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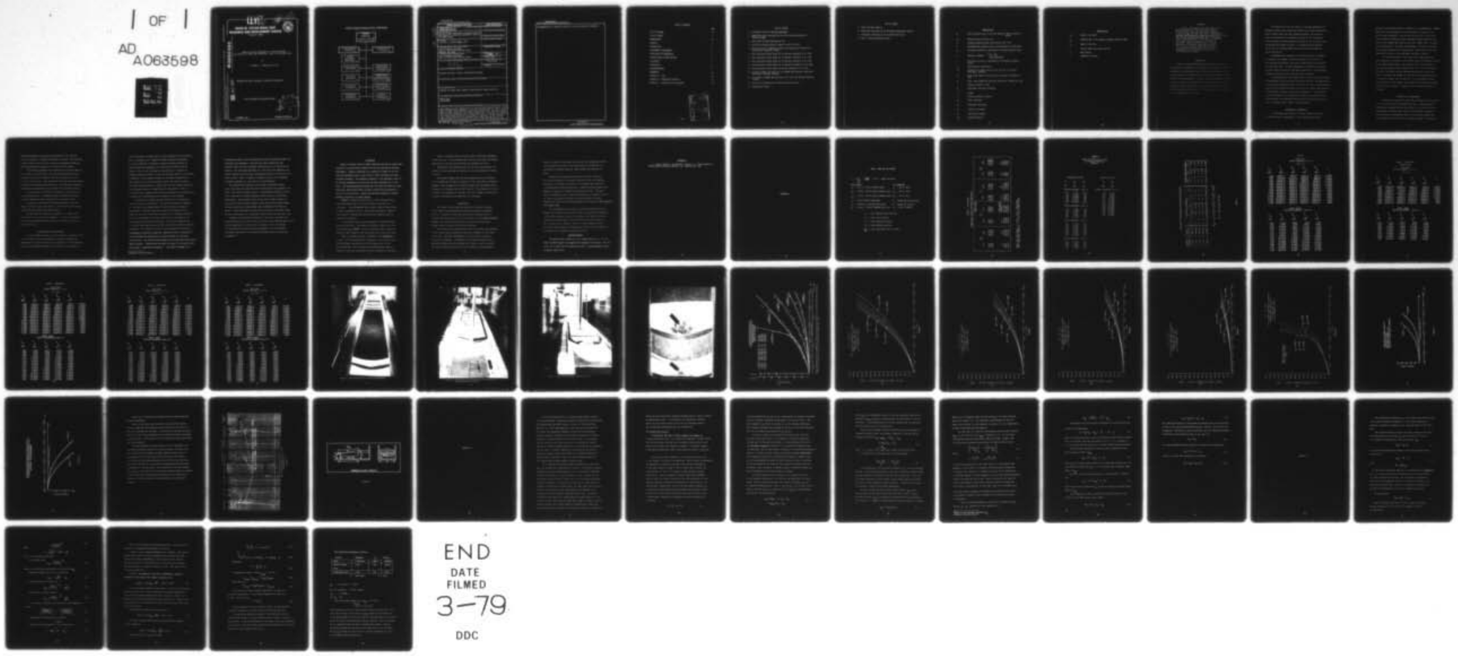

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Bethesda, Md. 20084

RESULTS OF MODEL EXPERIMENTS TO DEFINE RESISTANCE AND SINKAGE OF A LARGE SHIP TRANSITING A LOCK OF THE PANAMA CANAL

by

S. Fisher, D. Jenkins and W. Day

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SHIP PERFORMANCE DEPARTMENT REPORT

DECEMBER 1978

DTNSRDC/SPD-0881-01

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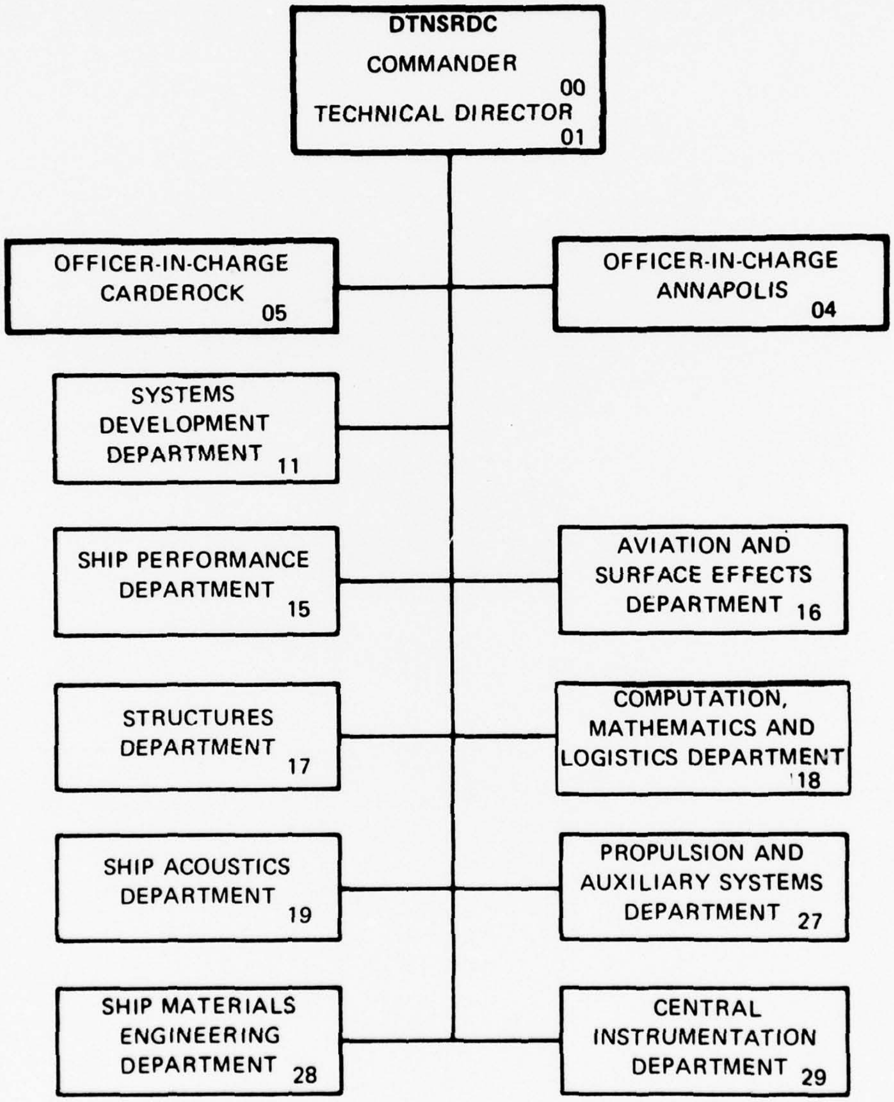

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A 1:35.2 scale model of the Pedro Miguel Lock was constructed in the 140-foot model basin at David W. Taylor Naval Ship R&D Center (DTNSRDC). A 19.2-foot L_{WL} ship model was used in experiments to define resistance and sinkage characteristics of a ship with maximum beam and draft transiting a lock of the Panama Canal. Model data are presented and a quasi-steady extrapolation technique is discussed. Results presented show a limiting speed due to resistance forces when entering the lock and a limiting speed due to grounding of the ship's bottom when exiting the lock.

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Recommendations of operation limits for full-scale ships are presented.

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NOMENCLATURE

A_o	Cross sectional area of the lock (depth of water x width of water)
A_x	Midships cross sectional area
B	Average distance between the ship and lock = $d/2$
C	Nondimensional quantity used in scaling model to ship speed
C_f	Frictional resistance coefficient for moving parallel plates
d	Hydraulic diameter = $\dfrac{4\ (A_o - A_x)}{\text{wetted perimeter}}$
f	Frictional resistance coefficient for stationary parallel plates
g	Gravitational acceleration
Δh	Difference in water levels in the lock due to the ship entering or leaving
h_1	Water level ahead of the ship when entering or leaving the lock
h_2	Water level behind the ship when entering or leaving the lock
J	Pressure gradient = $\Delta h/L$
K_s	Equivalent sand grain roughness
L	Length
q	Pressure gradient, psf/foot
R_t	Total resistance
R_f	Frictional resistance
R_p	Pressure resistance
S	Ship wetted surface
V_{BF}	Backflow velocity

NOMENCLATURE

V_m	Speed of the model
V_p	Velocity due to the pressure gradient along the ship
V_s	Speed of the ship
λ	Ship to model scale ratio (35.24)
ρ	Mass density
ν	Kinematic viscosity

ABSTRACT

A 1:35.2 scale model of the Pedro Miguel Lock was constructed in the 140-foot model basin at David W. Taylor Naval Ship R&D Center (DTNSRDC). A 19.2-foot L_{WL} ship model was used in experiments to determine resistance and sinkage characteristics of a ship with maximum allowable beam and draft transiting a lock of the Panama Canal. Model data are presented and a quasi-steady extrapolation technique is discussed. Results presented show a limiting speed due to resistance forces when entering the lock and a limiting speed due to grounding of the ship's bottom when exiting the lock. Recommendations of operational limits for full scale ships are presented.

INTRODUCTION

A project is being performed by the David W. Taylor Naval Ship R&D Center (DTNSRDC) for the Panama Canal Company involving the measurement of hydrodynamic forces on large ships operating in the confined waters of the canal or in the locks. Three phases of the project have been proposed: a study of the ship entering and leaving the lock, a study of ships meeting and passing, and a study of the acceleration and deceleration of a ship crossing Lake Mira Flores. The work performed in the study of the ship entering and leaving the lock is presented in this report.

The objective of the lock study is to provide guidelines for expedient operation with large ships during lock transiting maneuvers. Faster transit times will mean increased revenues, yet practical limits are imposed by the available tow force of the locomotives or by the speed at which the ship will bottom on the lock door sills. By modeling the extreme situation of a maximum beam and maximum draft ship, the limiting speeds and forces may be determined for future application.

Experiments were conducted in the 140-foot basin at DTNSRDC to determine the sinkage, trim and resistance forces acting on a ship entering and exiting a lock using a model-scaled lock and model of a full-form ship. The model represented a ship with the maximum allowable beam and draft for the Panama Canal Locks. The experiments included variations in ship speed and bottom clearance.

The extrapolation of the model data to the full-scale predictions is complicated by the restricted flow around the ship. Straightforward Froude scaling assumptions cannot be used in this case. An extrapolation theory which has been developed on the basis of a quasi-steady analysis of the dynamic situation is discussed in Appendix B. The resulting full-scale predictions of sinkage and resistance are presented along with guidelines for operating restrictions such as maximum locomotive force or maximum transit speed to avoid grounding.

EXPERIMENTAL ARRANGEMENT

The limiting beam and draft for ships transiting the lock is 106 and 39 feet, respectively. A ship whose beam and draft approach these limiting values is referred to as a PANMAX ship. DTNSRDC Model 5194, which represents a full form tanker, was chosen to be used in these experiments. The linear scale ratio ($\lambda = 35.24$) used in all geometric scaling for these experiments was determined by the ratio of the limiting ship beam and the beam of Model 5194. The model was then ballasted to the draft corresponding to 39 feet, full scale. The principal dimensions and characteristic coefficients of the ship model which was used in the experiments are shown in Table 1.

