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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

DRAG OF THE THIN LINE
TOWED ARRAY

by

P. Rispin

SHIP PERFORMANCE DEPARTMENT
DEPARTMENTAL REPORT

January 1977

Report SPD 754-01

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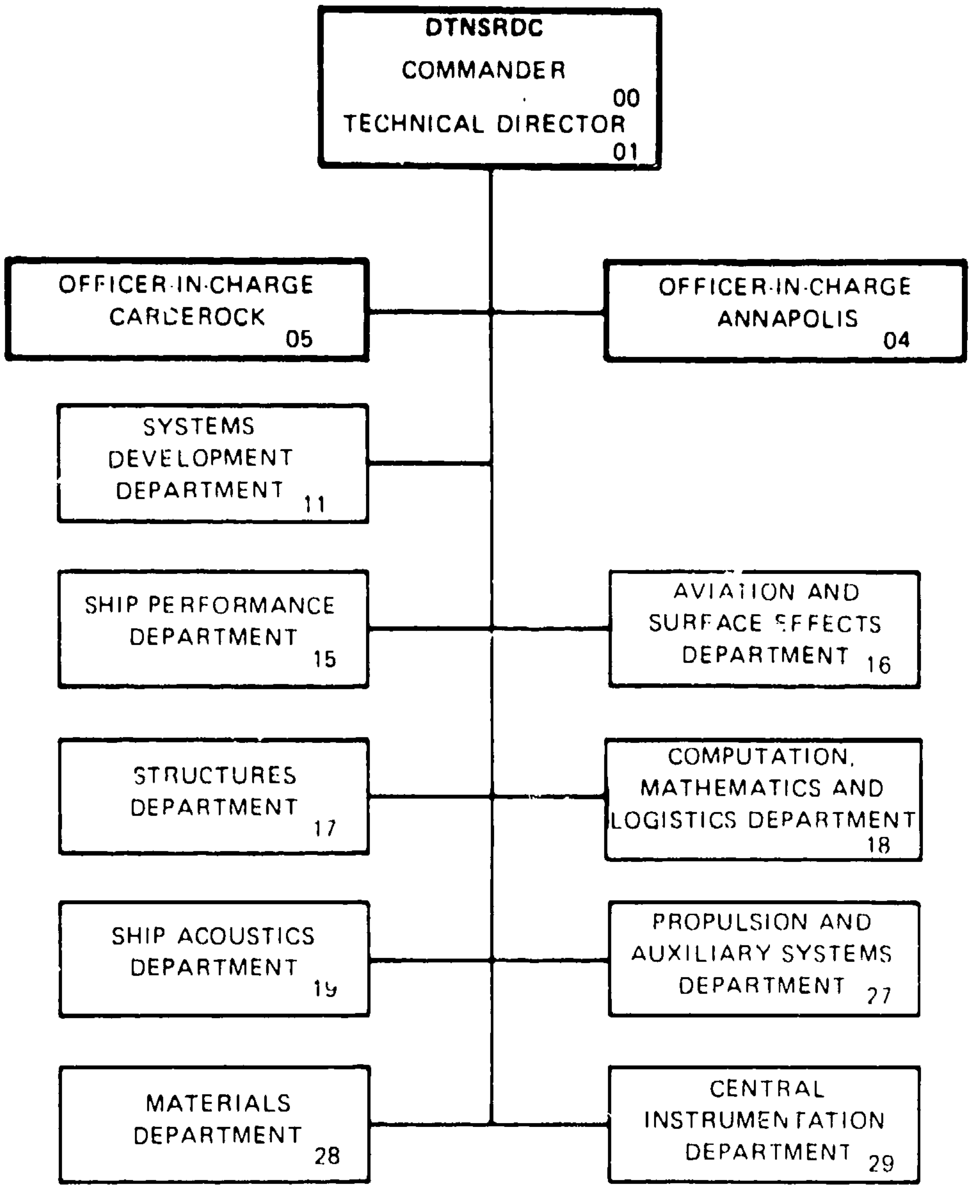
MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER SPD-754-01	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Drag of the Thin Line Towed Array		5. TYPE OF REPORT & PERIOD COVERED Departmental
		6. PERFORMING ORG. REPORT NUMBER SPD 754-01
7. AUTHOR(s) P. Rispin		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Ship Performance Department Bethesda, MD 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NIF DTNSRDC W.U. 1548-078
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Underwater Systems Center New London Laboratory For Trumbull, New London, CT 06320		12. REPORT DATE Jan[redacted]77
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Towed Arrays
Drag Characteristics
Tangential Drag
Cable Deceleration Behavior

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A number of modules of the Thin Line Array were towed in the High-Speed Basin of the David W. Taylor Naval Ship R&D Center. The objectives were to verify that the drag on the array varied directly with its length and to measure the drag on a module as a function of speed. These objectives were attained. The report describes the array modules, outlines the procedure used and presents the results. The tangential drag coefficient as a function of speed is presented for both the array and the drogue. In addition, it was shown that the

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20. ABSTRACT (cont'd)

array does not overrun the towpoint during deceleration. Finally, some predictions are made for drag on a typical array configuration.

