the sub-category

Table 12 Equipment Failure Assigned Values

Sub-category	Relative Importance			Assigned Value
	Task 5.2 « (Task Importance)	Zurich (Effect Category)	MCIS*	
Hull Structure	.29	Catastrophic	.39	10
Main Engine	.45	Critical	.36	9
Propeller	.02	Critical	.03	5
Steering Systems	.07	--	.08	4
Electrical Generators	.17	Negligible	.15	1

« Proportion of incidents per running hour. Only 5 critical generator incidents are included.

*Proportion of MCIS casualties with a contribution from the sub-category

Table 13 Undetectable Ice Assigned Values

Sub-category	Relative Importance			Assigned Value
	Task 5.2 (Task Importance)	Zurich (Effect Category)	MCIS (%)	
Multi-year Ice Inclusion	10/20[1]	--	--	10
Growlers	Only one impact	Marginal	--	10

Note 1. Ten out of twenty undetected encounters with old ice resulted in impacts of heavy severity according to bridge observers (based on an extraction from IDIADS database, Canarctic, 1992).

In the Undetectable Ice Category both multi-year ice inclusions and growlers were given an Assigned Value of 10. Impacts with either of these ice types is considered serious (D. Loughnane, pers. comm., 1992). Since no other information was available to rank the relative severity of these two sub-categories, they were given identical Assigned Values.

10.2.6 Derivation of the Exposure Indices

Table 14 lists the general factors which comprise the Exposure Indices. These were identified to be important causal factors in Task 5 reports and in the marine casualty literature. Numerous authors have recognized and assessed contributing factors to marine casualties. The following authors have collectively analyzed most of the factors identified in this study: Dickins and Krajczar, 1990, Cohen and Aylesworth, 1990, Commission of European Communities, 1988, Lamb, 1987, Cockcroft, 1982, and Wenk, 1982. In order to determine the relative importance of these factors, hazardous thresholds were defined and the relative incidence of occurrence of each factor was measured.

Table 14 Exposure Index Factors

Wind
Wave Height
Currents
Wind-chill
Ice
Icebergs
Rain/snow
Visibility
Fatigue
Survey Accuracy
Topographic Relief
Communications
Nearness to Land
Traffic Volumes

Tables 15 through 18 highlight the applicable Exposure Index factors and hazard threshold values used to model each Sub-category. Each Sub-category is then discussed in terms of its associated Exposure Index factors and hazard thresholds to highlight the relevance of each factor. Hazard thresholds are used to indicate the point at which the presence of a hazardous condition or factor is likely to contribute to a casualty. Values above the threshold value are expressed as either the percentage occurrence per unit time during the August 15 to September 30 period (e.g., wave height frequency $\geq$ 1 m) or as a percent of the route segment length (e.g., cross track currents $\geq$ 1 knot). The use of thresholds in this way is common in marine traffic analysis (e.g., Cockcroft, 1982).

The selection of contributing factors and their hazard levels is discussed for each sub-category following Table 17.

Table 15 Exposure Indices for Human Performance by Sub-categories

Exposure Index		**Sub-category**			
Factor	Threshold	Ship-Handling	Navigation	Machinery Operations	Collision Avoidance
Wind speed	≥ 20 knots	X			
Wave height	≥ 1 metre		X		X
Wave height	≥ 3 metres	X		X	
% of segment with cross track currents	≥ 1 knot	X			
% of segment with along track currents	≥ 4 knots	X			
Wind-chill	≥ 1500 W per sq. metre			X	
Multi-year ice	≥ 1/10	X			X
Total ice	≥ 7/10	X			
Glacial ice	any	X			X
Precipitation	Mod/Heavy		X		X
Visibility	< 2.2 n.m..		X		X
External navigation aid failure	any		X		
Topographic relief	% poor relief (≤ 20 n.m.)		X		
Nearness to land	≤5 n.m.	X	X		
Vessel encounters	per n.m.				X
Bridge communications	% of highest rating	X	X		X
Fatigue of bridge-watchkeepers	% of highest rating	X	X		X

Note: X indicates factor is applicable

Table 16 Exposure Indices for Equipment Failure by Sub-categories

Exposure Index: Factor	Threshold	Sub-category: Hull Structure	Main Engine	Electrical Generators	Steering Systems	Propeller
Wave height	8 metres	X				
Multi-year ice	≥7/10	X				
Total ice	≥7/10		X	X		
Multi-year ice and total ice only	≥1/10 ≥7/10				X	X seg. 1
Multi-year ice and total ice 11	≥1/10 ≥9/10					X seg. 2-

