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LOW FRICTION HULL COATINGS FOR ICEBREAKERS

PHASE III TECHNICAL REPORT

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Rensselaer Polytechnic Institute

OCTOBER 1978

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
Office of Research and Development
Washington, D.C. 20590

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16. Abstract

Phase III is a continuation of the Low Friction Hull Coatings for Icebreakers program in which nonsolvented coatings gave the best protection for icebreaker hulls. This effort documents the reduction in resistance obtained, a laboratory study to determine the optimum application parameters, fouling characteristics and the cost benefit obtained from coating an icebreaker hull with the nonsolvented coatings.

In addition, a model test program was run to determine the effect of a partial hull coating.

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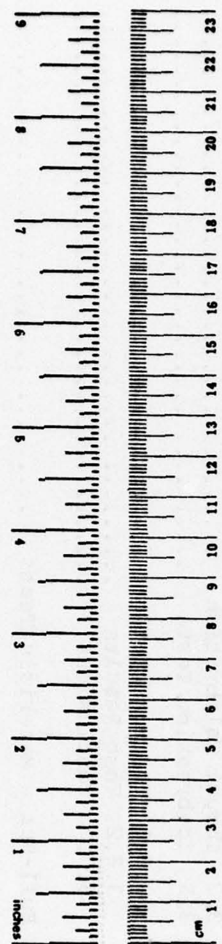
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

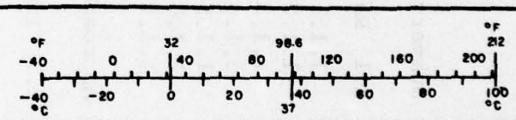
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SECTION 1
SUMMARY OF PROGRAM

Historically the hulls of Coast Guard icebreakers have not been coated since conventional coating systems are removed by abrasion within hours after the ship enters an ice field. Therefore the hull plating is constantly subjected to ice abrasion, corrosion and weld decay. Hull deterioration in turn results in a larger than necessary scantling design margin, more frequent hull repair and increased frictional drag.

Recognizing the potentionally large benefits to be gained from reduced corrosion and lower fuel consumption a three phase program was established by the U.S. Coast Guard to evaluate candidate materials for possible use as icebreaker hull coatings. The first phase [1] was concerned with a laboratory evaluation of candidate materials. The second phase [2] was concerned with full scale testing of the most promising materials on an icebreaker hull. This phase is concerned with the advantages or disadvantages of utilizing the best candidate materials as hull coatings.

During Phase I and Phase II it was shown that a nonsolvented polyurethane would remain 98% intact after one year of icebreaking service. During that effort certain qualitative statements were made concerning the advantages of using a coating of this nature. The Phase III portion of this program was aimed at obtaining more quantitative data concerning the advantages of using the coating.

1.1 Rationale for Program Tasks

1.1.1 Icebreaker Hull Resistance

There were indications that the most promising hull coating would reduce the resistance on the hull during icebreaking. Makinen has shown that the icebreaking resistance would decrease if a low friction coating was applied to the hull [7]. Vessel operators on the U.S. Coast Guard Cutter RARITAN have claimed that after coating the hull during the Phase II efforts less power was required during icebreaking. Further, laboratory evaluations indicated that a reduction in friction coefficient can be obtained if the hull is coated with the nonsolvented polyurethane. Therefore a task in this phase of the program was to obtain quantitative data on the hull resistance during icebreaking. To this end, two ships were instrumented and resistance measurements were taken during icebreaking.

1.1.2 Coating Antifoul Characteristics

The results of full-scale tests in which polyurethanes were used as hull coatings indicated that while the coating has no antifoul characteristic, the fouling material could be removed without damage to the coating. During this Phase III portion a series of tests were conducted by placing test panels in the water on both coasts of the United States. They were periodically removed, cleaned, inspected and placed back in the water for further testing. In addition, corrosion tests were performed on the test panels to determine how far the corrosion would progress underneath the coating if the polyurethane edges were exposed.

1.1.3 Additional Icebreaker Coatings

During Phase II a nonsolvented epoxy, Inerta 160 and an unfilled nonsolvented polyurethane, Zebron, were evaluated in the laboratory and gave promising results. Full-scale tests were performed with both materials. The Inerta 160 was applied to the USCG Cutter OJIBWA and the nonsolvented polyurethane (unfilled) was applied to a commercial icebreaker. In addition, both coatings were applied to the Coast Guard Cutter GLACIER.

1.1.4 Cost Benefit Analysis

There are several economic advantages to applying a low friction, wear resistant coating to an icebreaker hull. They include:

1. Reduction in maintainence
2. Reduction in power requirements during icebreaking
3. Fuel savings
4. Decrease in probability of the ship getting "stuck" in an ice field.

However, there also also disadvantages to the application of these exotic materials. They are:

1. Material cost
2. Small range of application conditions (temperature and humidity)
3. Specialized application equipment
4. Lack of qualified applicators.

In order to determine the cost benefit of applying these coatings to an icebreaker hull, an analysis was performed to compare the cost of applying the nonsolvented materials to current practice on the same hull. Projected savings due to a reduction in fuel consumption and lower hull maintenance cost were predicted for the economic life of four classes of icebreakers.

1.1.5 Partial Hull Coating

The cost for materials and application for the nonsolvented coatings is significantly higher when compared to the cost of a more conventional material. In some cases it might cost two to three times more to coat the entire hull. In order to reduce cost a task was initiated which would determine the areas on the hull which contribute most to the overall resistance in ice and only those areas would be coated with a low friction coating. A model testing program was performed by Arctec Incorporated to establish if this assumption was correct and what areas should be coated to obtain the highest cost benefit. It should be stressed, however, that the total hull must be coated for corrosion and fouling protection but this coating can be a less expensive material.

1.1.6 Environmental Parameters

The application and curing parameters which will give the best bond strength for the nonsolvented coatings are well defined. However, it is not always possible to obtain these conditions at a dry dock. Little is known concerning the coating properties when applied under less than optimum conditions. A study was conducted to determine the coating properties when applied under less than optimum conditions. The results allow one to determine what the properties of a coating might be if applied under poor conditions.

1.1.7 Environmental Control During an Icebreaker Coating

The use of an environmental chamber to control application conditions has been common practice in Finland for several years. The long winter and cold climate makes it necessary to use a technique such as this to obtain proper climatic conditions for the coating.

During the coating of the USCG Cutter OJIBWA, an environmental cover was used to obtain proper application conditions. The application and curing conditions attained are described in this report.

SECTION 2
APPROACH TO THE PROBLEM

2.1 Introduction

High frictional resistance of ice against the hulls of icebreakers is a problem which has existed for many years. Because of this, higher power is required than would otherwise be necessary. Even more serious, icebreakers and other vessels can become "stuck" in ice fields and considerable effort must be expended to free them. Any means to reduce the friction between the ice and the hull would be highly desirable. Several means have been proposed to reduce the friction and abrasion of ice either by improved design of the hull or by auxiliary devices. These have in several instances proved to be successful. They are, however, costly to install and maintain. A simpler approach is to identify a coating which would give lower friction against ice than the steel hull. Since hull maintenance is equally important the coating concept would also serve to protect the hull against abrasion and corrosion as well as reduce the resistance during icebreaking.

In order to achieve a reduction in resistance on the hull of an icebreaker and reduce wear on the plating, Phase I and II of this program were focussed on protective hull coatings. Phase I dealt with identifying materials and Phase II dealt with the problems of full-scale application and testing.

This report (Phase III) is concerned with the cost effectiveness of using an exotic coating material on an icebreaker hull and with further identifying problems which might result from the use of these coatings on all icebreaking vessels. In order to apply these materials at a dry dock, certain conditions and procedures must be met:

- Special application equipment is necessary
- Experienced applicators are required
- The application and curing conditions are more stringent
- Increased material cost when compared to standard coatings.

Our understanding of the effect of poor application conditions on the properties of a hull coating was incomplete. Therefore, one of the tasks in this Phase was to determine the optimum conditions for applying these exotic coatings. Conversely, another important portion of this task was to determine what the properties of the coating would be if one was forced to apply the coating under less than optimum conditions. This situation exists during approximately 40% of the dry-docking period in some climates. In order to meet dry dock scheduling, mission time or budgeted costs, it is, at times, necessary to apply the coating under adverse conditions. A series of tests were run in which the coating was applied under less than optimum conditions and the curing cycle was interrupted by moisture and cold temperatures. The bond strength of the finished coating was measured and compared to the same coating that was properly applied and cured.

A cost effectiveness study was performed to determine if a savings would be realized by applying an expensive and exotic coating to the hull of an icebreaker. It was found that a cost savings could be realized if a coating was applied. The extent of the cost savings is dependent on the size of the ship, the hull design, the condition that the hull was in before application and the economic life of the ship.

New materials were also tested for possible use as an icebreaker hull coating. Preliminary testing on a new nonsolvented epoxy manufactured in Finland was performed during the Phase II portion of this program. The laboratory evaluation was completed during the Phase III and the results were positive. The coating was then selected for further evaluation and applied to an icebreaker under controlled conditions. The results of this evaluation after one year of icebreaking service are encouraging.

SECTION 3

FULL-SCALE RESISTANCE TESTS

3.1 Full-Scale Tests for Ice Resistance

Laboratory testing has shown that various materials have different friction and wear characteristics when sliding against ice. Essentially the friction coefficient of a material will vary depending on the generic base, the surface roughness, ice temperature, speed, time in contact and presence of moisture on the surface. At the present time, it is difficult to determine mathematically the reduction in resistance obtained because there is little known about the contribution of friction to the total resistance of the ship. Therefore a method was devised to measure the total hull resistance during icebreaking. The method used was to compare the thrust of a ship coated with the nonsolvented polyurethane and a sister ship coated with a bituminous epoxy. Both ships were coated two years before the tests were performed. The ships used were:

USCG Cutter RARITAN - coated with nonsolvented polyurethane in July 1974

USCG Cutter ARUNDEL - coated with a bituminous epoxy during 1974.

Both ships have overall dimensions and characteristics as follows:

110 ft long (WYTM)

27.3 ft beam

12.25 ft draft

380 tons maximum displacement steel hull.

3.2 Thrust Calibration

A calibration was accomplished by subcontract to Arctec Inc. The procedure is discussed in Appendix A of this report. Both ship's power plants were "tuned up" by Coast Guard Naval Engineers immediately before calibration. This was to insure that both ship's amperage, voltage, and shaft speed were the same at each step. Data were taken at each power step in open water to establish a calibration curve of thrust vs shaft rpm. A series of curves were generated by ballard testing, tow rope and measured mile at each power step. A strain-gaged load cell was used to measure thrust while monitoring the shaft rpm. The load cell was essentially a shackle on which a full bridge strain gage circuit was mounted and precalibrated. The shackle was mounted in series with an 8 inch hawser line, tied to the towing ballard between the two ships or the ship and dock ballard, depending on the test in progress. Photographs showing the ships during the calibration are shown in Figures 1 and 2.

The shaft speed was monitored by a magnetic probe positioned to sense a key mounted in the drive shaft. The pulses from the magnetic probe and the signal from the strain gage were recorded on a dual channel strip chart recorder. The wind velocity and direction were measured during each run by an anemometer mounted on each ship. The ice thickness, temperature and texture were measured and recorded at the end of each run. The air temperature and relative humidity were also measured and recorded at the end of each run. A communications network was set up between ships, engine room, bridge and instrument room on each ship to establish a single "mark" time from the beginning and to the end of the test.

3.3 Icebreaking Tests

3.3.1 Instrumentation

During the icebreaking tests, the shaft speed was monitored by a light probe sensing a reflective pattern on the shaft in addition to the magnetic probe sensor used during the thrust calibration tests. The light probe was used to obtain an analog signal of shaft rpm and determine the fluctuation in speed at any given time. The magnetic sensor was used as a cross check against the light probe. The light signal was recorded on one channel of a strip chart recorder and the magnetic sensor was recorded simultaneously on a second channel. A sample of the data obtained is shown in Figure 3. The signal from the light probe was also read in parallel on a digital voltmeter at 15 second intervals throughout the testing period. All instrumentation was powered by a 12 volt wet cell battery which was converted to 110 volt AC. This procedure was used to eliminate the problems of ship's power fluctuation with engine speed.

The distance traveled was measured by navigational sightings on channel markings. The travel time was measured by three stop watches operated by testing personnel. The watches were spot checked and recorded at each power step during the test.

3.3.2 Test Results

A series of tests were run in brash ice in the Saint Marie River Channel immediately after the calibration test. Figure 4 shows the ice conditions during testing.

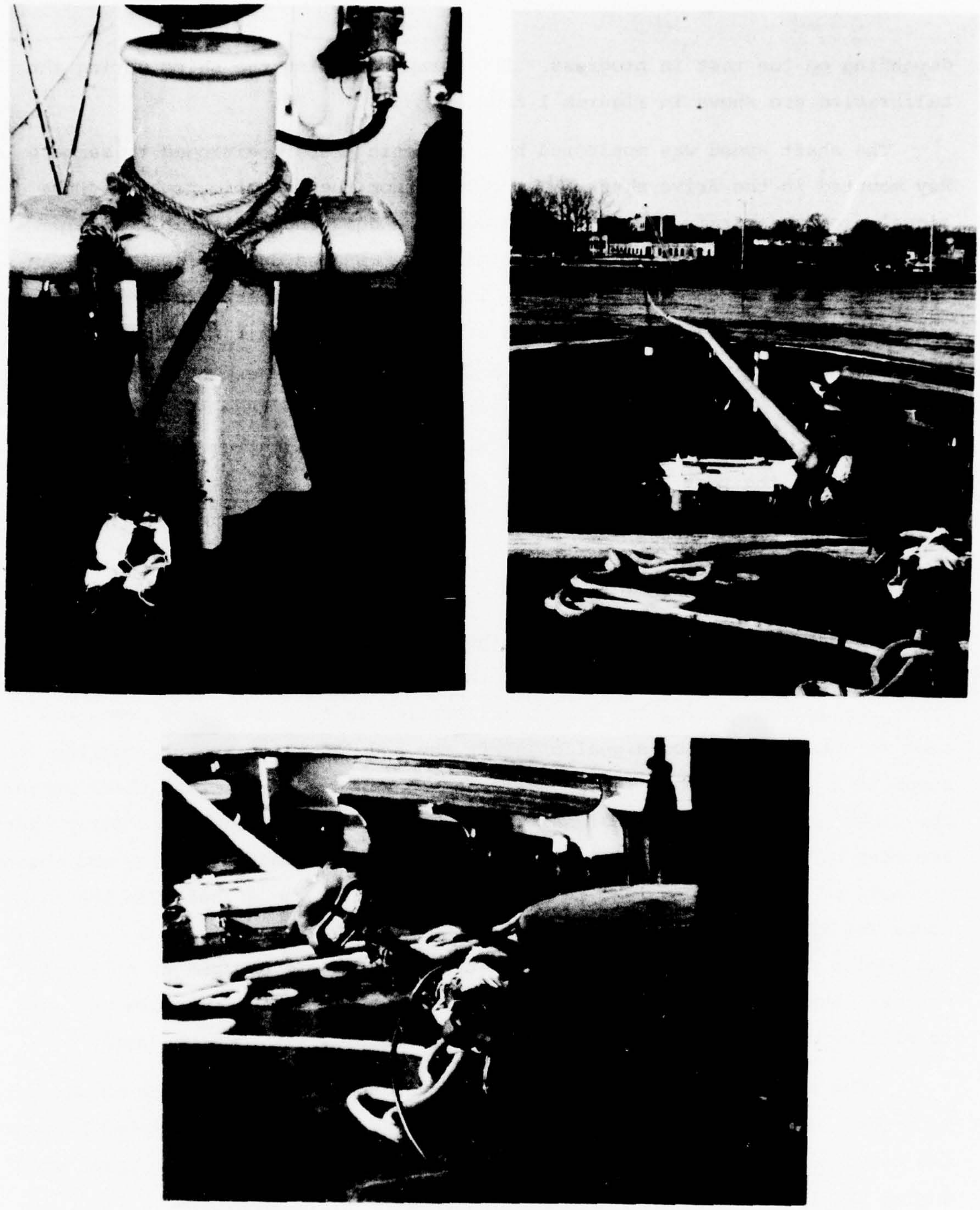


Figure 1 Photographs of the Instrumented Shackle Used to Calibrate the Thrust vs Shaft Speed During the Ballard Test Calibration. Photograph on the right shows the hawser attached to a dock-side ballard.

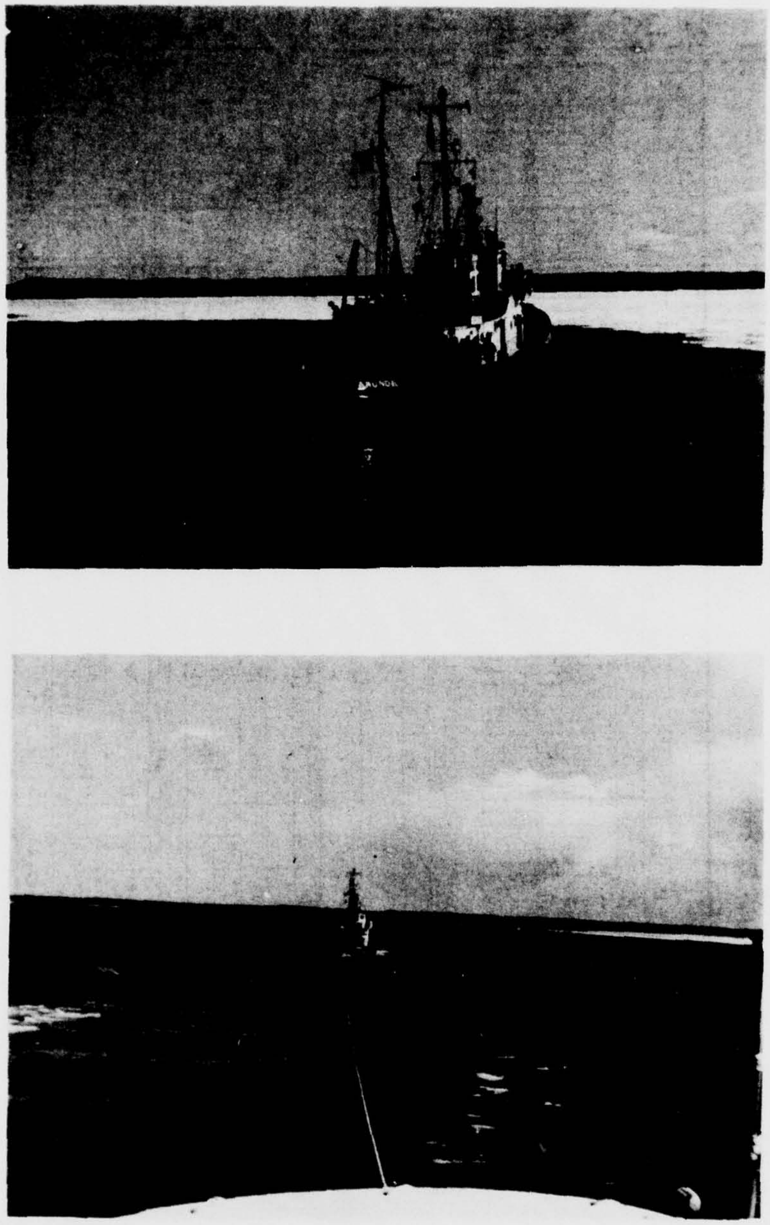


Figure 2 Photographs of the USCG Cutter ARUNDEL During the Tow Rope Pull Calibration

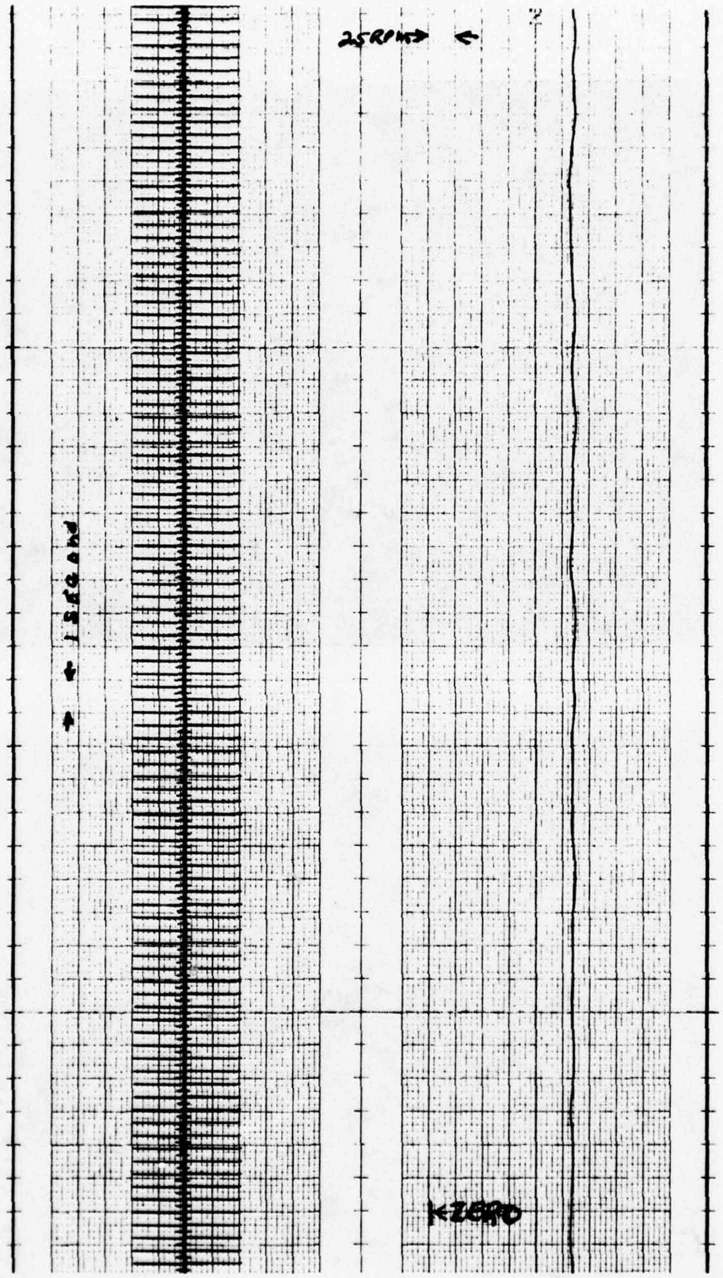


Figure 3 Typical Trace Obtained During the Full-Scale Ice Resistance Tests Obtained on the USCG Cutter RARITAN

Figure 4 Typical Conditions Existing During Full-Scale Testing in Brash Ice

A sighting was taken on a channel marker and a signal given when the ship had reached full power for that given power step. As the ship passed the markers a radio signal was given to start measuring time and mark the trace from the instrumentation. The ship proceeded to the next channel marker and as it passed, the radio signal was given indicating the end of the test. A continuous record was taken throughout the testing period. At that point the second ship would approach the first and pass it at full speed. Again the signal was given to start test and it would proceed to the next channel marker. The testing would proceed in this "hopscotch" manner, increasing power steps with each successive run. In this way, each ship would proceed through undisturbed brash ice without interference from the other ship and without acceleration effects.

Both ships would proceed in the same direction for each comparative test to reduce the effect of current and wind influences. The results of the brash ice test are shown in Figure 5. The Cutter RARITAN (polyurethane coated ship) gave a 15% reduction in power at 6 knots and an 8.0% reduction at 3 knots over the Cutter ARUNDEL. The reduction in power is increasing with the increasing speed as would be expected from previous friction laboratory tests. Table 1 shows the ice test condition for each run.

A second series of tests were run in a solid ice sheet field. The tests were inconclusive because of the condition of the ice. The tests were run in April when the ice had started to decay. The ice thickness ranged between 11 and 16" but the top 6" was soft with heavy pock marks. The results of the test were essentially the same as the brash ice except for one high point from both ships. Figure 6 shows the condition of the ice sheet during testing.

It should be noted that at one point during the testing, both ships were asked to proceed through the field at the lowest possible step. The RARITAN was able to proceed in the 5th step but the ARUNDEL had to proceed in the 7th step. Since both ships had essentially the same shaft horsepower, the difference in power requirement was attributed to the hull resistance.

3.3.3 Conclusions

The results from this evaluation indicate that the ship coated with the nonsolvented polyurethane gave a reduction in resistance varying from 8.0% to 15.0% depending on the speed. The tests were run on brash ice. The comparison made was with two sister ships coated approximately two years before testing.

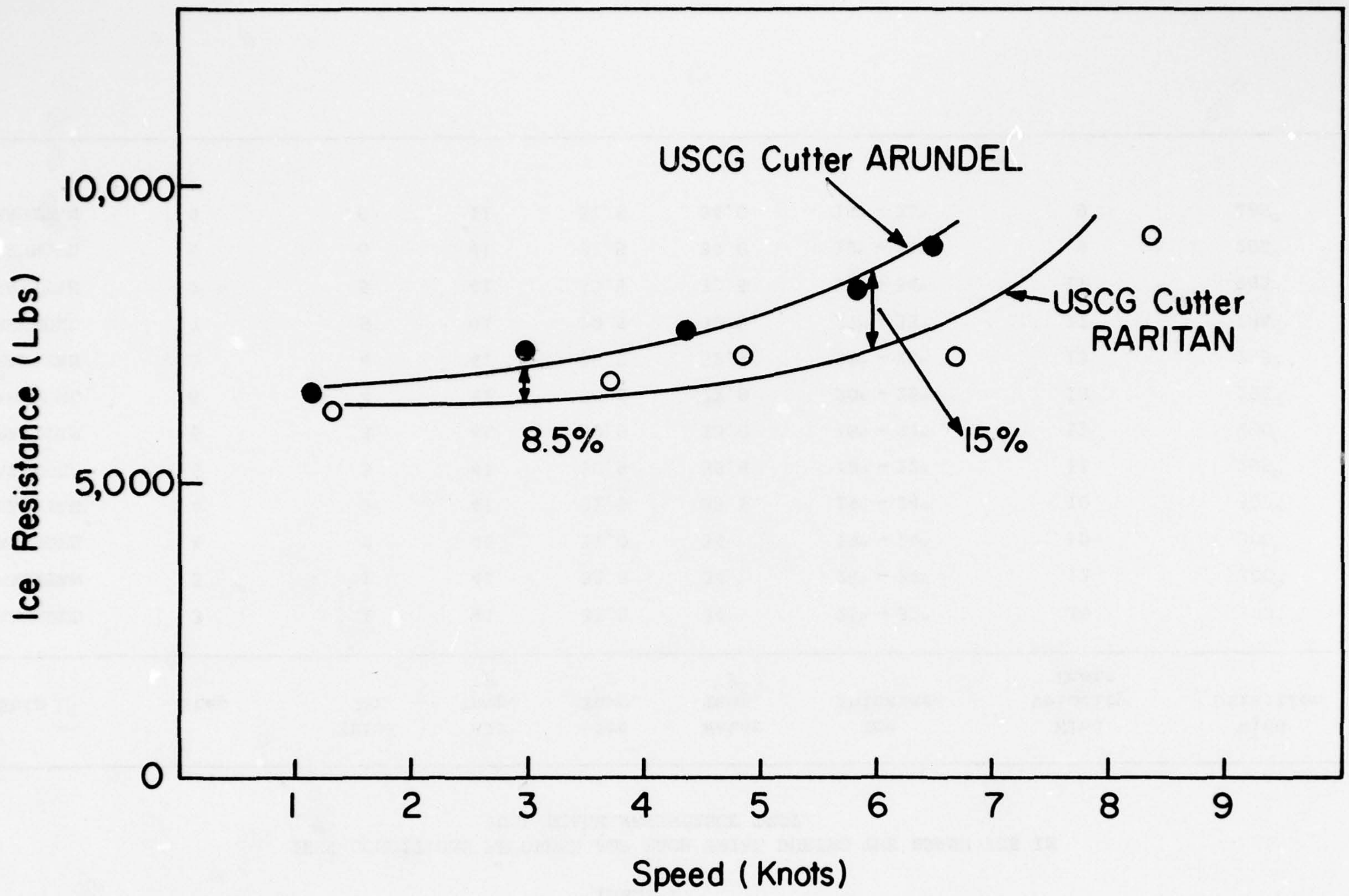


Figure 5 Results of Full-Scale Tests in Brash Ice

TABLE 1

TEST CONDITIONS RECORDED FOR EACH TRIAL DURING THE BRASH ICE IN FULL-SCALE RESISTANCE TEST

Ship	Step	Trial No.	Air Temp. °F	Ice Temp. °F	Water Temp. °F	Ice Thickness	Wind Velocity Knots	Wind Direction
ARUNDEL	3	1	41	31.5	34	26" - 32"	10	300°
RARITAN	3	1	41	31.5	34	26" - 32"	12	300°
ARUNDEL	4	2	41	31.0	34	19" - 24"	10	300°
RARITAN	4	2	41	31.0	33.5	19" - 24"	10	300°
ARUNDEL	5	3	41	30.9	33.5	18" - 22"	11	295°
RARITAN	5	3	41	30.9	33.0	18" - 24"	11	290°
ARUNDEL	6	4	41	30.5	32.8	20" - 25"	13	295°
RARITAN	6	4	41	30.5	32.8	20" - 25"	13	295°
ARUNDEL	7	5	41	30.5	33.5	27" - 33"	12	285°
RARITAN	7	5	41	30.5	33.5	27" - 34"	11	285°
ARUNDEL	9	6	41	31.5	34.0	18" - 33"	9	285°
RARITAN	9	6	41	31.5	34.0	19" - 33"	9	285°

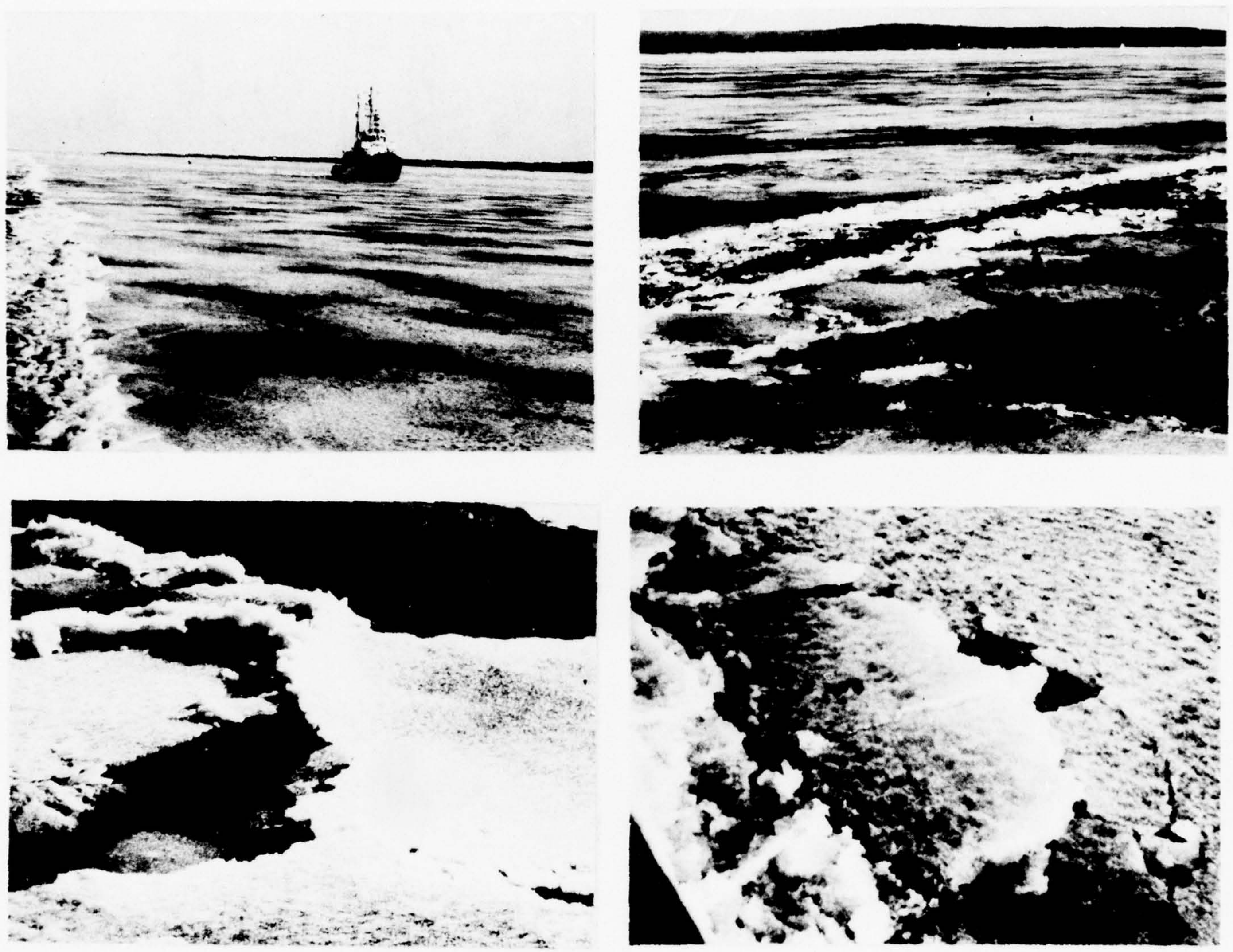


Figure 6 Condition of the Sheet Ice Field During Resistance Tests. Several inches of the top ice are heavily pock-marked and rotted.

Therefore both ships were coated for a period of time before testing, eliminating the question concerning the length of time the reduction in resistance will be effective.

SECTION 4

FULL-SCALE MATERIALS TESTS

4.1 Full-Scale Coating Tests

In Phase I and II of this program several ships were coated with the most promising candidate coatings and evaluated. Results are discussed in the Phase II Report [2]. However, there were some unanswered questions concerning the use of an unfilled polyurethane and Inerta 160 nonsolvented epoxy. These questions were pursued during Phase III.

During the laboratory evaluation, very little difference in performance was found between the amorphous silica filled nonsolvented polyurethane and the unfilled. Inerta 160, a nonsolvented epoxy, was also found to have promise as an icebreaker hull coating. A series of full-scale tests were conducted to determine if:

a) The unfilled polyurethane was as wear resistant as the filled material

b) The Inerta 160 was acceptable as an icebreaker coating

c) The Inerta 160 and the Zebron were comparable as an icebreaker hull coating.

The following ships were coated as follows:

1) ALASKA HUSKY (in cooperation with FOSS Launch & Tug, Seattle, Washington)
Starboard Side - unfilled-nonsolvented polyurethane
Port Side - amorphous silica filled, nonsolvented polyurethane

2) USCG Cutter OJIBWA - Inerta 160 entire hull

3) USCG Cutter GLACIER - Inerta 160 - starboard side, nonsolvented polyurethane - port side.

4.2 Coating Measurements During Application

As with previous hull coating applications, test specimens and certain physical properties of the coating were obtained at the dry dock site. The purpose was to obtain data on the specific coating being applied to the hull using the same equipment, application conditions and curing environment as the coating applied to the hull.

The properties examined were:

1. Bond strength (adhesion of the primer/topcoat system to the substrate)
2. Application and curing conditions
3. Coating thickness
4. Surface roughness
5. Tensile strength (cohesive strength)
6. Hardness
7. Surface condition (overall surface appearance before and after the ship has seen icebreaking service).

A more detailed discussion of the procedure used is given in Ref. [1].

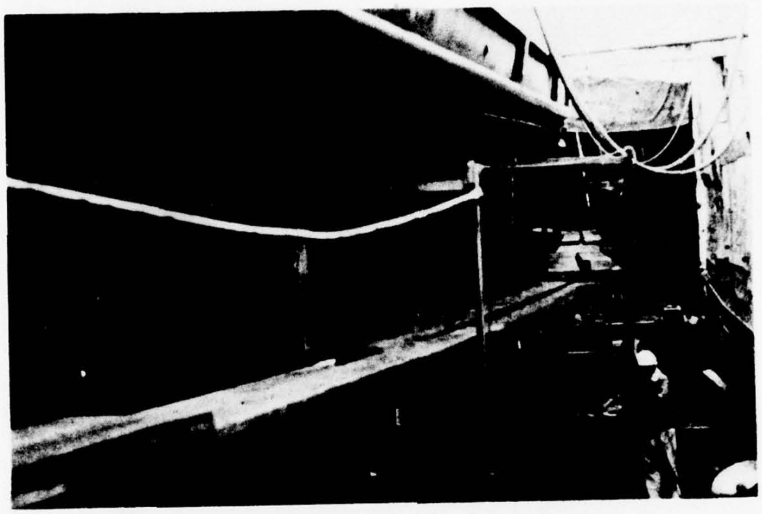
4.3 Application of the Nonsolvented Epoxy

The USCG Cutter OJIBWA was coated with the nonsolvented epoxy (Inerta 160) during October 1976. The overall dimensions of the Cutter OJIBWA are:

110 ft long
27.3 ft beam
12.25 ft draft
384 tons maximum displacement steel hull.

The OJIBWA is a sister ship to the Cutter RARITAN which already had the nonsolvented polyurethane hull coating.

The coating was applied at Sturgeon Bay, Wisconsin. A polyethylene tent arrangement was built around the hull of the ship to control the application parameters. The temperature was controlled at $60^{\circ}F$ with four industrial heaters placed inside the tent. The outdoor temperature was $30^{\circ}F$ with heavy snow. It should be noted that the cost for the tent arrangement was approximately $4,000. The cost of the dry dock use is $5,000 per day. If the tent was not used it would not have been possible to apply the coating on that day and probably could not have been applied during the entire week because of the unsettled and cold conditions. Therefore, the tent was cost effective as well as a necessity. Photographs of the OJIBWA after the application are shown in Figure 7. The lower photograph in Figure 7 shows a tent arrangement similar to the one used to coat the hull of the OJIBWA. Because of the heavy snow it was not possible to take photographs of the tent from outdoors. The cover arrangement shown in Figure 7 lower, was used to control the conditions during the application of Inerta 160 to the hull of a 1,000 ft tanker at Wartsilla Shipyard in Helsinki, Finland.



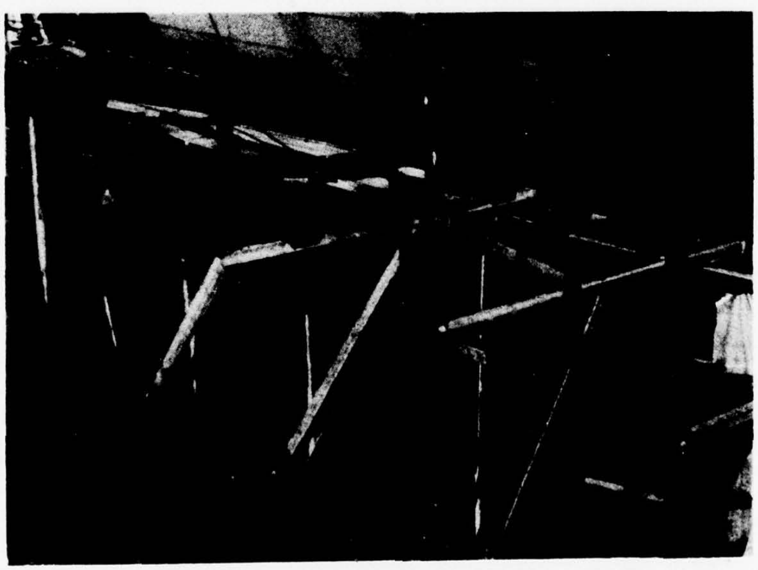


Figure 7 Application of the Inerta 160 to the Cutter OJIBWA

The OJIBWA coating conditions are shown in Table 2. Note that the entire 110 ft hull was coated in approximately 2 hours. It is not necessary to apply a primer coat to the steel before the Inerta 160 is applied. The application is done in one step and the curing time is approximately 16 hours. The coating was applied with a modified Hydrocat airless system manufactured by Greyco. Table 3 shows the physical properties of the coating applied to the hull of the OJIBWA. This table is shown on page 24.

4.3.1 <u>Results</u>

The condition of the hull of the OJIBWA after 358 hours of icebreaking service is shown in Figure 8. Heavy scratches on the bow section can be seen near the stem. The area coated by brush after the weld repair (see Table 2) had some coating removed. The total extent of the coating damage was less than 2%.

In December of 1977 the ship was again examined. After 900 hours of icebreaking the extent of the damage was minimal with 95% of the coating still intact. Major areas of damage were at the bow stem and near the rudder.

It is also worth noting that the ship's commanding officer felt there was less of an extraction problem in heavy ice after the hull was coated. Normally if an icebreaker enters heavy ice and cannot proceed, the ship is extracted from the ice sheet and again the ice sheet is rammed. One major problem is that the hull may progress too far onto the ice sheet and be very difficult to "back off" due to the friction between the hull and the ice. After the hull was coated with the nonsolvented epoxy the problem appeared to be minimal. The ship did not get stuck in the ice when other ships working in the same area and at the same time did.

4.4 <u>Nonsolvented Polyurethane</u>

A full-scale test was conducted to determine if the unfilled polyurethane was as effective as the filled polyurethane as an icebreaker hull coating. With the cooperation of Foss Launch and Tug Company, Seattle, Washington, their 140 ft icebreaker, the ALASKA HUSKY was coated with the nonsolvented polyurethane during May 1976. The port side was coated with the amorphous silica-filled polyurethane and the starboard side with unfilled polyurethane. In addition to wear from icebreaking the HUSKY also suffered from abrasion due to silt in the water

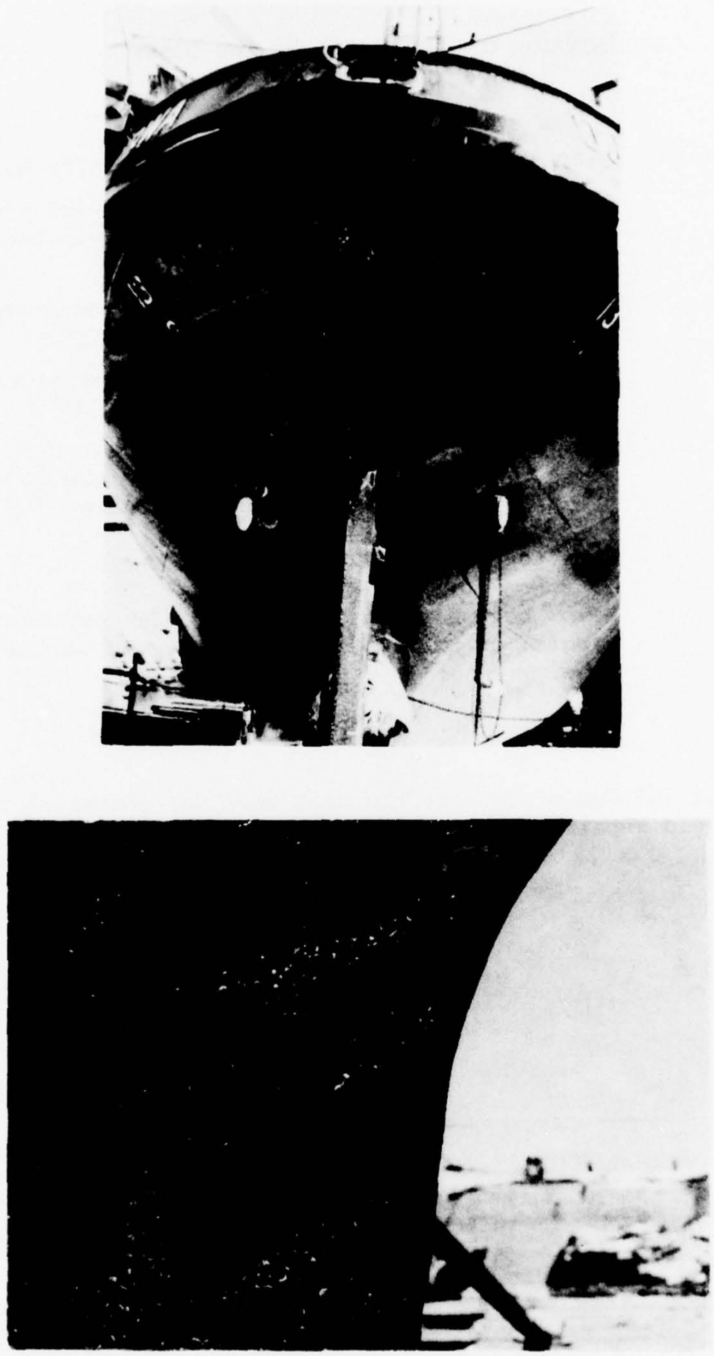


Figure 8 Condition of OJIBWA after 358 Hours of Icebreaking

TABLE 2

APPLICATION OF INERTA 160 TO THE COAST GUARD CUTTER OJIBWA

October 19, 1976 --	3:00 p.m. -	finished sandblasting entire hull
	3:15 p.m. -	started coating port bow and proceeded toward starboard bow. Temperature 60°F, RH 58%
	4:30 p.m. -	starboard side coated. Temperature 59°F, RH 55%, hull temperature 55°F
	5:15* p.m. -	entire hull coated. Temperature 60°F, RH 78%, hull temperature 55°F
	5:30 p.m. -	original portion coated at 3:30 p.m. today but not cured. Temperature 60°F, RH 76%, overnight cure temperature 55°F, RH 80%

Boot topping - .022" to .033" DFT

Below boot topping - .018" to .025" DFT an overall diagram of the coating thickness was made at this time.