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NOTATION

A	Drag on a single array module
C_t	Tangential drag coefficient
d	Diameter of array
D	Drag on drogue
L	Length of array
Re	Reynolds number
S	Drag due to towing shackle
T	Tangential drag
V	Tow speed
ν	Kinematic viscosity of water
ρ	Density of water

ABSTRACT

A number of modules of the Thin Line Array were towed in the High-Speed Basin of the David W. Taylor Naval Ship R&D Center. The objectives were to verify that the drag on the array varied directly with its length and to measure the drag on a module as a function of speed. These objectives were attained. The report describes the array modules, outlines the procedure used and presents the results. The tangential drag coefficient as a function of speed is presented for both the array and the drogue. In addition, it was shown that the array does not overrun the towpoint during deceleration. Finally, some predictions are made for drag on a typical array configuration.

ADMINISTRATIVE INFORMATION

This work was sponsored by the Naval Underwater Systems Center, New London Laboratory and by the Naval Sea Systems Command and was performed under David W. Taylor Naval Ship R&D Center Work Unit 1548-078.

INTRODUCTION

The Thin Line Towed Array has been under development at the New London Laboratory of the Naval Underwater Systems Center (NUSC) since 1972. At present, plans are being made to conduct high-speed sea trials prior to further development of the thin line concept. As a result, the David W. Taylor Naval Ship R&D Center (DTNSRDC) was requested by NUSC under the auspices of the Naval Sea Systems Command (NAVSEA) to measure the drag on a number of array modules at speeds up to 35 knots.

This report describes the array modules and the experimental procedure used in the high-speed towing basin at DTNSRDC, presents the experimental results, and relates the measured drag values to longer array lengths.

DESCRIPTION OF MODEL

The array consisted of six vibration isolation modules, each 100 feet (30.5m) long, and a rope drogue, also 100 feet (30.5m) long. The outer diameter of the array is 1.0 inch (2.5cm) and, for this test, the array was ballasted to be nominally neutrally buoyant in fresh water. Each module had heavy metal connectors at each end of a polyurethane hose of 0.1 inch (0.25cm) thickness with a smooth outer finish. This is illustrated in Figure 1. The modules used had no hydrophones, electronics, or electrical cables. Two intertwined nylon and Kevlar strength members passed through the interior of the hose.

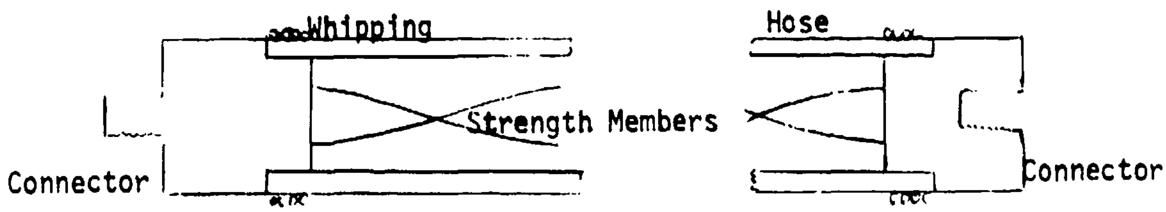

Figure 1 - Array Construction

The hose, or skin, was not linked to the strength members by any internal supports. It carried only the tension generated on its own module and was attached to the connectors at each end. This attachment was effected by means of a cord whipping which bound the hose to the connector by means of radial compression.

The array cavity was filled with a light oil, Shellsol 71, of specific gravity 0.75. Buoyancy was controlled by adding or subtracting small amounts of oil through fill ports in the connectors.

The 100-foot (30.5m) long rope drogue was 1 inch (2.5cm) in diameter and was nominally neutrally buoyant.

PROCEDURES

After array buoyancy was checked, the array was towed in the high-speed basin from a submerged towpoint at speeds of 5 (2.57m/s), 10 (5.14), 15 (7.72), 20 (10.3), 25 (12.9), 30 (15.4) and 35 (18.0) knots, and the drag was measured using a 200-pound (890N) capacity ring gage tensiometer. The array was towed with and without the drogue and in various lengths so as to determine the validity of extrapolating drag values to longer lengths.

To begin with, the array was assembled and placed in the towing basin. The parts of the array containing the inter-module connectors were observed to sink and the centers of the modules to rise. However, the tendency to sink or rise was not large so re-ballasting was deemed unnecessary. Array shape at 5 knots (2.57m/s) was used as the determining factor in checking the ballast.

A 10:1 ogive strut, submerged to a depth of 5 feet (1.52m) was used as a towpoint and is shown in Figure 2.