Note: X indicates factor is applicable

Table 17 Exposure Indices for Undetectable Ice by Sub-categories

Exposure Index: Factor	Threshold	Sub-category: Multi-year Ice Inclusion	Growlers
Multi-year ice and total ice	= 1/10 ≥7/10	X	
Wave height	≥1 metre	*	X
Precipitation	Mod/Heavy	*	X
Visibility	< 2.2 n.m.	*	X
Glacial Ice			X

Note: X indicates factor is applicable
* assumed that inclusion is undetectable regardless of visibility or sea state

10.2.6.1 Ship-handling with Respect to Human Performance

The difficulty of ship-handling increases with winds, currents, adverse sea conditions, limited sea room due to draught constraints, icebergs, and sea ice. For all contributing factors, the number of engine or helm movements (which involve bridge communications) and fatigue will further decrease human performance. These factors comprise the Exposure Index used here for the Sub-category of Ship-handling. In practice many other factors could influence ship-handling, but there is no means of quantifying every possible influence.

In a review of short-range aids to navigation in the vicinity of Bent Horn by the Canadian Coast Guard, a preliminary threat rating was devised for the MV *Arctic* (Ireland, 1989). These threats included several of the geographic factors used in the derivation of Exposure Indices for this study. The rationale presented by Coast Guard was used here as a basis for formulating realistic hazard thresholds.

Adverse wind conditions could affect ship-handling at Montreal and Bent Horn where the positioning the ship precisely is critical. The Coast Guard threat rating value for wind speed (≥ 20 knots) was indicated to be "highly significant". This value was chosen to represent the hazard threshold for winds.

Threat rating values indicated by Coast Guard to be "significant" were chosen to represent the hazard thresholds for along track currents (4 knots) and across track currents (1 knot). Currents of this magnitude would only be realized in confined waters such as those in the Arctic Islands and the St. Lawrence River, therefore, along and across track current information was only obtained for route segments 1 through 6, 10 and 11. These data are summarized in Appendix A.

The Coast Guard study classified a wave height of 3 metres as a "highly significant" threat to a ship of 10,000 to 60,000 GRT. It is presumed that the threat of heavy weather in that study is associated with sea-keeping and ship-handling characteristics, as well as the effect of motion on the crew of the MV *Arctic* (United Kingdom, Ministry of Defence, 1983). This value was chosen as a hazard threshold for the calculation of an Exposure Index.

While the Coast Guard study indicates that a nearness to land of ≤ 400 metres is a highly significant threat, Canarctic (1992) suggests that 5 nmi. provides a more appropriate measure of a narrow channel based upon its experience in Arctic waters. This is intuitively a safer estimate of the threshold of the danger posed by the proximity to shoals in waters covered only by small scale, poorly sounded hydrographic charts (characterizing much of the Arctic).

High ice concentrations place demands on ship-handling and routing. As multi-year ice is hazardous and transiting through ice requires more power and slower speeds than open water, a vessel will actively avoid ice where possible. In low to medium ice concentrations, routing is relatively easy. As concentrations increase, the bridge officers spend more time selecting routes through leads and open water areas. This changeover takes place at about 6-7 tenths ice concentration. The minimum concentration for close pack ice as defined by WMO (1970) is 7 tenths and is used here as the threshold value to indicate the need for more demanding ice routing decisions (operations in ice concentrations > 7 tenths involve unavoidable impacts with floes). Data from the IDIADS database was used to calculate frequency of total ice concentrations ≥ 7 tenths.

The presence of any multi-year ice or growlers requires increased attention on the part of the crew. Collisions with multi-year ice, regardless of surrounding ice concentrations, are potentially hazardous. The same is true of impacts with glacial ice (icebergs, bergy bits, and growlers). Frequency of multi-year ice concentrations ≥ 1 tenth were calculated from the IDIADS data presented in Task 5.1 (see Appendix B for derivation of values). Frequency of parent ice (iceberg and bergy bits) as well as frequency of growlers was used to determine growler hazards. Glacial ice data from the IDIADS database was converted from frequency per nmi. to frequency of time that the ice would be within 2 nmi. of an approaching vessel.

Conning the ship involves verbal communication between a bridge officer and a helmsman. However, there is no intermediary required for engine movements (Buck and Webb, 1992). Communication "face to face" is critical while conning and the frequency of the requirement to con the ship varies with the ship's current activity. Conning requirements are heaviest when approaching or leaving a berth, when maintaining course in a river, when transiting fishing grounds or when maneuvering clear of glacier or sea ice. Therefore, increased "face to face" communication requirements accompany these activities.