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* The sea chest and one plate near the keel were not coated at this time. Plate needed weld repair.

throughout the rest of the year. As a result the hull was continually wearing throughout the entire operating period. According to the owners any coating that was applied to the hull would only last approximately four months before it was completely worn off. Since the ship is dry-docked approximately every two years, it operated without a hull coating for 20 months between dry dockings. Significant costs were incurred because of the need for plating repair and replacement due to the continuous hull wear.

4.4.1 Application of Coating

The nonsolvented polyurethane was applied during the evening hours since several plates had to be replaced and the welding was done during the daylight hours. Because of the weather conditions in Seattle several periods of rain and clearing would occur within a 24-hour period. Therefore a tent arrangement was set up with four propane heaters to control the temperature and reduce the relative humidity around the hull. The physical properties of the coating ate shown in Table 4. Photographs of the hull after coating are shown in Figure 9.

4.4.2 Test Results

The ALASKA HUSKY has not yet been dry docked. However, during December 1977, Foss Launch and Tug Company was contacted. They indicated that most of the coating damage was at the bow and stem area near the ice line. The coating appeared to be intact below the ice line except for some 6" diameter areas subjected to hard contact with the dock during docking. Areas that were visible below the water line appeared to be still intact. However, the underside of the hull could not be seen while the ship was still in the water. It does appear that the hull is being protected after one and one-half years while other coatings had lasted only four months, but it is not possible to differentiate between the filled and the unfilled polyurethane.

4.5 Coating Application for Weld Protection

A weld erosion problem has existed with the Coast Guard Cutter GLACIER for several years. An attempt to arrest the problem by applying putty to the weld areas had been made with marginal success. Essentially, most of the weld protection was removed during service. A decision was made to try the nonsolvented coatings on the GLACIER hull, since in all past cases where the nonsolvented coatings had been used, minimal if any damage had occurred beneath the water line.

TABLE 3

TABULATION OF THE PROPERTIES OF THE INERTA 160
APPLIED TO USCG CUTTER OJIBWA

	Starboard	Port
Average Bond Strength	1300 psi	1150 psi
Final Coating Roughness	150 μ" CLA	160 μ" CLA
Coating Thickness		
Boot Topping	.022" - .033" DFT	.020" - .035" DFT
Below Boot Topping	.018" - .025" DFT	.015" - .025" DFT
Hardness (pencil)	E4	E4

TABLE 4

TABULATION OF THE PROPERTIES OF THE NONSOLVENTED POLYURETHANE
COATING APPLIED TO THE HULL OF THE ALASKA HUSKY

	Port	Starboard
Average Bond Strength	1510 psi	1420 psi
Final Coating Roughness	110 μ" CLA	80 μ" CLA
Coating Thickness	.020" - .030" DFT	.020" - .030" DFT
Hardness (pencil)	E5	E5

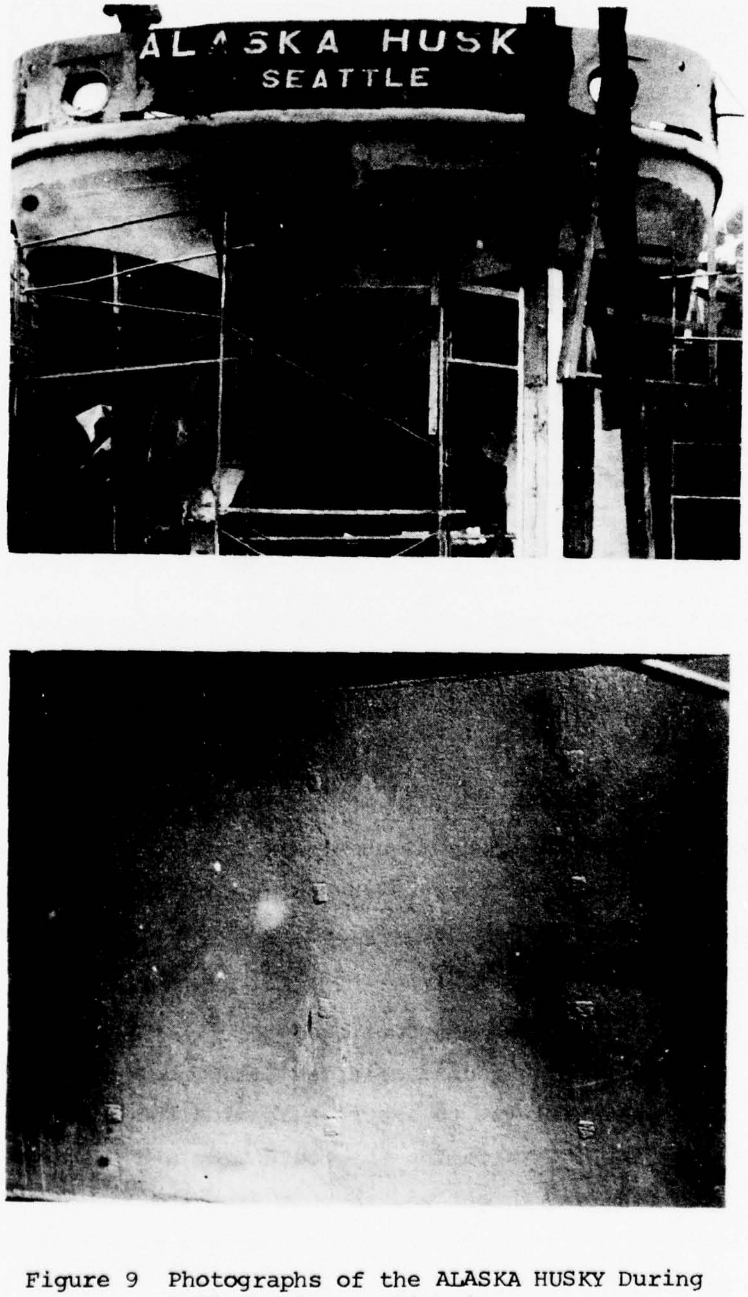


Figure 9 Photographs of the ALASKA HUSKY During
Hull Coating Application

Both the nonsolvented polyurethane (Zebron) and the nonsolvented epoxy (Inerta 160) were applied to the bow section of the Cutter GLACIER. The first coat was applied and squeegeed to fill the hull pits and the eroded welds. The second coat was applied to build up to the desired thickness. A "stopper" coat of Inerta 160 was used to smooth the hull (this is essentially Inerta 160 with a filler to increase the viscosity). Unmodified Zebron was used as the filler coat for the polyurethane.

4.5.1 Application of the Inerta 160

The Inerta 160 was applied by a modified super Hydrocat airless spray unit. The applicators were qualified by International Paint Company, Inc., (distributor of Inerta 160 in the United States). At the time of the application a technical representative and a spray specialist from Technos Maalit Oy (Finnish manufacturer of Inerta 160) were present to insure quality control of the product. The Inerta 160 was applied to 5 ft of the port side near the bow and progressed around the bow to the starboard. This was to insure that no seam between the two coatings would be present at the bow stem where the most severe abrasion and ice impact would be seen in service. The coating was applied to the bow section from boot topping to keel and proceeded 70 ft toward midship.

Tables 5 and 6 show the application conditions and properties of the Inerta 160 applied to the GLACIER hull. Photographs of the GLACIER during various stages of coating application are shown in Figure 10.

4.5.2 Application of Zebron

The nonsolvented polyurethane (Zebron) was applied with a specially designed airless gun which was manufactured by Xenex Corporation who also manufactures the coating. The coating was applied by applicators who were first qualified by the coating manufacturer.

The first coat was applied and squeegeed to fill the existing pits and weld cavities in the hull. The second coat was immediately applied for buildup while the first coat was still wet to insure a chemical bond between coats. The Zebron overlapped the Inerta on the starboard side and proceeded toward midship for 73 ft. The original intent was to coat from the top of the boot topping to the keel over a 70 ft length. However, because of a time problem, the coating was not completed but stopped approximately 7 ft above the keel.

TABLE 5

APPLICATION OF INERTA 160 TO THE STARBOARD SIDE OF THE USCG CUTTER GLACIER

Feb.26, 1977 - 2 p.m.	- Started to apply stopper to 5 ft back from the bow port sides and progress toward bow to starboard. Applied .040" of stopper and squeegeed hull immediately. Temperature 62°, RH 40%.
Feb.26, 1977 - 6 p.m.	- Finished applying stopper to the starboard side. Temperature 58°F, RH 50%.
Feb.26, 1977 - 7:30 p.m.	- Applied Inerta 160 to water line. Temperature 55°F, RH 50%.
Feb.26, 1977 - 8:30 p.m.	- Finished water line with Inerta 160. Temperature 52°F, RH 56%.
Feb.27, 1977 - 9 a.m.	- Started to apply Inerta 160 to build up thickness on previously applied stopper. Temperature 60°F, RH 55%.
Feb.27, 1977 - 11:15 am	- Finished coating application. Temperature 60°F, RH 55%.

TABLE 6

TABULATION OF THE PROPERTIES OF INERTA 160 APPLIED TO THE HULL OF THE USCG CUTTER GLACIER

Average bond strength	1210 psi
Final coating thickness	.040" to .070" DFT
Final coating roughness	.70 µ" to 210 µ" CLA
Hardness pencil	E5

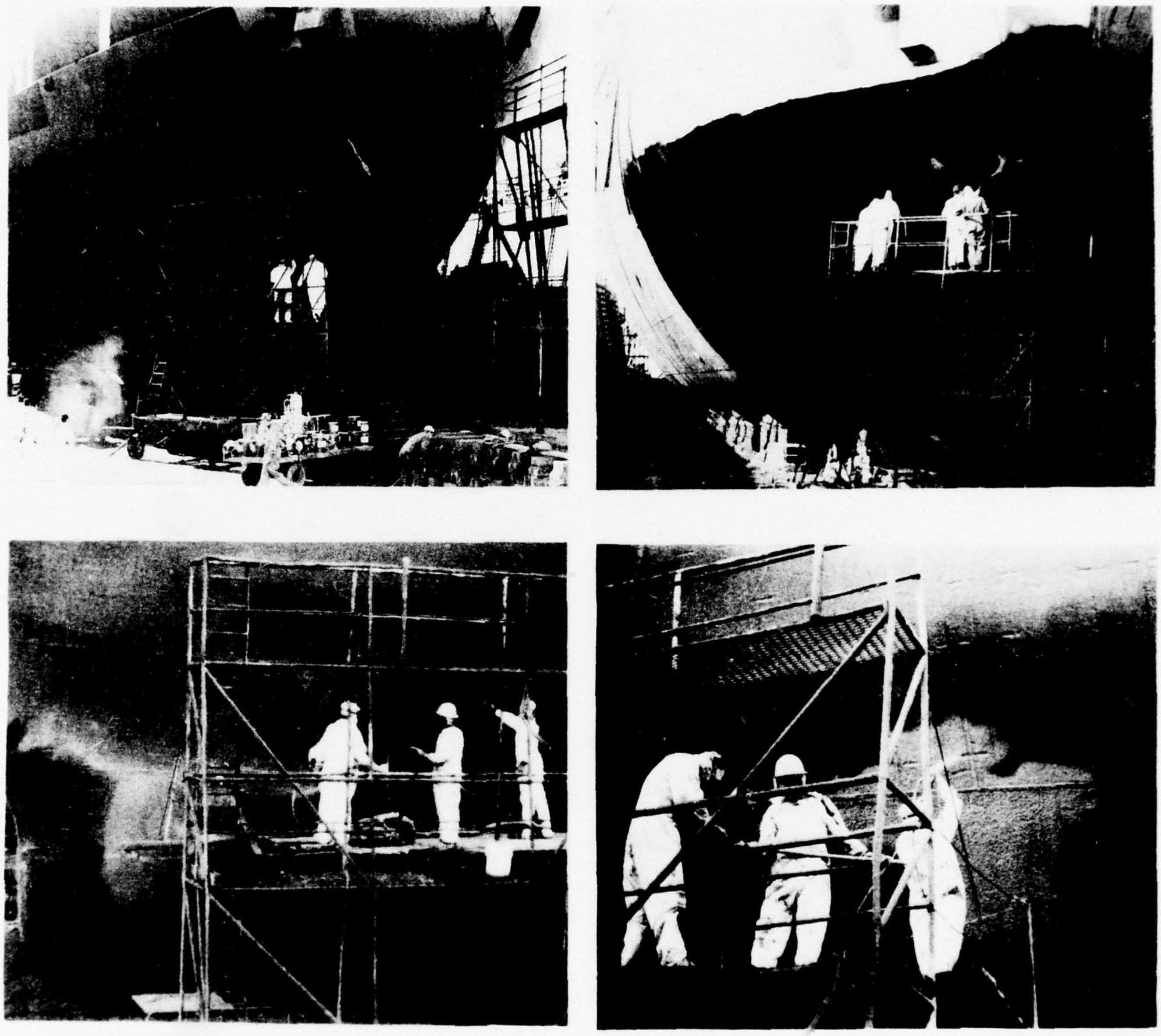


Figure 10 Photographs of the GLACIER During the Application of Inerta 160 (Upper) and Zebron (Lower)

Tables 7 and 8 show the application conditions and properties of the Zebron applied to the starport side of the Cutter GLACIER.

4.5.3 Test Results

At the time of this writing, the GLACIER had not been dry-docked for a full examination. However, a preliminary examination was made after the first icebreaking mission while the ship was still in the water. The ship had broken ice for approximately 168 hours.

Small areas of the Zebron were delaminated between the top coat and the filler coat. It appeared as though the bond between the two layers of coating had failed. The areas where the delamination occurred were still covered by the filler layer and therefore no exposed plating was evident. It is not known if the delamination was a result of spray gun mismetering or of application of the second coat after the first coat had completely cured. It should be emphasized however, that the entire hull still appeared to be coated.

There did not appear to be any damage to the Inerta 160. However, the observers could not get close to the hull on the starboard side and because of the black coloring of the Inerta and the distance from the observer, it could not be determined if the coating had suffered any damage.

4.6 Results of the Nonsolvented Polyurethane Coating Applied to the Cutter RARITAN

In July of 1974 the nonsolvented polyurethane coating (Zebron) was applied to the Cutter RARITAN. A description of the coating procedure and application conditions is given in the Phase II portion of this program [2]. After one year of service, approximately 98% of the coating remained intact. The damaged areas were repaired and in addition, the upper bow section was coated. The nonsolvented polyurethane was used but in this instance it was hand applied and not sprayed.

In April of 1976 the hull was re-examined. Figure 11 shows the condition of the hull after two years of service. Most of the coating that was removed is the hand applied material. The boundary line between the sprayed-on coating and the hand applied coating is clearly evident (Figure 11). Approximately 95% of the sprayed-on material and approximately 70% of the hand applied material was still intact. This is somewhat misleading since 100% of the hand applied

TABLE 7

APPLICATION OF ZEBRON TO THE PORT SIDE OF THE USCG CUTTER GLACIER

Feb.28, 1977	9:00 a.m. -	Started to apply primer at 9 a.m. Temperature 52°F, RH 55%
	11:00 a.m. -	Finished primer application. Temperature 60°F, RH 45%
	1:00 p.m. -	Started application of polyurethane and squeegee. Temperature 60°F, RH 60%
	4:10 p.m. -	Applied second coat of polyurethane beneath the water line. Temperature 62°F, RH 61%
	7:30 p.m. -	Approximately 2/3 finished. Temperature 58°F, RH 68%.

Coating was discontinued at this point due to a time and availability problem.

TABLE 8

TABULATION OF THE PROPERTIES OF ZEBRON APPLIED TO THE HULL OF THE USCG CUTTER GLACIER

Average bond strength	1620 psi
Final coating thickness	.050" to .080" DFT
Final coating roughness	120 μ" to 160 μ" CLA
Hardness pencil	Would not scratch

Figure 11 Condition of the USCG Cutter RARITAN after One Year, 600 Hours (Above) and Three Years, Approximately 1800 Hours (Below) of Icebreaking Service

coating is in the high wear and impact area. As of the winter of 1977 season (after approximately 1800 hours icebreaking service) there does not appear to be any wear on the under portion of the hull. The coating is still the original thickness and there is no evidence of corrosion. The only wear is at the ice line near the bow.

4.7 Nonsolvented Polyurethane Applied to the Hull of the USCG Cutter MACKINAW

During June 1975 the bow of the Cutter MACKINAW was coated with the non-solvented polyurethane system. The coating particulars are given in [1]. The entire bow section was coated and tapered back to a 10 ft wide strip at the boot topping. The strip extended approximately 70 ft back from the bow. After approximately two years of icebreaking service (1100 hours in ice) the MACKINAW was re-examined. Most of the 10 ft strip at the boot topping was removed. Some material could be seen on the bottom 2 ft of the strip but even there the coating was only partially intact. The coating beneath the boot topping at the bow was almost totally intact. There were portions of the coating which appeared to be delaminating from the lower layer. The first layer of material was applied and squeegeed to smooth the hull. The following day a second layer was applied to build up the coating thickness. In areas where delamination was apparent the layer still attached to the hull turned a greenish tint. The outer layer remained the original tan color. It is believed that the reason for the change in color is due to random mismetering in the spray gun.

Photographs of the condition of the hull of the MACKINAW are shown in Figure 12. It is important to note that the weld seams beneath the hull were not visible which indicated that the coating is adequately protecting the hull from corrosion. The results of this test indicate that the bottom can be completely coated and the coating will remain throughout the season. All of the coating wear took place on the upper portion of the hull while the area beneath the boot topping continues to be coated. Since the hull of the MACKINAW is severely pitted it should be completely coated to protect it against further corrosion. Certainly the fuel savings plus the weld and plating repair cost will offset the cost of a complete hull coating.

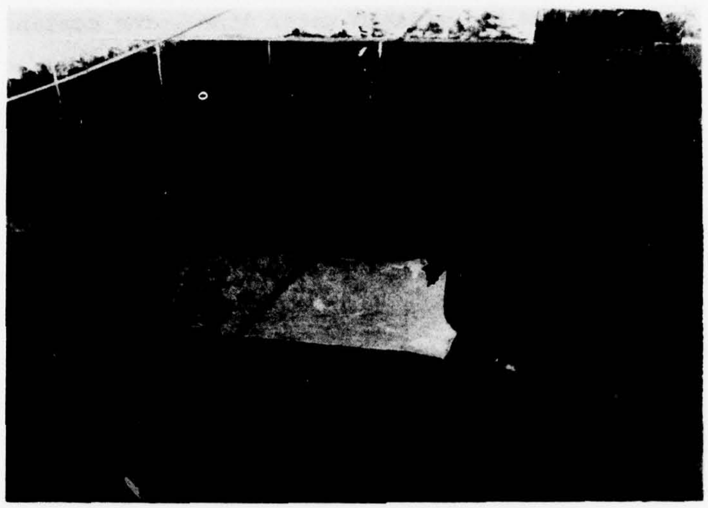


Figure 12 Photographs of the MACKINAW after Two Years of Service

4.8 Foreign Icebreaker Tests

Several Finnish icebreakers have been coated with the Inerta 160 over the past few years. A visit was made to Turco, Finland to examine the hull of the KAHRU, a commercial icebreaker, and gather coating data in June 1976. The ship is 240 ft long and had seen approximately 800 hours of icebreaking during the previous season. The condition of the hull can be seen in Figure 13. The coating was removed near the bow and midship water line. The coating beneath the water line had several areas where corrosion was evident. The corrosion was evident at the top of asperities and in the weld areas. Approximately 90% of the hull was still coated but the 10% where corrosion had started was on random areas throughout the hull surface. As an experiment, two coats of Inerta had been applied on one area of the ship. In this area the coating had delaminated and a white scum formed between the two layers. The scum was a result of the absorption of CO_2 by the amine component in the Inerta 160. The CO_2 can unite with moisture forming a barrier which prohibits adhesion between coats.

4.9 Conclusions

Both nonsolvented coatings appear to have adequate properties to withstand icebreaking conditions. Both materials show wear patterns at the bow area near the water line. Hulls coated with Inerta 160 had several areas beneath the water line where rust was apparent. These areas include welds and the top of asperities near pits or other discontinuities. The Zebron coated vessels show no signs of rust leaching through the coating on the underside of the hulls. It is, however, apparent that an icebreaker can be coated with one of the above coatings and survive several years of service without significant damage or corrosion to the hull. In the case of the RARITAN the coating has protected the hull for four years of icebreaking service. That is certainly a significant improvement over the few hours of icebreaking that a conventional hull coating can survive.

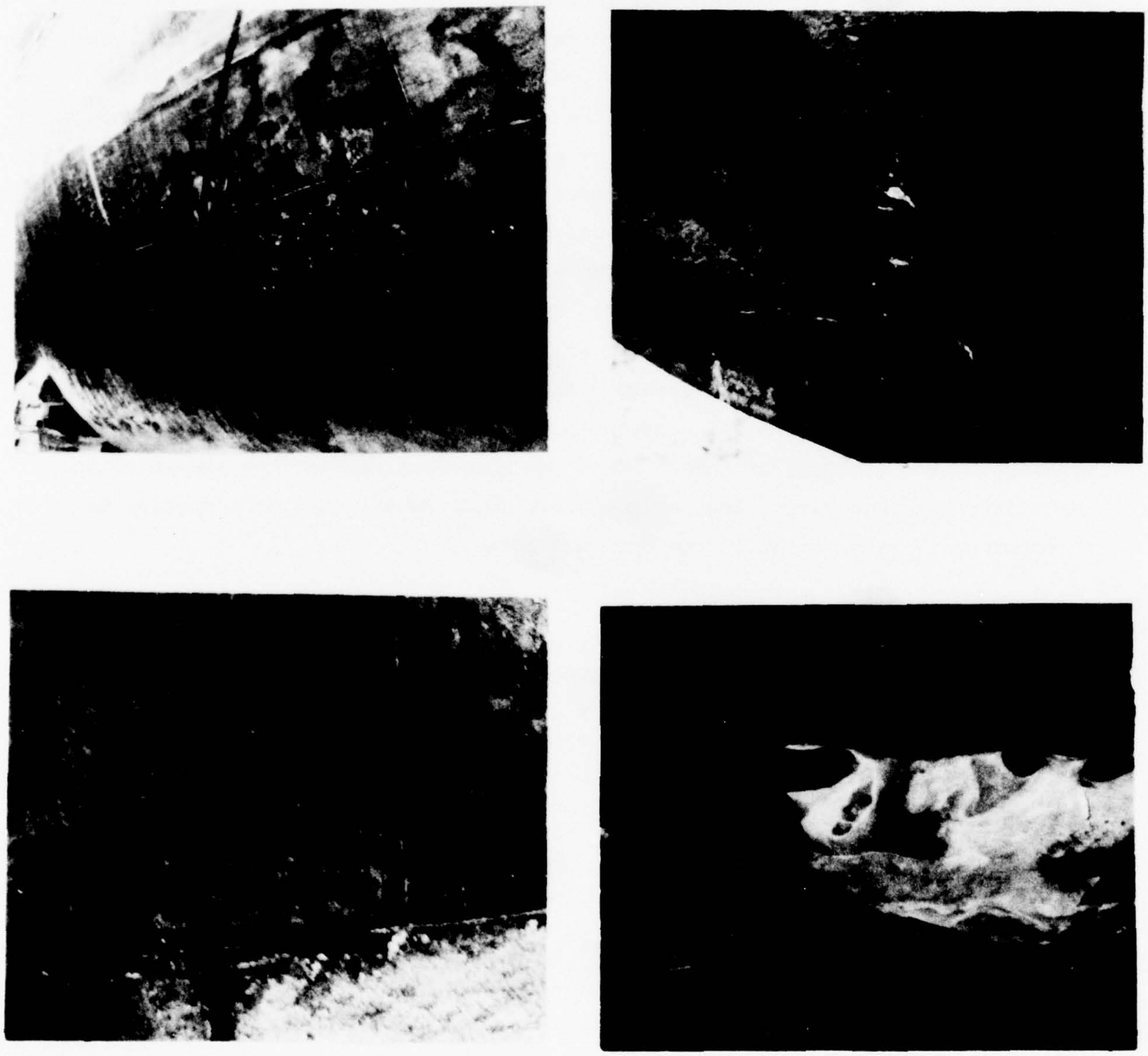


Figure 13 Condition of the Hull of the Icebreaker KAHRU after 800 Hours of Icebreaking

SECTION 5

FOULING TESTS

5.1 Fouling Characteristics

The satisfactory performance obtained from the use of nonsolvented coatings on icebreakers has prompted interest in the possibility of utilizing the coatings for other applications. However since the materials do not have antifoul characteristics there was concern over the problem of marine fouling. During the full-scale testing, it was noted that the algae, scum and barnacles which had attached to the hull could be removed by scraping the surface. In fact, the hull of the RARITAN was completely cleaned by high pressure water without damage to the coating. It appeared that the use of such a coating would lend itself to the underwater cleaning techniques which are presently being evaluated [3]. Systems such as "S-Camp", "Brush-Kart", "Marina Brush" and "Brush Buoy" all utilize a coarse brushing action which will scrape or remove organisms from the hull plating without the need for dry docking. The problem is that, in some cases, during organism removal, conventional hull coatings are damaged due to abrasion by the cleaning brushes. Since the nonsolvented coatings are abrasion resistant, the underwater cleaning technique could be utilized on a regular basis to continually keep the hull free from barnacles.

Two methods are envisioned:

Method 1 - Application of a nonsolvented coating and periodical underwater inspection and cleaning.

Method 2 - Application of a nonsolvented coating and immediate application of an antifoul while the base coat is still wet.

Both methods were evaluated as part of this task on a limited scale.

5.2 Test Program - East Coast

The Coast Guard has an ongoing test program with Battelle Marine Facility in Daytona, Florida to evaluate coatings for buoys. It was decided to expose Zebron coated panels in conjunction with this test program and establish the fouling characteristics of this coating on various substrates. Five test panels were manufactured and coated with Zebron. The panel combinations were:

- Zebron on primed aluminum
- Zebron on primed steel
- Zebron on unprimed aluminum
- Zebron on unprimed polyethylene
- Zebron on primed polyethylene
- Transite control panel.

The specimens were placed in the water for 11 months and exposed to fouling conditions. Figure 14 shows the condition of the panels as removed from the water. The upper photograph shows the severity of fouling as removed from the water while the lower photograph shows the panels after the specimens were cleaned. As expected, the Zebron had fouled severely. The surfaces contained both hard and soft-shelled organisms. There were some areas where organisms had built up to the point where they could not support their own weight and eventually fell from the urethane surface. The unusual characteristic about this material is its ability to be cleaned without surface damage. The specimens were cleaned with a wooden spatula and heavy wire brushes. Most of the organisms were removed from the surface without damage to the coating surface. Only the upper half of the panels were cleaned and only the coatings on the steel and aluminum were evaluated.

Photographs of the cleaned specimen are shown in Figure 14 (lower). There were some very small edge chips on the coated steel and aluminum specimens. The surfaces however were completely intact with no borer holes or evidence of any other damage.

The coated polyethylene had failed catastrophically. They had warped and the coating had separated from the surface. It was evident that little if any bond existed between the polyethylene and polyurethane. The transite control specimen disintegrated after removal from the water. Before placing the specimens back into the water, a line was scribed on the surface of all metal-coated specimens. The scratch was made so that the metal surface would be exposed. This was done to determine if fouling organisms could lift the coating after the metal surface was exposed. The scribe line is shown in the lower photograph of Figure 14.

The specimens were placed back in the water for approximately six months. Upon removal, it was found that they had fouled severely similar to the previous 11-month exposure. The attached fouling was slightly harder to remove this time,

Figure 14 Condition of the Zebron Coated Panels after Exposure for Six Months

but it could be removed from the panels without damage to the substrate. Crustaceans had lodged in the scribe line on the metal surface but they were unable to lift the coating. The penetration under the coating edge was less than 1/16" Figure 15 (upper) shows the condition of the surface as removed from the water and an area which was cleaned after removal. There was no damage to the coating but a slight discoloration was evident. Figure 15 (lower) shows the scribe line where the bare metal had been exposed. Note the barnacles which had attached to the metal but which did not lift the coating at the edge. The metal tangent to the scribe line was still intact. An attempt was made to peel the coating back from the edge but very little (approximately 1/8") of coating could be lifted. The substrate (steel) was still clean with no evidence of corrosion taking place beneath the Zebron. After 17 months of exposure to fouling and two cleanings the coating thickness remained between .028" and .032". There appeared to be no change in thickness.

5.3 Test Program - West Coast

Fouling characteristics differ from one area to another and from one season to another throughout the year. Since Coast Guard vessels are stationed in different parts of the country, it is evident that the fouling conditions should be examined on both the East and West Coast in an effort to determine the effectiveness of the nonsolvented coatings.

A set of specimens were placed in the water at the Long Beach Navy Yard during November 1976. The specimens examined were Zebron, Zebron with antifoul, Inerta 160 and a steel control specimen. They were removed on February 27, 1977. The Zebron and the Inerta had fouling organisms attached to the surface. The Zebron and antifoul had no crustaceons but did have a scum on the surface. All specimens could be cleaned with a light brushing leaving the original coated surface undamaged. Figure 16 shows the condition of the coated specimen after partial cleaning. The specimens were placed back in the water for later examination.

5.4 Discussion of Test Results

The results of this investigation indicate that the application of a nonsolvented coating is an effective method to protect the submerged steel against fouling damage and corrosion. The coatings are not antifouling but do not appear to be significantly damaged by fouling. All organisms can be removed by brushing

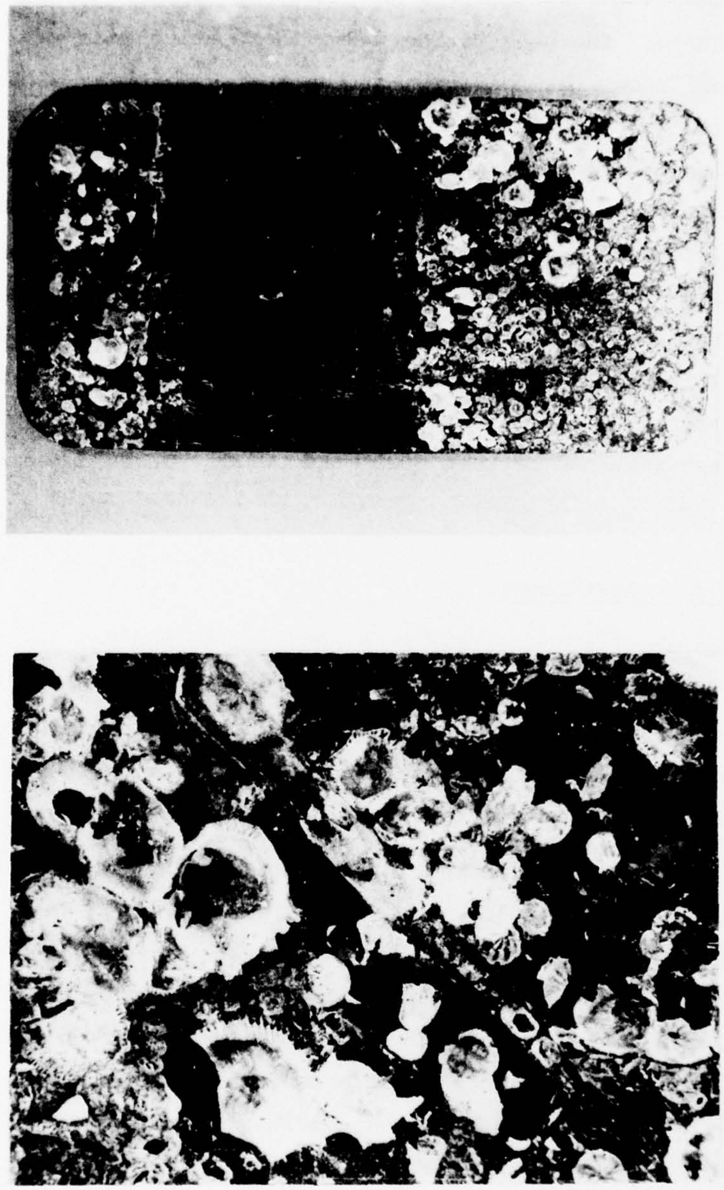


Figure 15 Condition of the Zebron Coated Specimens after Removal from Fouling Exposure. Upper photograph shows the coating before and after cleaning. Lower photograph shows the condition of the scribe line where bare metal was exposed. Mag. 3×.

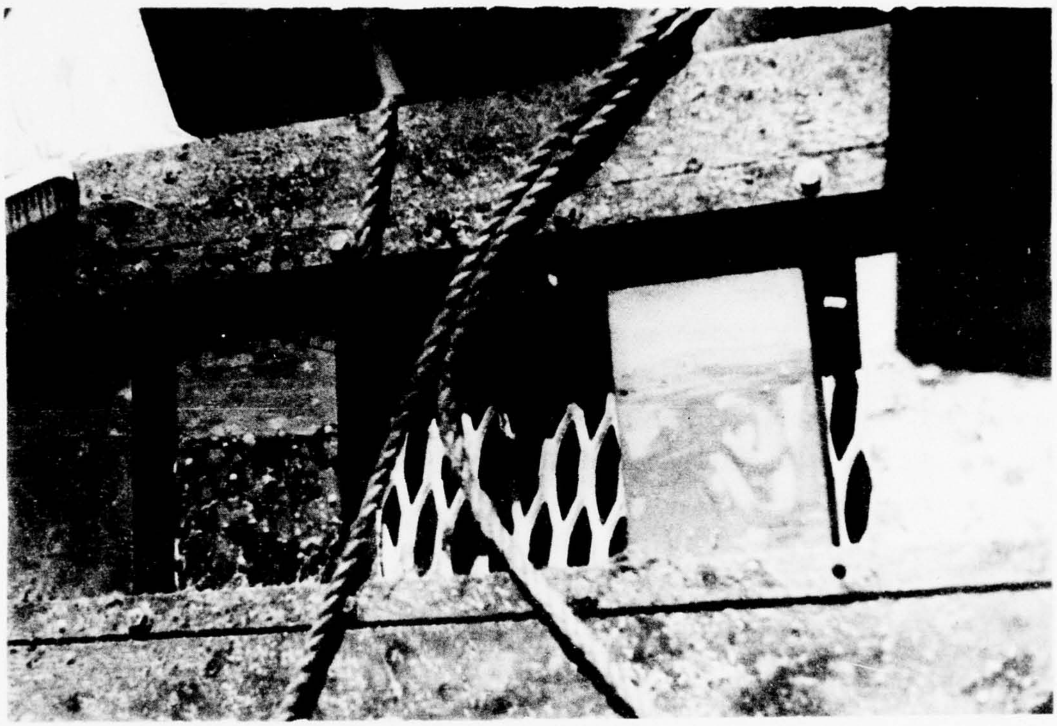


Figure 16 Condition of Test Panel after Four Months Exposure at Long Beach, California. A portion of the test specimen was cleaned by light brushing.

and in the case of Zebron, even after severe fouling. The Zebron also showed little sign of coating edge lifting due to corrosion or fouling build-up even after the coating was scratched through to bare metal. This is an important point since many coatings will disbond once the adjacent surface is exposed to fouling and subsequent corrosion.

The immediate application of an antifoul to the wet Zebron is an effective method to obtain a tenacious coating and still have antifoul protection. The bond strength of the antifoul to the Zebron will be discussed later in the report. However, further studies are recommended for the Zebron, Zebron + antifoul, Inerta 160 and Inerta 160 + antifoul.

It appears that the underwater cleaning technique would be extremely effective when using materials such as the nonsolvented coatings.

It has been estimated [4] that fouling cost the Navy 70 million dollars in added fuel cost per year. Over the life of the ship, 25% of the fuel cost for operating the ship is linked to hull fouling. With this statement in mind, it would be a definite advantage to continually maintain the hull of ships which have an effective corrosion protective coating and maintain a hull free from fouling. A program should be instituted that will utilize the nonsolvented coatings and the underwater cleaning technique to achieve these possible savings.

SECTION 6

LABORATORY INVESTIGATION

6.1 Laboratory Study

Throughout the Phase I and Phase II portions of this program a series of laboratory tests were conducted to evaluate the various coating materials for icebreaking service. During this portion of the program several laboratory studies were conducted to continue the search for materials, to establish certain application parameters of the best coatings and to determine certain bonding characteristics for the coatings. The various laboratory studies are discussed in this section of the report.

6.2 Environmental Parameters

A series of tests were conducted to establish the optimum application parameters for the nonsolvented polyurethane (Zebron) and the nonsolvented epoxy (Inerta 160). The coatings were applied to test specimens in a chamber in which the temperature and humidity could be controlled. The chamber used was a freezer compartment with a modified top to allow the insertion of the spray gun and the introduction of a desired relative humidity. A glove box arrangement was used to control and direct the spray gun. The specimen temperature and spray conditions were controlled but not the temperature of the coating material. This was done since for the coating to be applied at a dry dock under cold conditions, the coating components would probably have to be heated either in the individual containers or in the spray gun hoses to reduce the viscosity and allow it to flow. Thus, the coating would always be at a higher temperature than a cold hull. In order to simulate dry dock conditions, the coating components were at 65°F (room temperature) and the specimen temperature was varied. Photographs of the test chamber are shown in Figure 17.

6.2.1 Method of Control

The specimens were 1½" square by 1/4" thick grit blasted steel. Compressed air was bubbled through water and a drying tower to obtain the desired relative humidity conditions. The temperature was controlled with a rheostat mounted in the freezer chest. The temperature and humidity were monitored with a General Eastern Humidity/Temperature Indicator (Model 400 C). As each series of specimens was coated in the freezer at the desired conditions a second series

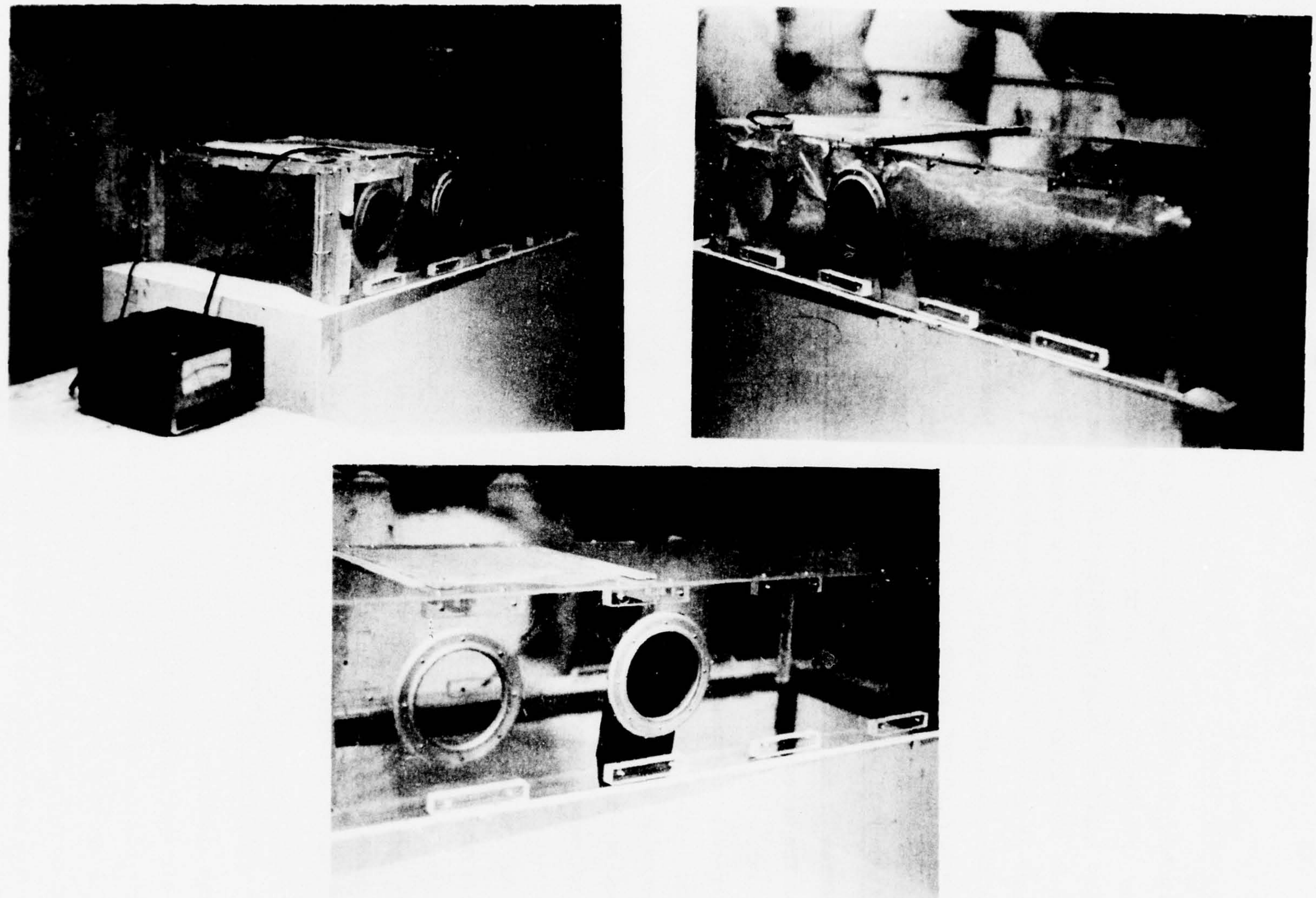


Figure 17 Freezer Compartment with a Modified Top Built for Environmental Control Tests Run at Xenex Corporation. Spray gun is placed in the top opening. The glove box arrangement was used to control and direct the spray gun. The temperature and humidity inside the box were controlled and monitored.

was coated at room temperature. The room temperature specimens were used as control specimens to establish that the gun was working correctly and the material was uniform from day to day.

The Zebron was sprayed on steel specimens while the Inerta 160 was applied by brush. All specimens were placed in the freezer for one hour before the coating was applied to insure that the surface had reached the desired temperature. A test procedure was established to simulate a dry dock environment. That is, the coating is applied to the hull during the daylight hours and allowed to cure overnight. The dock temperature will drop during the evening hours and increase during the morning. However, the increase in air temperature during the morning hours can cause moisture to condense on the cold hull surface. Therefore, the moisture does not become a problem until several hours after the coating has had a chance to cure. If the curing is retarded due to cold temperature at night the moisture could become a significant factor to the final coating properties.

6.2.2 <u>Test Procedure</u>

a) Grit blasted specimens were placed in the freezer and allowed to reach the desired spray conditions.

b) Primer was applied to the specimen surface. Only the Zebron required a primer. The Inerta 160 was applied directly to the steel substrate.

c) After the primer has cured the Zebron (and Inerta) were applied.

d) The temperature in the freezer was set to $15^{\circ}F$ and the humidity was maintained at 10% overnight.

e) After 15 hours, the specimens were removed from the freezer and allowed to cure at $40^{\circ}F$ and 60% RH for 24 hours.

f) The specimens were then removed and allowed to final set at room temperature $70^{\circ}F$ and 45% RH.

