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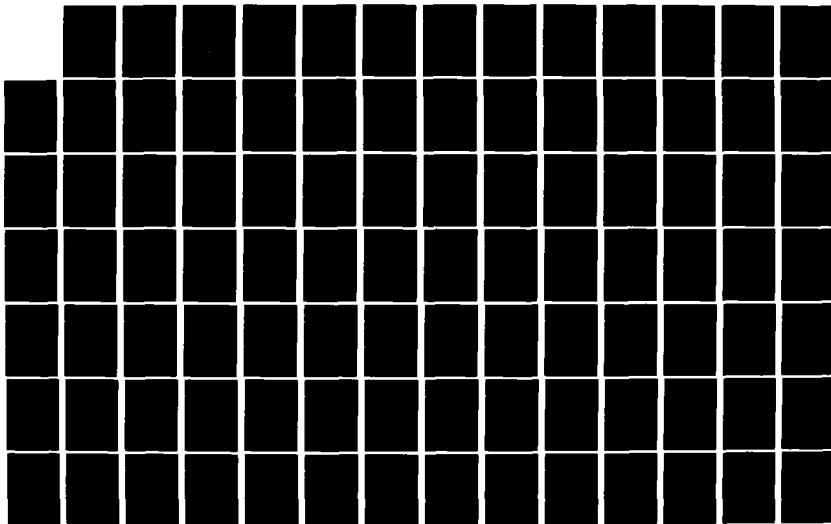
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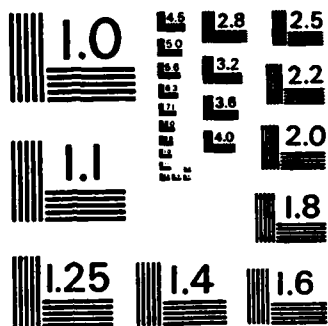
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TEST AND EVALUATION OF
CGC POLAR STAR
WAGB 10

VOLUME III BACKGROUND

JAMES P. WELSH, JR., EDITOR

Polar Oceanography Branch
Oceanography Division
Naval Oceanographic Laboratory

September 1978



Prepared for:
Coast Guard Research
and Development Center,
Groton, CT.

Approved for
Public Release

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NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
NSTL Station, Mississippi 39529

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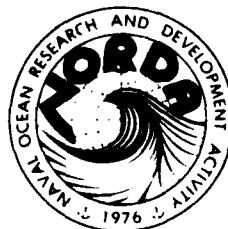
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**NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
NSTL Station, Mississippi 39529**

FOREWORD

CGC POLAR STAR is the first of a new class of American icebreakers built for and operated by the U.S. Coast Guard. The vessel's design incorporates many new and sophisticated systems not found on earlier icebreakers.

The primary objective of the test and evaluation program was to examine the performance characteristics under actual polar operations. Two field trials were conducted. The first in the Arctic (Appendix A) and the second in the Antarctic. During these field trials approximately 120 individual parameters were measured and recorded on magnetic tape (Appendix B). Additionally, the physical properties of the sea ice in which the ship was operating were measured.

Documentation of the complete program including preliminary screening of the data has been accomplished by NORDA under contract to the Coast Guard Research and Development Center. The documentation consists of the following four volumes: I. Antarctic trials, II. Test Plans, III. Background, and IV. Instrumentation Manual.

EXECUTIVE SUMMARY

Section I is a description of the POLAR class vessels. The description was prepared by excerpting the work of various individuals, including CWO V.B. Midgette and LCDR T.E. Braithwaite and the Welcome Aboard Pamphlet. This information has been published elsewhere in Coast Guard documents but is reproduced here for ready reference.

Section II through VI are the work of CDR G.P. Vance, USCG. During the summer of 1975 CDR Vance attempted to predict the icebreaking performance of the POLAR class vessels prior to their first use in the ice. This was done to assist in the development of the icebreaking test plan for these vessels. He based his predictions on the results of the various equations and theories available in the literature at that time. Vance evaluated the adequacy of these equations and theories by comparing the results of other classes of icebreakers to the actual performance of those vessels. The magnitude of measurement errors for various parameters and physical properties during the testing were estimated to determine their impact on the precision of the overall test results.

Ralph R. Goodman

RALPH R. GOODMAN
TECHNICAL DIRECTOR
NORDA

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I. GENERAL COMMENTS ON POLAR STAR

The USCGC POLAR STAR (WAGB 10) is the first new icebreaker to be built for the United States since 1954. The Lockheed Shipbuilding and Construction Company of Seattle, Washington, built the POLAR STAR and is presently completing her sister ship, USCGC POLAR SEA (WAGB 11). Eventually these two ships will operate out of a support complex located in their home port of Seattle, Washington.

POLAR STAR's design resulted from three years of research and testing. The design incorporates a number of improved and innovative features that affect nearly every aspect of her operation. Much of the equipment installed aboard is highly sophisticated such as the propulsion control system and electronic navigation equipment. There are three computers, one for monitoring engineering machinery, one for handling oceanographic data, and one for navigational capabilities. In keeping with current technology and the desire to reduce manpower requirements, automation fulfills functions to a degree unprecedented in the Coast Guard.

The hull shape for POLAR STAR is derived partially from studies made by Capt. Roderick M. White, USCG, whose ideas were incorporated into the bow design of the icebreaking tanker MANHATTAN. Basically, the hull is configured to maximize ice-breaking capability through the combined forces of the ship's forward motion (as it rides up onto the ice) and the downward pull of gravity.

The shell plating and support structures are fabricated from A-537 steel having chemical and mechanical properties which can withstand heavy impacts and loading at low temperatures. Essentially three different types of steel have been used in the construction of the ship (A-537, HY-80 and A-131). The icebelt plating in the forward and after portions of the hull is 1 3/4" thick. This shell plating thins down to 1 1/4" amidships. Portions of the hull that are above the waterline and clear from ice are 1/2" thick.

The propulsion system centers on a diesel-electric/gas turbine plant that powers three shafts. The diesel generators supply AC electrical power which is rectified for the DC propulsion motors. The gas turbines are coupled via a reduction gear directly to the shaft. Either the diesel-electric or the gas turbine mode of operation can be used, but not both together. The diesel-electric units produce a total of 18,000 continuous shaft horsepower and are the normal mode of propulsion. The gas turbine units produce a total of 60,000 continuous shaft horsepower for especially heavy icebreaking or emergencies. Due to the turbines' higher rate of fuel consumption, they will be used sparingly.

The propulsion machinery is spread over five separate compartments. The forward two compartments house diesel generators, supplying electricity for propulsion and shipboard use. The third engine room aft contains the gas turbines. The after two compartments contain reduction gears and electric motors.

The three shafts (34" diameter) turn four-bladed, controllable pitch propellers having 16' diameters. This type of propeller permits almost instantaneous control of the ship's direction of propulsion. Increased maneuverability is possible with this multiple shaft configuration. Additionally, the single rudder being mounted directly aft of the center line propeller will afford greater maneuverability than that of other U.S. icebreakers.

The shafts and motors are non-reversing and maneuvering control is obtained by adjusting the pitch of the blades on each propeller. The continuously turning shafts should be valuable during icebreaking as studies indicate an icebreaker's propeller is most vulnerable when stopped for reversing direction. With a controllable pitch propeller, the need for reversing the revolution of the shaft is eliminated.

A computer controlled monitoring system keeps watch over the equipment in the engineroom. Selected machinery parameters are continuously scanned and recorded. If critical values are reached, the monitor system sounds an alarm and automatically secures certain equipment before permanent damage is done.

It is impossible to describe even briefly all of the equipment aboard POLAR STAR. However, the following items may be of special interest.

One innovation, as far as the Coast Guard is concerned, is the central hydraulic system which provides a single hydraulic power source for the entire ship. This avoids the necessity of generating the hydraulic power electrically at each individual machinery location. The 15 ton cranes aft and 3 ton crane forward, for example, are both operated off this central system.

There is a heeling system aboard utilized to rock the ship as an aid in freeing herself when stuck in ice. The system consists of three pairs of tanks connected by flumes with axial flow reversible pumps. Operated hydraulically, the pumps transfer the contents of each (approximately 35,000 gallons) or all three tanks to its mate on the opposite side of the ship. This is accomplished in 50 seconds generating 24,000 foot tons of torque on the ship.

Icebreakers are infamous for their heavy roll in the open sea. To dampen this effect a passive roll stabilizing system is installed. A continuous port to starboard tank is kept approximately 40% full of water. The placement of vertical pipes within the tank produces a nozzle effect to keep the "sloshing" water out of phase with the roll of the ship, thus tending to counteract the roll. The effect is a dynamic one, that is, it requires the ship to be rolling before it operates.

One special feature of POLAR STAR is the aloft conning station approximately 104' above the waterline. This platform provides a necessary valuable visual extension to the conning officer as he carefully searches for the best route through concentrated ice fields. Complete rudder and engine controls and necessary navigational devices are located in the station aloft. Access is via a ladder inside the mast.

An impressive amount of space has been devoted to scientific purposes. Five laboratories and offices as well as space for accommodating portable scientific vans have been included in the design. There is berthing for 10 scientists and technicians. The pride of the oceanographic instrumentation is the computer complex located in the ocean data center, which assures rapid reduction and assimilation of gathered data without the traditional delay until return to homeport.

The aviation capability is immediately apparent as the flight deck can land the heavy HH3F helicopter, but it is expected that two HH52A helicopters will make normal deployments with POLAR STAR. The helicopters are a vital tool to operating in the ice. They are the ship's "eyes" when difficult circumstances are encountered.

Perhaps the most notable feature of the USCGC POLAR STAR is her habitability. Careful consideration was given to the needs of the crew to insure they received the best possible in care and comfort. Duty aboard an icebreaker is long and can be arduous, especially when your ship is going to spend eight months a year deployed at sea. The manning requirements, for example, have been reduced to approximately 150, primarily through automation and the use of low maintenance materials. That number compares to about 190 for the older WIND Class icebreakers. The resulting extra space has been put to good use. Single, double and four man staterooms are provided for the entire crew. Sizable lounges, a library, a gymnasium and a soda fountain have been incorporated into the ship. Bright colors and modern decor contrast noticeably with the drabness of traditional color schemes. These and other points all contribute to the "livability" of POLAR STAR.

II. COMMENTS ON VARIOUS METHODS OF EVALUATING AND/OR PREDICTING ICEBREAKER PERFORMANCE BY CDR G. P. VANCE

A. Introduction

The current literature contains many references to the prediction of icebreaker performance. Some of the work is dated, some of the work is unique and some of the work has been vastly improved upon. This note will attempt to clarify the utility of each reference in the prediction technique, however, time does not permit presentation of each technique and sample calculations. Examples can be found in the references cited.

The prediction techniques can be broken down into several categories. Category one would contain the techniques that are analytical in nature and depend on knowing only the ship and ice parameters, i.e., no model tests or full scale tests data are necessary. Included in this category are predictions for continuous resistance in homogeneous ice, continuous resistance in slush ice, ramming capability and extraction capability.

The second category involves prediction techniques where model or full scale data are available for regression analysis to establish coefficients for the prediction equation. A discussion of the various techniques is contained in the following sections. A summary is contained in Table 1.

B. Category I

1. Discussion

Kasteljan (1968) formulated an equation that expressed ice resistance encountered by an icebreaker. Although his equation has some coefficients in it that have to be determined experimentally, the values published are taken as suitable for all hull forms. This is a source of some error in his technique. His equation takes the form:

$$R_i = k_1 \mu_0 B \sigma h + k_2 \mu_0 B \sigma h^2 + k_3 \frac{1}{n_2} B^{k_4} V^{k_5} + R_4 ,$$

where: $k_1 = .004$
 $k_2 = 3.6$
 $k_3 = .25$
 $k_4 = 1.65$
 $k_5 = 1.0$

are determined experimentally and the other terms are explained in his 1968 paper.

The equation is cumbersome and is only accurate at low speeds (Vance, 1974). It appears to be outdated by the advance of technology and should only be used as a check. Details of its use are contained in Kasteljan's paper (1968).

White (1969) studied the downward force generated at the bow of an icebreaker and the effects that the bow shape had on this force. The assumption is that the icebreaker's capability is proportional to bow shape alone, which is not totally true. The performance is dependent on the entire shape of the vessel. Thus, this shortcoming permeates all of White's work. His equations should be used with extreme care, particularly the simplification to ice thickness broken for the application of a certain downward force.

Examination of White's equations show one limitation to the approach, i.e., it does not take into consideration the full ship. It should be used with extreme care as a check.

Milano's (1973) work does take into consideration all the ship's parameters as well as the ice characteristics. His solution is a complex algorithm that must be run on a computer. It has been my experience that the program does reflect what is happening for most icebreaking vessels. However, odd changes in shape must be analyzed with care. The current indications are that Milano's program yields results that are 10 to 15 percent lower than full scale results.

Table 1

Summary of I/B prediction techniques

CONTINUOUS HOMOGENOUS ICE

<u>AUTHOR</u>	<u>YEAR PUBLISHED</u>	<u>REMARKS</u>
Kasteljan	1968	Too linear, low
White	1969	Not too accurate
Milano	1973	Low, needs comp.
Lewis	1971	Good at low speeds
Edwards	1972	Too linear
Enkvist	1972	Good at low speeds
Vance	1974	Good within 5 percent

CONTINUOUS SLUSH ICE

Milano	1975	Unproved
--------	------	----------

RAMMING

White	1969	Very approximate
Lewis	1971	Improved White

EXTRACTION

White	1969	Relative only
-------	------	---------------

2. Slush

Milano's (1975) program for slush ice is the only predictive tool available for such work. It was first presented in April 1975 and has not been field tested, i.e., used enough by design engineers to give confidence in the results. There is not much that can be said for its application to date; it must be tested to gain more insight into its strength and weaknesses.

3. Ramming

White (1969) developed a technique that yields an approximation of the thickness of homogeneous ice that can be broken in a ramming mode. Again his development is limited to the bow, which is more realistic in this case. Lewis (1971) has taken White's approach and made some improvements, particularly in the application of the downward force necessary to break the ice. The equations should be taken as approximates and are sensitive to the friction coefficient and bow angles.

4. Extraction

White's (1969) approach to extraction difficulty is a relative one and should not be used as an absolute indication of the ship's ability to extract itself with a given thrust. It is very sensitive to bow angle and one should be aware that he is referring to the bow angle at the end of impact rather than the bow angle at the designer's waterline. A detailed explanation is available in the report on ramming and extraction prediction by Vance (1974).

C. Category II

Continuous homogenous ice:

The comments stated earlier pertaining to Kasteljan's equation apply here also. The coefficients in his equation are found through model tests or from full scale test data regression. His work although good in its basic concept is not precise enough for today's technology.

Lewis, in 1971, proposed an equation that appeared to be a good prediction but did not fit all shaped ships. It depended on model data to obtain coefficients in the equation.

Its difficulty lies in the fact that it does not contain the ship's length and the beam is not reflected in the breaking term. Lewis, et al., abandoned the equation in 1972 in favor of another equation (Edwards, 1972).

This equation has the inherent weakness of being linear in velocity which is contrary to most field data. It is a fairly good approximation at low speeds where the velocity effect is not predominant.

Enkvist (1972) used another regression technique that he felt was applicable to prediction of ice resistance. He did not include the length effect and his friction effect was ambiguous. His technique is complicated and requires several series of model tests to determine the applicable coefficients. His results appear to have the wrong slope for the resistance curve (Vance, 1974). In summary, I would not recommend Enkvist technique or equations for predicting full scale data.

Vance (1974) proposed a regression technique that included the length effect; however, because of the lack of any data to the contrary, he assumed the pressure effect was neutral, i.e., no adverse pressure fields existed. He also assumed that the friction effect was spread throughout all components and could not be separated out. His results were within 5 percent of full scale data.

It must be kept in mind that none of these techniques include the effect of pressure and are somewhat blase about the effect of friction, however,

that is the state of the art to date.

D. Summary

In summary, I would recommend Milano's approach for vessels that have not been model tested or are still on the drawing board. I would recommend Vance's approach for analyzing all model data.

III. PREDICTED OPEN WATER PERFORMANCE CHARACTERISTICS OF THE POLAR STAR BY CDR G. P. VANCE

A. Abstract

The enclosed information will provide an estimate of the performance of the POLAR STAR in open water. The information is based on the Model Test Report P-223-H-09, "Powering Predictions and Flow Observations for the U.S. Coast Guard Proposed Icebreaker Design (M-14-3) Represented by Model 5245," by M.P. Lasky, L.R. Crook and P.B. Mathis, dated April 1971.

The RPM reported in the report may not be the RPM experienced in the field, therefore one should use care in computing the torque, i.e., each torque computation should be made using measured RPM.

One should also be careful in determining the power distribution when underway. The power distributed to the shafts is up to the operator and may not be equal, however, the total power should be equal to the figures presented herein. (See Table 2 and Figs. 1-2).

B. Basic Equations

$$\text{IHP} = \frac{\text{PLAN}}{550} \text{ in engine}$$

$$\text{BHP} = \frac{2\pi QN}{550} \text{ at engine coupling}$$

$$\text{SHP} = \frac{d^4 G \theta N}{613033 L_s} \text{ at shaft before prop}$$

$$\text{DHP or PHP} = \text{at prop (takes into account stern tube losses)}$$

$$\text{THP} = \frac{T V_a}{550} \text{ powered by props}$$

$$\text{EHP} = \frac{RV}{550} \text{ power needed to drive ship}$$

$$\begin{aligned} \text{P.E. - Propulsive Eff.} &= \frac{\text{EHP}}{\text{IHP}} \text{ (for diesels)} \\ &= \frac{\text{EHP}}{\text{SHP}} \text{ (for turbines)} \end{aligned}$$

Reference page 372 PNA

$$\begin{aligned} \text{Propulsive Coefficient} \\ \text{(or Quasi-Propulsive Coefficient)} &= \frac{\text{EHP}}{\text{PHP}} = \frac{\text{EHP}}{\text{THP}} \times \frac{\text{THP}}{\text{PHP}} \end{aligned}$$

Table 2

POLAR STAR open water performance (Test 6A)

SP (KTS)	SP (FPS)	EHP	RESIST (LBS)	SHP	THRUST (LBS) (At shaft)	PC	TORQUE (FT LBS) (Total)
4	6.76						
6	10.14						
8	13.52	600	24,408	1000	40,608	.60	29,980
10	16.90	1150	37,426	1900	62,376	.60	56,962
12	20.28	2000	54,241	3400	90,401	.60	101,932
14	23.66	3375	78,455	5600	130,759	.60	167,888
16	27.04	5200	105,769	8600	176,282	.60	257,828
18	30.42	9300	169,050	15600	281,744	.60	467,688
20	33.80	15150	246,524	25000	410,872	.59	749,500

POLAR STAR
OPEN WATER
RESIST

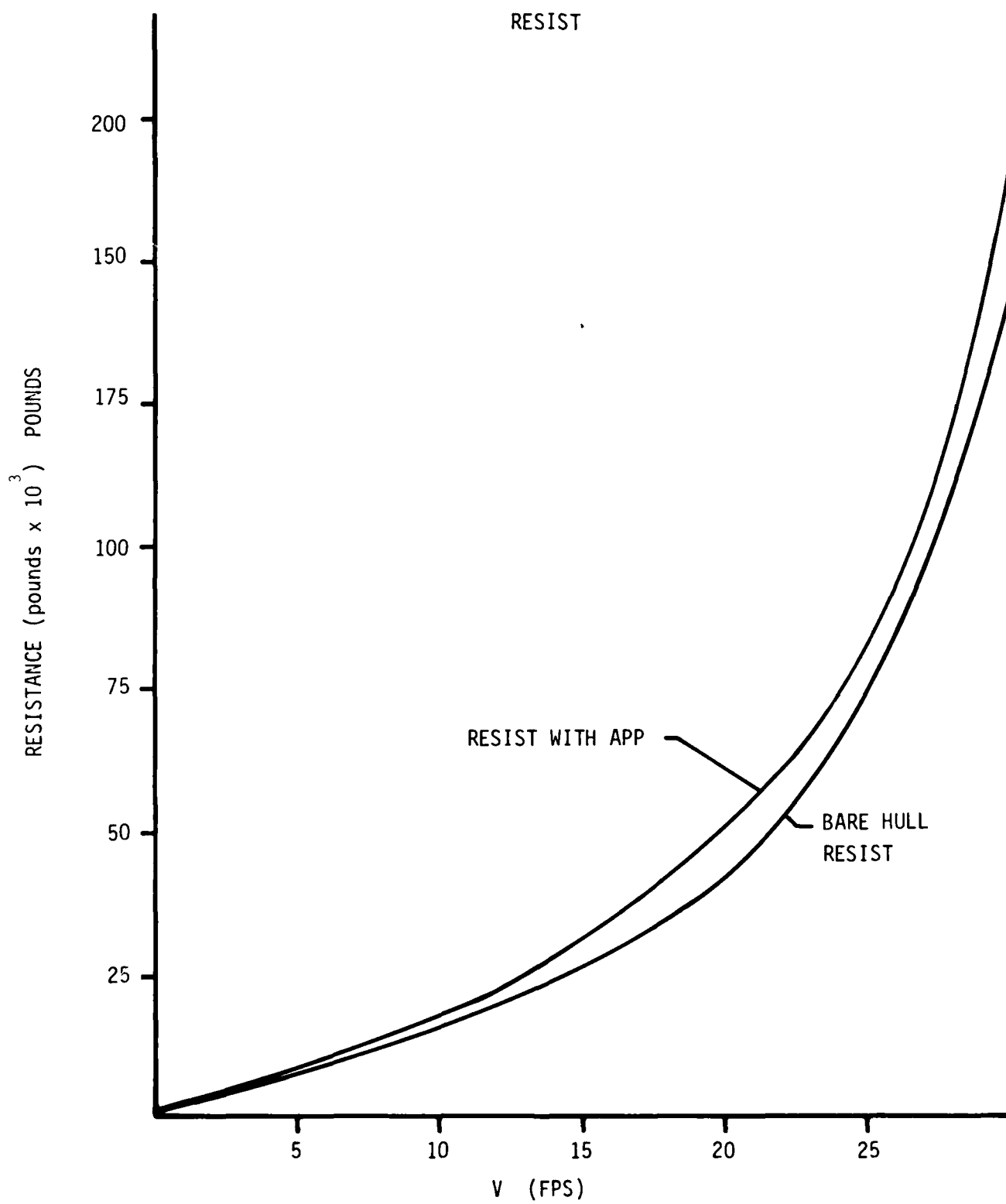


FIGURE 1

VELOCITY (FEET PER SECOND)

