DDS 568-1

THRUSTER MANEUVERING SYSTEMS

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, DC 20362-5101

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DESIGN DATA SHEET
DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND

DDS 568-1
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THRUSTER MANEUVERING SYSTEMS

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2. Wiegel, R.L., Oceanographical Engineering, Prentice-Hall, 1964.

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8. Equations and Coefficients for Simulation of T-ARC 7, NAVSEA Report 3213-79-31, October 1979.

9. Made, A.v.d. and Bussemaker, O., "Thrusters for Dynamic Positioning", Lips Propeller Symposium, 1976.

568-1-b. Nomenclature

A_f	Frontal projected area of ship, ft^2
A_s	Side projected area of ship, ft^2
A_{te}	Lateral projected area of model ship, ft^2
A_{ts}	Longitudinal projected area of model ship, ft^2
C_{xx}	Longitudinal wind force coefficient
C^c_{xx}	Longitudinal current force coefficient
C_{yy}	Lateral wind force coefficient
C^c_{yy}	Lateral current force coefficient
C^c_m	Current moment coefficient
C_m	Wind moment coefficient
c_f	Force scale factor for model ship
c_m	Moment scale factor for model ship
CRPP	Controllable Reversible Pitch Propellers
D	Duct diameter, ft
d_1	Distance from bow thruster to CG, ft
d_2	Distance from stern thruster to CG, ft
d_3	Distance of rudders to CG, ft
d	Distance of propeller shaft off ship centerline, ft
F^w_{xx}	Wind induced longitudinal force, lbs
F^w_{yy}	Wind induced lateral force, lbs
F_{ms}	Lateral force measured for model ship, lbs
F_{me}	Longitudinal force measured for model ship, lbs
F^e_{yy}	Environmentally induced force acting to port, lbs
F^e_{xx}	Environmentally induced force acting astern, lbs

F^c_{xx}	Longitudinal current force, lbs
F^c_{yy}	Lateral current force, lbs
F^R_x	Longitudinal force due to rudders, lbs
F^R_y	Lateral force due to rudders, lbs
F^F_x	Longitudinal force due to bow thruster, lbs
F^F_y	Lateral force due to bow thruster, lbs
F^A_x	Longitudinal force due to stern thruster, lbs
F^A_y	Lateral force due to stern thruster, lbs
F^p_{xx}	Thrust of port propeller, lbs
F^s_{yy}	Thrust of starboard propeller, lbs
F^2_{xx}	Second-order wave drift force in longitudinal direction, lbs
F^2_{yy}	Second-order wave drift force in transverse direction, lbs
g	Gravity, ft/sec^2
$H_{1/3}$	Significant wave height, ft
L_E	Thruster opening conical fairing length, ft
L	Tunnel length, ft
L_s	Ship length, ft
L_t	Model length, ft
MPD	Maneuvering Propulsion Device
M_m	Moment measured on model ship, ft-lbs
N^e_m	Environmentally induced moment to turn ship about CG, ft-lbs
N^2_m	Second order wave moment, ft-lbs
N^w_m	Wind induced moment, ft-lbs
N^c_m	Current induced moment, ft-lbs
r_e	Thruster opening fairing radius
R	Duct radius, ft

R_{xx}	Non-dimensional longitudinal wave force transfer function
R_{yy}	Non-dimensional lateral wave force transfer function
R_m	Non-dimensional wave moment transfer function
S_e	Wave spectrum, ft^2-sec/radian
T_o	Modal period, sec
V	Speed, ft/sec
V_s	Ship speed, ft/sec
V_c	Current speed, ft/sec
V_w	Wind speed, ft/sec
V_{xx}	X-component of relative water velocity, ft/sec
V_{yy}	Y-component of relative water velocity, ft/sec
X_T	Resistance of thruster opening, lbs
α	$180-\psi$, angle of wind relative to ship, degrees
α_c	$180-\psi_c$, angle of current relative to ship, degrees
δ	Distance of rudder force off shaft centerline, ft
$\Delta\omega$	Difference frequency, rad/sec
λ_n	Wave length, ft
τ_n	Non-dimensional wave length
ρ	Density, lb-sec^2/ft^4
ψ	Angle between V_s and V_w, degrees
ψ_c	Angle between V_s and V_c, degrees
ω_n	Absolute frequency, rad/sec
ω_e	Encounter frequency, rad/sec
θ	Current relative heading angle, degrees

568-1-c. Introduction

Thrusters are generally installed in Navy ships with severe low speed maneuvering requirements, such as maintaining a specific position at zero or low speed or maintaining a straight track at forward speed.

The purpose of DDS 568-1 is to provide guidance for the selection of the thruster power required to overcome the forces and moments imposed on a ship by wind speed, wave height, and current speed. In addition, this DDS provides guidance for selecting the type of thruster, area and volume requirements and electrical load.

The method of computing thruster force was adapted from a NAVSEA developed computer program "THRSIZ" which evaluates the performance of a thruster of known power. The hand calculation technique presented herein is sufficiently simple to be used when quick but accurate estimates of thruster size are needed to determine space and power requirements.

Guidance is included for selecting the design wind speed, wave height, current speed and ship heading angles to be used if these are not specified in the requirements for a specific ship design. An example illustrating the calculation procedure is presented at the end of the DDS.

It should be noted that active propeller rudders, high lift rudders employing flaps and/or rotors, steerable propeller Kort nozzles, or cycloidal (Voith-Schneider) propulsors may be suitable alternatives to stern thrusters for low speed maneuvering. These devices are not within the scope of ESWBS 568 and are not discussed herein.

568-1-d. Description of Thruster Types

There are three major types of thrusters:

- o Tunnel thrusters
- o Jet thrusters
- o Rotatable thrusters

These three types are each discussed below, and illustrated in Figures 1 through 5.

1. Tunnel Thrusters

Tunnel thrusters are the most economical type of thruster and have as a consequence seen the widest range of application. Their prevalence however, may not make them the best choice for some applications. Tunnel thrusters are not inherently steerable as the jet and rotatable types may be, but provide only lateral thrust. For stationkeeping applications tunnel thrusters have the disadvantage that the main engines must be cycled in order to hold position.

2. Jet Thrusters

Thrusters using axial flow pump output to provide controllable thrust are becoming increasingly popular and are offered in several configurations (depending on such factors as ship design and powering requirements) by at least three manufacturers. Both Schottel and Elliot have variations which take suction from the hull bottom at one side of the thruster housing and discharge back through the hull bottom, via a rotatable discharge deflector or a rotatable elbow, providing 360-degree manueverability. Schottel also manufactures a bow jet that provides thrust only to port and starboard. Omni-Thruster manufactures a unit that discharges port and starboard only, which steers by proportioning thrust between both sides of the hull at the same time either above or below the waterline.

The location of the jet thruster inlet near the keel allows a thruster to be installed in areas where ship motions may create a thruster emergence problem for tunnel type thrusters. If ship motions are such that the thruster inlet duct is emerged then thrust-loss will occur.

The jet type thrusters produce less thrust per horsepower than tunnel or rotatable thrusters. The bottom suction jet type thrusters should be avoided for ships expected to operate in extremely shallow water, as there is a potential for bottom material and debris to be ingested by the pump and cause serious damage to the thruster unit.

3. Rotatable Thrusters

The identifying characteristic of this type is that the screw propeller and pod can be rotated about a vertical axis which is

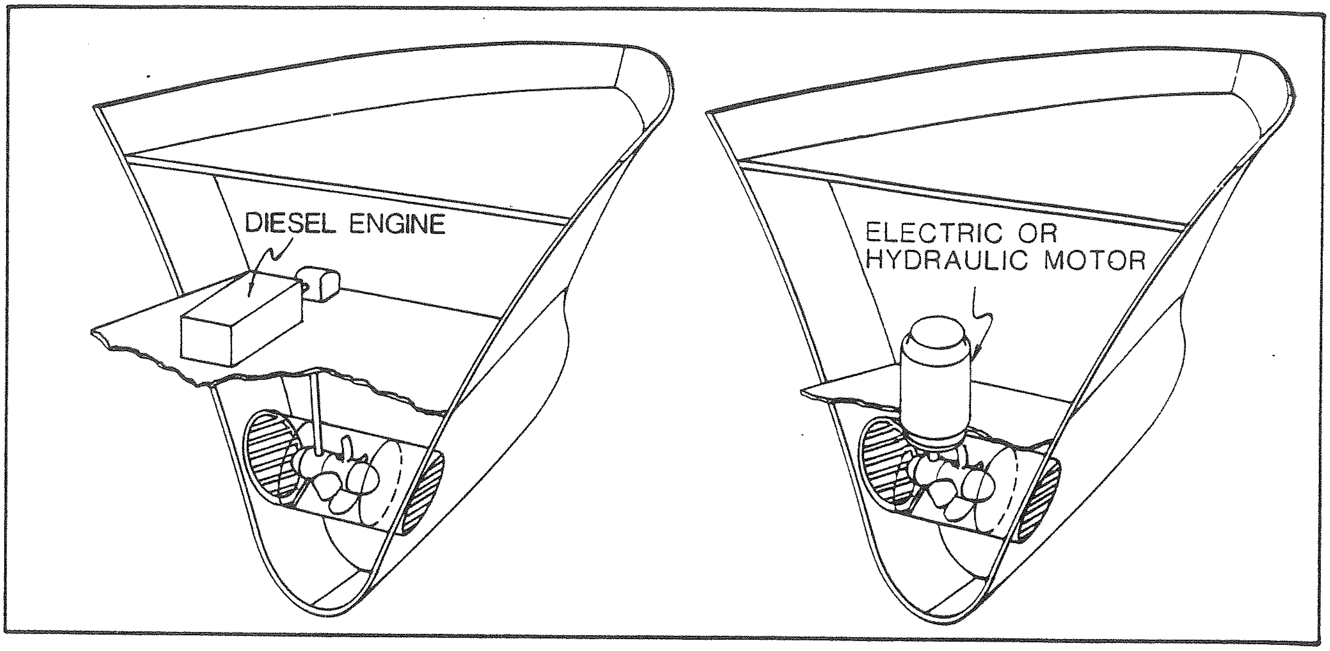


FIGURE 1 - TYPICAL TUNNEL THRUSTER INSTALLATIONS

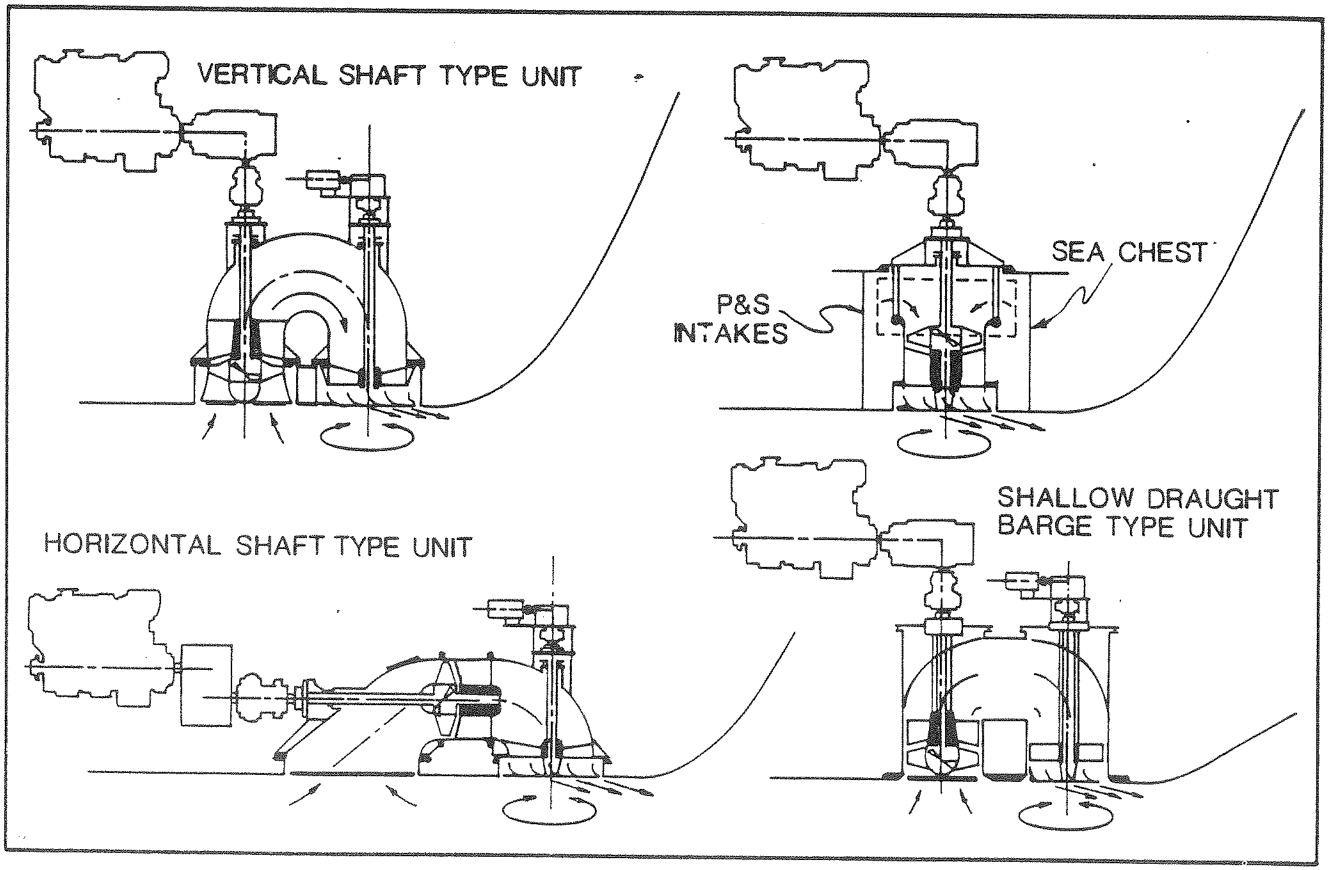


FIGURE 2 - TYPICAL JET THRUSTER INSTALLATIONS

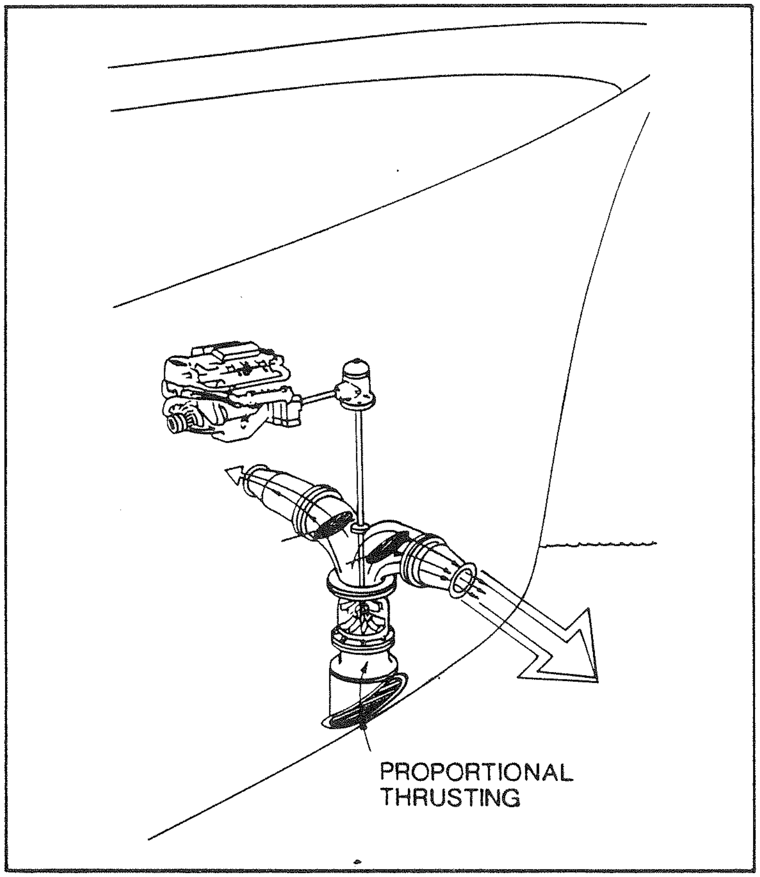


FIGURE 3 - PROPORTIONAL THRUSTING TYPE JET THRUSTER

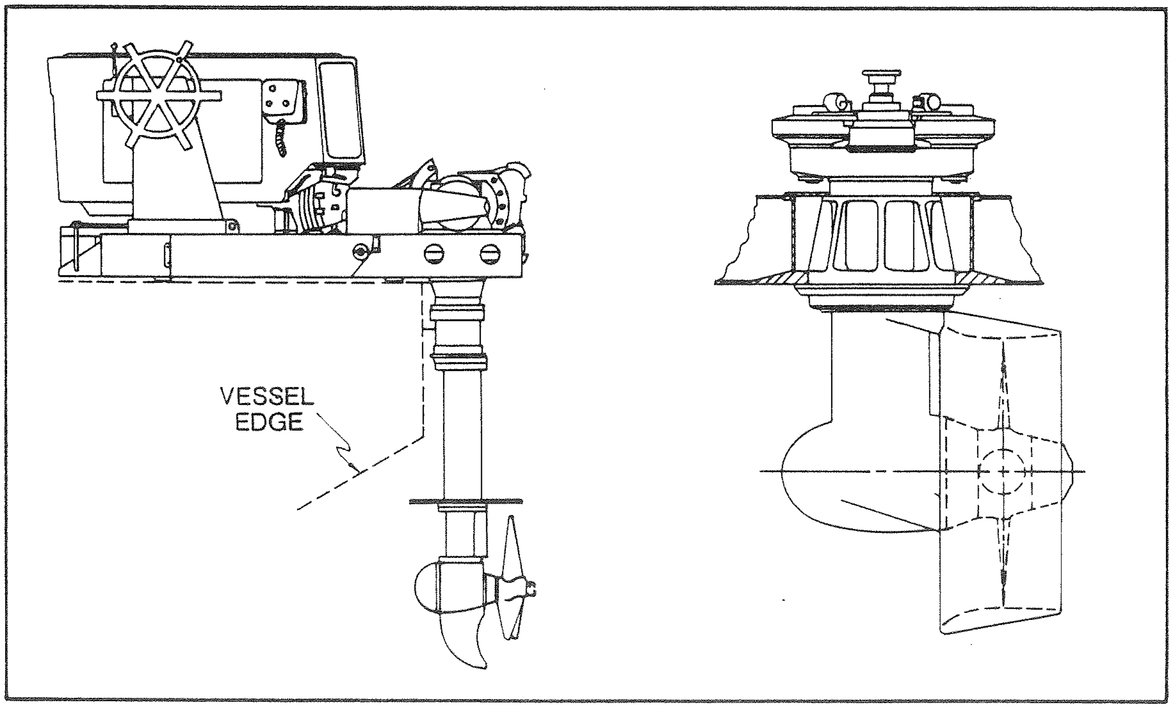


FIGURE 4 - TYPICAL ROTATABLE THRUSTERS

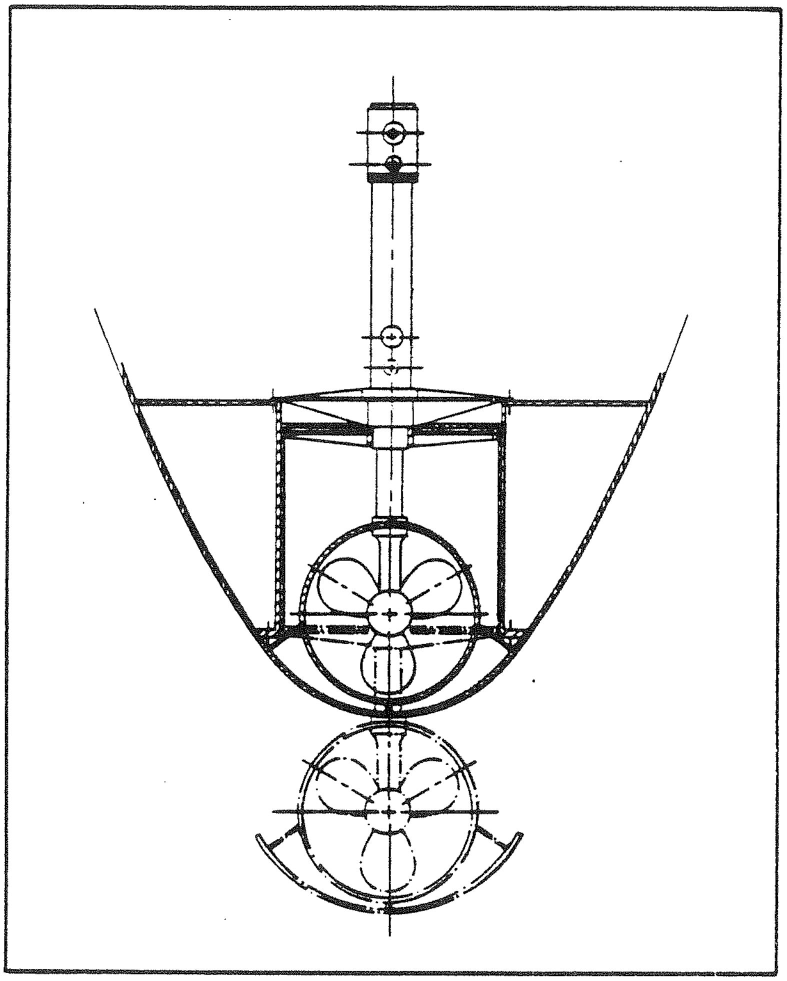


FIGURE 5 - TYPICAL RETRACTABLE TUNNEL TYPE THRUSTER

perpendicular to the propeller rotation axis. Three basic types are: 1) fixed in elevation, 2) pivoting retraction of the vertical shaft about an axis on the level with the prime mover, and 3) telescoping retraction, where the entire assembly slides up and down on shafts to permit extension and retraction through the hull. Propellers may be open or in Kort nozzles.