Final cure was determined to be after the coating had reached a hardness where it could not be scratched with the E4 lead.

6.2.3 Test Conditions and Results

Both coatings were applied under the following conditions:

Temp. (^oF)	RH (%)
10	10
30	10
30	30
50	10
50	30
50	60
70	10
70	30
70	80

After final cure, the specimens were returned to RPI where the bond strength was measured.

A set of four specimens were coated for each set of conditions. The bond strength (method described in [1]) was measured for three specimens from each set. The results are shown in Table 9. The table shows the coating material, application condition and area of failure. Little significance should be placed on values which indicate failures taking place at the adhesive epoxy. Essentially, that indicates that the coating system is stronger than the values shown. However, when failure occurs at the substrate, primer or coating, that indicates the strength of the coating and the "weak link" in the coating system. It must also be stressed that the temperatures and relative humidity values during coating were selected at levels to eliminate the possibility of moisture condensing on the cold specimen surface. It was assumed that if the bond surface was wet or had ice present, the adhesion would be poor or marginal at best. The results indicate that the polyurethane has a higher bond strength when compared to the epoxy. There also appears to be a slight increasing trend in adhesion as the application temperature increases. The adhesion of the nonsolvented epoxy does not appear to change significantly with application temperature. In most cases failure of the polyurethane system is associated with the primer while failure of the epoxy system is in a cohesive fashion. Photographs of typical test specimens after testing are shown in Figure 18. The lighter coating shown in Figure 18 is the polyurethane while the darker coating is the epoxy. In the upper photograph, the steel fixture, which is bonded to the coating and later pulled from the surface in tension, is shown. Note that the epoxy and polyurethane coatings are still bonded to the fixture. The polyurethane has separated at the primer failing in adhesion while the epoxy failed in a cohesive manner leaving part of

TABLE 9

TABULATION OF TEST RESULTS OBTAINED DURING ENVIRONMENTAL PARAMETER EVALUATION

Coating Material	Application Condition		Bond Strength psi		
Nonsolvented polyurethane	$10^\circ F$	10% RH	1420^{*2}	1450^{*2}	1550^{*3}
Nonsolvented epoxy	$10^\circ F$	10% RH	1220^{*2}	1110^{*3}	560^{*4}
Nonsolvented polyurethane	$30^\circ F$	10% RH	1500^{*2}	1540^{*3}	800^{*4}
Nonsolvented epoxy	$30^\circ F$	10% RH	1110^{*3}	1070^{*3}	900^{*3}
Nonsolvented polyurethane	$30^\circ F$	30% RH	900^{*4}	1400^{*2}	1600^{*2}
Nonsolvented epoxy	$30^\circ F$	30% RH	400^{*1}	1210^{*3}	1140^{*3}
Nonsolvented polyurethane	$50^\circ F$	10% RH	1610^{*2}	1550^{*3}	1420^{*2}
Nonsolvented epoxy	$50^\circ F$	10% RH	1010^{*3}	1140^{*1}	1200^{*1}
Nonsolvented polyurethane	$50^\circ F$	30% RH	1650^{*2}	1510^{*2}	800^{*4}
Nonsolvented epoxy	$50^\circ F$	30% RH	1100^{*1}	400^{*4}	1210^{*3}
Nonsolvented polyurethane	$50^\circ F$	60% RH	1620^{*1}	1800^{*2}	400^{*4}
Nonsolvented epoxy	$50^\circ F$	60% RH	900^{*1}	950^{*1}	1100^{*3}
Nonsolvented polyurethane	$70^\circ F$	10% RH	1600^{*3}	1700^{*2}	1680^{*4}
Nonsolvented epoxy	$70^\circ F$	10% RH	1010^{*3}	1080^{*3}	500^{*4}
Nonsolvented polyurethane	$70^\circ F$	30% RH	400^{*4}	1400^{*2}	1600^{*2}
Nonsolvented epoxy	$70^\circ F$	30% RH	1210^{*3}	1210^{*1}	1020^{*1}
Nonsolvented polyurethane	$70^\circ F$	80% RH	1650^{*1}	1500^{*2}	600^{*4}
Nonsolvented epoxy	$70^\circ F$	80% RH	1100^{*3}	1150^{*3}	900^{*3}

*1 Failed at substrate

*2 Failed at primer

*3 Failed at coating

*4 Failed in adhesive epoxy (bond between coating and metal failure)

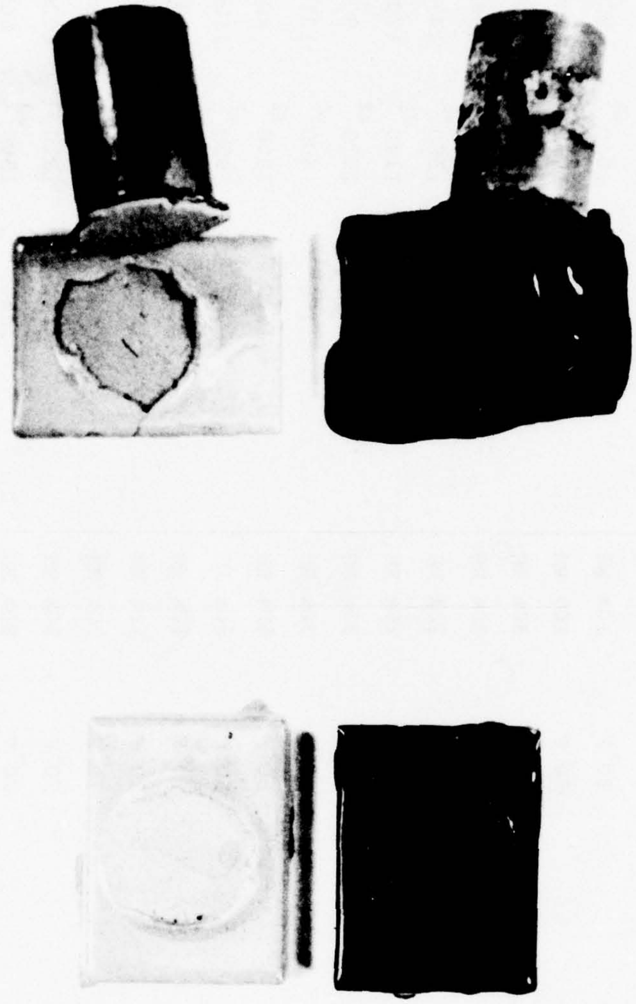


Figure 18 Typical Bond Strength Samples after Test. Gray specimen is nonsolvented polyurethane and black coating is nonsolvented epoxy.

the coating on the steel. The lower photograph shown in Figure 18 shows the polyurethane failure (gray coating) to be partially in the coating and partially at the primer while the epoxy coating failure is all in the coating.

During the application certain observations were made concerning the applications and curing. These observations are listed below.

- Both the Zebron and the Inerta could be applied under the worst conditions - 10°F and 10% RH.
- The vinyl phenolic primer could also be applied at the above temperature and did cure at that temperature.
- The Zebron partially cured during the evening hours but the Inerta 160 did not. Both materials were partially frozen at 10°F (evening hours).
- The Zebron completely cured at 40°F after the freeze period but the Inerta remained viscous.
- The Inerta did finally cure at room temperature after approximately one hour exposure.
- Moisture condensation on the cold coated surface, did not appear to affect the curing or overall final hardness of the finished coating.

As a result of this evaluation the following comments can be made concerning the application of the nonsolvented coatings (within the range of conditions evaluated).

The condition parameters for application of the nonsolvented polyurethane are less stringent than for the nonsolvented epoxy. The bond strength properties of both coatings are not changed significantly after curing. However, the polyurethane will cure at lower temperatures than the epoxy. The character of the coating bond strength does not change with application conditions. In general, the polyurethane failure is associated with the primer while the epoxy failure is in the coating itself (cohesive).

6.3 Bond Strength of Antifoul

A technique has been developed by Xenex Corporation to apply an antifoul coating to the nonsolvented polyurethane. This would afford a wear resistant, corrosion resistant coating and still maintain antifoul protection. The technique used is to apply a coating of antifoul immediately after the polyurethane is applied. Essentially the antifoul is applied while the polyurethane is still wet, resulting in the polyurethane curing while the antifoul is drying. This technique apparently results in a chemical bond between the antifoul and the polyurethane.

Usually the bond strength between the antifoul coating and the corrosion resistant coating is between 70 and 300 psi. The antifoul is applied after the corrosion resistant coating has been allowed to dry for several hours. In most cases it is not recommended that the antifoul be applied while the undercoat is still wet because it would tend to trap the solvents in the undercoat or form bubbles in the antifoul, resulting in a porous AF coating. In the case of the polyurethane there are no solvents and therefore the AF can be applied while the undercoat is wet. This gives the advantage of a chemical bond to the polyurethane and there is no need to wait between coats for curing.

6.3.1 Bond Strength Test Specimen

A set of bond strength specimens were coated with the polyurethane and antifoul system and tested for adhesion. The specimens were coated at 70°F and 45% relative humidity. The results are as follows:

Specimen No.	Bond Strength	Remarks
1	1052	Broke in the AF coating
2	1145	Broke in the AF coating
3	955	Broke in the AF coating
4	1110	Broke in the AF coating

The values obtained far exceed those which would be expected on a standard AF coating system. In all cases the separation took place in a cohesive manner in the AF coating. Photographs of typical test specimens are shown in Figure 19. Therefore, the fouling protection of this system remains unchanged while the coating bond strength is significantly higher. The antifoul used in these tests was the one which gave good antifoul protection in the West Coast tests (Section 6).

6.4 Reapplication of Additional Coating

The application and squeegee technique appeared to be a promising method to reduce the surface roughness of a severely pitted hull. However, the best

Figure 19 Bond Strength Test Specimen Used to Determine the Strength of Antifoul Coating on Nonsolvented Polyurethane

application method to facilitate an acceptable bond strength was not known. The methods attempted were:

- Apply to a coating of polyurethane previously cured
- Apply a second coat of polyurethane to the first coat while the first coat is still wet
- Mechanically abrade the surface of a previously cured coating before applying the second coat.

Certainly the simplest method is the first. That is, to apply a second coat of polyurethane with no additional surface preparation to the coating which had been applied the day before and allowed to cure overnight. The results can be seen in the photograph shown in Figure 20. The coating separated between layers; the bond strength was measured as 687 psi and 940 psi on the test specimens.

The second method used was to apply the second coat within 10 minutes after applying the first coat. Essentially the first coat was applied and any telescoping squeegeed off. The second coat was then immediately applied. The bond strength measured was 1670 and 1820 psi. Separation was not associated with the interface between the coatings. This method appeared to be satisfactory.

The third method examined was to mechanically abrade a previously coated surface with 180 grit abrasive paper and apply a second coat to the surface. The bond strength measured was 1150, 1352 and 1310 psi. The coating separation was associated with the interface between layers. The bond strength appears adequate for hull application but it is recommended that similar tests be run on a coating specimen which is first allowed to cure and is then exposed to water (salt and fresh) before applying a second coat. This is essentially the scenario which would apply to the repair of a damaged hull coating. It is also recommended that a similar test be run as described above but that the panel then be exposed to water before running bond strength measurements. This test would determine whether water exposure will deteriorate the bond at the individual layer interface.

6.4.1 Reapplied Coating Results

The results of the bond strength measurements on reapplied coatings indicate that the most acceptable method is to apply a second coat while the first coat is still wet. If the first coat has dried, the surface must be mechanically abraded before subsequent coatings are applied. It is also felt that further

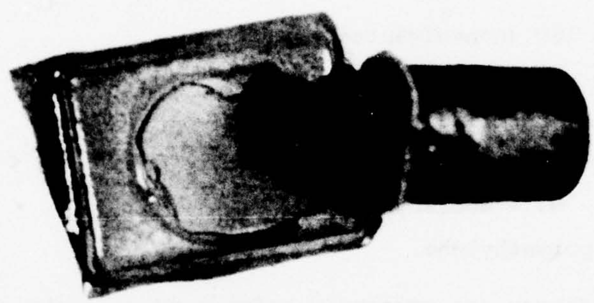


Figure 20 Bond Strength Specimen after Testing of Reapplied Polyurethane Coating. Coating peeled between layers of coating.

testing is necessary to establish the effect of water exposure on the bond between the two layers of coating.

6.5 Long Term Wear Tests

A long time wear test was devised to obtain comparative wear data on each of the candidate coatings. The test was set in a rotating drum containing ice chunks and abrasive particles. The drum was then placed in a freezer and rotated. This test was designed only to measure the relative abrasion resistance of various materials at low temperatures and represent only erosion on an icebreaker hull and not an attempt to simulate the high impacts which are experienced during icebreaking.

The materials evaluated were:

- Inerta 160 (nonsolvented epoxy)
- Zebron - amorphous silica filled
- Zebron - unfilled
- Polyurethane - solvented - moisture cure
- Epoxy - W2 - Woolsey Marine
- Solid polyethylene.

The Inerta and Zebron are presently being used on icebreaker hulls. The solvented polyurethane was chosen for comparative purposes. The W2 epoxy was a candidate for marine applications but at the time it was not commercially available. The solid polyethylene was used as a control.

6.5.1 Wear Test Results

There is a significant difference in wear resistance for each of the materials evaluated. All of the specimens were run simultaneously in the same drum for the same length of time. The total test time was 1320 hours.

Both the filled and the unfilled nonsolvented polyurethane gave very little wear. In both cases the area of abrasion could be seen but was not measurable with a micrometer. A surface profilometer trace showed that the roughness increased from 32 μ" CLA to 100 μ" CLA. However, even with the increased roughness, the tops of the asperities were even with the original surface. Therefore, a material removal parameter could not be measured on a macro scale. The measurements taken on the micro scale show that the lower portion of the asperities had worn .002" for the filled material and .0015" for the unfilled. The original coating thickness for both materials was .060".

The W2 epoxy gave poor results. The surface had worn .004"; some coating spalled at the edge and middle portion of the surface. The surface roughness increased from 60 μ" CLA to 128 μ" CLA.

The solvented polyurethane gave very low wear rate in the center of the test specimens (less than .001"). However, the edges had worn down to the steel surface. The surface roughness increased from 9 μ" CLA to 110 μ" CLA.

The Inerta 160 wore completely through at the end of the test. It should be noted that after 840 hours of testing the coating was completely intact. Once the coating started to wear, the wear rate had increased drastically until it had worn down to the steel substrate. The original coating thickness was .015".

A tabulation of the test results is given in Table 10. Photographs of the specimens are shown in Figure 21.

It is apparent from these tests that for light abrasion, the nonsolvented polyurethane gave the lowest wear rate and the least amount of damage. The solvented polyurethane which also gave a low wear rate, has a disadvantage in that the coating can only be applied to a thin dry film thickness (less than .010").

6.6 New Materials

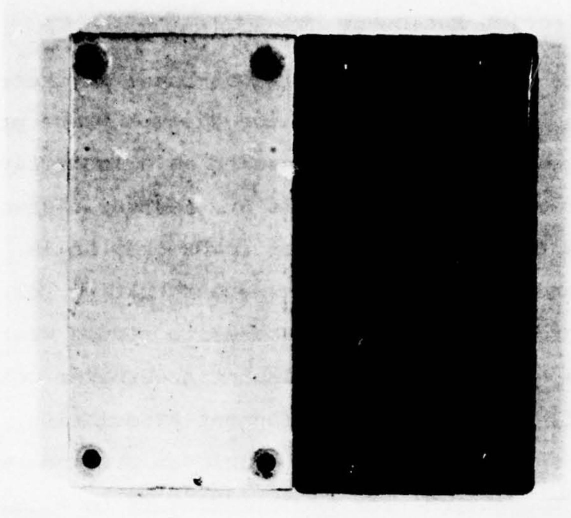
Efforts to obtain new materials which would be suitable for use on hulls of icebreakers continued throughout the program. The materials which had been most successful to date were the nonsolvented coatings. This was attributed to their increased bond strength and wear resistance. Therefore, the emphasis was placed on nonsolvented coatings during this Phase of the program. There are many nonsolvented resin systems available on the market but few are sprayable or low enough in viscosity to be applied under dry dock conditions.

The materials which were examined are Aquacoat 28.05, manufactured by Citosan Ltd., Canada, glass-filled epoxy, manufactured by International Paint Company, copper cladded steel, developed by Copper Development Association, Inc. In addition, the data on Inerta 160 which was not generated during the Phase II portion of this program was completed.

TABLE 10

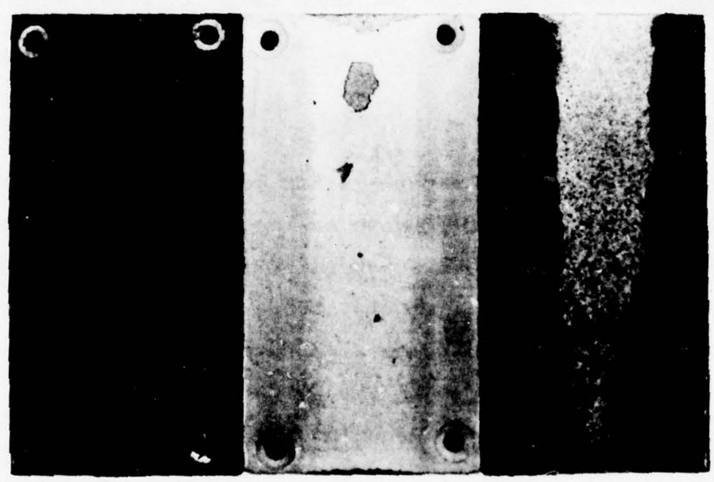
RESULTS OF THE LONG TERM WEAR TEST ON THE VARIOUS CANDIDATE COATINGS

Material	Surface Roughness Before Test	Surface Roughness After Test	Original Film Thickness	Wear Depth Specimen Center	Remarks
Zebron	32 μ"	100 μ"	.030"	.002"	No chipping evident
Zebron unfilled	34 μ"	102 μ"	.030"	.0015"	No chipping evident
W2 epoxy	60 μ"	120 μ"	.010"	.004"	Coating was chipping on the edge and in two large areas of the center
Polyurethane solvented	9 μ"	110 μ"	.006"	> .001	Edges worn
Inerta 160	9 μ"	185 μ"	.015"	.015"	Material in the center section completely removed



Filled Unfilled

Zebron Coating



Polyurethane Solvented W2 Epoxy Inerta 160

Figure 21 Test Specimens Used to Determine the Relative Wear Resistance of Materials Sliding Against Ice. Test was run for 1320 hours.

6.6.1 Material Selection Rationale

The selection of the above materials was based on their past performance in similar applications where abrasion or ice exposure were present. The Aquacoat 28.05 had been used with promising results as a protective coating and ice release agent on concrete lock walls in the St. Lawrence Seaway. Thus, this coating appeared to be a good candidate for icebreaker hulls. The glass-filled epoxy had been developed as an abrasion-resistant coating for ship hulls. Since glass or ceramic fillers are used in many cases to reduce wear it appeared to be an excellent candidate as an abrasion-resistant icebreaker coating. The copper cladding was developed by the Copper Development Association, Inc., originally for manufacture of a new hull. However, techniques are underway to apply cladding to an existing hull. The purpose for the cladding is to eliminate the need for an antifoul coating and reduce corrosion. The clad material was chosen since little is known concerning the damage resistance of copper to crushing ice, and since the cladded material could be utilized in future icebreaker construction. In addition, a 67 ft commercial shrimp trawler was built using the copper clad alloy and has operated successfully for more than six years with little hull maintenance required.

6.6.2 Testing Techniques

The tests used to screen materials for icebreaker hulls are described in Refs.[1] and [2]. Essentially they were an ice crushing test and an ice friction test. The crushing test was used to determine the abrasion resistance of the coating while crushing ice. The friction tests are used to determine the frictional characteristics of the coatings sliding against ice.

6.6.3 Damage Resistance During Crushing Ice

The surface roughness of the candidate materials was measured before and after tests. The test consisted of introducing 50 lbs of ice chunks between a stationary and oscillating plate. The oscillating plate was coated with a candidate coating. The ice was then crushed by the coated specimen surface. As the size of the ice particles was reduced the smaller particles dropped out of the test rig. After testing, the specimen surface was visually inspected and a surface profile trace taken for comparison with a trace recorded before the test.

6.6.3.1 Results

The results are summarized in Table 11.

The nonsolvented epoxy Aquacoat 28.05 increased in surface roughness and suffered some edge chipping. The glass-filled epoxy also increased in surface roughness. Examination under the microscope showed considerable glass particles chipping. The copper cladded steel had a slight increase in surface roughness which was a result of light surface scratches. Table 11 shows the surface roughness of the copper clad alloy before test was 0.6 μ" CLA. This was not the "as received" roughness. The specimens were ground and lapped to produce a roughness which would be acceptable for the test. The "as received" roughness was greater than 400 μ" CLA.

The results for Inerta 160 were encouraging, it had only a slight change in surface roughness and no apparent damage. However, the test results described previously on page 55 indicate that once the Inerta 160 starts to wear, it deteriorates rapidly.

6.6.4 Friction Tests

The friction tests were run on a test apparatus specially designed for this program. A complete description of the test rig is given in Ref. [1]; however, for completeness, a brief description follows.

The test specimen is a coated ring 2" OD × 1 1/4" ID × 1/2" thick. The ring is held in a holder driven through dowel pins and a ball and socket arrangement mounted to a drill press head. The coated surface slides against a cup containing ice, held in an angular contact bearing supported housing. The housing is restrained by torque arms on which strain gages are mounted. The test rig is mounted in a cold box on the bed of the drill press.

The breakaway, static and dynamic friction were measured for each of the candidate coatings. The test conditions were as follows:

Load - 30, 50, 90, 150 and 200 lbs

Temperature - 22°C (-7°F)

Relative humidity - 10%

Velocity -	breakaway	.4"/sec (maximum)
	static	.4"/sec (maximum)
	kinetic	283 ft/min

Environment - air

Surface roughness - as indicated

TABLE 11

RESULTS OF ABRASION TESTS (ICE CRUSHING) ON THE VARIOUS CANDIDATE COATINGS

Material	Brand Name	Surface Roughness		Coating Thickness	Results
		Before Test CLA	After Test CLA		
Nonsolvented epoxy	Aquacoat 28.05	20.0 μ"	35.0 μ"	.015"	Edge chipping
Glass-filled epoxy	-	75.0 μ"	130.0 μ"	.020"	Close in chipping
Copper clad steel	Grade 706	0.6 μ"	1.9 μ"	.070"	Light scratches
Epoxy	Inerta 160	78.0 μ"	75.0 μ"	.016"	No damage

6.6.4.1 Results

The test results are shown in Table 12. The Aquacoat 28.05 sample had a breakaway friction coefficient value of approximately .3 with the static friction coefficient of .25 and kinetic friction coefficient of .1 at all load levels.

The glass-filled epoxy specimen had the highest breaking values (.42 to .5) along with fairly high static and kinetic friction coefficients.

The copper clad steel produced friction coefficient values ranging from .45 breakaway to .09 kinetic. As with the abrasion tests, the surface roughness of the copper cladded specimens was ground and lapped. Therefore the surface roughness does not simulate that which would be expected on the hull of an ice-breaker.

The Inerta 160 specimen results ranged between .32 and .25 for the break-away friction coefficient and .08 to .09 for the kinetic friction coefficient.

Conclusions

Of the new materials tested in this phase of the program the Inerta 160 gave the best overall results.

6.7 Friction Testing on Hull Plating

The friction studies which have been conducted in the past were performed on specimens which were manufactured for the various tests. The steel composition was similar to that of a hull plate and the coating was applied to produce as smooth a surface as possible. However, the plating on the hull of a ship is usually corroded, sometimes with heavy pits and weld seams. Therefore, the specimen surface roughness does not simulate the hull surface roughness even though attempts have been made to produce a representative surface. In order to determine the effect of the large surface asperities, a series of tests was conducted in which a coating was applied to steel specimens made from scrapped hull plating. The plating was obtained from the U.S. Coast Guard Yard in Maryland. The surface roughness of the plate was greater than .004" profile and some pits were as deep as .030". Zebron unfilled polyurethane was used to coat the specimens. After coating the surface roughness was 300 μ" with some depressions approximately .005" deep. The tests were run under the following conditions:

TABLE 12

FRICTIONAL BEHAVIOR OF COATING MATERIALS

Material	30 lbs			50 lbs			90 lbs			150 lbs			200 lbs			Surface Roughness CLA	
	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic	Before Test (μ")	After Test (μ")
Aquacoat 28.05	.3	.25	.1	.3	.25	.1	.27	.24	.09	.29	.25	.09	.3	.26	.1	25.0	38.0
Glass-filled epoxy	.5	.4	.12	.45	.35	.1	.45	.35	.11	.42	.36	.12	.43	.33	.1	75.0	150.0
Copper clad steel	.4	.35	.11	.45	.3	.11	.5	.35	.1	.42	.25	.09	.45	.25	.09	0.6	4.5
Inerta 160	.3	.21	.08	.25	.21	.09	.26	.25	.09	.28	.25	.09	.32	.25	.09	65.0	68.0

Load - 200 lbs

Temperature - 18°C (2°F)

Relative humidity - 10%

Ice condition - "as frozen"

Surface roughness - steel > 4000 μ"

- coating 300 μ"

Velocity - as indicated.

Three tests were run under each condition. The results are plotted in Figure 22.

6.7.1 Results

The results show that there is a significant reduction in frictional resistance with the nonsolvented polyurethane coated hull plating. Under the conditions tested, the static friction coefficient of an uncoated hull is approximately .82 while with the coated steel the friction coefficient is .23. At 3.5 mph (5.13 ft/sec) the kinetic friction coefficient for the uncoated steel is approximately .13 while the coated steel gives a value of .07. During the uncoated test the ice was severely damaged leaving a white layer of ice chips on and surrounding the contact area. However, during the coated test the ice was lightly scratched with very little damage in the contact zone. The coated surface also had some light scratches on the surface but there was little evidence of coating removal.

On several occasions throughout the test the drive motor was kept at one speed for a continuous run. Essentially the test specimen was rotated at 1 mph (1.47 ft/sec) for one hour. The friction coefficient did not deviate from the .1 value significantly. It appeared to cycle between .12 and .09 throughout the test. This was also true with the uncoated steel specimen. The speed was kept at 1 mph (1.47 ft/sec) for one hour and the friction coefficient varied between .6 and .7.

6.7.2 Conclusions and Recommendations

The addition of a low friction coating to the hull will reduce the frictional resistance on the hull. But at the present time, the contribution of friction to the total resistance of a hull during icebreaking is not well understood. Several investigations have suggested that the friction contribution is extremely high. Tuukkanen and Tallgren [5] indicate that mechanical friction between ice and a ship hull accounts for 50 - 70% of the total resistance. The full-scale tests performed during this program indicate an 8 to 15% reduction in total resistance can be realized during icebreaking by coating the hull with the

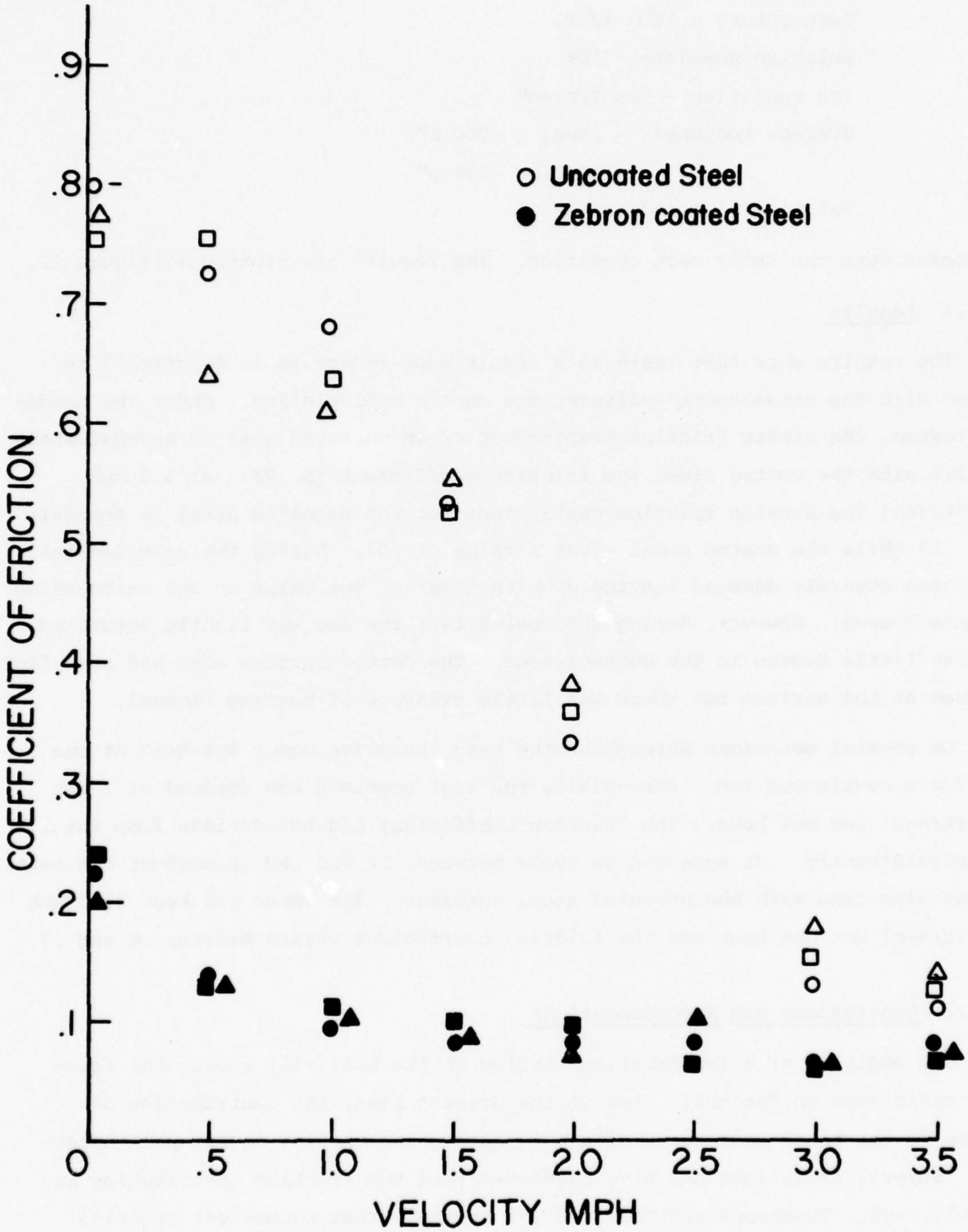


Figure 22 Comparison of the Friction Coefficient of Zebron Coated Steel and Uncoated Hull Plating as a Function of Velocity

nonsolvented polyurethane. There has not been a concerted effort to establish the friction forces on the hull of an icebreaker during icebreaking. This is an extremely difficult problem and the author believes that it can only be solved by instrumenting the hull of an icebreaker with force transducers and measuring resistance during icebreaking.

SECTION 7

PARTIAL HULL COATING

7.1 Model Testing

The cost for applying a low friction coating to the hull of an icebreaker can be as much as double the cost of applying a conventional coating. When coating a larger ship it may not be necessary to coat the entire hull with an exotic coating to achieve effective hull protection since most of the icebreaking damage occurs at or near the ice line and at the bow. Therefore it is possible that a partial coating technique can be used with a low friction coating applied at the areas of heaviest abrasion (exotic coating) and a less expensive (or thinner) coating applied to the areas subjected to less abrasion. Since the coating on an icebreaker is worn in selected areas, it also is reasonable to expect that these areas are those which contribute most to the frictional resistance of the hull. Therefore, the application of a low friction coating on selected areas may also significantly reduce the overall resistance to an icebreaker in ice.

A method of selecting the areas of a hull which are most subject to abrasion during icebreaking was devised and implemented under subcontract to ARCTEC, Incorporated. The friction coefficient was varied in these areas on the hull of an icebreaker model to determine contribution of friction to the overall resistance. The work was performed on models of the USCG Cutter POLAR STAR. The ARCTEC report, in its entirety, is attached as Appendix B.

7.2 Method of Determining Hull Areas Most Affected by Abrasion

A water resistant material with poor bonding characteristics was deposited on the hull of a model icebreaker. In this instance the coatings used were calamine lotion and cream car wax. The model was then placed in the ice tank and towed through the ice. The model was then removed and the areas where the coating had rubbed off in the ice examined. These areas were determined to be most subject to ice abrasion and were selected for study by changing the surface roughness, thereby changing the friction coefficient. By measuring overall hull resistance the areas on the hull which produce the most significant frictional resistance contribution could be determined.

7.3 Results

One of the most significant statements made in that report (Appendix B) is given on page B-46. It states, " ... the limiting ice thickness for operation of the POLAR STAR can be radically increased through the use of as little as 10% low friction abrasion resistance coating and with up to 20% coating a significant benefit can be obtained. Between 20% coating and totally coating the hull, little additional benefit is gained in performance". It should be understood that the statement refers to power reduction only and not corrosion or cavitation protection. This report does not recommend partial hull coatings but it is an alternative that offers lower costs than applying a full hull coating of an exotic material.

The technique of coating the model hull with a water resistant, weakly bonded coating to observe the major areas of contact between the ice and the hull represents a significant new analytical tool for model testing of ships in an ice basin. It is strongly recommended that this method be used by Naval architects in future hull design studies for both icebreakers and ice transiting vessels. Ice contact can be easily seen on areas such as bossing or underneath the hull which are poorly visible while the model is in the water.

SECTION 8

COST BENEFIT ANALYSIS

8.1 Introduction

There are two major advantages to coating a ship with an abrasion-resistant hull coating. They are:

- Resistance reduction
- Reduction in maintenance cost.

However, the application of these exotic coatings is expensive and at times difficult because of the temperature and humidity specifications. Therefore, a cost benefit analysis was performed to determine if a monetary savings could be realized from the application of ice coating and at what point the cost saved would offset the original investment. Traditionally, the hull of a large icebreaker is rarely coated because standard coatings cannot withstand even a few hours of abrasion in ice. Therefore, the coating cost used in this task includes surface preparation, materials and labor. Compared to a ship which would normally be coated with a standard antifoul/anticorrosion coating, the initial cost for switching to nonsolvented coatings would be much less since surface preparation and material cost would be similar regardless of the material used. Essentially the initial coating cost would be the cost for applying the nonsolvented coatings minus the cost for applying the standard coating.

The following paragraphs describe an economic analysis that was performed to establish the cost benefit obtained between a coated hull and an uncoated hull of the following Coast Guard icebreakers:

- USCG Cutter GLACIER
- USCG Cutter POLAR STAR
- USCG Cutter POLAR SEA
- 110 ft Class Icebreaking Tug
- 140 ft Class WYTM.

The method used in this analysis was based on data obtained from the Coast Guard Office of Engineering and the Economic Analysis Handbook [6]. Several parameters necessary for the analysis were not available, therefore a sensitivity analysis was performed to establish the cost trend over the life of the particular ship in question. One such parameter was the cost of fuel at the present time and in the future.

8.2 Operating Scenario and Economic Life

A. GLACIER: The GLACIER operates on a three-year cycle composed of the following scenarios:

First year - Deep Freeze 1 (Ross Sea)
Second year - Deep Freeze 1, Arctic West Summer
Third year - Arctic West Winter, Arctic West Summer

This three-year cycle is repeated until 1990, which is the latest expected decommission year for the GLACIER.

B. POLAR STAR and POLAR SEA: The POLAR STAR and POLAR SEA also operate on a three-year cycle, the expected decommission year for both ships is 2005:

POLAR STAR:

First year - Deep Freeze 2 (Weddel Sea)
Second year - Deep Freeze 1 (Ross Sea), Arctic West Summer
Third year - Arctic West Winter, Arctic West Summer.

POLAR SEA:

First year - Arctic West Winter, Arctic West Summer
Second year - Deep Freeze 2
Third year - Deep Freeze 2, Arctic West Summer

C. 110' and 140' Class: The 110' and 140' class icebreakers operate on a one-year cycle composed of 914 hours underway in open water, 748 hours breaking ice and 7098 hours not underway. The decommission year for the 110' class icebreaker is 1981 and for the 140' class is 2008. Please note that the starting year for the economic analysis was 1979.

Table 13 is a detailed breakdown of the operating scenarios listed above.

TABLE 13

OPERATING SCENARIOS

---

1. GLACIER

   a) Deep Freeze:

      75 days transit
      6 days icebreaking
      19 days science mission
      8 days channel running
      27 days in port, drifting

   b) Arctic West Summer:

      26 days transit
      2 days icebreaking
      47 days science mission
      15 days in port, drifting

   c) Arctic West Summer:

      20 days transit
      4 days icebreaking
      29 days science mission
      10 days in port, drifting.

   The following average engine operating profiles are assumed:

      Transit: 4 engines, 1900 BHP/eng., SFC = 0.37
      Icebreaking: 7 engines, 2100 BHP/eng., SFC = 0.37
      Science: 4 engines, 2100 BHP/eng., SFC = 0.37
      (SFC - Specific Fuel Consumption [lbs/BHP-HR])

2. POLAR STAR and POLAR SEA

   a) Deep Freeze 1:

      68 days transit
      1 day icebreaking (gas-turbine)
      3 days icebreaking (diesel engines)
      8 days channel running
      23 days science mission
      27 days in port, drifting

   b) Deep Freeze 2:

      75 days transit
      1 day icebreaking
      3 days icebreaking (diesel engines)
      40 days science mission
      26 days in port, drifting

   c) Arctic West Summer:

      20 days transit
      2 days icebreaking (diesel engines)
      53 days science mission
      15 days in port, drifting

(continued)

TABLE 13 - continued

d) Arctic West Winter

12 days transit
4 days icebreaking (diesel engines)
40 days science mission
7 days in port, drifting

Assumed average power profiles required for each mode:

Transit: 3 engines, 3200 BHP/eng., SFC = 0.37
Icebreaking (gas turbine): 3 engines, 25,000 BHP/eng., SFC = 0.45
Icebreaking (diesel engines): 6 engines, 3500 BHP/eng., SFC = 0.368
Channel running: 6 engines, 3500 BHP/eng., SFC = 0.368
Science mission: 2 engines, 3200 BHP/eng., SFC = 0.37

3. 110' and 140' Class Icebreakers:

For 80% of the 914 hours underway in open water, two engines are required for the 110' class at 1000 BHP/eng., SFC = 0.36, and for the 140', two engines at 2500 BHP/eng., SFC = 0.36. For the remaining 20%, the 110' uses two engines at 750 BHP/eng., and the 140' uses two engines at 1750 BHP/eng., SFC = 0.38. For icebreaking, the 110' uses two engines at 1000 BHP/eng. and the 140' uses two engines at 2500 BHP/eng., SFC = 0.36.

Table 14 shows the decommissioning year and the economic life of the icebreakers under consideration.

TABLE 14

ECONOMIC LIFE

Ship	Decommissioning Year	Economic Life
GLACIER	1990	12 years
POLAR STAR	2005	27 years
POLAR SEA	2005	27 years
110 Footer	1981	3 years
140 Footer	2008	30 years

8.2.1 Fuel Consumption

The fuel consumption for each operation mode can be calculated by the following formula:

$$FC = SFC \times BHP \times HRS/2240 \quad (8\text{-}1)$$

where

FC - Fuel consumption (tons)

SFC - Specific fuel consumption (lbs/BHP/hr)

BHP - Brake horsepower

HRS - Time engine in operation (hours)

2240 - For changing dimension lbs - tons.

The annual fuel consumption for each icebreaker is tabulated in Table 15. The fuel consumption values shown after coating are based on $x = 0.1$ reduction in open water resistance and $y = 0.3$ reduction in ice resistance for old ships. This reduction could vary depending on the friction coefficient, and therefore a sensitivity analysis was performed on these variables.

TABLE 15

ANNUAL FUEL CONSUMPTION

Ship	Year In Cycle	Fuel Consumption Uncoated	Fuel Consumption Coated	Percent Saved
GLACIER	First	3305 (tons)	2851 (tons)	14.
(3 year cycle	Second	5249 (tons)	4582 (tons)	13.
operating scenario)	Third	3302 (tons)	2932 (tons)	11.
POLAR STAR	First	4479 (tons)	3909 (tons)	13.
(3 year cycle)	Second	6741 (tons)	5779 (tons)	14.
	Third	4075 (tons)	3568 (tons)	12.
POLAR SEA	First	4075 (tons)	3568 (tons)	12.
(3 year cycle)	Second	4479 (tons)	3909 (tons)	13.
	Third	6751 (tons)	5921 (tons)	12.
110' Class	First	519 (tons)	419 (tons)	19.
(1 year cycle)				
140' Class	First	1297 (tons)	1047 (tons)	19.
(1 year cycle)				

8.2.2 Maintenance Costs

The average weld repair cost over the last eight years for the Cutter GLACIER has been $128,000 for each dry docking. The dry docking is scheduled at two-year intervals. The cost in this instance is unique to the GLACIER since much of the expense has been in weld corrosion. The cost for weld repair may be high, due to the severity of attack on the GLACIER hull welds. A sensitivity analysis was performed on a coated vs. uncoated hull in which the hull repair costs were varied.

An initial painting cost of $80,000 for the hull of the GLACIER (or other ships of the same surface area) and a paint repair cost of $16,000 for each subsequent two-year dry docking was assumed in the analysis. The weld and coating repair costs were eliminated for the year 1989 since the ship is scheduled for decommissioning.

The maintenance costs and savings over the economic life of the GLACIER are shown in Table 16.

TABLE 16

MAINTENANCE COST OF THE GLACIER

Year		Weld Repair Cost	Coating Repair Cost
1979		$ 128,000	$ 80,000 (initial coating cost)
1981		128,000	16,000
1983		128,000	16,000
1985		128,000	16,000
1987		128,000	16,000
	Total	$ 640,000	$144,000
	Saved	(640,000 - 144,000 = 496,000)	

Since data on weld repair costs of the POLAR CLASS icebreakers and the 110' and 140' WYTM are not available, only the initial coating costs, as shown in Table 17 was considered in calculating the total savings.

TABLE 17

INITIAL COATING COSTS OF THE POLAR STAR, POLAR SEA, 110' AND 140' WYTM

Ship	Initial Coating Cost
POLAR STAR	$ 100,000 quoted cost for applying Zebron
POLAR SEA	80,000 quoted cost for applying Inerta 160
110' Icebreaking tug	12,000 actual cost for applying Zebron
140' WYTM	20,000 quoted cost for applying Zebron

The scrap value of the decommissioned ship was excluded from the analysis since it will be approximately the same for the coated and uncoated cases.

Cash Flow Diagrams

Following are the cash flow diagrams for the icebreakers considered in this analysis. The time scale is represented by a horizontal line, with units in years. The starting year for this analysis is the year 1979. Costs are represented by vertical arrows whose locations indicate the time they occur. Note that in the cases of the POLAR CLASS, 110' Class and 140' Class, weld repair costs and paint repair costs were omitted because there were not sufficient data available. If these costs had been considered, as in the case of the GLACIER Class icebreakers, there would have been some additional benefit in favor of the coated hull.

a) GLACIER Class Icebreakers

	79	80	81	82	83	84	85	86	87	88	89	90
Uncoated:	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓
	WR		WR↓		WR↓		WR↓		WR↓			

	79	80	81	82	83	84	85	86	87	88	89	90
Coated:	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓
	IC↓		CR↓		CR↓		CR↓		CR↓			

F - Fuel cost (F for uncoated is not equal to F coated)

WR - Weld repair cost

CR - Coating repair cost

IC - Initial coating cost.

b) POLAR Class Icebreakers

Uncoated:	79	80	81	82	83	84	85	86	....	2002	2003	2004	2005
	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓		F↓	F↓	F↓	F↓
Coated:	79	80	81	82	83	84	85	86	....	2002	2003	2004	2005
	F↓	F↓	F↓	F↓	F↓	F↓	F↓	F↓		F↓	F↓	F↓	F↓
	IC↓												

c) 110' Class

Uncoated:	79	80	81	Coated:	79	80	81
	F↓	F↓	F↓		F↓	F↓	F↓
					IC↓		

d) 140' Class

Uncoated:	79	80	81	82	83	84	85	....	2006	2007	2008
	F↓	F↓	F↓	F↓	F↓	F↓	F↓		F↓	F↓	F↓
Coated:	79	80	81	82	83	84	85	....	2006	2007	2008
	F↓	F↓	F↓	F↓	F↓	F↓	F↓		F↓	F↓	F↓
	IC↓										

8.2.3 Hull Resistance

It has been shown that a reduction in ice resistance will be obtained if the icebreaker hull is coated with certain materials. Extensive work conducted by SNAME [7], Wartsilla Shipyards in Finland [8], and RPI has shown that the hull resistance on a coated ship will be less than that of an uncoated hull. The SNAME work indicated that a reduction of as high as 14% can be obtained in open water by reducing the surface roughness of the hull. The work in Finland shows a reduction of as high as 25% can be obtained in ice. The resistance measurements described in this report show a reduction of 15% in brash ice. Other data obtained during model testing by ARCTEC (described in this report) also shows a reduction in ice resistance when certain materials are applied to the hull of an icebreaker model. All of the above data was influenced by the hull design and size of the vessels investigated.