Despite the rating of maintaining course as a "very important" activity, face to face communication was not highlighted as a demanding or stressful component of ship-handling (Buck and Webb, 1992). No threshold is apparent, but it is most likely that the relative variation of this causal factor along the Canarctic route would be reflected by a direct proportional relationship between communications frequency and the chance of error. On a scale of 0 to 9, bridge officers rated these demands as 2.5 to 4.5 (0 = No physical, perceptual or mental effort required; 9 = Intense physical, perceptual or mental effort required). The ratings for the demands of this task relative to the highest rating are used in the derivation of the Exposure Index as a multiplier of the other time/frequency based contributing factors.

Buck and Webb (1992) grouped the fatigue experienced by MV *Arctic* bridge-watchkeepers into minor and major categories. The fatigue followed a pattern which "matched the disruptions of watch cycles, circadian rhythm and overtime reported during interviews" (Buck and Webb, 1992). The most frequent occurrence of major fatigue is described as "remote" or "may be experienced" (Route Segments 1, 2 and 3), whereas the highest average rating for minor fatigue was "occasional" (Route Segments 1 and 2). As minor fatigue was described on each route segment and had more variance between segments, it was a better basis for relative comparison than major fatigue. Therefore, occasional minor fatigue is used as the indicator of route segments where sub-optimal human performance is possible due to sleep disruptions and overtime.

10.2.6.2 Navigation with Respect to Human Performance

Factors which degrade the performance of navigation equipment, reduce visibility, or restrict the sea room (narrow channels, inadequate charts) affect one's ability to safely navigate a passage. Bridge communications and fatigue aggravate human performance in response to these hazards.

The ship's radars are crucial pieces of navigation equipment. Degradation of radar below normal values requires increased effort on the part of the crew to tune the radars and interpret returns. Radar performance is degraded by weather echoes and sea clutter (which may obscure navigational beacons, buoys or the shoreline), and is limited where the topographic relief gives a poor return.

The intensity of weather echoes, is dependent upon the radar in use; however, a poorer return is dependent upon the amount of precipitation. "Echoes are not usually produced by fair-weather cumulus clouds or by clouds from which only drizzle or very light rain is falling" (United Kingdom, Ministry of Defence, 1977). Moderate or heavy rain, hail, sleet and snow are all associated with weather echoes. Therefore, the frequency of moderate/heavy rain or snow is applied to the Exposure Index for navigation as an indication of potentially degraded information.

Sea clutter is quite apparent on a radar display when wave crests break. This is associated with a Beaufort wind force of 3 to 4, or wind speeds from 7 to 16 knots and a wave height of 1 metre. Frequency of waves $\geq$ 1 metre was used here to determine the severity of this factor.

Reduced visibility not only necessitates the use of radar equipment for navigation, but also involves a heightened listening watch for the whistles of ships and the sounds of buoys and other navigation aids. These activities are more demanding than visual navigation. A hazard level was selected based on a visibility which would require the crew to rely almost entirely on radar navigation. Assuming that a ship's position is in doubt and the ship is unknowingly proceeding towards a danger at a reduced speed of 10 knots in 2 miles visibility, she will have only 12 minutes to alter course to avoid grounding. Assuming a 7 minute time to turn 90°, this leaves only 5 minutes for the crew to visually recognize the danger and reach a decision on course changes. Visibility of less than 2.2 n.m. has also been selected by others (Eclectech Associates, 1981) as a reasonable threshold of restricted visibility.

The failure rates of navigation systems which are external to the ship, such as radio beacons, satellite navigation systems, and remote sensing systems are negligible except for High Frequency radio communication and facsimile transmission. The primary influence of radio black-outs or poor facsimile quality is ionospheric propagation disturbances in the Arctic (Dickins, 1992). The likelihood of these disturbances was derived in Task 5.3 and were used to determine the probability of external navigation system failure.

The benefit of nearness to land to visual navigation is countered by the hazards presented by shallow waters and channel constraints. The primary concern when safely navigating a passage is avoiding dangers such as shoals, reefs, and pinnacles. While the ability to position fix by visual means is obviously dependent upon the nearness to land, this proximity brings a vessel closer to these dangers and poses a greater threat from the consequences of error. The Canarctic threat rating of a channel of 5 n.m. width (also used in ship-handling) is used here to define the channel width threshold related to navigation.

Safe navigation is also dependent upon the quality of charts. Limitations of scale and survey accuracy are factors which may lead to groundings on uncharted rocks. The only information made available to Task 6 was the survey dates of the hydrographic charts, which on their own do not provide for a suitable assessment of accuracy. This potentially important factor could be included in future work if an assessment of sounding density, or the number of soundings per unit area, was conducted.

As with ship-handling, bridge communications and occasional minor fatigue are included as multipliers of all the factors contributing to sub-optimal human performance related to navigation. See section 2.6.1 for a description of these two factors.