A 1:35.24 scale model of the floor of the Pedro Migual Lock was constructed of concrete in the 140-foot basin from drawings provided by the Panama Canal Company. The sides and end of the model lock were made with three vertical layers of (8" x 8" x 16") cinderblocks. One wall of the model lock was extended beyond the end of the lock floor to represent the wingwall of the lock. The full-scale lock is 1,015 feet in length, and 110 feet wide. A 41 foot depth of water over the door sill was scaled. A photograph of the model lock without water is shown in Figure 1. Figures 2 and 3 show the ship model in the lock.

DESCRIPTION OF EXPERIMENTS

Measurements were made of model drag, sinkage, and trim relative to the at rest level for all experimental runs. During propulsion experiments, propeller RPM was also recorded. For the exiting runs, measurements of pressure were taken at four different locations on the lock floor as the propeller passed. The pressure gauges which were installed on the lock floor are shown in Figure 4. During the entering experiments the pressure was measured at the lock door sill, the location of minimum water depth in the lock. The variation in water level at the end of the lock was also measured during the entering experiments by means of a parallel wire wave gauge.

The exiting experiments were conducted with a bottom clearance of 2.4 feet at the ship scale. The entering experiments were done with ship scale bottom clearances over the lock door sill of 2.4, 5.3, 8.3, and 10.0 feet. Both model draft and water level were varied to obtain the different bottom clearances. For each bottom clearance, experiments were conducted with and without the propeller turning.

A time history of the data was recorded on a strip chart for each experimental run. In addition, digital voltmeters were used to obtain numerical values of the data at any instant of time.

A portion of the run when the entire model was in the lock showed relatively steady state results. This portion of the run was used in the quasi-steady state data analysis.

The model data are presented in Appendix A. A sample strip chart record is also included in Appendix A. It shows the behavior of the various parameters measured during a run when the model was entering the lock.

EXTRAPOLATION OF MODEL RESULTS

The fluid dynamic problem of a ship entering or leaving the lock is very complex in that the phenomenon is basically unsteady and simultaneously involves several laws of similitude. For this problem there is no established technique which allows us to translate the results obtained at a model scale to those applicable to the full-scale ship. In general, for a complex and highly unsteady flow problem, it is very difficult to establish a rigorous scaling procedure for making predictions regarding a full-scale ship from model-testing results. Even if such a procedure is established, it requires an extremely laborious analysis to treat the unsteady aspect of the problem. Fortunately, for the present problem, we are mainly concerned with ships moving at very low and constant speeds, and there is evidence from model testing results to indicate that the flow regime surrounding the ship model had only a slight degree of unsteadiness. Thus, it is believed that a simple and more practical approach of the quasi-steady technique will be sufficient for the analysis of this problem.

A steady state analysis has been developed for extrapolating the model results to ship scale. This theory is outlined in Appendix B. The theory first assumes that the total resistance consists of three parts: a pressure resistance caused by the change in water levels in the lock; a frictional resistance; and a residual resistance which is the remainder of the total resistance not accounted for by the pressure and frictional resistances. The second assumption made is that the flow regime around the model and ship have complete geometric similarity. The friction line used in the extrapolation was derived by Reichardt as reported on page 285, equation (13-37a) of reference 1* for flow between two moving walls in close proximity to each other (couette flow). The friction line assumes that the walls have hydraulically smooth surfaces. A modification was made to account for the ship surface being rough, as explained in Appendix C. The model is assumed to be

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*Reference listed on page 10.

hydraulically smooth in the extrapolation because the Reynolds number and equivalent sand roughness of the model are small enough that this assumption gives the most reasonable approximation to the frictional resistance. The frictional resistance of a full-scale ship depends on its surface condition which may vary considerably from ship to ship and is not known a priori. Hence, a number of estimated values of the equivalent sand-grain roughness, K_s, were used in the extrapolation.

The measured model resistance data showed considerable scatter. Hence, these data were first faired and extrapolation was performed on the basis of the faired resistance curves. Second-degree polynomial fit was used to represent the faired resistance curves in order to facilitate computations. The resistance curve for the case of model exiting the lock with very small bottom clearance (0.814 inches, model scale) showed an abrupt increase for speeds higher than approximately 0.06 feet per second. It was determined that such abrupt increase in resistance values was due to grounding (i.e., ship-model bottom touching the lock door sill).

Although a fourth-degree polynomial fit was used to represent the faired resistance curve of this case, the portion which appeared questionable has been represented by dotted curve in Figures 5 and 10 to indicate that grounding took place during the experiments. The corresponding polynomial coefficients for individual resistance curves are presented in Appendix A.

DISCUSSION

Figure 5 contains curves of model resistance (tow force) versus model velocity at a given bottom clearance for both the exiting and entering experiments. Curves of resistance as a function of speed for all the entering experiments show a clear trend of lower resistance as bottom clearance increases. The asymptotic behavior of the resistance curve for the exiting experiments was caused by the model grounding on the lock floor. The exiting experiment showed that even when the model was towed, there was a speed beyond which the model touched bottom (grounded) on the sill of the lock door. During the entering experiments a similar behavior occurred but at higher speeds.

Figures 6 through 10 contain plots of ship resistance (R_{t_s}) versus ship speed (V_s) for the four different lock door sill clearances. The extrapolation method used to obtain these results is that of Appendices B and C. Each figure represents a family of curves based on varying ship equivalent sand roughness, K_s, for a given sill clearance.

An accurate value of K_s is impossible to calculate without good full-scale data. This method of plotting a family of curves of different K_s was chosen so that an accurate value of K_s can be found by a small number of full-scale tests run at some later date.

Table 4, Appendix A, gives a breakdown of the resistances for K_s = .015 with different sill clearances. It should be noted that the pressure resistance term is the largest part of the total resistance. This indicates that increasing the number of culverts in the lock can decrease the total resistance of the ship.

Figure 5 indicates that the exiting speed is limited by grounding on the door sill. In the entering case, when the ship towed, the maximum speed into the lock will be limited by the available tow force.

Sinkage and trim characteristics for the towed and propelled conditions of a ship entering and exiting the lock are presented in Figures 11 and 12.

The midship sinkage data were made dimensionless by ship length. It is assumed that the data is applicable to full form ships of different lengths. Stern sinkage and trim angle increases with decreasing bottom clearance at a constant value of ship velocity. The sinkage and trim also increase if the propeller is turning. The stern sinkage is greater when the ship is exiting the lock than when it is entering.

CONCLUSIONS

The values of ship resistance presented in Figures 6 through 10 are based on the extrapolation technique described in Appendices B and C. It should be noted that the pressure resistance term is the most significant portion of the resistance for every **bottom clearance.** However, the frictional and residuary resistances are significant enough to have an effect on total ship resistance.

The values of total ship resistance can vary a great deal depending on the value of K_s, the equivalent sand grain roughness of the surface of the ship. The final determination of K_s will have to depend on full-scale information. In addition to flow conditions which will be dissimilar between the ship and model and therefore cannot be scaled, the actual pressure rise and tow force may depend upon some geometric detail not scaled in this model (such as the flow through the culverts in the bottom of the lock). Such a detail may be accounted for by considering a different hydraulic radius between the ship and the model.

Whatever the differences between the predicted values and the actual ship values of resistance entering a lock, the technique shown here for scaling the resistance is considered more valid than a straightforward Froude extrapolation. Response from the Panama Canal Company is requested in making the determination of K_s. Full-scale values of resistance (e.g. locomotive tow-force) as a function of speed for various clearances will allow the data shown here to be used generally as a guide for providing appropriate tow forces and for estimating lock-transit time.

The recommendation to be made from these data would be that the PANMAX ship be towed into the locks without using the ship's propeller. If the ship's propeller is used, the sinkage of the ship is increased significantly and the speed at which the ship would touch bottom on the lock door sill is reduced. Finally, it would appear from these data that a maximum speed of approximately one mile per hour should not be exceeded with a PANMAX ship entering the lock.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. W. E. Cummins and Dr. W. C. Lin for their continued support and suggestions throughout this project. The help of Mr. L. B. Crook for his knowledge and work in the experimental phases is greatly appreciated.

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APPENDIX A

TABLE 1 MODEL AND SHIP GEOMETRY

$$\lambda = \frac{B_{X_s}}{B_{X_m}} = \frac{106.0}{3.008} = 35.24 : \text{ Linear Scale Ratio}$$

MODEL GEOMETRY	SHIP DIMENSIONS
L_m = 19.2 ft. (5.85 m) waterline length	L_S = 677 ft. (206 m)
B_{X_m} = 3.008 ft. (0.917 m) beam at maximum section	B_{X_s} = 106 ft. (32 m)
T_{X_m} = 1.107 ft. (0.337 m) draft at maximum section	T_{X_s} = 39 ft. (12 m)
Δ_m = 3329 lb (14807 N) displacement	Δ_s = 64,980 tons (66,020 tonnes)
S_m = 87.668 ft^2 (8.145 m^2) wetted surface	S_s = 108,871 ft^2 (1753 m^2)
A_X = 3.319 ft^2 (0.308 m^2) maximum section area	A_X = 4122 ft^2 (383 m^2)

C_X = 0.997 maximum section coefficient

C_B = 0.836 block coefficient

C_P = 0.839 prismatic coefficient

C_W = 0.886 waterline coefficient

$\frac{LCB}{LWL}$ = 0.463 longitudinal center of buoyancy

TABLE 1 (continued)

DIMENSIONAL VALUES FOR DRAFT VARIATIONS

T_X		Δ		S		A_X	
			Model Scale				
ft	(m)	lbs	(N)	ft^2	(m^2)	ft^2	(m^2)
1.107	(0.337)	3329	(14807)	87.668	(8.145)	3.319	(0.308)
1.024	(0.312)	3079	(13695)	85.270	(7.922)	3.070	(0.285)
0.940	(0.287)	2827	(12575	81.872	(7.606)	2.820	(0.262)
			Ship Scale				
ft	(m)	tons	(tonnes)	ft^2	(m^2)	ft^2	(m^2)
39.01	(11.89)	64,980	(66,023)	108,870	(10,114)	4122	(383)
36.07	(10.99)	60,080	(61,044)	105,890	(9,838)	3812	(354)
33.14	(10.10)	55,200	(56,086)	101,673	(9,446)	3502	(325)

MODEL TEST CONDITIONS: T = 69°F (21°C), FRESH WATER
SHIP CONDITIONS (ASSUMED): T = 75°F (24°C), FRESH WATER

TABLE 2

MODEL TEST DATA USED IN THE POLYNOMIAL REGRESSION ANALYSIS

ENTERING THE LOCK

V_M FPS	R_{T_M} LBS	H_M IN.
BOTTOM CLEARANCE= .816 in.		
.057	1.4740	.050
.161	5.8970	.290
.218	10.0250	.430
.265	13.5630	.600
.321	18.8700	.750
.372	22.4080	1.000
BOTTOM CLEARANCE= 1.816 in.		
.130	1.7690	.050
.176	2.9480	.150
.272	6.4860	.270
.333	9.4340	.440
.385	11.9730	.490
BOTTOM CLEARANCE= 2.816 in.		
.180	1.7690	.140
.230	3.8330	.190
.240	2.9490	.100
.334	4.7180	.190
.428	7.9610	.340
.433	8.8460	.340
.470	11.9740	.480
BOTTOM CLEARANCE= 3.416 in.		
.218	1.7690	.050
.266	2.3590	.100
.367	4.4230	.240
.413	5.3070	.270