Previous studies [2] had shown that the friction coefficient is dependent on the ice conditions and the hull roughness. It is difficult to predict the exact friction coefficient at any given time without defining all conditions. Since the friction coefficient is not accurately predicted, the contribution of friction to the total resistance on the hull is also difficult to determine. Therefore, assumptions were made in order to obtain the cost benefit of coating the hull.

By coating the icebreaker, it is assumed that there will be an X% reduction in open water resistance and a Y% reduction in icebreaking resistance. Previous data from Wartsilla had suggested a resistance reduction of X = 10% and Y = 30% (old ship) and Y = 20% (new ship). In full-scale tests performed by RPI, the icebreaking friction reduction (Y) was found to be approximately 8% ~ 15%. It was assumed that this reduction in resistance resulted in the same X% and Y% reduction in fuel consumption. A sensitivity analysis on these two parameters was performed in the latter part of the analysis.

8.2.4 Present Value Cost

Since money is a productive commodity, its use involves an interest rate which is usually expressed as a percent or decimal. With this interest rate, a dollar, ten years from today will not have the same value as a dollar today. An investor must take this time value of money into account when analyzing an investment involving expenditures at varying points in time. This involves the use of "present value cost", which is the value at the present time, or the cost in terms of the present dollar of a specific amount of expenditure at a specific time in the future. This "present value cost" or N.P.V. (Net Present Value) is calculated by the following formula:

$$NPV = \sum_{t=0}^{n} \frac{A_t}{(1+k)^t} \tag{8-2}$$

where

NPV - Net present value

A_t - Cash flow in period t

n - Number of periods

t - Total number of periods (years)

In the analysis, most of the expenses occur at some time in the future and were converted into present value cost in terms of the 1979 dollar, which was the starting year for the analysis. A detailed explanation of present value cost can be found in the "Economic Analysis Handbook", [6].

Cost Benefit

The benefit gained by coating the icebreaker depends on many parameters that could not be decided specifically at the time such as oil price, discount rate ... . However, using conservative assumptions of values for these parameters, general ideas concerning cost savings can be obtained. In the second part of this task, a sensitivity analysis was performed to determine the effect of drift-off from the reference values used. The following values were used for calculating the cost benefit:

Oil price: $ 13.50/barrel (1979 price)

Discount rate: 0.1 (10%)

Resistance reduction parameters: $X = 0.1$, $Y = 0.3$ (old ship)

$X = 0.1$, $Y = 0.2$ (new ship.

The total discounted savings for each ship are contained in Table 18.

TABLE 18

TOTAL DISCOUNTED SAVINGS

Ship	Total Discounted Savings	(Discounted) % Saved
GLACIER (Economic life: 12 years)	$ 706,273	20.7 (including weld & coating repair costs)
	293,742	9.9 (excluding weld & coating repair costs)
POLAR STAR (Economic life: 27 years)	549,824	9.9
POLAR SEA (Economic life: 27 years)	504,624	9.9
110 Footer (Economic life: 4 years)	15,287	10.8
140' WYTM (Economic life, 30 years)	283,595	17.8

It must be emphasized that these values are calculated with a constant cost over the life of the ship. Certainly the cost of oil and the discount rate will increase over the next 30 years. Therefore the values shown are a minimum cost savings.

In the case of the GLACIER, where weld repair costs were considered, the savings due to welding cost and painting cost alone over the economic life of the ship comes to about $410,000 more than the savings due to friction reduction ($293,000). (The value of weld cost is different than the one in Table 16 because it has been converted into discounted cost.) On other ships, where only painting costs were considered, a saving in fuel cost due to resistance reduction is necessary to pay for this initial coating cost. However, only very small values of X and Y are required to overcome this cost.

8.3 Sensitivity Analysis

A sensitivity analysis was performed in which the following four parameters were varied. They are:

- Resistance reduction parameters (X,Y)
- Weld repair cost (on the GLACIER only)
- Discount rate
- Oil price.

Since varying these four parameters at the same time will generate a substantial amount of data (if 10 points are calculated for each parameter, there will be 10^4 = 10,000 sets of data), the computer programs were written so that only one parameter would vary at a time while the other three were kept at the constant values suggested. However, the program can be modified easily to run with any new set of the four parameters above.

8.3.1 Resistance Reduction Parameters

The resistance reduction parameter X (in open water) is varied from 0.02 to 0.2 in steps of 0.02; Y (in ice) was always equal to 3X for the GLACIER and the 110' Class (old hull). In cases of the POLAR Class Icebreakers and the 140' Class (new hull), Y was set at 2X during the first ten years of the ship's life and equal to 3X thereafter. The resistance reduction parameter X (open water) also varies with the ship's life but the difference is small enough to be neglected.

The results are plotted in Figure 23. Note that the minus savings on these figures is due to the initial coating cost, however only a small friction reduction of about 0.02 for X is enough to pay off for this initial coating cost. Figure 23 shows the important effect that the economic life of a ship has on the benefit that can be gained by coating.

8.3.2 Discount Rate

The discount rate was varied from 0.01 to 0.31 in steps of 0.03. The results are plotted in Figure 24. The amount of savings decreases exponentially with the discount rate but the percent saved over the uncoated case does not change significantly. This is due to a small present value cost corresponding to a high discount rate.

8.3.3 Weld Repair Cost

A weld repair cost analysis was done on the GLACIER only and was varied from $58,000/year to $198,000/year. This resulted in a linear increase both in savings and percent saved over the uncoated case, as indicated in Figures 25 and 26.

8.3.4 Oil Price

Because of the uncertainties surrounding the cost of oil over the next several years, the oil price sensitivity analysis was done in three ways:

a) Starting with a beginning oil price of $13.50/barrel (1979) and then increasing at A% per year. The value of A was varied from 0% to 30%. The results are plotted in Figure 27. The savings in present value cost increase exponentially with A and a longer economic life results in a higher slope. The percent saved increases slightly with A but begins to level off at A = 20 ~ 25%. When weld and paint repair costs are considered, the percent saved decreases with A. This is due to a fixed savings given by weld and paint repair costs compared to an increased expense for fuel.

b) Same as part a) but with a sudden increase of 50% in oil prices in 1985. The results are plotted in Figure 28 and they do not deviate very far from results of part a) above, especially in the region of higher values of A. There were some interesting numbers in this computer: with an oil price of $13.50/barrel in 1979 and an annual

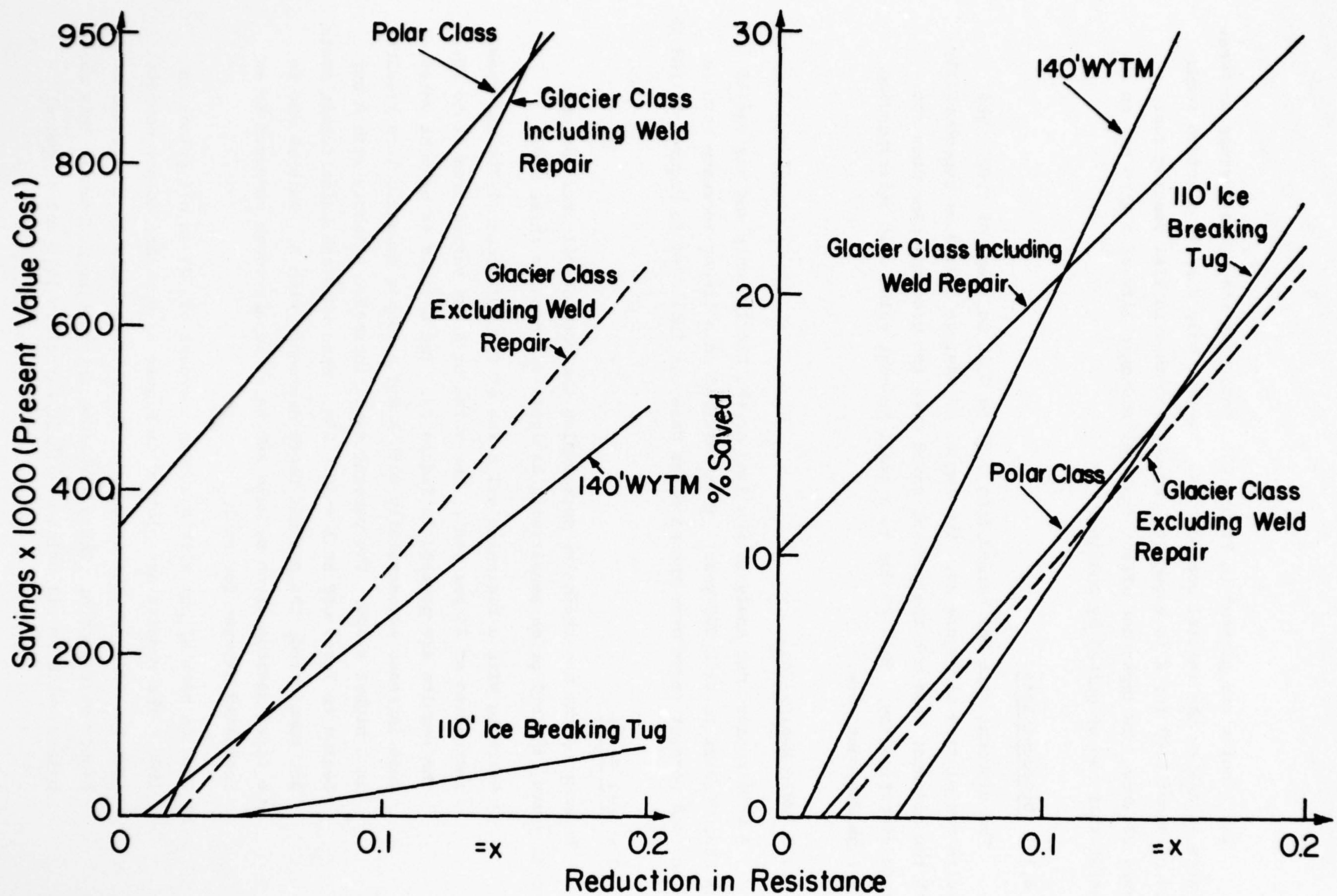


Figure 23 Effect of Reduction in Resistance on the Cost Savings Obtained by the Application of Nonsolvented Coatings

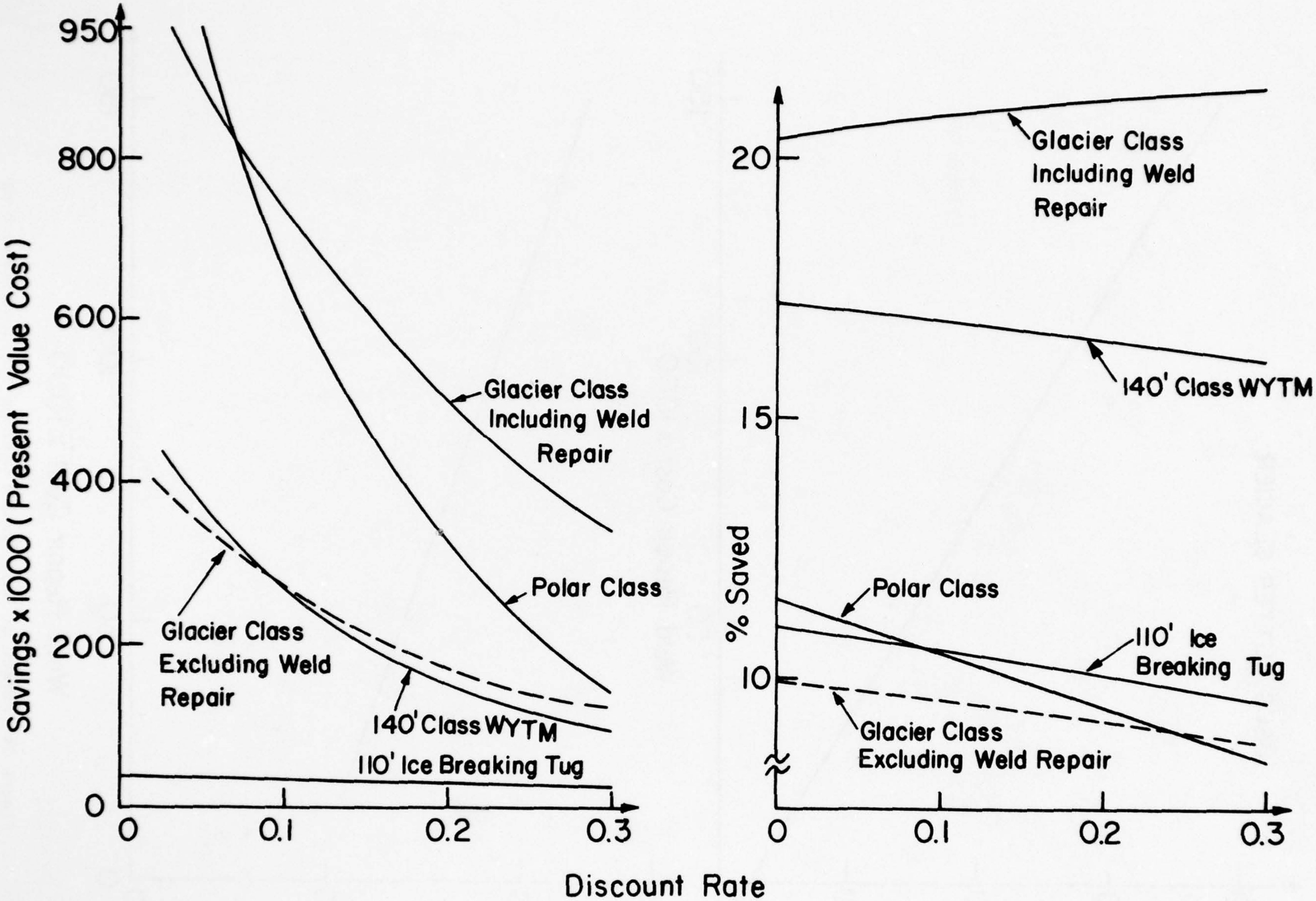


Figure 24 Effect of Discount Rate over the Economic Life of Various Ships on the Cost Saving Obtained by Applying Nonsolvented Coatings

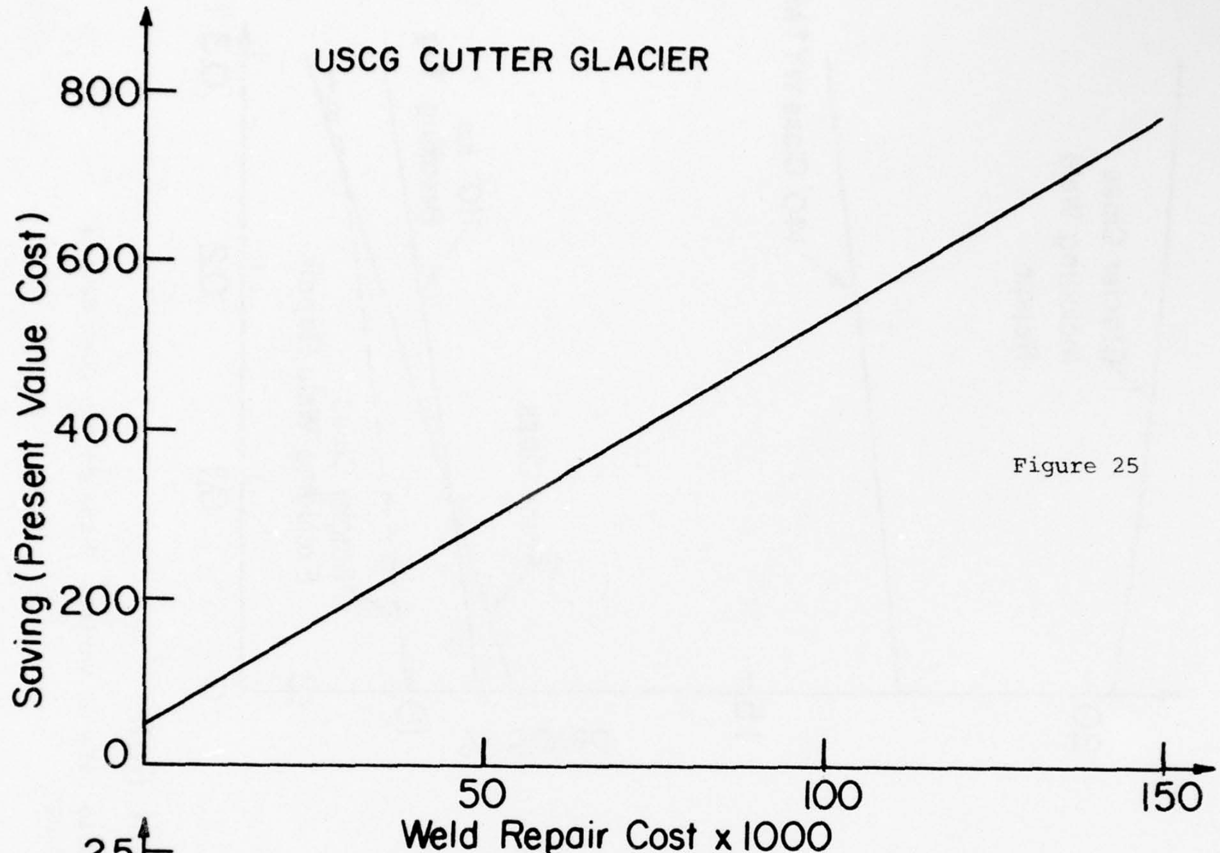


Figure 25

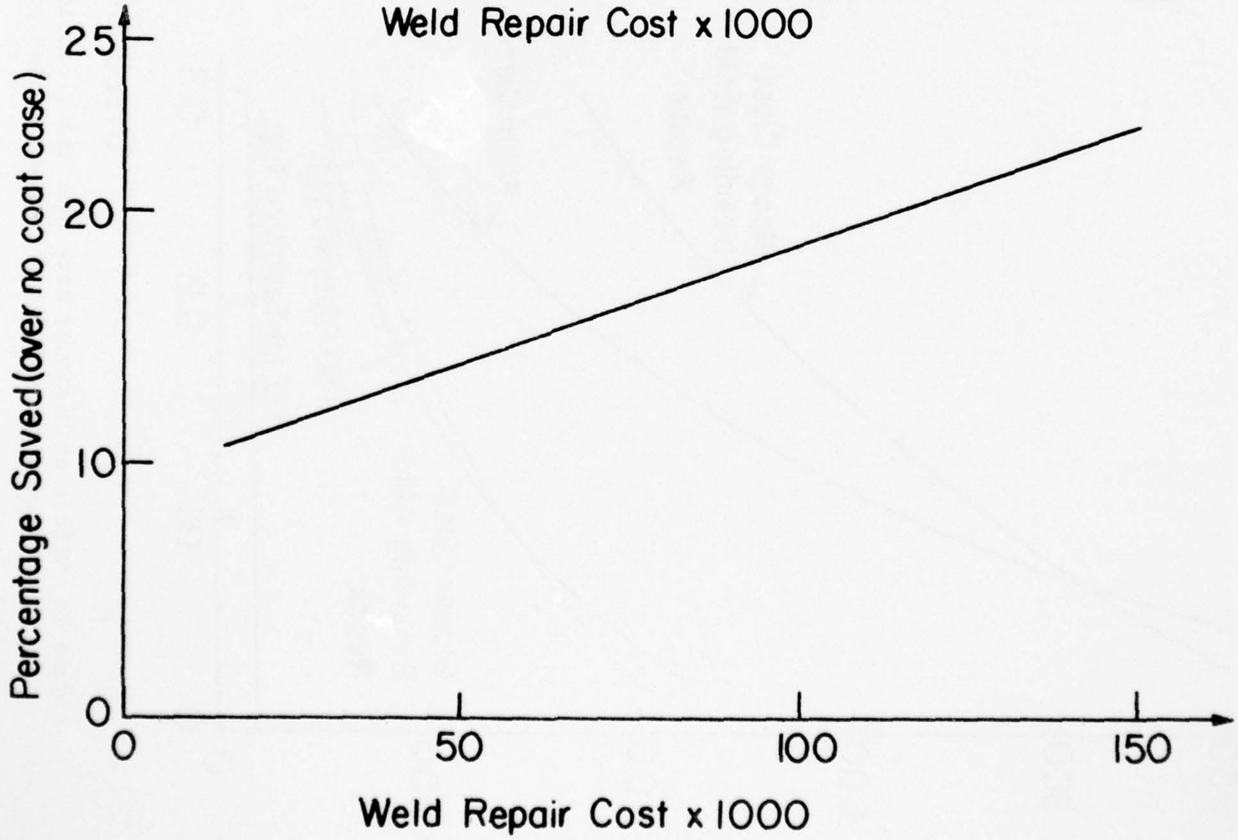


Figure 26 Effect of Weld Repair Cost on the Cost Benefit of Applying the Nonsolvented Coatings

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LOW FRICTION HULL COATINGS FOR ICEBREAKERS.(U)
OCT 78 S J CALABRESE, F F LING DOT-CG-61589-A

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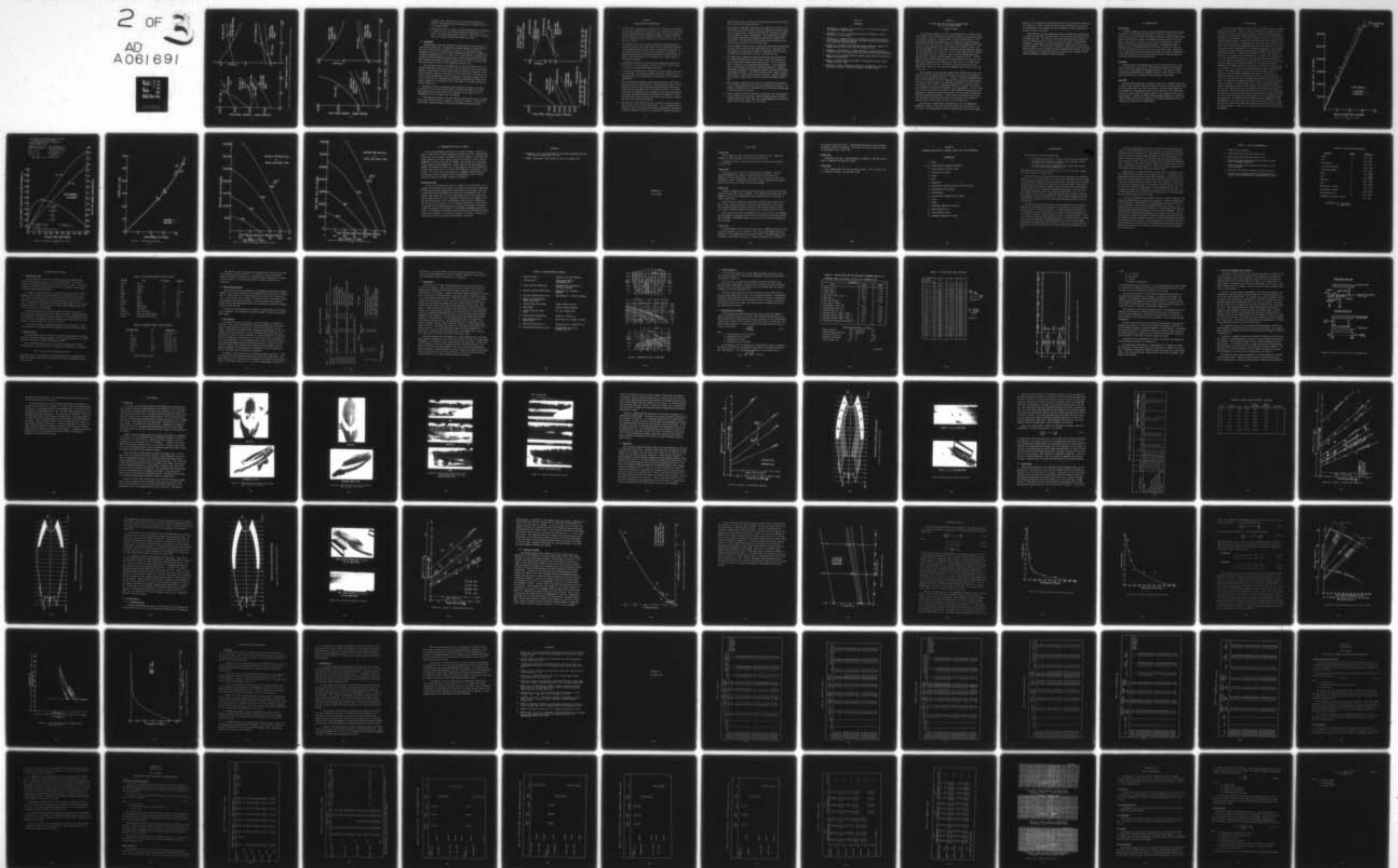

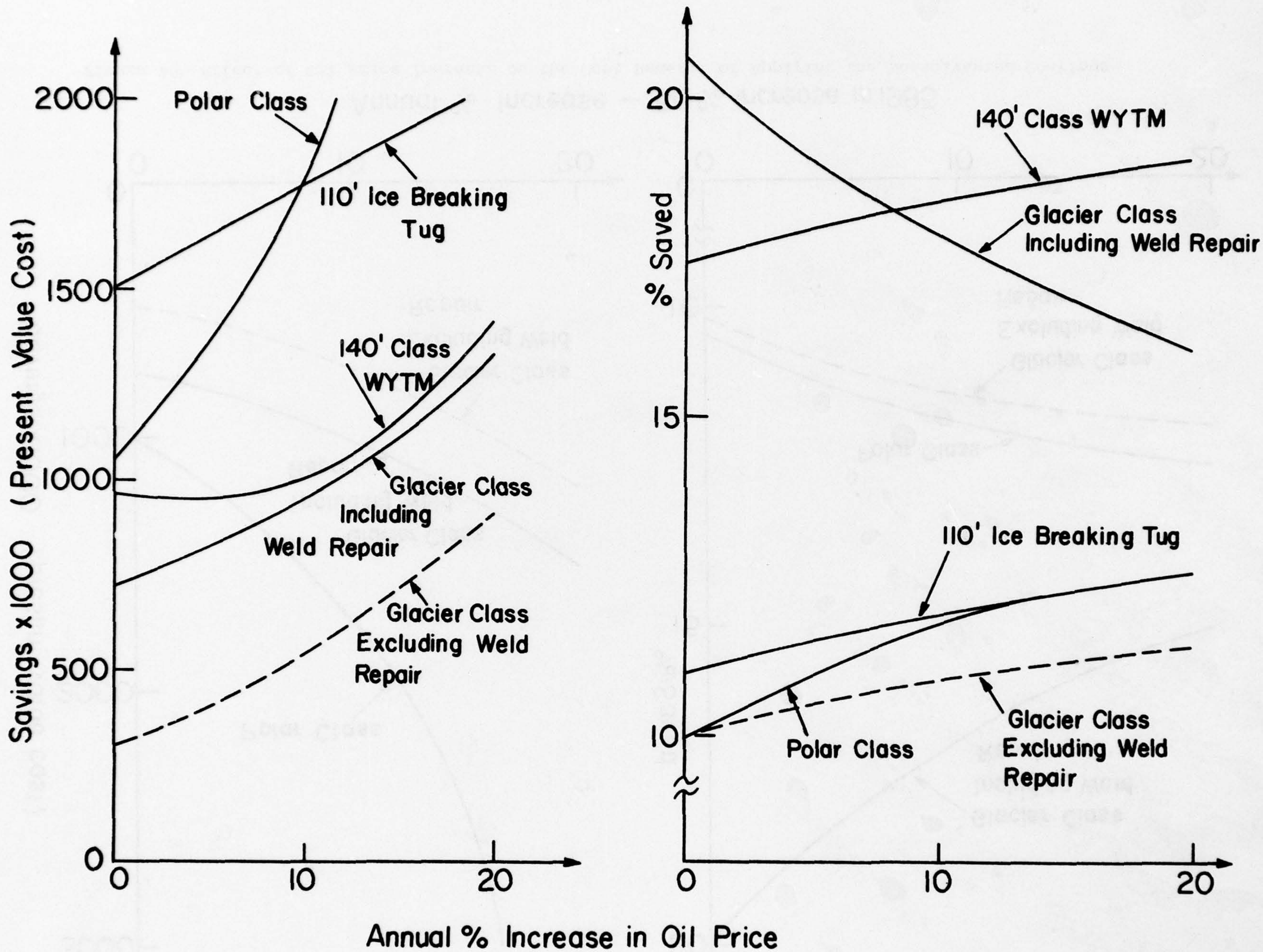

Figure 27 Effect of Oil Price Increase on the Cost Benefit of Applying the Nonsolvented Coatings

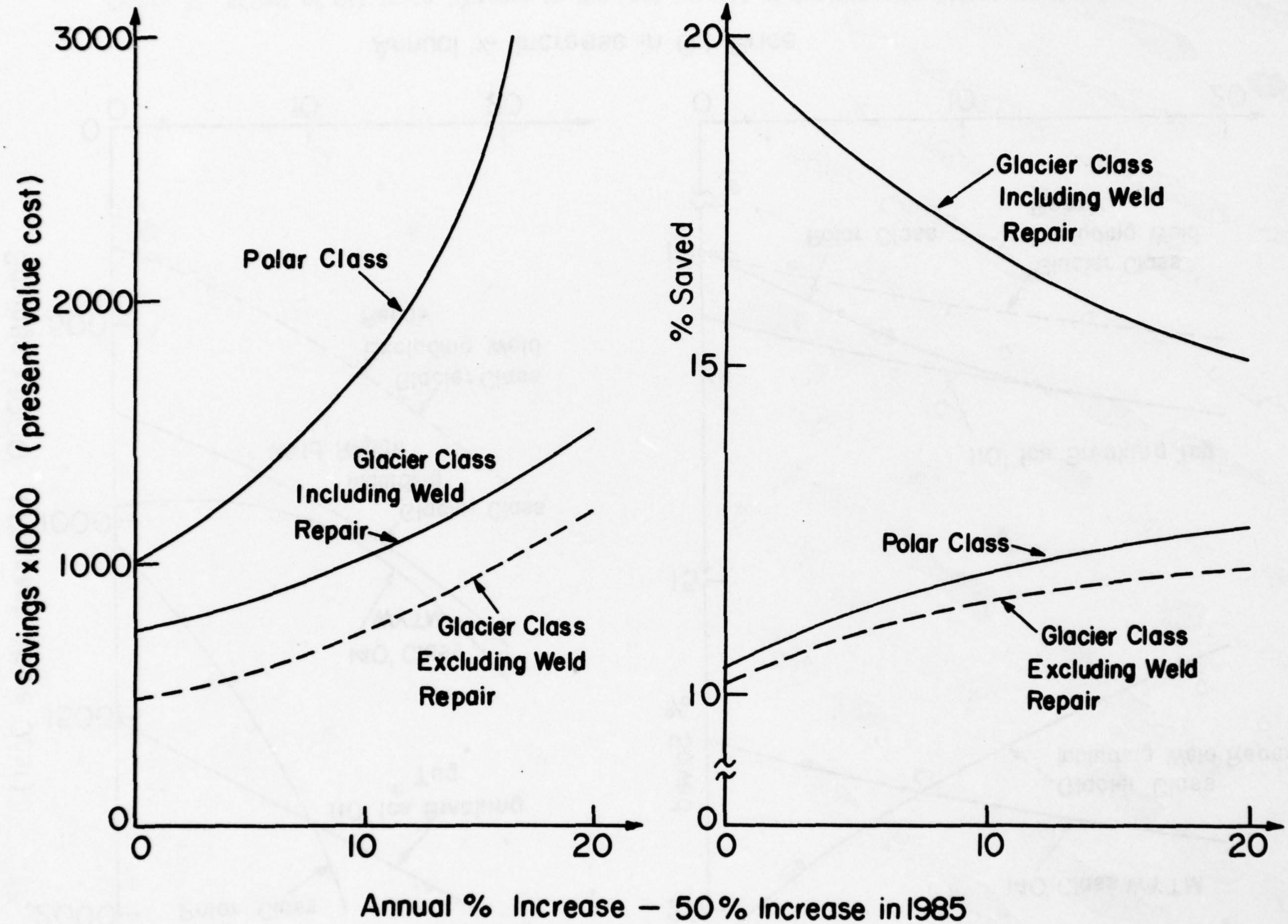

Figure 28 Effect of Oil Price Increase on the Cost Benefit of Applying the Nonsolvented Coatings

increase of 30%, one barrel of oil in the year 2005 would cost $12,800. This demonstrates the importance of the inflation rate in our economic system.

c) The starting oil price (1979) is varied from $10/barrel to $20/barrel in steps of $1.00, with a constant annual increase of 10% in oil price. The results are plotted in Figure 29. The savings in present value cost increase linearly with starting oil price.

8.4 Conclusions

When maintenance costs are considered, there is always a positive benefit in favor of the coated ships. From data of the Cutter GLACIER, an average weld repair cost of $128,000 per dry docking will result in a discounted savings in maintenance cost equal to $412,531 while the discounted saving due to reduced resistance corresponding with X = 0.1 and Y = 0.3 is only $293,742. Therefore, the selection of coating materials should involve a careful consideration of coating bond strength and abrasion resistance to insure that the ship's hull will be adequately protected in order to avoid expensive weld repair cost.

When maintenance costs are disregarded and only initial coating cost is considered, there must be some saving in fuel cost to offset the initial coating cost. However, as can be seen in the resistance reduction sensitivity analysis, a very small resistance reduction of the order of 2% for X and 6% for Y is enough to offset the initial coating cost. Even for ships with a very short economic life, as in the case of the 110' icebreaking tug which has an economic life of only three years, a reduction of the order of 5% for X and 15% for Y is enough to offset the initial coating cost.

The economic life is an important factor in potential savings: the longer the coating is on the ship, the more saved. Since the weld repair cost can be much higher than the coating repair cost (especially on an older hull) it is advantageous to coat the ship as soon as possible.

In the sensitivity analysis, the most uncertain and also most likely to change value is the future oil price. However, an inevitable increase in oil price will only further increase the benefit that can be obtained by coating the ships.

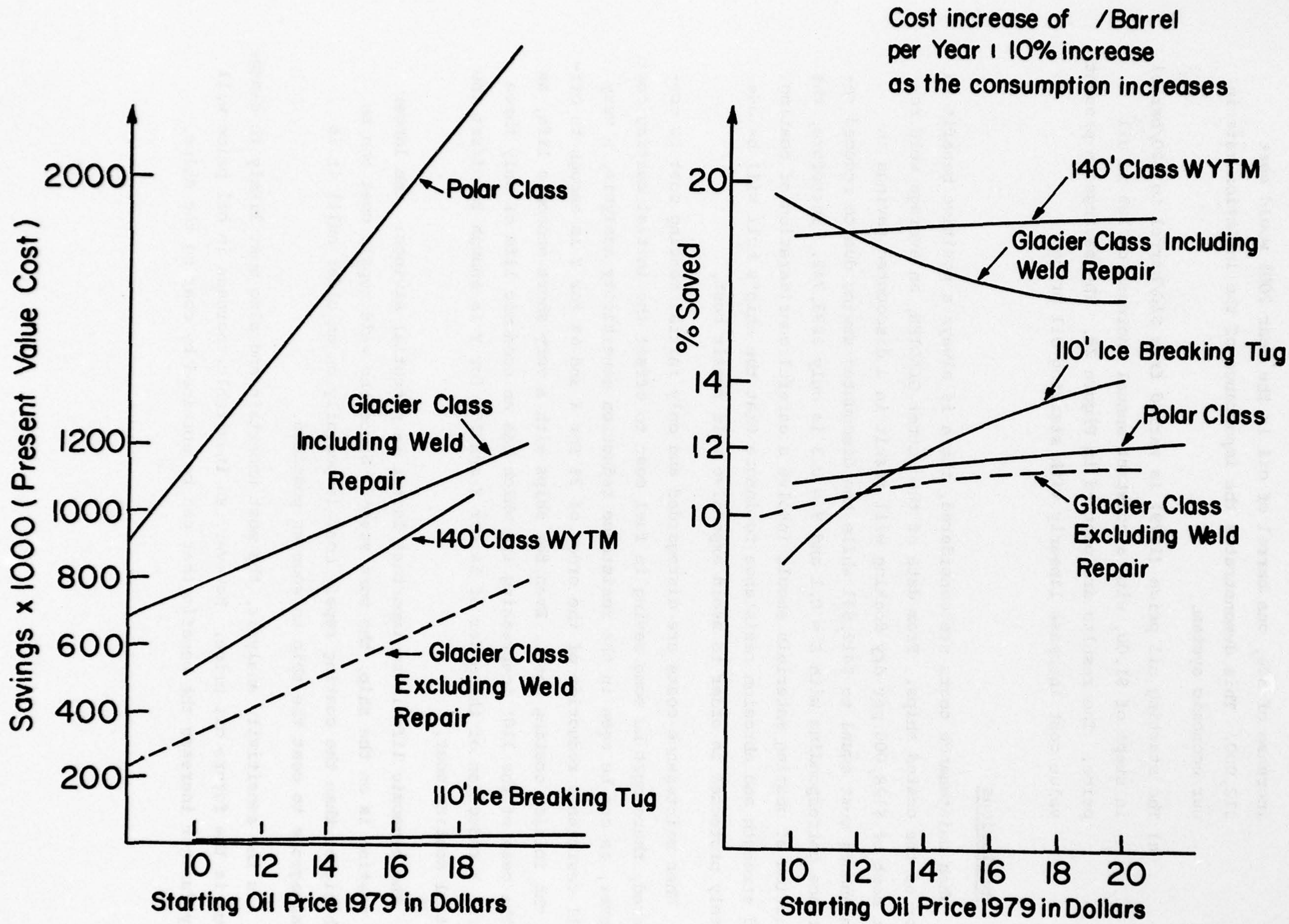

Figure 29 Effect of Oil Price Increase on the Cost Benefit of Applying the Nonsolvented Coatings

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

1. The full-scale resistance test indicates that a reduction in resistance in ice can be obtained by the application of a low friction hull coating. The percentage reduction is dependent on speed. The size and design of the hull will also influence percentage reduction. However, with the 110 ft icebreaking tugs the reduction was on the order of 15% at 8 knots and 8% at 3 knots.

2. A significant reduction in friction coefficient has been measured in laboratory tests of a hull plate coated with the nonsolvented materials. It is recommended that full-scale tests be performed to establish the contribution of friction to the overall resistance in icebreaking. This problem has existed for several years and unless a specific effort is made to solve that problem it will continue to be a major unknown in calculating resistance.

3. A significant reduction in resistance can be obtained by coating only 20% of the hull of an icebreaker. However, the rest of the hull must be coated for corrosion and abrasion protection.

4. A technique has been devised to determine the areas of heavy ice contact on a ship model. This technique should be used as a tool for the designer when new hull configurations or modifications to hull designs are contemplated.

5. The nonsolvented polyurethane has survived four years of icebreaking service and still is over 90% intact. The nonsolvented epoxy gave good results for one-half year of service and after one and one-half years service the coating appears to be over 95% still intact. It is recommended that all icebreaker hulls be coated with the nonsolvented system to protect them against corrosion, weld decay and cavitation. Even if the coating will eventually wear off at an ice line and bow, the rest of the hull will be coated and protected.

6. The full-scale tests indicate that the coating will protect the underwater portion of the hull for several years. It is recommended that the coating be used in other applications where submerged bodies experience corrosion or abrasion (either ice or particles). Applications such as

buoys, chains, piping, concrete or off-shore structures should be coated and the life of the coating monitored.

7. The technique of spraying, squeegeeing and reapplying the coating is the most effective application method tested for reducing the surface roughness of a pitted hull. Further studies should be conducted to determine the best method to repair a damaged hull. The studies should include a bond strength evaluation for polyurethane applied over already cured polyurethane. The study should also consider surface preparation and tenacity after exposure to salt and fresh water.

8. The environmental restrictions for applying the nonsolvented polyurethane are much less stringent than the nonsolvented epoxy. Essentially the polyurethane can be applied and cured at temperatures below $40^{\circ}F$ while the epoxy must be above $40^{\circ}F$ to achieve a satisfactory cure.

9. The nonsolvented polyurethane and the nonsolvented epoxy coatings have no antifoul characteristics but both appear to have the capability of being cleaned without damage after fouling occurs. At this time more data is available on the nonsolvented polyurethane. It is recommended that a trial program of underwater cleaning be conducted to establish maintenance procedures for the abrasion resistant coatings (nonsolvented polyurethane and epoxy). This could be done by coating smaller vessels which operate in waters which are prone to fouling. Periodic inspection and underwater cleaning should then be performed and complete records kept.

10. The technique of applying an antifoul to wet nonsolvented polyurethane gives a strongly bonded antifoul, corrosion resistant hull coating. The antifoul effectiveness is not inhibited by the bond and the bond strength to the A/C coating is excellent.

11. The cost saving realized in coating an existing hull will vary depending on the economic life of the ship. With the existing ships the savings realized without hull repair cost will be approximately 10% and with hull repair 20% over the economic life of the ship.

SECTION 10

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APPENDIX A

TOW ROPE PULL TESTS ON THE USCG CUTTER ARUNDEL AND THE USCG CUTTER RARITAN

I. SUMMARY OF TESTS

The USCG Cutter RARITAN, a 110 foot long icebreaking tug, has been coated with a solvent-free polyurethane hull surface which has now withstood two years of icebreaking service on the Great Lakes. The wear characteristics of this coating have surpassed the performance of all alternative coatings tested so far by the Coast Guard, and RPI. Personnel on board the RARITAN have felt that not only is the protection to the hull formed by the coating of benefit, but also the performance of the ship itself is improved through apparently reducing the friction between ice and the hull. The U.S. Coast Guard Office of Research and Development has given a contract to RPI to test the RARITAN among other portions of its friction reduction program for icebreaking service. RPI then came to ARCTEC to request assistance in the planning of the ice trials for the RARITAN and assistance in the conduction of those trials to a limited extent. This report covers a series of tow rope pull trials performed on both the RARITAN and a sister tug, the USCG Cutter ARUNDEL during the week of April 5th to 9th, 1976.

The performance of the propulsion system aboard RARITAN class tugs in producing tow rope pull depends upon the condition of the bottom, the propeller, and the electric propulsion machinery. In order to compare icebreaking performance of the RARITAN with her hull coated with the low friction surface against one without a special coating, the icebreaking resistance of each tug must be known during the ice trials. Icebreaking resistance will equal the tow rope pull developed by the propulsion machinery, hull and propeller. If the tow rope pull is known in advance as a function of vessel speed and propeller rpm, then measurement of these two parameters during the ice trials will be sufficient to determine icebreaking resistance. In other words, the purpose of these tests was to develop a functional relationship of tow rope pull as a function of propeller speed and ship speed for each of the two sister tugs.

This functional relationship was determined for both the RARITAN and ARUNDEL as a result of the trials conducted in Sault Ste. Marie prior to the ice trials. This relationship is shown in Figures A-4 and A-5 of this report.

Section II will discuss the instrumentation used to collect the data, Section III will present the results obtained during the trials, and Section IV will give an interpretation of the results and give an example for use in conducting reduction of the ice trial data.