10.2.6.3 Machinery Operations with Respect to Human Performance

The difficulty of operating critical machinery in the engine room, cargo spaces, on the weather decks, or even the galley increases with adverse sea conditions and with wind-chill. "Violent motion may reduce the efficiency of, or slow down, certain operations, such as those concerned with the control of engines" (United Kingdom, Ministry of Defence, 1983). In this way, sea conditions contribute to the potential for accidents which could result in serious flooding, fire or explosions, or equipment damage. The Coast Guard preliminary threat rating of 3 m wave heights (Ireland, 1989) is used here to indicate when human performance in the area of machinery operations begins to be affected by sea state.

Operation of machinery in a cold environment is characterized by equipment failures due to freezing temperatures as well as a reduction in human efficiency due to the necessity of wearing heavy protective clothing (Arctic Ship Safety, 1991). A suitable threshold for the wearing of heavy protective clothing is a wind chill factor of 1500 Watts/m^2 where exposed skin starts to freeze (Atmospheric Environment Service, Wind Chill Fact Sheet).

The frequency of waves $\geq$ 3 metres and wind chill $\geq$ 1500 Watts/m^2 comprise the two contributing factors of the Exposure Index for Machinery Operations.

10.2.6.4 Collision Avoidance with Respect to Human Performance

Many of the factors which contribute to an increased chance of an error in navigation also affect the task of collision avoidance. Collisions with multi-year ice, growlers, or other vessels are avoided primarily by the vigilant use of the gyro compass to assess bearing movement, by the plotting of the other ship's/or ice radar position to assess course and speed, or relative motion, and by the use of radio to establish another ship's intentions. Associated factors affecting collision avoidance include degradation of radar performance (wave heights $\geq$ 1 metre, moderate or heavy rain or snow), and restricted visibility. Visibility < 2.2 n.m. is used to represent restricted visibility since two ships proceeding head-on at 15 knots would only have 4 minutes to avoid a collision if they only detect each other visually at 2 n.m.. range. A further explanation of the hazard levels for radar degradation is given in Section 2.6.1

The probability of a collision is related to the physical presence of growlers, multi-year ice and other vessels. The frequencies of encountering multi-year ice $\geq$ 1/10, and growlers and parent icebergs, are applied to the Exposure Index for collision avoidance.

Collisions with other vessels have been consistently shown to have a linear relationship to traffic density (Judson, 1992; Canadian Coast Guard, 1991, Cockcroft, 1976).

Therefore, the incidence of vessel encounters is an important exposure variable when estimating the relative potential for collisions. The frequency of encountering other vessels was estimated for head-on and overtaking situations. See Appendix C for the derivation of vessel encounter frequency and traffic volume definitions and data.

The need for bridge communications increases in waters requiring interactions with other vessels and Vessel Traffic Services. However, it is the communication by radio with other vessels which is often associated with collisions due to language difficulties or misunderstanding. MV *Arctic* bridge officers indicate the demands for radio communications to be highest in the vicinity of Bent Horn, lowest and fairly constant from Austin Channel through to the Gulf of St. Lawrence, and slightly higher in the St. Lawrence River (Buck and Webb, 1992). Since higher radio activity is related to interaction with the Canadian Coast Guard escort and the terminal rather than ship traffic, traffic volume data are considered a better indicator of the relative frequency of an error in communication which may lead to a collision at sea.

As with ship-handling and navigation, an increased level of bridge communication and fatigue also increases the possibility of sub-optimal performance when a hazard is present (see Section 2.6.1 for descriptions of these two factors).

10.2.6.5 Hull Structure with Respect to Equipment Failure

Two contributing factors comprise the Exposure Index for hull structure: the probability of the vessel breaking up at sea and the probability of multi-year ice impacts.

There is a remote possibility of catastrophic failure of a vessel in extreme seas. These incidents are, at least on the first order, beyond the control of the crew. Violent storms are defined on the Beaufort Scale as those with mean wave heights greater than 9 m. The wave height data available (from the Atmospheric Environment Service) provides a wave height class for all waves greater than 8 m (higher wave heights classes are not available). Frequency of wave heights ≥ 8 m was used as a contributing factor in hull failure.

In extreme ice conditions the vessel may have no alternative but to transit through areas of multi-year ice. Multi-year ice concentrations ≥ 7 tenths represent an environment where frequent contact is almost unavoidable (isolated contacts will occur at much lower concentrations–see further discussion of sub-categories related to Undetectable Ice). Frequency of these conditions have been calculated from the IDIADS data presented in Task 5.1 (see Appendix B).

10.2.6.6 Main Engine with Respect to Equipment Failure

The probability of a main engine failure may increase when the cooling system is clogged by pieces of ice. Ice clogging of the intakes would most likely occur during icebreaking. Total ice concentrations ≥ 7 tenths are used a conservative threshold value (in lower concentrations the vessel would be able to travel in the open water areas between the ice).