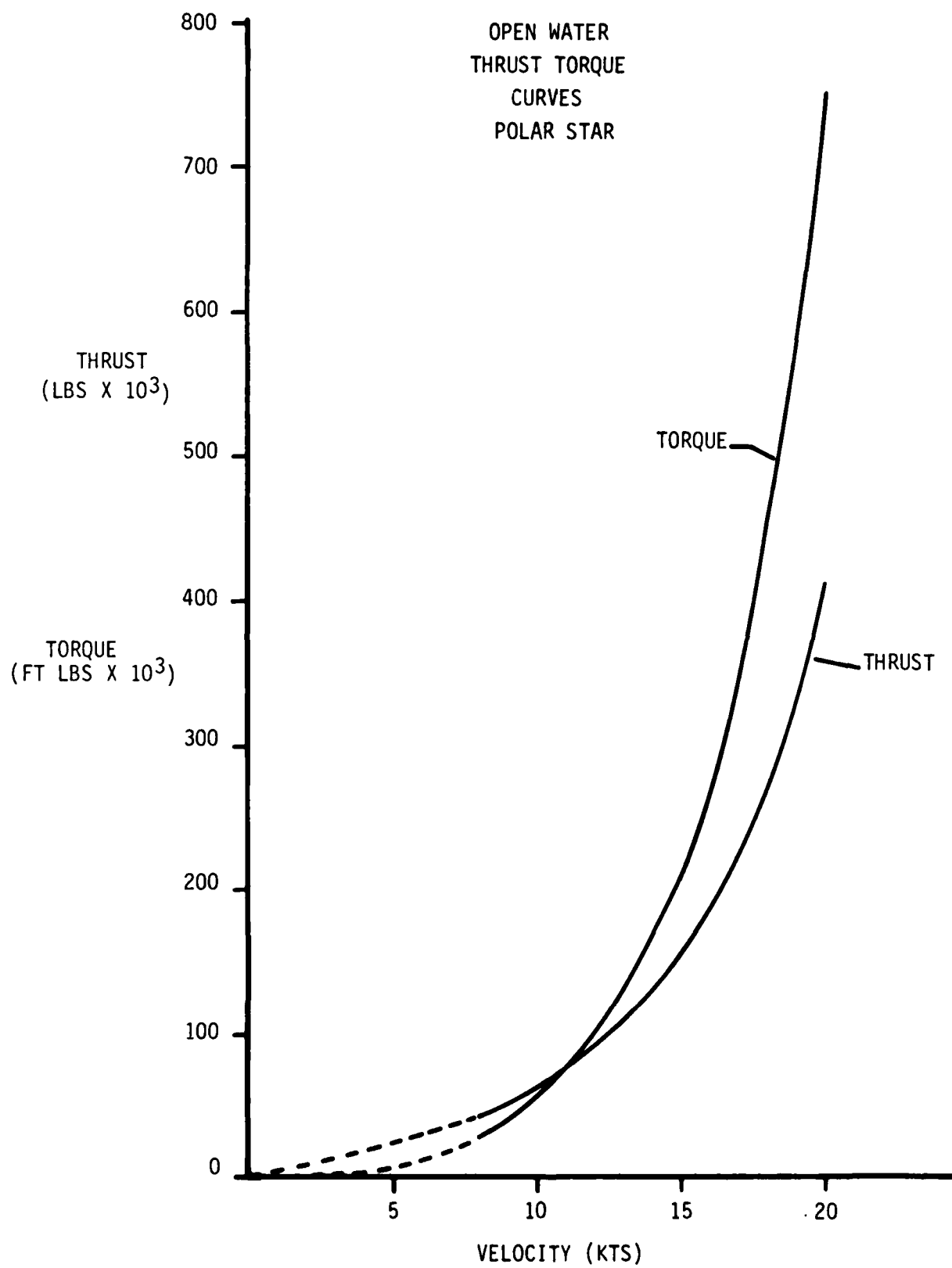


Figure 2.

$$= dh \times e_p \times e_{rr}$$

$$\text{Propulsive Efficiency} = \frac{\text{EHP}}{\text{PHP}} \times \frac{\text{PHP}}{\text{SHP}}$$

$$= e_h \times e_p \times e_{rr} \times e_t$$

$$e_t \sim 98\% \text{ mach. aft (rough approximation)}$$

$$\sim 97\% \text{ mach. midships (rough approximation)}$$

SHP should be measured as close to stern tubes as possible.

$$\begin{aligned} V - V_a &= \text{wake speed} \\ \omega &= \text{wake fraction} = \frac{V - V_a}{V} \end{aligned}$$

$$V_a = v(1 - \omega)$$

$1 + \omega$ is wake factor

$$R_t = (1 - t)T \text{ total resistance or available thrust}$$

$$t = \frac{T - R_t}{T} = 1 - \frac{R_t}{T} \text{ thrust deduction fraction}$$

$$(1 - t) = \text{thrust deduction factor}$$

$$\frac{\text{EHP}}{\text{THP}} = \frac{R_t V}{T V_A} = \frac{1 - t}{1 - \omega} = e_h = \text{hull eff.}$$

i.e. want t small ω - large

$$e_p = \frac{T V_A}{2\pi N Q_0} \text{ open water prop eff.}$$

$$e_b = \frac{T V_A}{2\pi N Q} \text{ eff. of prop behind ship}$$

$$e_r = \frac{e_b}{e_0} = \frac{Q_0}{Q} \text{ rel. rotative eff.}$$

$$.95 < e_r < 1.1 \text{ (rough approximation)}$$

$$\begin{aligned} \text{PC or QPC} &= \frac{\text{EHP}}{\text{PHP}} = \frac{R_t V}{\frac{T V_A}{e_b}} = \frac{R_t V}{T V_A} e_b \\ &= \frac{1 - t}{1 - \omega} e_r e_0 \end{aligned}$$

To go from shaft thrust to ship resistance we need

- hull efficient, i.e., $\frac{1-t}{1-\omega}$ i.e., need t and ω
- need e_p , i.e., open water prop eff.
- need e_r , i.e., relative rotative eff.
- need e_t , i.e., transmission eff.

C. Expected values of thrust

The total thrust that can be expected at the shafts is proportional to the total resistance encountered by the ship. If we assume the propulsion coefficient presented in report P-223-H-09 is correct then the expected total thrust is presented in the enclosed table.

It should be emphasized that the thrust figure is the total and the thrust on each shaft will depend on the power distribution set by the operator, i.e., 1/3, 1/3, 1/3 or 1/2, 0, 1/2, etc.

Example calculation

$$\text{Thrust (at shaft)} = \frac{\text{RESISTANCE}}{\text{P.C.}}$$

$$\text{RESISTANCE} = \frac{\text{EHPX550}}{V}$$

$$R (16 \text{ Kts}) = \frac{5200 \times 550}{27.04} = 105,769 \text{ lbs.}$$

$$\begin{array}{l} \text{Thrust} = \frac{105769}{.6} = 176282 \text{ lbs.} \\ \text{(Total)} \end{array}$$

D. Expected values of shaft torque

If angle of twist is measured:

$$\text{SHP} = \frac{(d_s)^4 G \theta N}{613033 L_s}$$

G-shear modules can be taken as 11,900,000 PSI for steel shafts

N is revolutions per second

L_s length over which angle θ is measured in inches

d_s shaft diameter in inches

θ angle of twist in degrees over L_s

For torque (foot pounds)

$$\text{SHP} = \frac{2\pi\theta N}{550}$$

Q in ft lbs

N in RPS

$$\text{RPS} = \frac{\text{RPM}}{60}$$

NOTE: The same cautions exist for torque as for thrust, i.e., the power distribution and RPM must be known.

E. Example of torque calculation

$$Q = \frac{\text{SHP } 550}{2\pi N} = \frac{\text{SHP } 87.535}{N}$$

Assuming RPM of 175, i.e., 2.92 RPS and calculating total torque

$$Q = \frac{\text{SHP } 87.535}{2.92} = 29.98 \text{ SHP}$$

At 8 KTS open water

$$Q = 1000 (29.98) = 29977.74 \approx 2978 \text{ ft. lbs.}$$

F. Propeller performance

Currently no detailed (i.e., computer printout) information is available for the controllable-pitch propellers on the POLAR STAR. The enclosed tables and graph will give some indication of the degradation of propeller performance with decreasing speed in the tow rope pull condition. One must be careful in approximating the P.C. in these conditions, particularly in ice. Not only will t and w change with speed but they also will be effected by ice flow in a detrimental manner. The extent of the effect is difficult to estimate due to the lack of any model or full scale data. (See Fig. 3 and Tables 3-7).

IV. PREDICTED ICEBREAKING PERFORMANCE CHARACTERISTICS OF THE POLAR STAR BY CDR G. P. VANCE

A. Abstract

The curves of ice resistance versus velocity for the POLAR STAR have been derived utilizing the basic program of Dr. V.R. Milano (Resistance to Ship Motion in Sheet Ice). Caution should be used when evaluating changes in resistance when there has been a dramatic change in any environmental parameter. The user should read "Variation of Ship/Ice Parameters on Ship Resistance to Continuous Motion in Ice" by V.R. Milano, (April 1975), SNAME Eastern Canadian Section paper, before using the program. The program has been modified to run on the U.S. Naval Underwater Systems Center UNIVAC 1108 computer and is on file there. The program can be called from the CG R&DC terminal with output at the CG R&DC terminal (very slow) and/or output at NUSC.

The program plots resistance versus velocity curves and thrust versus velocity curves (Fig. 4) for ice thickness from 1 to 9 feet and ship speeds from 0 to 24 feet per second. The environmental constants, with the exception of flexural ice strength, compressive ice strength, the coefficient of friction and the ice specific gravity are in the main program and are set for sea ice. The program will ask for the values of flexural ice strength (σ_f), in pounds per square foot (PSF), compressive ice strength (σ_c) in PSF, the coefficient of friction (μ) and specific gravity of sea ice. Examples of typical runs are contained in Table 8.

STOCK PROPELLER PERFORMANCE ON POLAR STAR

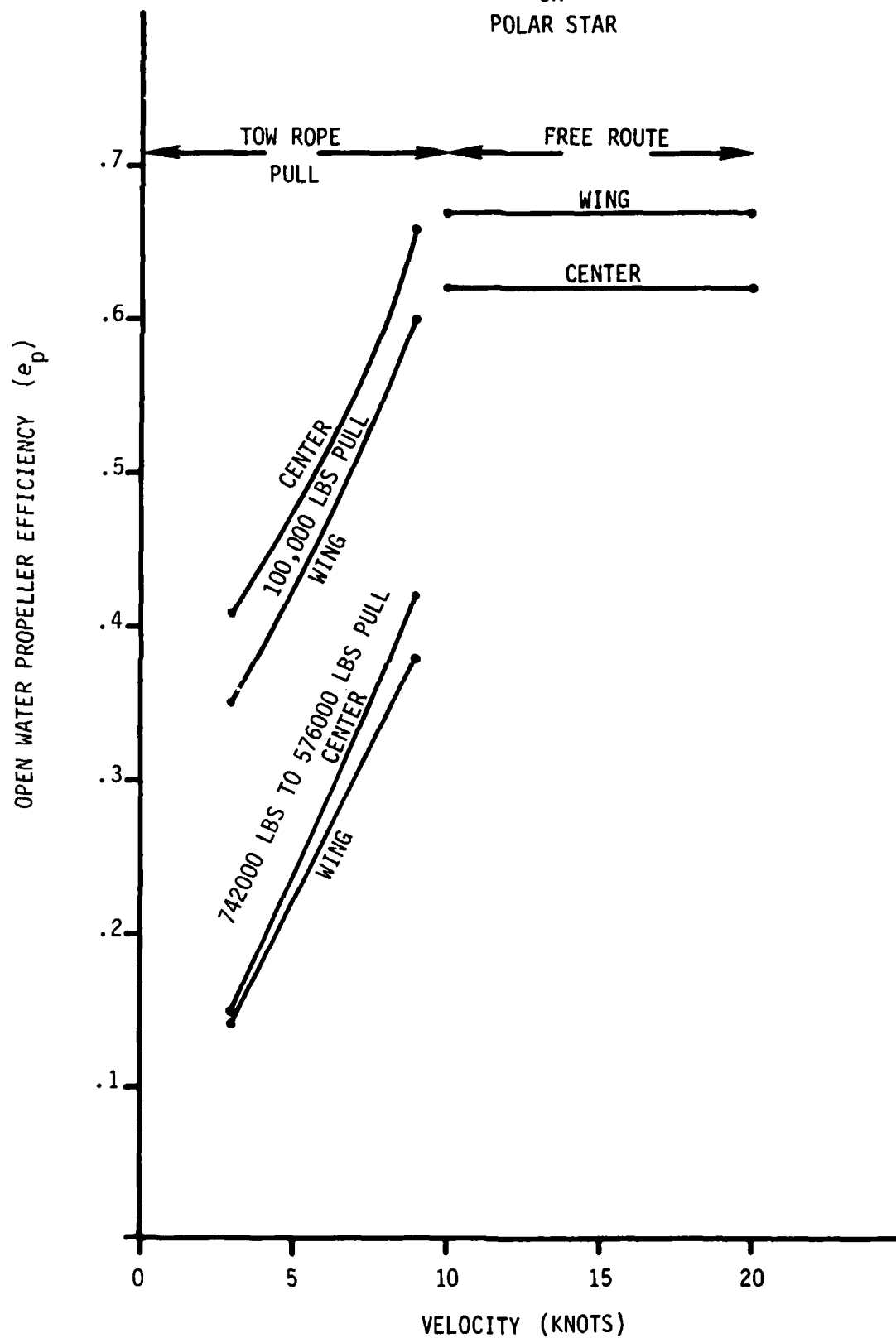


Figure 3

Table 3

The Test Program for the United States Coast Guard Proposed
Icebreaker Design (M-14-3)

Test Number	Test Type	Draft	Figure Number	Remarks
1	LOF	28'	5	Bossing Orientation
2	EHP	28'	6 , 7	Bare Hull
3	EHP	31'	10, 19	Free-Route
4	SHP	31'	10	Free-Route, Equal SHP/Shaft
5	EHP	28'	11, 12, 20	Free-Route
6	SHP	28'	11, 12	Free-Route, Equal SHP/Shaft
7	TRP-3	28'	13	Equal SHP to All Shafts
8	TRP-3	28'	14	No SHP to Center Shaft
9	TRP-3	28'	15	No SHP to Wing Shafts
10	TRP-6	28'	13	Equal SHP to All Shafts
11	TRP-6	28'	14	No SHP to Center Shaft
12	TRP-6	28'	15	No SHP to Wing Shafts
13	TRP-9	28'	13	Equal SHP to All Shafts
14	TRP-9	28'	14	No SHP to Center Shaft
15	TRP-9	28'	15	No SHP to Wing Shafts
16	BP	28'	13	Ahead, Equal SHP to All Shafts
17	BP	28'	14	Ahead, No SHP to Center Shaft
18	BP	28'	15	Ahead, No SHP to Wing Shafts
19	BPA	28'	16	Astern, Equal SHP to All Shafts
20	BPA	28'	17	Astern, No SHP to Center Shaft
21	BPA	28'	18	Astern, No SHP to Wing Shafts
22	CWC	28'/31'	19-37	Flow Observations of Tests 3 through 21

Table 4

A brief description of the stock propellers used in the Testing Program for Simulating Ahead Modes of Operation for the United States Coast Guard Proposed Icebreaker Design (M-14-3)

Propeller Number	Shaft	Shaft Direction of Rotation	<u>Pitch</u> <u>Diameter</u>
4305	Starboard Wing	Outboard Right Hand	0.80
4306	Port Wing	Outboard Left Hand	0.80
4307	Center	Right Hand	0.75
4454	Starboard Wing	Outboard Right Hand	1.00
4455	Port Wing	Outboard Left Hand	1.00
4456	Center	Right Hand	1.00

Table 5

Predicted Free-Route Propulsion Coefficients

(Test 4) Draft 31 feet (Zero Trim) Displacement = 12,650 Tons
Propellers 4305, 4306, 4307

Vs Kts	EHP SHP	t	C ^{W_T}		C ^{W_Q}		C ^{J_T}		C ^{e_p}		Thrust (lbs)	
			C	W	C	W	C	W	C	W	C	W
16	.60	.15	.17	.08	.17	.11	.66	.72	.62	.67	48,300	83,300
17	.60	.15	.17	.08	.17	.10	.65	.71	.62	.67	59,200	102,000
18	.59	.16	.17	.07	.17	.09	.64	.70	.62	.67	76,800	132,600
19	.58	.17	.17	.05	.17	.08	.62	.69	.62	.67	97,900	169,000

(Test 6) Draft 28 feet (Zero Trim) Displacement = 10,870 Ton
Propellers 4454, 4455, 4456

Vs Kts	EHP SHP	t	C		W _T		C		W _Q		C		J _T		C		e _p	W	Thrust (lbs)	
			C	W	C	W	C	W	C	W	C	W	C	W						
10	.65	.14	.17	.06	.18	.08	.83	.89	.73	.70	16,200	27,600								
12	.65	.14	.17	.06	.18	.08	.83	.89	.73	.70	24,000	40,800								
14	.65	.14	.17	.06	.18	.08	.83	.89	.73	.70	33,800	57,400								
15	.65	.14	.17	.06	.18	.08	.83	.89	.73	.70	38,900	66,400								
16	.65	.15	.17	.06	.19	.08	.83	.89	.73	.70	45,600	78,100								
17	.64	.15	.17	.06	.19	.08	.82	.87	.73	.70	56,300	97,000								
18	.63	.16	.17	.06	.19	.08	.79	.85	.72	.70	73,400	126,900								
19	.61	.17	.17	.05	.19	.08	.76	.83	.71	.69	92,200	159,100								

(Test 6A) Draft 28 feet (Zero Trim) Displacement = 10,870 Tons
Propellers 4305, 4306, 4307

Vs Kts	EHP SHP	t	C		W _T		C		W _Q		C		J _T		W		C		e _p	W	Thrust (lbs)	
			C	W	C	W	C	W	C	W	C	W	C	W	C	W						
10	.60	.15	.17	.08	.16	.10	.67	.74	.62	.67	16,200	28,000										
12	.60	.15	.17	.08	.16	.10	.67	.74	.62	.67	24,000	41,400										
14	.60	.15	.17	.08	.16	.10	.67	.74	.62	.67	33,800	58,200										
15	.60	.15	.17	.08	.17	.10	.67	.74	.62	.67	38,900	67,000										
16	.60	.15	.17	.08	.17	.10	.67	.73	.62	.67	45,600	78,500										
17	.60	.15	.17	.08	.18	.10	.66	.72	.62	.67	56,300	97,000										
18	.59	.16	.17	.07	.18	.09	.64	.71	.62	.67	73,400	126,900										
19	.58	.17	.17	.05	.18	.07	.62	.70	.62	.67	92,200	159,100										

Table 6

Predicted Tow-Rope Pull Propulsion Coefficients

Draft = 28 feet (Zero Trim) Displacement = 10,870 Tons

Equal Power Ahead to all Shafts - Vs = 3 Knots - Test 7

TRP (lbs)	Thrust C	(lbs) W	R/T	W _T		W _Q		J _T		e _p	
				C	W	C	W	C	W	C	W
100,000	41,100	69,900	.93	.30	-.10	.15	.02	.21	.33	.41	.35
200,000	78,200	140,300	.93	.23	-.18	.09	.00	.17	.26	.30	.27
300,000	108,300	217,600	.93	.18	-.26	.05	-.02	.15	.24	.25	.23
400,000	152,700	280,800	.93	.14	-.30	.04	-.02	.14	.22	.22	.20
500,000	189,500	351,600	.93	.12	-.32	.04	.00	.13	.20	.20	.18
600,000	226,900	421,700	.93	.10	-.33	.04	.04	.12	.18	.18	.17
700,000	264,000	492,100	.93	.06	-.33	.02	.09	.12	.17	.17	.16
800,000	313,100	550,600	.93	.03	-.33	.02	.14	.12	.16	.16	.15
876,000	329,100	616,400	.93	.01	-.33	.01	.18	.11	.15	.15	.14

Equal Power Ahead to All Shafts - Vs = 6 Knots - Test 10

TRP (lbs)	Thrust C	(lbs) W	R/T	W _T		W _Q		J _T		e _p	
				C	W	C	W	C	W	C	W
100,000	45,000	79,800	.91	.24	-.09	.24	.07	.38	.45	.51	.47
200,000	84,400	150,100	.91	.26	-.04	.24	.07	.29	.36	.49	.44
300,000	123,500	220,600	.91	.29	-.05	.24	.07	.24	.31	.44	.39
400,000	162,500	291,300	.91	.30	-.09	.24	.06	.21	.28	.39	.35
500,000	200,900	362,500	.91	.30	-.11	.24	.06	.19	.26	.36	.32
600,000	239,300	433,800	.91	.29	-.12	.24	.07	.18	.24	.34	.30
700,000	277,400	505,300	.91	.27	-.12	.24	.08	.17	.22	.32	.28
800,000	315,600	576,800	.91	.26	-.12	.24	.09	.17	.21	.30	.27
810,000	319,500	583,900	.91	.26	-.12	.24	.09	.16	.20	.29	.27