Three separate tests were conducted in order to develop the necessary data to construct tow rope pull curves for each of the two tugs. The first test was a bollard pull test. In this test, the tug was attached through a large tow line to a strong bollard at the end of one of the Soo locks. RPM was slowly increased in steps while the thrust was measured at steady state for each individual condition. The second test consisted of towing tests in which one tug towed the other tug over a measured course at different power levels. The third test consisted of free route tests with tugs operating over a measured course, without resistance in addition to that of the hull.

II. INSTRUMENTATION

Tow Rope Pull

In order to measure the tow rope pull during both the bollard test and the towing test, a 30,000 pound capacity load cell was used. This load cell consisted of a steel link on which a Wheatstone bridge of four semiconductor strain gages had been placed to measure the deformation during loading of the link. Prior to the conduct of the test, the load cell was hooked up to a source of battery excitation and a battery driven recorder, and calibrated using a hydraulic jack at the ARCTEC laboratory facilities. During the trials, the load cell was hooked up in the tow line of the tug being tested. During the test, a deflection measured on the recorder against time could be converted to a load with corrections for the strain gage excitation voltage and using the calibration factor from the laboratory test.

Ship Speed

The ship speed was determined during the free route test and the towing test, by measuring a course and the time required to complete traversing the course, both in the upbound and downbound direction. The course was marked with buoys and checked against landmarks on shore. Time to travel over the course was recorded on a stopwatch, and then logged on data sheets.

Shaft RPM

The shaft RPM was measured in two ways, through use of a magnetic probe and by using a light sensitive probe on the shaft of the tug. For the magnetic probe a block of metal made up of a key was attached to the shaft and rotated past the sensing face of the magnetic probe for each revolution of the shaft. When the block of metal passed the magnetic probe, a pulse appeared on the oscillograph recorder. The same oscillograph recorder which measured the time and the load also measured the RPM, so these were all measured sinultaneously and recorded on the same piece of instrumentation.

III. TEST RESULTS

Test results are presented here as a series of graphs on which the reduced data have been plotted. Figure A-1 shows the results of the bollard pull tests for both of the ships. Bollard pull should be a linear relationship between the square of the propeller revolutions and the pull, up until the inception of cavitation on the propellers. The circles plotted on Figure A-1 are data points obtained from the ARUNDEL. Ignoring the top data point, which appears to show some cavitation occurring, the best straight line fit was drawn through the data points. The squares for the RARITAN were plotted on the same figure and do not show quite as good a conformance to the expected straight line. There appears to be some extraneous loading occurring during the RARITAN trials which might have been due to wind or current forces during those tests. Also plotted on Figure A-1 is a straight line for the propeller as tested in the propeller tunnel at the David Taylor Model Basin, at the time the ships were constructed. It is not known for sure whether the propellers which are presently on the two ships are identical to this original propeller. Performance of both the RARITAN and the ARUNDEL appeared to be superior to that of the original propeller. Figure A-2 is a plot of the original propeller curves as extracted from Ref. [1]. The second equation on that plot is the one which is shown in Figure A-1, using the thrust coefficient obtained at a slip ratio of 1.0. Figure A-3 shows the results of the open water trials, or ship operations in free route. A curved line was fit through the data points for each of the two ships. The data for the ARUNDEL from Figures A-1 and A-3, using the straight line fit on Figure A-1 and the curved line on Figure A-3 was then plotted on Figure A-4 along the ordinate and the abscissa. The bollard pull tests represent the zero speed condition over the ground, and therefore are plotted up the ordinate. Points were picked off Figure A-1 for 100, 150, 200 and 250 RPM. For Figure A-3 and the open water trials, the speed over the ground was picked off for the same corresponding shaft revolutions. This was plotted along the horizontal axis. The single data point obtained when the ARUNDEL was towing the RARITAN was then also plotted and is shown as the circle dot for 231 RPM. The family of curves which placed this particular point in the proper location was then sketched in. Figure A-5 was constructed similarly using the data from the RARITAN.

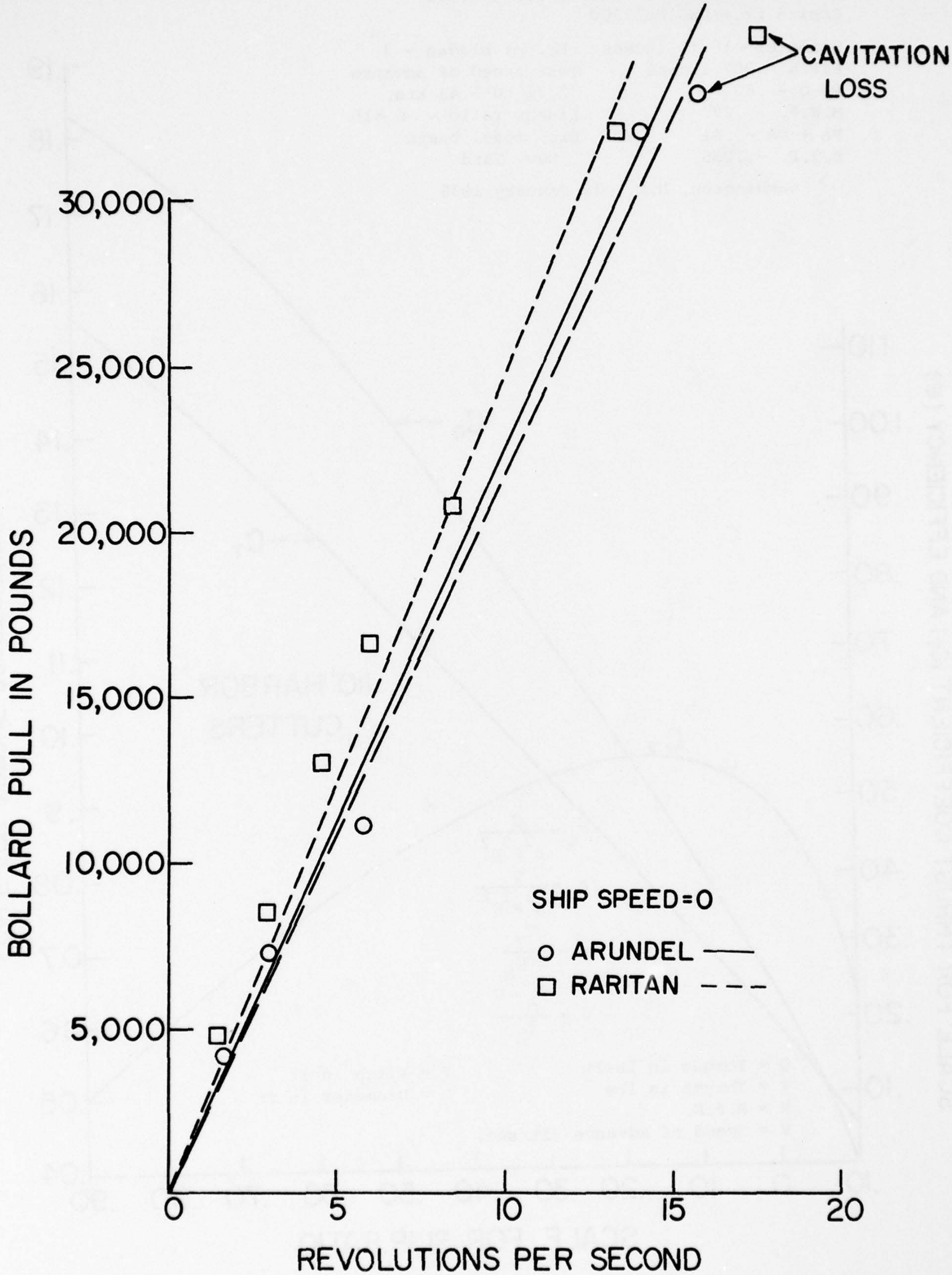


Figure A-1 Bollard Pull Curves

Characteristic Curves for Propeller No.1764
Designed by U.S. Coast Guard
Submitted for Test by U.S. Coast Guard
Copied from DWG No.7200

Diameter - 15.12 inches	No. of blades - 3
Pitch - 907 inches	Test speed of advance 2.71 to 5.43 kts.
P - D - .60	
M.W.R. - .27	Linear ratio - 6.615
PA ÷ DA - .41	Exp. model basin
B.T.F. - .035	Navy Yard

Washington, D.C., 19 January 1936

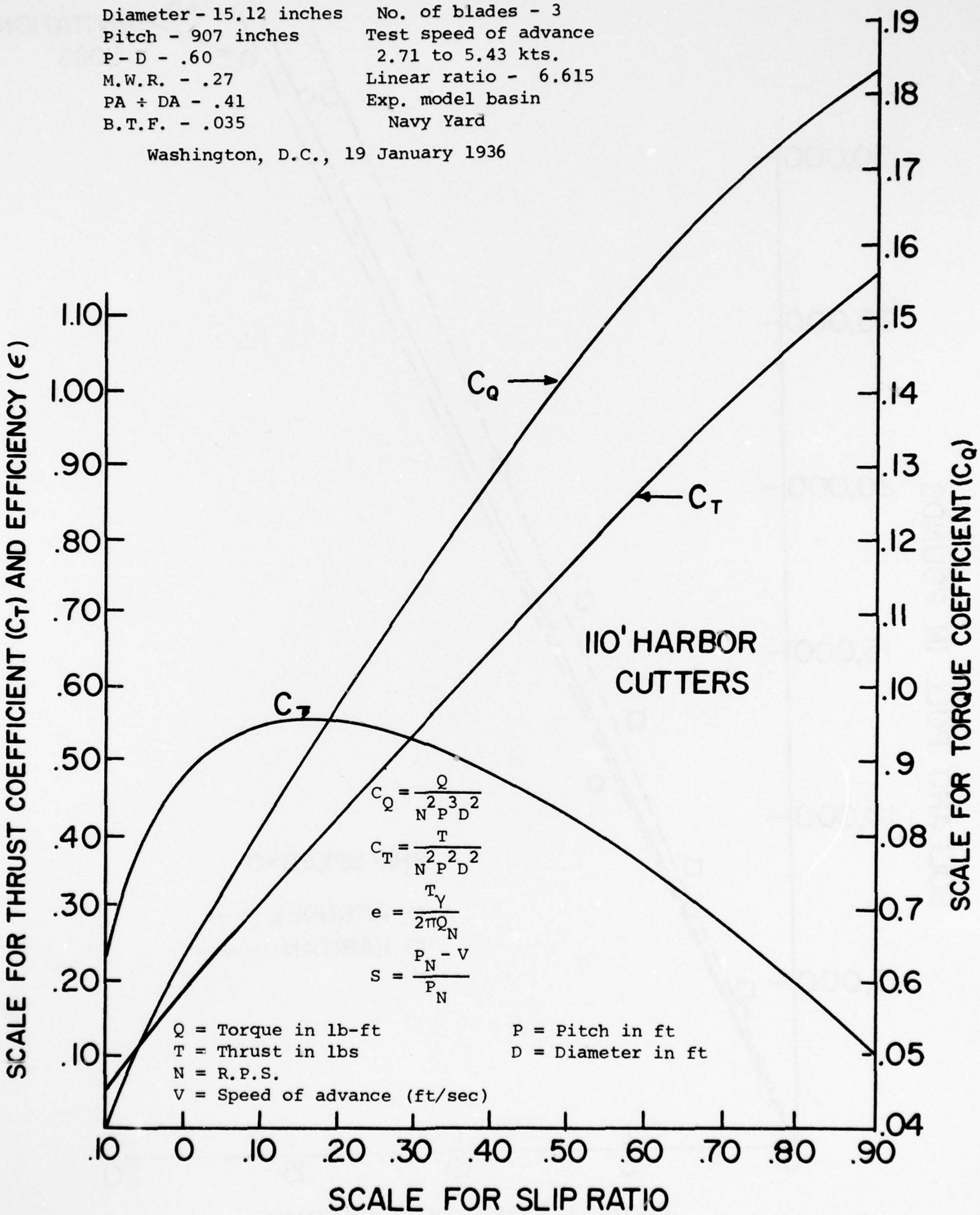


Figure A-2 Propeller Characteristic Curves

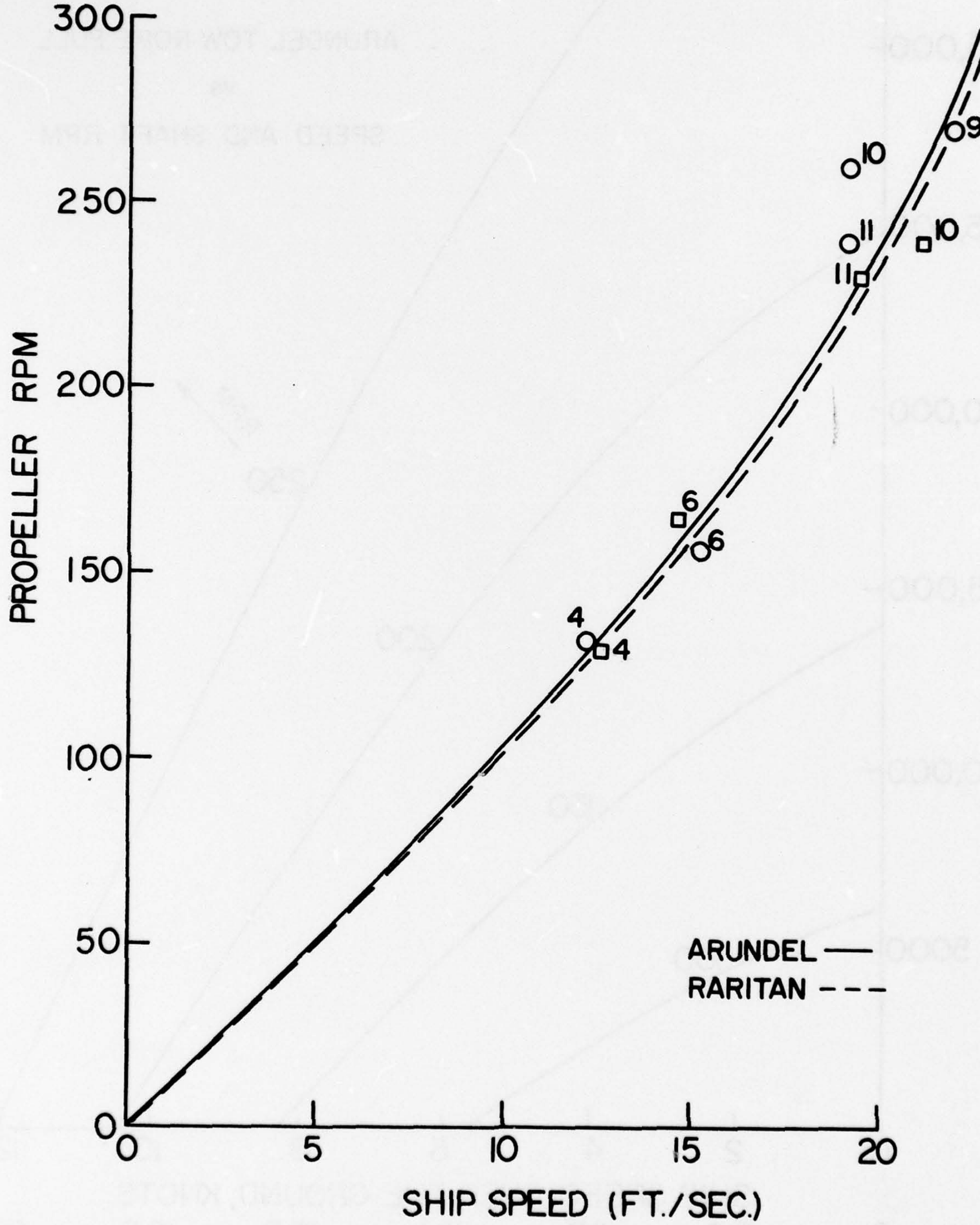


Figure A-3 Free Route Speed Curves

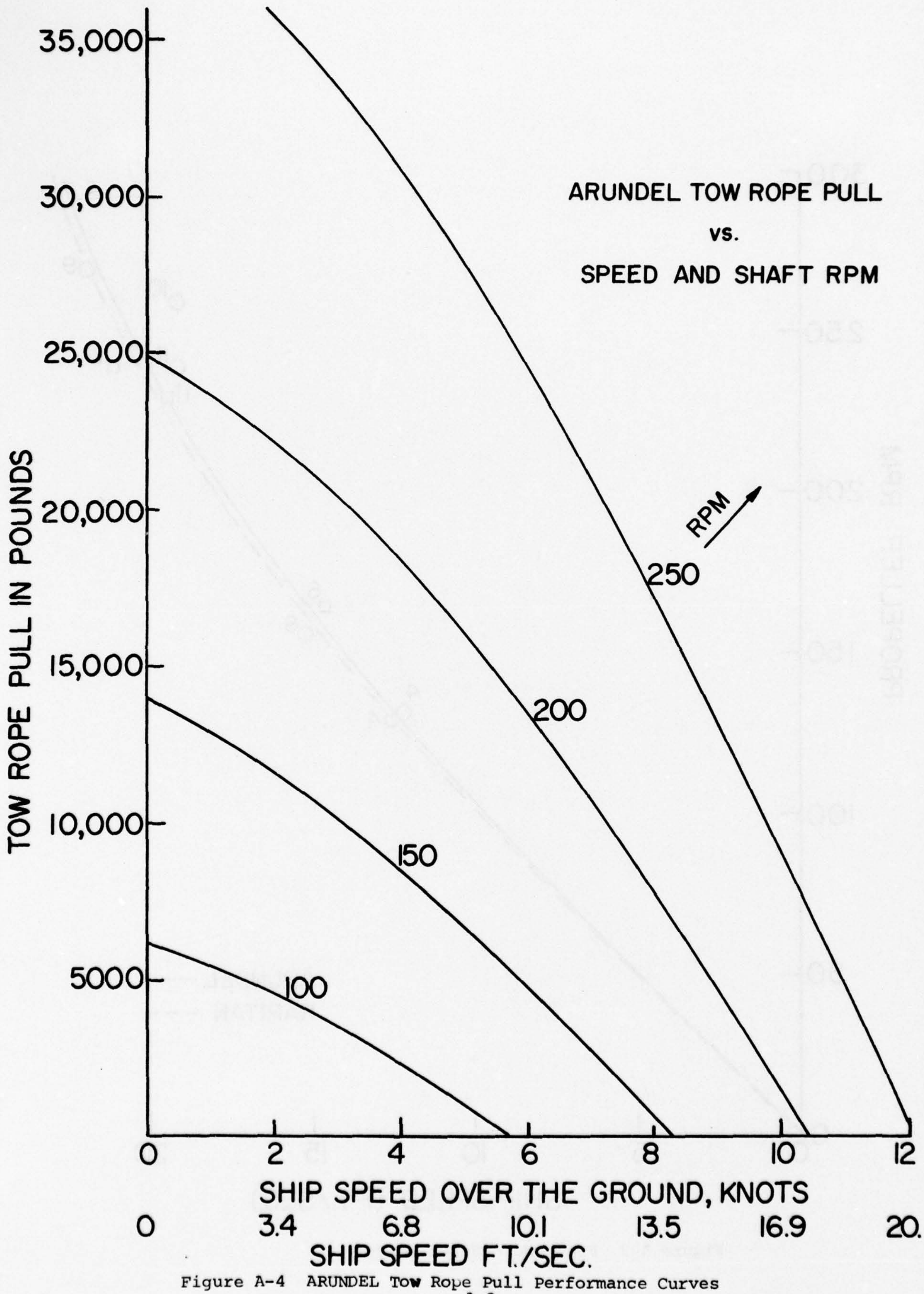


Figure A-4 ARUNDEL Tow Rope Pull Performance Curves

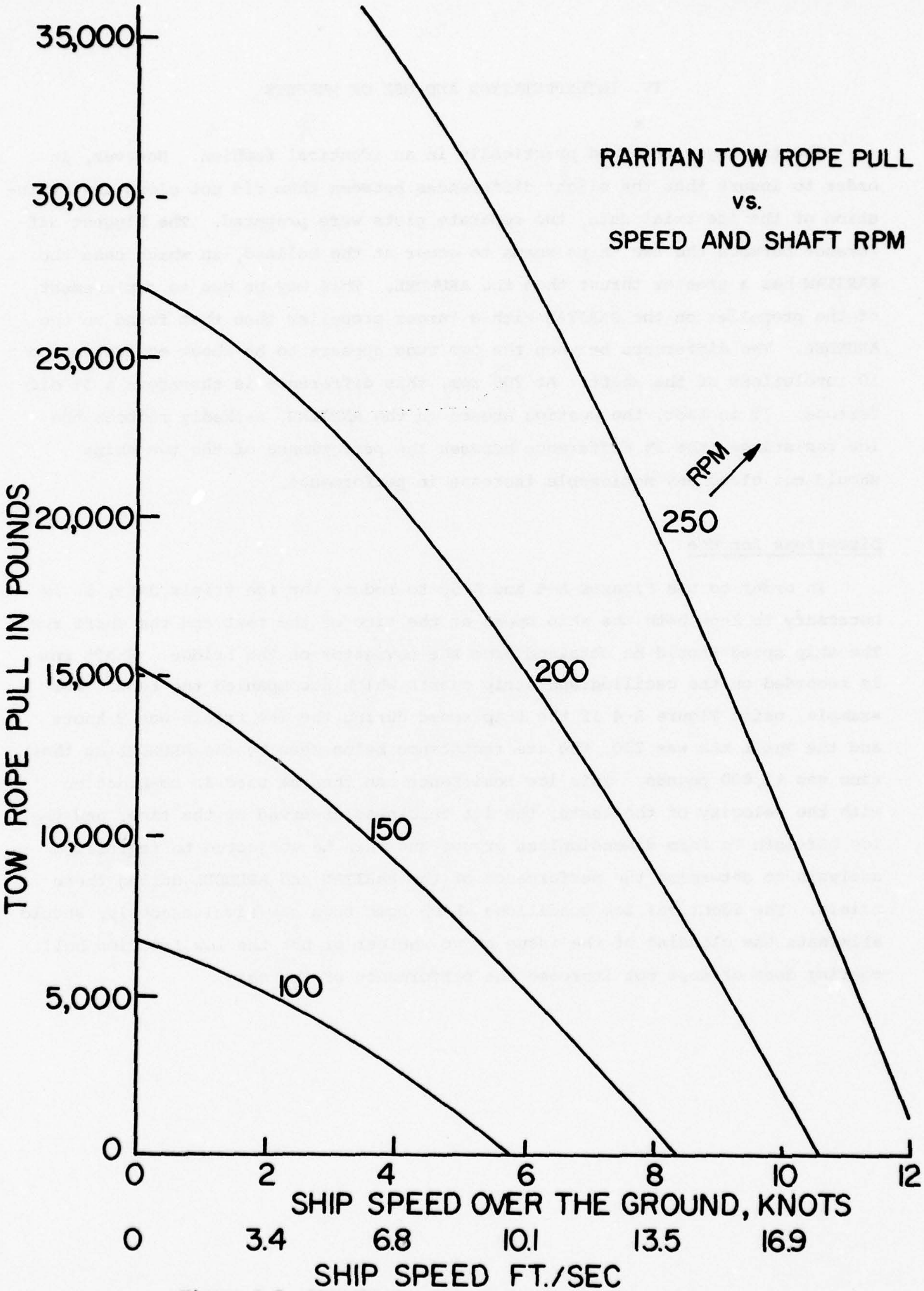


Figure A-5 RARITAN Tow Rope Pull Performance Curves

IV. INTERPRETATION AND USE OF RESULTS

The two tugs performed practically in an identical fashion. However, in order to insure that the slight differences between them did not cloud the evaluation of the ice trial data, two separate plots were prepared. The biggest difference between the two ships seems to occur at the bollard, in which case the RARITAN has a greater thrust than the ARUNDEL. This may be due to replacement of the propeller on the RARITAN with a larger propeller than that found on the ARUNDEL. The difference between the two tugs appears to be about equivalent to 10 revolutions of the shaft. At 200 rpm, this difference is therefore a 5% difference. If in fact, the coating aboard on the RARITAN, markedly reduces the ice resistance, the 5% difference between the performance of the two ships should not cloud any noticeable increase in performance.

Directions for Use

In order to use Figures A-4 and A-5, to reduce the ice trials data, it is necessary to know both the ship speed at the time of the test and the shaft rpm. The ship speed should be obtained from the navigator on the bridge. Shaft rpm is recorded on the oscillograph strip charts which accompanied the test. For example, using Figure A-4 if the ship speed during the ice trials was 8 knots and the shaft rpm was 230, the ice resistance being seen by the ARUNDEL at that time was 12,800 pounds. This ice resistance can then be used in combination with the velocity of the tests, the ice thickness observed at the time, and the ice strength to form dimensionless groups and then be subjected to regression analysis to determine the performance of the RARITAN and ARUNDEL during these trials. The identical ice conditions which both tugs saw simultaneously, should eliminate the clouding of the issue as to whether or not the low friction hull coating does or does not increase the performance of the ship.

REFERENCES

1. Edwards, R.Y., Jr., "The Performance of the Alexbow Icebreaking Bow Form," USCG Office of Engineering, July 1969.

2. ARCTEC, Incorporated, letter proposal to RPI of 25 November 1975.

APPENDIX A-I

LOG OF TESTS

LOG OF TESTS

4 April 1976

Arrived Sault Ste. Marie from Baltimore via Chicago at 1330. Rented car. Attempted to locate equipment that was to be waiting for us.

Proceeded to CG Base. Checked on vessels and set-up meeting for morning of 5 April 1976.

5 April 1976

Arrived at CG Base. Met with CO of base and CO of ARUNDEL. Took gear aboard CGC ARUNDEL and proceeded to downstream end of locks center pier. Attempted to conduct bollard pull. After parting tow rope 5½" Nylon twice, we returned to CG Base. RARITAN had not arrived on scene. RARITAN arrived approximately 1800 and took on 8" Nylon line from CGC MACKINAW.

6 April 1976

Underway on ARUNDEL at 0715 through the locks and up into Iroquois shoal area where we ran open water tests on ARUNDEL. After completing open water tests with ARUNDEL we laid to while RARITAN made final adjustments prior to attempting to conduct towing tests.

Towing tests were conducted by each vessel towing the other astern over the 4850' course. Earlier attempts to tow back to back with power on each vessel were aborted when throttle controls would not permit smooth increase in speed. This situation caused a dangerous condition and not considered worth the risk.

When towing head to stern was completed, the tow rope was put on the ARUNDEL and we proceeded to downstream center pier at the locks where we held the bollard pull on ARUNDEL. The RARITAN stayed in the Iroquois shoal area and completed her open water runs.

7 April 1976

We took RARITAN to locks for bollard pull tests. ARUNDEL went down St. Mary's river for examination of ice conditions. After bollard pull RARITAN proceeded downstream to meet ARUNDEL and set up testing schedule. Performed several tests in broken ice and some in solid cover. Results were passed to Mr. Calabrese on our way back to Sault Ste. Marie. RARITAN developed serious leaking problems and further testing was unfeasible. We arrived at CG dock in Sault Ste. Marie at approximately 0415, 8 April 1976.

8 April 1976

Squared away all gear. Packed equipment for shipment to Maryland and prepared for departure from Sault Ste. Marie.

9 April 1976

0530, departed Sault Ste. Marie on morning flight. Flew to Detroit, and on to Boston for meeting. 2110 arrived at BWI.

APPENDIX B

ICEBREAKING MODEL TESTS OF PARTIALLY COATED POLAR CLASS ICEBREAKERS

NOMENCLATURE

B - Beam

C_o, C_1 - Coefficients of regression equations

E - Elastic modulus of the ice sheet

I - Mass moment of inertia

L - Length

M - Mass

R - Resistance

f - Coefficient of kinetic friction (friction factor)

g - Acceleration due to gravity

h - Ice thickness

ℓ_c - Characteristic length of the ice sheet

t - Time

v - Speed

λ - Ship-model geometric scale ratio

ρ_i - Mass density of ice

ρ_w - Mass density of water

σ_f - Flexural strength of ice sheet

1. PROGRAM SUMMARY

The objectives of this test program were:

1. To determine the patterns of ice wear on the hull of the POLAR STAR.
2. To measure the resistance as a function of the coverage of these wear areas with low friction surfaces.
3. To verify a selection of optimum 10 and 20% surface area regions for low friction coating application [1].

These objectives were met for the condition of 1.2 m (4 ft) level ice. Thicker ice showed a change in important areas.

During the course of this test program, the wear areas while the POLAR STAR transited 1.2 m (4 ft) full-scale ice at a speed of 5 knots were portrayed through use of coatings of calamine lotion and cream car wax. The reduction in resistance was determined as a function of the coverage of these wear areas. That area indicated by the model coated with cream car wax was the area which contributed the greatest portion of the frictionally-related hull resistance. Areas of 10 and 20% optimum configuration were then selected for transiting 1.2 m (4 ft) ice. When tested in 1.8 m (6 ft) ice, these areas proved to have different resistance relationships to that of fully coated hull. The conclusion reached was that the wear pattern is a function of the ice thickness and perhaps velocity as well as the hull form.

The data collected during the course of this program was used to develop a prediction of the reduction in resistance as a function of the percentage of a hull coated with a low friction coating. In order to apply this prediction it is necessary to know the full-scale hull-ice friction on both the uncoated portion of the hull and the coated portion of the hull. Assuming values of .25 and .1 for these two conditions, some predictions as to the effect of partial coatings of 10 and 20% are made for the POLAR STAR hull form. These relatively small percentages of the underwater body coated with a low friction coating appear to drastically reduce the full-scale resistance and improve the performance of the ship.

An extensive examination of the hull-ice friction occurring during model tests was also conducted during this test program. Six long test planks were prepared with various surfaces, the roughnesses of these surfaces was measured, and the friction was measured between the model ice and these surfaces for a number of different conditions. It was found that only velocity affected the hull-ice friction factor, and that no change was discernable between submerged tests, those done in air, those using the edge of the ice sheet, those with the sample wet and those with the sample dry. Neither the ambient temperature nor the pressure during the test affected the friction factor.

Recommendations are made for additional model tests to be conducted using the cream car wax as a tracer for wear areas on the hull. In particular, the POLAR STAR hull form should be examined under differing ice conditions such as brash ice, pressure ridges and in much thicker ice to determine if the area requiring low friction coating is different under these conditions. Turning may also affect the important region. The cream car wax also appears to be a good tool for use in the early design stages to evaluate changes in hull form. It is possible to measure the resistance of a hull form while the cream car wax is in place, and thus not only trace the area affected by the ice, but also determine the relative merit of two hull forms.

No wear was discernable from roughness profiles on either the models or the plank test surfaces during the course of these tests. Although a definite correlation appears to exist between the CLA roughnesses of surfaces and the hull-ice friction factor, there appear to be additional factors involved. Also, friction factors which are of great interest in conducting model tests were not obtained through the normal preparation of the hulls using sandpaper. Test surfaces should be obtained having roughnesses in the range of the void area not covered by this program and a number of different preparations having the same CLA roughness should be examined to attempt to determine what additional factors are affecting hull-ice friction. Tests are required to determine the effect of the velocity upon ice friction up to the maximum model velocities tested, and perhaps even beyond up to the full-scale range of velocities existing between the ship and the ice.

TABLE B-1 LIST OF RECOMMENDATIONS

1. Conduct economic analysis
2. Conduct more model tests using cream car wax
3. Test different hull forms with cream car wax
4. Change hull design concentrating on areas which contribute most to icebreaking resistance
5. Conduct full-scale tests of partial hull coating with low friction surfaces
6. More work on the effect of velocity on hull-ice friction
7. Continue work on developing model hull preparations which create a hull-ice friction factor ranging between .2 and .4.

TABLE B-2 SCALING LAWS FOR MODELING*

Variable	Symbol	Scaling Law
Length	L	$L_{fs} = \lambda L_{ms}$
Beam	B	$B_{fs} = \lambda B_{ms}$
Ice thickness	h	$h_{fs} = \lambda h_{ms}$
Ice flexural strength	σ_f	$\sigma_{ffs} = \lambda \sigma_{fms}$
Ice elastic modulus	E	$E_{fs} = \lambda E_{ms}$
Speed	v	$v_{fs} = \sqrt{\lambda v_{ms}}$
Time	t	$t_{fs} = \sqrt{\lambda t_{ms}}$
Resistance	R	$R_{fs} = \lambda^3 R_{ms}$
Mass	M	$M_{fs} = \lambda^3 M_{ms}$
Mass moment of inertia	I	$I_{fs} = \lambda^5 I_{ms}$
Mass density of water	ρ_w	$\rho_{wfs} = \rho_{wms}$
Mass density of ice	ρ_i	$\rho_{ufs} = \rho_{ims}$
Coefficient of kinetic friction	f	$f_{fs} = f_{ms}$

* Subscripts - fs = full-scale
ms = model-scale

2. APPROACH FOR MODEL TESTS

2.1 Model Scaling Laws

For model testing to be correct, the model must be both geometrically similar and dynamically similar to the full-scale prototype. The first is achieved by scaling all dimensions by the geometric scale factor λ. The second condition is achieved by maintaining the ratio of significant forces the same for both the model and the prototype.

In testing a ship model in ice, the significant forces are gravity forces, dynamic forces, ice forces, and friction forces. Gravity forces will scale by λ^3 since the density of water is the same for both the model and the full-scale ship. It then follows that the dynamic forces must also scale by λ^3, which is achieved by testing the model at speeds corresponding to the full-scale speeds divided by $\sqrt{\lambda}$. This results in the Froude number $v/\sqrt{gL}$ being the same for both the model and the prototype.

From the principle that all forces acting on the model must scale by λ^3, the scaling laws listed in Table B-2 can readily be derived. These laws dictate that the model ice thickness h, flexural strength σ_f, and elastic modulus E, must be reduced from the appropriate full-scale values by the scale factor λ; and the density of ρ_i must be equal to the full-scale value.

In using this procedure, the viscous forces do not scale properly. These forces, however, will be negligibly small compared to the other forces involved.

2.2 System of Units

The international System of Units (SI) was used in the planning, data taking, and report writing for this test program. The official abbreviation SI is derived from the French phrase "Système International d'Unités."

The SI measurement system [2,3,4] is built upon the base units of meter-kilogram-second. The unit of force is the newton and is defined by the equation:

$$\text{force (N)} = \text{mass (kg)} \cdot \text{acceleration (m/s}^2) .$$

The weight (force due to gravity) of one-kilogram mass will be 9.806650 newtons, where the standard acceleration due to gravity g is taken as 9.806650 meters per second squared.

TABLE B-3 SI UNITS AND SYMBOLS (PARTIAL LISTING)

Quantity	Unit	SI Symbol	Formula
Length	Meter	m	---
Mass	Kilogram	kg	---
Time	Second	s	---
Force	Newton	N	$kg \cdot m/s$
Energy	Joule	J	$N \cdot m$
Work	Joule	J	$N \cdot m$
Power	Watt	W	J/s
Pressure	Pascal	Pa	N/m^2
Stress	Pascal	Pa	N/m^2
Area	Square meter	--	m^2
Volume	Cubic meter	--	m^3
Velocity	Meter per second	--	m/s
Acceleration	Meter per second squared	--	m/s^2
Density	Kilogram per cubic meter	--	kg/m^3

TABLE B-4 CONVERSION FACTORS (PARTIAL LISTING)

To Convert From	To	Multiply By
ft	m	$3.048\ 000^* \times 10^{-1}$
lbf	N	4.448 222
lbf/in^2	Pa	$6.894\ 757 \times 10^3$
lbf/ft^2	Pa	$4.788\ 026 \times 10^1$
kgf/cm^2	Pa	$9.806\ 650^* \times 10^4$
$slug/ft^3$	kg/m^3	$5.153\ 788 \times 10^2$
g/cm	kg/m^3	$1.000\ 000^* \times 10^3$
tonne	kg	$1.000\ 000^* \times 10^3$

* Exact conversion factor.

The quantities, units, SI symbols, and formulas that were used in the model test program are listed in Table B-3. Note that the SI unit for pressure, stress, and strength of materials is the pascal which is equivalent to a newton per meter squared. A few conversion factors are listed in Table B-4 for convenience.

2.3 Model Testing Facility

The model test series was conducted in the ARCTEC Ice Model Basin, Columbia, Maryland. This facility consists of a refrigerated model towing basin 30.5 meters long, 3.7 meters wide, and 1.5 meters deep, which is filled with a saline solution. On the surface, ice is frozen to a thickness equal to the geometric scale of the desired full-scale ice thickness. By controlling the water salinity, freezing rates, and temperatures, model ice is produced with properties correctly scaled for model testing.

The models are towed through the ice sheet at constant speed and the resistance is measured. The carriage drive system is capable of towing at any desired model speed.

2.4 Test Schedule

The tests were done in three series. The test schedule is contained in Table B-5. There was one day between the series to provide time to repaint the model, analyze results up to that point, and finish the models for the next series. The purpose of series one was to examine the wear patterns on the hulls through the use of coatings which are worn off rapidly during the model tests. The purpose of series two was to determine in a single thickness of ice what the effect of varying the low friction area on the hull would be on the resistance seen by the icebreaker. The areas examined under series two were based upon the wear patterns developed by the coatings under series one. Finally, in series three, two models having coatings which covered the area of highest wear and greatest resistance, were examined in two thicknesses of ice to determine the effect of thickness upon the reduction in resistance.

In addition to the resistance tests conducted using the two models, a series of friction tests were conducted using the ice grown for the model tests. The daily schedule for the friction tests is indicated at the right of the resistance tests. At the bottom of Table B-5 is a list of the preparations on each of six

TABLE B-5 DAILY TEST SCHEDULE

Date	Series	Sheet	Model Ice Thickness (mm)	Model Velocity mm/s	Friction Tests
10/8/76	Set-up in Model Basin				
10/11/76	1	1	25.4	372	Planks 1-6 (ice edge)
10/12/76	Select Series 2 Configurations, Conduct Roughness Measurements and Refinish Models				
10/13/76	2	1	25.4	$v_1 - v_5$	Planks 1-6 submerged
10/14/76	2	2	25.4	$v_1 - v_5$	Planks 1-6 high speed
10/15/76	2	3	25.4	$v_1 - v_5$	Model surfaces**
10/18/76	Analyze Data, Conduct Roughness Measurements, Select Optimum Areas and Refinish Models				
10/19/76	3	1	25.4	$v_1 - v_5$	Model Surfaces
10/20/76	3	2	38.1	$v_1 - v_5$	Model Surfaces
10/21/76	Clean-up and Conduct Roughness Measurements				

Velocity	Full-Scale Knots	Model Scale mm/s
v_1	1.0	74
v_2	2.75	204
v_3	4.50	335
v_4	6.25	464
v_5	8.0	594

Test Planks

1. Crocus cloth, heavy circular sanding
2. 400 grit, heavy circular sanding
3. Untouched polyurethane
4. Salt, applied and dissolved
5. 240 grit, heavy circular sanding
6. 240 grit, heavy circular sanding

** High speed movies

test planks. Test planks numbers 5 and 6 have identical preparations as the initial roughness measurement on test plank number 5 damaged the test surface so test plank number 6 had to be prepared as a replacement.

2.5 Preparations

For series one, two model coatings were used to trace the wear patterns on the hull of the models. This was the first time for a test of this sort, and therefore the coatings which would give the best indication of wear were not known prior to this program. A number of different candidate coatings were tested prior to series one to determine which coating would give an indication of wear on a single pass down the model basin. Table B-6 contains a list of the coatings tested prior to series one. First, each one of these coatings was applied to a plank coated with gloss polyurethane, the model surface for series one. These planks were then tested in the friction test apparatus by towing blocks of the model ice across the planks to determine what would happen to the wear indicating coating. The coatings listed provided a very large variation in wear resistance. Some of the coatings showed hardly any wear at all, while others were completely destroyed by the movement of ice across them and were even washed off by simple immersion in the model basin. The oil-based paints such as coatings Nos.3, 4 and 9 did not indicate any wear. Water-based paints such as coatings 6 and 8, however, tended to wash off without sufficient adhesion to indicate areas where there was no wear. The steel blue, paint No.1, also showed little effect of the motion of the ice. The two coatings which showed the best performance were coating No.2, calamine lotion, and coating No.11, the cream car wax. The next best coatings were the white shoe polish and the finger paint.

These four coatings were then applied to a surplus model and run in the model basin following completion of one of the earlier series of tests on the POLAR CLASS icebreakers. It was hard to get a uniform coating with shoe polish. Finger paint showed a tendency to wear off more easily than any of the other coatings. The cream car wax showed the least tendency to wear off of these four and therefore gave an indication of higher pressures on the hull while the calamine lotion showed more of the total extent of ice wear on the hull. These two coatings were then selected because of the range of pressure which they indicated.

TABLE B-6 COATINGS TESTED FOR SERIES 1

1.	Dykem Steel Blue	Dykem Co., St. Louis, Missouri
2.	Calamine Lotion*	Skyline/Acme Markets, Philadelphia, PA
3.	Protek Alkyd Flat White Paint	Baltimore Paint & Chemical Co. Baltimore, Maryland
4.	Marvelite Alkyd Flat White Paint	Marvelite, Inc., Baltimore, Maryland
5.	Ross Green Tempera Poster Color	Ross Chemical Co., Detroit, Michigan
6.	Reeves - Brilliant Tempera Powder Color (Green)	
7.	Crayola Finger Paint (Green)	Binney & Smith, New York
8.	Pepto-Bismol	Norwich Products, New York
9.	Incolac Flat White Primer Sealer	DAP, Inc., Dayton, Ohio
10.	Minwax Liquid Finishing Wax	Minwax Co., Clifton, NJ
11.	Turtle Wax High Gloss* Cream Car Wax	Turtle Wax, Inc., Chicago, Illinois
12.	Electrofilm Lubri-Bond "A"	Electrofilm, Inc., Cherry Hill, NJ
13.	Hollywood Semi-White Shoe Polish	Hollywood Shoe Polish, Inc. Richmond Hill, NY

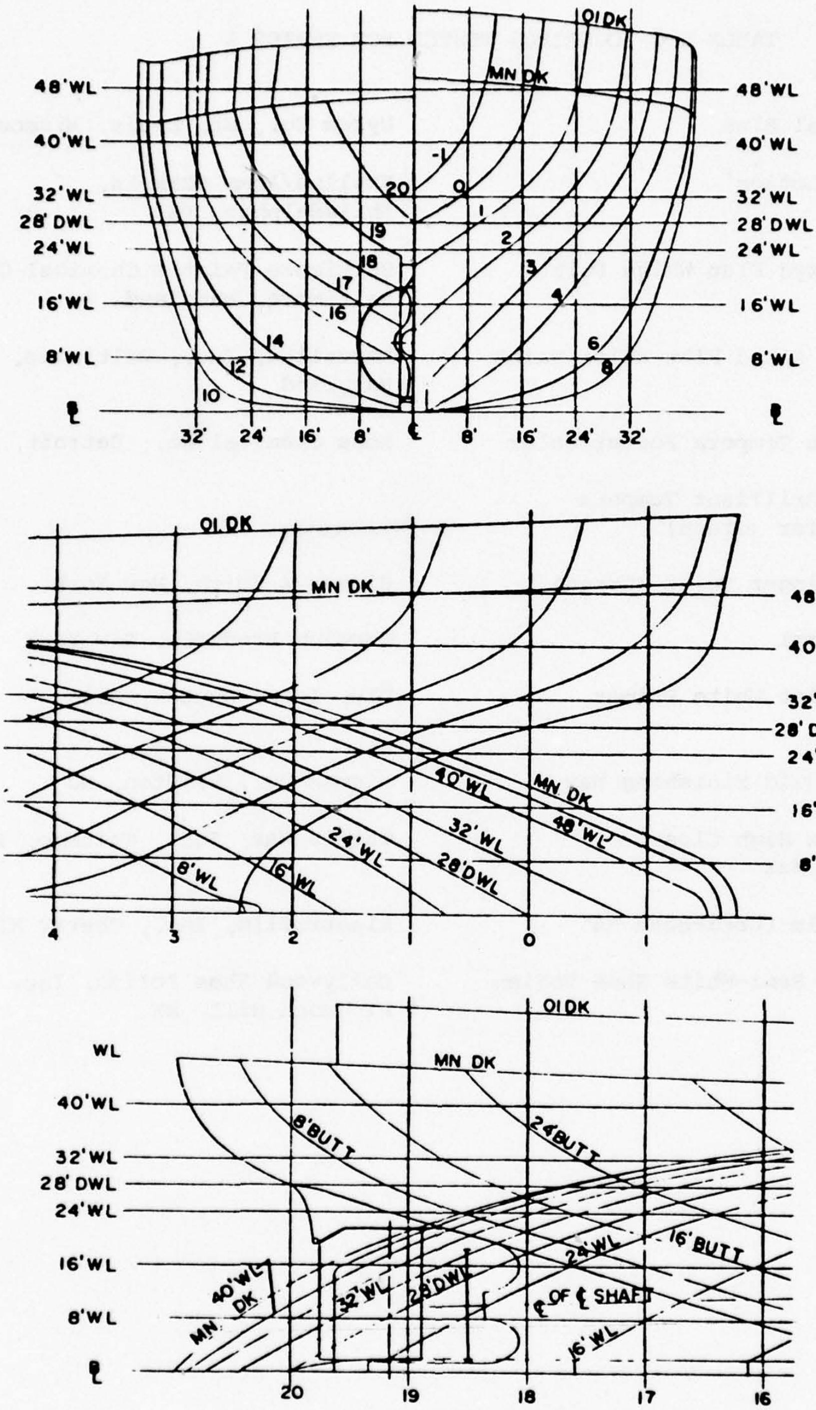


Figure B-1 Abbreviated Lines of POLAR STAR

2.6 Model Description

Two 1/48th scale models of the POLAR CLASS icebreakers were built to the lines shown in Figure B-1. The principle dimensions of the ship and the models are provided in Table B-7.