Although somewhat tenuous, this was the only direct link to natural or external conditions that could be attributed to main engine failures. The effect of this link (admittedly conservative) was found to be insignificant in the overall risk framework.

10.2.6.7 Electrical Generators with Respect to Equipment Failure

Electrical generator failures may also increase if the cooling system was frequently clogged by pieces of ice. The criterion developed for clogging of the main engine intakes (total ice concentrations ≥ 7 tenths) is used again here. As with the main engine, this was the only conceivable link between natural and external conditions and equipment reliability data used to determine the Assigned Value. Its inclusion at this stage is conservative and does not affect the overall outcome of the risk analysis.

10.2.6.8 Steering Systems with Respect to Equipment Failure

Pieces of multi-year ice can damage the rudder in extreme conditions. For this situation to occur the vessel would have to be icebreaking and therefore combined concentrations of at least 7 tenths of thick first-year and multi-year ice are required. For rudder damage an indicator of multi-year ice ≥ 1 tenth in total concentrations ≥ 7 tenths is used as a conservative threshold.

10.2.6.9 Propeller with Respect to Equipment Failure

Multi-year ice can damage the propeller if trapped in the propeller nozzle. During normal forward operations this is extremely unlikely, but it may occur when the vessel is backing. (It should be noted that the propeller of the MV *Arctic* has never been damaged by ice.) Backing is used as a maneuver during ramming of thick ridges of strong first year ice, or at the terminal to maneuver into position for berthing. Unfortunately, predictions of ice strength and ridging is beyond the scope of the data collected in Task 5.1. Instead, a combined ice concentration of first-year and multi-year ≥ 9 tenths is used to indicate the probability of backing and multi-year ice concentrations ≥ 1 tenth are used to indicate the probability of encountering multi-year ice while backing.

At Bent Horn, backing can be required regardless of ice concentrations, but only high concentrations would not be pushed aside by the movement of the vessel. Consequently, a reduced threshold of combined concentrations ≥ 7 tenths with multi-year concentrations ≥ 1 tenth is used as a contributing factor on segment 1 only.

10.2.6.10 Multi-year Ice Inclusion with Respect to Undetectable Ice

Given that multi-year ice floes may be undetectable when amongst rubbled, snow-covered first year ice, collisions with inclusions pose a serious threat to hull integrity. A close pack ice cover necessitating some icebreaking in combination with a variable multi-year ice concentration represents an environment where undetected multi-year ice could impact the vessel. A specific condition involving total ice concentrations ≥ 7/10 in combination with multi-year ice from 1 to 6 tenths is used to define this factor (collisions with detectable multi-year ice are covered in the Equipment Failure category).

10.2.6.11 Growlers with Respect to Undetectable Ice

The low profile of growlers provides a poor radar target which is further exacerbated by sea clutter and weather echoes on the radar return and by restricted visibility. The Exposure Index is calculated by adding the factors of radar degradation (moderate and heavy precipitation and waves $\geq$ 1m) and visual undetectability (visibility $<$ 2.2 n.m.) and multiplying these by the relative occurrence of growlers and parent ice. (The presence of parent ice in the form of icebergs and bergy bits is used as a relative indication that growlers may be present).

10.3.0 RESULTS

10.3.1 Characterization of Results

Table 18 presents a summary of the final casualty potential. Detailed tables presenting all the contributing factors and exposure index values for each segment are presented in Appendix G.

As expected, the two terminals have high casualty potentials: Bent Horn is ranked as the highest segment while Montreal is the third highest.

The two lowest ranked segments represent open ocean with no ice (Labrador Sea) and the protected, but still relatively open, waters of the Gulf of St. Lawrence (no ice present in August/September).

Table 18. Summary of Casualty Potential (August 15 to September 30)

Route Segment	General Location	Casualty Potential (as % of highest risk)	Rank
1	Bent Horn Terminal	88	2
2	Byam Martin Channel	65	4
3	Boyer Strait	100	1
4	Austin Channel	52	6
5	Barrow Strait	36	8
6	Lancaster Sound	31	9
7	Baffin Bay	45	7
8	Labrador Sea	23	10
9	Gulf of St. Lawrence	18	11
10	St. Lawrence River	55	5
11	Montreal	85	3

The sub-categories of Human Performance dominate the Casualty Potential in every segment. Figure 5 shows the distribution of the Casualty Potential on each segment. On the southern segments, Human Performance dominates totally, while in the Arctic, Equipment Failure and Undetectable Ice contribute somewhat. Undetectable ice accounts for 15% of the Casualty Potential on Route Segment 7 (the maximum contribution of this category) and Equipment Failure contributes 15% on Route Segment 3. These results compare well with the distribution of casualty cause determined from MCIS year round data where 82% of casualties were due to human performance, 9% from equipment failure and 9% by ice problems unrelated to human performance (Tables E2 to E4).

