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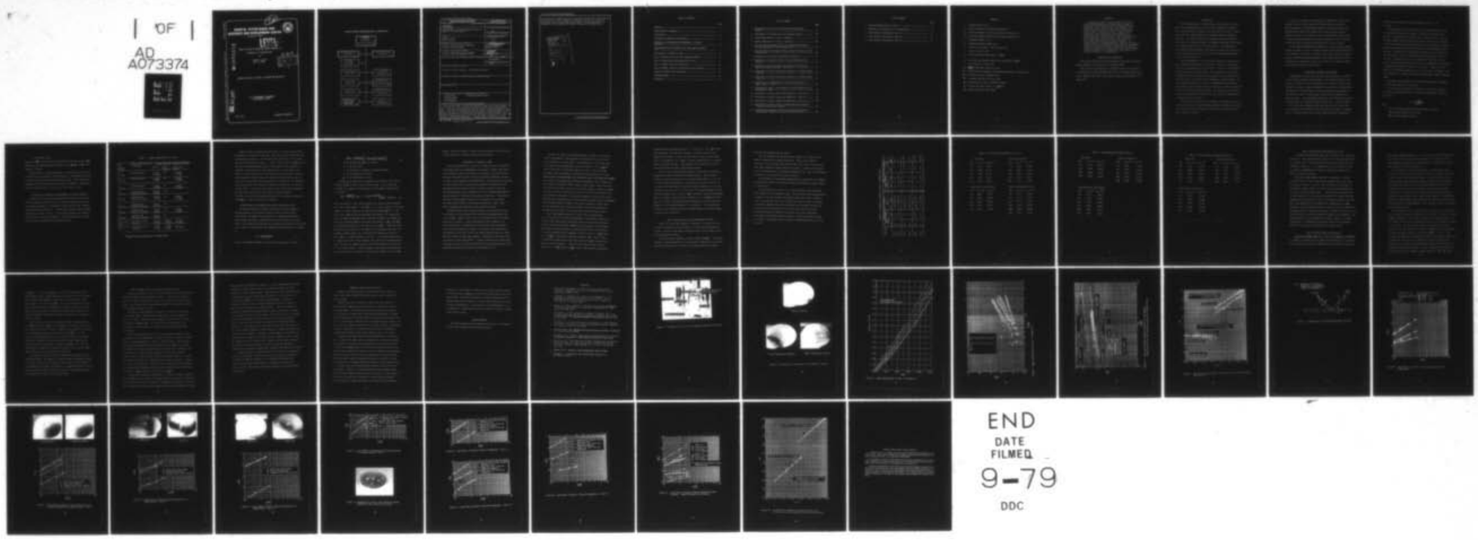

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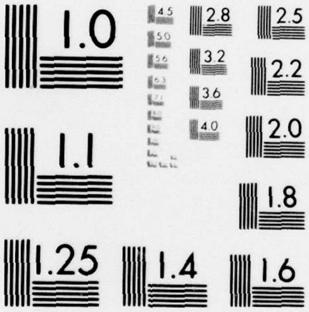
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# DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