Rotatable thrusters have the advantage of providing steerability (360-degree swing is available) in a simple mechanical system, and may have the disadvantage of protruding below the ship hull, depending on the ship configuration, thus being subject to damage in shallow water.

568-1-e. Design Requirements

1. Design Environment

Thrusters are sized to produce specific amounts of thrust to counter expected forces and moments produced by wind, waves and current in order to maintain heading or to provide the ship with a specified amount of maneuverability, such as rate of heading change. The thruster design process must therefore begin with the selection of the environment in which the ship is required to maintain the specified maneuverability.

This selection may be made with the aid of the ship requirements document. Manuevering requirements may be stated in these documents in terms of maintaining position or maintaining track in a specified sea state. With this information estimates of the forces and moments acting on the ship can be made. If specific sea state, wind and currents are not given in the document, the assumptions given below may be used to develop preliminary estimates of thruster size.

The design sea state, wind and current must be combined to determine the worst case for ship operation. This will typically not be a single readily apparent condition, but a number of conditions will have to be examined in order to determine which is actually the most severe. It can be assumed that the wind and waves always act from the same direction and that the current may come from any direction. For a good first approximation the worst case may be assumed to be when wind, waves and current all act from the same direction, between ship heading angles of 75 degrees and 105 degrees. It is recommended that analysis be performed at heading angles of 75 degrees, 90 degrees and 105 degrees because the maximum side force typically occurs at 90 degrees and the maximum moment occurs near 75 degrees or 105 degrees. However, care should be taken that the heading angles and assumed environmental conditions are physically meaningful.

In practice, most ship missions requiring the use of a thruster are specified to be carried out in sea states 3 or 4 depending upon the mission and ship size. Unless other guidance is available for the specific ship under consideration, the design wave height shall be assumed to be 6.2

feet (sea state 4) and the design wind speed shall be assumed to be 19 knots (corresponding to sea state 4). The following relationship between wind speed and significant wave height can be used to find the other when only one of the two parameters is specified:

$$V_w = (7\sqrt{H_{1/3}} + 0.5\,H_{1/3})\,(1.6878)$$

where,

V_w = wind speed, ft/sec

$H_{1/3}$ = significant wave height, ft

Based on data presented in Reference 1 the maximum current in a harbor rarely exceeds 3 knots and ocean currents are typically 1 to 3 knots (Reference 2). Unless other guidance is given for the specific ship under consideration the design current speed can be taken as 1.5 knots, which occurs most frequently.

2. Ship Operation Requirements

Two distinct maneuvering and control capabilities may be required of a thruster. On the one hand the critical maneuvering and control function may be when the ship is dead in the water or at extremely low headway. This type of duty is typical of ships with extended stationkeeping requirements. On the other hand, the critical function for control may be when the ship is operating at a sustained ahead speed for long periods of time following a track or in restricted waterways, such as channels or rivers. For this latter type of design a thruster must consider the interaction of the mainstream and the thruster jet flow, which can compromise the performance of the thruster compared to that of an essentially static condition. A stern thruster is affected by the flow of the main propellers as well. The installed power of the thruster must be sufficient to compensate for the loss in performance when the ship is moving at forward speed. This is described below in para. 568-1-h.

568-1-f. Environmental Forces and Moments

Determining the required thruster size begins with calculation of the forces and moments produced by the wind, wave and current conditions assumed above. These forces and moments are balanced by the forces and moments produced by the ship, that is, the rudders, propellers, and thrusters. The force balance then yields the force required from the thruster. Selection of the thruster size to be installed can be made from the manufacturers data, or from data presented herein.

1. Primary Assumptions

In the following calculation technique, the following assumptions have been made about the environmental conditions:

- A Bretschneider two parameter ($H_{1/3}$, T_o) wave spectrum has been assumed.

- If not explicitly specified, the wind speed is assumed to be related to the significant wave height by the relation given above in para 568-1-e.

- The wind and the waves act along the same heading with respect to the ship.

- The coordinate system shown in Figure 6 is assumed for the calculations presented below.

2. Calculation of Wave Forces

The wave forces are calculated by using the method presented in Reference 3. The wave force that is of interest in determining thruster size is the slowly-varying second-order drift force. The first-order wave forces which produce the primary ship motions are of too large a magnitude to be overcome by a practical thruster installation.

Reference 3 uses the steady time-average force in regular waves (transfer function) and the irregular wave spectrum to develop an asymptotic approximation to the mean of the slowly varying second-order force and moment.

The derivation of the equations for calculating the second-order wave force and moment will be omitted here and only the final equations needed for calculating the steady wave drift force and moment will be given.

The wave force is calculated using the following equation:

$$F^2_{xx,yy} = \tfrac{1}{2}\rho g L_s \; \Sigma_n \; 2S_e(\omega_n)\Delta\omega_e R_{xx,yy}(\omega_e,\psi)/(1-(2\omega_n/g)V_s \cos\psi)$$

where,

F^2_{xx} = second-order wave drift force in the longitudinal direction, lbs

F^2_{yy} = second-order wave drift force in transverse direction, lbs

ρ = sea water density, 1.9905 lb-sec^2/ft^4

g = acceleration due to gravity, ft/sec^2

L_s = ship length, ft

V_s = ship speed, ft/sec

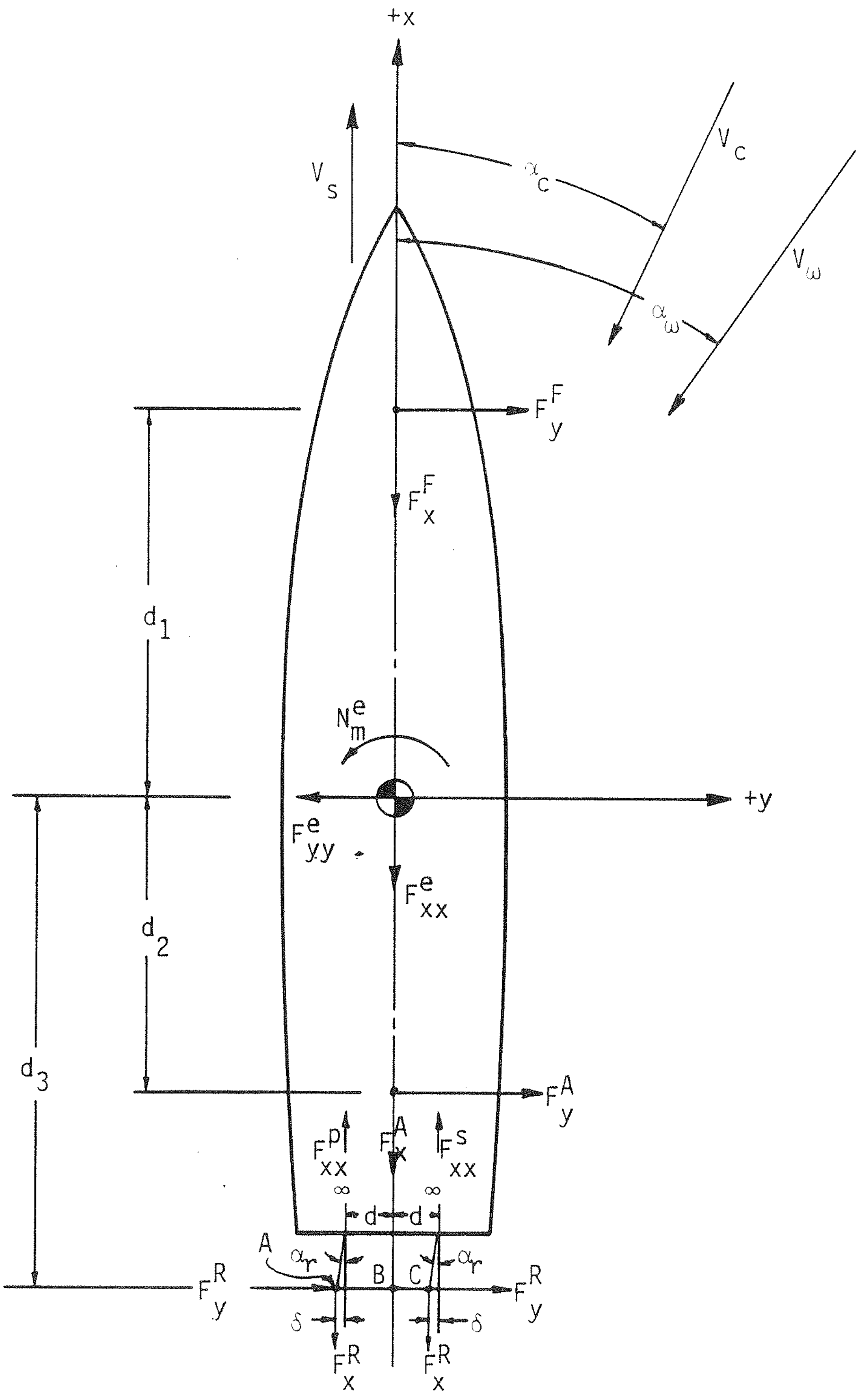


FIGURE 6 - DEFINITION SKETCH SHOWING POSITIVE DIRECTION OF ALL FORCES AND MOMENTS

ψ = wave heading angle with respect to ship heading

$R_{xx}(\omega_e,\psi)$ = non-dimensional longitudinal wave force transfer function taken from Table 1

$R_{yy}(\omega_e,\psi)$ = non-dimensional transverse wave force transfer function taken from Table 2

$S_e\ (\omega_n)$ = wave spectrum, ft^2-sec/rad

= $(483.5(H_{1/3})^2/T_o^4\ \omega_n^5)\ \exp\ (-1944.5/T_o^4\ \omega_n^4)$

$H_{1/3}$ = significant wave height, ft

= 6.5 feet for sea state 4

T_o = modal period, sec

= 7 sec for sea state 4

ω_n = wave absolute frequency, rad/sec

= $\sqrt{2\ \pi g/\ \tau_n\ L_s}$

ω_e = wave encounter frequency, rad/sec

$\omega_n\ (1-\omega_n\ V_s\ (\cos\psi)/g)$

$\Delta\omega_e$ = difference frequency, rad/sec

τ_n = λ_n/L_s

λ_n = wave length, ft

The wave moment is calculated using an equation of similar form:

$$N^2{}_m = \tfrac{1}{2}\rho g L_s^2\ \Sigma_n\ 2S_e(\omega_n)\Delta\omega_e R_m(\omega_e,\psi)/(1-(2\omega_n/g)V_s\ \cos\psi)$$

where,

$N^2{}_m$ = second-order wave moment, ft-lbs

$R_m(\omega_e,\psi)$ = non-dimensional wave moment transfer function taken from Table 3

All other variables are as defined above for the wave forces.

The non-dimensional transfer functions $R_{xx}(\omega_e,\ \psi)$, $R_{yy}(\omega_e,\ \psi)$ and $R_m(\omega_e,\ \psi)$ are determined from model tests in regular waves for the MCM ship and estimated analytically for the T-ARC. When model test data for the specific ship under consideration is not available, the data presented in

TABLE 1

LONGITUDINAL WAVE FORCE COEFFICIENTS FOR MCM AND T-ARC

MCM Wave Force Coefficients, R_{xx} $(\omega_e(\tau_n),\psi)$

ψ	τ_n									
	0.15	0.30	0.40	0.50	0.75	1.00	1.25	1.50	1.75	2.00
0°*	.250	.073	.085	.108	.058	.029	.016	.008	.003	.000
15°	.177	.105	.098	.104	.132	.098	.011	.010	.007	.005
30°	.123	.127	.105	.085	.179	.149	.007	.010	.008	.007
45°	.089	.135	.104	.055	.195	.170	.004	.008	.009	.008
60°	.060	.118	.088	.027	.170	.131	.003	.006	.008	.006
75°	.025	.051	.038	.012	.103	.038	.000	.003	.004	.002
90°	-.116	-.033	-.017	-.008	-.002	-.003	-.004	-.002	-.001	-.001
105°	-.015	-.010	-.012	-.020	-.048	-.031	-.013	-.007	-.002	-.001
120°	-.010	-.004	-.009	-.028	-.062	-.048	-.026	-.010	-.002	-.001
135°	-.014	-.006	-.014	-.032	-.062	-.056	-.029	-.011	-.002	-.001
150°	-.039	-.027	-.023	-.039	-.054	-.050	-.027	-.012	-.003	-.002
165°	-.100	-.069	-.046	-.050	-.039	-.034	-.020	-.011	-.004	-.002
180°**	-.195	-.127	-.094	-.066	-.021	-.009	-.011	-.009	-.006	-.003

T-ARC Wave Force Coefficients, R_{xx} $(\omega_e(\tau_n),\psi)$

ψ	τ_n									
	.170	.222	.303	.436	.538	.681	.889	1.21	1.743	2.151
0°*	.058	.058	.054	.016	.026	.034	.022	.025	.044	.041
15°	.056	.057	.057	.057	.053	.058	.034	.019	.037	.037
30°	.051	.051	.051	.051	.048	.049	.045	.021	.031	.031
45°	.041	.041	.041	.041	.040	.042	.035	.020	.026	.025
60°	.029	.029	.030	.029	.030	.030	.022	.011	.019	.018
75°	.015	.015	.016	.016	.016	.015	.010	.005	.010	.009
90°	-.074	-.057	-.030	.016	.015	.014	.010	.002	.000	-.000
105°	-.010	-.010	-.010	-.009	-.009	-.008	-.005	-.002	-.011	-.011
120°	-.018	-.018	-.019	-.019	-.019	-.018	-.013	-.007	-.023	-.021
135°	-.026	-.026	-.026	-.026	-.026	-.027	-.021	-.015	-.033	-.030
150°	-.032	-.032	-.032	-.032	-.031	-.033	-.028	-.031	-.043	-.039
165°	-.036	-.036	-.036	-.036	-.039	-.047	-.031	-.031	-.052	-.046
180°**	-.037	-.036	-.036	-.016	-.078	-.048	-.017	-.039	-.060	-.051

* Following Seas
** Head Seas

TABLE 2

TRANSVERSE WAVE FORCE COEFFICIENTS FOR MCM AND T-ARC

MCM Wave Force Coefficients, $R_{yy} \quad (\omega_e(\tau_n),\psi)$

ψ	τ_n									
	0.15	0.30	0.40	0.50	0.75	1.00	1.25	1.50	1.75	2.00
0°*	-.130	-.087	-.068	-.055	-.022	-.010	-.006	-.005	-.004	-.003
15°	-.165	-.150	-.140	-.080	-.080	-.015	-.005	-.005	-.005	-.003
30°	-.220	-.243	-.227	-.123	-.130	-.040	-.003	-.004	-.006	-.004
45°	-.304	-.389	-.335	-.185	-.167	-.077	-.001	-.004	-.007	-.004
60°	-.680	-.675	-.463	-.262	-.182	-.128	-.000	-.003	-.005	-.003
75°	-1.432	-1.065	-.595	-.318	-.187	-.158	-.000	-.001	-.002	-.001
90°	-1.710	-1.777	-.642	-.338	-.190	-.180	.001	.001	.001	.001
105°	-1.383	-1.025	-.567	-.319	-.190	-.173	-.015	-.007	-.005	-.004
120°	-.415	-.415	-.395	-.277	-.190	-.157	-.030	-.015	-.011	-.007
135°	-.230	-.227	-.220	-.215	-.187	-.120	-.040	-.020	-.014	-.009
150°	-.130	-.130	-.125	-.120	-.145	-.060	-.035	-.017	-.012	-.007
165°	-.055	-.055	-.050	-.050	-.095	-.028	-.025	-.013	-.008	-.004
180°**	.020	.008	-.000	-.010	-.016	-.015	-.013	-.009	-.005	-.001

T-ARC Wave Force Coefficients, $R_{yy} \; (\omega_e(\tau_n),\psi)$

ψ	τ_n									
	.170	.222	.303	.436	.538	.681	.889	1.21	1.743	2.151
0°*	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
15°	-.212	-.215	-.098	-.011	-.013	-.001	-.003	-.012	-.015	-.013
30°	-.411	-.411	-.412	-.336	-.143	-.035	-.021	-.028	-.030	-.025
45°	-.581	-.584	-.583	-.590	-.495	-.210	-.095	-.058	-.046	-.036
60°	-.714	-.713	-.721	-.713	-.786	-.510	-.209	-.096	-.062	-.046
75°	-.804	-.795	-.825	-.964	-1.181	-.630	-.261	-.126	-.075	-.054
90°	-.894	-.857	-.928	-1.162	-1.153	-.482	-.236	-.137	-.081	-.058
105°	-.797	-.901	-.822	-.885	-.949	-.485	-.227	-.130	-.080	-.057
120°	-.711	-.715	-.721	-.737	-.775	-.514	-.201	-.106	-.071	-.051
135°	-.580	-.582	-.583	-.603	-.561	-.271	-.112	-.071	-.056	-.042
150°	-.410	-.411	-.414	-.386	-.148	-.058	-.035	-.040	-.038	-.030
165°	-.212	-.214	-.099	-.026	-.025	-.008	-.007	-.018	-.020	-.016
180°**	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000

* Following Seas

** Head Seas

TABLE 3

WAVE MOMENT COEFFICIENTS FOR MCM AND T-ARC

MCM Wave Moment Coefficients, $R_m\ (\omega_e(\tau_n),\psi)$

ψ	τ_n									
	0.15	0.30	0.40	0.50	0.75	1.00	1.25	1.50	1.75	2.00
0°*	-.045	-.019	-.012	-.008	-.004	-.000	.005	.002	.001	-.000
15°	-.045	-.008	-.007	-.007	-.008	-.005	.004	.002	-.000	-.001
30°	-.046	-.000	-.003	-.007	-.013	-.011	-.006	-.003	-.002	-.001
45°	-.049	.006	.001	-.008	-.022	-.020	-.007	-.004	-.002	-.001
60°	-.054	.008	.003	-.009	-.033	-.032	-.006	-.003	-.002	-.001
75°	-.074	.011	.004	-.011	-.054	-.051	-.005	-.002	-.001	-.001
90°	-.099	.011	.003	-.014	-.083	-.078	-.004	-.001	.000	.000
105°	-.078	.007	-.000	-.013	-.055	-.041	-.005	-.001	.002	.002
120°	-.031	-.003	-.005	-.010	-.006	-.004	-.006	.000	.006	.004
135°	-.009	-.006	-.006	-.005	.001	.001	-.007	.001	.008	.006
150°	-.009	-.007	-.005	-.001	.001	.002	-.005	.002	.006	.004
165°	-.011	-.007	-.003	.003	-.001	.001	.005	.003	.003	.002
180°**	-.015	-.004	.001	.005	-.004	-.002	.007	.004	.001	.000

T-ARC Wave Moment Coefficients, $R_m\ (\omega_e(\tau_n),\psi)$

ψ	τ_n									
	.170	.222	.303	.436	.538	.681	.889	1.21	1.743	2.151
0°*	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
15°	-.017	-.011	.003	.010	.014	.012	.007	.006	.004	.003
30°	-.034	-.027	.001	.036	.042	.019	.014	.016	.010	.007
45°	-.020	-.063	-.046	.032	.033	.019	.039	.036	.019	.013
60°	-.041	-.097	-.059	-.060	-.004	.091	.102	.062	.026	.015
75°	.021	-.046	-.119	.023	.184	.201	.127	.058	.021	.012
90°	-.047	-.109	-.120	-.045	-.000	.015	.013	.007	.004	.003
105°	.010	-.059	-.043	-.086	-.200	-.168	-.097	-.042	-.013	-.007
120°	-.023	-.099	-.089	-.016	-.024	-.081	-.078	-.045	-.017	-.010
135°	-.034	-.078	-.045	-.047	-.040	-.027	-.031	-.024	-.012	-.007
150°	-.043	-.039	-.043	-.045	-.027	-.020	-.014	-.009	-.005	-.003
165°	-.028	-.047	-.035	-.013	-.005	-.008	-.007	-.003	-.001	-.001
180°**	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000

* Following Seas

** Head Seas

Tables 1, 2 and 3 can be used by selecting the ten values of $R_{xx}(\omega_e, \psi)$, $R_{yy}(\omega_e, \psi)$, and $R_m(\omega_e, \psi)$ for the corresponding heading angle, ψ. Data is presented for two different hull forms: for the T-ARC representing a moderate form ship and for the MCM representing a slender ship. The ship characteristics are given in Table 4.