EXITING THE LOCK

V_M FPS	R_{T_M} LBS
BOTTOM CLEARANCE= .816 in.	
.070	1.7130
.093	3.4330
.100	3.2380
.153	4.9480
.175	6.4360
.220	10.7660
.231	11.1760
.235	12.5020
.237	12.5340
.258	18.0600
.258	20.4800
.281	32.8400
.302	43.9600

POLYNOMIAL COEFFICIENTS OF THE FAIRED MODEL DATA

BOTTOM CLEARANCE	MODEL DIRECTION	RESISTANCE POLYNOMIAL C_0	C_1	C_2	C_3	C_4	WATER LEVEL POLYNOMIAL D_0	D_1	D_2
0.816	ENTERING	0.0	22.780	104.900	0.0	0.0	0.0	1.021	4.385
1.816	ENTERING	0.0	5.098	68.350	0.0	0.0	0.0	0.266	2.787
2.816	ENTERING	0.0	1.462	45.450	0.0	0.0	0.0	0.175	1.559
3.416	ENTERING	0.0	2.310	25.830	0.0	0.0	0.0	-0.049	1.765
0.816	EXITING	0.0	-32.940	1548.000	-11570.0	27930.00	0.0	1.021	4.385

$$R_{tm} = C_o + C_1 V_m + C_2 V_m^2 + C_3 V_m^3 + C_4 V_m^4$$

$$\Delta h = D_o + D_1 V_m + D_2 V_m^2$$

TABLE 3

TABLE 4

SHIP SCALE

BOTTOM CLEARANCE = 2.40 ft

K_S= 0.015

V	R	R	R	R	
S	T	R	P	F	C
S	S	S	S	S	
MPH	LBS	LBS	LBS	LBS	
.100	22267.5	6979.5	14417.0	871.0	1.9942
.200	51179.2	11756.9	35982.6	3439.6	1.5216
.300	87083.0	16261.6	63135.6	7685.9	1.3202
.400	130294.9	20814.1	95880.5	13600.2	1.2009
.500	181107.5	25578.3	134352.8	21176.5	1.1193
.600	239777.9	30657.3	178710.7	30409.8	1.0588
.700	306532.5	36124.3	229111.5	41296.7	1.0114
.800	381572.8	42034.4	285704.5	53833.9	.9729
.900	465080.5	48431.5	348630.0	68018.9	.9408
1.000	557220.3	55351.3	418019.5	83849.6	.9134
1.100	658143.5	62823.8	493995.9	101323.7	.8897
1.200	767989.4	70875.0	576674.7	120439.8	.8688
1.300	886887.6	79527.2	666164.5	141196.0	.8502
1.400	1014959.2	88800.2	762568.1	163591.0	.8336
1.500	1152317.6	98711.6	865982.5	187623.5	.8186
1.600	1299069.4	109277.3	976499.9	213292.1	.8049

MODEL SCALE

BOTTOM CLEARANCE= .816 IN

V	R	R	R	R
M	T	R	P	F
M	M	M	M	M
FPS	LBS	LBS	LBS	LBS
.017	.4302	.0800	.3303	.0199
.040	1.0796	.1766	.8245	.0786
.064	1.9038	.2815	1.4467	.1756
.090	2.9038	.3961	2.1970	.3108
.117	4.0846	.5222	3.0785	.4839
.144	5.4515	.6617	4.0949	.6949
.172	7.0096	.8162	5.2498	.9437
.200	8.7640	.9873	6.5465	1.2302
.229	10.7190	1.1764	7.9883	1.5543
.258	12.8791	1.3848	9.5783	1.9161
.288	15.2482	1.6137	11.3192	2.3154
.318	17.8300	1.8642	13.2136	2.7522
.348	20.6280	2.1374	15.2642	3.2265
.379	23.6456	2.4342	17.4731	3.7382
.409	26.8857	2.7556	19.8427	4.2874
.440	30.3515	3.1025	22.3751	4.8740

TABLE 4 (CONTINUED)

EXITING DATA

SHIP SCALE

BOTTOM CLEARANCE = 2.40 ft

$K_s = 0.015$

V_{S_S} MPH	R_{T_S} LBS	R_{R_S} LBS	R_{P_S} LBS	R_{F_S} LBS	C
.100	-29416.6	-44704.6	14417.0	871.0	1.9942
.200	11997.3	-27424.9	35982.6	3439.6	1.5216
.300	74861.5	4040.0	63135.6	7685.9	1.3202
.400	134230.2	24749.4	95880.5	13600.2	1.2009
.500	178566.8	23037.5	134352.8	21176.5	1.1193
.600	210726.1	1605.5	178710.7	30409.8	1.0588
.700	248987.5	-21420.7	229111.5	41296.7	1.0114
.800	327942.6	-11595.8	285704.5	53833.9	.9729
.900	499251.9	82602.9	348630.0	68018.9	.9408
1.000	832301.0	330431.9	418019.5	83849.6	.9134

MODEL SCALE

BOTTOM CLEARANCE= .816 IN

V_{M_M} FPS	R_{T_M} LBS	R_{R_M} LBS	R_{P_M} LBS	R_{F_M} LBS
.017	-.1620	-.5123	.3303	.0199
.040	.4912	-.4119	.8245	.0786
.064	1.6922	.0699	1.4467	.1756
.090	2.9787	.4709	2.1970	.3108
.117	4.0327	.4703	3.0785	.4839
.144	4.8244	.0347	4.0949	.6949
.172	5.7094	-.4840	5.2498	.9437
.200	7.5043	-.2724	6.5465	1.2302
.229	11.5491	2.0064	7.9883	1.5543
.258	19.7611	8.2667	9.5783	1.9161

TABLE 4 (CONTINUED)

SHIP SCALE
BOTTOM CLEARANCE = 5.33 ft

$K_s = 0.015$

V S S MPH	R T S LBS	R R S LBS	R P S LBS	R F S LBS	C
.100	5146.3	1216.8	3566.4	363.2	2.2515
.200	13693.4	2532.3	9726.8	1434.3	1.7143
.300	25978.4	4389.1	18384.3	3205.0	1.4859
.400	42250.1	6885.6	29693.1	5671.3	1.3508
.500	62703.7	10076.4	43796.6	8830.7	1.2584
.600	87499.3	13997.7	60820.3	12681.2	1.1900
.700	116772.6	18676.3	80875.1	17221.2	1.1364
.800	150641.8	24132.9	104059.4	22449.5	1.0929
.900	189211.1	30384.2	130461.9	28365.0	1.0566
1.000	232574.4	37444.3	160163.4	34966.7	1.0257
1.100	280816.8	45325.1	193237.8	42253.9	.9989
1.200	334016.1	54036.9	229753.5	50225.7	.9753
1.300	392244.3	63588.8	269773.9	58881.6	.9544
1.400	455568.4	73988.9	313358.5	68221.0	.9356
1.500	524050.6	85244.6	360562.8	78243.2	.9187
1.600	597749.6	97362.3	411439.5	88947.8	.9032
1.700	676720.5	110348.1	466038.1	100334.3	.8891

MODEL SCALE
BOTTOM CLEARANCE=1.816 IN

V M M FPS	R T M LBS	R R M LBS	R P M LBS	R F M LBS
.016	.1024	.0123	.0817	.0083
.038	.2894	.0338	.2229	.0328
.061	.5620	.0675	.4212	.0732
.085	.9265	.1165	.6804	.1296
.110	1.3883	.1830	1.0035	.2018
.136	1.9522	.2688	1.3936	.2898
.162	2.6222	.3756	1.8531	.3935
.189	3.4019	.5046	2.3844	.5130
.216	4.2946	.6571	2.9893	.6482
.244	5.3031	.8342	3.6699	.7990
.272	6.4302	1.0369	4.4278	.9655
.300	7.6782	1.2660	5.2645	1.1477
.328	9.0495	1.5225	6.1815	1.3455
.357	10.5461	1.8070	7.1801	1.5589
.386	12.1701	2.1204	8.2618	1.7879
.416	13.9233	2.4632	9.4275	2.0326
.445	15.8076	2.8362	10.6786	2.2928

TABLE 4 (CONTINUED)

SHIP SCALE
BOTTOM CLEARANCE = 8.27 ft

$K_S = 0.015$

V_{S_S} MPH	R_{T_S} LBS	R_{R_S} LBS	R_{P_S} LBS	R_{F_S} LBS	C
.100	487.7	-1708.8	2008.0	188.6	2.4488
.200	3885.1	-2200.0	5340.5	744.7	1.8621
.300	9798.5	-1757.6	9892.1	1664.0	1.6130
.400	18283.1	-385.6	15724.1	2944.6	1.4658
.500	29405.4	1921.7	22898.7	4585.0	1.3652
.600	43227.3	5170.8	31472.2	6584.2	1.2907
.700	59804.9	9368.1	41495.2	8941.5	1.2324
.800	79188.5	14519.4	53013.0	11656.2	1.1851
.900	101424.0	20629.9	66066.4	14727.6	1.1456
1.000	126552.9	27704.4	80693.1	18155.4	1.1119
1.100	154613.6	35747.0	96927.4	21939.1	1.0828
1.200	185641.4	44761.6	114801.4	26078.4	1.0572
1.300	219669.3	54751.8	134344.7	30572.8	1.0344
1.400	256728.0	65720.7	155585.2	35422.1	1.0140
1.500	296846.4	77671.4	178549.0	40626.0	.9956
1.600	340051.6	90606.6	203260.8	46184.2	.9788
1.700	386369.2	104528.8	229744.0	52096.4	.9634

MODEL SCALE
BOTTOM CLEARANCE=2.816 IN

V_{M_M} FPS	R_{T_M} LBS	R_{R_M} LBS	R_{P_M} LBS	R_{F_M} LBS
.016	.0344	-.0159	.0460	.0043
.036	.1124	-.0270	.1224	.0170
.058	.2398	-.0249	.2267	.0380
.082	.4216	-.0060	.3603	.0673
.106	.6616	.0322	.5247	.1048
.130	.9631	.0915	.7211	.1505
.156	1.3288	.1737	.9508	.2043
.181	1.7610	.2800	1.2147	.2664
.208	2.2619	.4115	1.5138	.3365
.234	2.8332	.5693	1.8490	.4149
.261	3.4767	.7544	2.2209	.5013
.288	4.1940	.9675	2.6305	.5959
.316	4.9864	1.2095	3.0783	.6986
.343	5.8555	1.4810	3.5650	.8094
.371	6.8023	1.7828	4.0912	.9283
.399	7.8282	2.1154	4.6574	1.0554
.428	8.9342	2.4795	5.2642	1.1905

TABLE 4 (CONTINUED)