LEVEL II

# DRAG OF SLIMES ON ROUGH AND SMOOTH SURFACES AS MEASURED BY A ROTATING DISK

by

GARNELL S. BELT
NEIL A. SMITH

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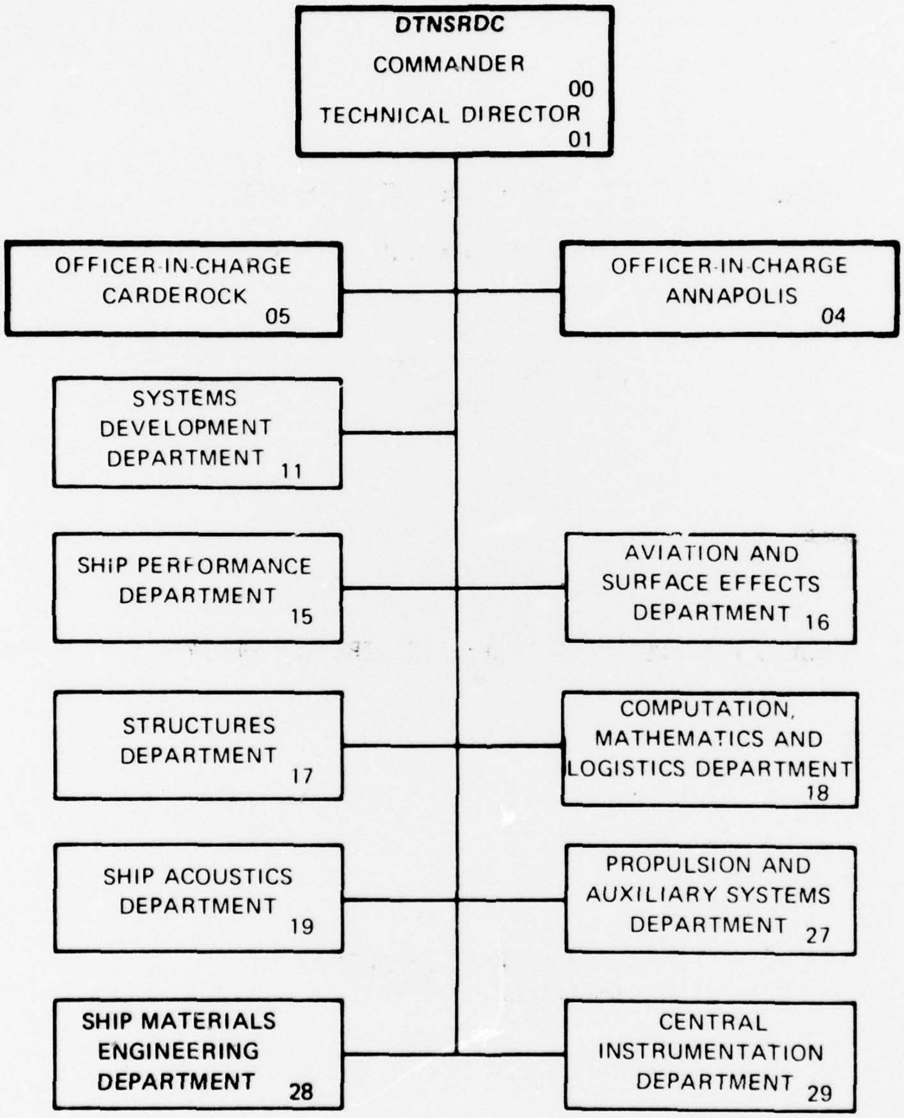

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Attempts were made to grow microbial slime films of controlled roughness on circular disks in order to assess the effects of slime films on hydrodynamic drag. An attempt to grow bacterial and algae slimes in the laboratory did not yield a slime that was sufficiently rough to cause a significant effect on drag. Natural slime grown in bay salt water in the absence of an antifouling paint produced barnacles an/or vegatation growth which gave a drag increase. Two disks coated with antifouling paint, were set in bay water, resulting in a slime covering visually free of barnacles. A marked increase in drag was measured. Cont

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However, the disks surface finish was sufficiently marred after the experimental evaluation, so that a definitive conclusion that slime by itself is a significant source of drag could not be reached. Further experiments are recommended to fully explore the effects of slimes on frictional drag.

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# NOTATION

A - Boundary-layer factor

$C_m$ - Moment coefficient, defined by Equation [1]

$C_{m_r}$ - Rough disk moment coefficient, defined by Equation [1]

$C_{m_s}$ - Smooth disk moment coefficient, defined by Equation [1]

k - Roughness height, ft (m)

k* - Roughness Reynolds number, $k/\nu$

2M - Torque on both sides of disk, ft-lbs (N.m)

R - Radius of disk, ft (m)

$R_{R_r}$ - Rotating disk Reynolds number, $R^2\omega/\nu$

$R_{R_r}$ - Rotating disk Reynolds number using rough disk, $R^2\omega/\nu$

u - Local velocity, ft/sec (m/s)

$u_\tau$ - $\sqrt{\tau_a/\rho}$ average shear velocity on disk

$\Delta B$ - Similarity-law roughness characterization defined in Equation [4]

$(\Delta B)'$ - Derivative of $\Delta B$, $d(\Delta B)/d \ln k^*$

$\nu$ - Kinematic visocity, sq ft/sec $m^2/s$)

$\rho$ - Mass density of fluid, lb-$sec^2/ft^4$ ($k/m^3$)

$\tau_a$ - Average wall shear stress, $3\ C_m = \omega^2 R^2/8$

$\omega$ - Angular velocity, ft/sec (m/s)

## ABSTRACT

Attempts were made to grow microbial slime films of controlled roughness on circular disks in order to assess the effects of slime films on hydrodynamic drag. An attempt to grow bacterial and algae slimes in the laboratory did not yield a slime that was sufficiently rough to cause a significant effect on drag. Natural slime grown in bay salt water in the absence of an antifouling paint produced barnacles an/or vegetation growth which gave a drag increase. Two disks coated with antifouling paint, were set in bay water, resulting in a slime covering visually free of barnacles. A marked increase in drag was measured. However, the disks surface finish was sufficiently marred after the experimental evaluation, so that a definitive conclusion that slime by itself is a significant source of drag could not be reached. Further experiments are recommended to fully explore the effects of slimes on frictional drag.