The summation over n in the force and moment equations is carried out for a range of wave length to ship length ratios, $\tau_n = \lambda_n/L_s$. The following ten values of τ_n are used in the force and moment calculation when the MCM data is used: .15, .30, .40, .50, .75, 1.00, 1.25, 1.50, 1.75 and 2.00. For the T-ARC data the values of τ_n are: .170, .222, .303, .436, .538, .681, .889, 1.21, 1.743 and 2.151. The calculations have been put into a tabular format in Table 5 to simplify the procedure.

An example calculation of the wave forces and moments is presented in para. 568-1-i.

TABLE 4

SUMMARY OF SHIP PARTICULARS, T-ARC AND MCM

	MCM	T-ARC
LBP, ft	240.0	464.0
Beam, ft	43.9	73.0
Draft, ft	11.8	24.0
Displacement, L. Tons	1,725	14,183
Block Coefficient	.484	.610
Prismatic Coefficient	.576	.648
No. Screws	2	2
$V/\sqrt{LBP}$	1.16	.696

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET

(1) n	(2) $\tau_n = \frac{\lambda_n}{L_s}$	(3) $\omega_n = \sqrt{\frac{2\pi g}{L_s \tau_n}}$	(4) $s = \frac{\omega_n}{g} V_s \cos\psi$	(5) $\omega_e = \omega_n(1-s)$	(6) $(1-2s)$	(7) $T_o^4 \omega_n^4$	(8) $e^{\left(\frac{-1944.5}{T_o^4 \omega_n^4}\right)}$
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

L_s = SHIP LENGTH (feet) =

V_s = SHIP SPEED (ft/sec) =

Ψ = HEADING ANGLE =

T_o = MODAL PERIOD (sec) =

$g = 32.2$ ft/sec^2 =

$H_{1/3}$ = SIGNIFICANT WAVE HEIGHT (ft) =

$\rho g = 64$ lbs/ft^3 SALT WATER

$\rho g = 62.4$ lbs/ft^3 FRESH WATER

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET (CONT'D)

(1) n	(5) ω_e	(9) $S_e(\omega_n) = \frac{1}{\omega_n} \frac{483.5(H_{1/3})^2}{T_o^4\omega_n^4} e^{\frac{-1944.5}{T_o^4\omega_n^4}} = \frac{483.5(H_{1/3})^2 x (8)}{(3)x(7)}$	(10) $\omega_{e_{mean_n}} = \frac{1}{2}(\omega_{e_n} + \omega_{e_{n+1}})$	(11) $\omega_{e_{mean_n}} - \omega_{e_{mean_{n+1}}}$	(12) $\omega_{e_1} - \omega_{e_2}$ $\omega_{e_9} - \omega_{e_{10}}$
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET (CONT'D)

(1) n	(5) ω_e	(13) $\Delta\omega_e$ (11)+(12)	(14) $\frac{2S_e(\omega_n)\ \Delta\omega_e}{(1-2s)}$ $= \frac{2x(9)x(13)}{(6)}$	(15) $R_{xx}(\omega_e)$	(16) $R_{yy}(\omega_e)$	(17) $R_m(\omega_e)$	(18) LONGITUDINAL WAVE FORCE $\frac{2S_e(\omega_n)}{(1-2s)}\ \Delta\omega_e\ R_{xx}(\omega_e)$ = (14)x(15)
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
							(21) Σ =

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET (CONT'D)

(1) n	(5) ω_e	(19) TRANSVERSE WAVE FORCE $\frac{2S_e(\omega_n)}{(1-2s)} \Delta\omega_e \; R_{yy}(\omega_e)$ $= (14)\times(16)$	(20) WAVE MOMENT $\frac{2S_e(\omega_n)\Delta\omega_e}{(1-2s)} \; R_m(\omega_e)$ $= (14)\times(17)$
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
		$\Sigma =$ (22)	(23)

$F_{xx}^2 = \frac{1}{2}\rho g \times L_s \times (21)$

$F_{yy}^2 = \frac{1}{2}\rho g \times L_s \times (22)$

$N_m^2 = \frac{1}{2}\rho g \times L_s^2 \times (23)$

3. Calculation of Wind Forces and Moments

Wind induced forces and moments are calculated using the equations given below and the empirical coefficients presented in Table 6.

$$F^{w}_{xx}(\psi) = \tfrac{1}{2} A_f V_w^2 C_{xx} (\psi)$$

$$F^{w}_{yy}(\psi) = \tfrac{1}{2} A_s V_w^2 C_{yy} (\psi)$$

$$N^{w}_{m} (\psi) = \tfrac{1}{2} A_s V_w^2 L_s C_m (\psi)$$

where,

$F^{w}_{xx}(\psi)$ = Longitudinal wind force, lbs

$F^{w}_{yy}(\psi)$ = Transverse wind force, lbs

$N^{w}_{m}(\psi)$ = Wind moment, ft-lbs

$C_{xx} (\psi)$ = Longitudinal wind force coefficient taken from Table 6

$C_{yy} (\psi)$ = Transverse wind force coefficient taken from Table 6

$C_m (\psi)$ = Wind moment coefficient taken from Table 6

A_s = Longitudinal projected area of ship hull and superstructure above waterline, ft^2

A_f = Transverse projected area of ship hull and superstructure above waterline, ft^2

V_w = Wind speed, ft/sec

ρ = Density of air, .0023602 $lb\text{-}sec^2/ft^4$

ψ = Angle from which wind is acting relative to ship heading

The coefficients presented in Table 6 are based on model experiments with the T-ARC. This data may be used if similar data for the ship under consideration is not available.

For cases where the wind speed is not specified it can be related to the significant wave height by the equation given in para. 568-1-e.

Reference 1 contains wind force and moment data based on model tests for several Navy surface ships (CVA 59, DD 692, AO 143 and EC 2 class Liberty ship). This data is not in the same format as required by the above equations but can be modified by the following:

$$C_{xx}(\psi) = 2c_f F_{ms}/(\rho A_{ts})$$

TABLE 6

WIND FORCE AND MOMENT COEFFICIENTS

Degrees	C_{xx}	C_{yy}	C_m
0*	.647	0.0	0.0000
15	.718	-.250	.0325
30	.557	-.545	.0670
45	.214	-.768	.0885
60	-.109	-.850	.0775
75	.048	-.840	.0300
90	-.014	-.883	-.0020
105	-.062	-.875	-.0375
120	-.190	-.818	-.0640
135	-.262	-.810	-.0925
150	-.652	-.520	-.0695
165	-.775	-.233	-.0370
180**	-.723	0.000	0.0000

* Following Wind
** Head Wind

$C_{yy}(\psi) = 2c_f\, F_{me}/(\rho A_{te})$

$C_m(\psi) = 2c_m\, M_m/(\rho A_{ts}\, L_t)$

where,

F_{ms} = Lateral force measured for model ship, lbs

F_{me} = Longitudinal force measured for model ship, lbs

M_m = Moment measured for model ship, ft-lbs

A_{ts} = Longitudinal area for model ship, ft^2

A_{te} = Transverse area for model ship, ft^2

L_t = Length of model ship, feet

c_f = Force scale factor for model ship

c_m = Moment scale factor for model ship

All of the above data can be found on the model test curves presented in Figures 7 through 10.

A calculation worksheet is presented in Table 7. An example calculation is presented in para. 568-1-i.

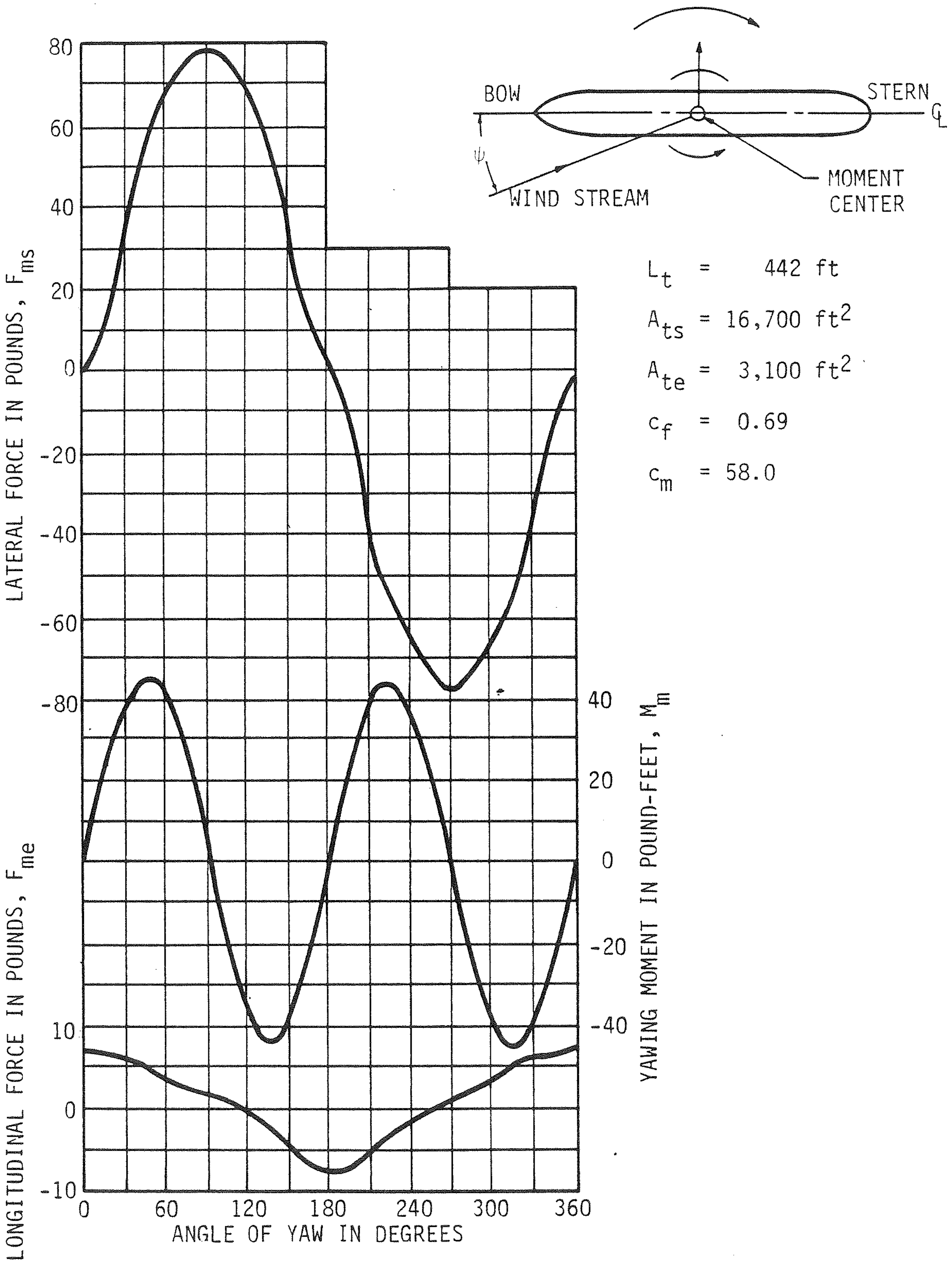
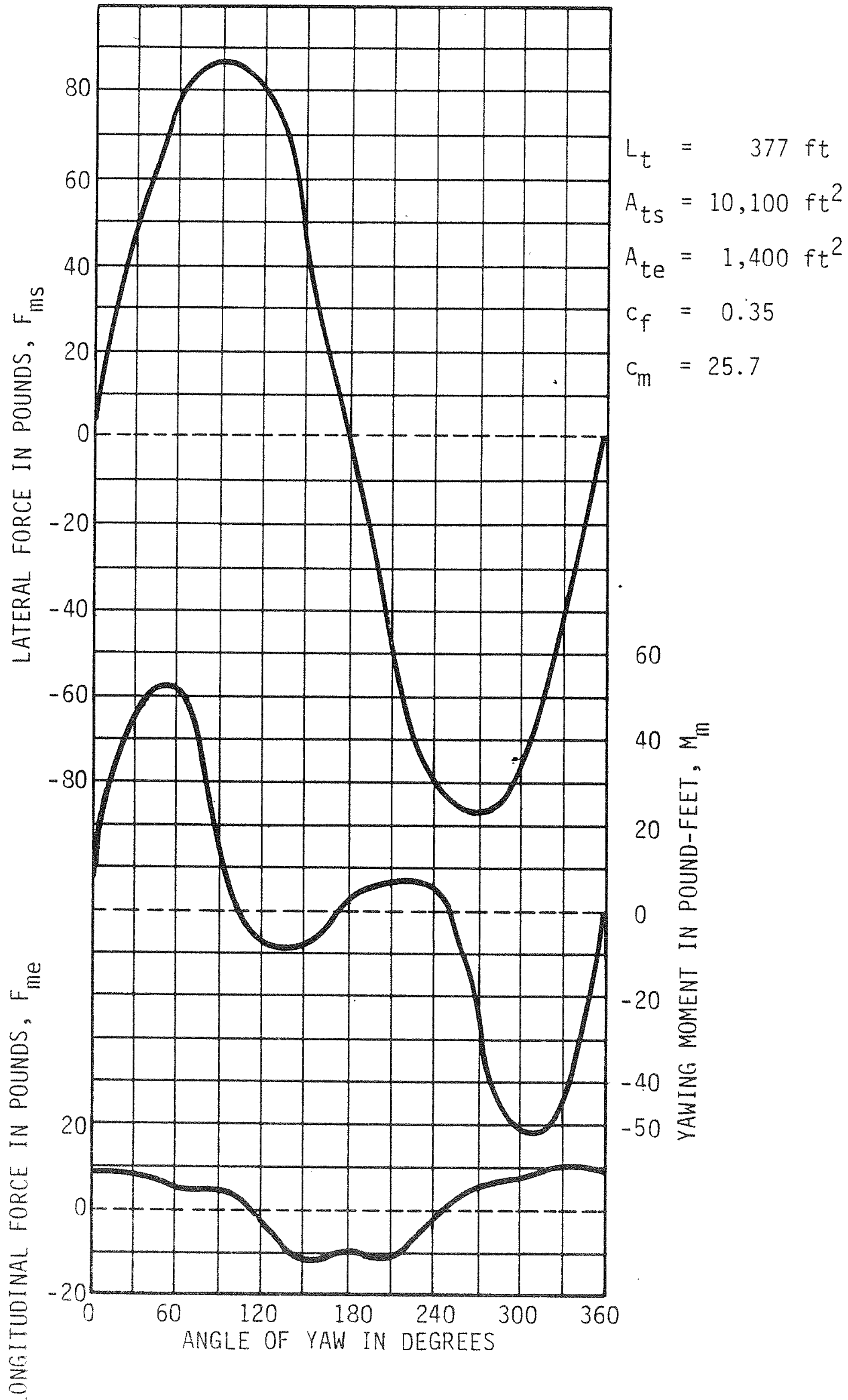


FIGURE 7 - VARIATION OF LATERAL FORCE, YAWING MOMENT, AND LONGITUDINAL FORCE WITH ANGLE OF YAW FOR A SINGLE 1:83.2-SCALE MODEL OF EC-2 CLASS LIBERTY SHIPS; WIND SPEED 100 KNOTS; MOMENT CENTER AT CENTER OF MODEL



L_t = 377 ft

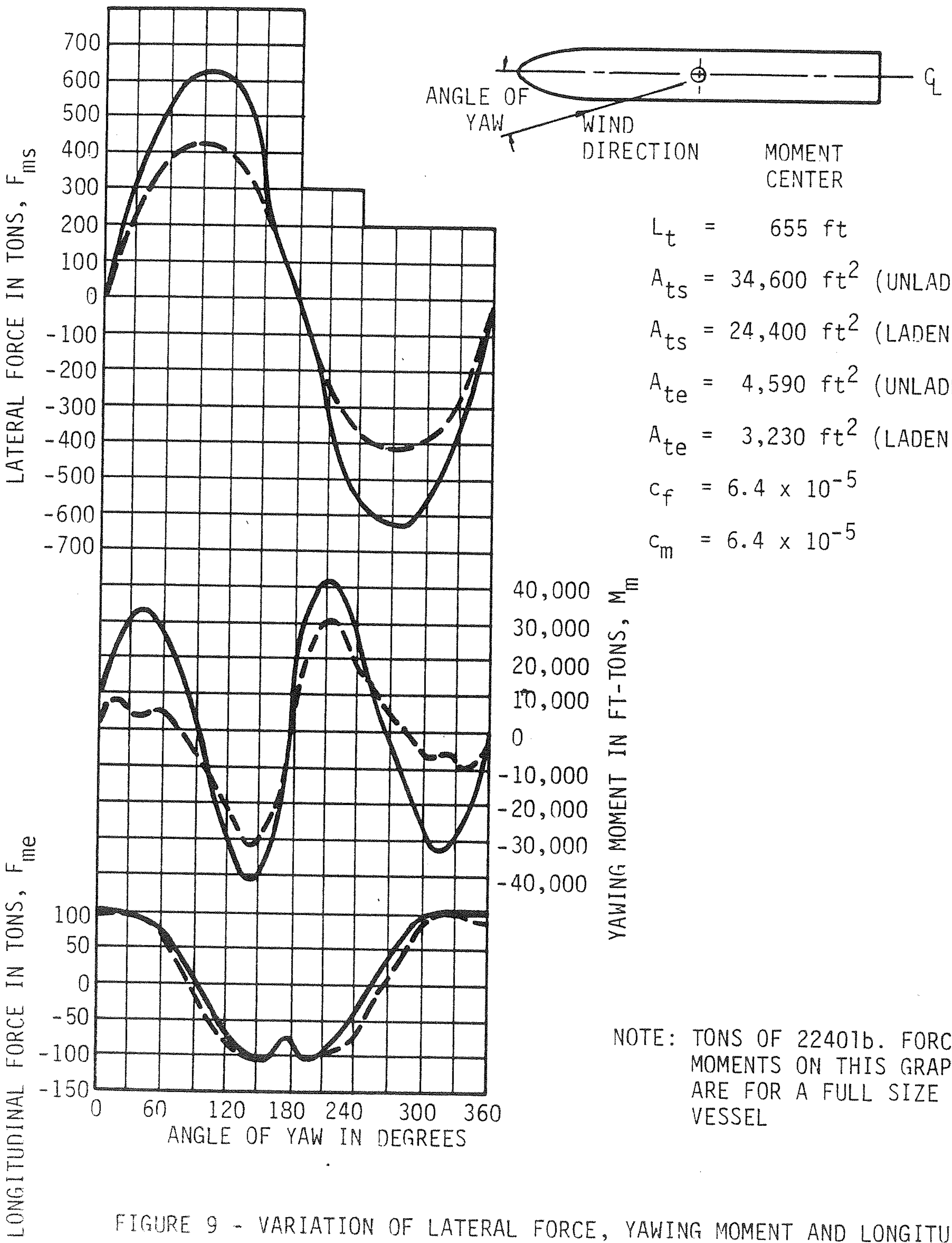
A_{ts} = 10,100 ft^2

A_{te} = 1,400 ft^2

c_f = 0.35

c_m = 25.7

FIGURE 8 - VARIATION OF LATERAL FORCE, YAWING MOMENT, AND LONGITUDINAL FORCE WITH ANGLE OF YAW FOR ONE 1:73.8 SCALE MODEL OF DD-692 CLASS DESTROYERS AT WIND SPEED OF 125 KNOTS; THE MOMENT CENTER IS AT THE CENTER OF THE MODEL.