SHIP SCALE
BOTTOM CLEARANCE = 10.01 ft

$K_s = 0.015$

V_{S_S} MPH	R_{T_S} LBS	R_{R_S} LBS	R_{P_S} LBS	R_{F_S} LBS	C
.100	4749.9	4816.3	-215.9	149.5	2.5161
.200	8833.3	7928.7	314.0	590.6	1.9148
.300	13699.5	10460.1	1919.6	1319.7	1.6592
.400	19654.7	12558.1	4761.2	2335.4	1.5081
.500	26879.1	14291.2	8951.4	3636.5	1.4049
.600	35500.3	15700.1	14578.0	5222.2	1.3284
.700	45617.2	16811.8	21713.5	7091.9	1.2685
.800	57310.8	17646.1	30419.6	9245.1	1.2199
.900	70649.9	18218.0	40750.6	11681.3	1.1793
1.000	85694.1	18539.4	52754.5	14400.2	1.1447
1.100	102496.3	18620.1	66474.8	17401.4	1.1148
1.260	121104.0	18468.2	81951.2	20684.6	1.0885
1.300	141560.1	18090.7	99219.9	24249.5	1.0651
1.400	163904.4	17493.6	118314.9	28096.0	1.0441
1.500	188173.3	16682.1	139267.5	32223.7	1.0251
1.600	214400.7	15661.0	162107.2	36632.4	1.0079
1.700	242618.3	14434.4	186861.8	41322.1	.9920

MODEL SCALE
BOTTOM CLEARANCE=3.416 IN

V_{M_M} FPS	R_{T_M} LBS	R_{R_M} LBS	R_{P_M} LBS	R_{F_M} LBS
.016	.0422	.0437	-.0049	.0034
.036	.1153	.0946	.0072	.0135
.057	.2182	.1441	.0440	.0302
.080	.3527	.1903	.1091	.0534
.104	.5207	.2324	.2051	.0831
.129	.7234	.2701	.3340	.1193
.153	.9624	.3029	.4975	.1621
.179	1.2388	.3306	.6970	.2113
.205	1.5537	.3530	.9337	.2669
.231	1.9079	.3701	1.2088	.3291
.257	2.3025	.3817	1.5232	.3976
.284	2.7382	.3877	1.8778	.4727
.311	3.2157	.3881	2.2735	.5541
.338	3.7359	.3829	2.7110	.6420
.366	4.2993	.3719	3.1911	.7363
.393	4.9066	.3551	3.7144	.8371
.421	5.5584	.3325	4.2817	.9443

Figure 1 Lock Model Set-up for Exiting Experiment

Figure 2 PANMAX Ship Model Entering the Lock with Bow Approaching Pressure Gages

Figure 3 Stern View of Model Entering the Lock

Figure 4 Lock Floor Showing Pressure Gages on Lock Door Sills

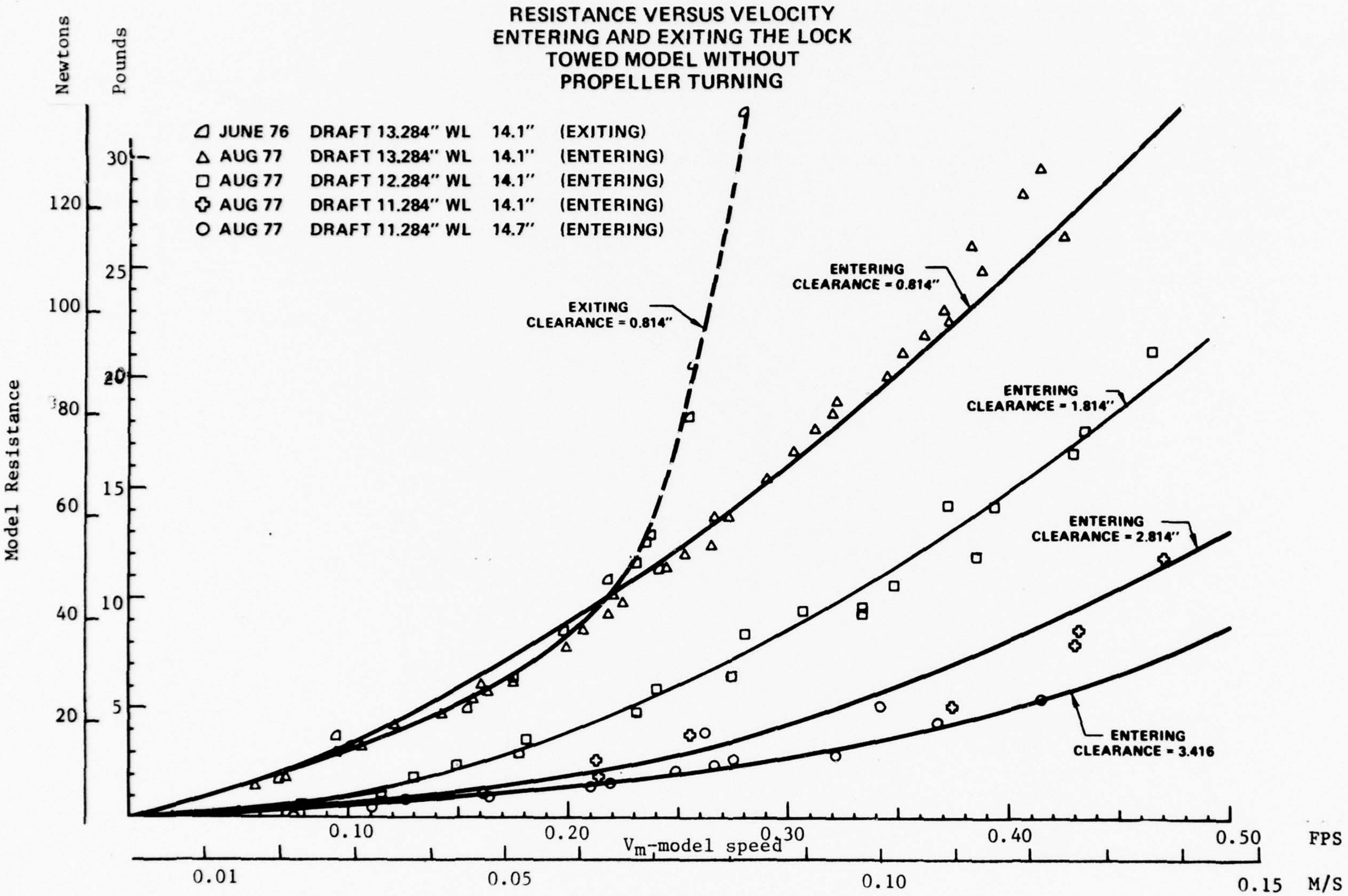


Figure 5 Measured Drag for PANMAX Ship Model 5194 Entering and Exiting the Lock Without Propeller Turning
* Dashed line indicates region where model bottom touches door sill.

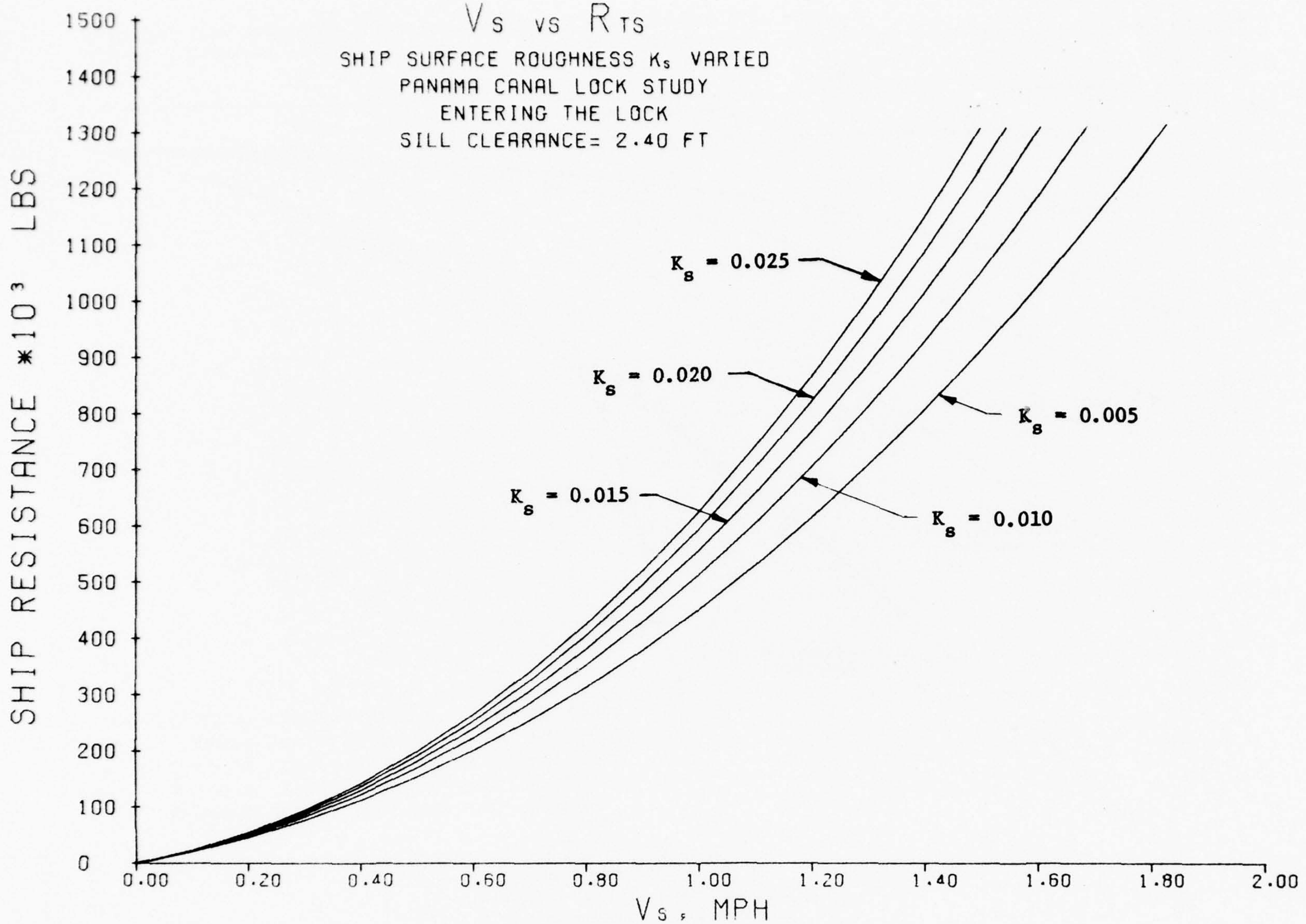

V_S vs R_{TS}
SHIP SURFACE ROUGHNESS K_s VARIED
PANAMA CANAL LOCK STUDY
ENTERING THE LOCK
SILL CLEARANCE= 2.40 FT
SHIP RESISTANCE *10³ LBS
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
V_S, MPH
K_s = 0.025
K_s = 0.020
K_s = 0.015
K_s = 0.005
K_s = 0.010