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# INTRODUCTION

Marine microfouling is a natural process that involves the interaction of microorganisms with a solid surface submerged in seawater. This interaction usually results in the formulation of slime, a complex film, which may contain deposited or entrapped organic or inorganic materials. The common feature of all organisms constituting slime is their ability to produce and exude a mucilaginous substance which results in a semirigid jelly layer on the hull surface. The properties of slime films in general depends on the kinds of bacteria and other microorganism populating the layer as well as other entrapped particulates such as silts and detrites.

Earlier measurements of the frictional resistance of towed plates with antifouling paints show 10 to 20 percent increase in resistance after only 10 days exposure in sea water(1). Little, or no fouling was observed except for the slime layer. This drag effect is not really unexpected when one considers that the geometric scale of slime and its components are the same order as the roughness of coating systems. The slime organisms range in size from 40 to 2000μ-inches for bacteria, alga diatoms, spores and other special shapes and from 6000 to 16,000 μ-inches for the larger filamental shapes. The complexity of the slime film is very great and its thickness can vary from a few thousandths up to several tenths of and inch.

Further work by others(2) also confirmed the significance of slime on drag as measured by a rotating drum apparatus. However, results were only qualitative since thickness of slime layers were altered at different speeds of rotation.

As part of the efforts to reduce drag on submarines, smoother antifouling (AF) hull coating systems are being screened and selected. Despite resistance to macrofouling attachment and growth, most AF hull coatings become covered with slimes after relatively short exposure periods in the sea. The question of how such microfouling affects drag is largely unresolved despite some sparse evidence that slime formation on painted surfaces increases drag sufficiently to be of concern.

In the present experimental investigation a slime film was developed through two means; the first, synthetic and the second through immersion of test specimens in bay water. The drag of each slime specimen was experimentally evaluated through measurement of the torque required to drive a rotating disk, covered with slime, over a fixed set of rotational speeds in chlorinated tap water and sea water.

## EXPERIMENTAL APPARATUS AND PROCEDURE

Measurements of torque and rotational speed were made on a series of 9 inch (0.228 m) diameter disk specimens. Each disk was mounted on the end of a 1/2-inch (1.27 cm) diameter shaft in a 39 gallon (14.75 litre) cylindrical housing. Power was supplied to the shaft by a variable-speed (0-2200 rpm), 1-1/2 hp DC motor; torque was sensed and transmitted by a BLH Electronic type "A" Torque Sensor, and rotation was measured by a 60-tooth sensor. The experimental apparatus[2], with associated electronic instrumentation for recording torque and speed data, is shown in Figure 1. Two of the three voltmeters shown were used to record torque data, one to monitor the instantaneous torque output and the other to integrate over a 10 second interval after torque stability had been established.

The ohm scale was used on the third voltmeter to monitor the disk rpm.

The apparatus, with the shaft only, was filled with tap water and run through the operating rpm range to establish the system's torque no-load. A smooth-surface reference disk of known shear torque was run. The data obtained, which included the no-loads, were used as a standard to check the operating no-load consistency over a long period of operation. Before sliming each disk the reference torque on each unslimed disk was measured. In measuring the unslimed disk reference torque the disk was rotated through a series of fixed speeds ranging from about 800 rpm to 2000 rpm. The speed series was run a minimum of three times for each disk in tap water while carefully monitoring the temperature of the liquid to determine the kinematic viscosity of the water. Because of joule heating of the liquid, temperatures could rise as much as 3 degrees C over a test period of 15 minutes, thus causing a significant change in Reynolds number.

Throughout the experiments the torque measurements were repeatable to within three quarters of one percent.

The raw torque data minus the no-loads were converted to the non-dimensional form presented herein. The torque coefficients ($C_m$) may be defined as:

$$C_m = \frac{2M}{1/2 \rho \omega^2 R^5} \qquad [1]$$

where

2M is the torque experienced by both sides of the disk

$\rho$ is the mass density of the fluid

$\omega$ is the disk angular velocity

$R$ is the disk radius

Values of $1/\sqrt{C_m}$ for each disk were determined and plotted against $R_R\sqrt{C_m}$, where $R_R$ is disk Reynolds number, defined by $R_R = \omega R^2/\nu$, and $\nu$ is the kinematic viscosity.

The procedure for torque measurements of slimed disks was basically the same with the exception of first coming up to the maximum disk speed and then collecting data while decreasing the speed. This sequence was followed to allow the slime cultural residue to slough-off, thereby permitting a stable torque to be measured at lower values of rpm.

## MECHANICAL AND EXPERIMENTAL MEASUREMENTS OF SURFACE ROUGHNESS

Torque and rotational speed measurements were made on nine, 9-inch (0.228 m) diameter, 1/8-inch (0.318 cm) thick titanium-disks with regular machined roughnesses. Photographs showing different disk roughness patterns are shown in Figure 2. The measured roughness heights (average amplitude) are listed in Table 1. The roughness heights were measured by the National Bureau of Standards on a minicomputer/stylus instrument system, using an interferometrically measured step.