L_t = 655 ft

A_{ts} = 34,600 ft^2 (UNLADEN)

A_{ts} = 24,400 ft^2 (LADEN)

A_{te} = 4,590 ft^2 (UNLADEN)

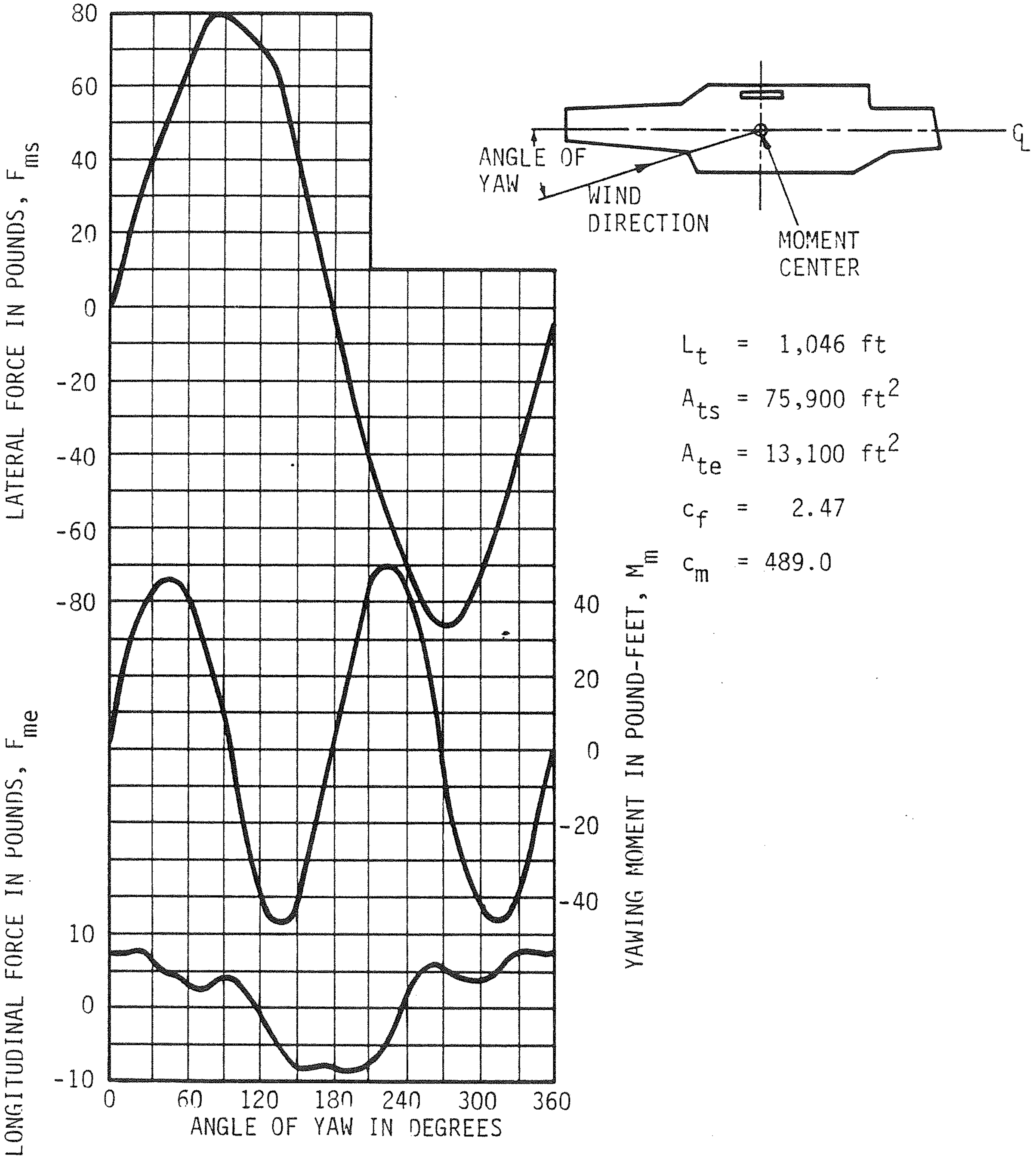
A_{te} = 3,230 ft^2 (LADEN)

c_f = 6.4×10^{-5}

c_m = 6.4×10^{-5}

NOTE: TONS OF 2240lb. FORCES & MOMENTS ON THIS GRAPH ARE FOR A FULL SIZE VESSEL

FIGURE 9 - VARIATION OF LATERAL FORCE, YAWING MOMENT AND LONGITUDINAL FORCE WITH ANGLE OF YAW FOR A SINGLE AO-143(T5 TANKER) WIND SPEED 125 KNOTS, DASHED LINE-LADEN CONDITION, SOLID LINE-UNLADEN CONDITION.



L_t = 1,046 ft

A_{ts} = 75,900 ft^2

A_{te} = 13,100 ft^2

c_f = 2.47

c_m = 489.0

FIGURE 10 - VARIATION OF LATERAL FORCE, YAWING MOMENT AND LONGITUDINAL FORCE WITH ANGLE OF YAW FOR A SINGLE 1:198-SCALE MODEL FORRESTAL CLASS AIRCRAFT-CVA 59; WIND SPEED 126 KNOTS; MOMENT CENTER AT CENTER OF MODEL.

TABLE 7 - WIND FORCE AND MOMENT CALCULATION WORKSHEET

				F^W_{xx}	F^W_{yy}	N^W_m
(1)	ρ_{air}	Density of air	$lb\text{-}sec^2/ft^4$	.0023602	.0023602	.0023602
(2)	A_s	Long proj area	ft^2	N.A.		
(3)	A_f	Trans proj area	ft^2		N.A.	N.A.
(4)	V_w	Wind Speed	ft/sec			
(5)	Ψ	Heading Angle	degrees			
(6)	$C_{xx}(\Psi)$	From Table 6	N.A.		N.A.	N.A.
(7)	$C_{yy}(\Psi)$	From Table 6	N.A.	N.A.		N.A.
(8)	$C_m(\Psi)$	From Table 6	N.A.	N.A.	N.A.	
(9)	L_s	Ship length	ft			
(10)	$V_w{}^2$	(4)x(4)	ft^2/sec^2			
(11)	$0.5\rho V_w{}^2$	0.5(1)(10)	lb/ft^2			
(12)	F^W_{xx}	(11)(3)(6)	lb	☐	N.A.	N.A.
(13)	F^W_{yy}	(11)(2)(7)	lb	N.A.	☐	N.A.
(14)	N^W_m	(11)(2)(9)(8)	ft-lb	N.A.	N.A.	☐

4. Calculation of Current Forces

The general form of the current force and moment equation is:

$$\begin{bmatrix} F^c{}_{xx} \\ F^c{}_{yy} \\ N^c{}_m \end{bmatrix} = 0.5\rho L_s{}^2 \, (V_{xx}{}^2 + V_{yy}{}^2) \begin{bmatrix} C^c{}_{xx}(\theta) \\ C^c{}_{yy}(\theta) \\ L_s C^c{}_m(\theta) \end{bmatrix}$$

where,

$F^c{}_{xx}$ = Longitudinal current force, lbs

$F^c{}_{yy}$ = Transverse current force, lbs

$N^c{}_m$ = Current moment, ft-lbs

$C^c{}_{xx}(\theta)$ = Longitudinal current force coefficient taken from Table 8

$C^c{}_{yy}(\theta)$ = Transverse current force coefficient taken from Table 8

$C^c{}_m(\theta)$ = Current moment coefficient taken from Table 8

L_s = Ship length, feet

$V_{xx} = V_s - V_c \cos\psi = V_s + V_c \cos\alpha$

$V_{yy} = V_c \sin\alpha$

V_s = Ship forward speed, ft/sec

V_c = Current speed, ft/sec

ψ = Absolute heading angle of current relative to ship heading (angle between the two vectors representing velocities)

$\alpha = \pi - \psi$

$\theta = \tan^{-1}(V_{yy}/V_{xx}), \; V_{xx} > 0$

$= \pi + \tan^{-1}(V_{yy}/V_{xx}), \; V_{xx} < 0$

$= \pi/2, \; V_{xx} = 0$

and θ is measured clockwise as shown in Figure 11.

TABLE 8

CURRENT FORCE AND MOMENT COEFFICIENTS

	T-ARC			MCM		
Degrees	C^c_{xx}	C^c_{yy}	C^c_{m}	C^c_{xx}	C^c_{yy}	C^c_{m}
180*	.00195	0.0000	0.00000	.00300	-.0020	0.00000
165	.00168	-.0070	.00127	.00256	-.0105	.00055
150	.00135	-.0158	.00211	.00207	-.0197	.00101
135	.00097	-.0258	.00243	.00150	-.0275	.00135
120	.00048	-.0350	.00222	.00087	-.0339	.00150
105	-.00030	-.0411	.00151	.00000	-.0383	.00130
90	-.00168	-.0435	.00040	-.00091	-.0405	.00040
75	-.00212	-.0408	-.00116	-.00116	-.0385	-.00253
60	-.00226	-.0333	-.00237	-.00134	-.0341	-.00415
45	-.00231	-.0226	-.00290	-.00146	-.0279	-.00470
30	-.00224	-.0188	-.00255	-.00156	-.0198	-.00422
15	-.00203	-.0065	-.00156	-.00162	-.0105	-.00280
0**	-.00173	0.0000	0.00000	-.00165	-.0010	0.00000

* Following Current
** Head Current

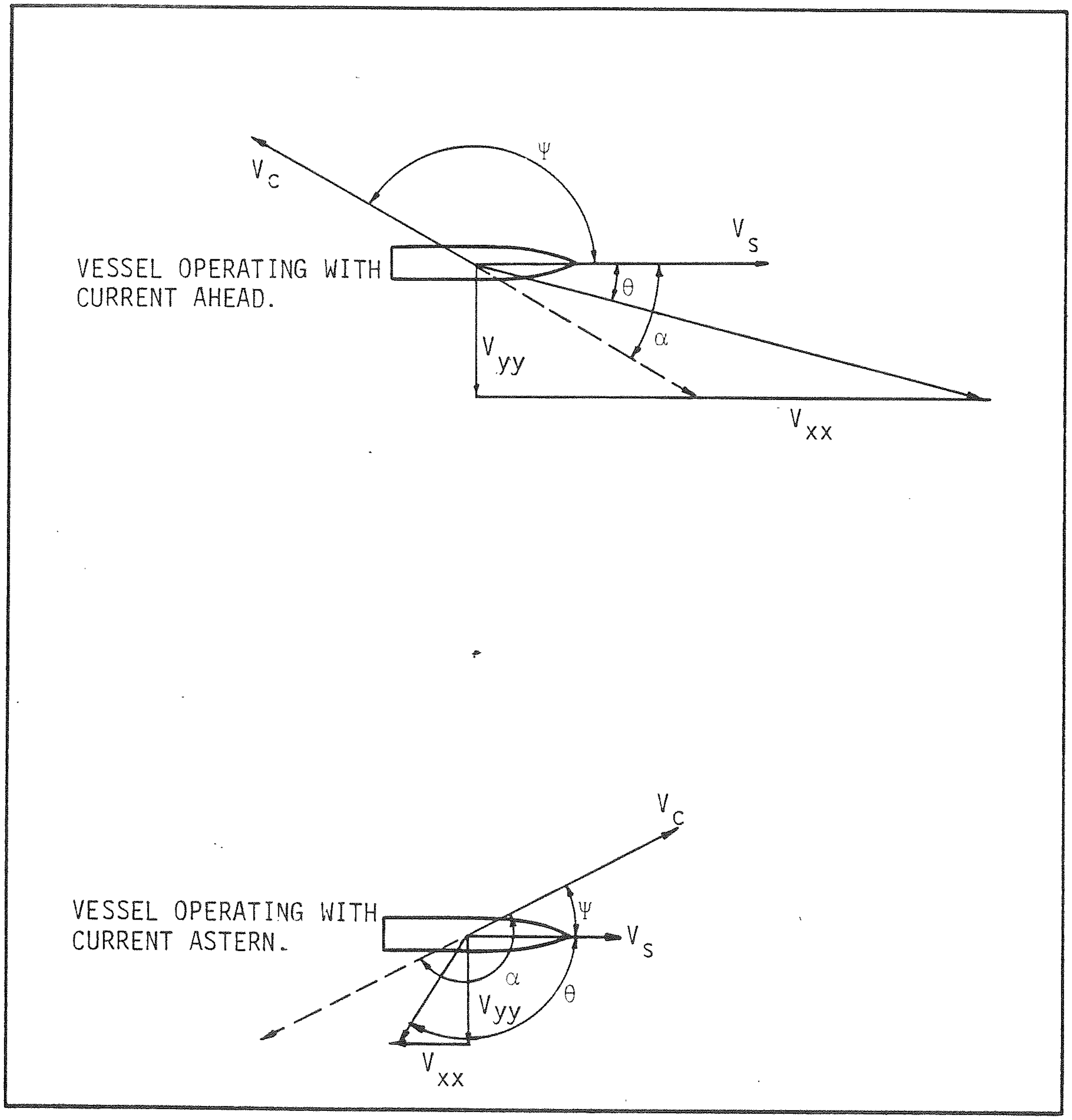


FIGURE 11 - DEFINITION OF ANGLES FOR COMPUTING CURRENT RELATIVE HEADING ANGLE, θ.

Current and moment force coefficients are presented in Table 8 which are based on model tests of the T-ARC and MCM. This data should be used when similar data for the ship under consideration is not available.

A current force and moment calculation worksheet is included as Table 9. A sample calculation of the current induced force and moment is included in the sample problem in para. 568-1-i.

5. Total Force and Moment

The total external forces and moment due to wind, waves and current is obtained by adding the components calculated above:

$$F^e_{xx} = F^2_{xx} + F^w_{xx} + F^c_{xx}$$

$$F^e_{yy} = F^2_{yy} + F^w_{yy} + F^c_{yy}$$

$$N^e_m = N^2_m + N^w_m + N^c_m$$

Table 10 is provided to record the calculated values of each component of the external forces and moments and to find the totals.

TABLE 9

CURRENT FORCE AND MOMENT CALCULATION WORKSHEET

				F^c_{xx}	F^c_{yy}	N^c_m
(1)	ρ	Density water	$lb\text{-}sec^2/ft^4$	1.9905	1.9905	1.9905
(2)	L_s	Ship length	feet			
(3)	V_s	Ship speed	feet/sec			
(4)	V_c	Current speed	feet/sec			
(5)	ψ	Heading angle	degrees			
(6)	V_{xx}	(3) - (4) cos ψ	feet/sec			
(7)	V_{yy}	(4) sin ψ	feet/sec			
(8)	θ	If (6) > 0.0; $\tan^{-1}((7)/(6))$	degrees			
		If (6) < 0.0; $180+\tan^{-1}((7)/(6))$	degrees			
		If (6) = 0.0;	degrees	180	180	180
(9)	$C^c_{xx}(\theta)$	from Table 8	N.A.		N.A.	N.A.
(10)	$C^c_{yy}(\theta)$	from Table 8	N.A.	N.A.		N.A.
(11)	$C^c_m(\theta)$	from Table 8	N.A.	N.A.	N.A.	
(12)	$V_{xx}^2 + V_{yy}^2$	$(6)^2 + (7)^2$	$feet^2/sec^2$			
(13)	$.5\rho L_s^2$	.5(1)(2)(2)	$lb\text{-}sec^2/ft^2$			
(14)	$.5\rho L_s^2 \times (V_{xx}^2 + V_{yy}^2)$	(12)(13)	lbs			
(15)	F^c_{xx}	(14)(9)	lbs		N.A.	N.A.
(16)	F^c_{yy}	(14)(10)	lbs	N.A.		N.A.
(17)	N^c_m	(14)(2)(11)	ft-lbs	N.A.	N.A.	

TABLE 10

TOTAL FORCE AND MOMENT WORKSHEET

(1)	F^2_{xx}	From Table 5	lbs	
(2)	F^2_{yy}	From Table 5	lbs	
(3)	N^2_m	From Table 5	ft-lbs	
(4)	F^w_{xx}	From Table 7	lbs	
(5)	F^w_{yy}	From Table 7	lbs	
(6)	N^w_m	From Table 7	ft-lbs	
(7)	F^c_{xx}	From Table 9	lbs	
(8)	F^c_{yy}	From Table 9	lbs	
(9)	N^c_m	From Table 9	ft-lbs	
(10)	F^e_{xx}	(1)+(4)+(7)	lbs	
(11)	F^e_{yy}	(2)+(5)+(8)	lbs	
(12)	N^e_m	(3)+(6)+(9)	ft-lbs	

568-1-g. Estimate of Thruster Size

The thruster force can be computed based on a static solution of the force and moment equations. Solutions are presented for the case of both a bow and stern thruster, bow thruster only and stern thruster only. The general equations are presented followed by individual solutions for each case.

Consider the ship as a rigid body with a speed V_s along the centerline. Assume two propellers, two rudders, a bow and a stern thruster. Let the environmental loads as calculated above be applied at the C.G. of the body. Let the propeller thrusts act through the shafts along the positive x axis, any rudder loads through the corresponding center of pressure of the rudders ($F^R{}_x$, $F^R{}_y$). Assume the thrusters produce ($F^F{}_x$, $F^F{}_y$) and ($F^A{}_x$, $F^A{}_y$) forces as shown in Figure 6.

The motion is assumed steady (no rotations or accelerations). For equilibrium of forces and moments the following equations result:

$$F^p{}_{xx} + F^s{}_{xx} + F^e{}_{xx} - (F^F{}_x + F^A{}_x) - 2F^R{}_x = 0$$

$$F^F{}_y + F^A{}_y + 2F^R{}_y + F^e{}_{yy} = 0$$

$$(F^F{}_y d_1 - F^A{}_y d_2) + (F^p{}_{xx} - F^s{}_{xx})d + N^e{}_m - 2F^R{}_y d_3 = 0$$

The last equation can be rewritten as:

$$(F^F{}_y d_1 - F^A{}_y d_2) = -N^e{}_m - N^{PR} + 2F^R{}_y d_3$$

$$= -N^e{}_m - N^{PR} + N^R{}_m$$

where,

$$N^{PR} = (F^p{}_{xx} - F^s{}_{xx})d$$

$$N^R{}_m = 2F^R{}_y d_3$$

1. Both Bow and Stern Thrusters

Solving for $F^F{}_y$, $F^A{}_y$

$$\begin{matrix} F^F{}_y \\ F^A{}_y \end{matrix} = \frac{1}{(d_1+d_2)} \begin{bmatrix} (-N^e{}_m - N^{PR} + 2F^R{}_y\, d_3) + d_2\,(-F^e{}_{yy} - 2F^R{}_y) \\ -(-N^e{}_m - N^{PR} + 2F^R{}_y\, d_3) + d_1\,(-F^e{}_{yy} - 2F^R{}_y) \end{bmatrix}$$

which cannot be explicitly solved without any assumptions.

In the absence of other information we can assume a value for $F^R{}_y$ within the capability of the rudder and that $F^R{}_x$, $F^F{}_x$, $F^A{}_x$ are all zero, which means that:

$$FP_{xx} = FS_{xx} = \tfrac{1}{2}(F^e{}_{xx} + (F^F{}_x + F^A{}_x) + 2F^R{}_x)$$

$$\text{or } FP_{xx} = FS_{xx} = \tfrac{1}{2}F^e{}_{xx}$$

By definition $N^{PR} = (FP_{xx} - FS_{xx})d_1$, i.e., $N^{PR} = 0$ as assumed.

$$\text{thus,} \quad F^F{}_y = \frac{-\,N^e{}_m - d_2F^e{}_{yy} + (d_3-d_2)2F^R{}_y}{d_1+d_2}$$

$$F^A{}_y = \frac{N^e{}_m - d_1F^e{}_{yy} - (d_3+d_1)2F^R{}_y}{d_1+d_2}$$

A worksheet is provided as Table 11.