Figure 3-2 shows the breakdown of the Human Performance Sub-categories. Ship-handling and Navigation are in general the most important sub-categories. Ship-handling is especially important at the terminals, on the St. Lawrence River and on some of the ice-infested segments. In general whenever Ship-handling is important the Casualty Potential is also high. On segments 8 and 9, where the Casualty Potential is lowest, Collision Avoidance is more important than Ship-handling. Machinery Operations contribute very little to the Human Performance category in part due to the extreme conditions necessary to bring sub-optimal performance into the handling of equipment. On segment 8, where the wave climate is the most severe, Machinery Operations comprise 3% of the Casualty Potential.

Single sheet summaries highlighting the casualty potential, contributing hazards, and environmental sensitivities on each segment are presented in Section 3.2.

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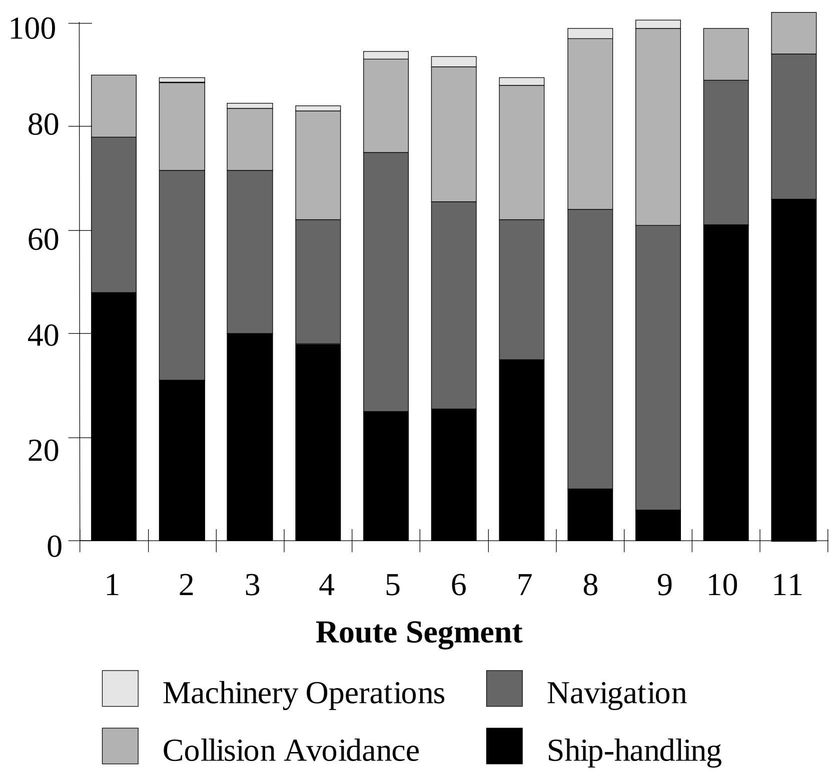
Figure 3-1. Contribution of Categories to Casualty Potential

Figure 3-2 shows the breakdown of the Human Performance Sub-categories. Ship-handling and Navigation are in general the most important sub-categories. Ship-handling is especially important at the terminals, on the St. Lawrence River and on some of the ice-infested segments. In general whenever Ship-handling is important the Casualty Potential is also high. On segments 8 and 9, where the Casualty Potential is lowest, Collision Avoidance is more important than Ship-handling. Machinery Operations contribute very little to the Human Performance category in part due to the extreme conditions necessary to bring sub-optimal performance into the handling of equipment. On segment 8, where the wave climate is the most severe, Machinery Operations comprise 3% of the Casualty Potential.

Figure 3-2. Contribution of Human Performance Sub-categories



Single sheet summaries highlighting the casualty potential, contributing hazards, and environmental sensitivities on each segment are presented in Section 3.2.

10.3.2 Route Segment Risk Summaries: Segments 1 to 11

not included

10.3.3 Risk Profile

The risk diagram presented in Figure 7 provides a graphical means of displaying the relative contributions of both sides of the generic risk equation expressed as

Risk = f(Frequency x Consequences)

In this study the frequency of an event (oil spill) is assumed to be related strongly to the potential for having a significant marine casualty. The environmental consequences are represented by a cumulative sensitivity ranking–a crude indicator of the relative severity of the worst consequences in the case where the coastline along an entire route segment is oiled in a catastrophic spill.

Given the number of variables involved in each risk factor and the uncertainty of defining the functionality in the above equation, it is not considered realistic at this stage of analysis to compute an actual risk value by multiplying sensitivity and casualty potential in some absolute form.