FIGURE 6

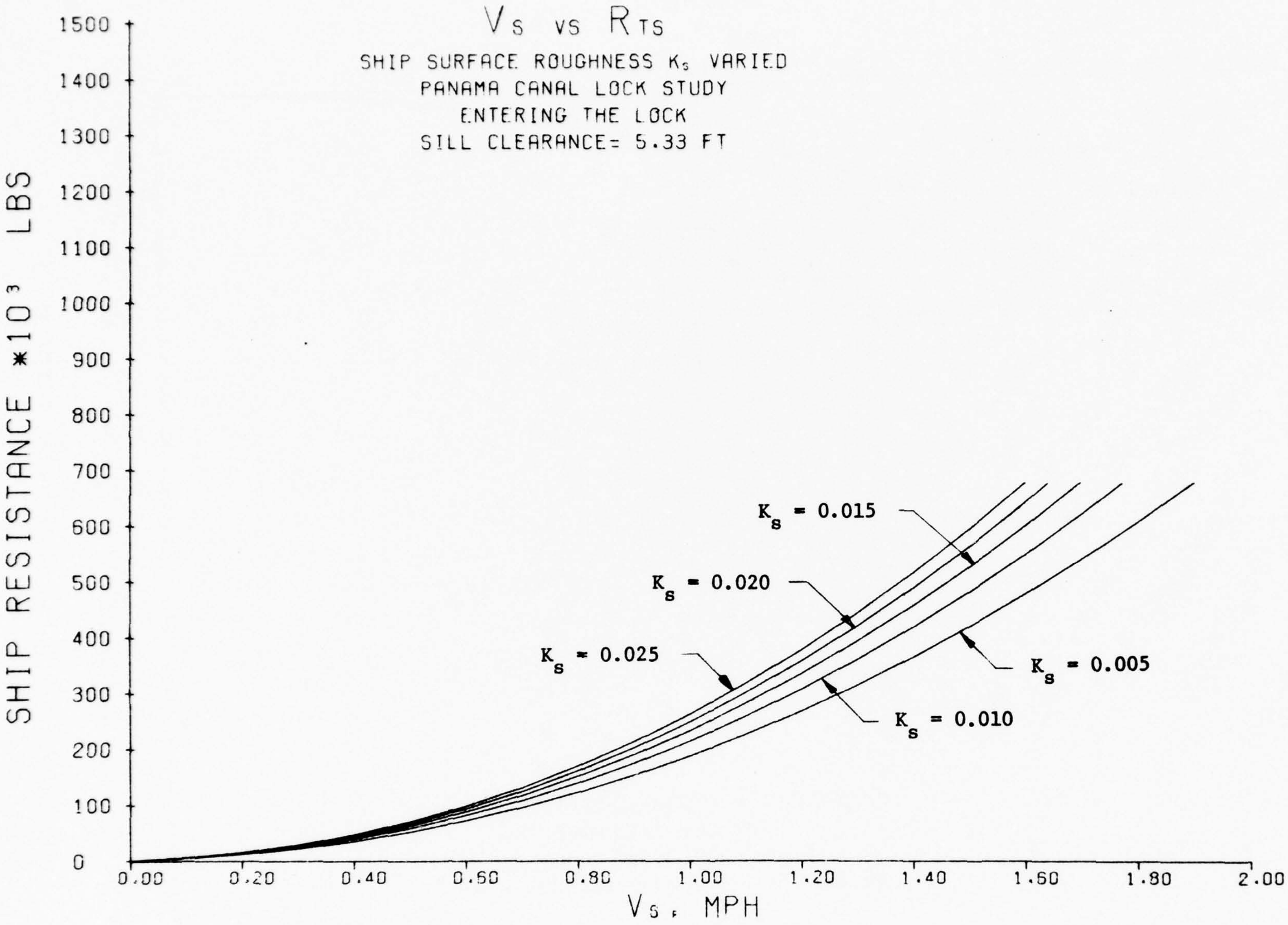

Vs vs RTS
SHIP SURFACE ROUGHNESS Ks VARIED
PANAMA CANAL LOCK STUDY
ENTERING THE LOCK
SILL CLEARANCE= 5.33 FT
SHIP RESISTANCE *10³ LBS
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
Vs, MPH
Ks = 0.015
Ks = 0.020
Ks = 0.025
Ks = 0.005
Ks = 0.010

FIGURE 7

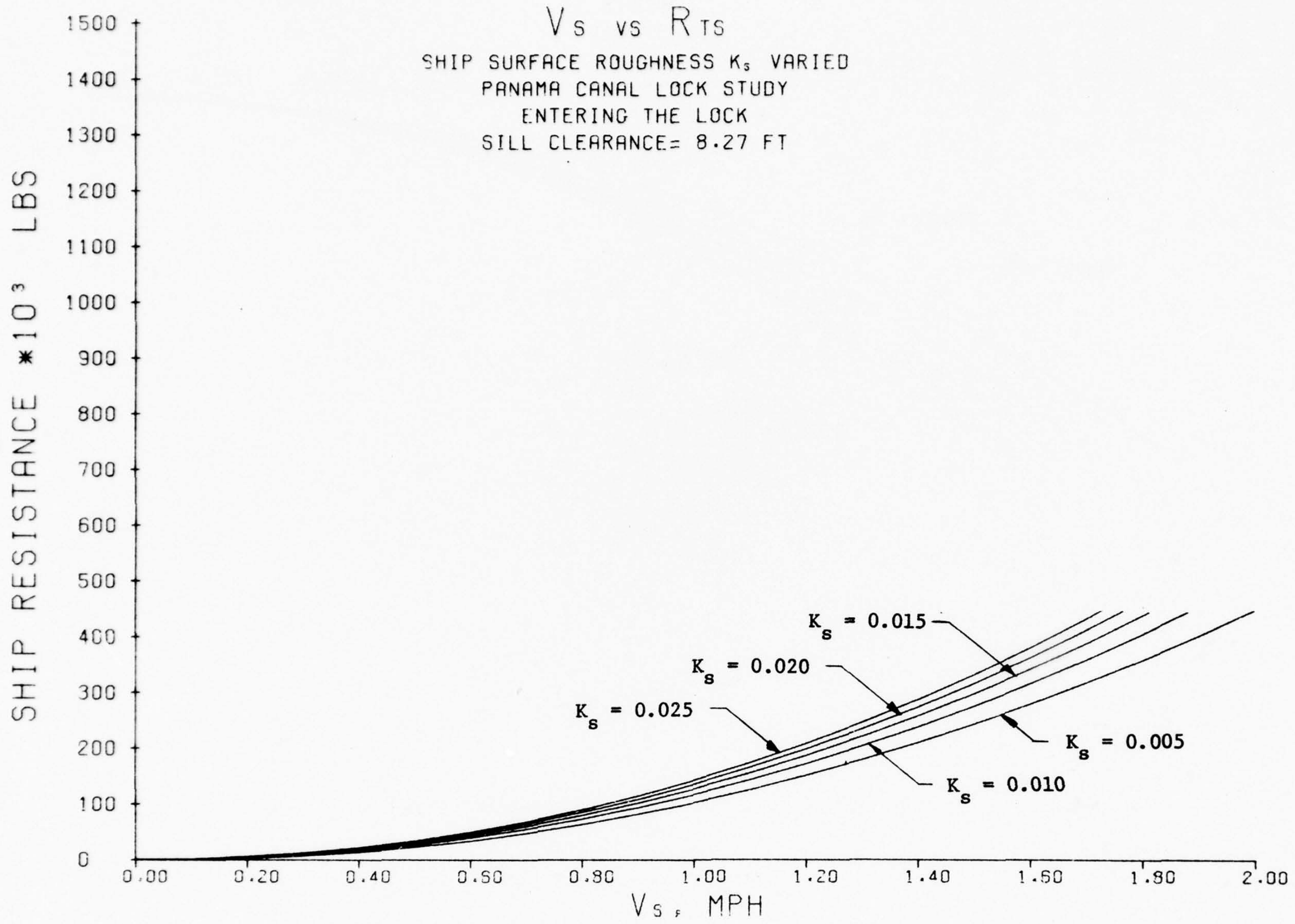
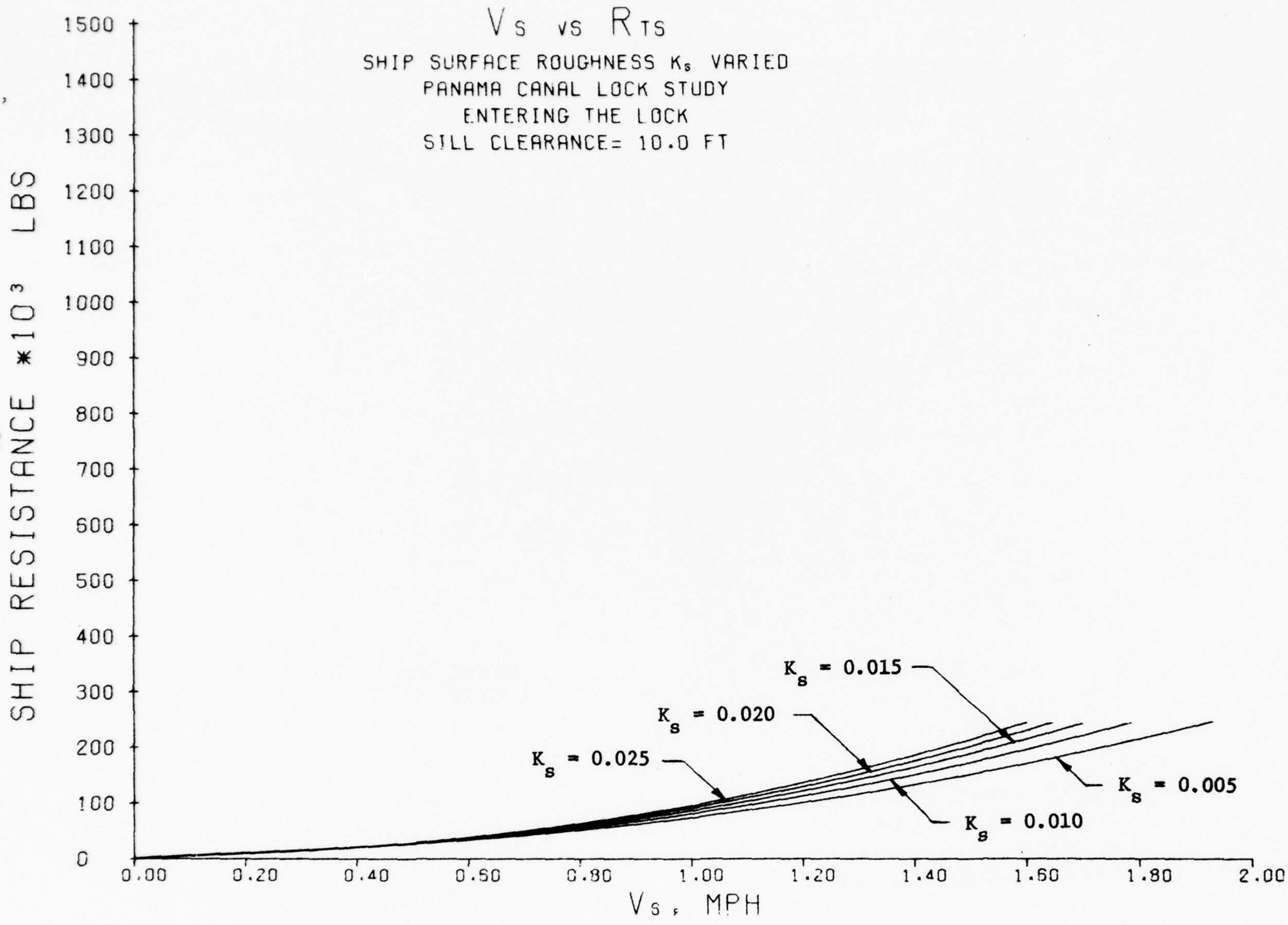