TABLE 11

FORCE BALANCE WORKSHEET FOR TWO THRUSTERS, BOW AND STERN

(1)	F^e_{yy}	(11) from Table 10	
(2)	N^e_m	(12) from Table 10	
(3)	d_1	Distance from bow thruster to CG in feet	
(4)	d_2	Distance from stern thruster to CG in feet	
(5)	d_1+d_2	(3)+(4)	
(6)	d_3	Distance from rudder to CG in feet	
(7)	F^R_y	Rudder force, lbs.	
(8)	F^F_y	$-\frac{(2)-(4)(1)+((6)-(4))2(7)}{(5)}$, Bow Thruster Force, lbs	
(9)	F^A_y	$\frac{+(2)-(3)(1)-((6)+(3))2(7)}{(5)}$, Stern Thruster Force, lbs	

2. Bow Thruster Only

Taking moments about the C.G.:

$$N^e_m + F^F_y d_1 - 2F^R_y d_3 = 0$$

or $F^F_y = - (N^e_m - 2F^R_y d_3)/d_1$

Summing the forces in the y-direction:

$$F^F_y + 2F^R_y + F^e_y = 0$$

or $2F^R_y = - F^e_{yy} - F^F_y$

Substituting and solving for F^F_y:

$$F^F_y = - (F^e_{yy} d_3 + N^e_m)/(d_1 + d_3)$$

Since F^e_{yy}, N^e_m, d_2 and d_3 are known, we can find F^F_y and then get $2F^R_y$ by the equation:

$$2F^R_y = - F^e_{yy} - F^F_y$$

A worksheet for the above calculation is provided as Table 12.

TABLE 12

FORCE BALANCE WORKSHEET FOR BOW THRUSTER ONLY

(1)	F^e_{yy}	(11) from Table 10	
(2)	N^e_m	(12) from Table 10	
(3)	d_1	Bow thruster lever, feet	
(4)	d_3	Rudder lever, feet	
(5)	d_1+d_3	(3)+(4)	
(6)	F^F_y	$-\frac{(1)(4)+(2)}{(5)}$, Bow Thruster Force, lbs	
(7)	$2F^R_y$	-(6)-(1), Rudder Force, lbs	

3. Stern Thruster Only

Taking moments about the C.G.:

$$N^e_m - F^A_y d_2 - 2F^R_y d_3 = 0$$

or $F^A_y = -(N^e_m - 2F^R_y d_3)/(d_1)$

Summing the forces in the y-direction:

$$F^A_y + 2F^R_y + F^e_y = 0$$

or $2F^R_y = - F^e_{yy} - F^A_y$

Substituting and solving for F^A_y:

$$F^A_y = -(F^e_{yy} d_3 + N^e_m)/(d_3 - d_2)$$

Since F^e_{yy}, N^e_m, d_2 and d_3 are known we can find $2F^R_y$ and then get F^A_y by the equation:

$$2F^R_y = - F^e_{yy} - F^A_y$$

A worksheet for the above calculation is provided as Table 13.

TABLE 13

FORCE BALANCE WORKSHEET FOR STERN THRUSTER ONLY

(1)	F^e_{yy}	(11) from Table 10	
(2)	N^e_m	(12) from Table 10	
(3)	d_2	Stern thruster lever, feet	
(4)	d_3	Rudder lever, feet	
(5)	d_3-d_2	(4)-(3)	
(6)	F^A_y	$-\frac{(1)(4)+(2)}{(5)}$, Stern Thruster Force, lbs	
(7)	$2F^R_y$	-(1)-(6), Rudder Force, lbs	

4. Thruster Performance Degradation Due to Ship Speed

If the duty cycle of the thruster includes operation while the ship is making speed ahead or astern, then it is necessary to account for the degrading effects of ship speed on thruster performance. The speed of the ship will reduce the effective force and moment of the thruster by an effectiveness factor. The effectiveness factor is reported in percent and is defined as the thruster effective force or moment divided by the thruster static force or moment. To produce estimates of the thruster effectiveness factor for ships operating at speed, Figures 12 and 13 (References 4-6) are provided.

To use Figures 12 and 13 to estimate the effectiveness, enter the lower part of the figure with the speed ratio, shown at the bottom of the figure, and read the effectiveness factor from the center scale.

When using these figures to estimate the effectiveness factor of stern thrusters, the speed that is used is not simply the vessel speed, but must be increased by an amount equal to the propeller slip and given the opposite sign, i.e. a ship making 8 knots with a slip ratio of 1.25 would be figured on the basis of minus 10-knots speed.

The previously calculated thrust levels, $F^{F}y$ and $F^{A}y$ are divided by the smaller of the corresponding force or moment effectiveness to get the thrust at speed.

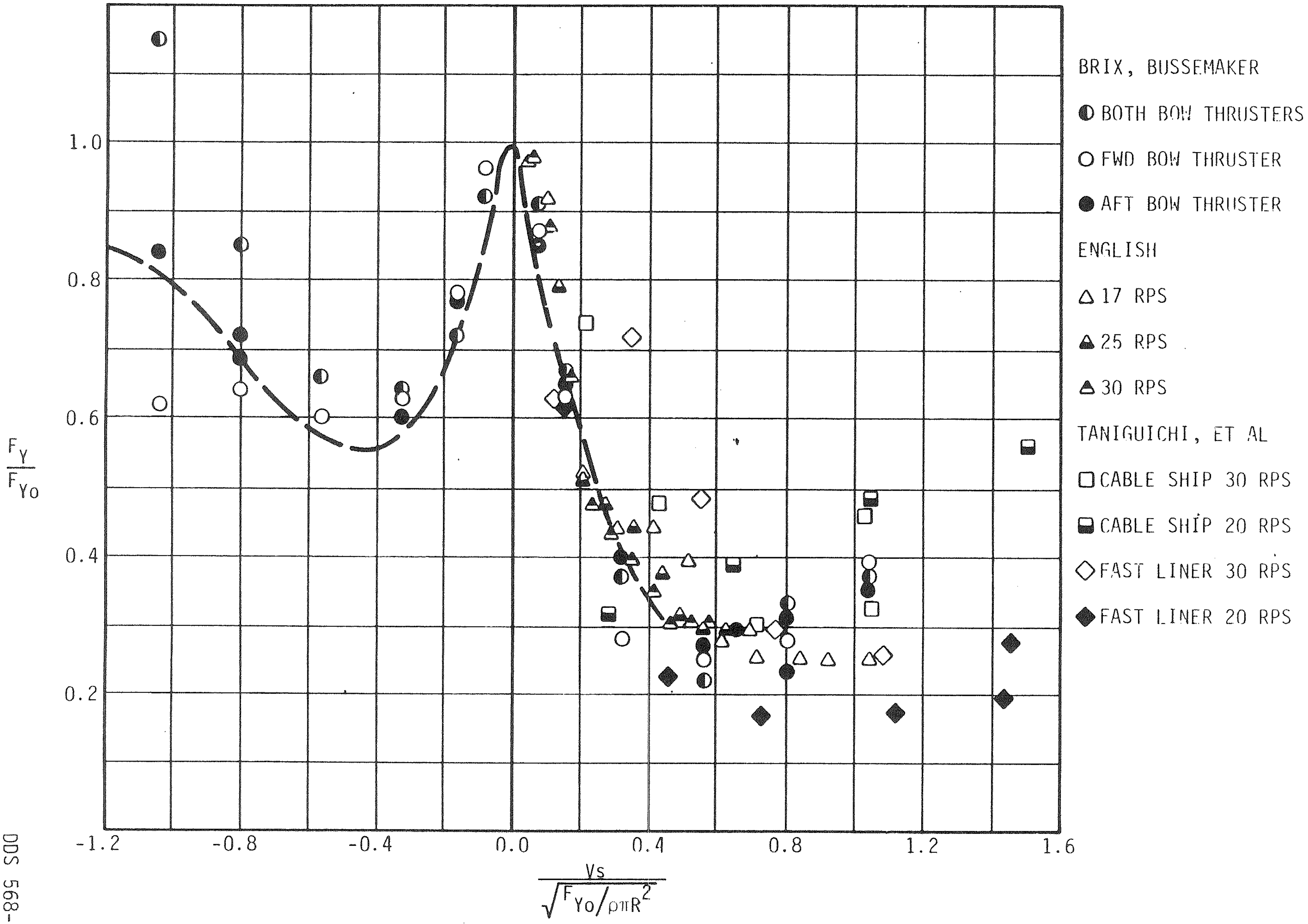


FIGURE 12 - THRUST EFFECTIVENESS FACTOR

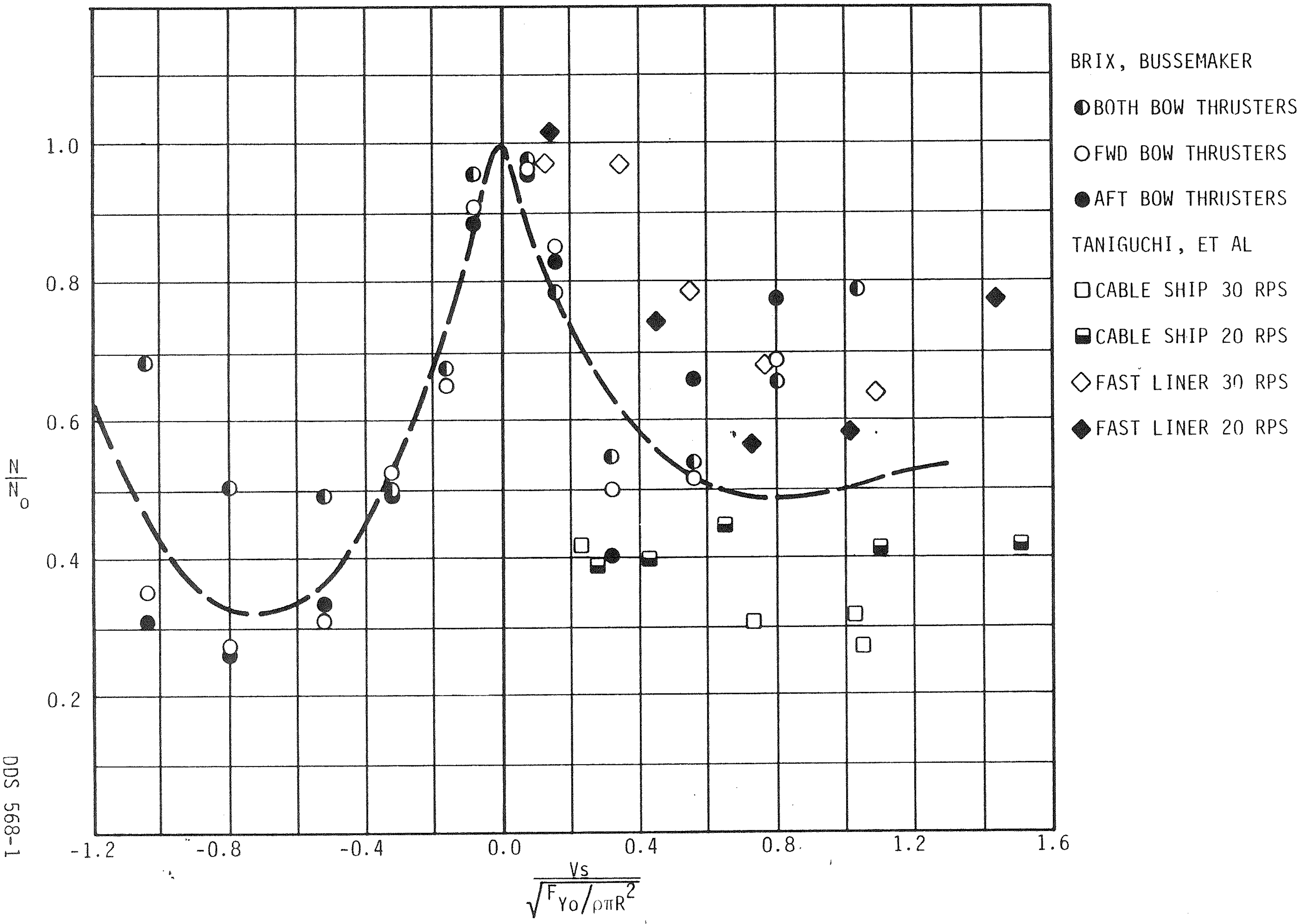


FIGURE 13 - MOMENT EFFECTIVENESS FACTOR

568-1-h. Installation Design

For optimum performance, the thruster configuration must meet certain minimum hydrodynamic constraints and the constraints of the hull shape, in terms of the area and volume available for the thruster installation. While thruster weight is also required, it varies considerably due to type of thruster and prime mover and must be considered on a case basis.

The thruster opening must also be designed to have minimum adverse impact on the ahead resistance of the ship in transit. However, in practice the resistance penalty that must be paid for the thruster is accepted and the thruster is located for maximum effectiveness. The location for maximum effectiveness is the subject of this section.

1. Thruster Specific Power

Thruster performance is most frequently reported in terms of thruster specific power, that is, the pounds of thrust produced by a single horsepower of input energy. This value varies with the type of thruster and with the size of thruster, as the larger thrusters are slightly less efficient than the smaller ones, due primarily to increased gear train and ancillary systems losses.

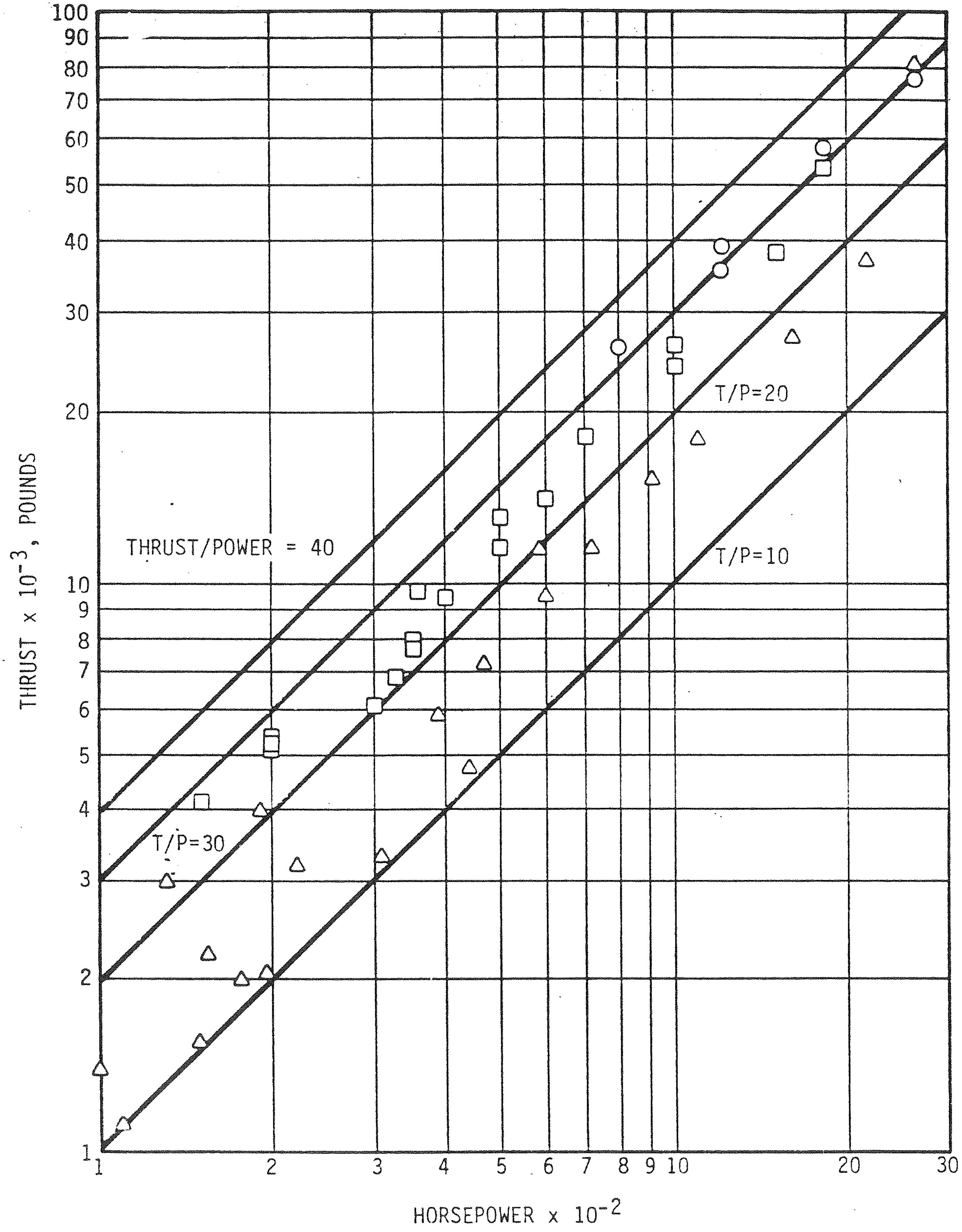
Figure 14 is a plot of thruster output versus input horsepower for a wide range of thruster types and sizes. The lines of constant specific power are presented for easing the task of interpolating between thrusters. A preliminary knowledge of thruster output, as determined in accordance with para. 568-1-g, may be used in conjunction with this figure to make fairly accurate estimates of the size of prime mover required for the thruster.

2. Area/Volume Requirements

As there are a variety of thruster types, manufacturers and prime movers, it is impossible to set out a rigorous technique for determining the amount of space a particular thruster installation requires. The actual space requirements depend on particulars of the thruster that are only available after a specific manufacturer has been selected. It is possible however, to produce working estimates of the space requirements of various thruster types based on the thruster output. This data has been compiled from manufacturers data and arrangement drawings for recent ship designs, and is presented in Figures 15 through 20.

Figures 15, 16 and 17 give the tunnel diameter, tunnel length, and machinery space area, respectively, for tunnel type thrusters. Figures 18, 19 and 20 give the inboard height, duct length, and machinery space area respectively for jet type thrusters.

The values given for tunnel type thrusters may be used for retractable rotatable type thrusters, as depicted in Figure 5.



□ TUNNEL THRUSTERS, SEE FIG. 1.

○ ROTATABLE NOZZLE THRUSTERS, SEE FIG. 5.

△ JET THRUSTERS, SEE FIG. 2.