Instead, the risk diagram provides a clear indicator of which segments are most "risky" in terms of sensitivity alone (reading up the y-axis), in terms of potential for a casualty or spill (reading along the x-axis), and in terms of the overall risk expressed as a combination of both factors (reading along a 45° line from the zero origin–see the arrow of increasing risk).

Figure 7. Risk Diagram

10.4.0 SUMMARY AND CONCLUSIONS

10.4.1 Summary

This report contains the results of a two step process: First, to develop a casualty profile of the entire route from Bent Horn to Montreal (using the output from earlier Tasks); and Second, to summarize the overall risk within each segment (made up of both the casualty potential and environmental sensitivity).

The casualty profile examines operations during the August 15 to September 30 navigation season. Results show that the casualty potential is highest at the terminals, the St. Lawrence River and in the high Arctic due primarily to oceanographic and/or ice conditions present (Table 3-1). As expected, human performance was determined to be the greatest contributor to marine casualties followed to a much lesser extent by equipment failure and undetectable ice (Figure 5).

Risk summary sheets provide a synopsis of the primary environmental concerns and operational considerations for each route segment. They are designed to provide the mariner with an overall appreciation of the environmental risk illustrated by the risk diagram (Figure 7). The most important operational considerations are summarized below.

Ship-handling and navigation difficulties were shown to be the most important contributors to casualty potential, followed closely by the collision avoidance and to a much lesser extent by the machinery operations sub-categories (Figure 6). Seventeen exposure variables were used to characterize the variation in casualty potential due to sub-optimal human performance (Table 15). Of these, eight could be considered primary contributing factors.

Nearness to land and across track currents are primary factors of concern at Bent Horn and in the St. Lawrence River. Multi-year ice is a significant hazard to ship-handling and collision avoidance from Route Segments 1-5 in the high Arctic. Glacial ice is a concern for ship-handling and navigation along Route Segment 7. Poor topographic relief is also a navigation consideration along Route Segments 1-3. The potential for sub-optimal radar navigation or collision avoidance due to radar clutter caused by wind driven sea-state echoes is apparent along Route Segments 4-10.

Communications and fatigue compound human performance difficulties. It is difficult to conclude that fatigue is more dominant on any one route segment over another, given the low importance and minimal variation reported by ships officers. Higher than average ratings were evident for Route Segments 1-6, with the highest ratings given for Route Segments 1 and 2 (Table D-2). Communications demands are higher than average in the vicinity of Bent Horn (Route Segments 1-3) as well as in the St. Lawrence River and the Port of Montreal.

Extreme wave heights and various ice hazards were used as an exposure index to characterize possible variations in the types of equipment failure that would be dependent upon geographic factors along the Canarctic shipping route (Table 16). The potential for critical casualties related to equipment failure was greatest in the Arctic due to ice concentrations (Figure 5 and Appendix G).

The presence of multi-year ice inclusions, as well as the presence of parent glacial ice compounded by restrictive wave heights, precipitation and visibility, were used to characterize the variation in the undetectable ice hazard. The potential for casualties caused by undetected ice is present from the high Arctic to the northern tip of Labrador and is greatest along Route Segment 7 due to the presence of glacial ice (with associated growlers and bergy bits) and restrictive detection conditions (Figure 3-1 and Appendix G).

A comparison of Casualty Potential and Environmental Sensitivity showed a greater overall risk is present in the high Arctic and in the St. Lawrence River. A risk diagram was used to illustrate the relative contribution of both environmental sensitivity and casualty potential without losing information through the multiplication of "event frequency by consequences" (Figure 7). The benefit of this method of displaying increasing overall risk is apparent from the examination of the Bent Horn Route Segment where a high overall risk is driven by a very high Casualty potential and a low Environmental Sensitivity.

10.4.2 Conclusions

A methodology was originally conceived whereby the frequency of marine casualties and their causes were estimated through the analysis of a marine casualty database. This procedure would have involved the manipulation of the database to reflect local geographic conditions and the experience of the mariner (casualty data for the Arctic is not yet sufficiently large enough to generalize about the site-specific details of factors contributing to causes of marine casualties). This original approach was considered unworkable for the following reasons:

1. There is no credible way of comparing the casualty risk associated with a "typical" deep sea bulker (represented by the marine casualty database) and the MV *Arctic.*

2. There appears to be no acceptable method for comparing any assessment of human performance on the MV *Arctic* to that of a "typical commercial vessel crew".

Instead, a Casualty Potential index was developed which not only enabled the ranking of casualty potential, but also organized causes and contributory ship specific factors in a logical framework. This method integrated the experience of ships officers familiar with local operating conditions. This framework lends itself to modification and improvement in future work related to the weighting of exposure index variables and refinement of the model.