Vs vs RTS
SHIP SURFACE ROUGHNESS Ks VARIED
PANAMA CANAL LOCK STUDY
ENTERING THE LOCK
SILL CLEARANCE= 8.27 FT
SHIP RESISTANCE *10³ LBS
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
Vs, MPH
Ks = 0.015
Ks = 0.020
Ks = 0.025
Ks = 0.005
Ks = 0.010

FIGURE 8



V_S vs R_{TS}
SHIP SURFACE ROUGHNESS K_s VARIED
PANAMA CANAL LOCK STUDY
ENTERING THE LOCK
SILL CLEARANCE= 10.0 FT
SHIP RESISTANCE $*10^3$ LBS
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
V_S, MPH
K_s = 0.015
K_s = 0.020
K_s = 0.025
K_s = 0.005
K_s = 0.010

FIGURE 9

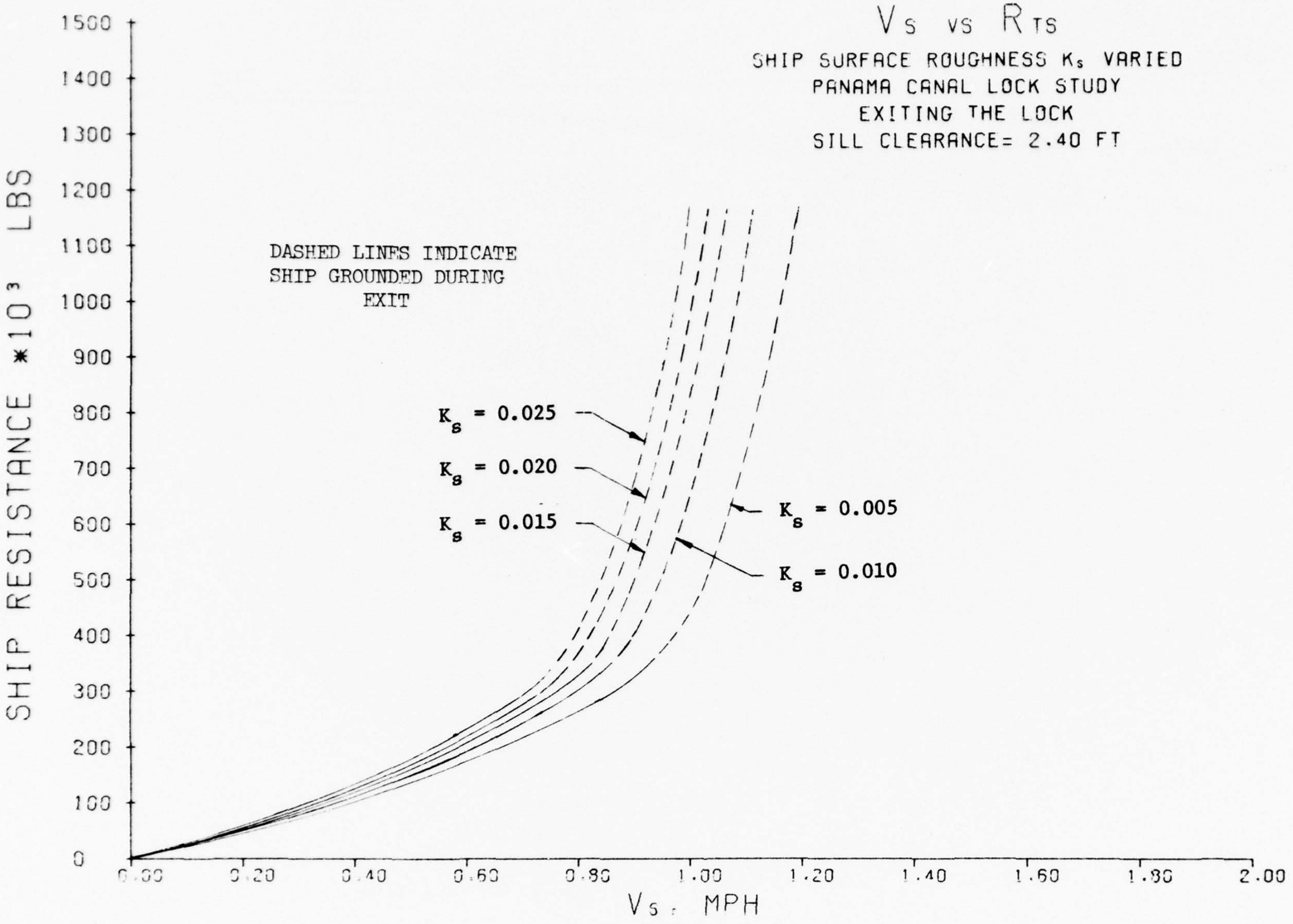
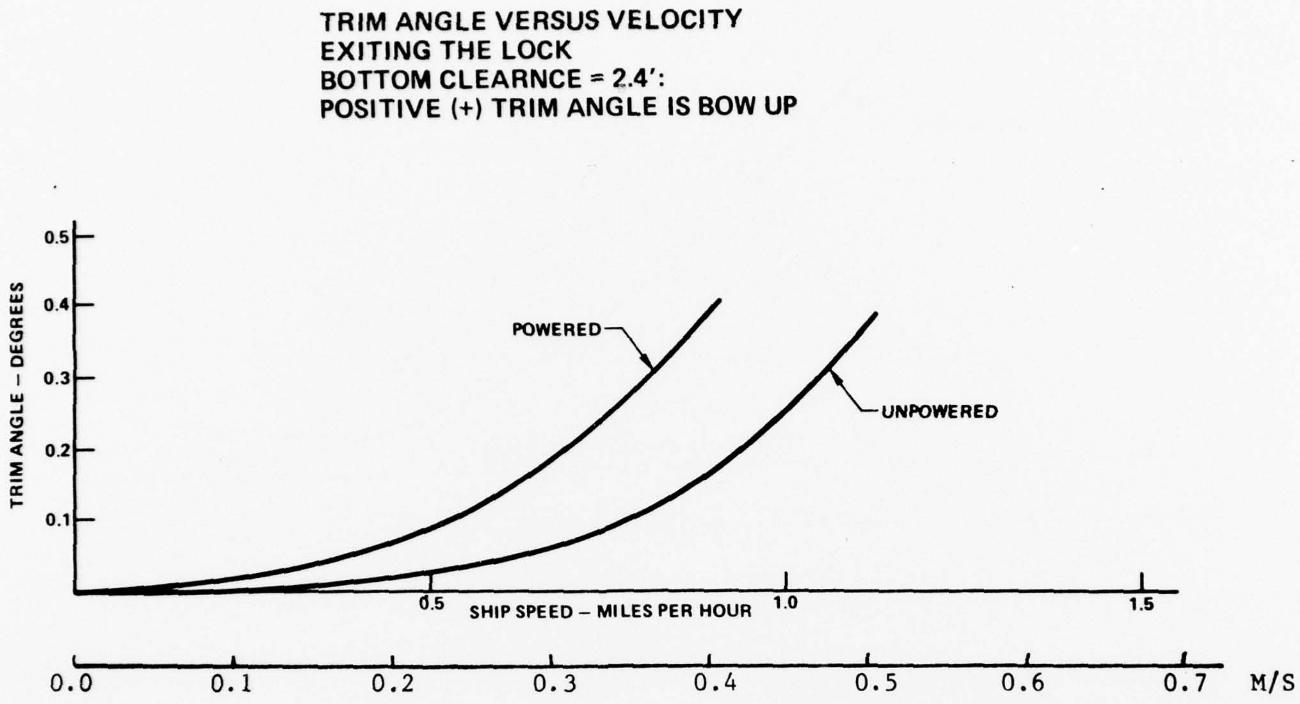

Vs vs RTS
SHIP SURFACE ROUGHNESS Ks VARIED
PANAMA CANAL LOCK STUDY
EXITING THE LOCK
SILL CLEARANCE= 2.40 FT
DASHED LINES INDICATE
SHIP GROUNDED DURING
EXIT
Ks = 0.025
Ks = 0.020
Ks = 0.015
Ks = 0.005
Ks = 0.010
SHIP RESISTANCE *10³ LBS
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
Vs, MPH