Table 6 (Continued)

Equal Power Ahead to all Shafts - Vs = 9 Knots - Test 13

TRP (lbs)	Thrust (lbs)		R/T	W _T		W _Q		J _T		e _p	
	C	W		C	W	C	W	C	W	C	W
100,000	54,600	89,800	.90	.24	.03	.19	.09	.46	.58	.66	.60
200,000	93,500	162,100	.90	.25	.04	.20	.09	.38	.49	.62	.56
300,000	132,300	234,400	.90	.25	.02	.21	.09	.33	.44	.56	.51
400,000	170,900	306,800	.90	.26	.00	.24	.09	.30	.40	.51	.47
500,000	209,500	379,400	.90	.27	.01	.25	.10	.28	.38	.48	.43
600,000	248,100	452,000	.90	.27	.02	.25	.10	.26	.36	.45	.41
700,000	286,600	524,500	.90	.28	.03	.25	.10	.24	.34	.43	.39
742,000	304,700	553,200	.90	.28	.03	.25	.10	.23	.33	.42	.38

Equal Power Ahead to All Shafts - Vs = 0 Knots - Test 16

TRP (lbs)	Thrust (lbs)		R/T	W _T		W _Q		J _T		e _p	
	C	W		C	W	C	W	C	W	C	W
100,000	36,800	67,100	.96	---	---	---	---	---	---	---	---
200,000	72,900	133,700	.96	---	---	---	---	---	---	---	---
300,000	108,300	202,200	.96	---	---	---	---	---	---	---	---
400,000	142,400	274,300	.96	---	---	---	---	---	---	---	---
500,000	179,700	340,300	.96	---	---	---	---	---	---	---	---
600,000	217,900	409,100	.96	---	---	---	---	---	---	---	---
700,000	255,600	475,300	.96	---	---	---	---	---	---	---	---
800,000	292,600	547,400	.96	---	---	---	---	---	---	---	---
900,000	329,500	618,000	.96	---	---	---	---	---	---	---	---
926,000	338,600	635,100	.96	---	---	---	---	---	---	---	---

Table 6 (Continued)

Equal Power Ahead to Wing Shafts Only - $V_s = 3$ Knots - Test 8

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
100,000	115,200	.93	-.09	.05	.27	.35
200,000	223,400	.93	-.05	.12	.20	.26
300,000	331,300	.93	-.05	.18	.16	.21
400,000	439,500	.93	-.07	.20	.15	.18
500,000	543,700	.93	-.07	.26	.13	.17
577,500	631,400	.93	-.08	.32	.13	.16

Equal SHP to Wing Shafts Only - $V_s = 6$ Knots - Test 11

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
100,000	130,000	.93	-.01	.07	.43	.52
200,000	237,400	.93	-.03	.10	.34	.42
300,000	344,100	.93	-.04	.11	.30	.37
400,000	451,500	.93	-.06	.12	.27	.34
500,000	558,200	.93	-.08	.14	.25	.32
529,000	589,300	.93	-.09	.16	.24	.31

Equal Power Ahead to Wing Shafts Only - $V_s = 9$ Knots Test 14

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
100,000	151,100	.93	.03	.10	.50	.58
200,000	259,700	.93	.02	.10	.42	.51
300,000	367,500	.93	.00	.11	.38	.46
400,000	476,000	.93	-.02	.12	.35	.43
468,800	495,800	.93	-.02	.12	.34	.43

Table 6 (Continued)

Equal Power Ahead to Wing Shafts Only - Vs = 0 Knots - Test 17

TRP (lbs)	Thrust 9lbs)	R/T	W_T	W_Q	J_T	e_p
100,000	103,100	.97	---	---	---	---
200,000	206,200	.97	---	---	---	---
300,000	309,300	.97	---	---	---	---
400,000	412,400	.97	---	---	---	---
500,000	515,500	.97	---	---	---	---
600,000	618,600	.97	---	---	---	---
620,000	639,200	.97	---	---	---	---

Ahead Power to Center Shaft Only - Vs = 3 Knots - Test 9

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
50,000	66,600	.92	.25	.22	.18	.22
100,000	121,300	.92	.25	.22	.14	.18
150,000	175,900	.92	.24	.21	.12	.16
200,000	229,300	.92	.24	.20	.11	.14
250,000	281,800	.93	.23	.18	.10	.13
300,000	334,200	.93	.22	.17	.10	.12
301,000	335,400	.93	.22	.17	.10	.12

Ahead Power to Center Shaft Only - Vs = 6 Knots - Test 12

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
50,000	87,200	.91	.26	.16	.28	.36
100,000	142,400	.91	.27	.17	.23	.29
150,000	197,300	.91	.27	.18	.20	.26
200,000	250,700	.91	.27	.19	.18	.24
250,000	303,800	.92	.27	.19	.17	.22
267,000	322,300	.92	.27	.19	.16	.21

Table 6 (Continued)

Ahead Power to Center Shaft Only - Vs = 9 Knots - Test 15

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
50,000	128,600	.79	.14	.08	.39	.48
100,000	181,900	.83	.13	.07	.34	.42
150,000	236,700	.85	.13	.06	.31	.38
200,000	290,800	.86	.13	.04	.29	.36
213,000	305,200	.86	.13	.04	.28	.35

Ahead Power to Center Shaft Only - Vs = 0 Knots - Test 18

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
50,000	51,500	.97	---	---	---	---
100,000	103,100	.97	---	---	---	---
150,000	154,600	.97	---	---	---	---
200,000	206,200	.97	---	---	---	---
250,000	257,700	.97	---	---	---	---
300,000	309,300	.97	---	---	---	---
337,000	347,400	.97	---	---	---	---

Equal Power Astern to All Shafts - Vs = 0 Knots - Test 19

TRP (lbs)	Thrust C	(lbs) W	R/T	W_T	W_Q	J_T	e_p
100,000	38,100	70,100	.93	---	---	---	---
200,000	78,800	146,100	.89	---	---	---	---
300,000	119,900	226,400	.87	---	---	---	---
400,000	159,600	306,300	.86	---	---	---	---
500,000	200,000	381,800	.86	---	---	---	---
600,000	238,000	459,700	.86	---	---	---	---
700,000	276,300	536,400	.86	---	---	---	---
800,000	315,300	613,600	.86	---	---	---	---
892,000	352,700	683,500	.87	---	---	---	---

Table 6 (Continued)

Equal Power Astern to Wing Shafts Only - $V_s = 0$ Knots - Test 20

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
100,000	119,000	.84	----	----	----	----
200,000	240,600	.83	---	---	---	---
300,000	362,500	.83	---	---	---	---
400,000	484,400	.83	---	---	---	---
500,000	606,000	.83	---	---	---	---
561,000	686,000	.83	---	---	---	---

Astern Power to Center Shaft Only - $V_s = 0$ Knots - Test 21

TRP (lbs)	Thrust (lbs)	R/T	W_T	W_Q	J_T	e_p
50,000	61,600	.81	---	---	---	---
100,000	124,800	.80	---	---	---	---
150,000	187,100	.80	---	---	---	---
200,000	247,300	.81	---	---	---	---
250,000	307,400	.81	---	---	---	---
290,000	355,700	.81	---	---	---	---

Table 7

Summary of Predicted Towing Performance for the M-14-3 Design Icebreaker
 Shaft Horsepower = 20,000 SHP/SHAFT

Maximum Power to All Shafts

VS KTS	C	RPM	W	TRP (lbs)	Thrust (lbs)		Total SHP
					C	W	
0 Astern	164.5		157.8	892,000	352,700	683,500	60,000
0 Ahead	165.6		158.6	926,000	338,600	635,100	60,000
3 Ahead	167.1		163.7	876,000	329,100	616,400	60,000
6 Ahead	170.0		168.3	810,000	319,500	583,900	60,000
9 Ahead	176.9		175.8	742,000	304,700	553,200	60,000

Maximum Power to Wing Shafts - No Power to Center Shaft

0 Astern	Wind Milling	158.9	561,000	_____	686,200	40,000
0 Ahead	Wind Milling	157.8	620,000	_____	639,200	40,000
3 Ahead	Wind Milling	162.3	577,500	_____	631,400	40,000
6 Ahead	Wind Milling	168.8	529,000	_____	589,300	40,000
9 Ahead	Wind Milling	175.2	468,800	_____	547,400	40,000

Maximum Power to Center Shaft - No Power to Wing Shafts

0 Astern	164.2	Wind Milling	290,000	355,700	_____	20,000
0 Ahead	162.7	Wind Milling	337,000	347,400	_____	20,000
3 Ahead	166.8	Wind Milling	301,000	335,400	_____	20,000
6 Ahead	171.1	Wind Milling	267,000	322,300	_____	20,000
9 Ahead	176.9	Wind Milling	213,000	305,200	_____	20,000

POLAR STAR TOW ROPE THRUST

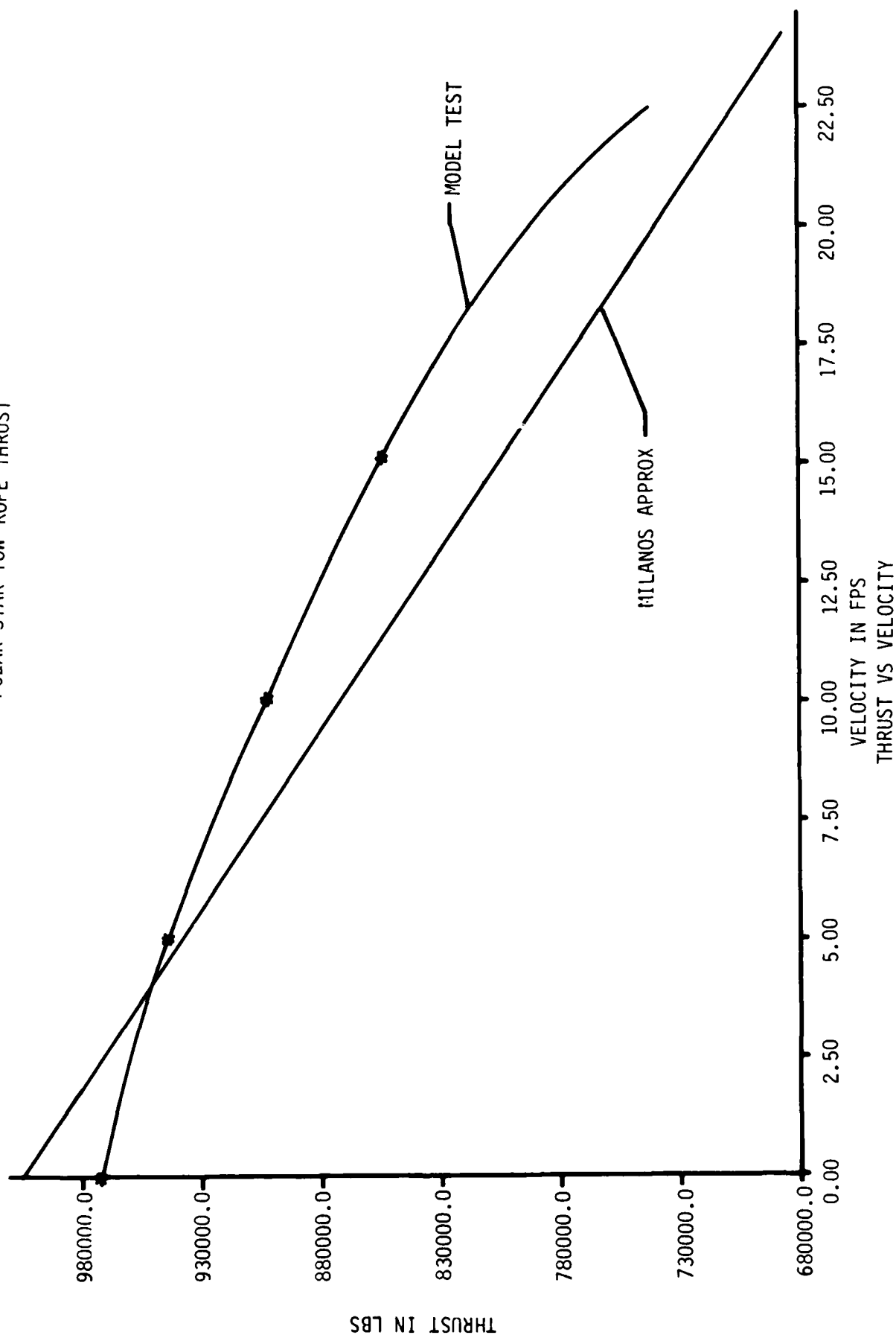


Figure 4

Table 8

Summary of runs

Run	Ship	σ_f (PSF)	σ_c (PSF)	μ	SG ICE	Remarks
1.	POLAR STAR	10,000	100,000	.2	1.03	CG R&DC Ouput
2.	POLAR STAR	10,000	100,000	.2		
3.	POLAR STAR	12,000	100,000	.2		
4.	POLAR STAR	15,000	100,000	.2		
5.	POLAR STAR	10,000	100,000	.4		
6.	POLAR STAR	10,000	200,000	.2		
7.	POLAR STAR	10,000	100,000	.2		
8.	POLAR STAR	10,000	100,000	.2		Plot RT Change Plot to Milano
9.	POLAR STAR	15,000	100,000	.2		
10.	POLAR STAR	20,000	100,000	.2		
11.	POLAR STAR	10,000	100,000	.2		Plot missing
12.	WIND	24,000	40,000	.2	.92	Same as Milano SG ice changed σ_f high, ODR RES
13.	WIND	10,000	100,000	.2		
14.	POLAR STAR	10,000	100,000	.2		
15.	POLAR STAR	20,000	100,000	.2		
16.	POLAR STAR	12,000	100,000	.2		
17.	POLAR STAR	15,000	100,000	.2		
18.	POLAR STAR	10,000	100,000	.1		
19.	POLAR STAR	15,000	100,000	.3		Term doubt
20.	POLAR STAR	15,000	100,000	.3		Term doubt
21.	POLAR STAR	15,000	50,000	.2		Printout missing
22.	POLAR STAR	15,000	50,000	.3		
23.	WIND	15,000	50,000	.2		
24.	MACKINAW	15,000	50,000	.2		

Table 8 (Continued)

<u>Run</u>	<u>Ship</u>	<u>σ_f (PSF)</u>	<u>σ_c (PSF)</u>	<u>μ</u>	<u>SG ICE</u>	<u>Remarks</u>
25.	MACKINAW	20,000	50,000	.2	.92	
26.	MACKINAW	30,000	50,000	.2	.92	
27.	POLAR STAR	30,000	50,000	.2	.92	
28.	POLAR STAR	15,000	50,000	.2	.82	CHD pro to call for SPGR ice
29.	POLAR STAR	15,000	50,000	.1	.82	
30.	POLAR STAR	20,000	50,000	.2	.92	
31.	MACKINAW	20,000	50,000	.2	.92	
32.	POLAR STAR	12,000	50,000	.2	.92	
33.	POLAR STAR	15,000	50,000	.2	.96	
34.	POLAR STAR	15,000	52,500	.2	.92	
35.	POLAR STAR	15,000	45,000	.2	.92	
36.	POLAR STAR	14,300	50,000	.2	.92	
37.	POLAR STAR	16,000	50,000	.2	.92	
38.	POLAR STAR	18,000	50,000	.2	.92	
39.	POLAR STAR	15,000	50,000	.1	.92	
40.	POLAR STAR	15,000	50,000	.25	.92	
41.	POLAR STAR	15,000	50,000	.235	.92	
42.	MACKINAW	20,000	50,000	.2	.945	FR water
43.	POLAR STAR 30'	15,000	50,000	.2	.945	FR water
44.	POLAR STAR 30'	15,000	50,000	.2	.92	Salt water
45.	POLAR STAR 28'	15,000	50,000	.2	.92	GML=3501.1 G BETA 14 ST
46.	POLAR STAR 30'	15,000	50,000	.2	.92	G DELT 14 ST

B. Introduction

The ship data is read into the program as data file. At present the program is set up such that the data file for the ship of interest must be called for. The POLAR STAR data is contained in a data package called ICEDTA. Any ship's data can be called for by using the @ ASGA (file name) and the @ USE 15. (file name), cards. The following tables describe the program input data, with examples for the POLAR STAR (Table 9), the WINDCLASS (Table 10) and the MACKINAW (Table 11), the program constants and the program output. The wind data is contained in a file called WINDTA, the MACKINAW data is in a file called MACDTA.

Once the terminal is activated by turning it on, dialing NUSC (447-3251) and entering the CG R&DC ID U1108P, the runs are made by following the enclosed samples.

The printout of the curves of Resistance versus Velocity and Thrust versus Velocity are contained in appendix A of this report.

C. Nomenclature for ice resistance program (Input)

- | | |
|----------------|--|
| 1. RLEN | Length between perpendiculars in feet |
| 2. BX | Maximum beam in feet |
| 3. DEL | Displacement in tons |
| 4. SHP | Shaft horsepower per shaft in horsepower |
| 5. PDIA | Propeller diameter in feet |
| 6. X | Distance from bow to the section of maximum beam in feet |
| 7. DELD | Distance from maximum beam to LCG IN FEET (aft is positive) |
| 8. CBXL2 | Distance from maximum beam to amidship in feet (aft is positive) |
| 9. DRAFT | Draft in feet |
| 10. CX | Midship section coefficient |
| 11. CW | Waterplane coefficient |
| 12. GML | Longitudinal metacentric height in feet at stated draft |
| 13. ALPHA | Angle of inclination of the bow measured from horizontal in radians |
| 14. ALCG | Distance from LCG to LCF in feet (aft is positive) |
| 15. NP | Number of propellers |
| 16-18 CBI (I) | Station beam coefficient, $C_{bi} = B_i / B_x$ a 21 component array from station 0 to 20 |
| 19-21. CXI (I) | Station area coefficient $C_{xi} = A_{xi} / A_x$ a 21 component array from station 0 to 20 |

Table 9

POLAR STAR input data (ICEDTA) 28 foot draft

TERMINAL INACTIVE

>@RUN TDSMET, X832JOESMITH,A99614STC000,60,500

DATE: 061775 TIME: 152842

>@ASG,AX ICEDTA.

READY

>@DATA,L ICEDTA.

123456789012345678901234567890123456789012345678901234567890123456789012

25:>P 1 40

352.0

78.0

10863.0

20000.0

16.0

140.g

33.3

35.2

28.0

.852

.740

350.1

.26179

1.35

3

0.0	.242	.465	.648	.789	.890	.955
.989	1.0	.999	.990	.974	.953	.925
.883	.823	.740	.622	.459	.249	.000
0.0	.032	.150	.353	.556	.735	.856
.922	.973	.992	1.0	.968	.911	.824
.714	.636	.406	.267	.150	.032	.000
.524	.593	.716	.794	.922	1.114	1.257
1.295	1.309	1.326	1.335	1.344	1.335	1.274
.489	.471	.419	.353	.257	.175	.112
.056	0.0	0.0	0.0	0.0	0.0	0.0

1.

2.

3.

4.

5.

6.

7.

8.

9.

0.0

SCAN:4

EOF:35

0:>SCALE 1

123456789012345678901234567890123456789012345678901234567890123456789012

0:>EXIT

LINES:35 FIELDATA

>@FREE ICEDTA.

READY

>@@SKIP 60

>@FIN

Table 10

WINDCLASS input data (WINDTA)

123456789012345678901234567890123456789012345678901234567890123456789012

25:>P 1 40

250.0

63.75

5300.0

5000.

17.

125.

1.

0.

25.75

.752

.724

201.4

.523

-.220

2

0.0

0.225

.432

.605

.737

.840

.910

.958

.982

.992

1.0

.993

.9770

.951

.91

.844

.754

.630

.462

.246

0.0

0.0

.045

.202

.386

.554

.696

.810

.895

.947

.980

1.0

.997

.978

.929

.854

.741

.593

.415

.250

.079

0.

.916

.916

.960

1.082

1.169

1.239

1.265

1.274

1.274

1.274

1.274

1.274

1.274

1.274

.526

.471

.436

.367

.285

.209

.148

.087

.052

.026

0.

0.0

0.0

0.0

1.

2.

3.

4.

5.

6.

7.

8.

9.

0.0

SCAN:4

EOF:35

0:>SCALE 1

123456789012345678901234567890123456789012345678901234567890123456789012

0:>

Table 11

MACKINAW input data (MACDTA.)

123456789012345678901234567890123456789012345678901234567890123456789012

25:> P 1 40

280.

70.

5252.

5000.

17.

140.

1.0

00.

19.

.812

.728

321.5

.523

.1

2

0.000	0.236	0.434	0.599	0.732	0.830	0.906
0.957	0.983	0.997	1.000	0.998	0.984	0.957
0.917	0.855	0.769	0.644	0.473	0.221	0.0
0.000	0.052	0.239	0.411	0.567	0.699	0.809
0.891	0.950	0.985	1.000	0.993	0.958	0.906
0.809	0.676	0.527	0.351	0.181	0.047	0.0
0.843	0.855	0.890	0.942	0.994	1.047	1.094
1.143	1.178	1.204	1.213	1.213	1.204	1.18
0.532	0.489	0.436	0.367	0.300	0.227	0.166
0.105	0.061	0.035	0.018	0.0	0.0	0.0

1.

2.

3.

4.

5.

6.

7.

8.

9.