For series one, the surface of each model was coated with Sapolin #174 High Gloss clear polyurethane. When this paint was fully cured, the coatings of calamine lotion on one model and cream car wax on the second model were applied uniformly to the entire underwater body.

For series two and series three, the area which was to be tested for low friction coating application was left in the high gloss condition. The remainder of the hull was coated with a second coat of urethane on which salt crystals were liberally sprinkled until no more would adhere to the wet surface. The surface was allowed to dry and once cured, was rinsed leaving a pock-marked surface for the rough portion of the hull.

2.7 Resistance Test Procedure

The two models were tested side-by-side in order to obtain the greatest number of data points from each ice sheet. This procedure has been shown to be valid providing the distance between the models is greater than six characteristic lengths and the distance from the models to the basin walls is greater than three characteristic lengths [5]. For this criterion, the characteristic length ℓ_c of the ice is defined by:

$$\ell_c = \sqrt[4]{\frac{Eh^3}{12\ \rho_w g}} \tag{B-2.1}$$

where

E = elastic modulus of the ice sheet

h = thickness of the ice sheet

ρ_w = mass density of water

g = acceleration due to gravity.

The arrangement of the two models in the towing basin is shown in Figure B-2. The radio d/ℓ_c (where d is the distance from the side of the model to the basin wall) must exceed 3. Thus, maximum ice thickness for dual model tests is:

$$h_{max} = \sqrt[3]{\frac{12\ \rho_w g \ell_c^4}{E}} = 41.4 \text{ mm}.$$

TABLE B-7 SHIP AND MODEL DATA FOR POLAR CLASS ICEBREAKER MODEL NO. 278

APPENDAGES: Rudder and Bossings Lines Dwg No. 400WAGB0101-1000

Dimensions		
Item	Ship	Model
Length (LOA), m	121.62	2.534
Length (LWL), m	110.79	2.308
Length (LBP), m	107.29	2.235
Beam, Max (at LWL), (B_x), m	24.08	0.502
Beam, Max, m	25.51	0.531
Draft (at test WL), m	9.14	0.190
Trim (test) (+ AFT), m	0	0
Displacement, metric tons	12,200	0.110
Wetted surface area, sq. m	2990	1.298
Distance from FP to B_x, m	42.92	0.894
Distance from B_x to LCF (+ AFT), m	10.05	0.209
Distance from B_x to $\overline{\underline{\mathrm{DD}}}$ (+ AFT), m	10.73	0.224
Distance from LCG to $\overline{\underline{\mathrm{DD}}}$ (+ AFT), m	0.95	0.020
Longitudinal metacenter above keel, m	117.2	2.442

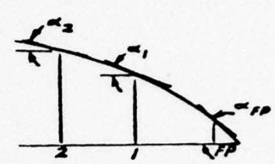
COEFFICIENTS AND ANGLES (AT TEST WL)

Block coefficient	0.487	Length/beam	4.60
Midship section coefficient	0.835	Beam/draft	2.63
Prismatic coefficient	0.585	μ_o	1.359
Waterplane coefficient	0.767	η_2	3.144
Bow stem angle, deg.	16.0	λ	48.0

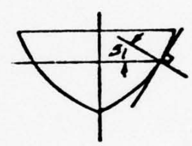
(continued)

TABLE B-7 SHIP AND MODEL DATA (continued)

Item / Station	B_i/B_x	α_i	β_i
0	.088	27.0	60.0
1	.310	25.2	53.0
2	.514	22.4	46.7
3	.688	18.7	40.3
4	.816	13.9	33.8
5	.904	9.0	25.0
6	.962	5.1	18.5
7	.990	2.2	15.2
8	1.000	0.0	14.2
9	.997	- 0.8	13.0
10	.990	- 1.8	12.5
11	.972	- 2.4	12.5
12	.953	- 2.9	13.2
13	.927	- 3.9	14.5
14	.890	- 6.5	17.0
15	.831	- 8.0	19.8
16	.758	- 12.0	25.1
17	.650	- 15.5	32.4
18	.499	- 22.4	39.6
19	.302	- 25.2	43.9
20	.060	- 31.7	47.2



α definition



β definition

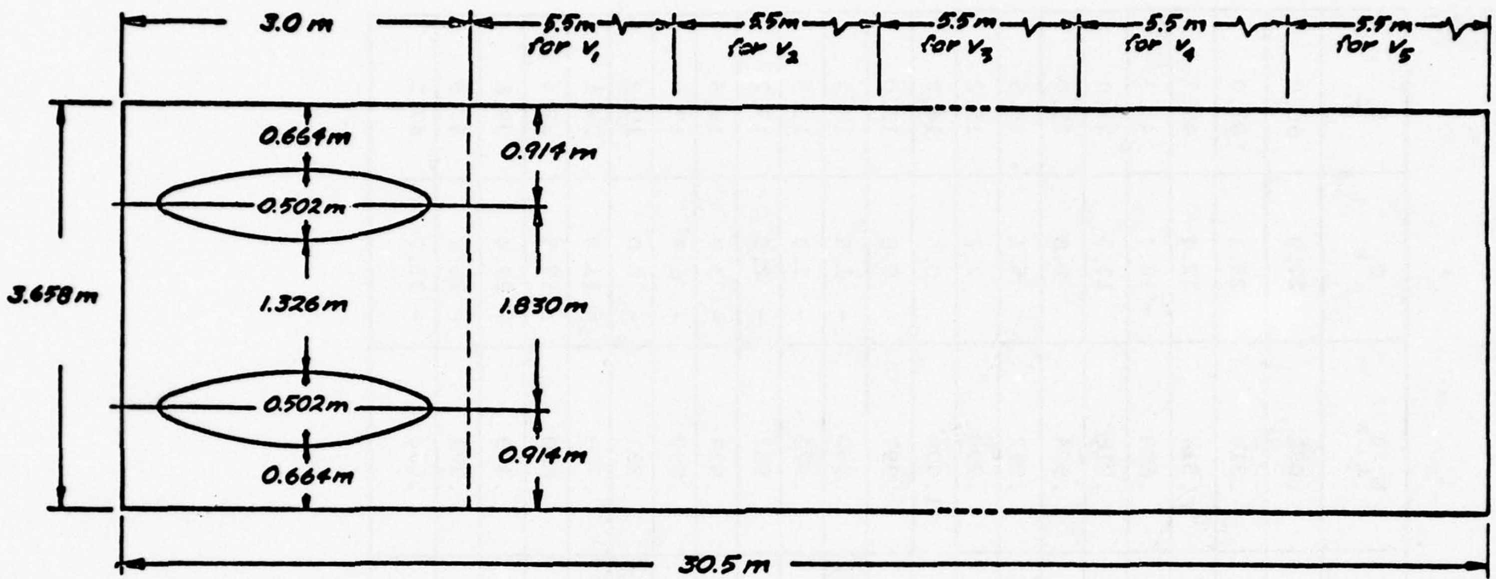


Figure B-2 Arrangement of Models in Towing Basin where

$$E = 4 \times 10^6 \text{ N/m}^2$$
$$\rho_w = 1005 \text{ kg/m}^3$$
$$g = 9.807 \text{ m}$$
$$d = 664 \text{ mm (see Figure B-2).}$$

All proposed tests meet this criterion. By using approximately two model lengths per data point, the models could be towed at five different velocities in each ice sheet, thereby collecting ten data points per ice sheet.

For each test the speed v of the towing carriage and the resistance R of each model were recorded on an oscillograph. In addition, the flexural ice strength σ_f was measured in three locations before and after each test. The elastic modulus E was measured at three positions prior to each test, and the ice thickness was measured every meter on both sides of the broken channel following the test run. This data is tabulated in Appendix B-I.

The resistance of each model was measured using a strain-gaged force block. Each model was attached to the force block in such a way to allow pitching, rolling, and heaving motions. The models were restrained in yaw and sway. A daily calibration of each force block was performed in order to ensure accurate measurements.

The model speed and position were measured simultaneously by recording the passing of six spokes in a wheel of the carriage drive system. Each pulse on the oscillograph indicates a carriage movement of a fixed distance. By recording the distance traveled on a time-based recorder, the velocity can be calculated. The carriage position in relation to the ice sheet was determined by noting the starting position of the models and then counting the pulses.

A description of the methods used to measure the flexural ice strength and elastic modulus are provided in Appendix B-II.

High-speed movies were taken at a frame speed of 24 $\sqrt{\lambda}$ frames per second. When projected at normal speed, the motion of the model is viewed in full-scale time. Supplemental surface and underwater footage was taken with a normal speed camera. Test films were edited, spliced together, and titled to produce a film summary of the program.

2.8 Friction and Roughness Test Procedure

An extensive series of friction and roughness tests was an integral part of this test program. These tests were meant to both supplement and extend the rather extensive series of tests conducted in conjunction with the earlier resistance tests done for the POLAR STAR test program. As a standard test, the upper surface of the model ice was towed face down against test planks on a daily basis throughout this test program, to give a basis upon which to compare variations in test procedure.

Initially, six test planks were prepared for use during this program. The preparation on each test plank is given in Table B-5. One test plank was left with a high gloss urethane finish. The roughest test plank was prepared in similar fashion to the preparation on the models, in that salt was poured on a wet urethane surface until no additional salt would stick to the paint. The paint was then allowed to dry following which the salt was washed off with fresh water and a hose. The remaining planks were sanded by hand using various grits of sandpaper. When sandpaper was used, the paper was wrapped around a soft desk eraser 25 mm by 60 mm and pressed against the plank with one hand as hard as possible. Small circular motions were used in the sanding with about 30 circles per 150 mm by 150 mm area. The planks were then rinsed with a hose and examined under bright light. Areas which still showed gloss were resanded until a uniform visual appearance existed over the entire test plank.

The roughness of each of the test planks was measured using a Rank Taylor Hobson Talysurf 4 system available at the University of Maryland. The procedure used to obtain the roughness from both the test planks and the models is detailed in Appendix B-II.

In addition to measuring the friction between the surface of the ice and the test planks in a standard procedure, the friction under different conditions was also measured. This included ice edge friction, friction submerged, and high speed friction. On the first test day, the edge of the ice was pressed against the test surfaces, and the friction factor under this condition determined. The thickness of the ice was 25 mm and in order to obtain a reasonable size piece, three thicknesses of ice were lined up side-by-side in the test rig.

Two additional tests using small samples on the test planks were conducted inside the model basin. Figure B-3 gives a set-up for these friction tests. For the submerged test, the plank was held against a table which was attached to

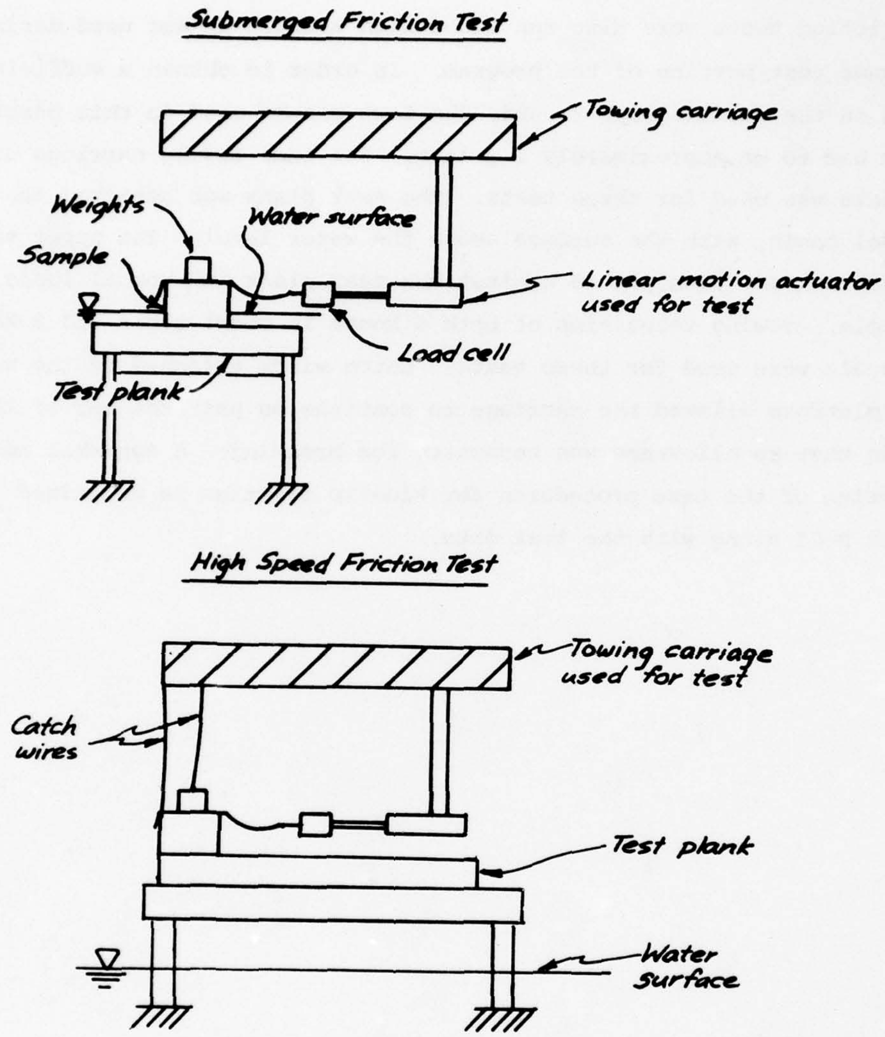


Figure B-3 Set-up for Friction Tests Inside Model Basin the bottom of the model basin. The linear motion actuator moved the load cell and test sample across the test plank.

Friction tests were also run at as high a speed as was used during the resistance test portion of the program. In order to obtain a sufficient period of data on the oscillograph record, the test planks used in this portion of the program had to be approximately 2 m long. The same towing carriage used to tow the models was used for these tests. The test plank was attached to a table in the model basin, with the surface above the water level. The upper surface of the model ice was then placed against the test plank and normal loads added to the sample. Towing velocities of both 4 knots in model scale and 8 knots in model scale were used for these tests. Catch wires attached to the weight and sample platform allowed the carriage to continue on past the end of the test plank so that no allowance was necessary for breaking. A somewhat more detailed description of the test procedures for kinetic friction is contained in Appendix B-II along with the test data.

3. TEST RESULTS

3.1 Series One

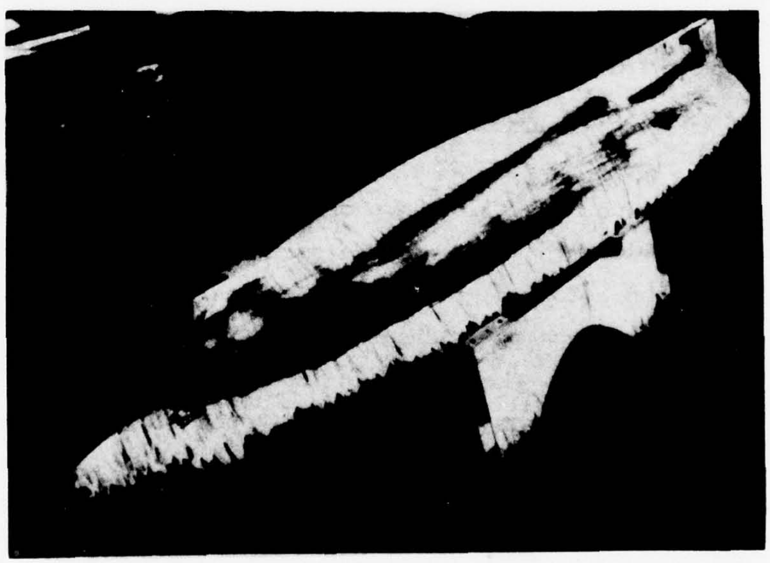
For series one the two model coatings selected under the preliminary program, conducted during the POLAR STAR tests, were applied to each of the models. One model had a uniform coating of calamine lotion applied over high gloss urethane finish and allowed to dry. The second model was coated with cream car wax which was allowed to dry to a matte powdery surface. The two models were then placed in the model basin carefully under the towing carriage so as not to damage the coatings. Both models were towed side-by-side down the model basin at constant velocity of 372 mm/sec (5 knots full-scale). Immediately following the completion of the run, the models were disconnected from the towing carriage and lifted directly up and out of the broken channel without allowing additional ice contact.

Figure B-4 shows the model coated with calamine lotion after the completion of the tests. All of the calamine lotion was completely removed in a band from just below the 30 foot waterline to approximately half the depth of the keel, tapering back aft and stopping just aft of amidships. In addition, there was a band of wear located just below the turn of the bilge. The band of wear below the turn of the bilge continued on aft and completely removed the coating around approximately one-third of the propeller bossing.

Figure B-5 shows the model which was coated with cream car wax. On this model less of the coating was removed, however, a close examination of the part where coating appears untouched in the photograph showed that gouges had been formed by passage of ice blocks along this portion of the hull. Also notice that in this model the band below the turn of the bilge is not present, yet the bossings also show wear although to a lesser extent. The band in the forward portion of the hull, just below the waterline, to approximately half the keel depth, shows that the direction of ice passage at this speed is very constant and parallel from the stem back to the midships section. This band therefore seems to be formed during the actual breakage of cusps in the model basin.

Figures B-6 and B-7 are close-up views of the two hulls following the model tests. Note in Figure B-6 that the midship section between the band of high wear near the waterline and the turn of the bilge shows a great deal of ice scraping and that this continues on back as far as station 14. The vertical

BOW VIEW



STARBOARD SIDE VIEW

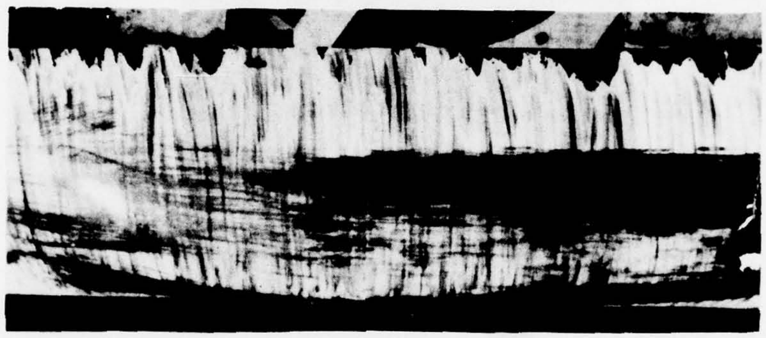
Figure B-4 Model Coated with Calamine Lotion after Test at 5 kts. in 4 ft Ice

BOW VIEW

STARBOARD QUARTER VIEW

Figure B-5 Model Coated with Cream Car Wax after Test at 5 kts. in 4 ft Ice

BOW



AMIDSHIPS BOW →

STERN

Figure B-6 Model Coated with Calamine Lotion. Starboard side shown. Port side showed identical wear.

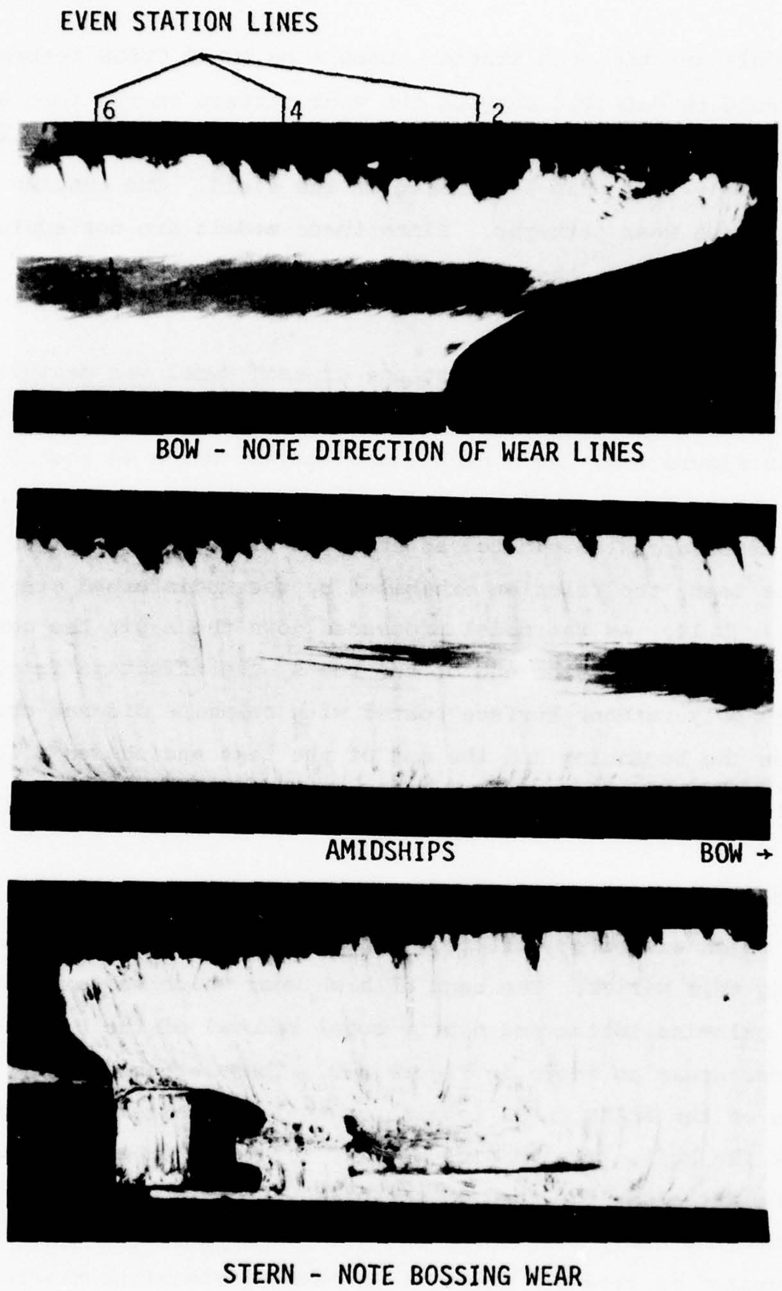


Figure B-7 Model Coated with Cream Car Wax lines on the models are the even station numbers on POLAR CLASS icebreakers. No difference could be detected between the wear pattern on the port and starboard sides, indicating that this wear pattern is not random following the passage of approximately four ship lengths in an ice field. One caution should be mentioned about these wear patterns. Since these models are not equipped with self propulsion, a change in the pattern around the rudders and stern would be expected due to wake.

During the coating tests the resistance of each model was measured as it passed down the model basin. The results of this test are quite interesting and are portrayed in Figure B-8. As a background against which we should examine these results, the test for each of the four model hull preparations used during the POLAR STAR tests are also plotted as straight lines on this figure. At the beginning of the test, the friction exhibited by the undisturbed cream car wax was approximately 0.14. As the model proceeded down the basin the coating was progressively worn off until the end of the tests, the effective friction was 0.08. The gloss polyurethane surface coated with calamine did not change resistance between the beginning and the end of the test and showed a friction factor of 0.05.

3.2 Series Two

The areas which exhibited different types of wear were divided into sections for study during this series. The band of high wear which was exhibited by total removal of the calamine lotion and nearly total removal of the cream car wax was divided into four areas as shown in Figure B-9. These areas are plotted on a shell expansion of the POLAR CLASS icebreaker hull and therefore represent actual surface area of the hull. The band of heavily scratched area from the lower portion of the stem aft along the turn of the bilge is designated as area 6. The area which showed the heavy scratching but not complete removal in the calamine lotion is designated as area 5. Since it is hard to visualize the location of waterlines on Figure B-9, a photograph of the models with the actual test areas laid out on them is given in Figure B-10. Area A-1 goes from the stem aft to a line drawn vertically up from the location of the keel and the bow stop. Area A-2 runs from this position aft to station 4. Area A-3 runs from station 4 aft to station 6, while Area A-4 runs from station 6 aft to station 10. Areas A-5 and A-6 are more complex and their shape may also be seen on the photograph.

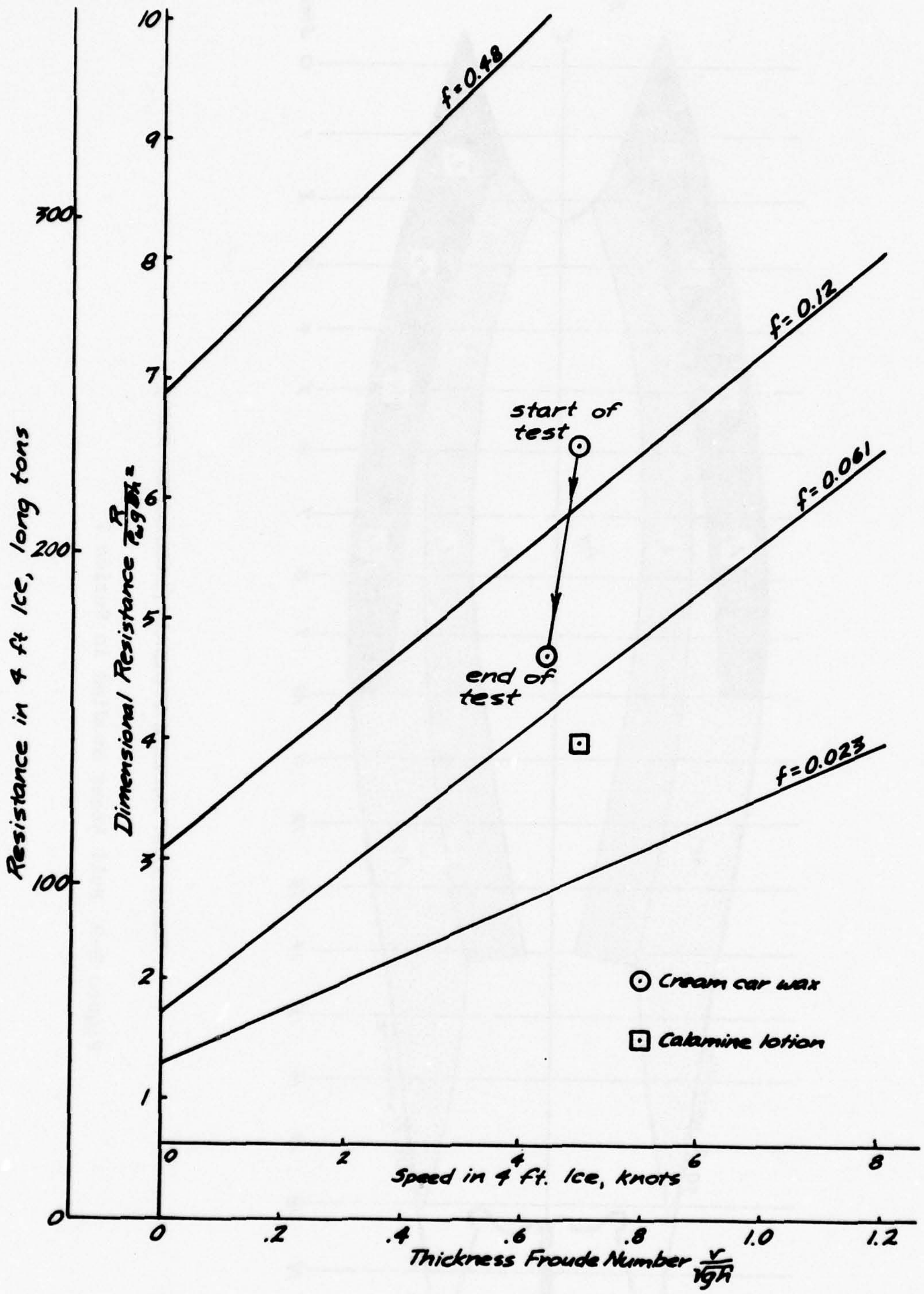
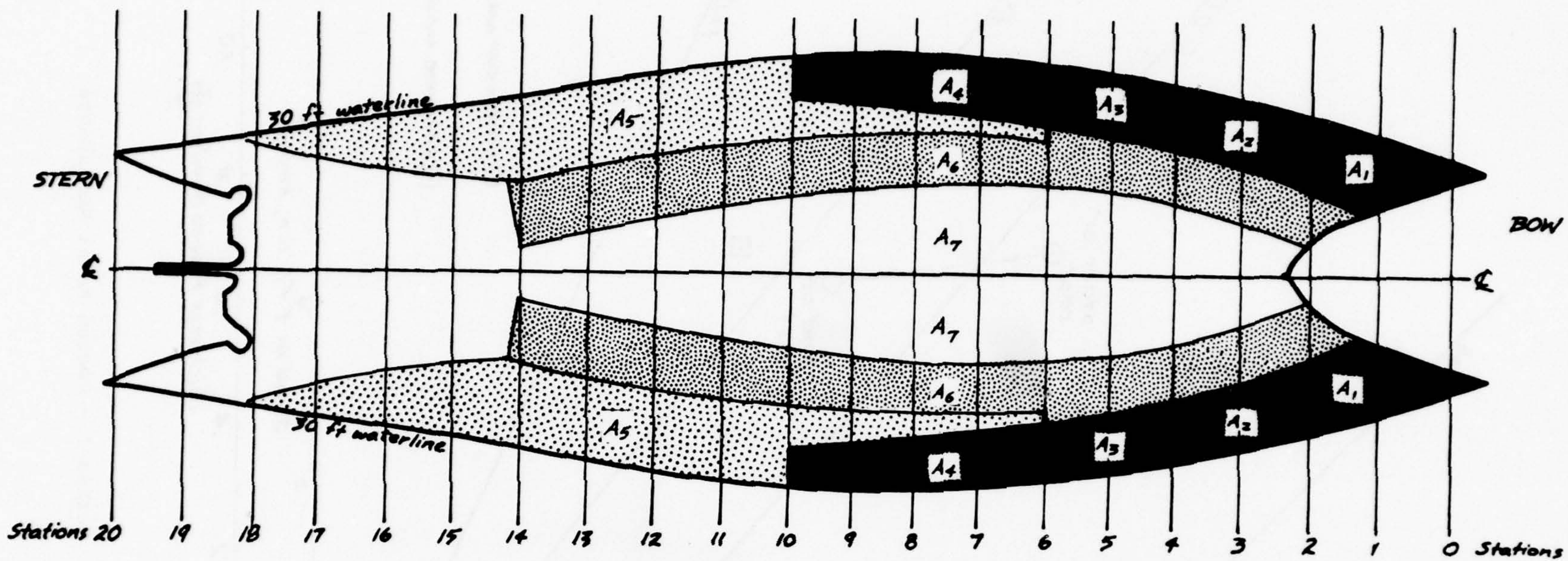
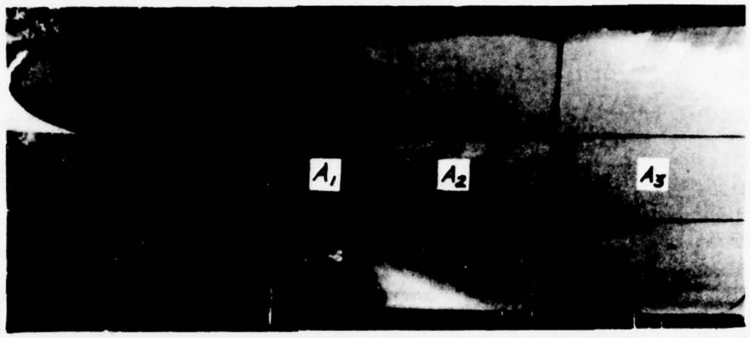


Figure B-8 Series 1 - Coated Model Resistance

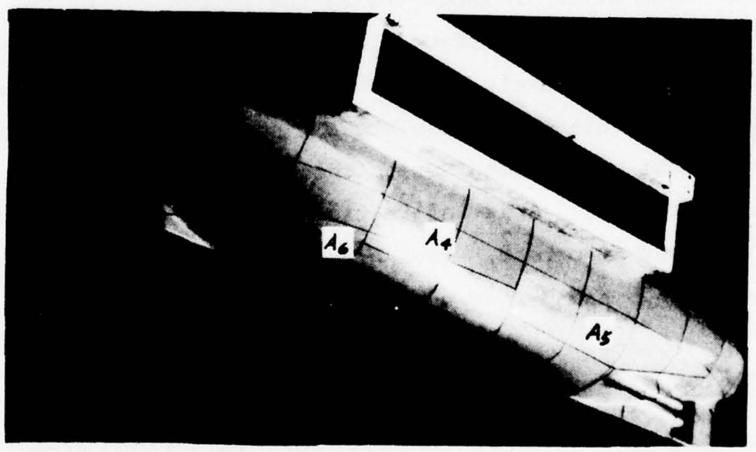


POLAR STAR SHELL EXPANSION (UNDERWATER BODY)

Figure B-9 Hull Areas Studied in Series 2



AREAS A_1, A_2, A_3 ON ONE MODEL



AREAS A_4, A_5, A_6 ON SECOND MODEL

Figure B-10 Test Areas on Models for Series 2

The test results plotted in a dimensionless format are given in Figure B-11. The models were painted such that the area of low friction surface decreased from one test to the next. The data points labeled entire hull smooth and entire hull rough were obtained from the basic program of resistance tests on the POLAR STAR hull form. The remaining six straight lines were obtained from tests in series two. The bottom three lines were obtained from tests on one model, starting with areas A-1 to A-6 smooth and completing with just Areas A-1 to A-4 smooth, whereas the second model started with Areas A-1 through 3 smooth and completed the series with only A-1 smooth. The visual regression lines on the data have been forced to take the form of a family of curves and therefore may not be the best fit to each individual set of model data. The percentage of the total hull area represented by each of the data points is also tabulated in this figure.

Each of the lines plotted in Figure B-11 represents an equation having two coefficients. The form of the equation is as follows:

$$\frac{R}{\rho_w g B h^2} = C_o + C_1 \frac{v}{\sqrt{gh}} \qquad \text{(B-3.1)}$$

In Table B-8 the coefficients for each of the straight lines plotted in Figure B-11 are tabulated. Also given in Table B-8 is the percentage of the total hull surface represented by a smooth surface, the percentage of the hull surface which was roughened, the areas represented by each one of the conditions, and the change in each one of the coefficients in absolute and percentage terms. In order to select the test areas to be used during series three, the areas in series two were examined on a per unit basis. This information is tabulated in Table B-9. Areas A-1 and A-3 are the most important. Area A-2 is third in importance while Area A-4 is fourth. Areas 5,6 and 7 show much less contribution to the total resistance.

3.3 Series Three

Based on this evaluation of the importance of various areas tested, the configuration of the smooth area of the hull was adjusted to obtain an optimum distribution for a 10% coating and a 20% coating. Since areas A-1 and A-3 were most important it was felt that for the 10% coating as much as possible of these two areas should be included in the smooth portion of the hull. Figure B-12 shows the selected configuration for the 10% coating area. The coated area is represented by a band from the 30 foot waterline down to approximately half the keel depth and then tapering back aft to the cut-off point at station 6. For the 20%

TABLE B-8 RESISTANCE EQUATIONS FOR SERIES 2

Model Condition	Smooth	Rough	C_o	C_1	$C_o - (C_o)_{smooth}$	$C_1 - (C_1)_{smooth}$	$F_o = \frac{\Delta C_o}{(C_o)_{rough} - (C_o)_{smooth}}$	$F_1 = \frac{\Delta C_1}{(C_1)_{rough} - (C_1)_{smooth}}$
All rough	0.0	100.0	6.867	4.983	5.572	2.757	100.0	100.0
A_1	5.4	94.6	4.04	4.69	2.745	2.464	49.3	89.4
$A_1 + A_2$	8.9	91.1	3.73	4.11	2.435	1.884	43.7	68.3
A_1, A_2, A_3 smooth	11.9	88.1	2.56	3.59	1.265	1.364	22.7	49.5
A_1, A_2, A_3, A_4 smooth	19.1	80.9	2.13	3.22	0.835	0.994	15.0	30.3
A_1, A_2, A_3, A_4, A_5 smooth	38.3	61.7	1.76	2.93	0.465	0.704	8.35	25.5
A_1 A_2 A_3 A_4 A_5 A_6 smooth	60.5	39.5	1.64	2.90	0.345	0.674	6.19	24.4
All smooth	100	0.0	1.295	2.226	0.0	0.0	0.0	0.0

TABLE B-9 RELATIVE EFFECT OF SERIES 2 TEST AREAS

Area	% of Hull	ΔC_o	ΔC_1	$\frac{\Delta C_o}{\text{Unit Area}}$	$\frac{\Delta C_1}{\text{Unit Area}}$	Importance
A_1	5.4	2.827	0.293	0.531	0.54	1
A_2	3.5	0.31	0.58	0.089	0.17	3
A_3	3.0	1.17	0.52	0.390	0.17	2
A_4	7.2	0.43	0.37	0.063	0.05	4
A_5	19.2	0.37	0.29	0.019	0.02	5
A_6	22.2	0.12	0.03	0.005	0.00	7
A_7	39.5	0.345	0.674	0.009	0.02	6

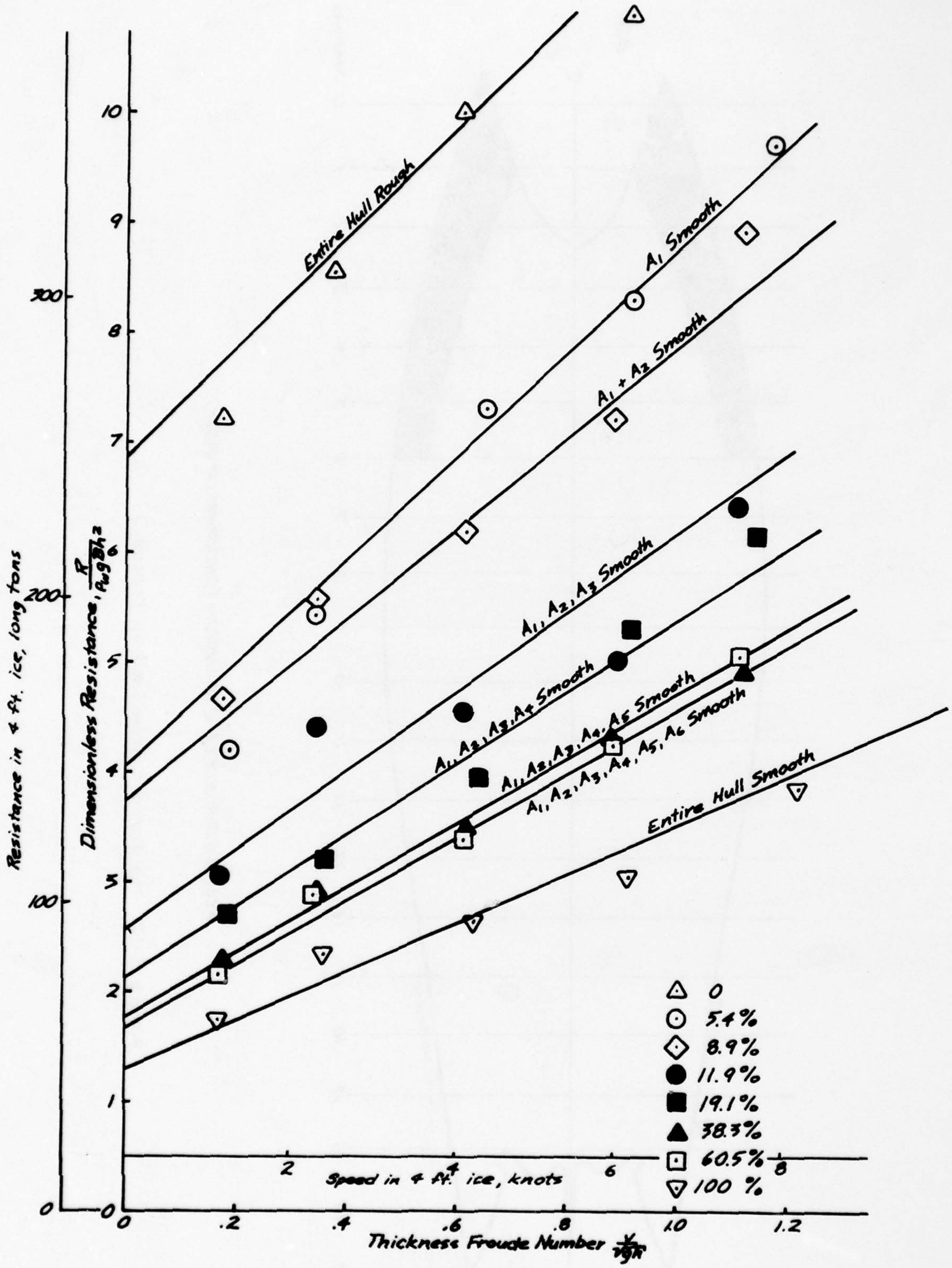
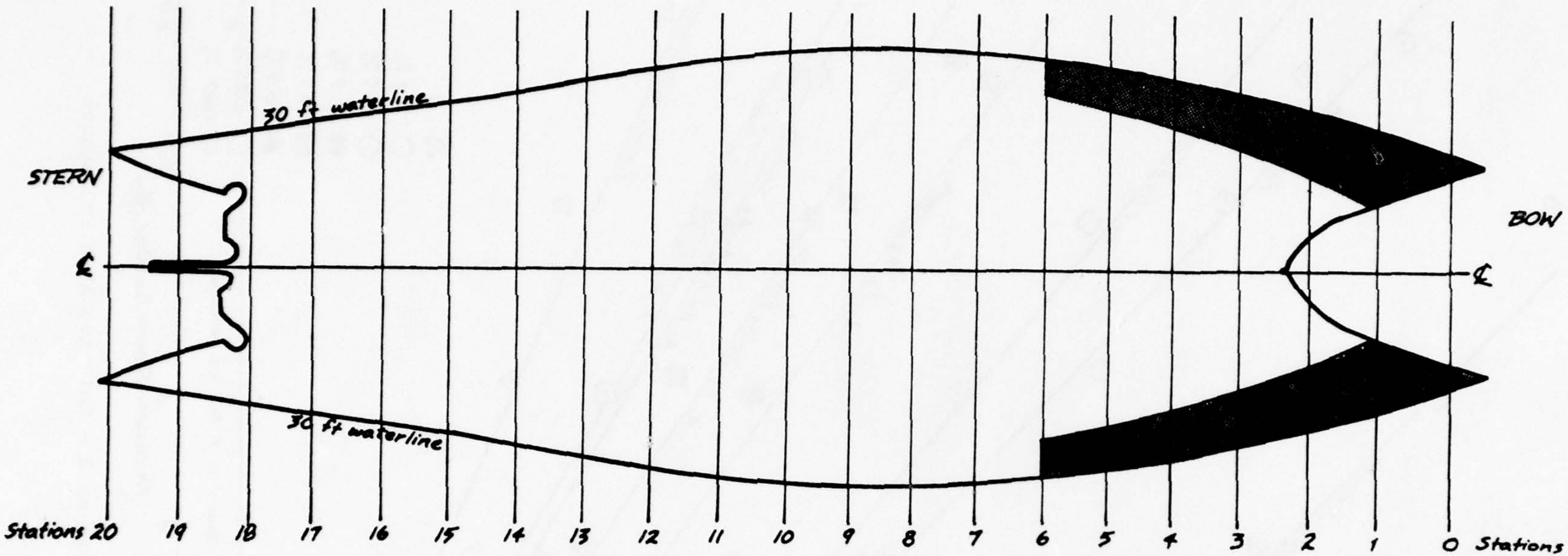


Figure B-11 Series 2 - Relative Area Importance



POLAR STAR SHELL EXPANSION (UNDERWATER BODY)

Figure B-12 Ten Percent Area Used in Series 3 area configuration, additional depth of coating was included over the 10% coating going down to the bottom of Areas A-1, A-2 and A-3, and also including Area A-4 an and a small portion aft from A-4 to station 11.3. This is indicated in Figure B-13. Photographs of the actual changes as laid out on the models are indicated in Figure B-14.