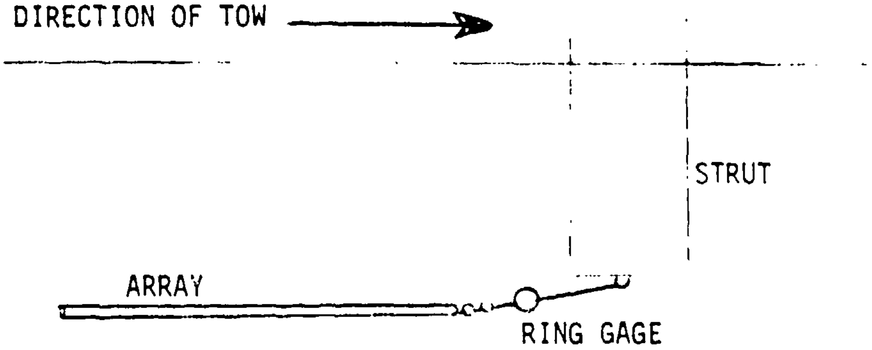

Figure 2 - Towpoint Diagram

The array nose cone was attached through a shackle to the ring gage tensiometer which measures tension up to 2000 pounds (8896N) with an accuracy of 2 pounds (8.90N). The electrical cable from the tensiometer was taken up through a hole in the strut onto the towing carriage where the tension signal was converted to a digital display in pounds and was recorded on a Brush recorder. The carriage speed, held accurately to within 0.01 knot (0.005m/s) over the course of a run, also was recorded on the strip-chart recorder. Before a run, the array was stretched horizontally in the water between a fixed point and the carriage. The carriage was accelerated rapidly to the required speed. The array always reached a quasi-steady configuration before it reached the underwater observation windows. Movies were taken of the array at twice normal speed as it passed the 3-foot (0.91m) deep observation window. Visual observations were made through the 5-foot (1.52m) window and video-tape recordings were made from an underwater camera located on the floor of the basin and looking up at an angle of 45° in the direction of motion of the carriage.

During initial deployment of the array the whipping on two of the modules was abraded, resulting in opening of the hose. Thus the longest array used was 400 feet(122m) plus 100 feet(30.5m) of drogue. This array was towed past the observation windows at 5 knots(2.57m/s) and was seen to rise less than 1 foot(0.30m) along its length as it passed by. There appeared to be little effect due to the heavy spots at the connectors, and no further ballasting was deemed necessary. The following configurations were run at the speeds indicated in Table 1.

TABLE 1 - SPEED/CONFIGURATION MATRIX

Length in feet(m)		Speed in knots(m/s)						
Array	Drogue	5 (2.57)	10 (5.14)	15 (7.72)	20 (10.3)	25 (12.9)	30 (15.4)	35 (18.0)
400(122)	100(30.5)	x	x	x	x	x	x	x
400(122)	-	-	-	-	-	-	-	x
300(91.4)	100(30.5)	x	x	-	x	-	x	-
300(91.4)	-	x	x	x	x	x	x	-
200(61.0)	100(30.5)	x	x	x	x	x	x	-
200(61.0)	-	x	x	x	x	x	x	-
100(30.5)	100(30.5)	x	x	x	x	x	x	x
-	100(30.5)	x	x	x	x	x	x	x

PRESENTATION OF RESULTS

The array towed very stably at all times with the only oscillations being visible at the tail end of the drogue. These were of the order of about 2 to 4 Hertz, had a magnitude about at most 2 to 3 inches(0.051 to 0.076m) and extended forward along the drogue about 3 feet(0.91m). Detailed examination of the movie frames allow a close estimation of these values. The vibration amplitudes given here were maximum values and tended to occur mainly at the high speeds. Often there was little or no vibration visible. In particular, the main body of the array always towed very smoothly with no visible transverse motion.

On some of the runs special note was made of the behavior of the array during deceleration at the end of the run. A typical plot of array tension during a deceleration is shown in Figure 3. Straight line segments representing decelerations of 0.2g and 0.1g are shown for comparison.

The measured values of tension at the towpoint as functions of speed and configurations are given in Table 2.

DISCUSSION OF RESULTS

Taking the deceleration results first, Figure 3 shows that the tension and speed decrease together. In fact, except for the last few seconds of the deceleration, the tension is very nearly proportional to the square of the speed at all times. This suggests that the array is in quasi-static equilibrium even during such high decelerations as observed here. Even at decelerations up to 0.20g the array showed absolutely no tendency to move forward of the towpoint. Examination of the tension record shows a smooth drop in tension during deceleration and, in particular, no negative tensions were observed. Drag effects dominate inertia effects on array behavior.

Next consider the drag measurements. The questions addressed are whether the drag varies directly with length for a given speed and whether, for a given length, the drag varies with the square of the speed.

To answer the first question, look at the 30-knot data. Let A be the drag on a module, D the drag on the drogue, and S the drag on the shackle and nose cone arrangement. Now assume that the drag on four modules is four times the drag on one module. Then,

$$4A + D + S = 949 \text{ pounds } (4221 \text{ newtons})$$
$$3A + D + S = 800(3558)$$
$$3A + S = 510(2268)$$
$$2A + D + S = 635(2824)$$
$$2A + S = 347(1543)$$
$$A + D + S = 469(2086)$$
$$D + S = 300(1334)$$