0.0

SCAN:4

EOF:35

0:>SCALE 1

123456789012345678901234567890123456789012345678901234567890123456789012

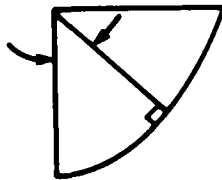
0:>EXIT

LINES:35 FIELDATA

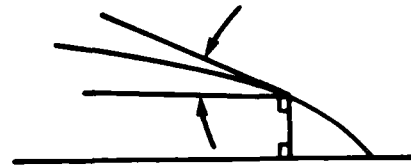
22-23. GBETA (I) Station transverse spread angle complement in radians an 11 or 15 component array station 0 to 10 or 14 taken from body plan depending on location of maximum beam

24-25. GDELTA (I) Station waterline inclination in radian an 11 or 14 component array station 0 to 10 or 13 taken from half breadth plan depending on location of maximum beam

GBETA (I)



GDELTA (I)



26-34. HICE Ice thickness in feet

35. Termination of loop with 0.0 ice thickness

D. Nomenclature for ice resistance program (Program constants)

1. RHOW Mass density of water in $\text{LBsec}^2/\text{FT}^4$ normally taken as 1.99
2. RHOI Mass density of ice in $\text{LBsec}^2/\text{FT}^4$ normally taken as 1.79
3. GAMW Specific weight of water normally taken as 65.0 LB/FT^3
4. SPGR Specific gravity of ice normally taken .92
5. SIG Tensile (flexural) strength of ice in LB/FT^3 . In the area of 10,000 PSF for seawater ice and 20,000 PSF for fresh water ice. This value should be investigated by user.
6. SIGC Compressive strength of ice in LB/FT^2 . This value depends on ice temperature. 50,000 can be taken as an average value.
7. FRICT Coefficient of dynamic friction. This value will vary and should be investigated by user. Range of values would be .1 to .5.
8. XNU Kinematic viscosity of water normally taken as $1.97 \times 10^{-5} \text{ FT}^2/\text{sec}$
9. GRA Acceleration of gravity normally taken as 32.2 FT/sec^2
10. DELCF Hull roughness allowance normally taken as .0004 (used for open water resistance)
11. PSIO Bow wedge included angle normally taken as 1.18 radians

12. PSIC Cusp wedge included angle normally taken as 1.85 radians
13. E Young modulus for ice normally taken as 1×10^8 LB/FT²
14. XK Foundation (water) modulus normally taken as 64 LB/FT²
15. ACCYF An epsilon factor used in computing open water resistance normally taken as .001E-3

E. Nomenclature for ice resistance program (Output)

1. HICE Ice thickness in feet
2. U Ship speed in feet per second
3. E1 Energy through ice filled channel in foot pounds
4. THURST Total thrust available in pounds
5. TT1 Time to break
6. E3 Energy for climbing on ice in foot pounds
7. TT Time in seconds
8. E4 Energy for fracturing ice in foot pounds
9. E5 Energy for submerging ice in foot pounds
10. E21 Energy for local crushing in foot pounds
11. ET Total energy in foot pounds
12. FT Total resistance in pounds
13. XFT Non-dimensional resistance ($R/\rho g B H^2$)
14. XFROU Thickness froude number ($U/\sqrt{g h}$)
15. XSIG Non-dimensional strength ($\sigma/\rho g h$)

F. POLAR STAR station beam coefficient

<u>STA</u>	<u>BEAM/2</u>	<u>Bi/Bx</u>
0	0	.000
1	9-5-2	.242
2	18-1-5	.465
3	25-3-1	.648
4	30-9-0	.789
5	34-8-2	.890

<u>STA</u>	<u>BEAM/2</u>	<u>Bi/Bx</u>
6	37-2-5	.955
7	38-6-6	.989
*8 (bx)	38-11-7	1.000 (38.9895)
9	38-11-6	.999
10	38-7-2	.990
11	37-11-5	.974
12	37-2-0	.953
13	36-0-7	.925
14	34-5-0	.883
15	32-1-0	.823
16	28-10-3	.740
17	24-3-3	.622
18	17-10-5	.459
19	9-8-5	.249
20	0 0 0	.000

G. POLAR STAR station area coefficient

<u>STA</u>	<u>AREA</u>	<u>Ai/Ax</u>
0	0	.000
1	60	.032
2	280	.150
3	660	.353
4	1040	.556
5	1374	.735
6	1600	.856
7	1725	.922
8	1820	.973
9	1855	.992

<u>STA</u>	<u>AREA</u>	<u>Ai/Ax</u>
10	1870	1.000
11	1810	.968
12	1704	.911
13	1540	.824
14	1336	.714
15	1190	.636
16	760	.406
17	500	.267
18	280	.150
19	60	.032
20	0	.000

- (See Figure 5) -

H. Transverse spread angle complement [GBETA (I)]

<u>STA</u>	<u>ANGLE (DEC)</u>	<u>ANGLE (RAD)</u>
0	30.0	.524
1	34.0	.593
2	41.0	.716
3	45.5	.794
4	52.8	.922
5	63.8	1.114
6	72.0	1.257
7	74.2	1.295
8	75.0	1.309
9	76.0	1.326
10	76.5	1.335
11	77.0	1.344
12	76.5	1.335
13	73.0	1.274

POLAR STAR
SECTION AREA CURVE
(28 FT. W.L.)

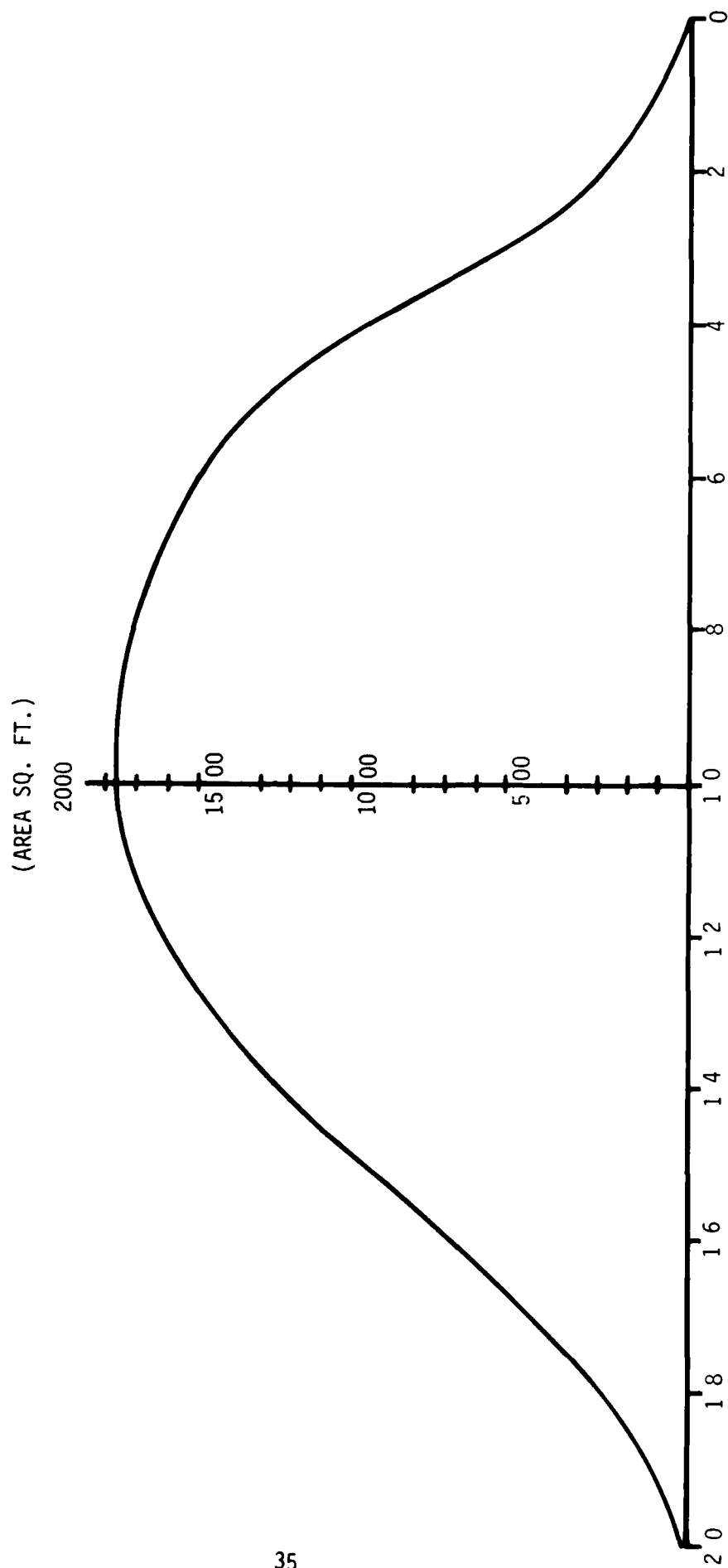


Figure 5

<u>STA</u>	<u>ANGLE (DEC)</u>	<u>ANGLE (RAD)</u>
14	71.0	1.239
15	66.8	1.166

I. Station waterline inclination [GDELT (I)]

<u>STA</u>	<u>ANGLE (DEG)</u>	<u>ANGLE (RADIAN)</u>	
		(Used)	(Act)
0	28	.489	
1	27	.471	
2	24	.419	
3	20.25	.353	
4	14.70	.257	
5	10.00	.175	
6	6.4	.112	
7	3.2	.056	
8	0.0	.000	
9	-1.0	.000	-.017
10	-2.0	.000	-.035
11	-2.5	.000	-.044
12	-3.5		-.061
13	-5.0		-.087
14	-7.0		-.122
15	-10.0		-.175

J. Expected thrust values when breaking ice

The thrust experienced at the shafts when breaking ice will be directly proportioned to the resistance experienced by the vessel. The expected value of total thrust (as in open water, the distribution of power on the shafts is up to the operator) can be found by referring to the resistance curve that matches the operating conditions. All that need be done to find total thrust at the shaft is divide the total resistance by the propulsive coefficient.

Example calculation from Run #21

$$\sigma_f = 15,000 \text{ PSF} \quad \sigma_c = 50,000 \text{ PSF} \quad \mu = .2 \quad SG = .92$$

$$R = 340,000 \text{ lbs.}$$

$$T_{\text{shaft}} = \frac{R}{PC} = \frac{340,000}{.6}$$

$$566,667 \text{ lbs. (total)}$$

NOTE: The P.C. may be less than .6, which was taken from the open water tests, because of the ice interrupting the water flow about the propellers.

K. Expected torque values when breaking ice

When in the icebreaking mode, the torques experienced on the shafts will be much higher than those experienced while in open water. The torque will depend on the total resistance of the vessel as well as the speed through the ice.

In order to estimate the torque the power distribution (i.e., 1/3, 1/3, 1/3) must be specified. The total resistance is distributed accordingly (another assumption) and the resistance changed to EHP which is converted to SHP, using a P.C. of approximately .6 (another assumption, the P.C. will probably be lower because of ice interfering with water flow). The SHP can be converted to shaft torque knowing the RPM of the shaft.

This procedure does not take into account any torques that may be encountered due to interaction between the ice and the propeller itself. These torques (i.e., ice-propeller) will show up as large peaks on an oscillograph or recorder record and can be eliminated from any power calculation if desired.

L. Calculation of expected ice resistance torque

$$Q = \frac{550 \text{ SHP}}{2\pi N}$$

$$N - \text{RPS} \quad S - \text{FT LBS}$$

$$\text{SHP} = \frac{\text{EHP}}{\text{P.C.}}$$

$$\text{P.C.} = e_h e_p e_{rr} e_t$$

$$\text{EHP} = \frac{\text{Ice resistance} \times \text{vel}}{500}$$

$$\text{Ice resist} = \text{lbs (obtained from Resist Curves)}$$

$$\text{VEL} - \text{FPS}$$

NOTE: Ice resistance must be divided in accordance with power distribution example calculation

$$\text{Ice resistance} = 340,000 \text{ lbs}$$

From plots R vs V for run #21

$$10 \text{ FPS (7.7 KTS)} \quad 4 \text{ ft ice} \quad \sigma_f = 15,000 \text{ PSF} \quad \mu = .2$$

$$\sigma_c = 50,000 \quad SG = .92 \quad RPM = 175$$

$$EHP = \frac{340,000 \times 13}{550} = 8036$$

$$\frac{EPH}{3} = \frac{8036}{3} = 2678.8$$

$$SHP = \frac{EHP}{P.C.} = \frac{2678.8}{.6} = 4464.6$$

$$Q_{cs} = \frac{550 \text{ SHP}}{2\pi N} = \frac{550 (4464.6)}{2\pi 2.92}$$

$$Q = 133906 \text{ ft lbs per shaft rotating at 175 RPM}$$

M. Prediction program verification

Although the program may be over sensitive to the various parameters entered, both ship and environment, one can obtain an appreciation of its relative merit by comparing the output for the POLAR STAR with the MACKINAW. The MACKINAW output can then be compared to full-scale data obtained in field tests. This is done for Run #21 and Run # 24 (i.e., thickness plot - see Figs. 6-7).

The comparison must be made with care since Run #21, and Run #24 made with the following parameters:

$$\sigma_f = 15,000 \text{ PSF}$$

$$\sigma_c = 50,000 \text{ PSF}$$

$$\mu = .2$$

$$SG = .92$$

The program appears to predict a resistance that is 15 percent lower than full scale at speeds greater than 7 FPS (4.2 KTS). There may be several reasons for this discrepancy:

- The coefficient of friction may not have been measured correctly in the field
- The environmental or power parameters may not have been correctly determined in the field
- The program algorithms may not be correct.

In any event, one should be aware of these shortcomings when comparing field data with the program output.

V. PREDICTION OF ERROR SOURCES FOR FULL SCALE TEST OF POLAR STAR BY G. P. VANCE

A. Abstract

An error analysis, based on Dr. Milano's resistance prediction program is made. The resulting error in predicting resistance from errors made in measuring environmental and shipboard parameters are presented.

The analysis indicates that velocity, ice thickness and the specific gravity of the ice are the most important parameters to be measured. Flexural

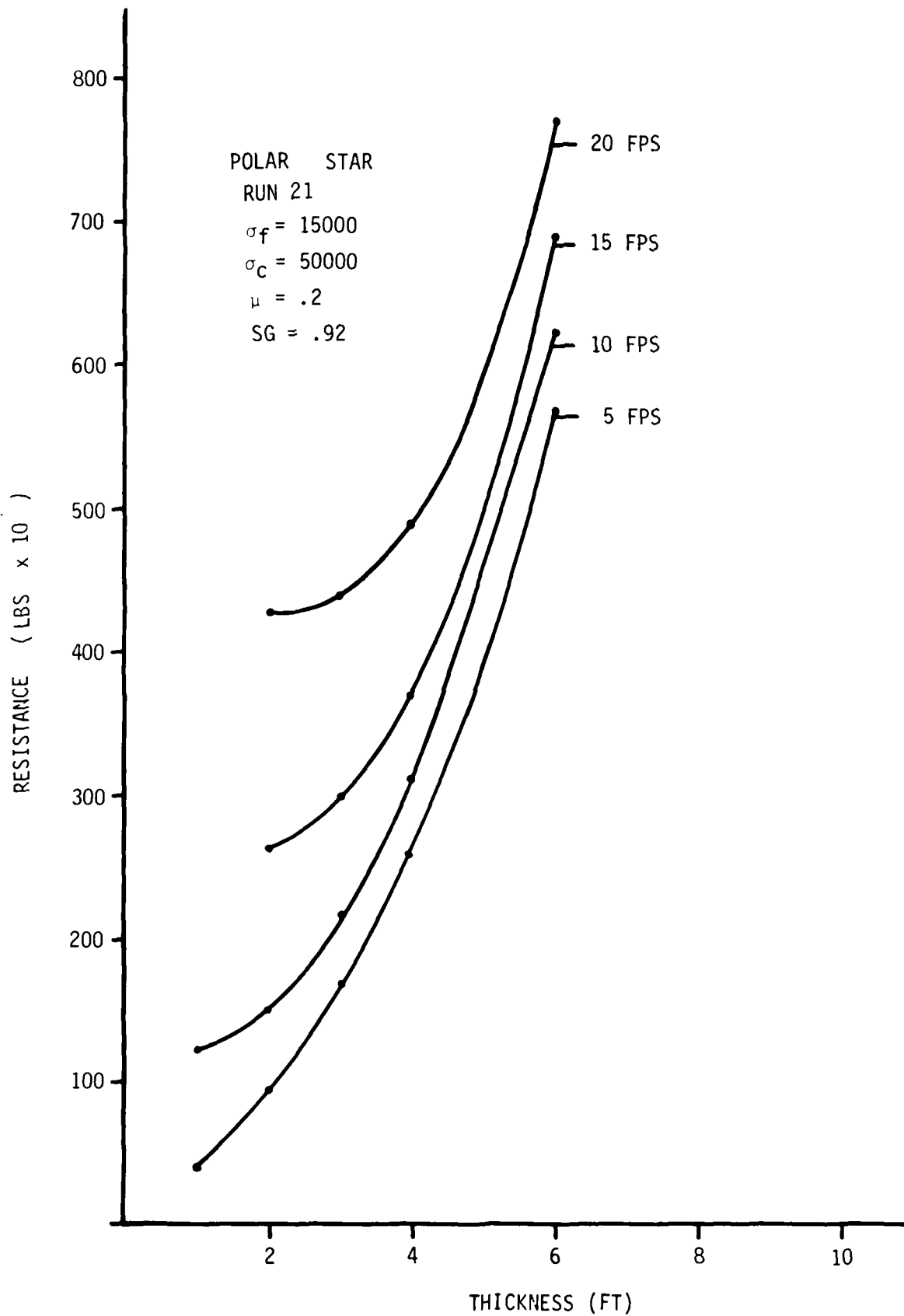


Figure 6.

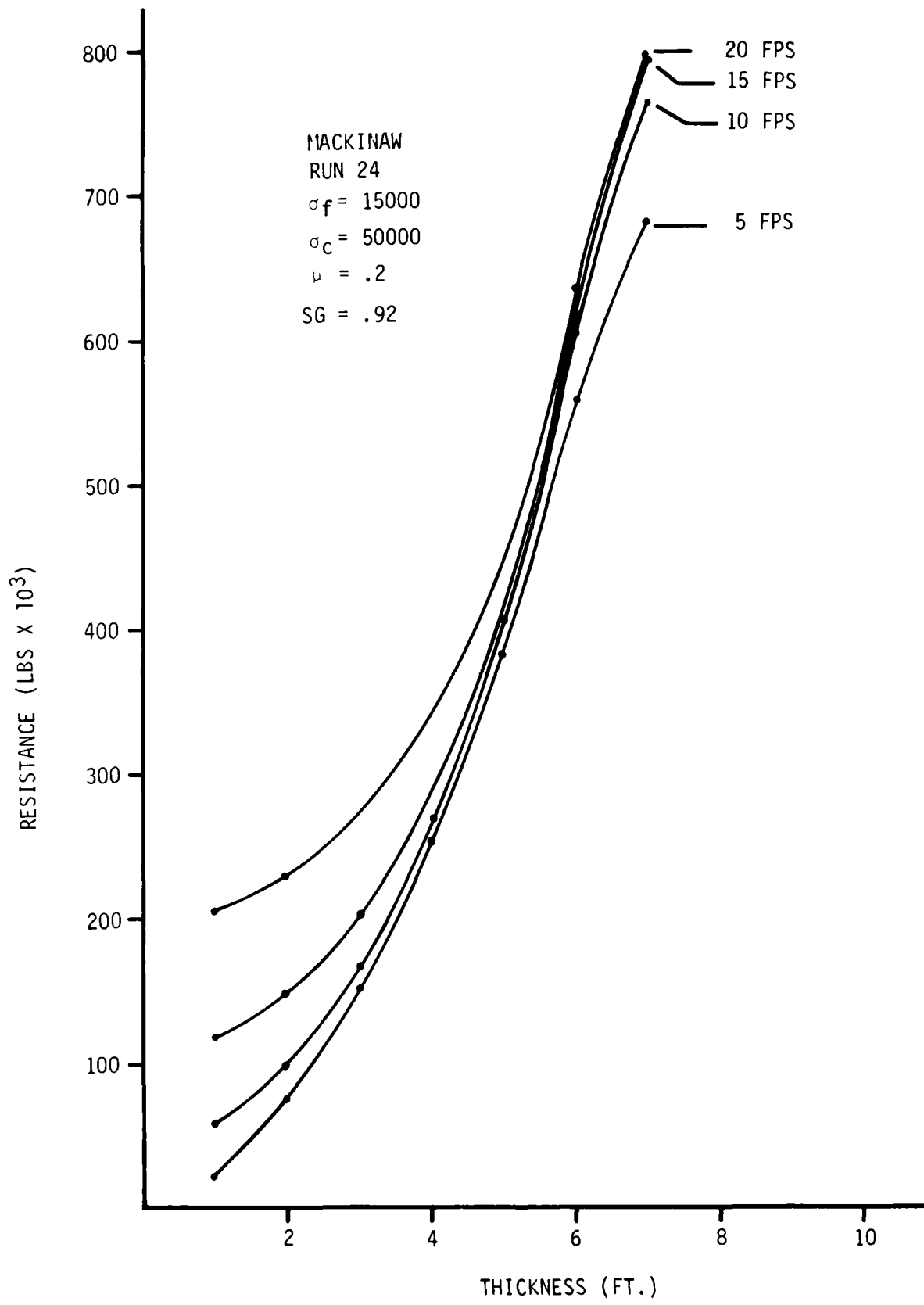


Figure 7
40

strength and friction coefficients must also be measured; however, small errors in these values do not lead to significant errors in the resistance predicted.

Any errors made in measuring propulsion parameters will lead to a corresponding error in calculating resistance.

B. Introduction

The effect of various parameters, both environmental and machinery, will have different impacts on computation of the overall resistance of the POLAR STAR in ice.

It would be a fairly simple matter to evaluate the impact of these various parameters if there was a verified algorithm that was available that could isolate each parameter; unfortunately, there is no wide spread agreement on such an algorithm. Lewis (1972), Enkvist (1972), Milano (1972) and Vance (1974) have all published information along these lines. Although there is fair agreement on some of the parameters involved, Milano's presentation depends solely on ship and environmental parameters and will be used in this study to determine their effect on the overall resistance.