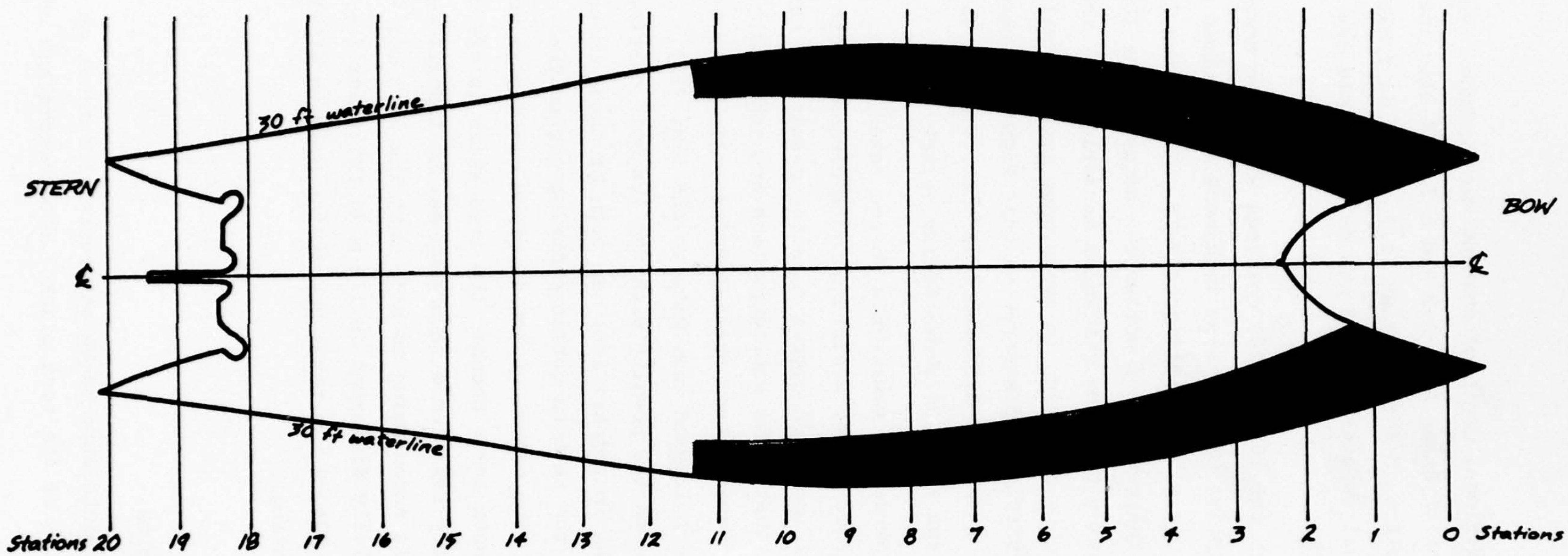
The two models with the 10% and 20% coatings were then towed in the same ice thickness as used for series two and also thickness of 1½ times this value. The results of these tests are plotted in Figure B-15. The dotted line plotted in this figure represents the results of series two adjusted for 10% and 20% total coating. In the ice having the same thickness as series two, the new configurations showed a considerable reduction in resistance from the value measured during series two. The small circles and squares on this figure represent these tests. The tests also indicate a smaller difference in the reduction in resistance between the 10% and 20% area than was shown during series two.

In a thicker ice however, a remarkable change takes place. Both the 10% and 20% configurations show higher resistance on a dimensionless basis in this ice than they did in thinner ice, even higher than the results of series two. This is in spite of the fact that these configurations are supposedly optimized and would logically give a decrease from these results. (In other test programs, dimensionless plots have collapsed test data to one line [16].) There is a substantial difference between the results with the 10% hull coating and the results with the 20% hull coating in thicker ice. In both of these cases the line through the data is higher than the results obtained during series two. This leads us to two conclusions. First, the extent of low friction coating is more important in thicker ice than in thinner ice. Second, the area which is effective in thin ice in creating a satisfactory resistance reduction may be insufficient in thicker ice. Nevertheless, it is encouraging to note that the data for the 20% hull coating is not substantially different in 1.8 m (6 ft) thick ice than in 1.2 m (4 ft) ice, and coating 20% of the total underwater body is still a substantial reduction from total coating.

3.4 Friction Results

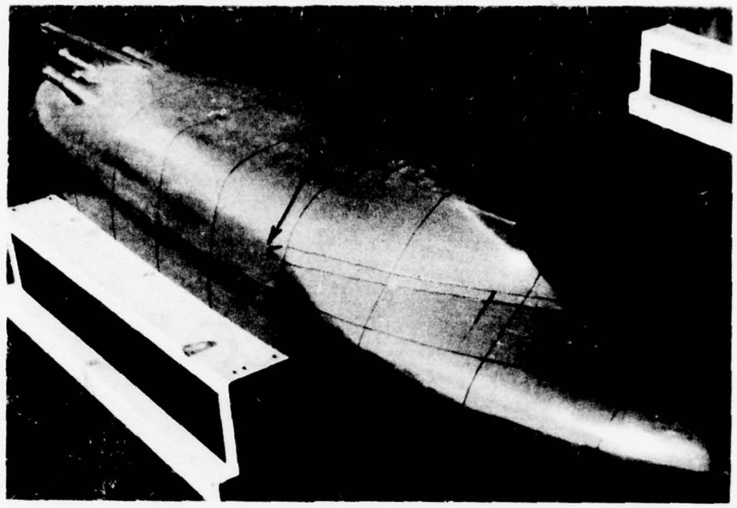
3.4.1 Roughness Results

Roughness measurements were taken at several locations on the models and at three locations on each of the test planks, both before and at the completion

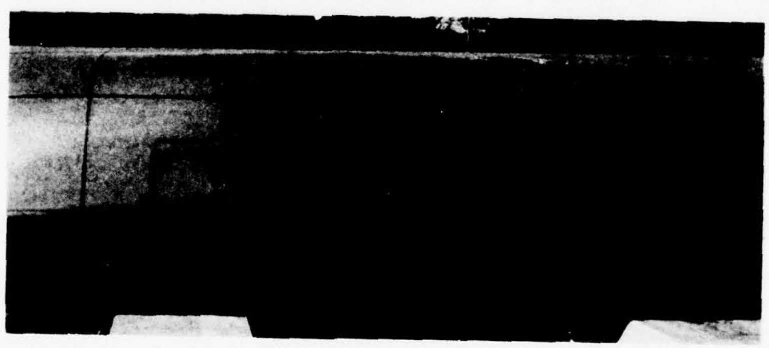


POLAR STAR SHELL EXPANSION (UNDERWATER BODY)

Figure B-13 Twenty Percent Area Used in Series 3



AREA SUBTRACTED FROM AREAS A_1, A_2, A_3
FOR 10% SMOOTH MODEL



AREA ADDED TO AREAS A_1, A_2, A_3, A_4
FOR 20% SMOOTH MODEL

Figure B-14 Test Areas on Models for Series 3

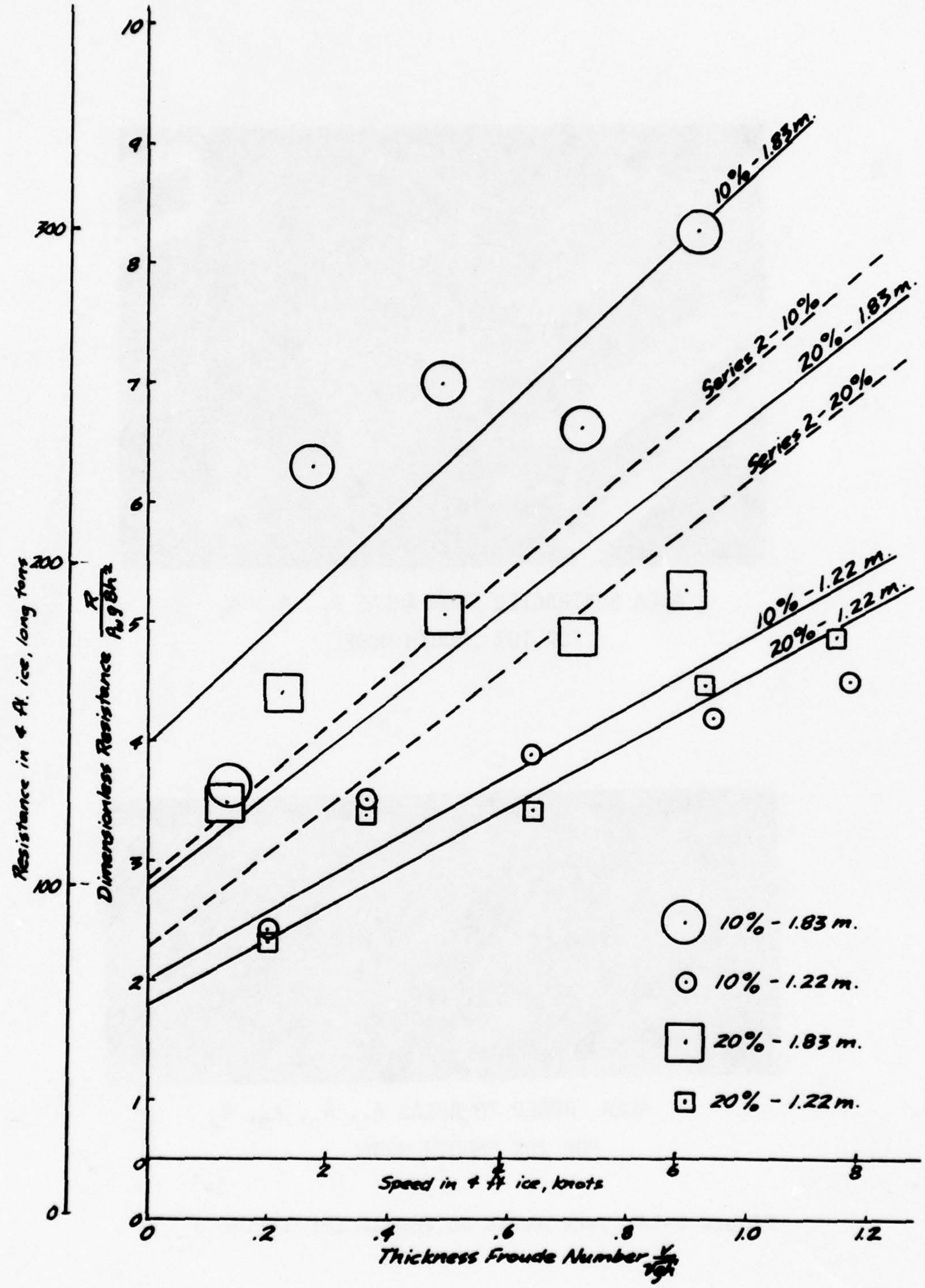


Figure B-15 Series 3 - Thickness Effect on Areas of these tests. A tabulation of the roughness readings is found in Appendix B-II. These results show that the roughness did not change from the beginning of the tests to the end of the test program. On the test planks and on the models, the roughness was such that the three locations tested showed negligible difference between them and also showed no wear. The three smooth test points on the models were located within Area A-1 on one model and within Area A-1, 2, 3 and 4 on the second model. The rough test points on the models were located around the midships section at the waterline on either side and at the centerline amidships. On the test planks the test locations represent quarter points down the length of the test plank. Roughness readings did not vary between models, thus allowing direct comparison between test results.

3.4.2 Friction on Planks

The standard method used by ARCTEC over the past several years (see Appendix B-II) to determine the friction between model ice and a test surface was used on a daily basis with the planks. Towing speed is 3.59 mm/sec. This speed is lower than any towing velocity used in the resistance tests and is chosen to just exceed static condition so that the friction force is constant. Figure B-16 gives the results of the average friction factor determined throughout this test program plotted against the roughness measured by the surface profilimeter. In addition to the data which was collected during this test program, the results of the tests conducted during the POLAR STAR resistance program are also plotted. We can see from this figure that friction factor increases with roughness. However, the accuracy with which the friction factor of a particular test surface can be predicted is only $\pm.04$ on friction factor when roughness is known. Friction tests in the model basin have much less scatter than this. This indicates that CLA roughness is not a final indicator of the behavior of the ice as it is dragged across the model and that tests using model ice to determine the friction factor are still necessary. There is also a wide gap in this figure between CLA roughnesses of 2 and 4 μm. Comparison of model data with full-scale test results has indicated that correlation between model and full-scale results, at least in snow covered ice, should be in this range. There is a need to develop a method of preparing models to roughnesses in this range so friction factors in the area of .2 to .4 can be obtained.

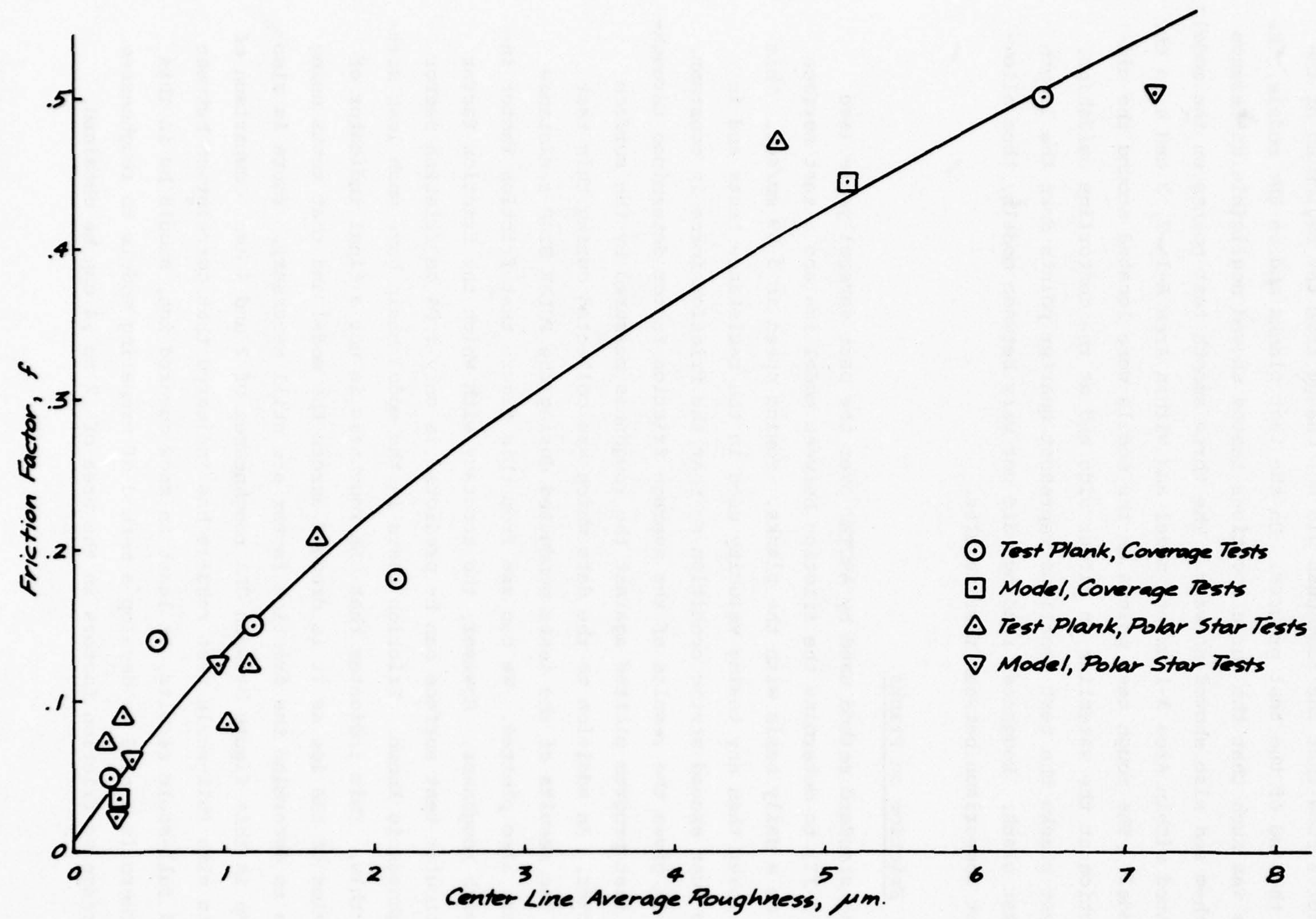


Figure B-16 Correlation of Standard Friction with Roughness

Friction tests were also conducted using the edge of the ice against these test surfaces, with the test surface submerged, and with the sample drawn across the test surface at model testing velocities. Ice edge and submerged tests exhibited no difference from the top surface. Tests were also run with the test surface wet and dry showing no difference. These test results are reported in Appendix B-II. When the tests were run at model testing velocities an increase in the friction factor was noted from the tests conducted near zero speed. These results are plotted in Figure B-17. A family of curves has been drawn through the data. The most accurate data points in this figure are those which are represented by zero speed, as they represent the average of multiple tests conducted daily throughout the test program. The test at 4 knots model speed (approximately 300 mm/sec) and at 8 knots model speed (600 mm/sec) represent an average of only three tests each. It is believed that this increase in friction factor with speed in a linear fashion is due to encountering more discontinuities in the surface per unit time. As more information becomes available on both model and full-scale hull-ice friction, the reduction of model data may be changed to include a variation in friction with speed or changed modeling values for friction.

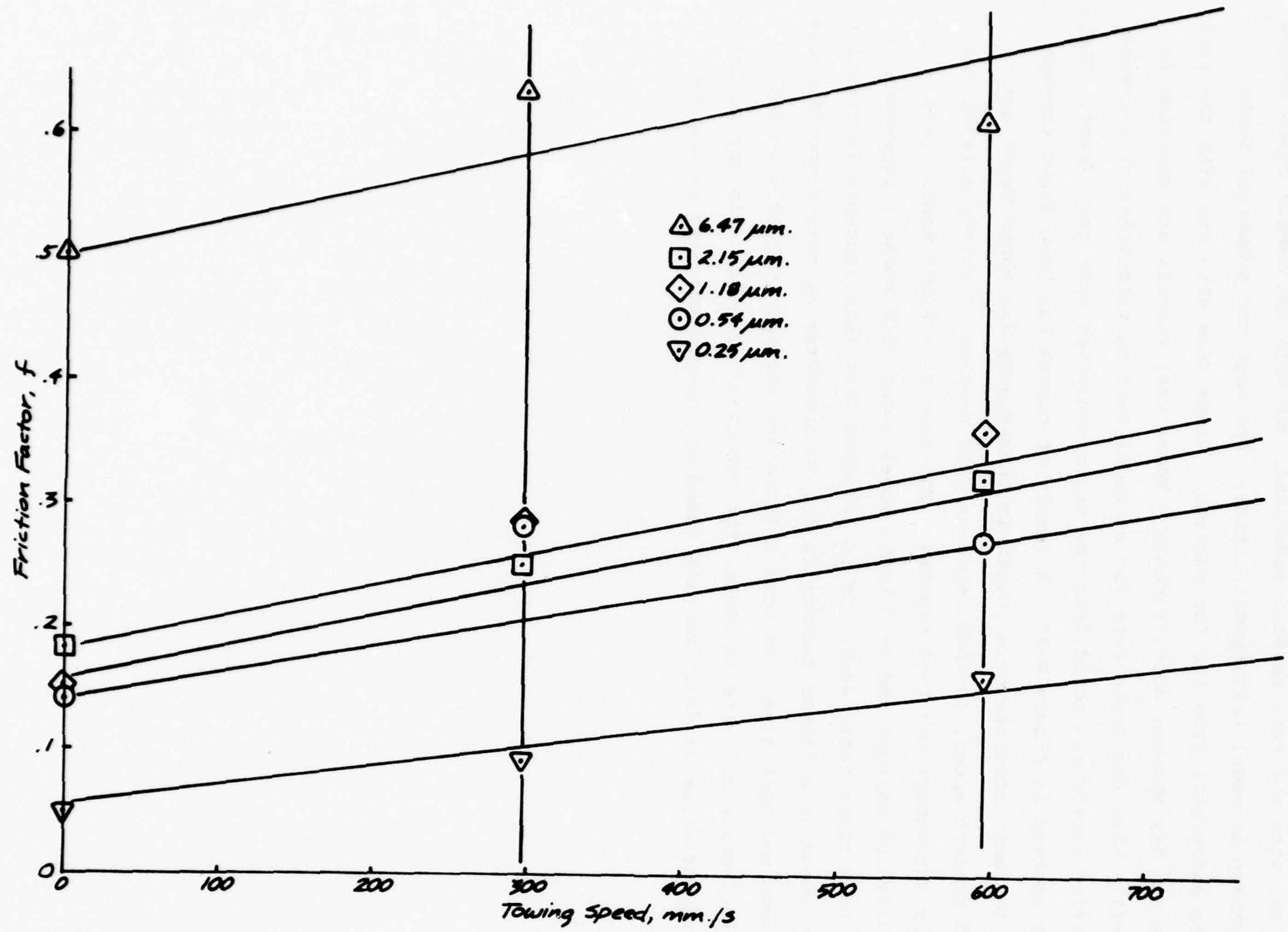


Figure B-17 Effect of Speed on Friction

4. ANALYSIS OF RESULTS

The equation developed during the test program on the POLAR STAR resulted in a predictor equation for both model and full-scale icebreaking resistance as follows [6]:

$$\frac{R}{\rho_w g B h^2} = C_o + C_1 \frac{v}{\sqrt{gh}} \qquad \text{(B-4.1)}$$

where

$$C_o = 1.15 + 12.1\, f \qquad \text{(B-4.2)}$$

$$C_1 = 3.82 + 4.13\, f \qquad \text{(B-4.3)}$$

$$19.6 < \frac{\sigma_f}{\ell_w g h} < 65.6$$

In this equation both of the coefficients of the predictor equation (4.1) are linear functions of the hull-ice friction factor. These coefficients can be further modified to include the effect of partial coating with coatings of one friction factor. The effect of partial coatings on the predictor equation is shown in Figures B-18 and B-19. In these figures the percentage of the difference in each coefficient of the predictor equation as a function of the percentage of the hull which is smooth is plotted. The data comes from Table B-8. In this particular plot, the coefficients are plotted exactly as they came out of the test results from series two. They are thus strictly applicable only to performance in 1.2 m (4 ft) of ice. There is some variation from a smooth curve due to a difference in base coating friction factor from the POLAR STAR program, and also a variation in order of the effectiveness of areas since A-3 is more important than A-2. Since these curves represent area effects they would not change shape if different friction factors were tested. They would, however, change shape with ice thickness as seen in series three.

These two figures coupled with the POLAR STAR resistance predictor equation based on tests with the entire hull uniform can then be used to predict the effect of partial coating in full-scale. As an example of how this information could be used it is assumed that the majority of the hull is smooth uncoated steel with a friction factor of approximately 0.25 and a small portion of the hull is coated with a coating exhibiting a friction factor of .1. These values are picked for illustration only since there is still much controversy over full-scale hull-ice friction values. RPI reports [8] and [9] indicate a value of 0.1, the 140 ft WYTM report uses 0.2, while some recent model/full-scale tests of the

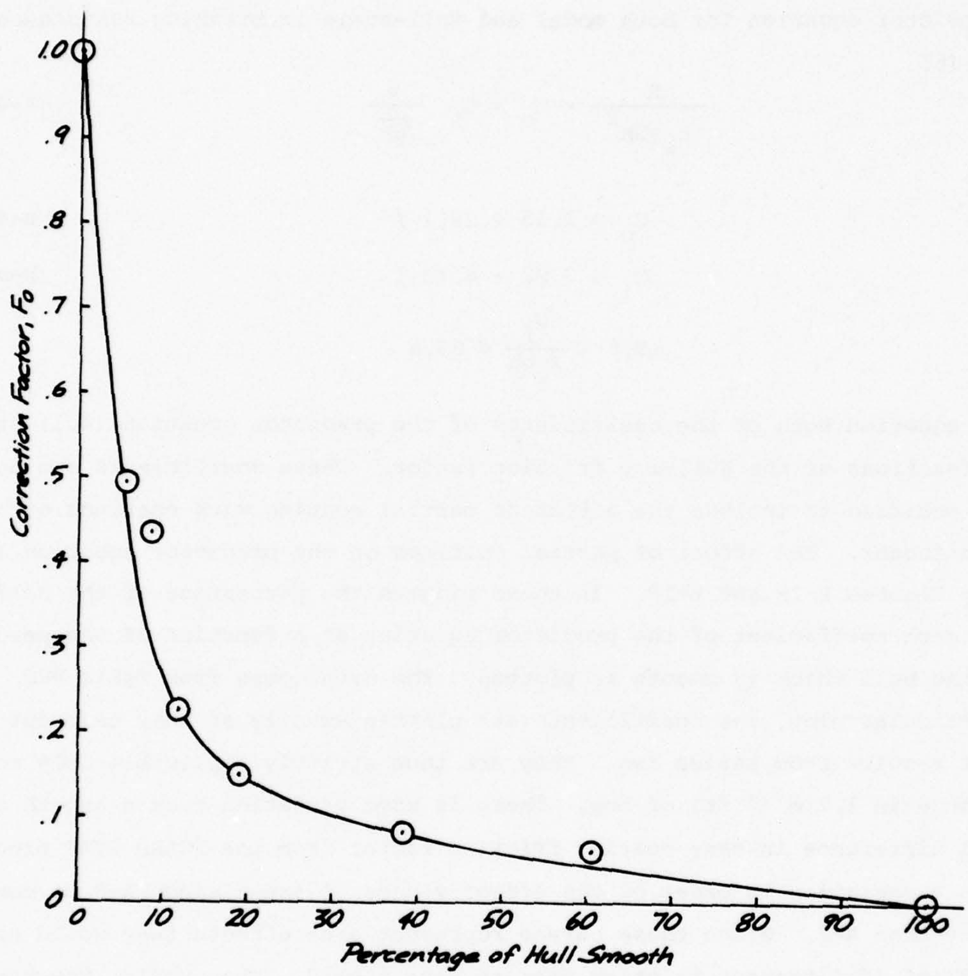


Figure B-18 Effect of Coating on Predictor Intercept

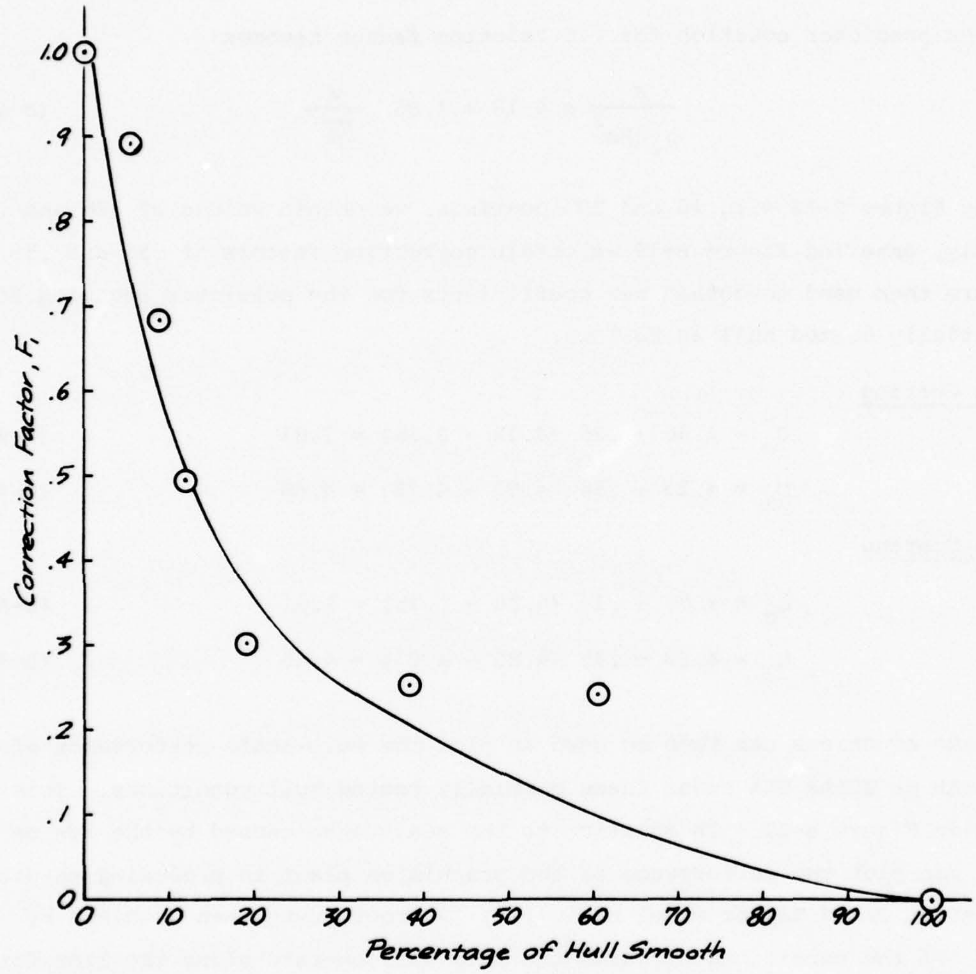


Figure B-19 Effect of Coating on Predictor Slope

LOUIS S. ST. LAURENT [12] and WARTSILA's reports indicate 0.3 to 0.5. The predictor equation for .1 friction factor then becomes:

$$\frac{R}{\rho_w g B h^2} = 2.36 + 4.23 \frac{v}{\sqrt{gh}} \tag{B-4.4}$$

while the predictor equation for .25 friction factor becomes:

$$\frac{R}{\rho_w g B h^2} = 4.18 + 4.85 \frac{v}{\sqrt{gh}} \tag{B-4.5}$$

Entering Figure B-18 with 10 and 20% coatings, we obtain values of .26 and .14. Similarly, entering Figure B-19 we obtain correction factors of .56 and .35. These are then used to obtain new coefficients for the predictor equation for the partially coated hull as follows:

<u>10% Coating</u>

$$C_o = 2.36 + .26\ (4.18 - 2.36) = 2.83 \tag{B-4.6}$$

$$C_1 = 4.23 + .56\ (4.85 - 4.23) = 4.58 \tag{B-4.7}$$

<u>20% Coating</u>

$$C_o = 2.36 + .14\ (4.18 - 2.36) = 2.61 \tag{B-4.8}$$

$$C_1 = 4.23 + .35\ (4.85 - 4.23) = 4.45 \tag{B-4.9}$$

These equations can then be used to plot the full-scale performance of the POLAR STAR or POLAR SEA under these partially coated hull conditions. This is plotted in Figure B-20. In addition to the resistance caused by the ice on the hull we can plot the performance of the propulsion plant in producing thrust as developed at David Taylor model basin [7]. A cross curve then obtained by picking off the conditions at which the ship will operate along the line for full power of 44.8 MW (60,000 shaft horsepower) allows us to plot velocity as a function of the thickness of the surrounding ice cover in Figure B-21. Also plotted on this figure is a line corresponding to 5 km/hr, which is usually considered the minimum velocity at which a ship can maintain continuous progress. The conditions at this minimum velocity are then plotted in Figure B-22 and indicate that the limiting ice thickness for operation of the POLAR STAR can be radically increased through use of as little as 10% coating and that with up to 20% coating a significant benefit is obtained. Between 20% coating and totally coating the hull, little benefit is gained in performance.

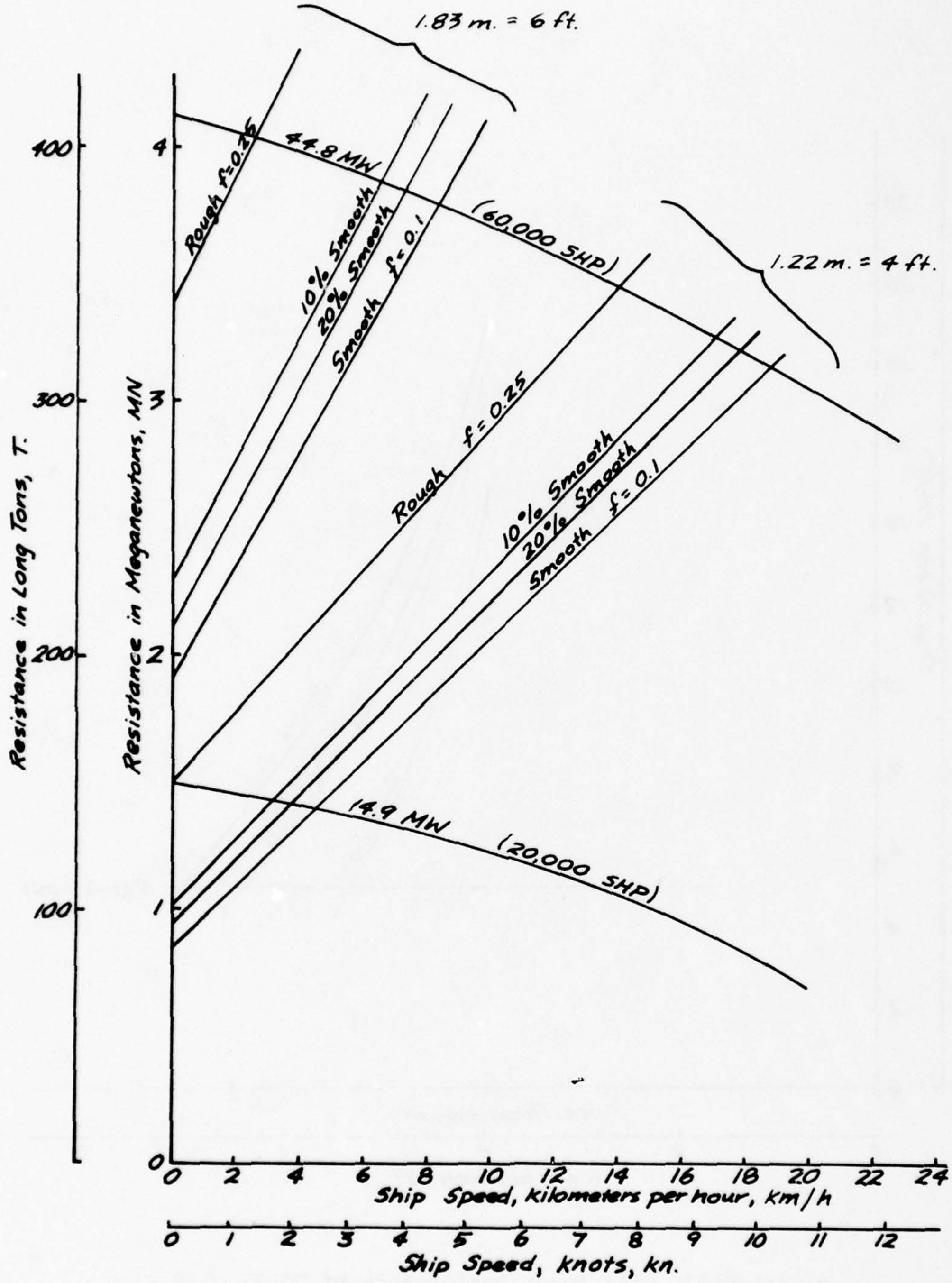


Figure B-20 POLAR STAR Resistance with Partial Coatings

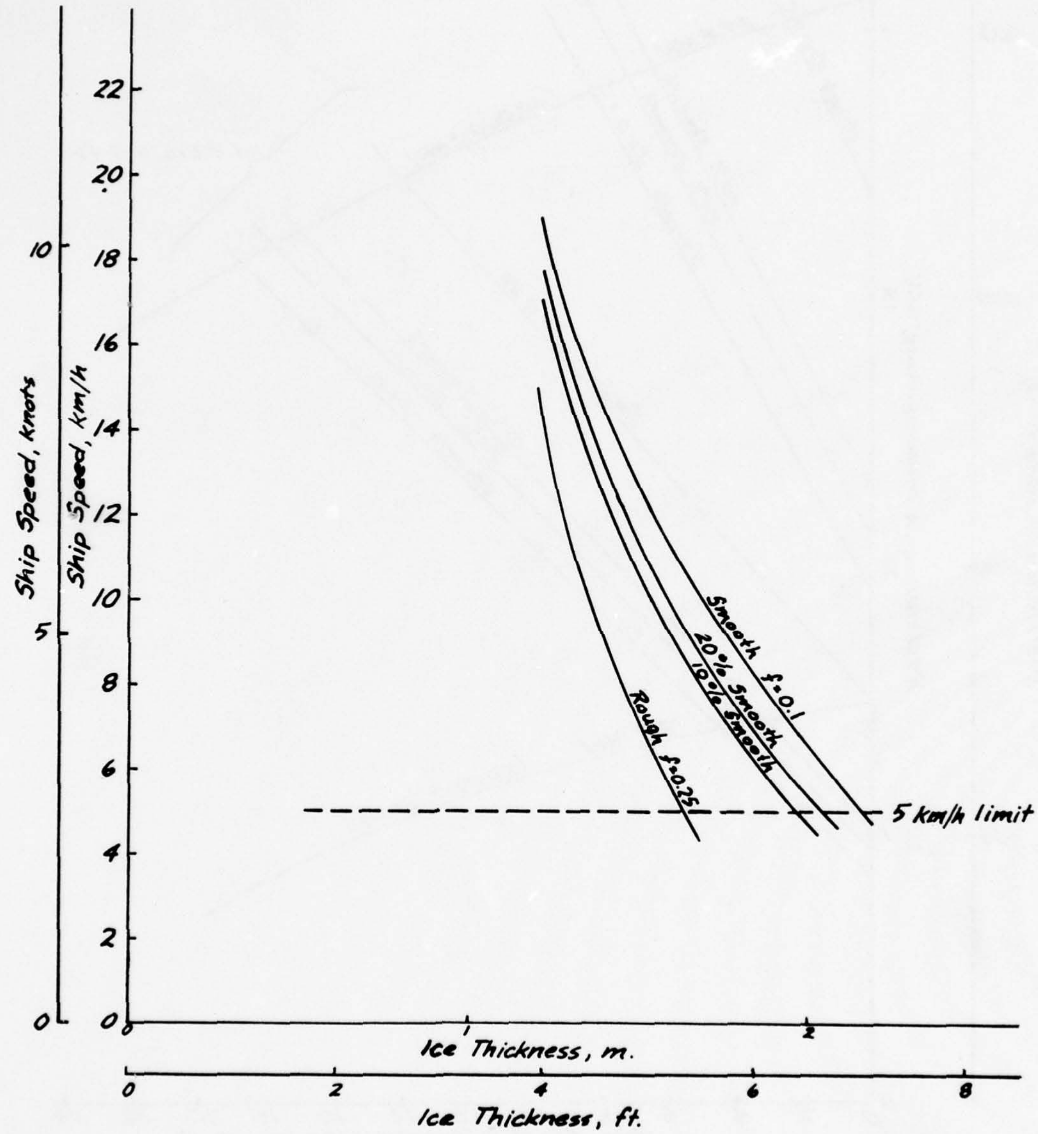


Figure B-21 Full Power Performance of POLAR STAR with Partial Coatings

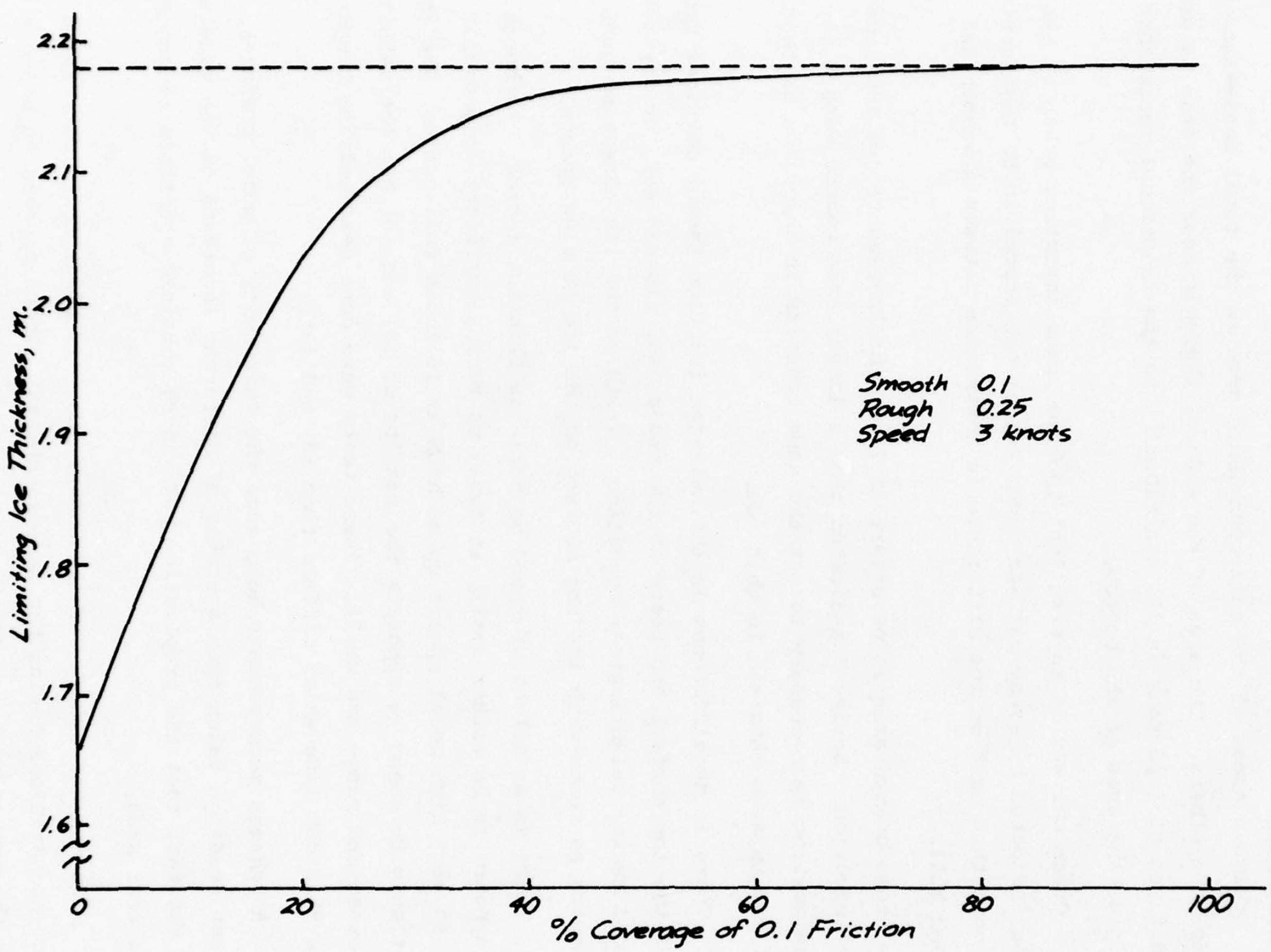


Figure B-22 Maximum Thickness for Continuous Progress

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Certain areas of the hull contribute more to the total resistance of the ship than others. The area of the side of the ship near the stem is several hundred times as important in its contribution to the frictional resistance of the ship as the area of the bottom.