TABLE 1 - SURFACE CHARACTERISTICS OF DISKS

| Disk No Subtrate Material | Surface characteristics on coatings | Surface Roughness (Average Amplitude) | | |
|---|---|---|---|---|
| | | Initial | After Soaking* | After Slime Removal |
| T-1<br>Titanium | Machined Smooth | 6.8 μin<br>0.172 μm | NA | 5.8 μin<br>0.147 μm |
| T-2<br>Titanium | Machined Smooth | 5.5 μin<br>0.14 μm | NA | 5.3 μin<br>0.135 μm |
| T-3<br>Titanium | Machined Smooth | 6.5 μin<br>0.165 μm | NA | 5.3 μin<br>0.136 μm |
| T-4<br>Titanium | Machined Grid<br>Pattern of Grooves | 393 μin<br>9.99 μm | NA | |
| T-5<br>Titanium | Machined Grid<br>Pattern of Grooves | 348 μin<br>8.85 μm | NA | 345 μin<br>8.75 μm |
| T-6<br>Titanium | Machined Grid<br>Pattern of Grooves | 636 μm<br>16.2 μm | NA | |
| T-7<br>Titanium | Machined Grid<br>Pattern of Grooves | 518 μm<br>13.2 μm | NA | 518 μin<br>13.2 μm |
| T-8<br>Titanium | Machined Grid<br>Pattern of Grooves | 355 μm<br>9.01 μm | NA | |
| P-2<br>Sand blasted<br>Steel | Navy Paint System<br>F119/F121 | 720 μin<br>183 μin | 686 μm<br>1.74 μm | 758 μm<br>19.3 μm |
| P-12<br>Sand blasted<br>Steel | Navy Paint System<br>F119/F121 | 479 μin<br>12.2 μm | 446 μin<br>11.3 μm | 492 μin<br>12.5 μm |

*Soaked 10 days in salt water (3-percent NACl)

Figure 3 gives raw torque reference data for the disks with machined roughnesses as a function of disk rpm. These data were non-dimensionalized and presented in Figure 4. To help assess the correctness of the results the data are replotted in Figure 5. Figure 5 shows that for $R_R \sqrt{C_m} > 5 \times 10^4$ the curves are approximately parallel to Von Karman's[4] and Goldstein's[5] turbulent torque coefficient lines respectively for a free disk in the absence of an enclosure, and of an enclosed disk whose turbulent boundary-layer thickness is several times less than the distance from the base of the disk to the bottom of the housing (Schultz and Grunow)[6]. The measured torque coefficients fall between the theoretical predictions for free and enclosed disks. The torque coefficients for the various disk roughnesses are parallel to each other at high values of Reynolds number. Therefore, the flow on the rotating disk under all experimental conditions with $R_R \sqrt{C_m} > 5 \times 10^4$ was turbulent, as desired.

## CHARACTERIZATION OF ROUGHNESS DRAG USING $\Delta$B SIMILARITY LAW

The $\Delta$B similarity-law roughness drag characterization needed for scaling purposes can be obtained indirectly from the overall torque coefficient[7]. The $\Delta$B may be interpreted as a roughness drag function which governs the change in boundary-layer velocity profile in the wall region. The procedure for applying the similarity laws derived by Granville[8] is as follows. By definitions, the roughness Reynolds number, k*, is given by

$$k^* = (u_\tau/\omega R) R_R (k/R) \qquad [2]$$

and the corresponding average local friction velocity, $u_\tau$, is given by

$$(u_\tau/\omega R) = \sqrt{5/8\pi}\,\sqrt{C_m}\left\{1 - \left[2A + (\Delta B)'\right]\sqrt{1/40\pi}\sqrt{C_m}\right\} \qquad [3]$$

$R_R$ is the Reynolds number of the disk

R is the disk radius

k is the height of roughness (average amplitude)