In addition to the difficulty pointed out above, there is also the problem of the interaction of various parameters, i.e., the effect of ice flexural strength increases with a decrease in ship speed and ice thickness. Thus, when attempting to determine measurement precision, these various interactions must be taken into consideration.

This analysis is based on the ship operating at its design waterline of 28 feet.

C. Program Parameters

1. Milano's Algorithm

Ship Parameters - Invariant, determined from ship's plans

Environmental Parameters:

- Thickness of ice
- Flexural strength of ice
- Compressive strength of ice
- Density of ice
- Density of water
- Specific gravity of ice
- Coefficient of dynamic friction
- Specific gravity of water
- Velocity

2. Vance's Algorithm

Ship Parameters - Invariant, determined from ship's plans

Environmental Parameters:

- Thickness of ice
- Flexural strength of ice
- Density of ice
- Density of water
- Coefficient of dynamic friction
- Velocity

D. Effect of thickness

1. Run 21

$\sigma_f = 15,000$ $\sigma_c = 50,000$ $\mu = .2$ $SG = .92$

V = 5 FPS (3 KTS) % INC TH % INC RES

$R_1 = 40,000$ lbs	50.0	56.5
$R_2 = 92,000$ lbs	33.3	46.5
$R_3 = 172,000$ lbs	25.0	33.3
$R_4 = 258,000$ lbs	20.0	30.2
$R_5 = 370,000$ lbs		

V = 10 FPS (6 KTS)

$R_1 = 125,000$	50.0	16.6
$R_2 = 150,000$	33.3	31.2
$R_3 = 218,000$	25.0	29.7
$R_4 = 310,000$	20.0	31.1
$R_5 = 450,000$		

V = 5 FPS (3 KTS)

$R_{2.0} = 92,000$]	10	16.36
$R_{2.2} = 110,000$]		

$R_{3.0} = 170,000$]	10	12.18
$R_{3.3} = 195,000$]		

$R_{4.0} = 258,000$]	10	<u>16.77</u>
$R_{4.4} = 310,000$]		
		15.31 MEAN

V = 10 FPS (6 KTS)

$R_{2.0} = 150,000$]	10	6.25
$R_{2.2} = 160,000$]		

$R_{3.0} = 215,000$]	10	8.50
$R_{3.3} = 235,000$]		

$R_{4.0} = 315,000$]	10	<u>12.24</u>
$R_{4.4} = 362,000$]		
		9.24 MEAN

<u>V = 5 FPS (3 KTS)</u>	<u>% INC TH</u>	<u>% INC RES</u>
$R_{2.0} = 92,000$ $R_{2.1} = 100,000$	5	8.0
$R_{3.0} = 170,000$ $R_{3.15} = 180,000$	5	5.5
$R_{4.0} = 258,000$ $R_{4.2} = 285,000$	5	$\frac{9.5}{7.6 \text{ MEAN}}$
<u>V = 10 FPS (6 KTS)</u>		
$R_{2.0} = 150,000$ $R_{2.1} = 155,000$	5	3.2
$R_{3.0} = 215,000$ $R_{3.15} = 228,000$	5	5.7
$R_{4.0} = 315,000$ $R_{4.2} = 340,000$	5	$\frac{7.3}{5.4 \text{ MEAN}}$

2. Run 30

$$\sigma_f = 20,000$$

$$\sigma_c = 50,000$$

$$\mu = .2$$

$$SG = .92$$

<u>V = 5 FPS</u>	<u>% INC TH</u>	<u>% INC RES</u>
$R_{1.0} = 44,410$ $R_{1.05} = 46,000$	5	3.45
$R_{2.0} = 127,200$ $R_{2.2} = 135,000$	5	5.77
$R_{3.0} = 240,000$ $R_{3.15} = 257,000$	5	6.60
$R_{4.0} = 386,300$ $R_{4.2} = 420,000$	5	$\frac{8.02}{5.96 \text{ MEAN}}$

<u>V = 10 FPS</u>	<u>% INC TH</u>	<u>% INC RES</u>
R _{1.0} = 127,500 R _{1.05} = 130,000]	5	2.3
R _{2.0} = 173,200 R _{2.1} = 187,000]	5	7.3
R _{3.0} = 283,500 R _{3.15} = 310,000]	5	8.5
R _{4.0} = 431,200 R _{4.2} = 475,000]	5	<u>9.2</u> 6.8 MEAN

<u>V = 5 FPS</u>	<u>% INC TH</u>	<u>% INC RES</u>
R _{1.0} = 44,410 R _{1.1} = 50,000]	10	11.18
R _{2.0} = 127,200 R _{2.2} = 147,000]	10	13.46
R _{3.0} = 240,000 R _{3.3} = 278,000]	10	13.67
R _{4.0} = 386,300 R _{4.4} = 450,000]	10	<u>14.15</u> 13.09 MEAN

<u>V = 10 FPS</u>	<u>% INC TH</u>	<u>% INC RES</u>
R _{1.0} = 127,500 R _{1.1} = 132,000]	10	3.40
R _{2.0} = 173,200 R _{2.2} = 197,000]	10	12.08
R _{3.0} = 283,500 R _{3.3} = 330,000]	10	14.09
R _{4.0} = 431,200 R _{4.4} = 495,000]	10	<u>12.80</u> 10.59 MEAN

E. Summary of thickness

1. At low speeds (5 FPS) a 5 percent error in ice thickness will lead to a 7 to 8 percent error in resistance.
2. At higher speeds (10 FPS) a 5 percent error in ice thickness will lead to a 5 to 6 percent error in resistance.
3. At low speeds (5 FPS) a 10 percent error in ice thickness will lead to a 15 percent error in resistance.
4. At high speeds (10 FPS) a 10 percent error in ice thickness will lead to a 9 percent error in resistance.
5. A 25 percent increase in flexural strength has very little effect on the percent error given above.

F. Effect of flexural strength

1. Run 32

$$\sigma_f = 12,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 ft	TH = 4 FT	TH = 2 FT	TH = 4 ft
R = 76,317	R = 195,144	R = 137,017	R = 249,767

2. Run 21

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 ft	TH = 4 FT	TH = 2 ft	TH = 4 FT
R = 92,500	R = 258,000	R = 150,000	R = 310,000

3. Run 30

$$\sigma_f = 20,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 127,268	R = 386,365	R = 173,169	R = 431,200

4. Run 27

$$\sigma_f = 30,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 214,812	R = 731,220	R = 234,237	R = 758,726

5. RUN 36

$$\sigma_f = 14,300$$

$$\sigma_c = 50,000$$

$$\mu = .2$$

$$SG = .92$$

$$V = 5 \text{ FPS}$$

$$V = 5 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$TH = 2 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$TH = 2 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$R = 89,165$$

$$R = 242,246$$

$$R = 146,192$$

$$R = 294,426$$

6. RUN 37

$$\sigma_f = 16,000$$

$$\sigma_c = 50,000$$

$$\mu = .2$$

$$SG = .92$$

$$V = 5 \text{ FPS}$$

$$V = 5 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$TH = 2 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$TH = 2 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$R = 99,607$$

$$R = 381,174$$

$$R = 153,616$$

$$R = 331,355$$

Calculation Data

<u>% INC σ_f</u>	<u>% IN R</u>	<u>SPEED*</u>	<u>THICKNESS*</u>
5% (14.3K to 15K)	3.6	L	L
	6.1	L	H
	2.5	H	L
	5.0	H	H
10% (14.3K to 16K)	10.0	L	L
	13.8	L	H
	4.8	H	L
	11.14	H	H
20% (12K to 15K)	17.5	L	L
	24.4	L	H
	8.7	H	L
	19.4	H	H
25% (15K to 20K)	27.3	L	L
	33.2	L	H
	13.4	H	L
	28.1	H	H
*L in speed column refers to the low speed range, H refers to the higher speeds used in the sample calculations. The same is true for the thickness used. The exact number can be found by referring to the above sample calculations.			

G. Summary of flexural strength

The effect of flexural strength is related to the speed of the vessel and the thickness of the ice. As shown in the accompanying example calculations, the greatest effect occurs at low speed, high thickness. In this case a 5 percent error in measuring flexural strength will lead to a 6.1 percent error in resistance. At high speeds with low thicknesses the results show an opposite trend, i.e., 5 percent error in measuring flexural strength will lead to a 2.5 percent error in resistance.

It should be noted that the results presented here are from Milano's

(1972) program and show a slightly stronger dependence of resistance and flexural strength than shown by Lewis (1972) and Vance (1974). This fact should be kept in mind when utilizing the data presented herein.

H. Effect of ice specific gravity

1. RUN 28

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .82$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 106,971	R = 304,183	R = 162,786	R = 355,560

2. RUN 21

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 92,500	R = 258,000	R = 150,000	R = 310,000

3. RUN 33

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .966$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 86,900	R = 235,722	R = 142,715	R = 287,099

Calculation Data

% INC SG	% DEC R	SPEED	THICKNESS
10% (.82 to .92)	15.6	L	L
	17.9	L	H
	8.5	H	L
	14.7	H	H
5% (.96 to .966)	6.4	L	L
	9.4	L	H
	5.1	H	L
	8.0	H	H
15% (.82 to .966)	23.1	L	L
	29.0	L	H
	14.1	H	L
	23.8	H	H

I. Summary of specific gravity

Although the specific gravity of the ice falls within small limits, i.e., .89 to .94 with a mean of .92, errors made in measuring the S.G. will have a large effect on the calculation of the resistance of the vessel. This is particularly

true at low speeds and high thicknesses, which one would suspect, for it is in this operational mode that the energy utilized to submerge the ice is the greatest percentage of the overall resistance. However, one should be aware, the thicker the ice the greater the impact of the specific gravity of the ice.

The sample calculations using Milano's program indicate a 5 percent error in S.G. will lead to a 9.4 percent error in resistance at the worst condition. A 15 percent error in S.G. will lead to a 20 percent error in resistance at the worst condition.

J. Effect of velocity

1. Run 21

$\sigma_f = 15,000$ $\sigma_c = 50,000$ $\mu = .2$ $SG = .92$

<u>TH = 1 FT</u>	<u>% INC VEL</u>	<u>% INC R</u>
5-7 FPS	30	36
7.5-10 FPS	25	40
9.5-10 FPS	10	18
9.5-10 FPS	5	6.4

<u>TH = 2 FT</u>		
5 - 7	30	16.3
7.5 - 10	25	23.3
9 - 10	10	12.0
9.5 - 10	5	6.7

<u>TH = 4 FT</u>		
5 - 7	30	6.5
7.5 - 10	25	9.0
9 - 10	10	2.9
9.5 - 10	5	1.6

<u>TH = 6 FT</u>		
5 - 7	30	3.1
7.5 - 10	25	5.3
9 - 10	10	2.1
9.5 - 10	5	1.3

2. RUN 30

$\sigma_f = 20,000$ $\sigma_c = 50,000$ $\mu = .2$ $SG = .92$

<u>TH = 1 FT</u>	<u>% INC VEL</u>	<u>% INC R</u>
5 - 7	30	35.8
7.5 - 10	25	39.1
9 - 10	10	17.3
9.5 - 10	5	8.6

<u>TH = 2 FT</u>	<u>% INC VEL</u>	<u>% INC R</u>
5 - 7	30	9.4
7.5 - 10	25	16.6
9 - 10	10	7.9
9.5 - 10	5	3.9
<u>TH = 4 FT</u>		
5 - 7	30	4.4
7.5 - 10	25	4.9
9 - 10	10	.9
9.5 - 10	5	.5
<u>TH = 6 FT</u>		
5 - 7	30	10
7.5 - 10	25	3.4
9 - 10	10	1.5
9.5 - 10	5	.7

K. Summary of velocity effect

The effect of velocity is more pronounced at low thickness and in weaker ice as one would suspect. The sample calculations indicate a 10 percent error in velocity measurements will lead to an 18 percent error in resistance in one foot of ice. In 2 feet of ice a 10 percent error in velocity will lead to a 12 percent error in resistance. In 6 feet of ice when other resistance components predominate, a 10 percent error in velocity measurement will only cause a 2 percent error in resistance.

The interaction of the various components can be seen from the decrease in velocity effect where the flexural strength is increased. The 25 percent increase in strength causes a decrease in the effect of velocity on the resistance.

The importance of accurately measuring velocity is not only emphasized by the errors pointed out herein, but in addition, the velocity of the ship is utilized directly when making power calculations from machinery readouts.

L. Effect of compressive strength (σ_c)

1. Run 35

$\sigma_f = 15,000$	$\sigma_c = 45,000$	$\mu = .2$	SG = .92
V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 94,579	R = 261,071	R = 105,394	R = 312,448

2. Run 21

$\sigma_f = 15,000$	$\sigma_c = 50,000$		
V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 93,000	R = 258,000	R = 150,000	R = 310,000

3. RUN 34

$$\sigma_f = 15,000$$

$$\sigma_c = 52,500$$

$$V = 5 \text{ FPS}$$

$$V = 5 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$TH = 2 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$TH = 2 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$R = 92,829$$

$$R = 256,421$$

$$R = 148,644$$

$$R = 307,798$$

4. RUN 17

$$\sigma_f = 15,000$$

$$\sigma_c = 100,000$$

$$V = 5 \text{ FPS}$$

$$V = 5 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$V = 10 \text{ FPS}$$

$$TH = 2 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$TH = 4 \text{ FT}$$

$$R = 86,813$$

$$R = 240,437$$

$$R = 142,628$$

$$R = 291,814$$

Calculation Data

<u>RUN</u>	<u>% INC σ_c</u>	<u>% INC R</u>	<u>SPEED</u>	<u>THICKNESS</u>
(34-21)	5%	.2	L	L
		.6	L	H
		.9	H	L
		.7	H	H
(21-35)	10%	1.7	L	L
		1.2	L	H
		.3	H	L
		.8	H	H
(34-35)	15%	1.8	L	L
		1.8	L	H
		1.2	H	L
		1.5	H	H
(21-17)	50%	6.6	L	L
		6.8	L	H
		4.9	H	L
		5.9	H	H

M. Summary of compressive strength effect

Small changes in the compressive strength of the ice has very little effect on the resistance predicted. It is not until we encounter errors in the range of 50 to 60 percent do we see a 5 to 6 percent change in resistance.

For all practical purposes, acceptable values of compressive strength of ice presented in the literature can be used without any significant effect on the resistance prediction.

N. Effect of friction (μ)

1. RUN 39

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .1 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 78,533	R = 206,913	R = 140,948	R = 262,825

2. RUN 21

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 92,500	R = 258,000	R = 150,000	R = 310,000

3. RUN 40

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .1 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	V = 4 FT
R = 100,786	R = 283,325	R = 153,301	R = 332,435

4. RUN 41

$$\sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .235 \quad SG = .92$$

V = 5 FPS	V = 5 FPS	V = 10 FPS	V = 10 FPS
TH = 2 FT	TH = 4 FT	TH = 2 FT	TH = 4 FT
R = 98,561	R = 275,684	R = 152,066	R = 325,474

RUN 39 (.1) - 21 (.2)	50%	RUN 21 (.2) - 41 (.235)	15%
RUN 21 (.2) - 40 (.25)	20%	RUN 41 (.235) - 40 (.25)	6%

Calculation Data

<u>% INC μ</u>	<u>% INC R</u>	<u>SPEED</u>	<u>THICKNESS</u>
6% (41-40)	2.2	L	L
	2.7	L	H
	.8	H	L
	2.1	H	H
15% (21-41)	6.1	L	L
	6.4	L	H
	1.4	H	L
	4.8	H	H
20% (21-40)	8.2	L	L
	8.9	L	H
	2.1	H	L
	6.7	H	H

Calculation Data (Continued)

<u>% INC μ</u>	<u>% INC R</u>	<u>SPEED</u>	<u>THICKNESS</u>
50% (39-21)	15.1	L	L
	19.8	L	H
	6.0	H	L
	15.2	H	H

O. Summary of friction effect

The effect of the coefficient of friction (defined as the normal force divided by the tangential force, for the lack of any better understanding of the phenomenon) is difficult to appreciate. If one is dealing with dynamic friction, the coefficient can vary from .025 to as high as .5. Most of the published data confines the range from .1 to .3.

Milano's program indicates that for small changes in the friction coefficient, i.e., 6 percent (.235 to .25) there is only a small effect on the overall resistance, i.e., 3 percent. However a 50 percent increase, .1 to .2, could cause a 70 percent error in the resistance estimate.

Recent model tests (Lecourt, 1975) have indicated that an increase in the coefficient from .037 to .28 (7.5 fold increase) has lead to a 40 percent increase in resistance. Full scale tests run by the Wärtsilä Shipyard in Finland (Makimer, 1975) have indicated a 30 percent decrease in resistance of the ice-breaking vessel SILMA after being coated with a low friction coating. Unfortunately, no friction measurements were taken on the vessel.

In summary, it can be said that small errors in measuring the friction coefficient, i.e., ± 10 percent, will have only a minor effect on the resistance prediction, however, one must know or have some good idea of what the friction coefficient is, i.e., .10 or .20.

P. Effect of propulsion equipment measurements

From the equations in the next section, it can be seen that the relationship between the measured parameters and the computed resistance in a linear one and any error made in measuring the parameter, i.e., torque, RPM, velocity or propulsive coefficient (which is estimated from the model tests) will result in an error of equal magnitude in computing the resistance. Several examples of typical values are presented.

Q. Equations

1. Effect of thrust

$$\text{RESISTANCE} = \text{THRUST}_{(\text{AT SHAFT})} \times \text{P.C.}$$

@ 13 FPS 4' THICKNESS R = 338,633

$$\text{THRUST} = \frac{R}{\text{P.C.}} = \frac{338633}{.6} = 564,388$$

	% INC T_{SHAFT}	% INC R
$T_{\text{SHAFT}} = 564,388$		
P.C. = .6	5	5
RESIS = 338,632	($T = 564388 - T = 536000$)	
$T_{\text{SHAFT}} = 536,000$		
P.C. = .6	10	10.2
RESIS = 321,600	($T = 564388 - T = 507000$)	
$T_{\text{SHAFT}} = 507,000$		
P.C. = .6		
RESIS = 304,200		
$T_{\text{SHAFT}} = 564,388$	5	5
P.C. = .6	($P.C. = .6 = P.C. + .57$)	
RESIS = 338,632		
$T_{\text{SHAFT}} = 564,388$	10	10
P.C. = .57	($P.C. = .6 - P.C. = .54$)	
RESIS = 321,701		
$T_{\text{SHAFT}} = 564,388$		
P.C. = .54		
RESIS = 304,769		

2. Effect of torque

$$\text{SHP} = \frac{R \pi Q N}{550}$$

$$\text{EHP} = \text{SHP} \times \text{P.C.}$$

$$\text{RESISTANCE} = \frac{\text{EHP} \times 550}{V}$$

$$\text{RESISTANCE} = \frac{2 \pi Q N \text{ P.C.}}{V}$$

Vel. -

5-7 FPS
7.5 - 10 FPS
9 - 10 FPS
9.5 - 10 FPS

FACTOR/ERROR

FACTOR/ERROR

P.C. = .6
5% .57
10% .54

N = 2.92 RPS
5% 2.77 RPS
10% 2.63 RPS

RUN 21 13 FPS 4' ICE: $EHP = \frac{RES \times VEL}{550} = \frac{338633 \times .3}{550} = 8004$

$SHP = \frac{EHP}{P.C.} = \frac{8004}{.6} = 13340$

$Q = \frac{550 \times SHP}{2 \times N} = \frac{(550)(13340)}{2 \times (2.92)} = 399904$

Q = 399904
N = 2.92 RPS
V = 5 FPS
P.C. = .6
R = 880428
Q = 380000
N = 2.92 RPS
V = 5 FPS
P.C. = .6
R = 836608
Q = 360000
N = 2.92 RPS
V = 5 FPS

% INC Q
5
(Q=399904-Q=380000)

% INC R
4.9

10
(Q=399904-Q=360000) 9.9

P.C. = .6
R = 792576
Q = 399904
N = 2.92 RPS
V = 5 FPS
P.C. = .6
R = 880438
Q = 399904
N = 2.77 RPS
V = 5 FPS

% INC N
5
(N=2.92 - N=2.77)

% INC R
5.1

10
(N=2.92 - N=2.63) 9.9

P.C. = .6
R = 835210
Q = 399904
N = 2.63 RPS
V = 5 FPS
P.C. = .6
R = 792997

% INC P.C.
5
(P.C.=.6 - P.C.=.57)

% INC R
5

P.C. = .6
R = 880439
Q = 399904
N = 2.92
V = 5 FPS

10
(P.C.=.6 - P.C.=.54)

10

$$P.C. = .57$$

$$R = 836417$$

$$Q = 399904$$

$$N = 2.92$$

$$V = 5 \text{ FPS}$$

$$P.C. = .54$$

$$R = 792395$$

$$R = \frac{2\pi Q N P.C.}{V}$$

$$Q = 399904 \quad N = 2.92 \quad P.C. = .6$$

VEL		% INC VEL	RESISTANCE	% INC R
5			880439	
7	-	30	628885	28.5
7.5			586959	
10	-	25	440219	25
9			489133	
10	-	10	440219	10
9.5			463389	
10	-	5	440219	5

R. Electrical power measurement

By noting voltage and amperage to the motor, a rough estimate of the power being used can be obtained.

$$P = E I \text{ watts}$$

$$\text{SHP} = \text{watts}/746$$

$$\begin{aligned} \text{RESISTANCE} &= \frac{\text{EHP} \times 550}{V} \\ &= \frac{EI \times 550 P.C.}{746 V} \end{aligned}$$

$$\text{RESISTANCE} = \frac{.7372 EI P.C.}{V}$$

Thus, as in the previous equations, due to the linear relationship between power and resistance, an error in measuring voltage or amperage would lead to an equal percentage error in the resistance computed.