FIGURE 10



TRIM ANGLE VERSUS VELOCITY
EXITING THE LOCK
BOTTOM CLEARNCE = 2.4':
POSITIVE (+) TRIM ANGLE IS BOW UP

FIGURE 11

AMIDSHIPS SINKAGE/LENGTH VERSUS VELOCITY
EXITING THE LOCK - BOTTOM CLEARANCE = 2.4':
SHIP SPEED – MILES PER HOUR

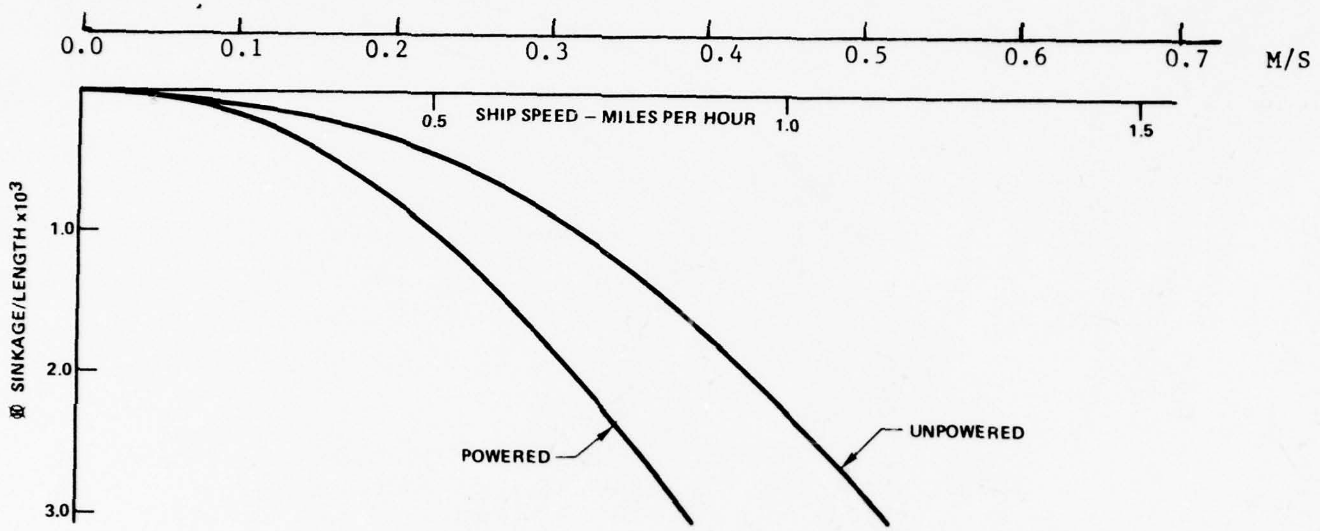
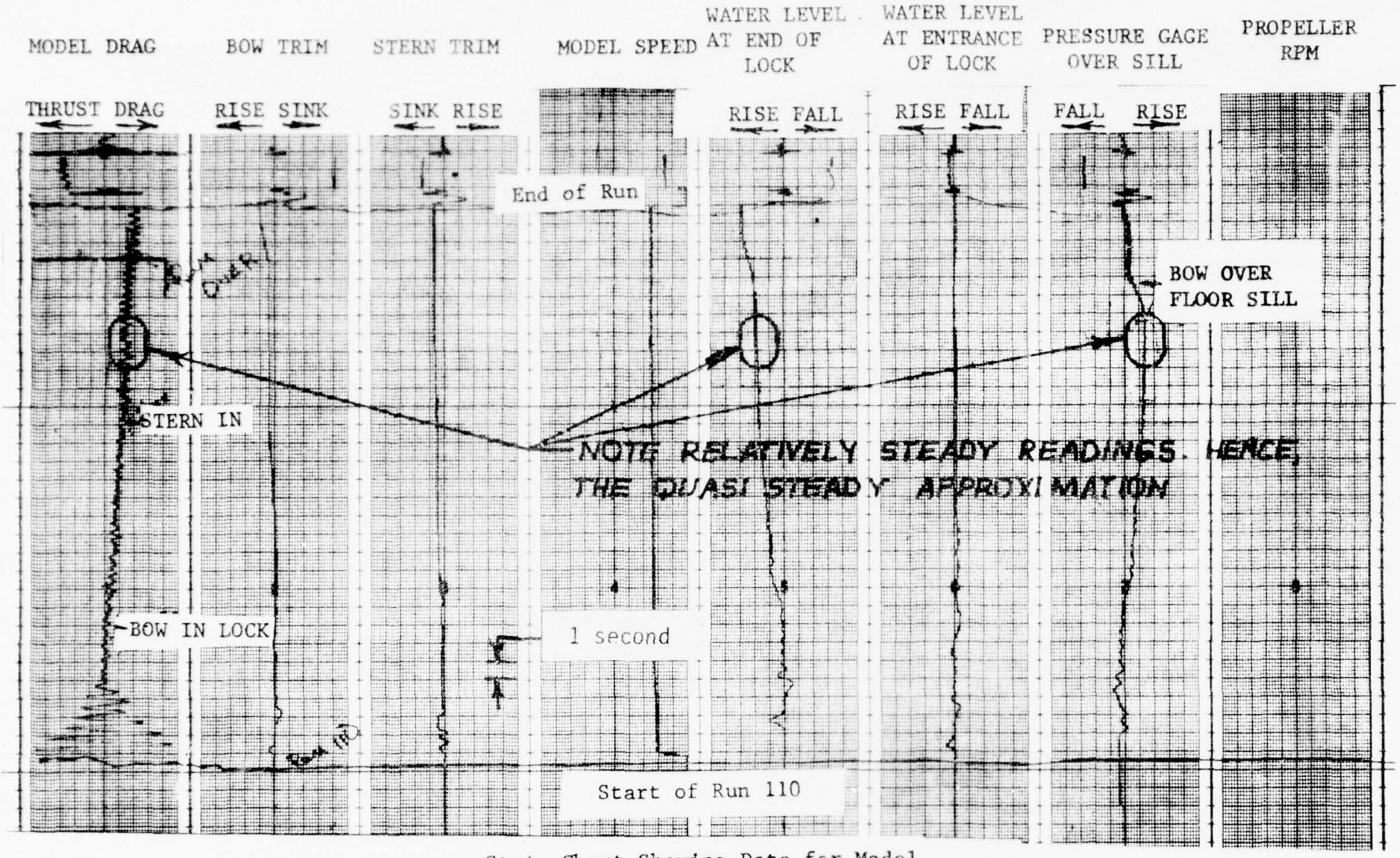


FIGURE 12

Figure 13 is a strip chart recording from a run made during the entering experiments.

Points on the strip chart are noted for when the bow entered the lock, when the stern entered the lock, when the bow was over the door sill, and when the run ended. A portion of the run when the entire model was in the lock and conditions were relatively steady is indicated by circled areas. This portion of the run was used for the quasi-steady state data analysis.

The data recorded on the strip chart are for a resistance run. Information recorded includes the resistance signal, the output from the bow and stern trim gauges, the model speed, the water level at the inside end of the lock model, the water level at the entrance to the lock, and the pressure measured at the floor of the door sill. The start of the run is at the bottom of the page and the chart speed corresponds to 5 mm per second. The indicators for the data channels were zeroed in the center of the strip chart channels except for channels 4 and 8 which were recording speed and propeller rpm, respectively. Channels 4 and 8 were zeroed on the right edge of the strip chart channel.



Strip Chart Showing Data for Model Entering the Lock

FIGURE 13

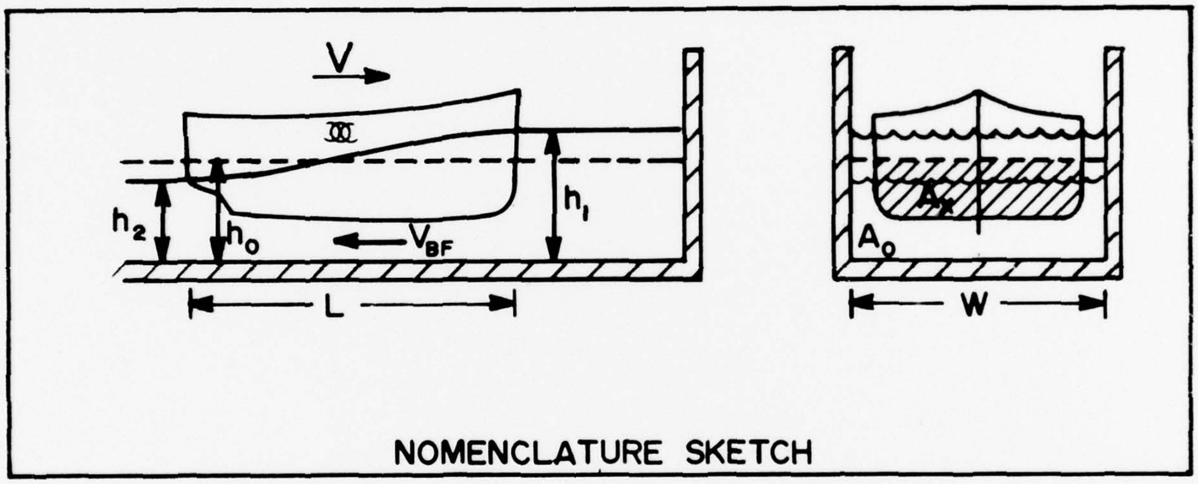


FIGURE 14

APPENDIX B

As a basic building block to a complete quasi-steady treatment of the flow problem, a steady-state theory of analysis has been developed for extrapolating the model results to those of a full-scale ship. Moreover, as a first approximation, it has been further assumed that the entire flow regime was completely steady and the steady-state method of analysis developed in this project has been used to predict performance characteristics of the full-scale ship. It is proposed that the predicted full-scale ship results so obtained be checked against the actually observed results of a full-scale ship of comparable size and type. A careful comparison of the predicted and actually measured full-scale results will enable us to determine whether the present simpler technique is valid or a more laborious approach of the complete quasi-steady technique should be used.

If the complete quasi-steady analysis should prove to be necessary, the problem may be approached as follows. To illustrate a general technique of the quasi-steady approach, let us consider the resistance and speed relationship of a ship entering the lock. Suppose that the ship speed is held constant; nevertheless, the flow regime surrounding the ship is unsteady. In conducting a model test to investigate this problem, we shall measure, among others, the model speed and resistance. However, the resistance is now time dependent and therefore it is customary to plot the measured resistance versus time. To perform the quasi-steady analysis for extrapolating the model results to those of the full-scale ship, the time scale which covers the range of interest would be divided into a finite number of sub-intervals. Within each of such sub-intervals, the whole flow regime is assumed to be completely steady and the steady-state technique described above is used to analyze the experimental data. In carrying out the steady-state analysis within each time sub-interval one can use the time-mean values of all the measured experimental data for computations.

The Steady-State Analysis

To illustrate the idea, we shall consider the example of a ship entering the lock. For a steady-state analysis, we shall assume that the ship speed, the drag force, the water levels at the bow and stern, and the whole flow regime are constant. A schematic diagram illustrating nomenclatures used in this problem is given in Figure 14.

Let R_t be the total resistance, V the constant velocity, and L the length of the ship at the waterline. Since we shall be discussing the experimental results at the model scale and the extrapolation of the model results to those of the full-scale ship, we shall use the subscripts "m" and "s" to denote the model and ship results, respectively. From the schematic diagram, Figure 14 it is clear that at least two factors contribute to the ship resistance: (i) the pressure resistance caused by the difference in water levels at the bow and stern, respectively, and (ii) the frictional resistance due to the water flowing through the space between the ship-hull surface and the lock surface which includes the walls and the bottom. Thus, it would appear reasonable to decompose the total resistance, R_t, as follows:

$$R_t = R_p + R_f + R_r \qquad (1)$$

In this decomposition, R_p and R_f are, respectively, the pressure resistance and the frictional resistance as described in (i) and (ii) above. The third component, R_r, shall be referred to as the residuary resistance. The residuary resistance here represents that part of the total resistance which is not properly accounted for by R_p and R_f .

In order to predict the resistance at the ship scale from that obtained at the model scale, it is necessary to establish appropriate scaling laws for this specific problem. It seems apparent that each of the **resistance components** in equation (1) is governed by different laws of similitude. One can reach such a conclusion by starting from dimensional analysis. Instead, we shall analyze the problem **by direct observations.** The fundamental question of our problem may be posed as follows: What is the corresponding ship speed in order to achieve an exact similitude of the flow regime if the speed and flow regime at the model scale are specified? Here, obviously, a complete geometric similarity between the ship (including the lock) and the model is assumed.

In the following we shall investigate the computation of each of the component resistance in (1) and their extrapolation to the ship scale. First, we shall assume that the pressure resistance, R_p, may be computed hydrostatically. Thus, if T_{1m} and T_{2m} are the drafts of the model at the bow and stern, respectively, then R_{pm} may be approximated by using the following equation:

$$\begin{aligned} R_{pm} &= \rho g B_{xm} \cdot \tfrac{1}{2} (T_{1m} - T_{2m}) \\ &\cong \rho g A_{xm} (h_{1m} - h_{2m}) \end{aligned} \tag{2}$$

where A_{xm} is the underwater portion of the cross sectional areas at the midship, and h_{im} and h_{2m} are, respectively, the water levels at the bow and stern. In deriving equation (2) we have assumed that the waterline from the stern to bow is a straight line.