A is the boundary-layer factor

$\omega$ is the disk angular velocity

In Figure 4 the values of $C_m$ and $R_R$ data are plotted in the form of $1/\sqrt{C_m}$ and $R_R\sqrt{C_m}$ for both rough and smooth disks. At the same value of $R_R\sqrt{C_m}$, the roughness characterization function $\Delta B$ is obtained from the equation[8]

$$\Delta B = \sqrt{8\pi/5}\left\{\left[(1/C_m)_r - (1/C_m)_s\right] + (\Delta B)'/5\right\}\Big|_{R_R\sqrt{C_m}} = \text{Constant} \qquad [4]$$

where the subscript r and s denote respectively rough and smooth surfaces. For a smooth surface $\Delta B = 0$ and $(\Delta B)' = 0$. A first estimate of the value of $\Delta B$ for a rough surface can be obtained by assuming $(\Delta B)' = 0$. The final value of $\Delta B$ may then be determined from equation [4] through iteration, by making successively better estimates of $(\Delta B)'$. In summary the procedure to determine $\Delta B$ is as follows. The values of $1/\sqrt{C_m}_r$ and $1/\sqrt{C_m}_s$ are obtained from Figure 4 at the same value of $R_R\sqrt{C_m}$. These values are substituted into equation [4] and $(\Delta B)$ is first assumed to be zero. The roughness Reynolds number, $k^*$, is obtained from equations [2] and [3] where $(\Delta B)'$ is assumed initially to be zero. A first approximation plot of $-\Delta B$ versus in $k^*$ is then obtained. The slope of the correlating line gives the values of $(\Delta B)'$ which are then used in equations [3] and [4] for the second iteration. Typical changes in the initial and second iteration values of B as a function of $k^*$ are shown in Figure 6 for two roughnesses. Since the values of ( $\Delta$B)' are almost equal for the initial and second iterations, no further iterations are necessary.

## DEVELOPMENT OF SYNTHETIC SLIMES

The work described here is part of a series of efforts to establish a microbial slime on an experimental test surface to assess slime drag. In an attempt to produce film slimes, a 30 gallon (11.35 litre) marine aquarium (35 percent salinity) with marine killfish (Fundulus) was used to inhibit living organisms from metabolizing. The killfish were fed daily. The fish excreta and any uneaten food unavoidably introduced into the aquarium served as nutrient sources for marine bacteria in the tank. The initial bacteria were introduced by the fish, the sea water, and the aquarium surfaces. The disks were placed into the tank. Titanium was chosen as the disk material because of its stabililty in sea water. The disks listed in Table 1 and torques referenced in Figure 3 were used to determine the drag effect due to synthetic slimes.

Microbial slime films are highly hydrated, containing 90% or more of the medium so that evaporation of the medium during measurement had to be avoided. Changes in the slime film thickness during drag testing were also of interest. These considerations led to adoption of an optical method due to Schmalz(9) for slime film thickness measurement which allows the specimen to remain in a container whose atomsphere in equilibrium with the vapors of the test medium and which does not require physical contact with the slime surface. Tolansky has presented a good description of this technique(10). A Gaertner Scientific Co. Model M-308 instrument was used for this work because its long working distance allows measurement within closed dishes with transparent covers.

Briefly, the light section method measures thickness of transparent films by measurement of the separation of reflections from the top and bottom surfaces of the film when it is illuminated by a fine light beam at an angle to the perpendicular, as shown in Figure 7. The separation must be corrected for refractive index of the film. Since the films considered here are expected to be less than 10% concentration of slime solids in the sea water medium, the refractive index of sea water was assumed. The accuracy of the method was verified by measurement of the thickness of known objects in sea water medium. Large circular plastic dishes were used, which were fitted with a cover 1/32 inch acrylic plastic. Disks were removed from sea water using fittings which did not touch the slime outside of the circle masked by the shaft of the rotation apparatus, held vertically with the edge touching filter paper to allow drainage of excess liquid. Immediately after drainage ceased, the edge of the disk was wiped with filter paper, and the disk placed in the dish and covered. Slime film thickness was determined on both sides of the disks before and after drag testing.

After slime growth periods of 10 and 30 days, the disks were set up for slime film thickness measurements. The Gaertner Scientific Co. -Model M-308, light-section microscope, which can measure film thickness greater than 394 micro-inches (10 μm) and the transparent film thickness measurement technique was used to estimate the bacterial film thickness. The initial measured surface roughness on disk T-1 was, k = 6.9 μ-inches rms (0.18 μm), indicating a hydraulically smooth disk. After 30 days of immersion a smooth film of less than one mil (25.4 μm) thickness had grown on the disk surfaces. Disk T-9, which had an initial surface roughness k = 191 μ-inches (4.85 μm), with a wide machined crosshatched roughness pattern, exhibited lumps 0.5 - 1.0 mil (12.7 - 25.4 μm) thick which appeared to be bacterial colonies. No visible slime was seen between the colonies. On disk T-6, which had an initial surface roughness k = 635.8 μ-inch (16.15 μm), no slime extended above the roughness ridge on the disk surfaces. Disks immersed for 10 days did not reveal any slime between the widely spaced small colonies.