S. Summary of propulsion equipment

It is evident from the equations presented here and in other sections of this report that the relationship between propulsion equipment measurements, i.e., torque, thrust, volts, amps, RPM and the prediction, or in this case, the calculation of resistance, is a direct one. That is, any error made in measuring these parameters leads to an error of equal magnitude in the resistance calculated.

T. Effect of draft

$$1. \text{ RUN } 45 \quad \sigma_f = 15,000 \quad \sigma_c = 50,000 \quad \mu = .2 \quad \text{SG} - .92 \text{ DR } 28$$

2. RUN 44 $\sigma_f = 15,000$ $\sigma_c = 50,000$ $\mu = .2$ SG = .92 DR 30

THICKNESS = 2 FT

VEL	RESISTANCE (45)	RESISTANCE (44)	% DIFF
5	95,440	92,088	3.5
10	149,259	144,460	3.2
15	261,422	253,155	3.1
20	425,813	411,587	3.3

THICKNESS = 4 FT

5	266,586	251,771	5.5
10	313,702	293,055	6.6
15	369,833	345,800	6.4
20	486,721	454,911	6.5

THICKNESS = 6 FT

5	585,930	558,699	4.6
10	642,720	611,227	4.8
15	698,052	656,581	5.9
20	771,628	724,291	6.1

U. Summary of draft effect

The change in draft of the POLAR STAR from 28 feet to 30 feet changes many of the parameters that enter the icebreaking prediction equation, i.e., displacement changes from 10,860 tons to 12,200 tons, the bow angle change from 15° to 14.5° , etc. Therefore, a whole new data set was used in Dr. Milano's program for a draft of 30 feet (see Appendix B). The results of the comparison indicate that when the draft is increased to 30 feet, the overall ice resistance decreased from 3 to 6 percent with the larger percentages at the higher ice thicknesses. See Figure 8.

In addition to the icebreaking capability, there are two other aspects of increased draft that must be kept in mind. One is the effect on the extractor difficulty encountered; this effect will be covered in the Ramming and Extractor Prediction aspect. The record aspect is the decreased clearance (overhang) caused by increased draft. The POLAR STAR was designed with a vertical clearance of 5 feet between the 28 foot waterline and the start of the curvature of the stern to the vertical. The increased draft would decrease this clearance to approximately 3 feet.

VI. RAMMING AND EXTRACTION PREDICTIONS FOR THE POLAR STAR BY CDR G. P. VANCE

A. Abstract

This report contains predictions for the POLAR STAR in the ramming mode. The calculations indicate that the POLAR STAR would be capable of breaking almost 21 feet of homogenous ice in ramming (see Appendix C).

Utilizing the theory available the extraction difficulty is also predicted.

B. Introduction

The prediction of a vessel's capability to break ice in the ramming mode,

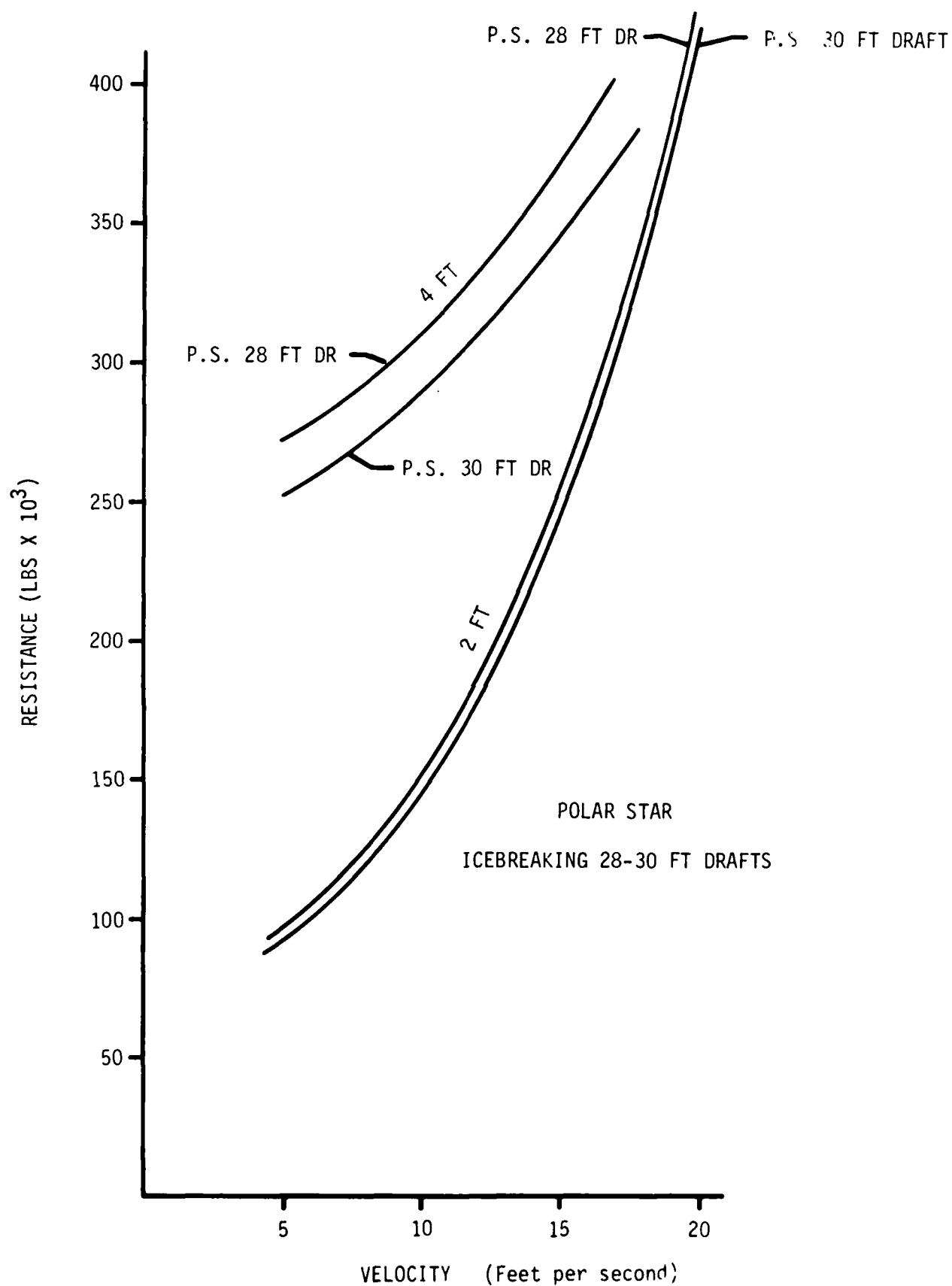


Figure 8

i.e., backing up and ramming into the ice and coming to a complete stop, has been attempted by White (1969) and modified by Lewis (1970). The method assumes a rigid flat sheet of homogenous ice with a specified tensile strength. The vessel rides up on the ice sheet and exerts a downward force on the ice until failure occurs. The downward force generated is a function of the surge, heave and pitch motions of the ship and the impact velocity and displacement of the ship (see Fig. 9).

White assumed a relatively simple relationship between the downward force exerted to break the ice and Lewis introduced some field data to refine the force equation.

The extraction difficulty is a more elusive number to pin down. White assumed that the extraction difficulty was a function of the downward force, the coefficient of static friction and the bow angles. He then formed a ratio of the thrust needed to extract the vessel from the ice and the bollard forward thrust available from the vessel. This "Difficulty of Extraction Ratio" was not an absolute number, i.e., it was a number one could compare to other vessels such as the WIND class and the GLACIER.

This report presents calculations made for the POLAR STAR.

Where: B = maximum beam in feet
 d = draft of the vessel in feet
 C_w = water plane area coefficient
 C_b = block coefficient
 SA = spread angle complement in radians
 f_k = coefficient of kinetic friction (assumed to be .2 for uniformity)
 BA = bow angle in radians

Figure 9 is a plot of the predicted ice thickness that can be broken by the POLAR STAR. The sample calculations are shown in the appendices. It should be noted the plot reflects a 28 foot draft and $\sigma_f = 235$ PSI.

Lewis (1970) has indicated that $k = .45$ used by White may have been too low and recommends a figure of $k = 1.02$ from full scale tests, he also indicates that a $\sigma_f = 235$ PSI may be too high and a more realistic figure would be in the area of 100 to 140 PSI.

C. Ramming capability

The equations used in predicting the thickness of ice by White are:

$$F_{BZR} = k \cdot t^2$$

substituting value of .45 for k and 235 PSI for the tensile (flexural) strength of ice:

$$t_r = \frac{F_{BZR}}{100}$$

where " t_r " stands for thickness of standard ice broken due to ramming, in inches, and " F_{BZR} " is the relatively sustained downward force against the ice in pounds. This last parameter " F_{BZR} " further depends on three factors: impact velocity " v " in FPS, ship displacement " Δ " in pounds, and the White Ratio "WR". The equation for calculating " F_{BZR} " is as follows:

$$F_{BZR} = 6.64 V_j (WR \Delta)^{0.845}$$

PREDICTION OF THICKNESS OF STANDARD SEA ICE BROKEN
AS A RESULT OF RAMMING AS A FUNCTION OF IMPACT VELOCITY

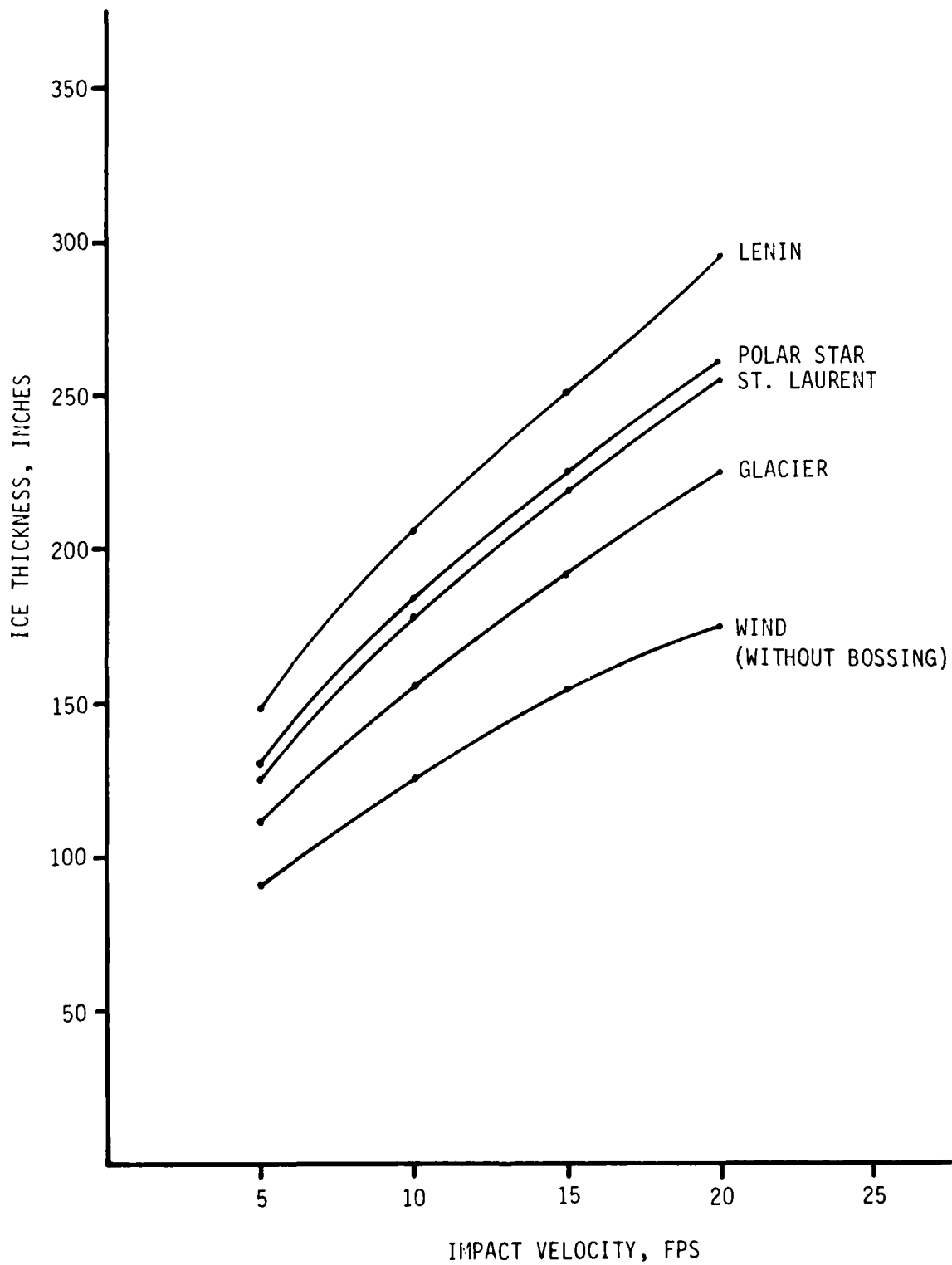


Figure 9.

The White Ratio is a coefficient of performance that was developed by White, in his study of the mechanics of icebreaking. The equation used to obtain this numbers is:

$$WR = 1.000234(10.72+B/d)(0.1833+C_W)(1.652-C_b) \times (6.14-SA^2)(0.725-f_k)(1.718-BA)$$

The recommended equations would be:

$$F_{BRZ} = 1.02 \sigma_f t^2 \text{ or}$$

$$t_r = \frac{F_{BZR}}{106.25}$$

$$\text{i.e., } \sigma_f \approx 104.16 \text{ PSI} \approx 15000 \text{ PSF} \approx 7.32 \text{ kg/cm}^2$$

D. Extraction difficulty

White (1969) has proposed an index of extraction difficulty that reflects a computed extraction thrust based on the hull form and coefficient of static friction divided by the maximum bollard thrust available. This ratio is more of a comparison to other vessels rather than an exact indication of the thrust available or necessary to extract the vessel after ramming. Figure 10 shows the computed index of extraction for several icebreakers and that of the POLAR STAR. The POLAR STAR curve is presented for a bow angle of 15° and a bow angle of 30°. The equations are very sensitive to the bow angle and this fact is reflected in the careful design of the POLAR STAR bow. The POLAR STAR has a bow angle of 15° at the 28 foot water line this angle gradually increases to 30° at the 18 foot water line where it is carried to a 6 foot vertical step. Thus when computing the extraction difficulty one must determine how far the ship will penetrate the ice to determine its extraction difficulty. In most instances of ramming the momentum of the vessel will be sufficient to carry it to a trim of 1° or 2° which will insure a bow angle of greater than 15° and close to 30°. Thus the POLAR STAR should not encounter any unusual difficulty in extracting itself from a ram (Fig. 10).

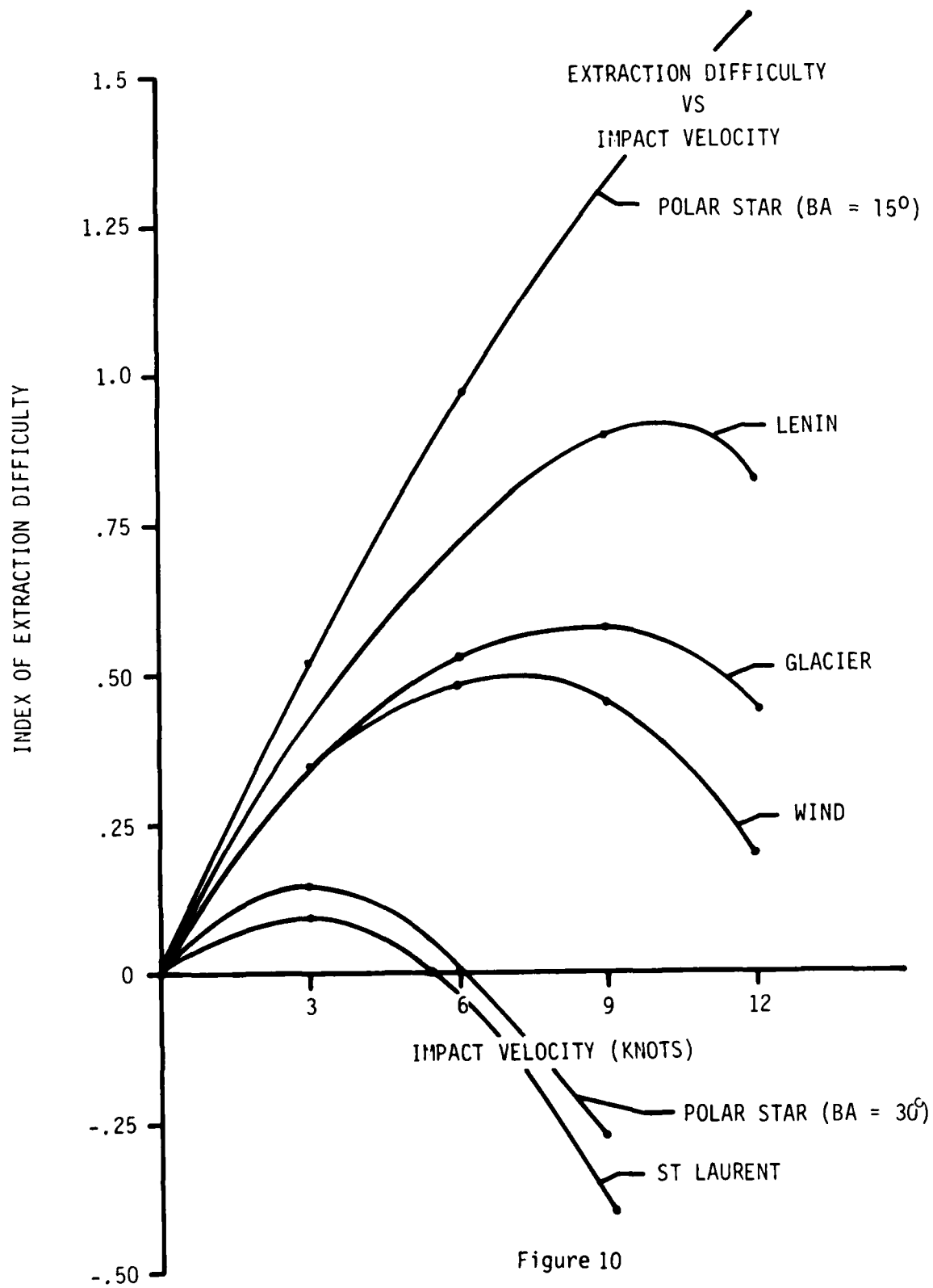


Figure 10

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APPENDICES

- A. Curves of Resistance versus Velocity and Thrust versus Velocity
- B. POLAR STAR 30 ft Draft Particulars
- C. Sample Calculation
- D. Literature Citations and Selected Bibliography

APPENDIX A

Curves of Resistance versus Velocity
and Thrust versus Velocity

APPENDIX A: CURVES OF RESISTANCE VERSUS VELOCITY AND THRUST VERSUS VELOCITY

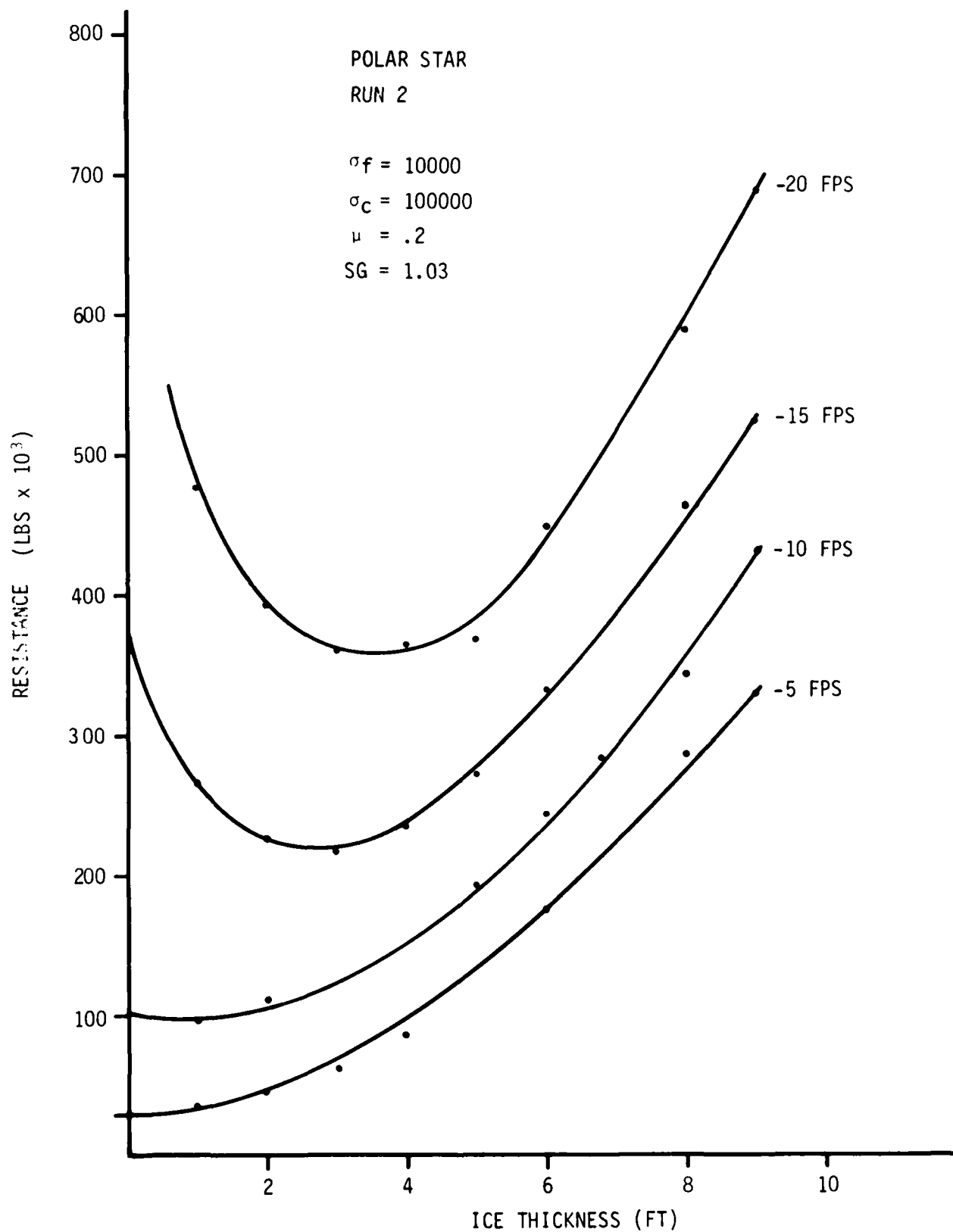


Figure 11.