The identification and measurement of factors which contribute to casualty potential for a specific vessel along each route segment was the main objective of the analysis. When considered together with the sensitivity of the environment, the product could readily evolve into a planning tool which provides the most relevant summary information for the safe passage of any given vessel or vessel type. The results lend themselves to the development of a passage planning guide and for possible inclusion in a revised Arctic Pilot for use by watchkeepers, ship managers and government authorities.

REFERENCES

Arctic Ship Safety. 1991. Arctic Waters Oil Transfer Guidelines. TP 10783. Ottawa: Canadian Coast Guard, Coast Guard Northern.

Atmospheric Environment Service. Wind Chill Fact Sheet. Environment Canada.

A.E.S. (Atmospheric Environment Service). 1992. MAST runs for 8 areas definining the route corridor.

Buck, L. and R.D.G. Webb. 1992. Arctic Tanker Risk Analysis: Human Factors. Milton, Ont.: Prepared for Canarctic Shipping Company Ltd. by Humansystems Inc.

Canadian Coast Guard. 1991. 1991 Vessel Traffic Services (VTS) Update Study. Prepared for Canadian Coast Guard by Consulting and Audit Canada. TP 11267.

Canadian Coast Guard Nordreg Database 1990-1991, Ice Operation Centre, Halifax.

Canadian Coast Guard. 1991. Eastern Arctic Sealift Operation and Co-ordination Plan. TP2178 (1991).

Canadian Coast Guard. 1987. Examen des Systemes D'Aides a la Navigation Maritime de Courte Portee--Secteurs Quebec/Montreal. Unpublished.

Canarctic Shipping Company, Zurich Hazard Workshop. 1992. Zurich Hazard Catalogue. Unpublished.

Canarctic Shipping Company. 1992. Task 5.1 Report: Natural Hazards. Unpublished.

Canarctic Shipping Company. 1992. Task 5.2 Report: Internal Hazards. Unpublished.

Cockcroft, A.N. 1982. Cause Relationships of Collisions and Groundings. The Journal of Navigation. 35 (2), 305.

Cockcroft, A.N. 1976. Statistics of Collisions at Sea. The Journal of Navigation. 29, 215.

Cohen, P. and R. Aylesworth. 1990. Oil Spill Risk for Southern B.C./Northern Washington Coast Marine Area. Vancouver: States/British Columbia Task Force.

Commission of the European Communities. 1988. COST 301, Shore-Based Marine Navigation Aid Systems, Main Report. Luxembourg: Office for Official Publications of the European Communities.

Dickins, D.F. 1992. Task 3 Report: Definition of Environmental Sensitivity. Vancouver: Prepared for Canarctic Shipping Company Ltd. by DF Dickins Associates Ltd.

Dickins, D.F. 1992. Task 5.3 Report: Definition and Quantification of External Hazards. Vancouver: Prepared for Canarctic Shipping Company Ltd. by DF Dickins Associated Ltd.

Dickins, D.F, and K. Krajczar. 1990. Review of Tanker/Barge Safety. Vancouver: States/British Columbia Oil Spill Task Force.

Eclectech Associates. 1981. An At-Sea Experiment for the Comparative Evaluation of Radar Piloting Techniques. Washington, D.C.: United States Department of Transportation, United States Coast Guard Office of Research and Development.

Ireland, D. 1989. Bent Horn, N.W.T. - Short-Range Aids to Navigation Review. Ottawa: Canadian Coast Guard. Unpublished.

Judson, B.H. 1992. Collision Risk Circumstances and Traffic Routing in the Approaches to the Strait of Juan de Fuca. The Journal of Navigation. 45 (3), 1.

Lamb, W.P.G. 1987. The Calculation of Crossing Risk at Sea. The Journal of Navigation. 40, 52.

Stronach, J.A. et. al. 1987. Tidal Elevations and Tidal Currents in the Northwest Passage. Canadian Technical Report of Hydrography and Ocean Sciences No. 97. Sidney: Department of Fisheries and Oceans.

Transportation Safety Board of Canada Maritime Casualty Information System, 1977-1991, Ottawa.

United Kingdom, Ministry of Defence. 1983. Admiralty Manual of Seamanship Volume 3. London: Her Majesty's Stationery Office.

United Kingdom, Ministry of Defence. 1977. Admiralty Manual of Navigation Volume 2. London: Her Majesty's Stationery Office.

Wenk, E. 1982. Improving Maritime Traffic Safety on Puget Sound Waterways-A Technology Assessment. Seattle: University of Washington.

WMO (World Meteorological Organization). 1970. WMO Sea-Ice Nomenclature. Secretariat of the World Meteorological Organization, WMO/OMM/BMO No. -259. TP. 145, Geneva, Switzerland.