Due to a lack of measured drag changes on these disks, an alternate approach was tried to artificially simulate slimes. Since the major component of slime is reported to be polysacchoride, disks T-2, T-4, and T-7 were slimed by dipping them in agar solution (2-percent) kept at 60 - 70 deg C, and then rotating them while allowing cooling to occur. This resulted in disk films of 2 to 3 mils (50.8 to 76.2 μm) average thickness and local patches of up to 5 mils (12 μm) thickness. During the experiment disk T-4, having an initial surface roughness of k = 393.3 μ-inches (9.99 μm), with closely crosshatched machined roughness, as shown in Figure 2, seemed to retain polysacchoride gel in the grooves. The rotating disk torque data for the polysacchoride gel demonstrated no significant change in drag as seen in Figure 8.

## DRAG OF NATURAL SLIME WITH YOUNG BARNACLES (SPATS)

Disks T-3, 5 and 8 were immersed at Annapolis in June over the sea - wall near the mouth of the Severn River in a salt water environment for 2 weeks. Growth on these disks consisted of brown colonial algae, slime, and young barnacles (spats).

The barnacle sizes ranged up to about 15 mils (381 μm). The smaller barnacles, sizes determined by a 30x microscopic examination, were covered with slime within some of the hills in the slime layer and the larger barnacles protruded through the slime.

The film thickness was measured before testing by the light section method in regions not occupied by barnacles. Disk rotation removed nearly all of the colonial algae from the disk, and a nearly clear gel-like slime layer remained, together with spat barnacles. Slime film thicknesses were also measured after the completed experimental run. The film thicknesses on disks, T-3, T-5, and T-8 are given in Table 2.

The drag effect of the residue slough-off was accounted for by scrubbing and testing the disks in clean water and water containing the residue slough-off respectively.

Torque measurements on disks T-3, 5 and 8 indicated large incremental drag increases over the reference disks. The torque data are shown graphically in Figures 9, 10, and 11 with a photographic presentation and in Tables 3, 4 and 5. The data for disk T-3, a smooth disk, shown in Table 3 and Figure 9, includes a condition in which the barnacles were removed from the disk because the data with barnacles give no direct measure of slime drag. The barnacles were only removed to the extent that visual observation permitted and the barnacle adhesive substance could have remained attached to the disk. Figure 9 shows that the drag was still higher than that of the clean disk.

TABLE 2 - THICKNESS OF NATURAL SLIME ON TITANIUM DISKS

| Disk/Side | Before Torque Measurement | | | | After Torque Measurement | | | |
|---|---|---|---|---|---|---|---|---|
| | Layer between hills | | Hills | | Layer between hills | | Hills | |
| | Mil | µm | Mil | µm | Mil | µm | Mil | µm |
| T-3/1 | 1-6 | 41 | 6-10 | 152-254 | 1.2 | 31 | 3 | 76 |
| T-3/2 | 3-6 | 76-152 | 6-10 | 152-254 | 1.5-3 | 38-76 | 3 | 76 |
| T-5/1 | 0.5 | 13 | up to 8 | up to 8 | 0.25 | 6.4 | 0.5-1.5 | 13-38 |
| T-5/2 | 0.5 | 13 | 5-6.5 | 127-165 | 0.5 | 13 | 1.5 | 38 |
| T-8/1 | 3-6 | 76-152 | up to 8 | up to 8 | 1.5 | 38 | 3-4 | 76-102 |
| T-8/2 | 3 | 76 | 5-9 | 13-229 | 2-3 | 51-76 | 4-8 | 102-203 |

## TABLE 3 - TEST CONDITION AND RESULTS, DISK T-3

Clean Disk

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 901 | 0.677 | 13.337 |
| 1021 | 0.664 | 15.113 |
| 1496 | 0.624 | 22.144 |
| 1939 | 0.604 | 28.701 |
| 2032 | 0.594 | 30.077 |

Slime with Barnacles

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 779 | 0.853 | 11.665 |
| 1021 | 0.800 | 15.289 |
| 1496 | 0.754 | 22.402 |
| 1939 | 0.722 | 29.036 |
| 2032 | 0.713 | 30.429 |

Scrubbed Disk in Test Residue

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 901 | 0.663 | 11.665 |
| 1021 | 0.649 | 15.644 |
| 1496 | 0.606 | 22.823 |
| 1939 | 0.576 | 29.711 |
| 2032 | 0.572 | 31.136 |

Slime with Barnacles Removed

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 779 | 0.737 | 13.806 |
| 901 | 0.716 | 13.492 |
| 1021 | 0.702 | 15.289 |
| 1496 | 0.659 | 22.402 |
| 1939 | 0.629 | 29.036 |
| 2032 | 0.621 | 30.429 |

## TABLE 4 - TEST CONDITION AND RESULT DISK T-5

Clean Disk

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 1021 | 0.757 | 12.412 |
| 1496 | 0.718 | 18.186 |
| 1939 | 0.689 | 23.571 |
| 2032 | 0.684 | 24.702 |