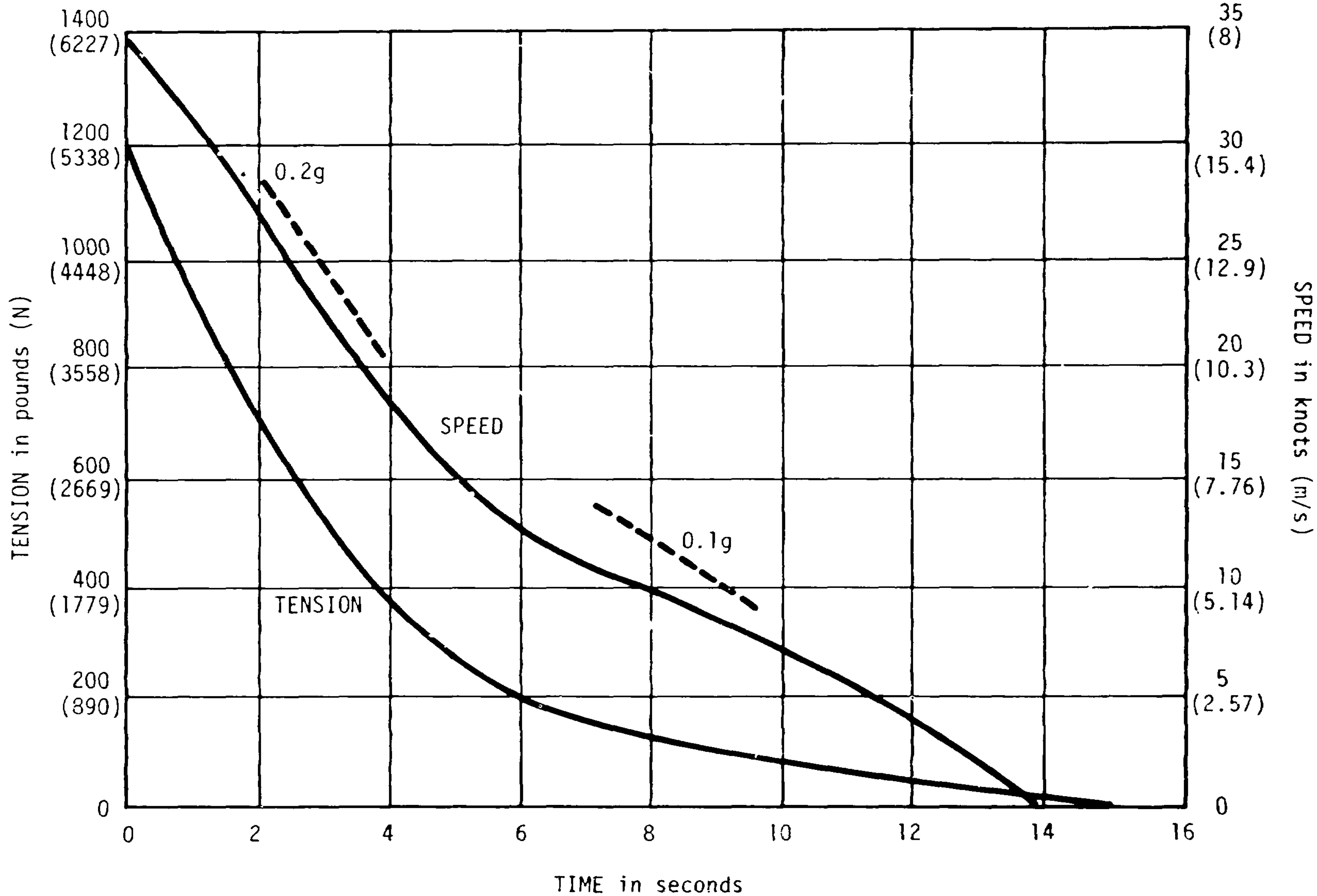

Figure 3 - Tension Decrease During Deceleration

TABLE 2 - DRAG AS A FUNCTION OF SPEED FOR VARIOUS CONFIGURATIONS

Length in feet (m)		Speed in knots (m/s)						
Array	Drogue	5(2.57)	10(5.14)	15(7.72)	20(10.3)	25(12.9)	30(15.4)	35(18)
		Drag in pounds (N)						
400(122)	100(30.5)	31(138)	117(520)	258(1148)	447(1988)	677(3011)	949(4221)	1285(5716)
400(122)	-	-	-	-	-	-	-	935(4159)
300(92)	100(30.5)	26(116)	98(436)	-	370(1646)	-	800(3558)	-
300(92)	-	18(80.1)	63(280)	136(605)	237(1054)	363(1615)	510(2268)	-
200(61)	100(30.5)	22(98)	79(351)	168(747)	296(1317)	450(2002)	635(2824)	-
200(61)	-	14(62.3)	43(191)	93(414)	161(716)	249(1107)	347(1543)	-
100(30.5)	100(30.5)	16(71.2)	56(249)	121(538)	212(943)	322(1432)	469(2086)	680(3025)
-	100(30.5)	10(44.5)	36(160)	77(342)	140(623)	219(974)	300(1334)	403(1792)

Solving these seven equations for the three unknowns A, D, and S using the method of least squares, the values are:

A = 163 pounds(725N)   D = 284 pounds(1263N)   S = 21 pounds(93.4N)

These values of A, D and S backfit into the equations the right hand side becomes 956(4252), 794(2532), 510(2268), 631(2807), 347(1543), 468(2082), and 305(1357) pounds(newtons). These differ from the measured values by 7(31.1), -6(-26.7), 0(0), -4(-17.8), 0(0), -1(-4.45) and 5(22.2) pounds(newtons), respectively. The rms value of these residuals is 4.5 pounds(20N), a low value which indicates that the equations are consistent and that the hypothesis that the drag is linear with length is valid. This also may be seen from a close examination of Figure 4, which contains only data from configurations which include a drogue. Straight lines fit the data extremely well. The results for the array drag A and the drogue drag D appear quite reasonable and are given in Table 3.