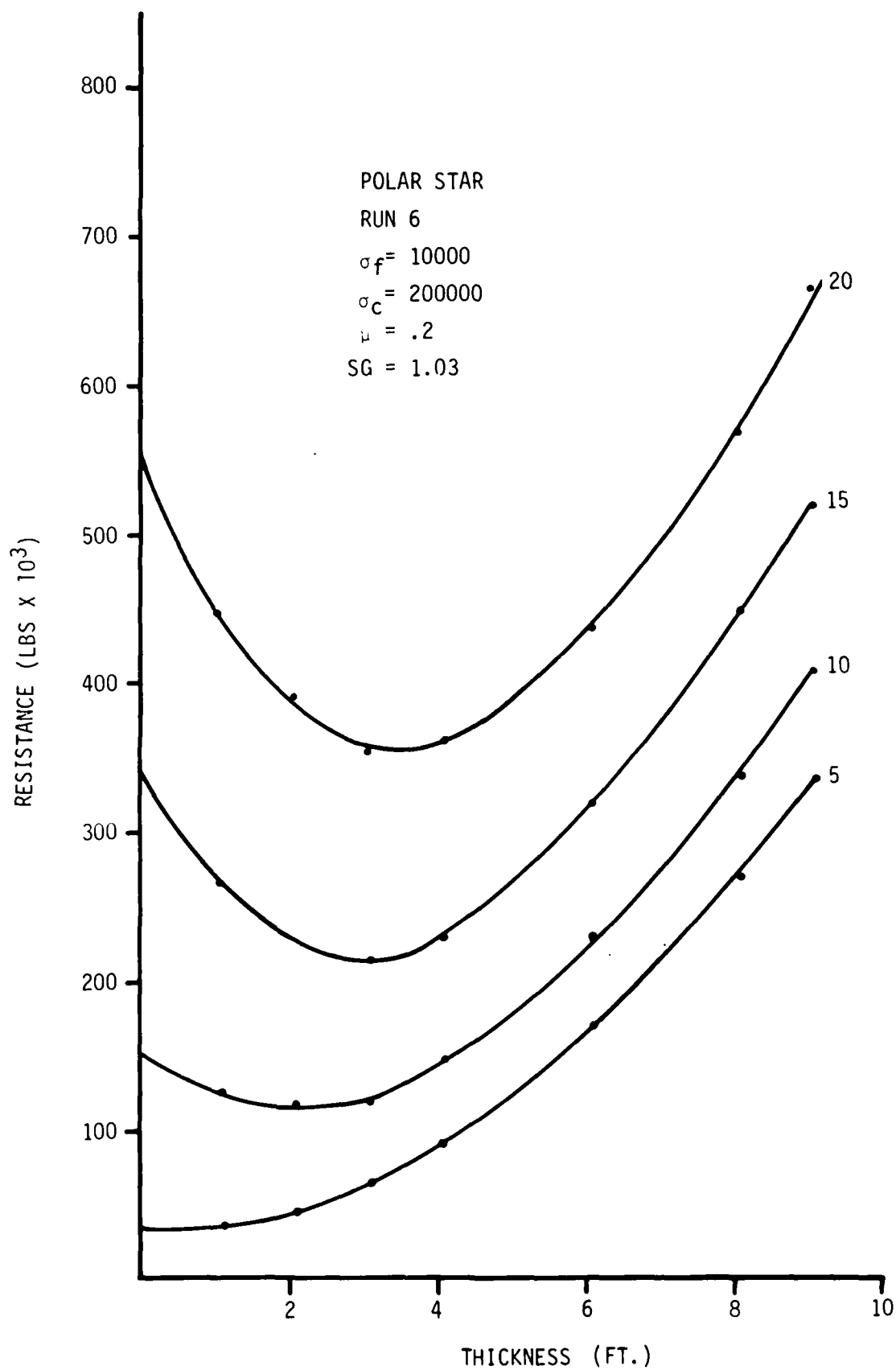


Figure 12.

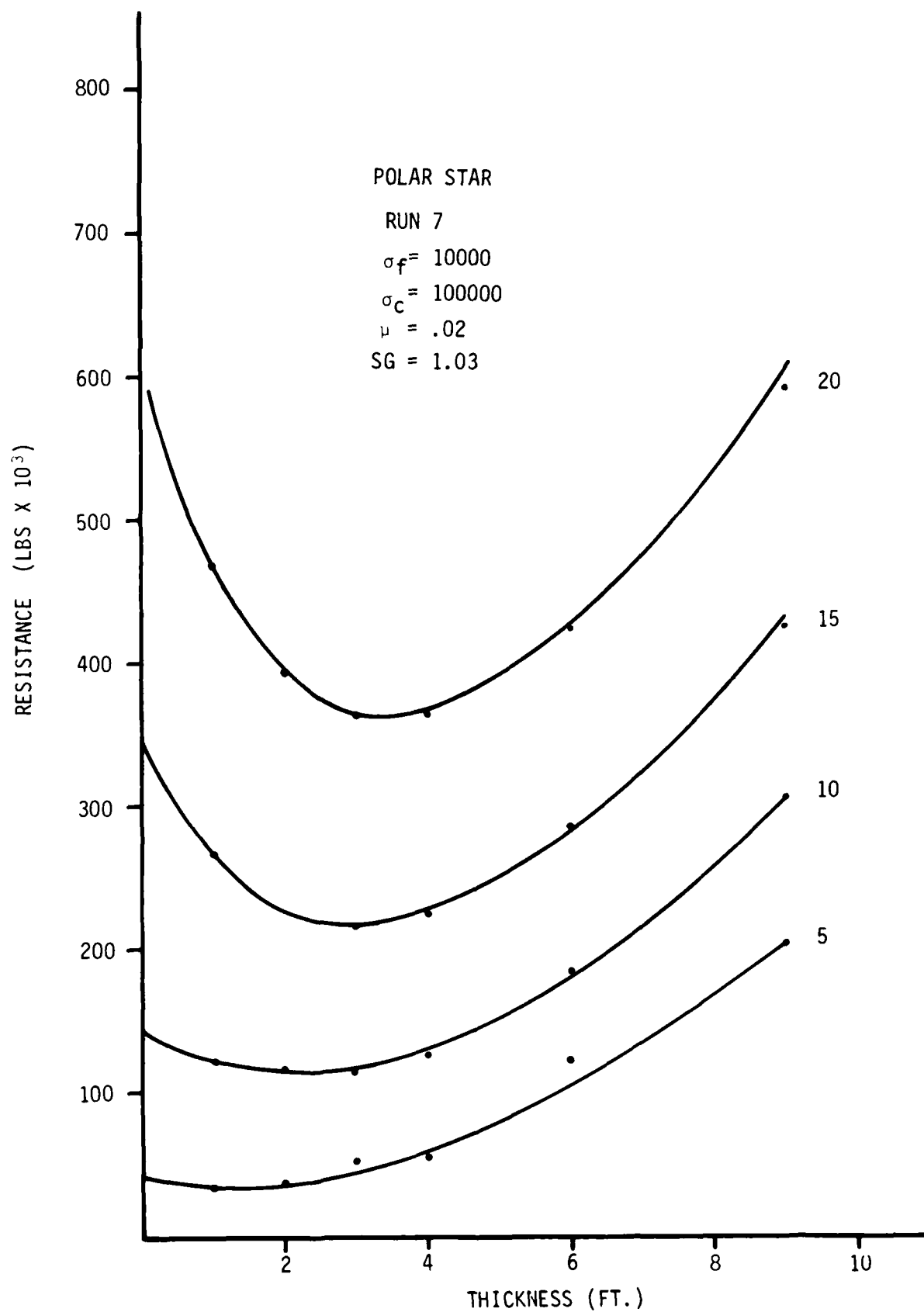


Figure 13.

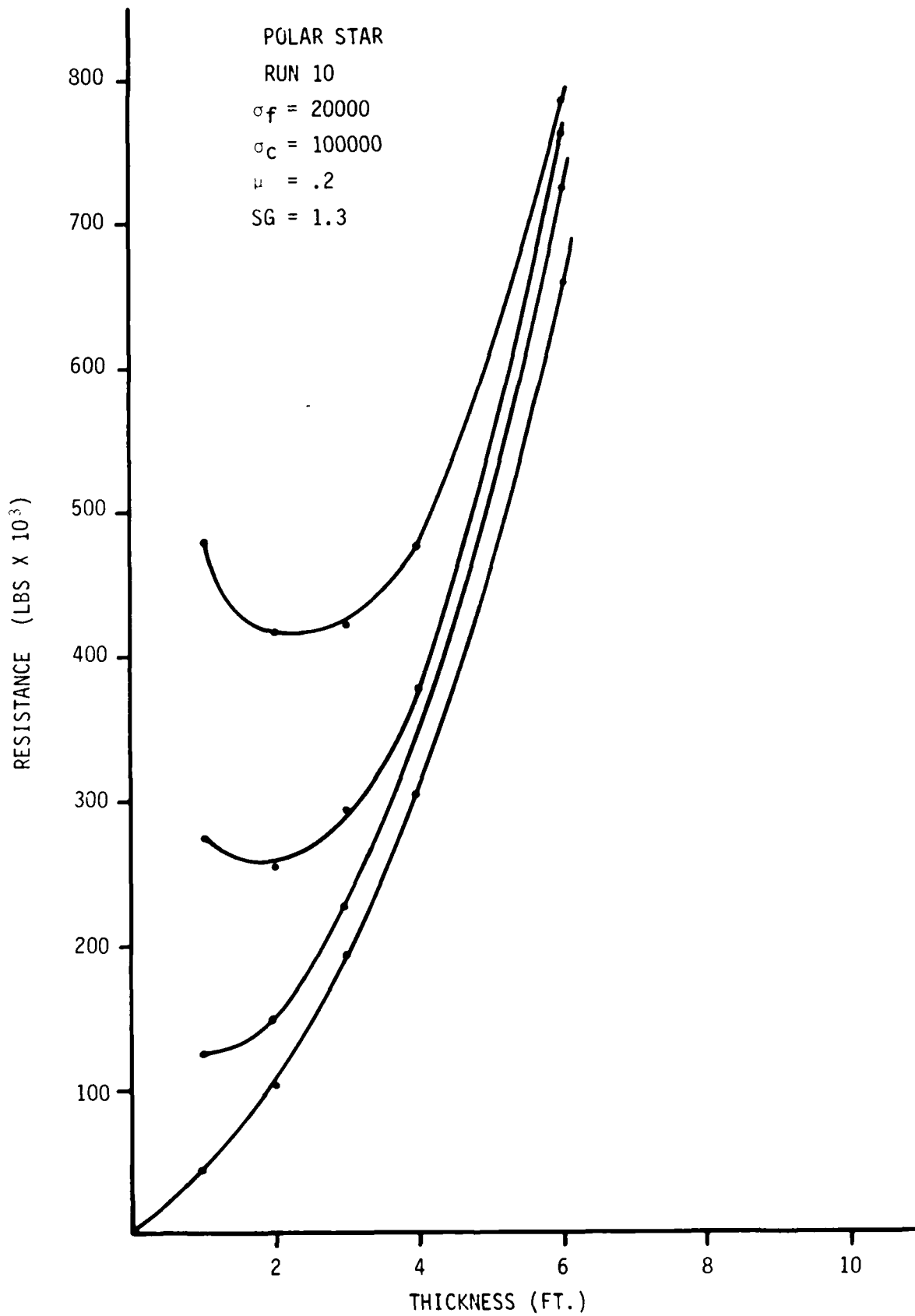


Figure 14

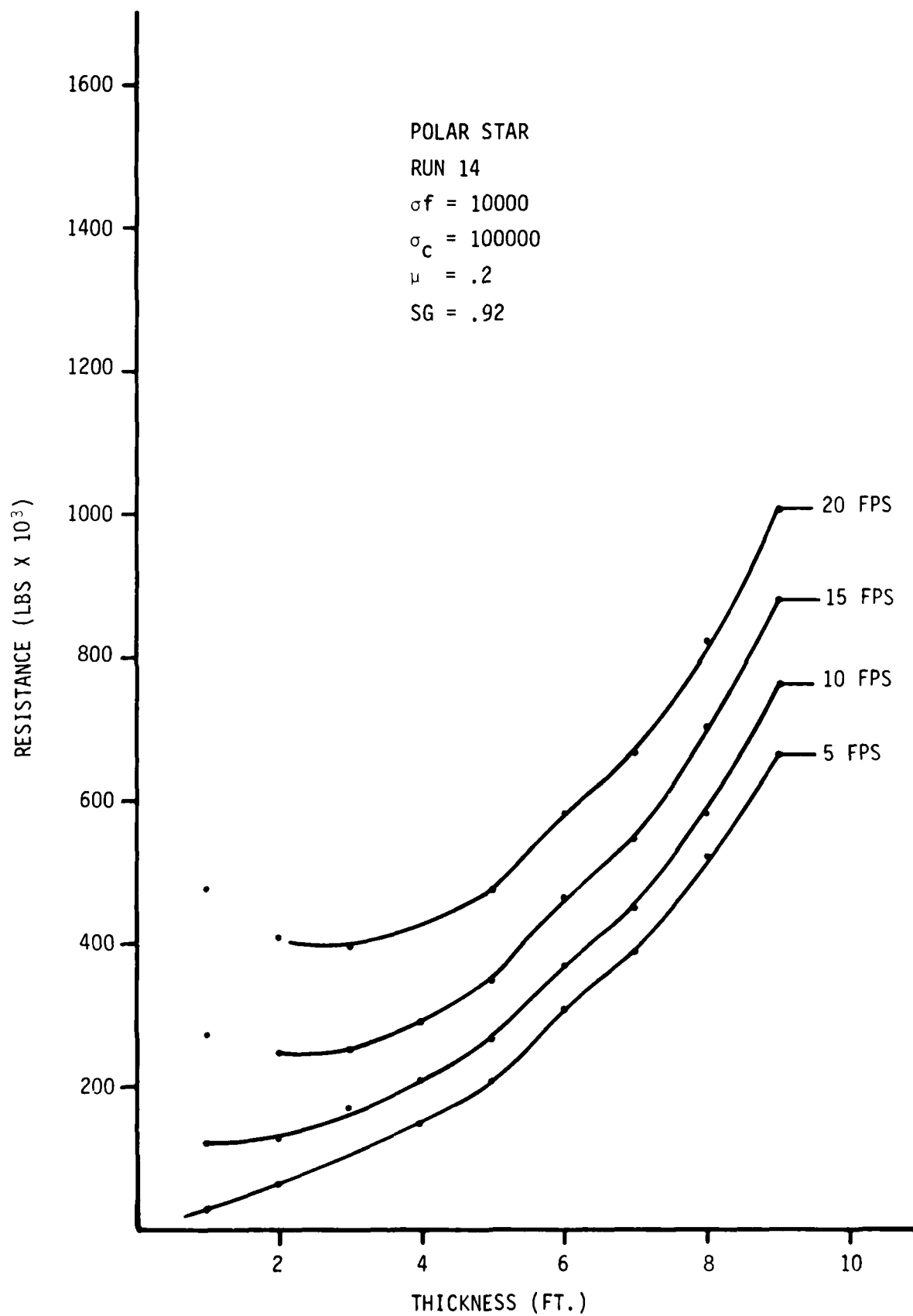


Figure 15

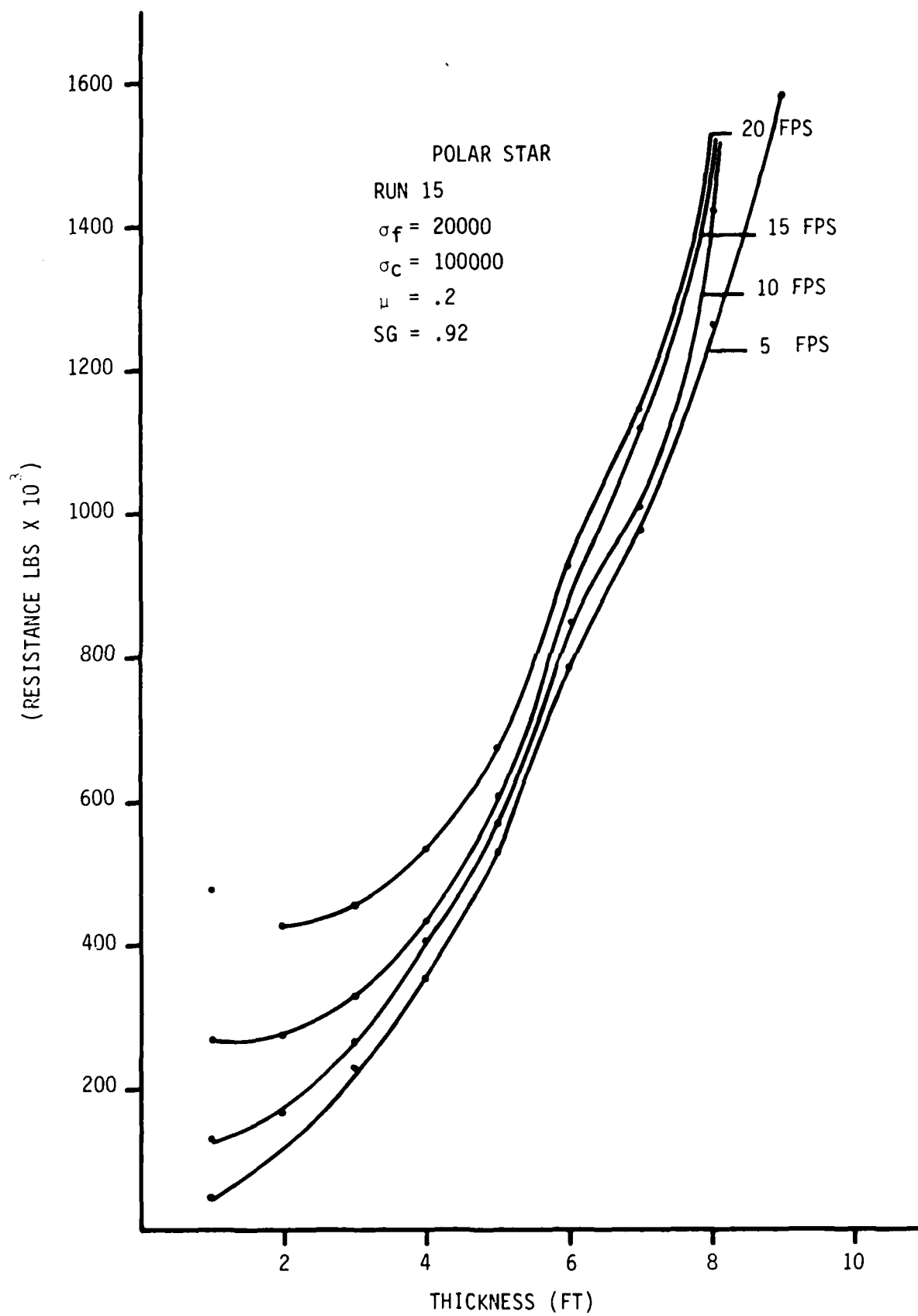


Figure 16.