FIGURE 14 - THRUSTER OUTPUT VS. INPUT HORSEPOWER

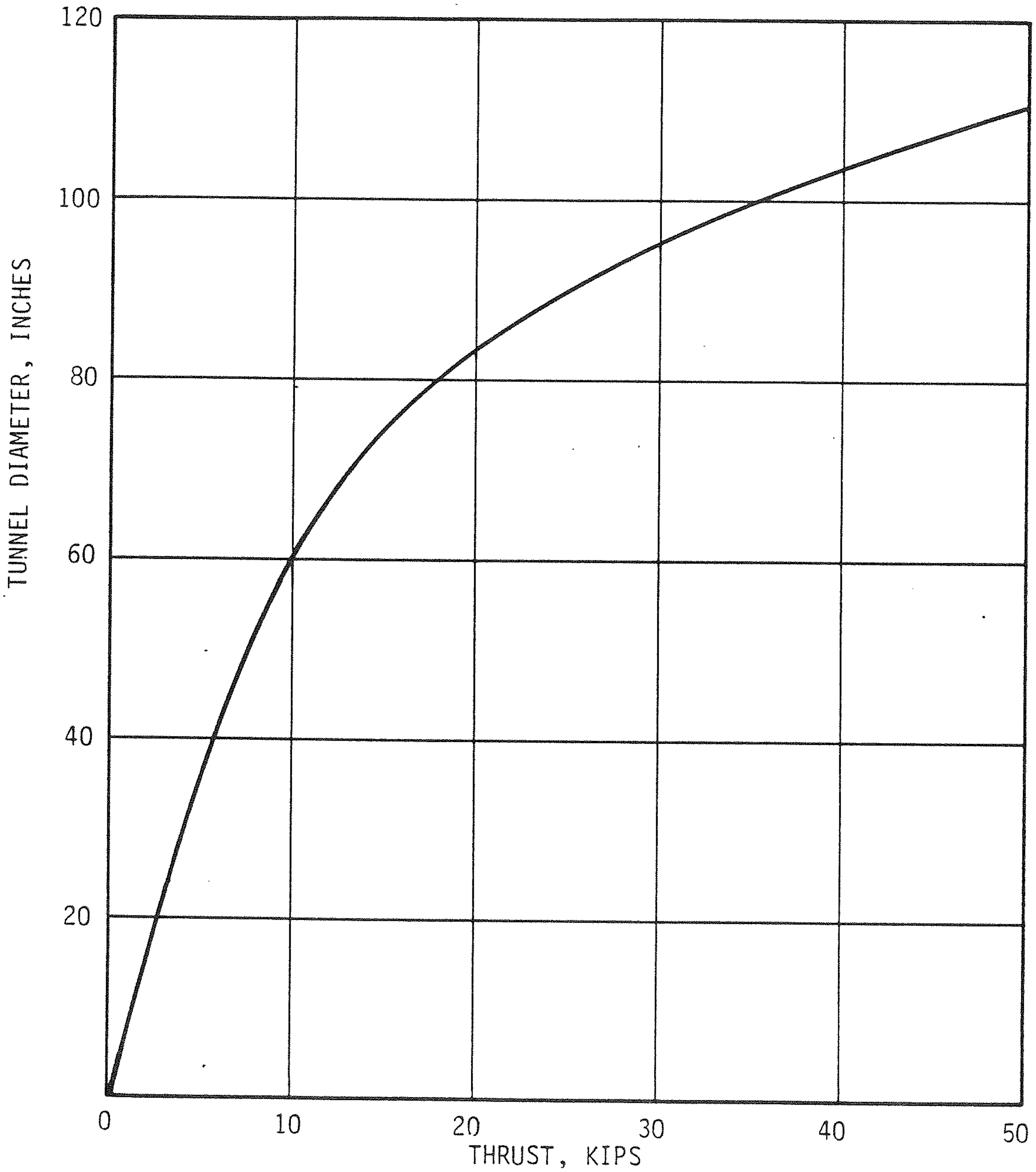


FIGURE 15 - TUNNEL THRUSTER TUNNEL DIAMETER vs. THRUST

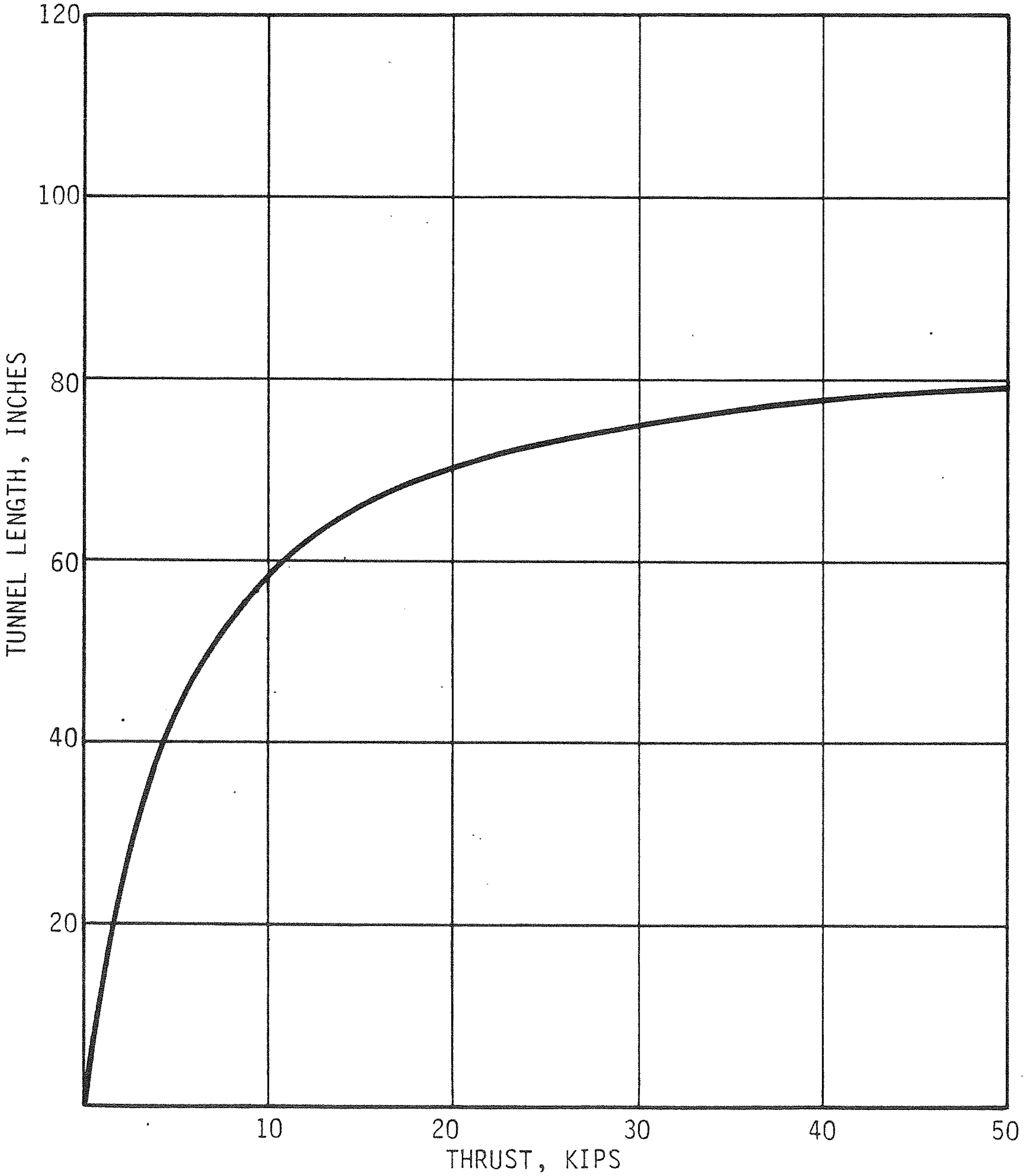


FIGURE 16 - TUNNEL THRUSTER TUNNEL LENGTH vs. THRUST

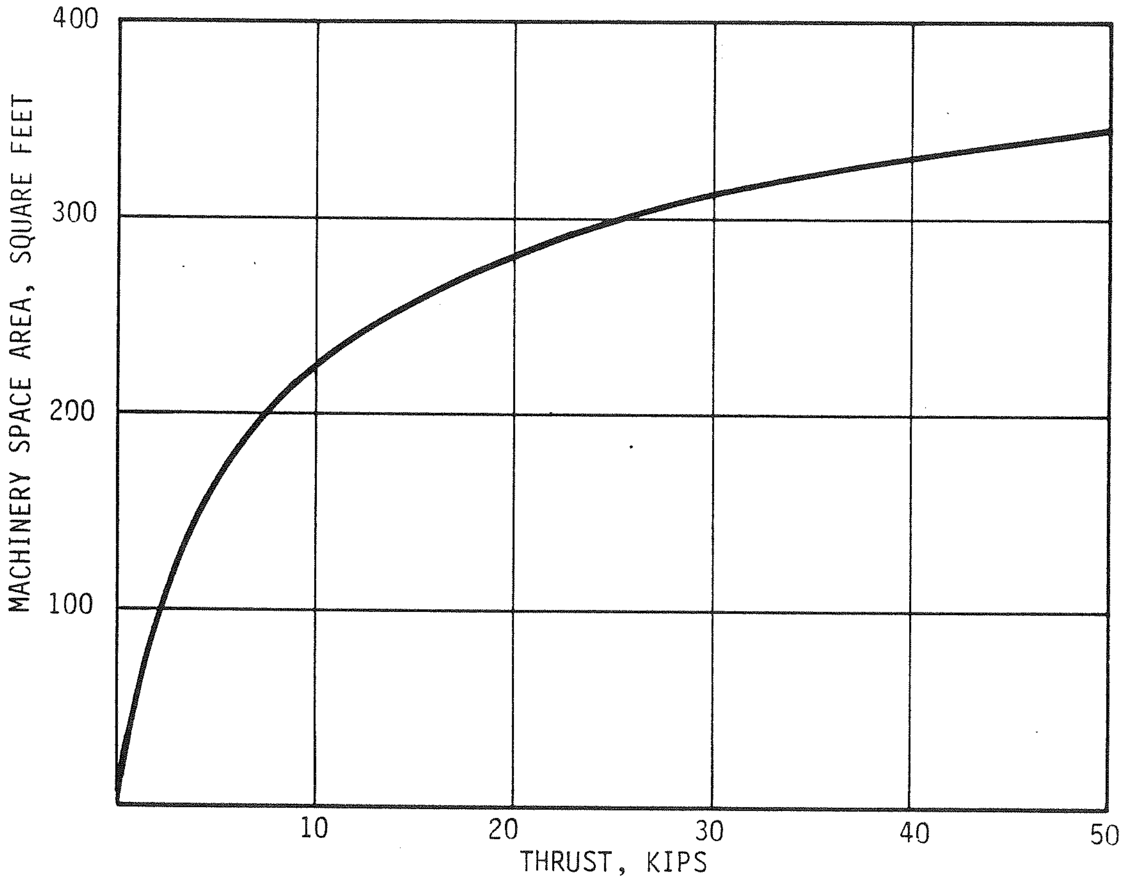


FIGURE 17 - TUNNEL THRUSTER MACHINERY SPACE AREA vs. THRUST

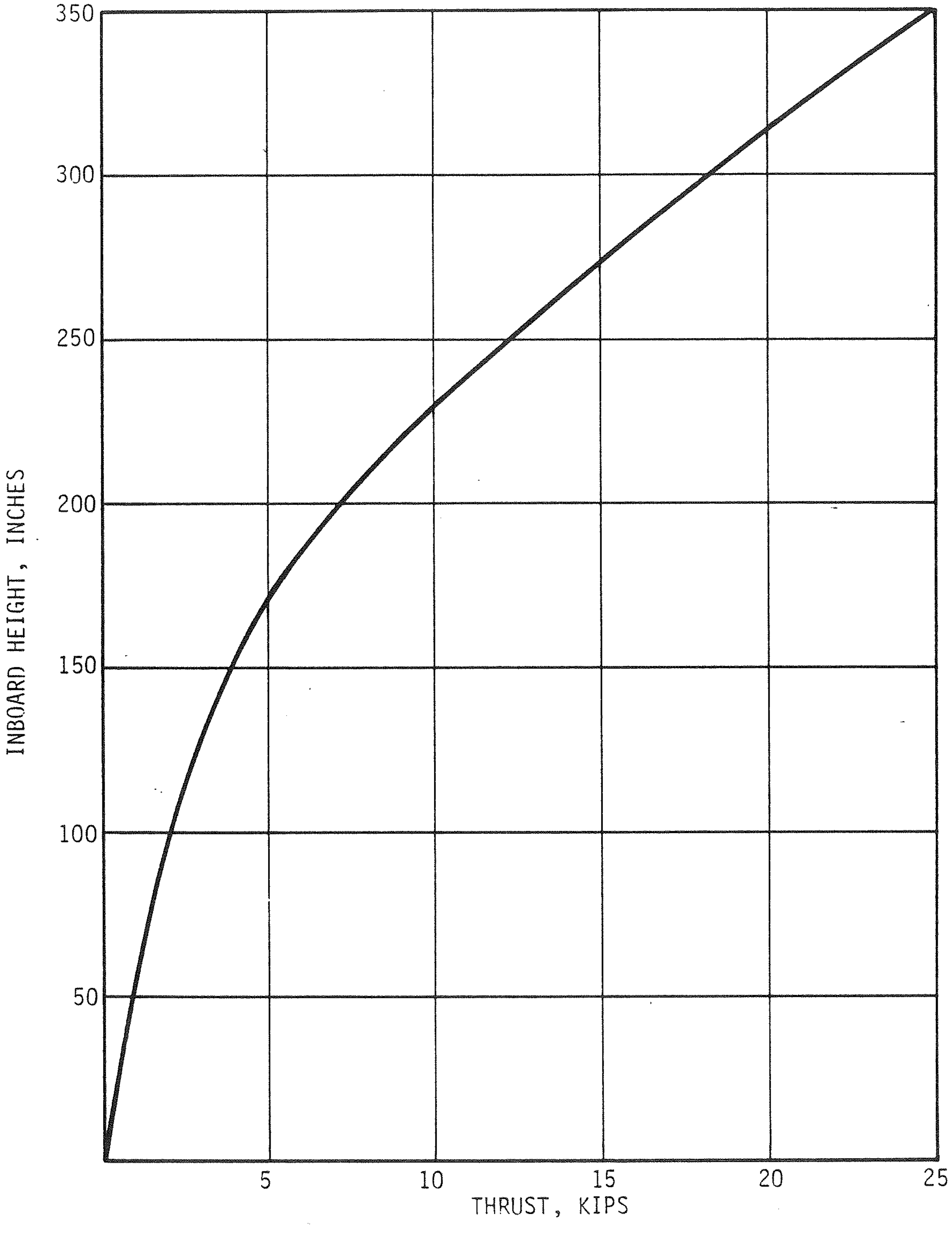


FIGURE 18 - JET THRUSTER INBOARD HEIGHT vs. THRUST

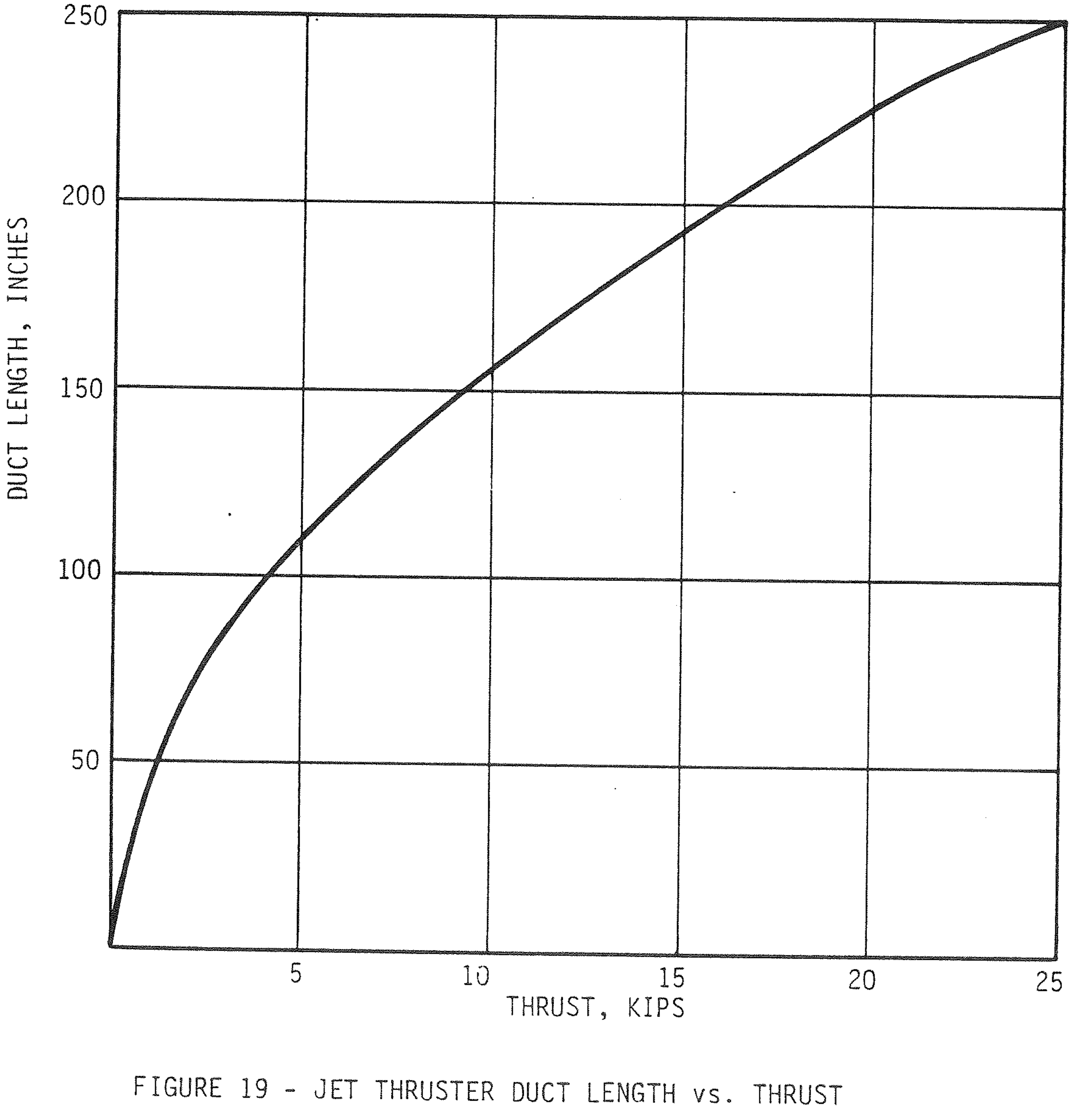


FIGURE 19 - JET THRUSTER DUCT LENGTH vs. THRUST

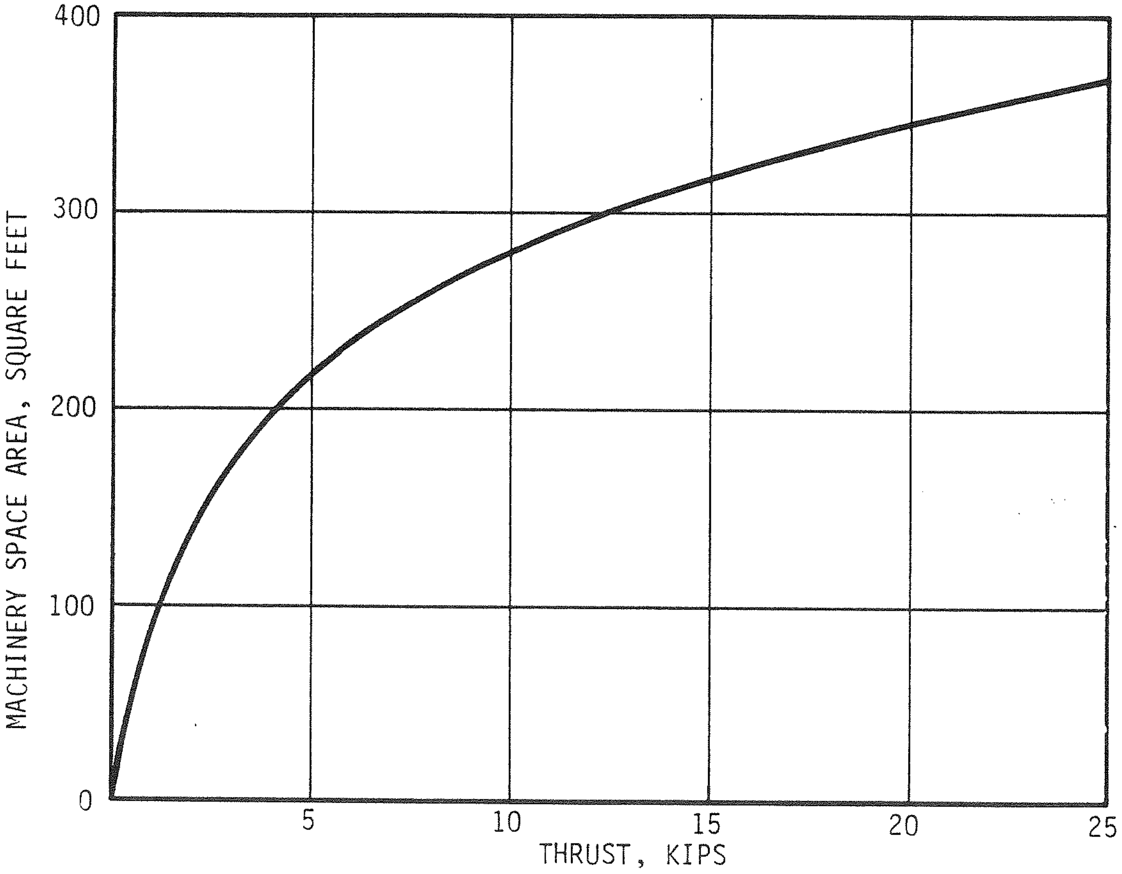


FIGURE 20 - JET THRUSTER MACHINERY SPACE AREA vs. THRUST

To obtain this data from the figures, enter the figure with the thruster output force, along the horizontal axis, and read the data on the vertical scale at the left.

Note that the sizes so obtained are averages, and thrusters may most likely be obtained both larger and smaller than the sizes estimated. The purpose of the preliminary estimate is to aid in the determination of thruster location requirements, and to assist in the allocation of ship space to equipment subsystems.

With jet type thrusters suction may be taken either directly through the ships hull or from a sea chest. In this latter case the volume and area of the sea chest must be added to the area and volume of the thruster.

For diesel prime mover installations additional area and volume is required for the diesel and its intakes and uptakes.

3. Restraints on Thruster Location

Longitudinal Restraints. - The thruster should be located as far from the ship LCG as is feasible. This means locating the bow thruster as near the FP as possible. Thrusters should not be located forward of station 2, however, as hull curvature at the forward end of the waterplane can adversely affect thruster performance, particularly as related to added resistance. The narrowing of the hull forward may also severely restrict the tunnel length. For tunnel type thrusters the tunnel length should not be less than 1.0 duct diameter, and should preferably be nearer 2.0 duct diameters.

For transversely mounted jet type thrusters the requirements for width are greater than for the proportional thrusting type jet, and in fact it is preferable to mount the directional jet thrusters with the inlet and outlet aperatures on the same longitudinal line.

Vertical Restraints. - The thruster must be located far enough below the waterline to insure adequate submersion at the inlet through a wide range of ship motions. For typical installations this means that the centerline of the inlet duct should not be less than 1.0 diameter below the calm water plane. For jet type thrusters with their intakes below the hull, care must be taken that they do not suck bottom material into the jet. Similarly, the retractable rotatable nozzles must not extend so far below the waterline that they touch the bottom.