TABLE 3 - ARRAY MODULE AND DROGUE DRAG AS A FUNCTION OF SPEED

	Speed in knots(m/s)						
	5 (2.57)	10 (5.14)	15 (7.72)	20 (10.3)	25 (12.9)	30 (15.4)	35 (18)
	Tension in pounds(N)						
A	5 (22.24)	20 (89.0)	45 (200.2)	77 (342.5)	113 (502.6)	163 (725.0)	216 (960.8)
D	8 (35.6)	34 (151.2)	72 (320.2)	133 (591.6)	196 (871.8)	284 (1263)	359 (159)
S	3 (13.3)	2 (8.90)	4 (17.8)	6 (26.9)	24 (106.7)	21 (93.4)	70 (311.4)
RMS	0.6 (2.67)	1.5 (6.67)	1.8 (8.01)	2.0 (8.90)	5.2 (23.1)	4.5 (20.0)	22.2 (98.7)

The case for shackle drag S is different, especially above 20 knots. Two points should be borne in mind. S is the residual of relatively large values of A and D, and above 20 knots(10.3m/s) intermittent ventilation occurred in the neighborhood of the towpoint. This was due to air being sucked down through the cable hole in the strut. The high value for S at 35 knots(18m/s) may, perhaps, be explained in this way. In

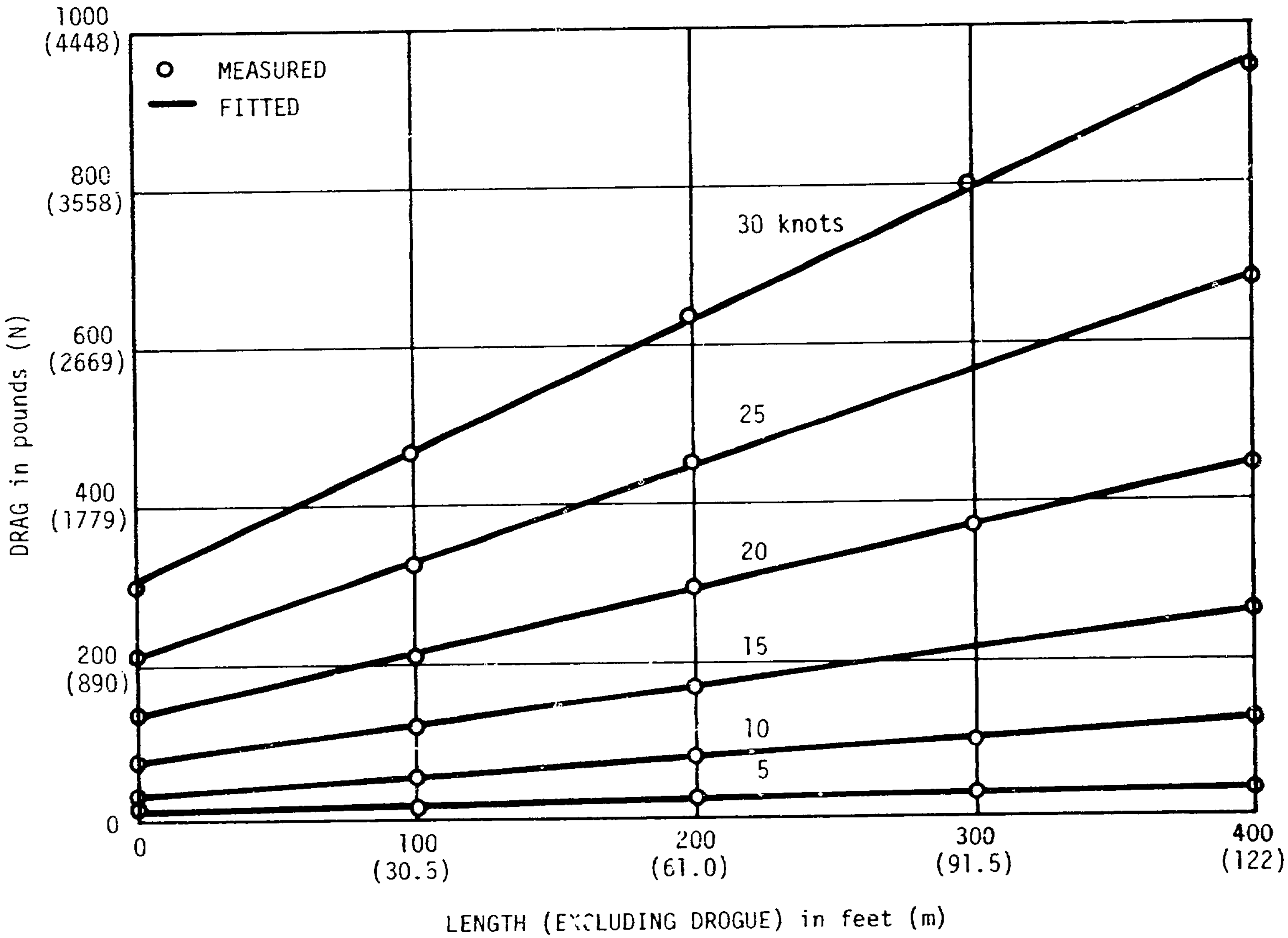

Figure 4 - Measured Drag on Array as a Function of Length for Various Speeds

general, the relatively low rms residual values indicate that extrapolation from short to long lengths may quite safely be done.

Next examine the speed dependence. First divide the values of A and D by V^2. The values obtained are almost constant, dropping a little with speed. On further examination it can be found that

$$A = 0.231\ V^{1.931} \qquad (A = 0.285\ V^{1.931})$$
$$D = 0.354\ V^{1.963} \qquad (D = 0.436\ V^{1.963})$$

where V is in knots(m/s)

The drag rise is seen to be a little less than V^2, as is usual for array drag.