Slime with Barnacles

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 779 | 0.952 | 11.396 |
| 901 | 0.933 | 13.181 |
| 1021 | 0.921 | 15.113 |
| 1496 | 0.873 | 22.144 |
| 1939 | 0.836 | 29.036 |

Scrubbed Disk in Test Residue

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 779 | 0.735 | 11.801 |
| 901 | 0.720 | 13.649 |
| 1021 | 0.712 | 15.467 |
| 1496 | 0.686 | 22.923 |
| 1839 | 0.655 | 29.171 |
| 2032 | 0.651 | 31.136 |

## TABLE 5 - TEST CONDITION AND RESULTS, DISK T-8

Clean Disk

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 901 | 0.700 | 13.492 |
| 1021 | 0.690 | 15.289 |
| 1496 | 0.656 | 22.402 |
| 1939 | 0.633 | 29.036 |
| 2032 | 0.628 | 30.429 |

Slime with Barnacles

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 779 | 1.209 | 10.997 |
| 901 | 1.175 | 12.720 |
| 1021 | 1.123 | 14.587 |
| 1496 | 1.052 | 21.374 |
| 1939 | 0.997 | 27.703 |

Scrubbed Disk in Test Residue

| RPM | $C_m \times 10^2$ | $R_R \times 10^5$ |
|---|---|---|
| 901 | 0.708 | 13.492 |
| 1021 | 0.698 | 15.289 |
| 1496 | 0.658 | 22.402 |
| 1939 | 0.632 | 29.036 |
| 2032 | 0.628 | 20.429 |

## DRAG OF THEAODACTYLUM TRICORNUTUM ALGAE SLIME

A Theaodactylum Tricornulum Algae was cultivated in the laboratory on disk T-1. The resulting surface slime had the same smooth appearance as a natural slime. The disk was then tested and the torque data are presented in Figure 12. At the maximum test rpm the disk was allowed to rotate for approximately 3 minutes to permit the sample slime to detach from the disk surface.

This slime seemed somewhat resistant to detachment. The data were then taken at 3 minute intervals at decreased rpm, and are shown in Figure 12 as data 1, 2, and 3. When the data were referenced to a hydraulically smooth surface, the torque increases were approximately 23, 16, and 11 percent respectively. The slime was then removed from the disk surfaces. After cleaning the surfaces a fine white sand like roughness was found attached on the outer 20-percent radius of the disk. The average amplitude of the roughness was 130 μ-inches (3.3 μm). Therefore, the above mentioned initial increase in torque at maximum and decreasing values of rpm may have been due to removal of a portion of the slime by surface friction and subsequent exposure of the roughness. The added torque due to the roughness can be seen in Figure 12. Further investigation of Theaodactylum Tricornutum Algae slime is necessary before it can be used as a substitute for a natural slime.

## DRAG OF NATURAL SLIME WITH VEGETATION

Unpainted titaninum disks T-2, 5, and 6 were immersed at Annapolis in October in salt water near the mouth of the Severn River. The disks were carefully caged inside of plankton netting in order to protect the disks against barnacle attachment. At the end of the slime forming period, which lasted 30 days, the disk surfaces were free of barnacles, but a vegetable growth developed on the disk surfaces. A photograph of typical slime vegetation is shown in Figure 13.

For the purpose of this slime experiment, a hydraulically smooth disk and two rough disks were selected for sliming to evaluate the effect of slime on both smooth and rough surfaces. After the sliming process the disk surfaces were covered with lightly attached slime and residue. These disks were placed in the rotating disk apparatus and rotated at the maximum test rpm to allow the lightly attached slime and residue to slough-off. The water after the slough-off procedure was evaluated and found to have no effect on the torque values measured. The remaining slimes on all disk surfaces were measured by the light section microscope method and found to be approximately 1 mil (25.4 $\mu$m) thick, on the average, between vegetation areas.

For the purpose of the slime evaluation, the torque of a clean hydraulically smooth disk (disk T-0) was used as a reference to relate all surface roughness changes to a known surface condition. All data obtained in the disk surface evaluation were nondimensionalized and are presented in Figures 14, 15, and 16. The smooth surface disk (T-2) evaluation is shown in Figure 14. The disk surfaces with slime and vegetation give an approximate 23 percent increase in torque at a value of $R_R \sqrt{C_m} = 1.5 \times 10^5$. When the slime and vegetation were removed the torque of the smooth surface disk coincided with the torque of the hydraulically smooth reference disk. Therefore, the surfaces of the hydraulically smooth slimed disk were not damaged during the sliming process. Figure 15 presents torque data for a rough disk (T-5) with a roughness average amplitude of 348.4 $\mu$- inches

(8.65 $\mu$m). At a value $R_R \sqrt{C_m} = 1.5 \times 10^5$ this rough disk surface, when cleaned, shows a torque increase of 18 percent due to the roughness of the surface when compared to the torque of a hydraulically smooth disk surface. At a value of $R_R \sqrt{C_m} = 1.5 \times 10^5$, when the disk surfaces were covered with slime and vegetation the torque was about 31 percent greater than the torque of a hydraulically smooth disk; therefore, the slime and vegetation increased the torque of the initially rough disk by about 13 percent.