2. Cream car wax is an excellent tool to trace important areas on the hull. The area indicated by cream car wax under series one proved to be that contributing more than half of the difference in resistance between a smooth and roughened hull.

3. Less coated area is necessary at lower thicknesses to get the same percentage reduction. Series 3 indicated that a larger area coated with a low friction coating is necessary to get the same benefits in thick ice as that which a small smooth area obtained in thin ice.

4. There is no difference in the hull-ice friction factor obtained from tests of the top surface and tests in the submerged, flushed wet, or dry (direct from model basin, unlubricated) condition. Tests of the ice edge also gave the same results as tests with the top surface of the ice at slow speeds.

5. There is an effect of speed on hull-ice friction factor. Although this effect appears to be rather small, it could be very significant, especially when testing at very high model speeds up as high as 15 knots full-scale. The increase in friction with speed is opposite the results of [8] and [9] but the magnitude of the speed and range are small. These tests were done near melting temperature and in a straight line which differs from [8] and [9].

6. Roughness measurements help gage the uniformity of model surfaces. Consistent readings taken from a number of different locations on the models confirm the fact that the preparation has indeed obtained a uniform roughness over the test area.

7. Friction correlates with roughness, but different friction results from different preparations having the same roughness. There appears to be more to indicate the proper hull-ice friction than CLA roughness alone. Perhaps the sharpness of the peaks is also important.

8. It appears that insignificant wear takes place on the surfaces of the model during the course of a model test program. An examination of the roughness readings over the course of these tests show that no change took place. Changes in testing temperature between -2 and -8°C and in normal pressure between 0.88 and 2.2 kn/m^2 (0.13 - 0.32 psi) also create no change in the hull-ice friction factor.

5.2 Recommendations

1. An economic analysis should be made using these results to identify what the magnitude of coated area would be that is justified by the cost benefit occurring from reduction in wear and powering required. It was the major objective of this test program to develop such data. It therefore is important that this follow-on work be done in order not to lose the benefits of this program and also to quantify in real economic terms what benefits can be accrued from partially coating icebreaker hulls.

2. Since cream car wax accurately indicated both high wear areas and the greatest part of frictional resistance, more model tests should be done using this medium. The first set of tests which should logically be accomplished following this program would be tests of the POLAR STAR hull form in a range of ice conditions. Tests should include maximum continuous ice thickness and her maximum ramming ice thickness. Then tests in other conditions such as heavy brash, very thick floes having less than 100% coverage, ice ridges of both the first year and consolidated types should follow. It may also be instructive to test the coating at different velocities other than the 5 knots chosen for this program.

3. Different hull forms should be tested using the cream car wax coating. This would indicate the variation in the areas which contribute most to ice resistance and aid in formulating a hull form with a more efficient shape. It appears that this particular tool would be of great benefit to use in testing a new Arctic east design and perhaps in evaluating the difference between the White bow form used on the POLAR STAR and the straight stem used on European designs.

4. Changes in the hull design to reduce the total resistance should concentrate on those areas which contribute the most to icebreaking resistance. These were areas designated as A-1 and A-3 in this program and are the areas immediately adjacent to the stem and at the shoulder of the bow.

5. When the next opportunity arises it appears that full-scale tests of partial hull coating with low friction surfaces should be attempted. As this test program was conducted on the POLAR STAR hull form it appears that 10% coating on the POLAR STAR might be well worthwhile. When the POLAR SEA becomes available the utility of the 10% coating could therefore be tested with side-by-side tests of the two ships.

6. The effect of velocity upon hull-ice friction appears to be something which needs more work. The first and most important gap to be filled is tests at maximum speed used during the POLAR STAR test program. It is believed that with some additional preparations, the test planks used during this program could be rigged up in a back-to-back arrangement such that the acceleration of the carriage did not take a great part of the test surface. In this way, tests could be conducted as high as 15 knots model speed and perhaps beyond.

7. Work should continue on developing hull preparations which create a hull-ice friction factor in the range of .2 to .4. It appears that sanded polyurethane will not develop friction factors in this range. Paste on surfaces or perhaps use of different grits to pot mark or coat the surface similar to the method used for high roughness during this program should be examined. Finely powdered glass or fine sand appear to be good candidates.

6. REFERENCES

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APPENDIX B-I

RESISTANCE DATA

TABLE B-I-1 MODEL DATA

Date	Series	Ice Sheet	Resistance (N)	Ice Thickness (mm)	Model Speed (mm/s)	Ice Strength kPa	Elastic Modulus kPa	% Smooth	Friction On Smooth Part	Friction On Rough Part	
10/11/76	1	1	26.9	27.8	362.0	7.16	2750	--	--	--	NOTE: Wax at Start
10/11/76	1	1	19.9	29.0	341.0	7.16	2750	--	--	--	NOTE: Wax Worn Off
10/11/76	1	1	15.2	27.5	362.0	7.16	2750	--	--	--	NOTE: Calamine
10/13/76	2	1	9.6	25.0	85.3	6.07	2170	11.9	0.036	0.44	
10/13/76	2	1	15.1	26.1	175.0	7.44	2170	11.9	0.036	0.44	
10/13/76	2	1	15.7	26.2	309.0	8.81	2170	11.9	0.036	0.44	
10/13/76	2	1	15.4	24.7	438.0	8.59	2170	11.9	0.036	0.44	
10/13/76	2	1	21.7	25.9	559.0	8.36	2170	11.9	0.036	0.44	
10/13/76	2	1	7.2	25.8	85.3	6.07	2170	60.5	0.036	0.44	
10/13/76	2	1	10.2	26.6	175.0	7.44	2170	60.5	0.036	0.44	
10/13/76	2	1	11.6	26.1	309.0	8.81	2170	60.5	0.036	0.44	
10/13/76	2	1	13.4	25.0	438.0	8.59	2170	60.5	0.036	0.44	
10/13/76	2	1	17.2	26.0	559.0	8.36	2170	60.5	0.036	0.44	
10/14/76	2	2	14.4	24.8	88.0	5.3	1890	8.9	0.036	0.44	
10/14/76	2	2	18.8	25.9	175.0	6.2	1890	8.9	0.036	0.44	
10/14/76	2	2	19.5	25.0	306.0	7.1	1890	8.9	0.036	0.44	
10/14/76	2	2	23.1	25.2	439.0	8.0	1890	8.9	0.036	0.44	
10/14/76	2	2	29.5	25.7	564.0	8.8	1890	8.9	0.036	0.44	
10/14/76	2	2	7.2	25.0	88.0	5.3	1890	38.3	0.036	0.44	
10/14/76	2	2	9.8	26.0	175.0	6.2	1890	38.3	0.036	0.44	
10/14/76	2	2	11.2	25.2	306.0	7.1	1890	38.3	0.036	0.44	
10/14/76	2	2	14.0	25.4	439.0	8.0	1890	38.3	0.036	0.44	
10/14/76	2	2	16.5	25.8	564.0	8.8	1890	38.3	0.036	0.44	
10/15/76	2	3	11.4	23.2	89.6	6.56	1535	5.4	0.036	0.44	
10/15/76	2	3	15.1	23.5	175.0	6.56	1535	5.4	0.036	0.44	
10/15/76	2	3	19.3	22.9	308.0	6.56	1535	5.4	0.036	0.44	
10/15/76	2	3	23.3	23.6	442.0	6.56	1535	5.4	0.036	0.44	
10/15/76	2	3	28.4	24.1	569.0	6.56	1535	5.4	0.036	0.44	

TABLE B-I-1 MODEL DATA (continued)

Date	Series	Ice Sheet	Resistance (N)	Ice Thickness (mm)	Model Speed (mm/s)	Ice Strength kPa	Elastic Modulus kPa	% Smooth	Friction On Smooth Part	Friction On Rough Part
10/15/76	2	3	7.6	23.6	89.6	6.56	1535	19.1	0.036	0.44
10/15/76	2	3	9.4	24.1	175.0	6.56	1535	19.1	0.036	0.44
10/15/76	2	3	11.0	23.5	308.0	6.56	1535	19.1	0.036	0.44
10/15/76	2	3	15.0	23.7	442.0	6.56	1535	19.1	0.036	0.44
10/15/76	2	3	20.0	25.4	569.0	6.56	1535	19.1	0.036	0.44
10/19/76	3	1	6.0	22.1	94.5	5.86	1196.6	10.0	0.036	0.44
10/19/76	3	1	10.4	24.2	179.0	6.70	1391.5	10.0	0.036	0.44
10/19/76	3	1	13.1	25.9	323.0	7.53	1586.4	10.0	0.036	0.44
10/19/76	3	1	11.0	22.8	448.0	8.11	1357.6	10.0	0.036	0.44
10/19/76	3	1	13.1	24.3	573.0	8.68	1128.8	10.0	0.036	0.44
10/19/76	3	1	6.0	22.5	94.5	5.86	1196.6	20.0	0.036	0.44
10/19/76	3	1	10.3	24.5	179.0	6.70	1391.5	20.0	0.036	0.44
10/19/76	3	1	11.2	25.5	323.0	7.53	1586.4	20.0	0.036	0.44
10/19/76	3	1	12.6	23.6	448.0	8.11	1357.6	20.0	0.036	0.44
10/19/76	3	1	15.6	25.2	573.0	8.68	1128.8	20.0	0.036	0.44
10/20/76	3	2	27.2	38.6	83.4	8.06	5771.3	10.0	0.036	0.44
10/20/76	3	2	48.9	39.3	171.0	8.06	5091.1	10.0	0.036	0.44
10/20/76	3	2	53.8	39.1	305.0	8.06	4410.9	10.0	0.036	0.44
10/20/76	3	2	43.2	36.0	431.0	8.06	4699.2	10.0	0.036	0.44
10/20/76	3	2	58.6	37.5	554.0	8.06	4987.2	10.0	0.036	0.44
10/20/76	3	2	26.4	38.8	83.4	8.06	5771.3	20.0	0.036	0.44
10/20/76	3	2	33.3	38.8	171.0	8.06	5091.1	20.0	0.036	0.44
10/20/76	3	2	37.6	38.4	305.0	8.06	4410.9	20.0	0.036	0.44
10/20/76	3	2	32.8	36.5	431.0	8.06	4699.2	20.0	0.036	0.44
10/20/76	3	2	39.7	38.7	554.0	8.06	4987.2	20.0	0.036	0.44

TABLE B-I-2 SCALED UP DATA

Date	Series	Ice Sheet	Resistance (MN)	Ice Thickness (m)	Ship Speed (km/h)	Ice Strength kPa	Elastic Modulus kPa	% Smooth	Friction on Smooth Part	Friction On Rough Part	
10/11/76	1	1	2.97	1.33	9.03	343.68	132000	--	--	--	NOTE: Wax at Start
10/11/76	1	1	2.20	1.39	8.51	343.68	132000	--	--	--	NOTE: Wax Worn Off
10/11/76	1	1	1.68	1.32	9.03	343.68	132000	--	--	--	NOTE: Calamine
10/13/76	2	1	1.06	1.20	2.13	291.36	104160	11.9	0.036	0.44	
10/13/76	2	1	1.67	1.25	4.36	357.12	104160	11.9	0.036	0.44	
10/13/76	2	1	1.74	1.26	7.71	422.88	104160	11.9	0.036	0.44	
10/13/76	2	1	1.70	1.19	10.92	412.32	104160	11.9	0.036	0.44	
10/13/76	2	1	2.40	1.24	13.94	401.28	104160	11.9	0.036	0.44	
10/13/76	2	1	.80	1.24	2.13	291.36	104160	60.5	0.036	0.44	
10/13/76	2	1	1.13	1.28	4.36	357.12	104160	60.5	0.036	0.44	
10/13/76	2	1	1.28	1.26	7.71	422.88	104160	60.5	0.036	0.44	
10/13/76	2	1	1.48	1.20	10.92	412.32	104160	60.5	0.036	0.44	
10/13/76	2	1	1.90	1.25	13.94	401.28	104160	60.5	0.036	0.44	
10/14/76	2	2	1.59	1.19	2.19	254.4	90720	8.9	0.036	0.44	
10/14/76	2	2	2.08	1.24	4.36	297.6	90720	8.9	0.036	0.44	
10/14/76	2	2	2.16	1.20	7.63	340.8	90720	8.9	0.036	0.44	
10/14/76	2	2	2.55	1.21	10.95	384.0	90720	8.9	0.036	0.44	
10/14/76	2	2	3.26	1.23	14.07	422.4	90720	8.9	0.036	0.44	
10/14/76	2	2	.80	1.20	2.19	254.4	90720	38.3	0.036	0.44	
10/14/76	2	2	1.08	1.25	4.36	297.6	90720	38.3	0.036	0.44	
10/14/76	2	2	1.24	1.21	7.63	340.8	90720	38.3	0.036	0.44	
10/14/76	2	2	1.55	1.22	10.95	384.0	90720	38.3	0.036	0.44	
10/14/76	2	2	1.82	1.24	14.07	422.4	90720	38.3	0.036	0.44	
10/15/76	2	3	1.26	1.11	2.23	314.88	73680	5.4	0.036	0.44	
10/15/76	2	3	1.67	1.13	4.36	314.88	73680	5.4	0.036	0.44	
10/15/76	2	3	2.13	1.10	7.68	314.88	73680	5.4	0.036	0.44	
10/15/76	2	3	2.58	1.13	11.02	314.88	73680	5.4	0.036	0.44	
10/15/76	2	3	3.14	1.16	14.19	314.88	73680	5.4	0.036	0.44	

TABLE B-I-2 SCALED UP DATA (Continued)

Date	Series	Ice Sheet	Resistance (MN)	Ice Thickness (m)	Ship Speed (km/h)	Ice Strength kPa	Elastic Modulus kPa	% Smooth	Friction On Smooth Part	Friction On Rough Part
10/15/76	2	3	.84	1.13	2.23	314.88	73680	19.1	0.036	0.44
10/15/76	2	3	1.04	1.16	4.36	314.88	73680	19.1	0.036	0.44
10/15/76	2	3	1.22	1.13	7.68	314.88	73680	19.1	0.036	0.44
10/15/76	2	3	1.66	1.14	11.02	314.88	73680	19.1	0.036	0.44
10/15/76	2	3	2.21	1.22	14.19	314.88	73680	19.1	0.036	0.44
10/19/76	3	1	.66	1.06	2.36	281.28	57436.8	10.0	0.036	0.44
10/19/76	3	1	1.15	1.16	4.46	321.6	66792.0	10.0	0.036	0.44
10/19/76	3	1	1.45	1.24	8.06	361.44	76147.2	10.0	0.036	0.44
10/19/76	3	1	1.22	1.09	11.17	389.28	65164.8	10.0	0.036	0.44
10/19/76	3	1	1.45	1.17	14.29	416.64	54182.4	10.0	0.036	0.44
10/19/76	3	1	.66	1.08	2.36	281.28	57436.8	20.0	0.036	0.44
10/19/76	3	1	1.14	1.18	4.46	321.6	66792.0	20.0	0.036	0.44
10/19/76	3	1	1.24	1.22	8.06	361.44	76147.2	20.0	0.036	0.44
10/19/76	3	1	1.39	1.13	11.17	389.28	65164.8	20.0	0.036	0.44
10/19/76	3	1	1.73	1.21	14.29	416.64	54182.4	20.0	0.036	0.44
10/20/76	3	2	3.01	1.85	2.08	386.88	277022.4	10.0	0.036	0.44
10/20/76	3	2	5.41	1.89	4.27	386.88	244372.8	10.0	0.036	0.44
10/20/76	3	2	5.95	1.88	7.61	386.88	211723.2	10.0	0.036	0.44
10/20/76	3	2	4.78	1.73	10.75	386.88	225561.6	10.0	0.036	0.44
10/20/76	3	2	6.48	1.80	13.82	386.88	239385.6	10.0	0.036	0.44
10/20/76	3	2	2.92	1.86	2.08	386.88	277022.4	20.0	0.036	0.44
10/20/76	3	2	3.68	1.86	4.27	386.88	244372.8	20.0	0.036	0.44
10/20/76	3	2	4.16	1.84	7.61	386.88	211723.2	20.0	0.036	0.44
10/20/76	3	2	3.63	1.75	10.75	386.88	225561.6	20.0	0.036	0.44
10/20/76	3	2	4.39	1.88	13.82	386.88	239385.6	20.0	0.036	0.44

TABLE B-I-3 DIMENSIONLESS DATA

Date	Series	Ice Sheet	Resistance Number $\frac{R}{\rho_w g B h^2}$	Thickness Froude No. $\frac{v}{\sqrt{gh}}$	Strength Number $\frac{\sigma_f}{\rho_w g h}$	Modulus Strength Ratio E/σ_f	% Smooth	Smooth Friction	Rough Friction	
10/11/76	1	1	6.91	0.693	25.6	384	--	--	--	NOTE: Wax at Start
10/11/76	1	1	4.70	0.640	24.6	384	--	--	--	NOTE: Wax Worn Off
10/11/76	1	1	3.99	0.697	25.9	384	--	--	--	NOTE: Calamine
10/13/76	2	1	3.05	0.172	24.2	357	11.9	0.036	0.44	
10/13/76	2	1	4.40	0.346	28.4	292	11.9	0.036	0.44	
10/13/76	2	1	4.54	0.610	33.5	246	11.9	0.036	0.44	
10/13/76	2	1	5.01	0.890	34.6	253	11.9	0.036	0.44	
10/13/76	2	1	6.42	1.11	32.1	259	11.9	0.036	0.44	
10/13/76	2	1	2.15	0.170	23.4	357	60.5	0.036	0.44	
10/13/76	2	1	2.86	0.343	27.8	292	60.5	0.036	0.44	
10/13/76	2	1	3.38	0.611	33.6	246	60.5	0.036	0.44	
10/13/76	2	1	4.25	0.885	34.2	253	60.5	0.036	0.44	
10/13/76	2	1	5.05	1.11	32.0	259	60.5	0.036	0.44	
10/14/76	2	2	4.65	0.179	21.3	356	8.9	0.036	0.44	
10/14/76	2	2	5.56	0.347	23.8	305	8.9	0.036	0.44	
10/14/76	2	2	6.19	0.618	28.3	266	8.9	0.036	0.44	
10/14/76	2	2	7.22	0.883	31.6	236	8.9	0.036	0.44	
10/14/76	2	2	8.86	1.12	34.1	215	8.9	0.036	0.44	
10/14/76	2	2	2.29	0.178	21.1	356	38.3	0.036	0.44	
10/14/76	2	2	2.88	0.347	23.7	305	38.3	0.036	0.44	
10/14/76	2	2	3.50	0.616	28.0	266	38.3	0.036	0.44	
10/14/76	2	2	4.31	0.880	31.4	236	38.3	0.036	0.44	
10/14/76	2	2	4.92	1.12	34.0	215	38.3	0.036	0.44	
10/15/76	2	3	4.20	0.188	28.1	234	5.4	0.036	0.44	
10/15/76	2	3	5.43	0.345	27.8	234	5.4	0.036	0.44	
10/15/76	2	3	7.30	0.650	28.5	234	5.4	0.036	0.44	

TABLE B-I-3 DIMENSIONLESS DATA (Continued)

Date	Series	Ice Sheet	Resistance Number $\frac{R}{\rho_w g B h^2}$	Thickness Froude No. $\frac{v}{\sqrt{gh}}$	Strength Number $\frac{\sigma_f}{\rho_w g h}$	Modulus Strength Ratio E/σ_f	% Smooth	Smooth Friction	Rough Friction
10/15/76	2	3	8.30	0.919	27.7	234	5.4	0.036	0.44
10/15/76	2	3	9.70	1.17	27.1	234	5.4	0.036	0.44
10/15/76	2	3	2.71	0.186	27.7	234	19.1	0.036	0.44
10/15/76	2	3	3.21	0.360	27.1	234	19.1	0.036	0.44
10/15/76	2	3	3.95	0.642	27.8	234	19.1	0.036	0.44
10/15/76	2	3	5.30	0.917	27.6	234	19.1	0.036	0.44
10/15/76	2	3	6.15	1.14	25.7	234	19.1	0.036	0.44
10/19/76	3	1	2.44	0.203	26.4	204.2	10.0	0.036	0.44
10/19/76	3	1	3.52	0.368	27.6	207.7	10.0	0.036	0.44
10/19/76	3	1	3.90	0.642	29.1	210.7	10.0	0.036	0.44
10/19/76	3	1	4.20	0.948	35.4	167.3	10.0	0.036	0.44
10/19/76	3	1	4.51	1.174	35.6	130.0	10.0	0.036	0.44
10/19/76	3	1	2.35	0.201	25.9	204.2	20.0	0.036	0.44
10/19/76	3	1	3.40	0.365	27.2	207.7	20.0	0.036	0.44
10/19/76	3	1	3.42	0.646	29.4	210.7	20.0	0.036	0.44
10/19/76	3	1	4.48	0.932	34.2	167.3	20.0	0.036	0.44
10/19/76	3	1	4.87	1.153	34.3	130.0	20.0	0.036	0.44
10/20/76	3	2	3.62	0.136	20.8	716.0	10.0	0.036	0.44
10/20/76	3	2	6.28	0.275	20.4	631.6	10.0	0.036	0.44
10/20/76	3	2	6.98	0.493	20.5	547.3	10.0	0.036	0.44
10/20/76	3	2	6.61	0.726	22.3	583.0	10.0	0.036	0.44
10/20/76	3	2	8.27	0.914	21.4	618.8	10.0	0.036	0.44
10/20/76	3	2	3.48	0.135	20.7	716.0	20.0	0.036	0.44
10/20/76	3	2	4.39	0.277	20.7	631.6	20.0	0.036	0.44
10/20/76	3	2	5.06	0.497	20.9	547.3	20.0	0.036	0.44
10/20/76	3	2	4.89	0.721	22.0	583.0	20.0	0.036	0.44
10/20/76	3	2	5.26	0.900	20.7	618.8	20.0	0.036	0.44

APPENDIX B-II

FRICTION DATA

TEST PROCEDURE

COEFFICIENTS OF KINETIC FRICTION AND SURFACE ROUGHNESS

Coefficient of Kinetic Friction

It has been recognized for some time that the friction between the hull of an icebreaker and ice contributes very significantly to the total resistance of the ship. The magnitude of the effect of friction on resistance has been noted in recent model tests.

Friction is the force along the hull related to the force normal to the hull by the following expression:

$$F = f \cdot N \qquad \text{(B-II-1)}$$

where

F = friction force

f = coefficient of friction (friction factor)

N = normal force.

The friction factor was determined by towing a sample of ice from the basin over the surface of the model with the top surface of the ice against the hull. A calibrated load cell was used to measure the friction force. The normal force was varied by adding weights.

The coefficient of friction tests were also conducted on planks with surfaces prepared in a manner similar to that of the model. A total of six prepared surfaces were tested. The models and the planks were first coated with Sapolin #174 High Gloss clear polyurethane, and the surfaces were roughened following the procedures listed in Table B-5.

The coefficient of friction data is presented in Tables B-II-1 through B-II-3. The average value for each test area was used for interpretation of the ice-breaking resistance data.

Surface Roughness

The roughness of the model surface was also measured using a Rank Taylor Hobson 'Talysurf' 4 System available at the University of Maryland. The procedure is to soften the surface of a strip of pure acetate with acetone and press it onto the surface of the model. When the acetone dries, the acetate hardens, leaving an impression of the model surface. Impressions were taken in three locations on each surface finish of the models.

The roughness of the hardened acetate strips is measured using the 'Talysurf' 4. The tape is positioned under a sharply-pointed stylus and a curved shoe. A gear-driven arm holding the stylus and shoe is moved horizontally across the surface. As the stylus traces the surface irregularities, an inductive-type transducer measures the vertical movements of the stylus referenced to the shoe. The signal is recorded on a panel meter as a value in micro-inches of the centerline average (CLA) of the surface irregularities. The CLA is defined as the average value of departures, both above and below its centerline, over a prescribed sampling length. Conversion to micrometers is accomplished by multiplying the reading in micro-inches by 0.0254.

Although this technique does not directly measure the coefficient of friction, it provides a means of comparing the roughness of one surface preparation to another. The surface roughness measurements were taken on a regular basis. The data are recorded on Tables B-II-4 and B-II-5.

A correlation between surface roughness and friction factor can be detected in Figure B-16. This indicates that roughness measurements will be useful in preparing model surfaces to achieve a specified friction factor. Additional data, however, will be needed.

Figure B-II-1 shows three surface profiles. The upper two have different roughness and nearly the same friction factor. The lower two have the same roughness but different friction factor.

APPENDIX B-II

FRICTION DATA

TEST PROCEDURE

COEFFICIENTS OF KINETIC FRICTION AND SURFACE ROUGHNESS

Coefficient of Kinetic Friction

It has been recognized for some time that the friction between the hull of an icebreaker and ice contributes very significantly to the total resistance of the ship. The magnitude of the effect of friction on resistance has been noted in recent model tests.

Friction is the force along the hull related to the force normal to the hull by the following expression:

$$F = f \cdot N \qquad \text{(B-II-1)}$$

where

F = friction force

f = coefficient of friction (friction factor)

N = normal force.

The friction factor was determined by towing a sample of ice from the basin over the surface of the model with the top surface of the ice against the hull. A calibrated load cell was used to measure the friction force. The normal force was varied by adding weights.

The coefficient of friction tests were also conducted on planks with surfaces prepared in a manner similar to that of the model. A total of six prepared surfaces were tested. The models and the planks were first coated with Sapolin #174 High Gloss clear polyurethane, and the surfaces were roughened following the procedures listed in Table B-5.

The coefficient of friction data is presented in Tables B-II-1 through B-II-3. The average value for each test area was used for interpretation of the ice-breaking resistance data.

Surface Roughness

The roughness of the model surface was also measured using a Rank Taylor Hobson 'Talysurf' 4 System available at the University of Maryland. The procedure is to soften the surface of a strip of pure acetate with acetone and press it onto

TABLE B-II-1 FRICTION ON PLANKS - LOW SPEED

		Before 10/11	Before 10/11	After 10/11	After 10/13	10/15	Before 10/19	Before 10/20	After 10/20	Avg.	Humidity	Velocity	Pressure	Air Temp.
Plank #1		.12	.17	.13	.14	.13	.18	.14	.11	.14	100%	3.59 mm/s	0.88-2.2 kN/m^2	-8 to 2°C
		.11	.17	.11	.13	.12	.16	.13	.10	.13				
		.12	.15	.14	.14	.14	.17	.14	.11	.14				
			.17							.17				
	Avg.	.12	.17	.13	.14	.13	.17	.14	.10	.14				
Plank #2		.16		.16	.16	.14	.15	.13	.13	.15				
		.15		.16	.15	.13	.14	.13	.13	.14				
		.17		.17	.16	.15	.16	.14	.15	.16				
	Avg.	.16		.16	.15	.14	.15	.13	.14	.15				
Plank #3		.04		.02	.08	.07	.05	.07	.06	.06				
		.03		.02	.05	.06	.04	.06	.04	.04				
		.03		.03	.05	.06	.04	.06	.04	.04				
	Avg.	.04		.02	.06	.06	.04	.06	.05	.05				
Plank #4		.53		.58	.51	.49	.48	.42	.37	.48				
		.51		.53	.58	.50	.48	.42	.39	.49				
		.58		.61	.57	.61	.53	.46	.45	.54				
	Avg.	.54		.57	.55	.53	.49	.43	.40	.50				
Plank #6		.21		.19	.18	.19	.17	.17	.16	.19				
		.20		.18	.15	.18	.18	.15	.16	.17				
		.22		.21	.17	.20	.20	.17	.18	.19				
	Avg.	.21		.19	.17	.19	.18	.16	.17	.18				

TABLE B-II-2 FRICTION ON MODELS - LOW SPEED

		10/15	10/19	Before 10/20	After 10/20	Avg.	Humidity	Velocity	Pressure	Air Temp.
Model #1 Smooth		.09	.20		.08	.12	100%	3.59 mm/s	0.88-2.2 kN/m^2	-8 to 2°C
		.08	.18		.07	.11				
		.08	.19		.08	.12				
		.09	.23		.08	.13				
		.08	.19		.08	.12				
		.08	.20		.08	.12				
	Avg.	.08	.20		.08	.12*				
Model #1 Rough		.53	.54		.39	.49				
		.42	.43		.38	.41				
		.46	.45		.42	.44				
		.52	.48		.43	.48				
		.40	.45		.38	.41				
		.46	.51		.44	.47				
	Avg.	.47	.48		.41	.45				
Model #2 Smooth		.05	.06	.04	.02	.04				
		.03	.04	.03	.02	.03				
		.03	.04	.03	.03	.03				
		.03	.08	.03	.03	.04				
		.03	.05	.03	.02	.03				
		.03	.05	.03	.03	.04				
	Avg.	.03	.05	.03	.03	.04				
Model #2 Smooth		.34	.46	.49	.43	.43	100%	3.59 mm/s	0.88-2.2 kN/m^2	-8 to 2°C
		.33	.44	.46	.41	.41				
		.43	.43	.49	.49	.46				
		.40	.51	.49	.38	.45				
		.42	.42	.43	.37	.41				
		.49	.45	.47	.44	.46				
	Avg.	.40	.45	.47	.42	.44				

* This value not used in analysis as it is much higher than other tests. Location was above WL while roughness tapes at test surface were the same as Model #2.

TABLE B-II-3 FRICTION ON PLANKS - ICE EDGE, SUBMERGED AND HIGH SPEED

		Before 10/11	After 10/11	Average	After 10/13	10/14
Plank #1						
Edge of Ice		.11	.15	.13		
		.11	.14	.13		
		.13	.15	.14		
	Average	.12	.15	.14		
Submerged Top					.21	
					.16	
					.18	
					.16	
					.14	
					.16	
	Average				.17	
4 Kts. Scaled						.29
						.28
						.23
	Average					.27
8 Kts. Scaled						.42
						.20
						.19
	Average					.27
Plank #2						
Edge of Ice		.17	.16	.17		
		.16	.15	.16		
		.17	.16	.17		
	Average	.17	.16	.17		
Submerged Top					.17	
					.15	
					.17	
					.17	
					.15	
					.17	
	Average				.16	

TABLE B-II-3 FRICTION ON PLANKS - ICE EDGE, SUBMERGED AND HIGH SPEED (Continued)

		Before 10/11	After 10/11	Average	After 10/13	10/14
4 Kts. Scaled						.31
						.27
						.28
	Average					.29
8 Kts. Scaled						.41
						.38
						.29
	Average					.36
Plank #3						
Edge of Ice		.06	.06	.06		
		.04	.06	.05		
		.05	.05	.05		
	Average	.05	.06	.06		
Submerged Top					.06	
					.03	
					.03	
					.05	
					.04	
					.04	
	Average				.04	
4 Kts. Scaled						.09
						.09
						.09
	Average					.09
8 Kts. Scaled						.15
						.18
						.15
	Average					.16

TABLE B-II-3 FRICTION ON PLANKS - ICE EDGE, SUBMERGED AND HIGH SPEED (Continued)

		Before 10/11	After 10/11	Average	After 10/13	10/14
Plank #4						
Edge of Ice		.49	.42	.46		
		.43	.41	.42		
		.51	.48	.50		
	Average	.48	.44	.46		
Submerged Top					.50	
					.45	
					.54	
					.38	
					.43	
					.52	
	Average				.47	
4 Kts. Scaled						.71
						.55
	Average					.63
8 Kts. Scaled						.67
						.61
						.55
	Average					.61

TABLE B-II-3 FRICTION ON PLANKS - ICE EDGE, SUBMERGED AND HIGH SPEED (Continued)

		Before 10/11	After 10/11	Average	After 10/13	10/14
Plank #6						
Edge of Ice		.21	.20	.21		
		.19	.19	.19		
		.21	.22	.22		
	Average	.20	.20	.20		
Submerged					.24	
					.21	
					.23	
					.23	
					.20	
					.22	
	Average				.22	
4 Kts. Scaled						.24
						.24
						.27
	Average					.25
8 Kts. Scaled						.32
						.33
						.31
	Average					.32

TABLE B-II-4 ROUGHNESS ON PLANKS

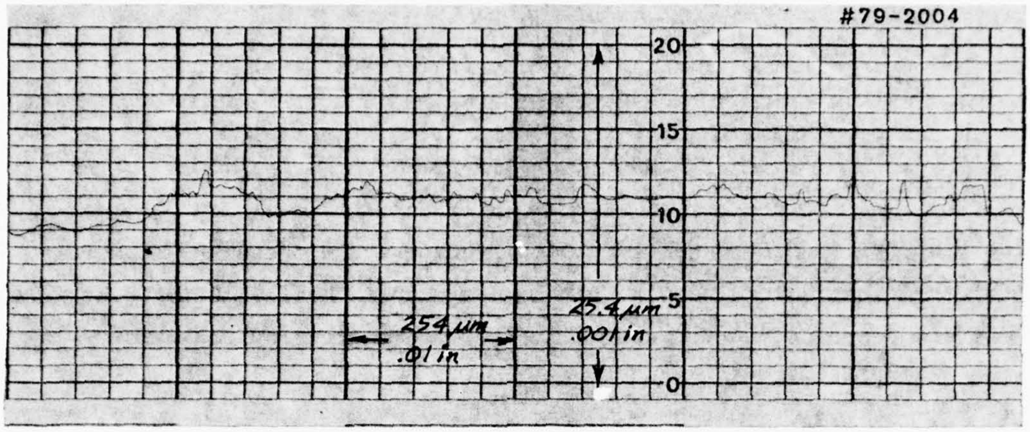
		10/18			Avg.	10/21			Avg.	Grand Avg.
Plank #1	A	.71	.56	.71	.66	.51	.48	.56	.52	
	B	.53	.51	.53	.52	.56	.43	.69	.56	
	C	.51	.48	.46	.48	.51	.46	.48	.48	
	Avg.	.58	.52	.57	.56	.53	.46	.58	.52	.54
Plank #2	A	1.12	.91	1.35	1.13	1.09	1.14	1.14	1.12	
	B	1.12	1.19	1.19	1.17	1.17	1.40	1.07	1.21	
	C	1.12	1.27	1.27	1.22	1.30	1.24	1.24	1.26	
	Avg.	1.12	1.12	1.27	1.17	1.19	1.26	1.15	1.20	1.19
Plank #3	A	.31	.15	.15	.20	.33	.28	.15	.25	
	B	.18	.31	.20	.23	.30	.15	.30	.25	
	C	.25	.28	.23	.25	.33	.30	.28	.30	
	Avg.	.25	.25	.19	.23	.32	.24	.24	.27	.25
Plank #4	A	6.81	6.40	7.11	6.77	6.99	6.91	5.94	6.61	
	B	9.45			9.45	6.15	5.18	5.08	5.47	
	C	5.56	6.81	6.60	6.32	4.57	6.73	6.48	5.93	
	Avg.	7.27	6.61	6.86	6.91	5.90	6.27	5.83	6.00	6.46
Plank #5	A	2.01	2.24	2.01	2.09					
	B	2.06	1.83	1.98	1.96					
	C	2.44	2.21	2.49	2.38					
	Avg.	2.17	2.09	2.16	2.14					2.15
Plank #6	A					2.29	2.36	1.88	2.18	
	B					1.73	1.98	1.98	1.90	
	C					2.34	2.34	2.57	2.42	
	Avg.					2.12	2.23	2.14	2.16	2.15

(All values are in micrometers)

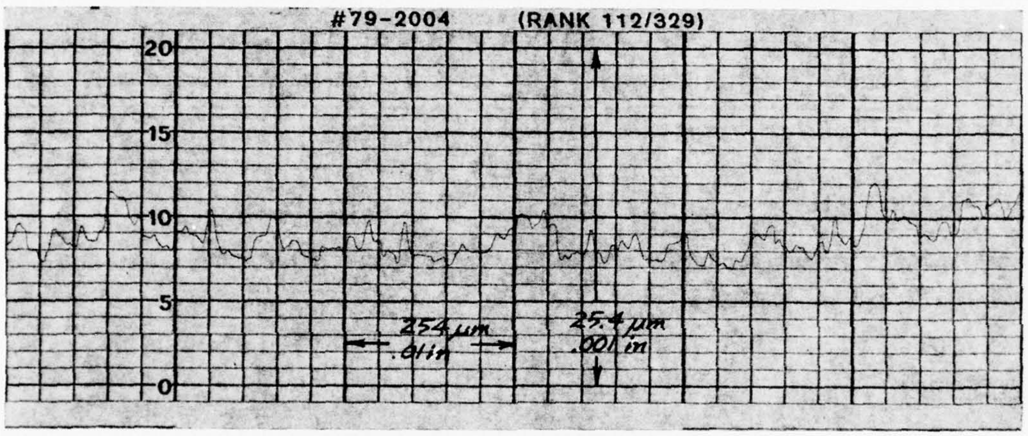
TABLE B-II-5 ROUGHNESS ON MODELS

		10/12				10/15				10/21				
					Avg.				Avg.				Avg.	Grand Avg.
Model #1	Smooth	.28	.36	.28	.31	.20	.31	.25	.25	.31	.41	.33	.35	
		.25	.23	.31	.26	.28	.31	.18	.26	-	-	-	-	
		.31	.31	.36	.33	.31	.36	.28	.32	.36	.31	.33	.33	
	Avg.	.28	.30	.32	.30	.26	.33	.24	.28	.34	.36	.33	.34	.31
Model #1	Rough	7.06	5.28	6.22	6.19	5.54	7.87	4.06	5.82	5.39	4.12	4.95	4.82	
		4.62	7.16	6.20	5.99	5.74	5.13	4.52	5.13	4.88	6.55	4.52	5.32	
		2.79	4.62	5.28	4.23	3.35	3.76	3.12	3.41	4.62	5.79	6.02	5.48	
	Avg.	4.82	5.69	5.90	5.47	4.88	5.59	3.90	4.79	4.96	5.49	5.16	5.20	5.15
Model #2	Smooth	.20	.41	.18	.26	.31	.20	.33	.28	-	-	-	-	
		.36	.28	.25	.30	.43	.31	.23	.32	.20	.25	.36	.27	
		.23	.33	.25	.27	.31	.25	.38	.31	.36	.33	.41	.37	
	Avg.	.26	.34	.23	.28	.35	.25	.31	.30	.28	.29	.39	.32	.30
Model #2	Rough	4.57	8.43	5.28	6.09	3.73	8.36	8.33	6.81	7.34	8.59	5.28	7.07	
		5.08	4.98	4.57	4.88	4.57	3.25	4.27	4.03	4.65	4.95	4.88	4.83	
		3.02	4.60	3.71	3.78	5.13	4.75	3.40	4.43	5.79	4.12	3.81	4.57	
	Avg.	4.22	6.00	4.52	4.91	4.48	5.45	5.33	5.09	5.92	5.89	4.66	5.49	5.16

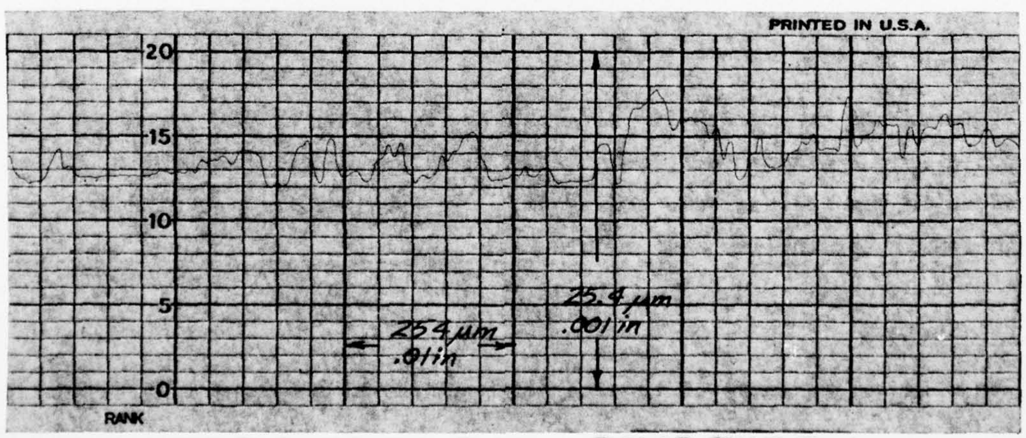
(All values are in micrometers)



Crocus Cloth - Heavy Sanding - Coverage Tests
Roughness 0.55 μm. Friction Factor 0.140



400 Grit - Heavy Sanding - Coverage Tests
Roughness 1.2 μm. Friction Factor 0.150



400 Grit - Medium Sanding - POLAR STAR Tests
Roughness 1.1 μm. Friction Factor 0.125

Figure B-II-1 Plank Surface Profiles

APPENDIX B-III

MODEL ICE PROPERTIES

Ice properties of thickness, salinity, temperature, density, flexural strength, and elastic modulus were taken on a regular basis. Brief descriptions of the techniques employed to make the measurements are provided below. The data is listed in Table B-III-1.

Ice Thickness

Following each test run, the ice thickness was measured at every meter along both sides of the two broken channels. These measurements were averaged for each data point in Appendix B-I. These ice thickness measurements were taken with calipers.

Ice and Water Salinity

Measurements of ice and water salinity were taken before the test run with a Beckman-Solu Bridge Salinometer.

Ice Temperature

Measurements of temperature were made in three locations prior to each test run. The readings were taken by rolling a mercury-glass thermometer on the ice surface.

Ice Density

Measurements of ice density were made periodically. Water from the basin was poured into a graduated cylinder and its volume and mass measured. Ice was then added to the cylinder and submerged. The total volume and mass were measured, and the density of the ice was calculated.

Flexural Strength

The flexural strength of the ice was measured by breaking in situ cantilevers. Relatively short cantilever beams were cut in the ice sheet with dimensions dependent upon the characteristic length ℓ_c. These beams were then loaded at their free end until failure occurred. The failure load was sensed by a load cell with its output recorded on an oscillograph. After the cantilevers were broken, their length, width and thickness were recorded. The flexural strength was then determined from the following equation:

$$\sigma_f = \frac{6P_f L}{bh^2} \qquad \text{(B-III-1)}$$

where

P_f = failure load

L = length of the cantilever

b = width of the cantilever

h = thickness of the cantilever.

The measurement sequence described above was repeated in three locations prior to the tests and three locations immediately following the tests. These measurements were then used to construct a profile of the flexural strength of the particular ice sheet.

Elastic Modulus

The elastic modulus was determined by applying a load that depressed the center of the ice sheet at a constant rate. The magnitude of the load was sensed by a load cell with its output recorded on an oscillograph. The deflection of the ice sheet at a distance away from the load was recorded simultaneously on the oscillograph. The characteristic length ℓ_c was evaluated using the expression:

$$w(r) = \frac{-P_o}{2\pi\rho_w g \ell_c^2} \, \mathrm{kei}\left(\frac{r}{\ell_c}\right) \qquad \text{(B-III-2)}$$

where

ℓ_c = characteristic length of the ice sheet

P_o = magnitude of the concentrated load

ρ_w = density of the water

g = acceleration due to gravity

r = distance from the load to the point where deflection w is measured

$w(r)$ = deflection of the ice sheet at a distance r away from the load

kei = modified Bessel function.

The elastic modulus E can then be calculated from the following relationship:

$$\ell_c = \left[\frac{Eh^3}{12\ \rho_w g(1 - \nu^2)}\right]^{1/4} \qquad \text{(B-III-3)}$$

where

E = elastic modulus

h = ice thickness

ν = Poisson's ratio.

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TABLE B-III-1 MODEL ICE PROPERTIES

Date	Ice Thickness (mm)	Ice Salinity PPT	Water Salinity PPT	Ice Temperature °C	Flexural Strength kPa	Elastic Modulus kPa
10/11	28.1	5.5	7.6	- 1.2	7.16	2750
10/13	25.7	5.4	8.2	- 0.9	7.85	2170
10/14	25.4	5.8	8.4	- 1.1	7.08	1890
10/15	23.8	5.8	8.2	- 0.9	6.56	1535
10/19	24.1	-	8.0	- 0.8	7.37	1100
10/20	38.2	6.3	8.3	- 2.1	8.06	4990