From these values the tangential drag coefficients are calculated for both the array modules and the drogue. The drag coefficient C_t is defined by

$$T = 1/2\rho\ V^2\ \pi\ C_t\ d\ L \qquad [3]$$

where

T is the total drag

ρ is the density of water

d is the array diameter, and

L is the array length

If ρ is 1.983 slugs per cubic foot(1022 kg/m^3) for fresh water, with T in pounds(N), V in knots(m/s), d in inches(m), L in feet(m)

$$T = 0.230\ V^2\ \pi\ C_t\ d\ L \qquad [4]$$
$$(T = 112\ V^2\ \pi\ C_t\ d\ L)$$

In our case d = 1(0.0254), L = 100(30.5)

$$T = 72.2\ V^2\ C_t \qquad [5]$$
$$(T = 27.3\ V^2\ C_t)$$

Hence

$$C_t(A) = 0.00320\ V^{-0.069} \qquad [6]$$
$$(0.00306\ V^{-0.069})$$
$$C_t(D) = 0.00490\ V^{-0.037} \qquad [7]$$
$$(0.00478\ V^{-0.037})$$

The drag generally depends on the Reynolds number

$$Re = \frac{Vd}{\nu} \qquad [8]$$

where ν is the kinematic viscosity of water.

For V in knots(m/s), d inches(m), and using fresh water

$$Re = 1.333 \times 10^4\ V\ d \quad (Re = 1.020 \times 10^6\ Vd) \qquad [9]$$

The tangential drag coefficient is plotted as a function of Reynolds number in Figure 5 and can be written as

$$C_t(A) = 0.00616\ Re^{-0.069} \quad [10]$$

$$C_t(D) = 0.00696\ Re^{-0.037} \quad [11]$$

To convert to sea-water at 70° F (21 C), pick a speed V and find Re from

$$Re = 1.270 \times 10^4\ V\ d \quad [12]$$

$$(Re = 2.47 \times 104\ V\ d)$$

Then find C_t from Equations [10] or [11] or from Figure 5. This gives

$$T = 74.12\ V^2\ C_t \text{ pounds per 100-foot module} \quad [13]$$

$$(T = 1246\ V^2\ C_t \text{ N per 30.5m module})$$

Example: Find the drag on 600 feet(183m) of array plus 100 feet(30.5m) of drogue at 20 knots(10.3m/s).

$$Re = 2.54 \times 10^5$$

$$C_t(A) = 0.00261$$

$$C_t(D) = 0.00439$$

$$T = 74.12 \times 400 \times (6 \times 0.00261 + 0.00439) = 594 \text{ pounds}$$

$$(T = 1246 \times 105.9 \times (6 \times 0.00261 + 0.00439) = 2640N)$$

A plot of the drag for this array is presented in Figure 6. The measured drag coefficients are given in Table 4 and also are marked on Figure 7, which is taken from Reference 1.

TABLE 4 - MEASURED DRAG COEFFICIENTS AS A FUNCTION OF SPEED

	Speed in knots(m/s)						
	5 (2.57)	10 (5.14)	15 (7.72)	20 (10.3)	25 (12.9)	30 (15.4)	35 (18.0)
$C_t(A)$	.00277	.00277	.00277	.00267	.00250	.00251	.00244
$C_t(D)$	.00443	.00471	.00443	.00461	.00434	.00437	.00406

Agreement is excellent when compared with predictions for a very smooth cylinder with a roughness factor of 0.001.

[1] Reid, R.D. and B.W. Wilson, "Boundary Flow Along a Circular Cylinder," National Engineering and Science Company, TR 204-4 (March 1962).