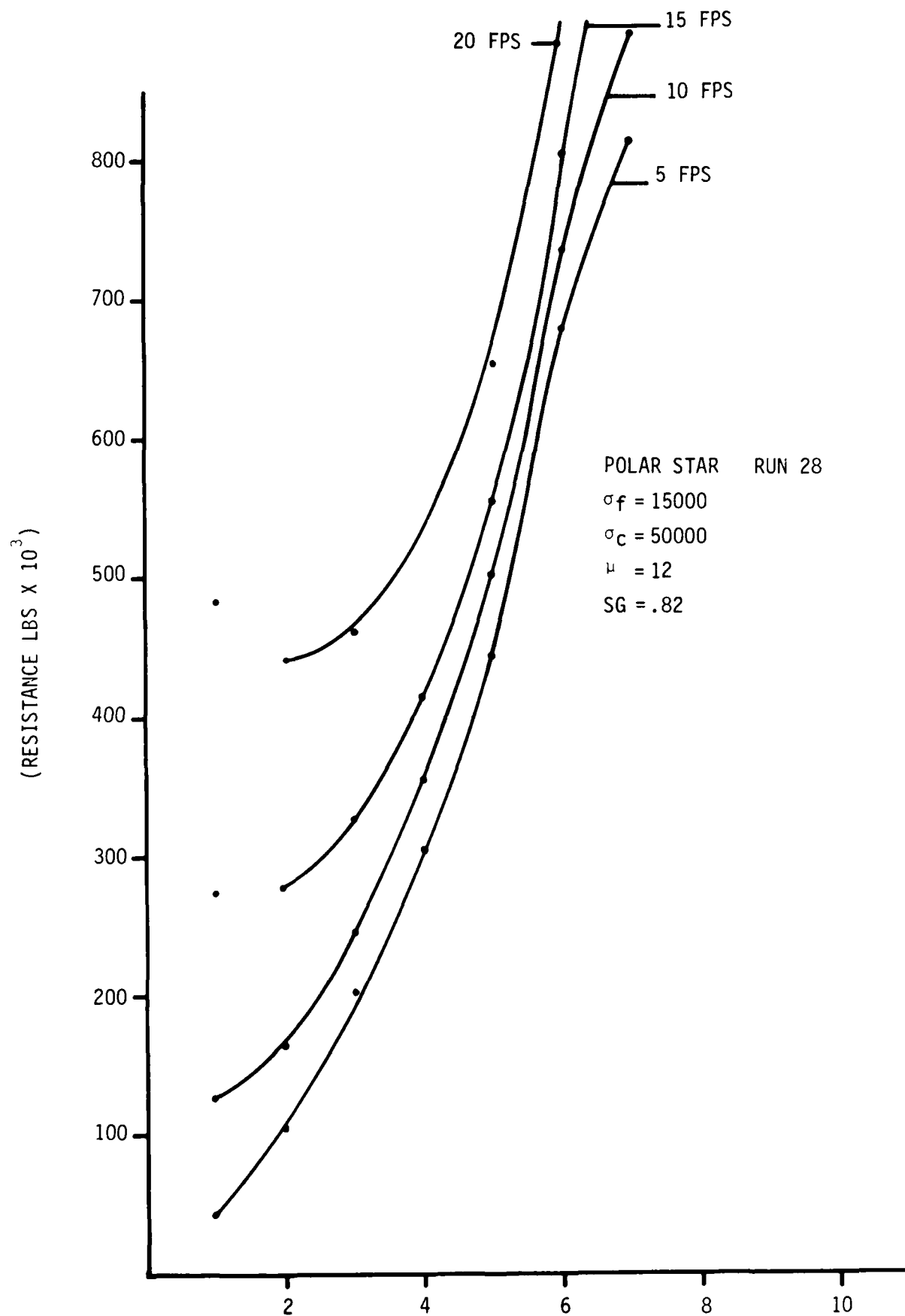


Figure 17

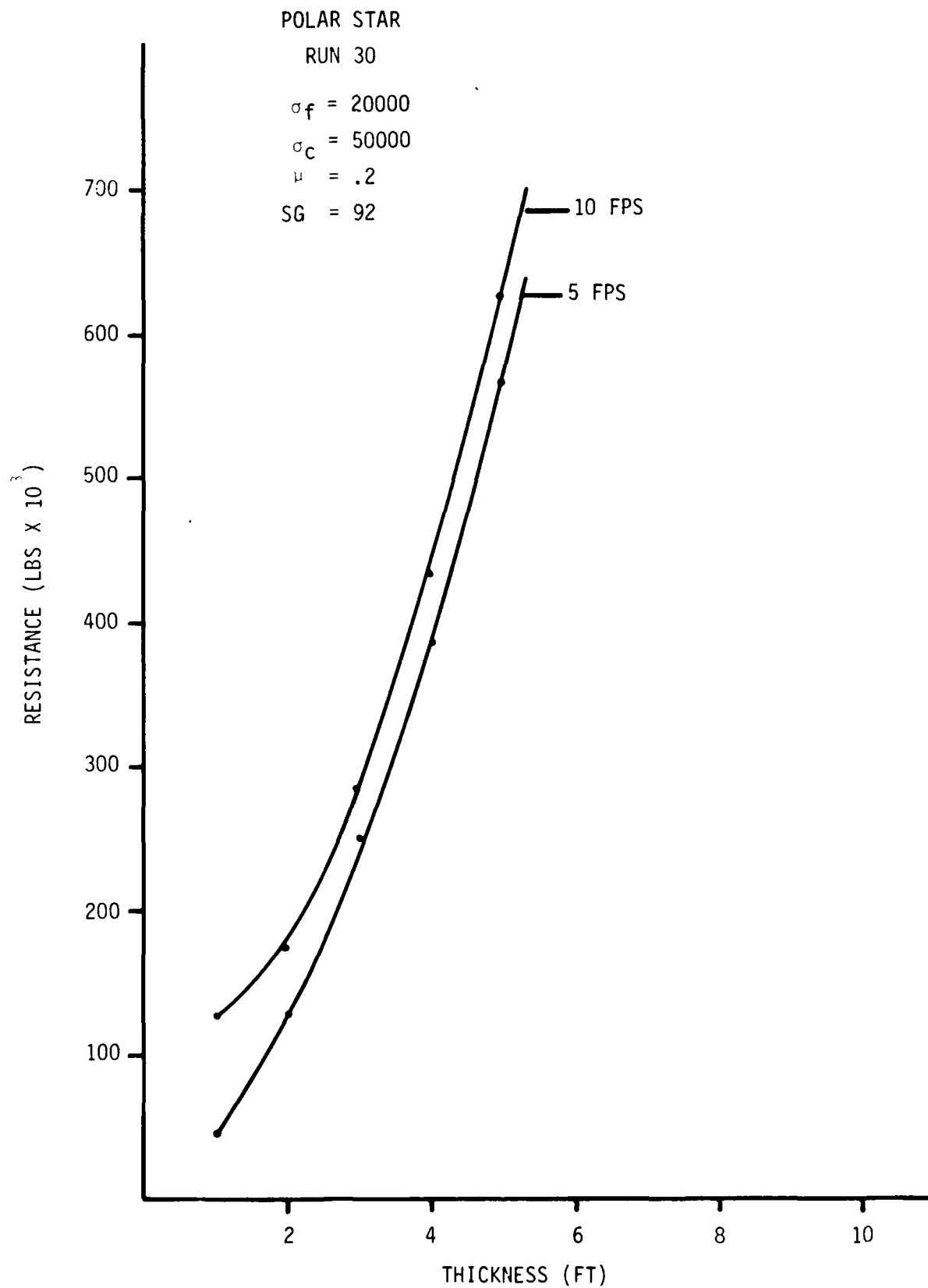


Figure 18.

APPENDIX B

POLAR STAR 30 ft Draft Particulars

POLAR STAR 30' particulars

$$LCF = 2.4 \text{ ft fsd}$$

$$LWL = 363.75 \text{ ft}$$

$$LCG = 3.1 \text{ ft fwd}$$

$$d = 30 \text{ ft}$$

$$K_6 = 28 \text{ ft}$$

$$BWL = 79.33 \text{ ft}$$

$$\Delta = 12,200 \text{ tons} - 27,328,000 \text{ lbs}$$

$$BA = 14.5^\circ = 25307 \text{ RAD}$$

$$SA = .42 \text{ RAD}$$

$$F_s = .6$$

$$C_w = .762$$

$$C_M = .85$$

$$C_p = .585$$

$$KM_L = 379.5$$

$$GM_L = 351.5$$

$$C_b = .5$$

$$\text{Water line entrance angle} = 59.5^\circ$$

$$\begin{aligned} WR_{30} &= (.000234) \left(10.72 + \frac{79.33}{30} \right) (.1833 + .762) (1.652 - .5) \\ &\quad (6.14 - (.42)^2) (.725 - .2) (1.7180.25307) \\ &= (.000234) (13.364) (.9453) (1.152) (5.9636) (.525) (1.457) \\ &= .0155346 \end{aligned}$$

$$\begin{aligned} F_{BZR} &= 6.64 \text{ V} (.0155346 \times 2.7328 \times 10^7)^{.845} \\ &= 6.64 \text{ V} (5.69617 \times 10^4) \\ &= 3.78226 \times 10^5 \text{ (V)} \end{aligned}$$

APPENDIX C
SAMPLE CALCULATIONS

POLAR STAR

Sample calculations of ramming capability (28 foot draft)

Eqns: 1. $t_r = \frac{F_{BZR}}{100}$

2. $F_{BZR} = 6.64 v (WR \times \Delta)^{0.845}$

3. $WR = \frac{0.000234(10.72 + \frac{B}{d})(0.1833 + C_w)(1.652 - C_b)}{(6.14 - SA^2)(0.725 - f_k)(1.718 - BA)} \times$

POLAR STAR

B = 78.0 feet
d = 28.0 feet
C_w = .74
C_b = .49
SA = .420
f_k = .2
BA = .261
Δ = 24,333,120 pounds

First, the White Ratio, WR was computed:

$$WR = \frac{0.000234(10.72 + \frac{78.0}{28.0})(0.1833 + .74)(1.652 - .49)}{6.14 - (.420)^2 (0.725 - .2)(1.718 - .261)} \times$$

$$WR = .015467$$

Then F_{BZR} @ speeds of 5 FPS, 10 FPS, 15 FPS, and 20 FPS were calculated in the respective order:

$$\begin{aligned} @5FPS: F_{BZR} &= 6.64(5)(.01546 \times 24,333,120)^{0.845} \\ &= 1,707,486.35 \text{ pounds} \end{aligned}$$

$$\begin{aligned} @10FPS: F_{BZR} &= 6.64(10)(.01546 \times 24,333,120)^{0.845} \\ &= 3,414,972.71 \text{ pounds} \end{aligned}$$

$$\begin{aligned} @15FPS: F_{BZR} &= 6.64(15)(.01546 \times 24,333,120)^{0.845} \\ &= 5,122,459.06 \text{ pounds} \end{aligned}$$

$$\begin{aligned} @20FPS: F_{BZR} &= 6.64(20)(.01546 \times 24,333,120)^{0.845} \\ &= 6,829,945.42 \text{ pounds} \end{aligned}$$

Finally t_r was computed:

$$@5FPS: t_r = \frac{1,707,486.35}{100} = 130" \text{ or } 10.8'$$

$$@10FPS: t_r = \frac{3,414,972.71}{100} = 184" \text{ or } 15.4'$$

$$@15FPS: t_r = \frac{5,122,459.06}{100} = 226" \text{ or } 18.9'$$

$$@20\text{FPS} \quad t_r = \frac{6,829,945}{100} = 261'' \text{ or } 21.8'$$

The following is a table of values computed

v	F _{BRZ}	t _r in.	t _r ft.
5	1,707,486.35 pounds	130	10.8
10	3,414,972.71 pounds	184	15.4
15	5,122,459.06 pounds	226	18.9
20	6,829,945.42 pounds	261	21.8

The values of t_r in inches were then plotted against a scale of impact velocity in FPS using speeds of 5, 10, 15, and 20 see Figure 9.

POLAR STAR

INDEX OF EXTRACTION DIFFICULTY (EQNS)

CALCULATION OF E_t

$$\text{Extraction difficulty index} = \frac{E_t}{T_{1b}}$$

$$1. \quad E_t = \frac{F_{BZR}}{\frac{a_7}{b_7} \cos \phi - \sin \phi}$$

$$2. \quad a_7 = (\cos SA) \cos(BA + \phi) + f_s \sin(BA + \phi)$$

$$3. \quad a_7 = (\cos SA) \sin(BA + \phi) + f_s \cos(BA + \phi)$$

$$4. \quad = \frac{A_4 C_3 - A_3 C_4}{A_3 B_4 - A_4 B_3}$$

$$5. \quad A_3 = (LBP)(B)(CW)(64.2) \text{ (Constant)}$$

$$6. \quad A_4 = \frac{F_{BZR}}{\tan BA}$$

$$7. \quad B_3 = A_3 (LCG - LCF) \text{ (Constant)}$$

$$8. \quad B_4 = F_{BZR} (d - KG) + \frac{LBP - LCG}{2} - (\Delta - F_{BZR}) (GM_1) \tan BA$$

$$9. \quad C_3 = F_{BZR}$$

$$10. \quad C_4 = F_{BZR} \frac{LBP}{2} - LCG$$

POLAR STAR 28' particulars

LCF = 1.9 ft	BA = .261
LBP = 352.0 ft	SA = .420
LCG = 3.3 ft	$f_s = .2 \times .6$
d = 28.0 ft	CW = .74
KG = 28.0 ft	C _B = .49
B = 78.0 ft	KML = 378.1 ft
$\Delta = 10863(\text{tons}) \times 2240(\text{lbs}) =$	6M _L = 350.1
24333120 lbs	

POLAR STAR

Index of extraction difficulty (calculations)

Calculation of E_t

• @ 5FPS, $F_{BZR} = 1,707,486.354$

$$A_3 = (352.0)(78.0)(.74)(64.2) = 1,304,379.65$$

$$A_4 = \frac{1,707,486.354}{\tan(.261)} = 6392862.96$$

$$B_3 = (1304379.65)(3.3-1.9) = 1,826,131.51$$

$$B_4 = -1707486.354 (28-28) + \frac{352}{2} - 3.3 - \frac{(24,333,120-1707,486.354)}{(350.1)}$$

$$= 1707486.354 (646.8) - 7921234339$$

$$B_4 = 1104430312 \times -9,025,636,513$$

$$C_3 = 1707486.354$$

$$C_4 = (1707486.354) \frac{352}{2} - 3.3 = 294,882,893.3$$

$$= \frac{A_4 C_3 - A_3 C_4}{A_3 B_4 - A_4 B_3}$$

$$= \frac{(6,392.863)(1,707,486.354) - (1,304,379.65)(294,882,893)}{(1,304,379.65)(9,025,636.513) - (6,392,863)(1,826,131)}$$

$$= \frac{(1.0916 \times 10^{13}) - 3.846 \times 10^{14}}{(-1.17728 \times 10^{16}) - 1.1674 \times 10^{13}}$$

$$= \frac{-3.73681 \times 10^{14}}{-1.178 \times 10^{16}} = .03172 \quad \text{Radians}$$

$$a_7 = \cos SA \cos(BA + a) + f_s \sin(BA + a)$$

$$\begin{aligned}
&= \cos .42 \cos (.262+.03172) + .6 \sin (.262+.03172) \\
&= (.913)(.957) + .6 (.289) \\
&= .874 + .1734 \\
&= 1.0474
\end{aligned}$$

$$\begin{aligned}
b_7 &= (-\cos SA) \sin (BA+\theta) f_s \cos (BA+\theta) \\
&= (-.913) (.2895) + .6 (.957) \\
&= -.2643 + .5743 - .31
\end{aligned}$$

$$\frac{a_7}{b_7} = \frac{1.0474}{.31} = 3.378$$

$$\begin{aligned}
E_t &= \frac{F_{BRZ}}{\frac{a_7}{b_7} \cos \theta - \sin \theta} \\
&= \frac{1.707486 \times 10^6}{3.378(\cos .03172) - \sin .03172} \\
&= \frac{1.707486 \times 10^6}{3.378(.99949)} = \frac{1.707486 \times 10^6}{3.3763 - .03171} \\
&= 5.10522 \times 10^5
\end{aligned}$$

$$T_{1B} = 973 \text{ 700 lbs (LASKY, NSRDC Rpt, 1971)}$$

$$\frac{E_T}{T_{IB5}} = \frac{5.10522 \times 10^5}{9.737 \times 10^5} = .52431$$

$$\bullet @ 10\text{FPS, } F_{BRZ} = 3,414,973 \text{ lbs}$$

$$A_3 = 1304378$$

$$B_3 = 1826132$$

$$C_3 = F_{BZR} = 3.414973$$

$$A_4 = \frac{F_{BZR}}{\tan BA} = \frac{3414973}{\tan .261} = 1.27857 \times 10^7$$

$$\begin{aligned}
B_4 &= F_{BZR} d-KG + \frac{LB^2}{2} - LC6 - (\Delta = F_{BZR})(GM_1) \\
&= (-3414973)(646.8) - (24,333,120 - 3414973)(350)
\end{aligned}$$

$$= (-2.2088 \times 10^9) - (7.321 \times 10^9)$$

$$= -9.53 \times 10^9$$

$$C_4 = F_{BZR} \frac{LB^2}{2} - LCG = 3.414973 \times 10^5 (172.7)$$

$$= 5.89765837 \times 10^8$$

$$\theta = \frac{(1.27857 \times 10^7)(3.414973 \times 10^6) - (1.304378 \times 10^6)(5.898 \times 10^8)}{(1.304378 \times 10^6)(-9.53 \times 10^9) - (1.2785 \times 10^7)(1.826 \times 10^6)}$$

$$\theta = \frac{4.4 \times 10^{13} - 7.7 \times 10^{14}}{-1.210^{16} - 2.3 \times 10^{13}} = \frac{-7.3 \times 10^{14}}{-1.2 \times 10^{16}}$$

$$= 061 \text{ RAD}$$

$$3.485$$

$$a_7 = (\cos .42) \cos (.262 + .061) + .6 \sin (.262 + .061)$$

$$= (.913) (.948) + .6 (.31646)$$

$$= .8655 + .1898$$

$$= 1.055324$$

$$b_7 = (-\cos .42) (\sin .323) + .6 L_r (.323)$$

$$= (-.913) (.317) + .56897$$

$$= -.2894 + .56897$$

$$= + .279549$$

$$\frac{a_7}{b_7} = \frac{1.055324}{.279549} = 3.775$$

$$E_T = \frac{3.414973}{3.775(\cos .061) - (\sin .061)} = \frac{3.414973}{3.775(.998) - .0609}$$

$$= \frac{3414973}{3.707} = \underline{921,203.2}$$

$$\frac{E_T}{T_1} = \frac{921203}{973700} = .946$$

$$\bullet @ 20FPS \quad F_{BZR} = 6.829 \ 945 \times 10^6 \text{ LBS}$$

$$A_3 = 1 \ 304 \ 378$$

$$B_3 = 1\ 826\ 132$$

$$C_3 = F_{BRZ} = 6.829945 \times 10^6$$

$$A_4 = \frac{F_{BRZ}}{\tan BA} = \frac{6.829945 \times 10^6}{\tan .261} = 2.557 \times 10^7$$

$$B_7 = F_{BRZ} \frac{d-KG + \frac{LB_2}{2} - LCG}{\tan BA} - (\Delta - F_{BRZ}) GM_L$$

$$= (-6.829945 \times 10^6) (646.8) - (24333120 - 6829945 \times 10^6) 350$$

$$= (-4.4176 \times 10^9) - (6.126 \times 10^9)$$

$$= -1.054371 \times 10^{10}$$

$$C_4 = F_{BZR} \frac{LBC}{2} - LCG = 6.829945 \times 10^6 (172.7)$$

$$= 1,179,531,502$$

$$\frac{A_4 C_3 - A_3 C_4}{A_3 B_4 - A_4 B_3} = \frac{(2.557 \times 10^7)(6.829 \times 10^6) - (1.3 \times 10^6) 1.18 \times 10^9}{(1.3 \times 10^6) (-1.0543 \times 10^{10}) - (2.557 \times 10^7) (1.826 \times 10^6)}$$

$$= \frac{1.7464 \times 10^{14} - 1.534 \times 10^{15}}{-1.371 \times 10^{16} - 4.669 \times 10^{13}}$$

$$= \frac{-1.359 \times 10^{15}}{-1.3756 \times 10^{16}} = .098788 \text{ RAD}$$

$$= 5.66^\circ$$

$$a_7 = \cos .42 \cos (.262 + .0988) + .6 \sin (.262 \times .0988)$$

$$= .913 (.936) + .6 (.353)$$

$$= .8542 + .2118$$

$$= 1.066$$

$$b_7 = (-\cos .42) (\sin .361) + .6 \cos (.361)$$

$$= (-.913) (.353) + .56136$$

$$= -.32289 + .56136 =$$

$$= .239$$

$$\frac{a_7}{b_7} = \frac{1.066}{.239} = 4.4589$$

$$\begin{aligned}
 E_T &= \frac{6.829 \times 10^6}{4.4589 (\cos .0988) - \sin (.0988)} \\
 &= \frac{6.8299 \times 10^6}{4.4589 (.995) - .0986} = \frac{6.8299 \times 10^6}{4.4371 - .0986} \\
 &= 1.574 \times 10^6
 \end{aligned}$$

$$\frac{E_r}{T_{1B20}} = \frac{1.574 \times 10^6}{973700} = 1.6143$$

POLAR STAR

Spread angle compliment

28' WL

W.L. Entrance = 60°

$$\frac{E_A}{2} = 30^\circ$$

Bow 4 = 15°

$$B = \text{SAC} = \arctan \frac{\sin 15}{\tan 30} = \tan^{-1} \frac{.25881}{.57735} = \tan^{-1} .44828$$

$$B = 24.146^\circ = .42139 \text{ Radians } .42$$

$$\text{SA } 90 - 24.146^\circ = 65.8^\circ$$

$$2 \text{ SA} = 131.7^\circ$$

30' WL

W.L. Entrance = 59.5°

$$\frac{E_A}{2} = 29.5^\circ$$

Bow 4 = 14.5°

$$B (\text{SAC}) = \arctan \frac{\sin BA}{\tan \frac{E_A}{2}} = \tan^{-1} \frac{\sin 14.5}{\tan 29.5}$$

$$B = \arctan \frac{.2503}{.5657} = \arctan .4425$$

$$B = 23.8715^\circ$$

$$B = .4165 \text{ } .42 \text{ Radians}$$

$$\text{SA} = 90 - 23.87 = 66.13$$

$$2 \text{ SA} = 132.26^\circ$$

APPENDIX D.
Literature Citations
and
Selected Bibliography

LITERATURE CITATIONS AND SELECTED BIBLIOGRAPHY

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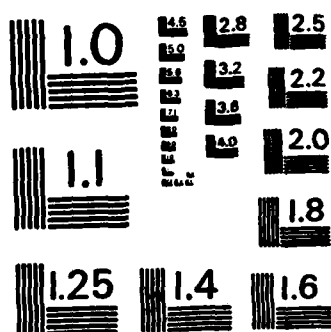
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) CGC POLAR STAR is the first of a new class of American icebreakers built for and operated by the U.S. Coast Guard. The vessel's design incorporates many new and sophisticated systems not found on earlier icebreakers. The primary objective of the test and evaluation program was to examine the performance characteristics under actual polar operations. Two field trials were conducted. The first in the Arctic and the second in the Antarctic. During these field trials approximately 120 individual parameters were		

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measured and recorded on magnetic tape. Additionally, the physical properties of the sea ice in which the ship was operating were measured.

Documentation of the complete program including preliminary screening of the data has been accomplished by NORDA under contract to the Coast Guard Research and Development Center. The documentation consists of the following four volumes: I. Antarctic Trials, II. Test Plans, III. Background, and IV. Instrumentation Manual.

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