Since we have assumed a complete similarity of the flow regime at the model and ship scales, the pressure resistance of the ship may be computed as follows:

$$\begin{aligned} R_{ps} &= \rho g B_{xs} \cdot 1/2(T_{1s} - T_{2s}) \\ &\simeq \rho g A_{xs} (h_{1s} - h_{2s}) \\ &= \lambda^3 R_{pm} \end{aligned} \qquad (3)$$

where $\lambda = L_s/L_m$ is the linear ratio between the ship and model.

In equation (3) we have made use of the relationship:

$$\frac{h_{1m} - h_{2m}}{L_m} = \frac{h_{1s} - h_{2s}}{L_s} \qquad (4)$$

The computation of the frictional resistance, R_t, is not as straightforward. As was defined previously, R_f is due to the water flowing through the space between the surfaces of the ship hull and the lock. This flow is somewhat analogous to that through a U-pipe except that now the water velocity may vary considerably within the space. We shall use this pipe-flow analogy to analyze the problem regarding R_f.

We shall assume that there exists a mean velocity, V_{BF}, which characterizes the back flow of water from the bow to stern. The back flow mean velocity, V_{BF}, is hypothetical and different from the apparent ship velocity V . However, we may assume that they are related as follows:

$$V_{BF_m} = (A_{xm}/A_{om})\ V_m \qquad (5)$$

where V_m is the apparent model velocity and A_{om} is the cross sectional area of the "pipe" (i.e., the underwater space between the lock and model cross sections) at the midship. In equation (5), the conservation of mass relationship has been applied.

Our next task is to find the corresponding back flow mean velocity, V_{BF_s} , at the ship scale from V_{BF_m} as obtained in (5). By consulting the equations governing pipe flows, [1],* we may assume, roughly, that the following relationship holds between the model and ship scales:

$$\left[\frac{q \cdot d}{\rho \cdot V_{BF}^2}\right]_m = C\left[\frac{q \cdot d}{\rho \cdot V_{BF}^2}\right]_s \qquad (6)$$

where

$$q = \frac{P_1 - P_2}{L} = \rho g \frac{(h_1 - h_2)}{L} \qquad (7)$$

is the pressure gradient of the "pipe" flow, d is the hydraulic mean diameter or radii and C is a constant for model-to-ship correlations. In general, the constant C is intended to account for the differences in Reynolds numbers, the pipe roughness, and any other relevant parameters between the model and ship scales. Thus, in principal, the values of C can be determined if there exist sufficient data at the model and ship scales. Unfortunately, at this time, there are no available ship scale data which correspond to the model-test results of this project. One method for finding C with a minimum of full scale data is given in Appendix C.

Since the pressure gradient is the same at the model and ship scales, $q_s = q_m$. Equation (6) then simplifies to:

---

*Number in the brackets indicates the reference listed on page 10.

$$V_{BF_s} = \sqrt{d_s/d_m} \cdot \sqrt{C} \quad V_{BF_m} \tag{8}$$

The apparent ship velocity may be obtained from the back flow mean velocity and relationship

$$V_s = A_{os}/A_{xs} \cdot V_{BF_s} = \sqrt{C} \cdot \sqrt{\lambda} \quad V_m \tag{9}$$

That is, the ship velocity is equal to the model velocity times the square root of the linear ratio and the square root of C. If C is assumed to be 1.0, equation (8) then reduces to the normal Froude scaling assumption.

The frictional resistance of the model may be computed from the back-flow mean velocity, V_{BF_m}.

$$R_{fm} = 1/2 \, \rho \, V_{BF_m}^{2} \; S_m \; C_{fm} \tag{10}$$

where S_m is the actual wetted surface of the model when entering the lock. The frictional coefficient C_{fm} is to be calculated from a Reynolds number based on V_{BF_m}.

Similarly, the frictional resistance at the ship scale is computed from

$$R_{fs} = 1/2 \, \rho \, V_{BF_s}^{2} \; S_s \; C_{fs} \tag{11}$$

where the frictional coefficient C_{fs} should be chosen for Reynolds number based on V_{BF_s}.

There remains the task of finding the residuary resistance, R_r. Firstly, at the model scale, we may compute

$$R_{rm} = R_{tm} - R_{pm} - R_{fm} \tag{12}$$

and

$$C_{rm} = R_{rm}/(1/2\ \rho\ V_m^{\ 2}\ S_m) \tag{13}$$

The origin and character of the residuary resistance here is not identical to that of the usual ship-resistance problem. However, they do bear some resemblance. Therefore, we shall hypothesize that the residuary resistance coefficients of the model and ship are the same, i.e.,

$$C_{rs} = C_{rm} \tag{14}$$

From this hypothesis the ship residuary resistance may be computed by

$$R_{rs} = 1/2\ \rho\ V_s^{\ 2}\ S_s \tag{15}$$

Finally, the total ship resistance is obtained by

$$R_{ts} = R_{ps} + R_{rs} + R_{fs} \tag{16}$$

APPENDIX C

The extrapolation technique used in the Panama Canal study is based on the theory presented in Appendix B. The analysis presented in Appendix C attempts to calculate C with a minimum amount of full scale data.

The backflow velocity as seen by the model consists of two parts - the forward motion of the model, V_m, and a velocity that is due to the change in waterlevels at the bow and stern, V_{pm}.

$$V_{BF_m} = V_{pm} + V_m \tag{1}$$

The conservation-of-mass relationship in the ship coordinate system requires that

$$V_{BF_m} = BF \cdot V_m \tag{2}$$

where

$$BF = \frac{A_o}{A_o - A_x} \cdot \eta$$

is the ratio of the actual backflow to the backflow of an impermeable lock. It accounts for the loss of backflow due to the flow through the sides and bottom of the lock. The lock model was designed to allow some flow through the lock sides to model the culverts in the bottom of the actual lock. Since it is impossible to determine the accuracy of the modeling, we can at best assume that $\eta_m = \eta_s$.

(1) and (2) give

$$V_{pm} = (BF - 1)\, V_m \tag{3}$$

Pipe flow analysis [1] tells us that the same relationship shown in Equations (1), (2), and (3) are assumed to hold at the ship scale.

$$V = \left[\frac{2gJd}{f}\right]^{1/2} \qquad (4)$$

where

$$J = \frac{P_1 - P_2}{\rho gL} = \frac{\Delta h}{L} = \frac{q}{\rho g}$$

and f is a frictional coefficient.

In our case we have

$$V_{pm} = \left[\frac{2gJd_m}{f}\right]^{1/2} \qquad (5)$$

where f, the frictional coefficient is a function of V_{BF_m}.

Combining Equations (2) and (3), we have that

$$V_{BF_m} = \frac{BF}{BF-1} \cdot V_{pm} \qquad (6)$$

Inserting Equation (5) gives us

$$V_{BF_m} = \left[\frac{2gJd_m}{f}\right]^{1/2} \cdot \frac{BF}{BF-1} \qquad (7)$$

The ship has a similar equation,

$$V_{BF_s} = \left[\frac{2gJd_s}{f}\right]^{1/2} \cdot \frac{BF}{BF-1} \qquad (8)$$

If we insert (7) and (8) into Equation (6) from Appendix B, we have

$$\left[\frac{qd(BF-1)^2}{\rho\left[\frac{2gJd}{f}\right]BF^2}\right]_m = C\left[\frac{qd(BF-1)^2}{\rho\left[\frac{2gJd}{f}\right]BF^2}\right]_s \qquad (9)$$

Performing the eliminations, (9) becomes

$$C = f_m/f_s \qquad (10)$$

Equation (8) from Appendix B can be rewritten as

$$C = V_{BF_s}^2 / (\lambda \cdot V_{BF_m}^2) \qquad (11)$$

Since f is a function of the backflow velocity, a solution can be found for C by iteration on Equations (10) and (11).

To find C, only a proper determination of f remains. Since we are dealing with a ship in a lock, the normal ship frictional lines that assume a flat plate undisturbed by a wall cannot be used. We will use two flat plates in close proximity to each other, one stationary, the other moving, as a model for a ship in a lock. This type of flow is called couette flow.

Reichart', as reported on page 285 of reference 1, deduced a relation for this type of flow, shown as Equation (12).

$$1/\sqrt{C_f} = 4.06 \text{ Log}_{10} \left(\frac{VB}{\nu} \cdot \sqrt{C_f} \right) - 0.83 \tag{12}$$

B is the distance between the two plates. One half of the hydraulic diameter was used as B in the calculations. The Reichart equation for for couette flow assumes hydraulically smooth surfaces. There is no equation to account for rough surfaces with couette flow. However, there are equations for flow between two stationary parallel plates with rough and smooth surfaces.

The equation for smooth stationary plates is

$$1/\sqrt{f} = 2.03 \text{ Log}_{10} \left(\frac{2VB}{\nu} \cdot \sqrt{f} \right) - 0.47 \tag{13}$$

For rough stationary plates with an equivalent sand roughness K_s, the equation is

$$1/\sqrt{f} = 2.03 \text{ Log}_{10} \left(\frac{B/2}{K_s} \right) + 2.11 \tag{14}$$

The relation of f to C_f can be shown:

$$\frac{P_1 - P_2}{L} = f \ . \ 1/2 \ \rho/d \ V^2 \tag{15}$$

and

$$\frac{P_1 - P_2}{L} = C_f \ . \ 1/2 \ \rho \, SV^2/(A_x \ . \ L) = R_f/(A_x \ . \ L) \tag{16}$$

This gives

$$f = \frac{S \ . \ d}{A_x \ . \ L} \cdot C_f \tag{17}$$

An assumption is made to find $C_{f_{rough}}$. That is:

$$C_{f_{rough}} / C_{f_{smooth}} = f_{rough}/f_{smooth} \tag{18}$$

which gives us

$$C_{f_{rough}} = f_{rough}/f_{smooth} \cdot C_{f_{smooth}} \tag{19}$$

At this point, we have equations describing C in terms of a frictional coefficient f. If we combine Equations (17) and (10), we have C in terms of C_f.

$$C = C_{fm}/C_{fs} \tag{20}$$

The only information that is needed to find C is the equivalent sand grain roughness of the model and lock and the ship and lock.

The equivalent sand grain roughness of the model and lock was calculated as follows. For each different type of surface, a value of K_s was found. It was then multiplied by the length of the wetted perimeter of the surface. The sum of these surfaces were divided by the total wetted perimeter to get an average value of K_s.

The calculation proceeded as follows:

Surface	Parameter	K_s	Product
Model	5.358 feet	.00015	.0008037
Smooth Concrete Floor	3.143	.001	.003143
Cinderblock wall	2.467	.005	.01175
	Σ = 10.97 feet		Σ = .0157

K_{sm} = .0157/10.97 = .00143

for sill clearance = 0.816 (model).

d_m = .204 feet

K_s / d_m = .007

And the Reynolds number is (at V_{BF_m} = .42 ft/sec)

$$\frac{d_m V_{BF_m}}{\nu} = 5.59 \times 10^4$$

Daily [1] gives a plot of f versus Reynolds number for pipe flow. This plot indicates that for the value of K_s/d_m assumed for the model and for Reynolds numbers up to the one that was calculated above, f is approximately the same as for hydraulically smooth surfaces. This is the basis for our assumption that the model is hydraulically smooth. However, the Reynolds numbers for the ship are so large that even if we assume that K_s/d_m decreases by a factor of 10, the best assumption for f will be the rough-surface friction line.