In cases where thrusters are expected to operate in severe seaways, the depth of immersion of the inlet must be increased above the 1.0 diameter stated above to insure freedom from thruster emergence. In this case a seakeeping analysis should be performed to establish the minimum submersion required, based on design sea state, and the allowable limit on thruster emergences/hour (30). A thruster tunnel emergence occurs when a point 1/4-tunnel diameter above the top of the tunnel emerges from the water.

4. Electrical Power Requirements

Electrical load requirements will depend on the type of thruster selected and the type of prime mover used to power the thruster. Thus, if the thruster will be totally electrically powered, then the electrical power requirements may be estimated from a knowledge of the horsepower requirements of the unit. If the thruster will be operated by an independent diesel engine, then the only electrical load requirement will be the control and sensing system, and that electrical power required to start and run the engine.

5. Effect of Thruster on Ship Resistance

The presence of the thruster openings in the ship will have an adverse effect on the resistance of the ship. A simple estimate for the resistance of the thruster opening is obtained from the following formula of Reference 7:

$$X_T = 0.07\frac{\rho}{2}\pi R^2 V^2$$

where,

X_T = resistance of thruster opening, lbs

R = thruster opening radius, feet

V = ship speed, ft/sec

ρ = density of water, lb-sec^2/ft^4

Model tests should be run to determine the actual resistance increment caused by inclusion of the thruster.

The thruster opening may be designed to have minimum impact on ship resistance by fairing its intersection with the hull. A fairing radius or conical section is recommended with the fairing radius increased and aligned with the flow, as determined from model flow tests, on the aft side of the thruster opening to lessen the resistance. Most thrusters are fitted with guards made from flat bars which minimize resistance as well as prevent ingestion of debris into the thruster. The guards are aligned with the local flow. Figure 21 shows a typical guard configuration.

The retractable rotatable type thruster may have no associated resistance penalty, when it is totally within the hull when not in use, and its closing port is fitted with a fairing to exactly match the hull shape in way of the thruster.

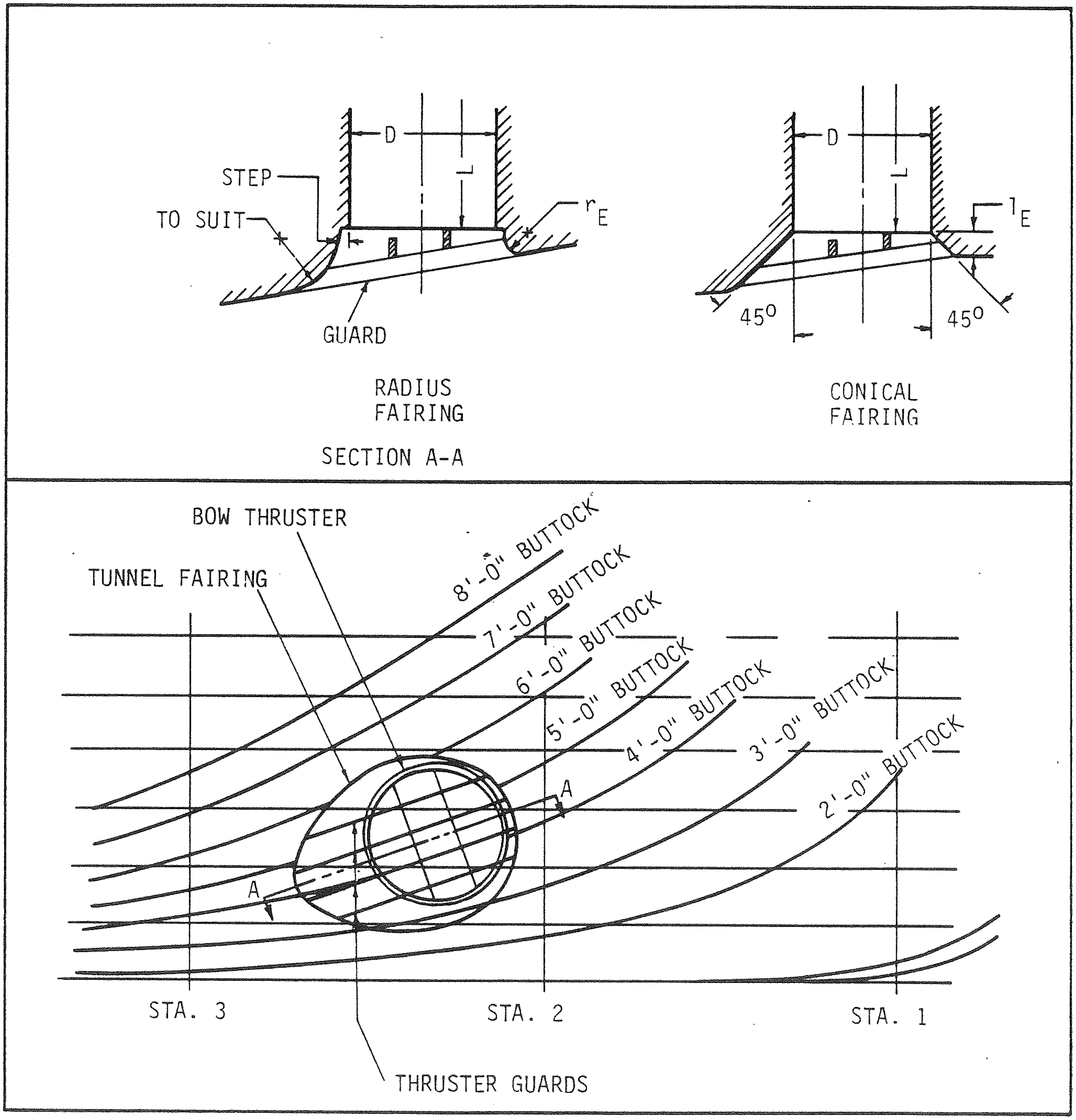


FIGURE 21 - TYPICAL THRUSTER GUARD AND OPENING INSTALLATION

One alternative for higher speed ships is to provide closure doors or covers for the thruster openings, which avoids the resistance increase. Thruster doors may be difficult to maintain, which accounts for the lack of recent design experience.

In addition to the resistance of the thruster openings, there is an increase in resistance when the thrusters are operating. This resistance is due to the acceleration of the water flowing through the thruster from rest to the speed of the ship. An estimate of this additional resistance is obtained from the following formula of Reference 8:

$$F_x = \rho \pi R^2 V_s \left(|F_y| / \rho \pi R^2 \right)^{\frac{1}{2}}$$

where,

ρ = density of water, lb-sec^2/ft^4

R = thruster outlet radius, feet

V_s = ship speed, ft/sec

F_y = lateral thrust, lbs

6. Thruster Opening Design

The thruster opening for a tunnel thruster serves as both the inlet and outlet for the propeller. As the inlet it should have a smoothly curved shape to minimize inlet losses. As the outlet it should have a sharp edge to keep the jet flow stable to minimize losses. A compromise which satisfies both requirements, see Figure 21, consists of an inlet radius which ends at the tunnel at a diameter of 1 to 2 inches larger than the tunnel diameter, leaving a step change in diameter. Alternatively, a conical opening which is left with a sharp angle edge at the tunnel, may be used. A jet thruster inlet opening would omit the step and the exit would be usually sharp edged.

Several installation parameters affect the rated thrust and torque values for tunnel thrusters. Correction factors from Reference 9, which account for the effects of the tunnel length, opening radius or cone length, and number of grid bars, are presented in Figures 22 and 23. The correction factors are based on reference values of a tunnel length of 2 tunnel diameters, an opening radius of 0.1 tunnel diameter and no grid bars. The scale for the effects of conical opening length are based on limited data which indicate that for the same performance the cone length should be 50% greater than the equivalent opening radius. The installed thrust is the rated thrust multiplied by the thrust correction factors obtained from Figure 22 for the particular installation. The installed torque or power is the rated torque or power multiplied by the torque correction factors obtained from Figure 23 for the particular installation. The propeller pitch may need to be adjusted to match the installed thruster torque or power to that of its motor.

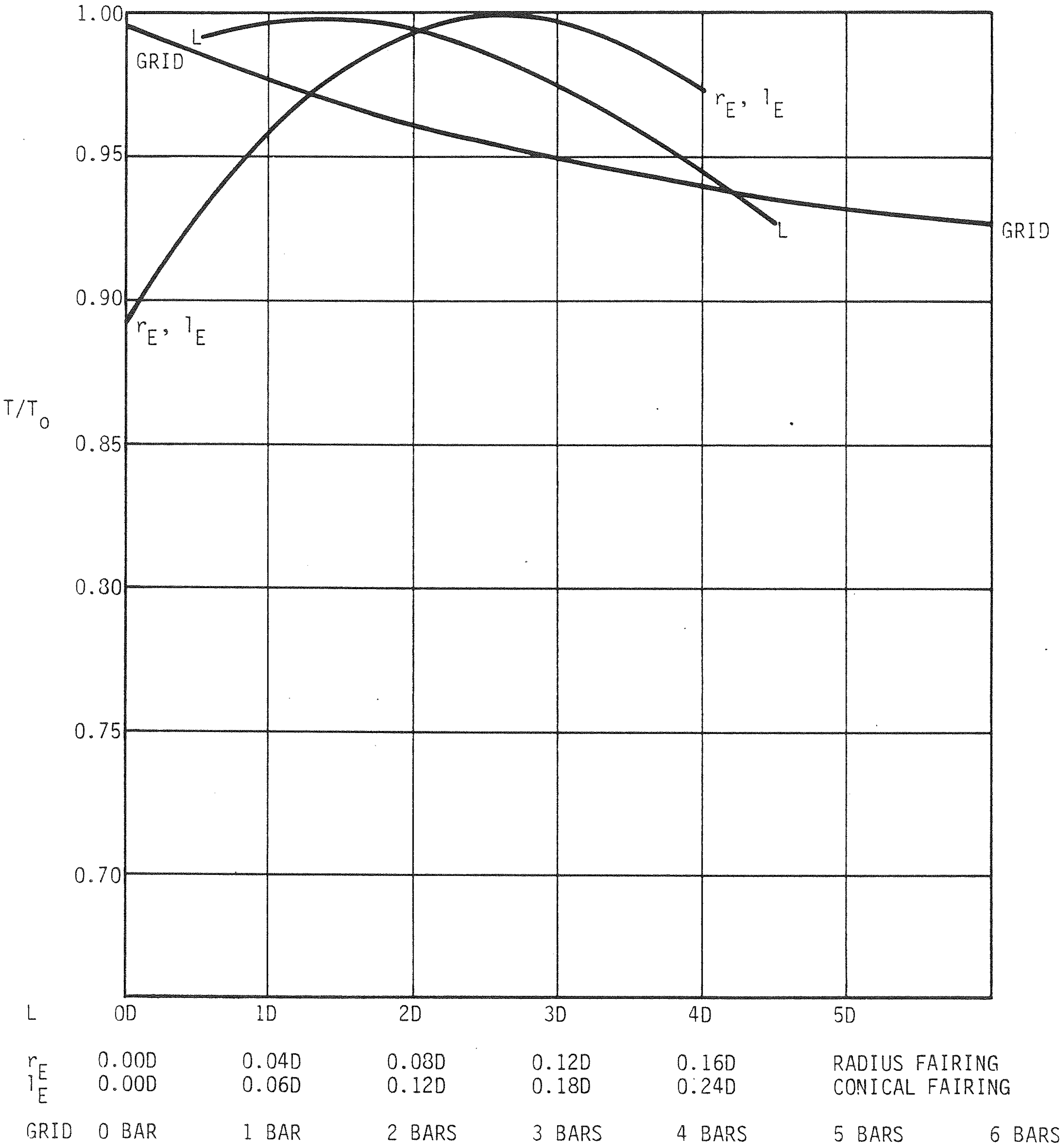


FIGURE 22 - INSTALLED THRUST FACTORS

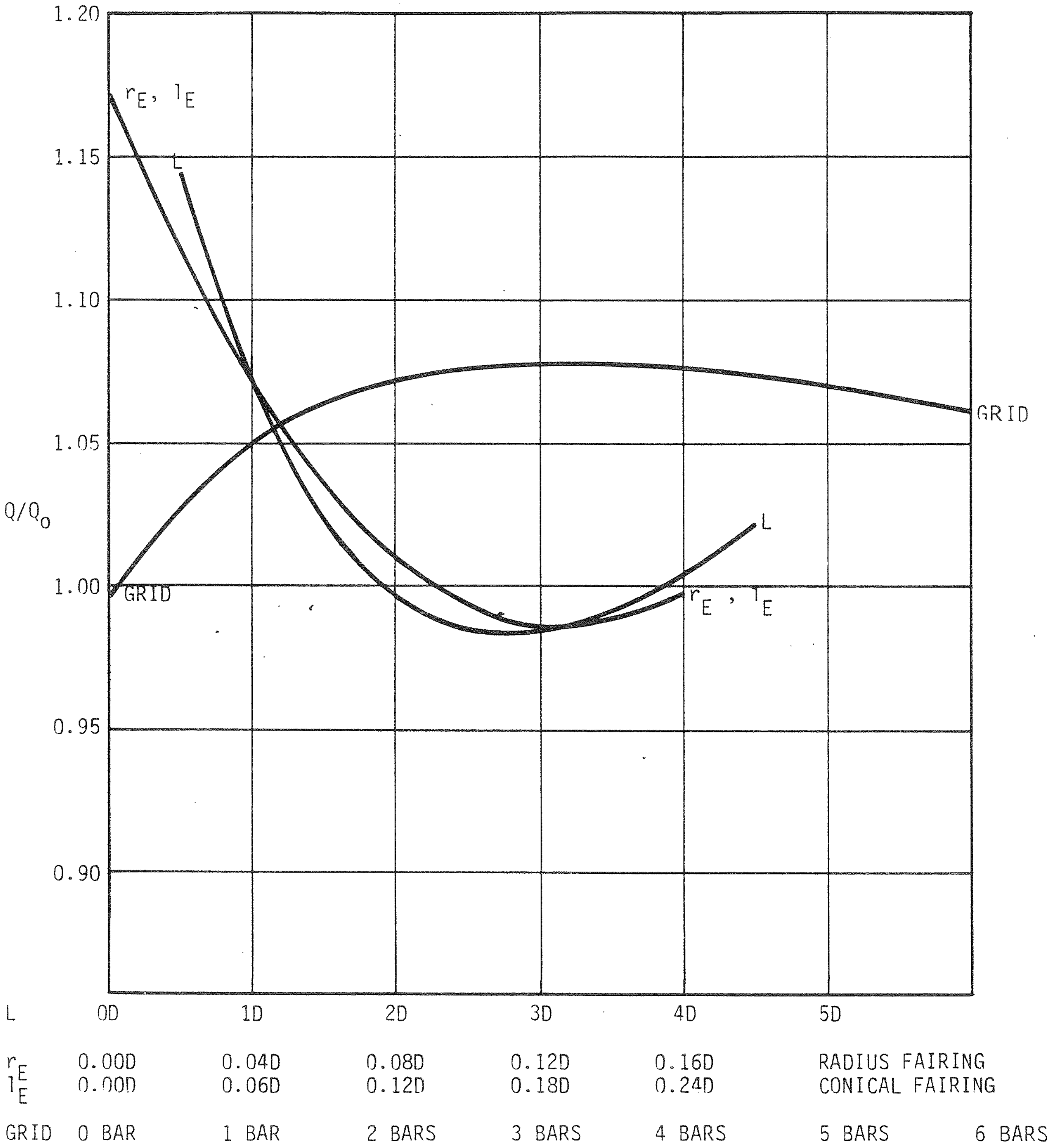


FIGURE 23 - INSTALLED TORQUE FACTORS

568-1-i. Sample Calculation

The following pages demonstrate the use of Tables 5 through 13 to perform a thruster sizing calculation. The ship in the example is the T-ARC mentioned earlier, and for which data is presented in the text. The tables should be self-explanatory. They follow consecutively beginning with the wave force calculation, Table 5.

The results of Table 5 are entered in Table 10 before beginning on Table 7. The results of Table 7 are then entered in Table 10 and Table 9 is begun. When all of Table 10 is complete either Table 11, 12 or 13 is used, depending on whether there are two thrusters or one.

In the example all three cases have been solved.

The ship is assumed to be making 1.0 knots ahead into a sea state 3, with a 4.90 feet significant wave height. The ship is 150 degrees from the waves, wind, and current. The calculation should also be repeated for other angles in order to isolate the most severe condition. The wind speed is 20.0 knots, and the current speed is 0.50 knots.

For case 1, both bow and stern thrusters, a thrust degradation calculation is included. For this calculation the propeller slip ratio is assumed to be 1.25, so the speed used for the stern thruster calculation was 1.25 knots, while 1.00 knots was used for the bow thruster.

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET

(1) n	(2) $\tau_n = \frac{\lambda_n}{L_s}$	(3) $\omega_n = \sqrt{\frac{2\pi g}{L_s \tau_n}}$	(4) $s = \frac{\omega_n}{g} V_s \cos\psi$	(5) $\omega_e = \omega_n(1-s)$	(6) $(1-2s)$	(7) $T_o^4 \omega_n^4$	(8) $e^{\left(\frac{-1944.5}{T_o^4 \omega_n^4}\right)}$
1	.170	1.602	-.073	1.718	1.145	4111.66	.623
2	.222	1.401	-.064	1.491	1.127	2411.07	.446
3	.302	1.202	-.055	1.267	1.109	1302.87	.225
4	.436	1.000	-.045	1.045	1.091	625.09	.045
5	.538	.900	-.041	.937	1.082	410.54	.009
6	.681	.800	-.036	.829	1.073	256.23	.001
7	.889	.700	-.032	.723	1.064	150.35	.000
8	1.21	.600	-.027	.617	1.054	81.16	.000
9	1.743	.500	-.023	.512	1.045	39.11	.000
10	2.151	.450	-.020	.459	1.041	25.68	.000

L_s = SHIP LENGTH (feet) = 464.0

V_s = SHIP SPEED (ft/sec) = 1.688

Ψ = HEADING ANGLE = 150.