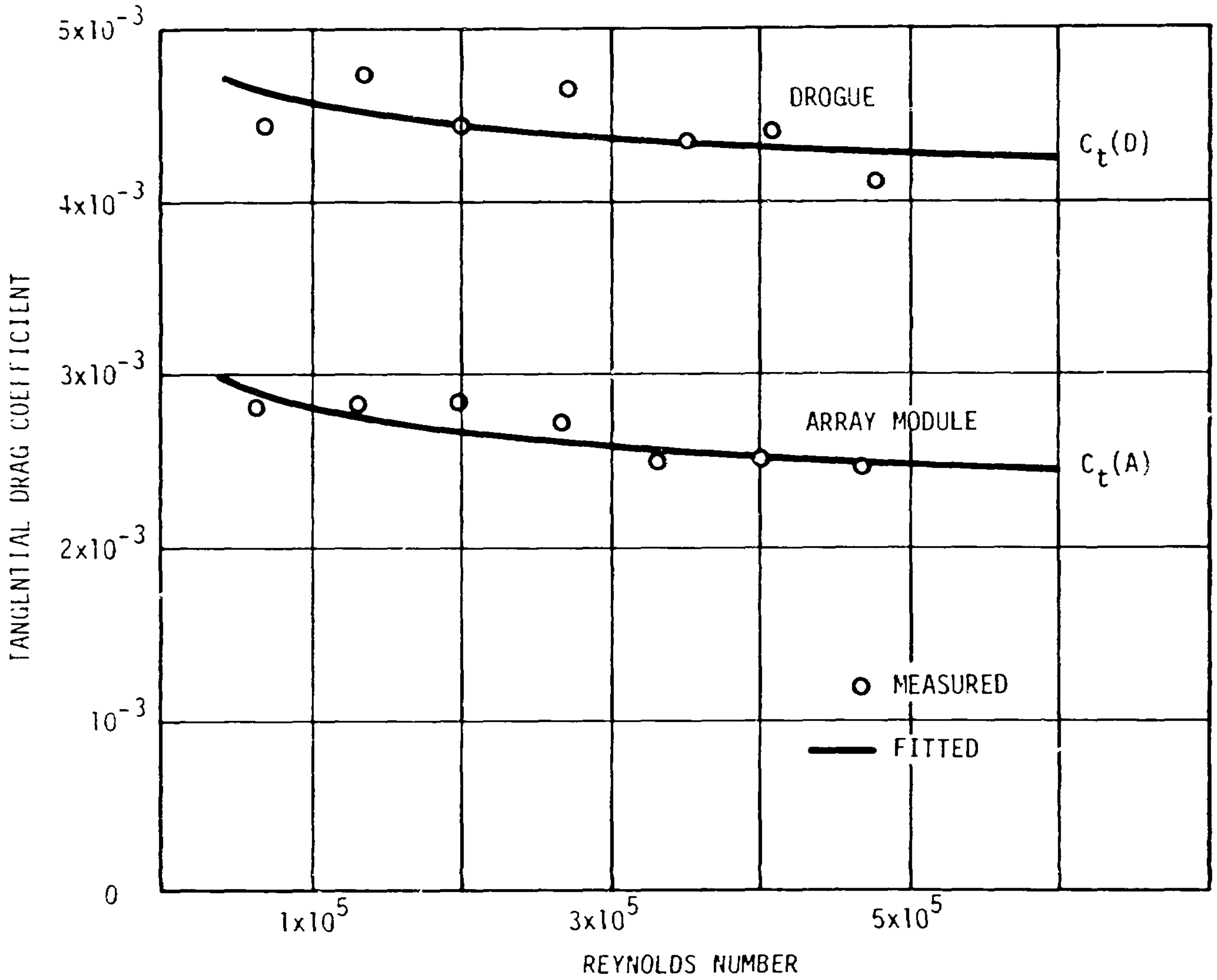

Figure 5 - Tangential Drag Coefficient as a Function of Reynolds Number

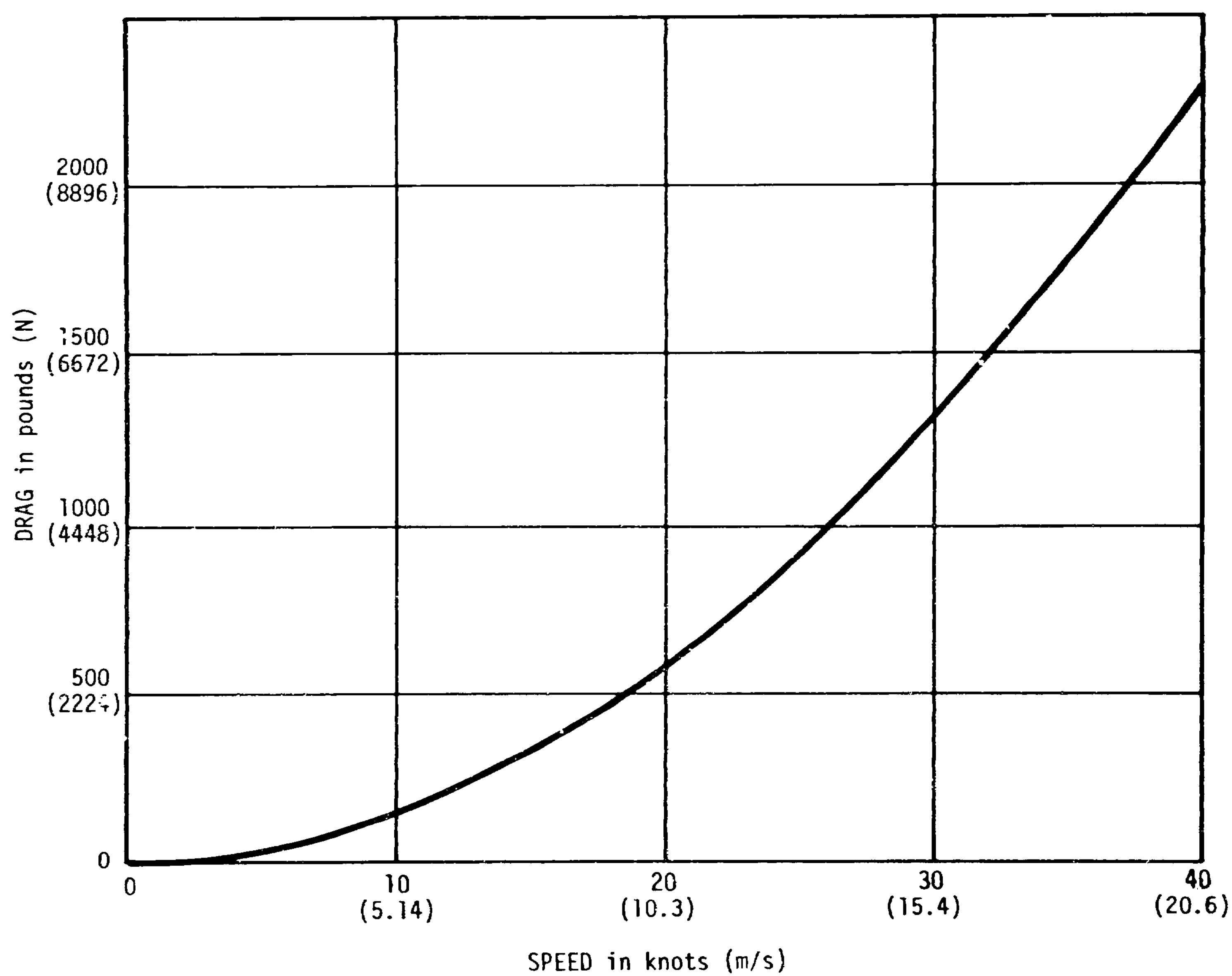

Figure 6 - Predicted Drag on a 600-Foot (182.9m) Array

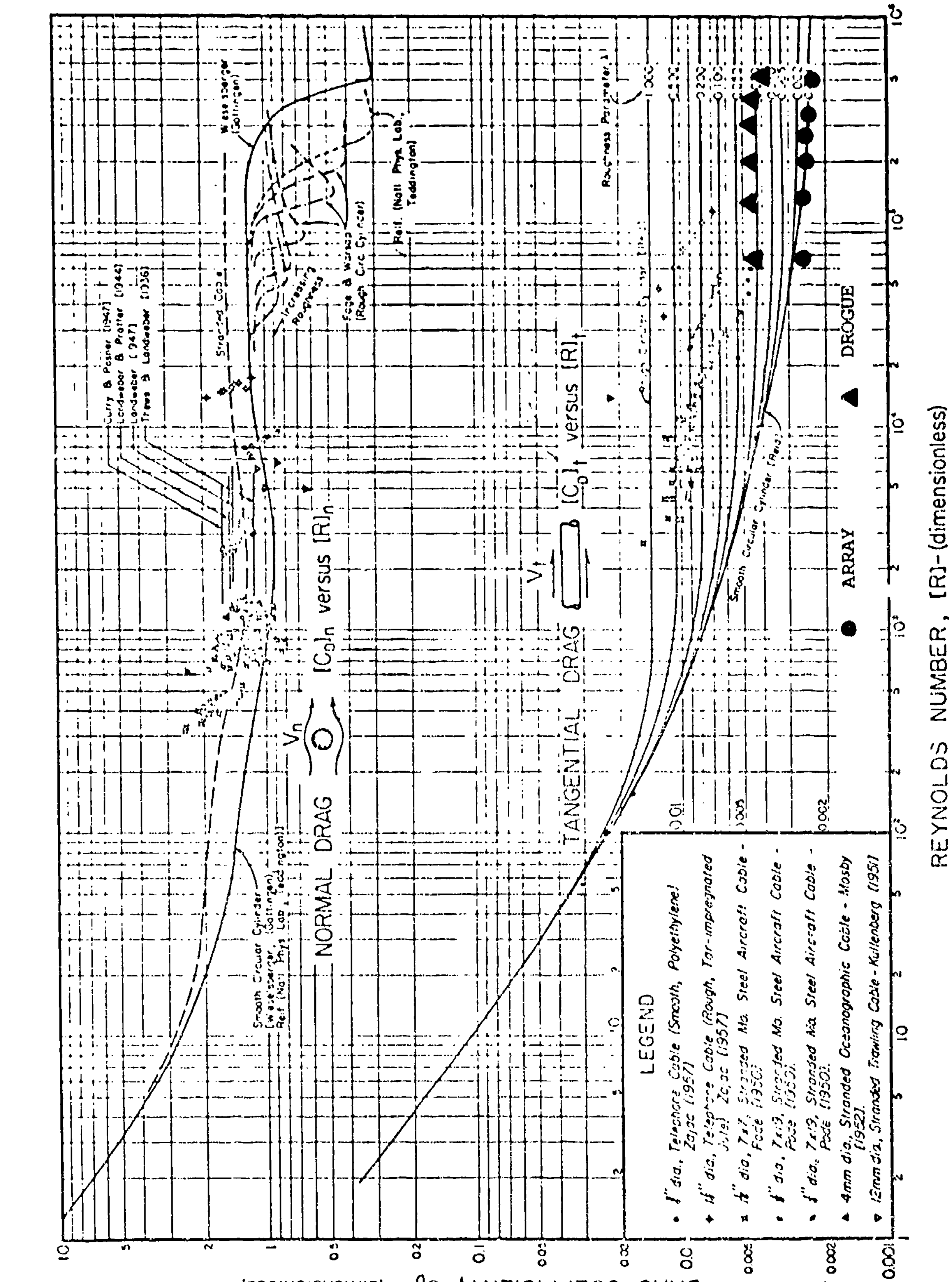

Figure 7 - Measured Drag Coefficients Compared with Reid's Results

CONCLUSIONS

Based on the results of the experiments the following conclusions are drawn:

1. The assumption that the drag varies directly with the length of the array is verified for lengths up to 400 feet(122m). There is no reason to suspect any different behavior beyond this length.

The drag of the Thin Line Array may be represented as:

$$D = 0.231\ n\ V^{1.931} + 0.345\ \alpha\ V^{1.963}$$

$$(D = 0.064\ n\ V^{1.931} + 0.156\ \alpha\ V^{1.963}$$

where

n is the number of modules

α = 0 is no drogue is used

α = 1 if a drogue is used, and

V is the towspeed in knots(m/s).

2. The measures of drag as functions of length and speed are consistent and are suitable for predictive purposes for similar arrays.

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