T_o = MODAL PERIOD (sec) = 5.0

g = 32.2 ft/sec^2

$H_{1/3}$ = SIGNIFICANT WAVE HEIGHT (ft) = 4.9

ρg = 64 lbs/ft^3 SALT WATER

ρg = 62.4 lbs/ft^3 FRESH WATER

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET (CONT'D)

(1) n	(5) ω_e	(9) $S_e(\omega_n) = \frac{1}{\omega_n} \frac{483.5(H_{1/3})^2}{T_o^4\omega_n^4} e^{\frac{-1944.5}{T_o^4\omega_n^4}}$ $= \frac{483.5(H_{1/3})^2 x(8)}{(3)x(7)}$	(10) $\omega_{e_{mean_n}} = \frac{1}{2}(\omega_{e_n} + \omega_{e_{n+1}})$	(11) $\omega_{e_{mean_n}} - \omega_{e_{mean_{n+1}}}$	(12) $\omega_{e_1} - \omega_{e_2}$ $\omega_{e_9} - \omega_{e_{10}}$
1	1.718	1.099			.227
2	1.491	1.534	1.605	.226	
3	1.267	1.667	1.379	.223	
4	1.045	.828	1.156	.165	
5	.937	.275	.991	.108	
6	.829	.029	.883	.107	
7	.723	.000	.776	.106	
8	.617	.000	.670	.105	
9	.512	.000	.565	.079	
10	.459	.000	.486		.053

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET (CONT'D)

(1) n	(5) ω_e	(13) $\Delta\omega_e$ (11)+(12)	(14) $\frac{2S_e(\omega_n)\ \Delta\omega_e}{(1-2s)} = \frac{2x(9)x(13)}{(6)}$	(15) $R_{xx}(\omega_e)$	(16) $R_{yy}(\omega_e)$	(17) $R_m(\omega_e)$	(18) LONGITUDINAL WAVE FORCE $\frac{2S_e(\omega_n)}{(1-2s)}\Delta\omega_e\ R_{xx}(\omega_e) = (14)x(15)$
1	1.718	.227	.436	-.032	-.410	-.043	- .014
2	1.491	.226	.615	-.032	-.411	-.039	- .020
3	1.267	.223	.670	-.032	-.414	-.043	- .021
4	1.045	.165	.250	-.032	-.386	-.045	- .008
5	.937	.108	.055	-.031	-.148	-.027	- .002
6	.829	.107		-.033	-.058	-.020	.000
7	.723	.106	.000	-.028	-.035	-.014	.000
8	.617	.105	.000	-.031	-.040	-.009	.000
9	.512	.079	.000	-.043	-.038	-.005	.000
10	.459	.053	.000	-.039	-.030	-.003	.000
							(21) Σ = -.065

TABLE 5 - WAVE FORCE AND MOMENT WORKSHEET (CONT'D)

(1) n	(2) ω_e	(19) TRANSVERSE WAVE FORCE $\frac{2S_e(\omega_n)}{(1-2s)} \Delta\omega_e \, R_{yy}(\omega_e)$ = (14)x(16)	(20) WAVE MOMENT $\frac{2S_e(\omega_n)\Delta\omega_e}{(1-2s)} R_m(\omega_e)$ = (14)x(17)
1	.170	- .179	- .019
2	.222	- .253	- .024
3	.302	- .277	- .029
4	.436	- .097	- .011
5	.538	- .008	- .001
6	.681	.000	.000
7	.889	.000	.000
8	.121	.000	.000
9	1.743	.000	.000
10	2.151	.000	.000
		Σ = -0.814 (22)	-.084 (23)

$F^2_{xx} = \frac{1}{2}\rho g \times L_s \times (21) = 964.\text{lbs}$

$F^2_{yy} = \frac{1}{2}\rho g \times L_s \times (22) = -12{,}084.\text{lbs}$

$N^2_m = \frac{1}{2}\rho g \times L^2_s \times (23) = -581{,}421.\text{ft.lbs}$

TABLE 7 - WIND FORCE AND MOMENT CALCULATION WORKSHEET

				F^W_{xx}	F^W_{yy}	N^W_m
(1)	ρ_{air}	Density of air	lb-sec²/ft⁴	.0023602	.0023602	.0023602
(2)	A_s	Long proj area	ft²	N.A.	24,500	24,500
(3)	A_f	Trans proj area	ft²	5,148	N.A.	N.A.
(4)	V_w	Wind Speed	ft/sec	33.756	33.756	33.756
(5)	Ψ	Heading Angle	degrees	150^o	150^o	150^o
(6)	$C_{xx}(\Psi)$	From Table 6	N.A.	-0.652	N.A.	N.A.
(7)	$C_{yy}(\Psi)$	From Table 6	N.A.	N.A.	-0.520	N.A.
(8)	$C_m(\Psi)$	From Table 6	N.A.	N.A.	N.A.	-0.0695
(9)	L_s	Ship length	ft	464.0	464.0	464.0
(10)	V_w^2	(4)x(4)	ft²/sec²	1,139.467	1,139.467	1,139.467
(11)	$0.5\rho V_w^2$	0.5(1)(10)	lb/ft²	1.344	1.344	1.344
(12)	F^W_{xx}	(11)(3)(6)	lb	$\boxed{-4,513.4}$	N.A.	N.A.
(13)	F^W_{yy}	(11)(2)(7)	lb	N.A.	$\boxed{-17,131.}$	N.A.
(14)	N^W_m	(11)(2)(9)(8)	ft-lb	N.A.	N.A.	$\boxed{-1,062,404}$

TABLE 9

CURRENT FORCE AND MOMENT CALCULATION WORKSHEET

				F^c_{xx}	F^c_{yy}	N^c_m
(1)	ρ	Density water	lb-sec^2/ft^4	1.9905	1.9905	1.9905
(2)	L_s	Ship length	feet	464.0	464.0	464.0
(3)	V_s	Ship speed	feet/sec	1.688	1.688	1.688
(4)	V_c	Current speed	feet/sec	0.8439	0.8439	0.8439
(5)	ψ	Heading angle	degrees	150°	150°	150°
(6)	V_{xx}	(3) - (4) cos ψ	feet/sec	2.42	2.42	2.42
(7)	V_{yy}	(4) sin ψ	feet/sec	0.42	0.42	0.42
(8)	θ	If (6) > 0.0; $\tan^{-1}$ ((7)/(6))	degrees	9.90°	9.90°	9.90°
		If (6) < 0.0; 180+$\tan^{-1}$((7)/(6))	degrees	-	-	-
		If (6) = 0.0;	degrees	180	180	180
(9)	$Cc_{xx}(\theta)$	from Table 8	N.A.	-.00193	N.A.	N.A.
(10)	$Cc_{yy}(\theta)$	from Table 8	N.A.	N.A.	-.00429	N.A.
(11)	$Cc_m(\theta)$	from Table 8	N.A.	N.A.	N.A.	-.00103
(12)	$V_{xx}{}^2 + V_{yy}{}^2$	$(6)^2 + (7)^2$	feet^2/sec^2	6.03	6.03	6.03
(13)	$.5\rho L_s{}^2$	.5(1)(2)(2)	lb-sec^2/ft^2	214,273.34	214,273.34	214,273.34
(14)	$.5\rho L_s{}^2 \times (V_{xx}{}^2 + V_{yy}{}^2)$	(12)(13)	lbs	1,291,608	1,291,608	1,291,608
(15)	Fc_{xx}	(14)(9)	lbs	-2,490	N.A.	N.A.
(16)	Fc_{yy}	(14)(10)	lbs	N.A.	-5,541	N.A.
(17)	Nc_m	(14)(2)(11)	ft-lbs	N.A.	N.A.	-617,046

TABLE 10

TOTAL FORCE AND MOMENT WORKSHEET

				F^e_{xx}	F^e_{yy}	N^e_m
(1)	F^2_{xx}	From Table 5	lbs	-964	N.A.	N.A.
(2)	F^2_{yy}	From Table 5	lbs	N.A.	-12,084	N.A.
(3)	N^2_m	From Table 5	ft-lbs	N.A.	N.A.	-581,421
(4)	F^w_{xx}	From Table 7	lbs	-4,513	N.A.	N.A.
(5)	F^w_{yy}	From Table 7	lbs	N.A.	-17,131	N.A.
(6)	N^w_m	From Table 7	ft-lbs	N.A.	N.A.	-1,062,404
(7)	F^c_{xx}	From Table 9	lbs	-2,490	N.A.	N.A.
(8)	F^c_{yy}	From Table 9	lbs	N.A.	-5,541	N.A.
(9)	N^c_m	From Table 9	ft-lbs	N.A.	N.A.	-617,046
(10)	F^e_{xx}	(1)+(4)+(7)	lbs	-7,967	N.A.	N.A.
(11)	F^e_{yy}	(2)+(5)+(8)	lbs	N.A.	-34,756	N.A.
(12)	N^e_m	(3)+(6)+(9)	ft-lbs	N.A.	N.A.	-2,260,871

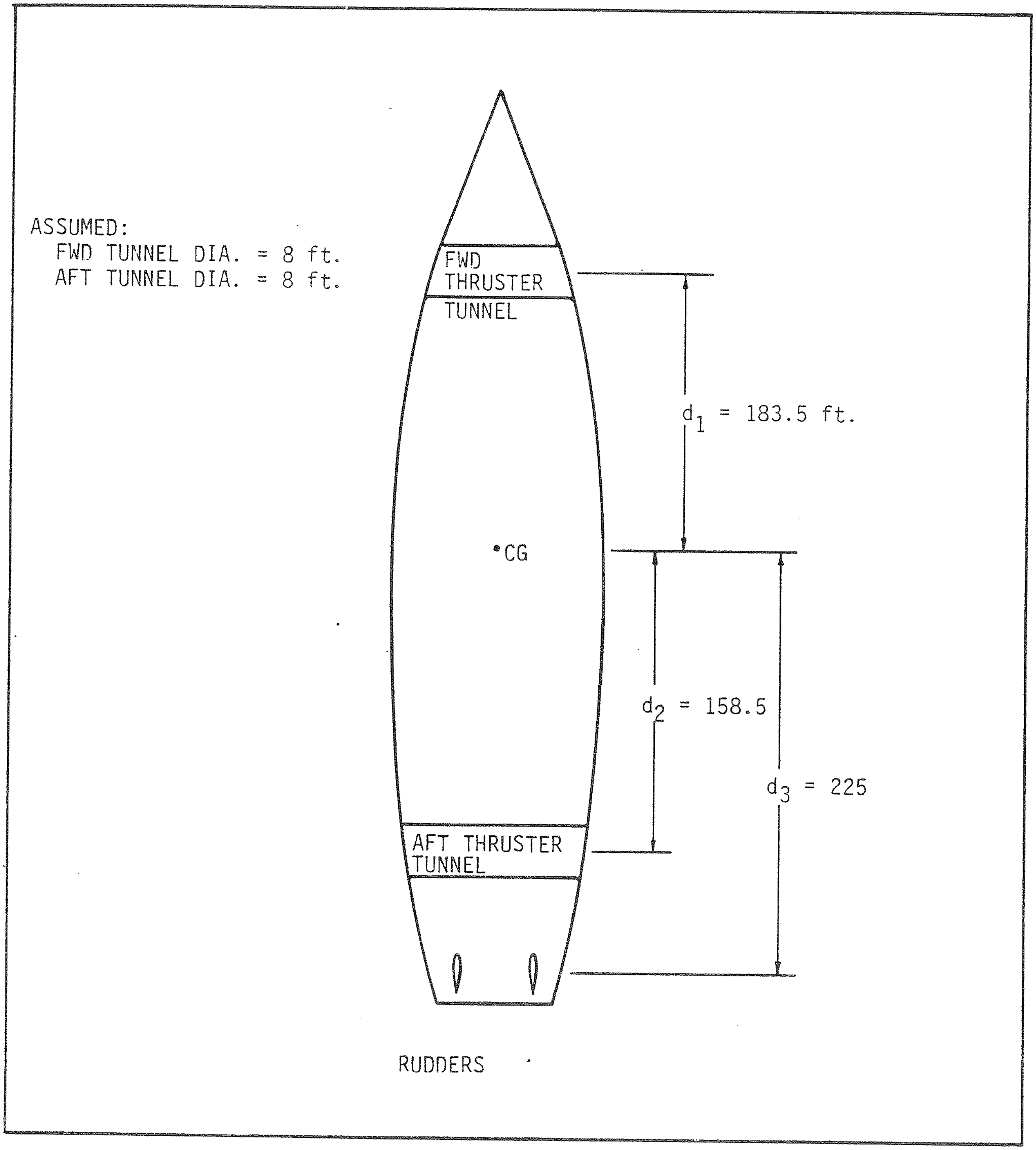


FIGURE 24 - DIMENSIONS FOR T-ARC EXAMPLE PROBLEM

TABLE 11

FORCE BALANCE WORKSHEET FOR TWO THRUSTERS, BOW AND STERN

(1)	F^e_{yy}	(11) from Table 10	-34,756
(2)	N^e_m	(12) from Table 10	-2,260,871
(3)	d_1	Distance in feet	183.5
(4)	d_2	Distance in feet	158.5
(5)	d_1+d_2	(3)+(4)	342
(6)	d_3	Rudder lever,feet	225
(7)	F^R_y	Rudder force, lbs	1,000
(8)	F^F_y	$-\frac{(2)-(4)(1)+((6)-(4))2(7)}{(5)}$, Bow Thruster Force, lbs	+23,107
(9)	F^A_y	$+\frac{(2)-(3)(1)-((6)+(3))2(7)}{(5)}$, Stern Thruster Force, lbs	+9,649

TABLE 12

FORCE BALANCE WORKSHEET FOR BOW THRUSTER ONLY

(1)	F^e_{yy}	(11) from Table 10	-34,756
(2)	N^e_m	(12) from Table 10	-2,260,871
(3)	d_1	Bow thruster lever, feet	183.5
(4)	d_3	Rudder lever, feet	225.0
(5)	d_1+d_3	(3)+(4)	408.5
(6)	F^F_y	$-\frac{(1)(4)+(2)}{(5)}$, Bow Thruster Force, lbs	-24,678
(7)	$2F^R_y$	-(6)-(1), Rudder Force, lbs	-59,434

The rudder side force required to balance the bow thruster force exceeds the rudder side force available from any type of rudder. A stern thruster is required for this environmental condition.

Corrections for thrust degradation due to forward speed, thruster guards and entrance fairings would be made similar to the bow and stern thruster case.

TABLE 13

FORCE BALANCE WORKSHEET FOR STERN THRUSTER ONLY

(1)	F^e_{yy}	(11) from Table 10	-34,756
(2)	N^e_m	(12) from Table 10	-2,260,871
(3)	d_2	Stern thruster lever, feet	158.5
(4)	d_3	Rudder lever, feet	225.0
(5)	d_3-d_2	(4)-(3)	66.5
(6)	F^A_y	$-\frac{(1)(4)+(2)}{(5)}$, Stern Thruster Force, lbs	151,594
(7)	$2F^R_y$	-(1)-(6), Rudder Force, lbs	-116,838

The rudder side force required to balance the bow thruster force exceeds the rudder side force available from any type of rudder. A bow thruster is required for this environmental condition.

Corrections for thrust degradation due to forward speed, thruster guards and entrance fairings would be made similar to the bow and stern thruster case.

Thrust Degradations

Bow thruster:

V_s = 1.0 knots = 1.689 ft/sec

F^F_y = 23,107 lbs

ρ = 1.9905 lb-sec^2/ft^4

R = 4 ft

$\frac{V_s}{\sqrt{\frac{F_y}{\rho\pi R^2}}}$ = .113 from Figure 12 Thrust effectiveness = .70
from Figure 13 Moment effectiveness = .80

Required ~~stern~~ bow thruster force = 23,107/.70 = 33,010 lbs

Assuming that a specific thrust of 25 lbs/hp (Figure 14)
the required thruster HP is 1,320 hp

Stern thruster:

V_s = -1.25 knots = -2.111 ft/sec

F^A_y = 9,649 lbs

ρ = 1.9905 lb-sec^2/ft^4

R = 4 ft

$\frac{V_s}{\sqrt{\frac{F_y}{\rho\pi R^2}}}$ = -.176 from Figure 12 Thrust effectiveness = .70
from Figure 13 Moment effectiveness = .70

Required stern thruster force = 9,649/.70 = 13,784

The required thruster horsepower is 13,784 = .551

Note: If the rudder force is not known it can be estimated by:

$$F^Y_R = \tfrac{1}{2}\,\rho\, C_L\, S\, V^2$$

where,

ρ = 1.9905 lb-sec^2/ft^4

S = surface area of rudder, ft^2

V = velocity in ft/sec

C_L = lift coefficient = about 1.0

Added Resistance of Thruster Openings

Bow thruster:

$$X_T = 0.035\ \rho\pi\ R^2 V^2_s$$

R = 4 ft

V_s = 1 knot = 1.689 ft/sec

ρ = 1.9905 lb-sec^2/ft^4

X_T = thruster resistance (bow thruster) = 10 lbs

Stern thruster:

$$X_T = 0.035\ \rho\pi\ R^2 V^2_s$$

R = 4 ft

V_s = 1.25 knots = 2.111 ft/sec

ρ = 1.9905 lb-sec^2/ft^4

X_T = thruster resistance (bow thruster) = 16 lbs

Total resistance of bow and stern thruster openings = 26 lbs

Added Resistance of Operating Thruster

Bow thruster:

$$F_x = \rho\pi\ R^2 V_s \left(\frac{|F_y|}{\rho\pi R^2}\right)^{\frac{1}{2}}$$

V_s = 1.689 ft/sec

$F^F{}_y$ = 33,010 lbs

F_x = 3,070 lbs

Stern thruster:

$$F_x = \rho\pi\, R^2 V_s \left(\frac{|F_y|}{\rho\pi R^2}\right)^{\frac{1}{2}}$$

$V_s = 2.111$ ft/sec

$F^A{}_y = 13{,}784$ lbs

$F_x = 2{,}479$ lbs

Effect of Thruster Guards and Entrance Fairings

Bow thruster:

$F^F{}_y = 33{,}010$ lbs

Number of guards = 10 (from Figure 25)

Assume a radius fairing whose raduis = .10D

$(T/T_o)_{fairing} = .995$

$(T/T_o)_{guards} = .925$ (extrapolated)

Assume $L/D = 2.0$

$(T/T_o)_{length} = .990$

Installed thrust for the bow thruster = $33{,}010 \left(\frac{1}{.995}\right)\left(\frac{1}{.925}\right)\left(\frac{1}{.990}\right) = 36{,}228$ lbs

Assuming the same dimensions for the stern thruster and the same number of guards:

$F^A{}_y = 13{,}784$ lbs

Installed thrust for the stern thruster = $13{,}784 \left(\frac{1}{.995}\right)\left(\frac{1}{.925}\right)\left(\frac{1}{.990}\right) = 15{,}128$ lbs

Assuming a specific thrust of 25 lbs/hp, the bow thruster would require 1,449 hp and the stern thruster would require 605 hp.

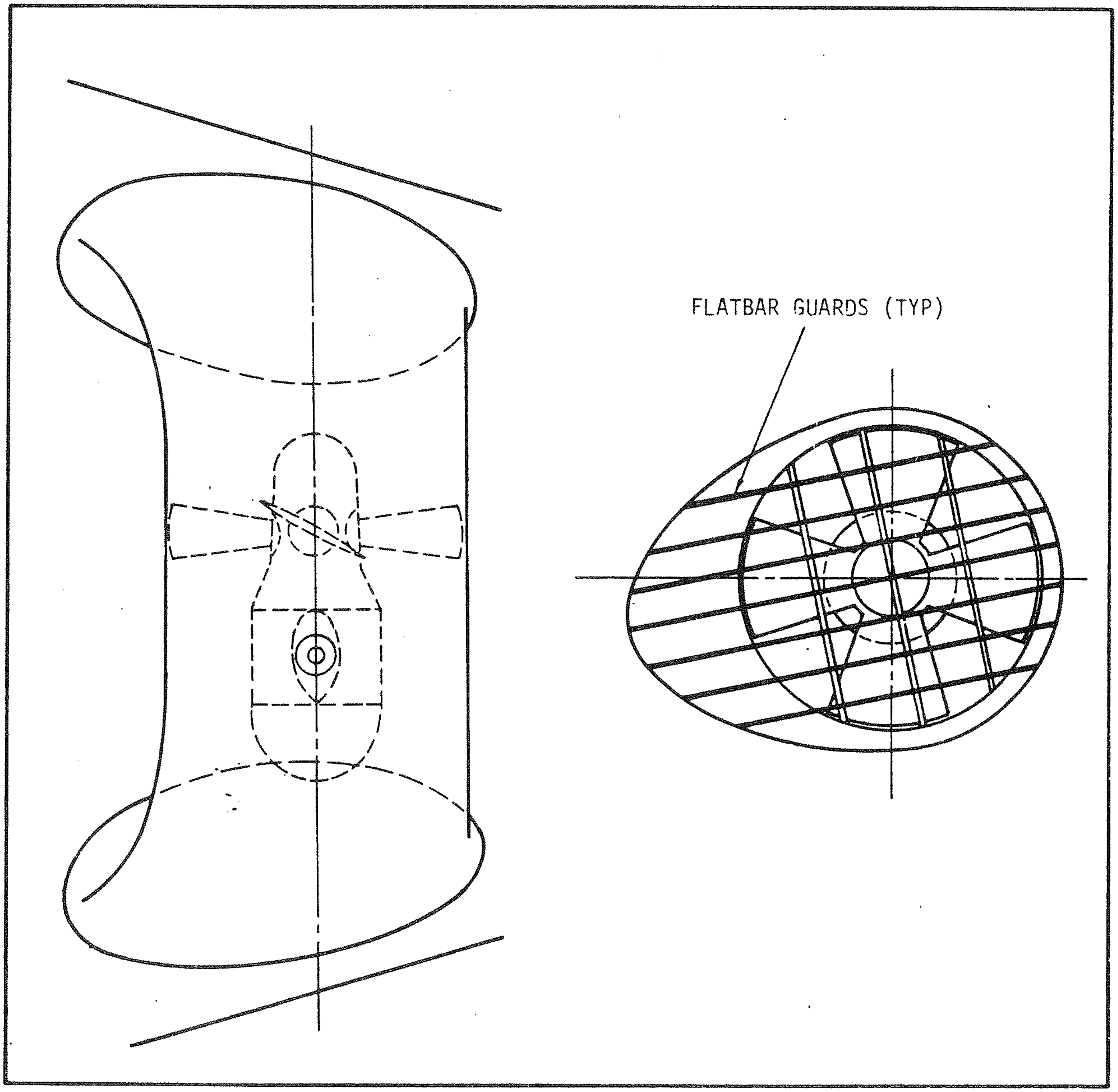


FIGURE 25 - TYPICAL BOW THRUSTER WITH FLATBAR GUARDS