The third disk, T-6, with an average amplitude roughness height of 635 $\mu$-inches (16.15 $\mu$m) was the roughest of the disks tested. When the torque values which are shown in Figure 16 are compared to the torque of the hydraulically smooth reference disk at $R_R \sqrt{C_m} = 1.5 \times 10^5$, the clean rough surfaces of disk T-6 is seen to increase the torque by 22 percent. When disk T-6 was covered with slime and vegetation the torque increased by 56 percent at a value of $R_R \sqrt{C_m} = 1.5 \times 10^5$ when referenced to a hydraulically smooth disk surface, and 34 percent higher when referenced to the clean initially rough disk.

The vegetation held its formation steadfastly throughout the test rotational speeds. The vegetation formation covered a substantial amount of the disk surfaces but the amount and size could not be determined. It is possible that the primary contribution to roughness-drag was due to the surface vegetation and not the slime. However, this possibility cannot be evaluated on the basis of the available data.

## DRAG OF NATURAL SLIME ON AN ANTIFOULING PAINT SURFACE

Two mild steel disks, P-2 and P-12, were painted with a Navy antifouling copper oxide base paint as described in Table 1. The disks were soaked in water for 10 days to determine the effects of soaking on the surface roughnesses. The average surface roughness measurements for the disks before and after soaking are given in Table 1.

The disks were then immersed at Annapolis in October near the mouth of the Severn River. The disks were removed after a slime accumulation period of 30 days. The disk surfaces appeared to be covered by two layers of slime with embedded lumps. The lumps were not identified but were determined not to be barnacles or vegetation growth when examined under a microscope.

Each of the two disks were run in the rotating disk apparatus at the maximum test rpm for approximately 3 minutes to remove any lightly attached matter. Torque measurements in Figure 17 were then taken. After testing the disks with slime the disks were removed from the apparatus to inspect the surfaces for surface irregularities and to measure the thickness of the remaining slime. A general visual inspection of the disks' surfaces revealed areas in which the paint surface may have been cracked. If cracks were present they could have caused the paint to flake or blister. However, it could not be determined if this did in fact happen during the experiment. The average slime thicknesses measured using 6 measuring point were disk P-2, 0.64 mils (16.26 $\mu$m) and disk P-12,1.2 mils (30.48 $\mu$m).

Following the slimed-disk experiments, the slime was carefully removed by hand scrubbing so that any paint flaw would remain on the surface. During the the slime removal process no barnacles or vegetation were attached. The disks were returned to the rotating disk apparatus and torque measurements were made.

These data are also reported in Figure 17. A curve representing the torque produced by a smooth surface disk (T-1) is shown to relate the torque increase to a known reference disk. These data show that a marked increase in drag may be caused by slimed surface coatings. At the points on the curves where $R_R \sqrt{C_m} = 2 \times 10^5$ there is approximately a 52-percent increase in torque, for disk P-2 and 58-percent increase in torque for disk P-12, when referenced to a smooth surface. When the slimed disk torques are referenced to painted surface torques, the increase in torque is 11 percent for disk P-2 and 42 percent for disk P-12. If it is assumed that paint flaking and/or blisters did not affect the torque it would appear likely that surface waves were formed in the slime during disk rotation. If the heights of the slime waves are less than the heights of the initial surface roughness, surface drag may be largely governed by the initial surface roughness. Conversely, if the heights of slime waves are greater than the heights of the initial surface roughness, then the waves may largely control the surface drag. However, the previously mentioned uncertainties concerning surface condition requires that additional experiments be conducted to definitively evaluate slime drag and its causes.

A $\Delta B$ correlation of roughness drag due to slime on the antifouling paint covered surfaces of disks P-2 and P-12 is presented in Figure 18. The values of $-\Delta B$ were computed in two iterations from equation (4) using the torque moment coefficients of a hydraulically smooth disk surface and the torque moment coefficients produced by the slime-covered disk surfaces.

# SUMMARY OF RESULTS AND CONCLUSIONS

Attempts to grown bacterial and algae slimes in the laboratory did not yield slime growth sufficiently rough to cause a significant effect on drag.

Immersion of disks in natural bay salt water that resulted in barnacles and/or vegetation growth resulted in a significant increase in measured drag. It was shown that when the barnacles were removed from the slime of a smooth disk, the disk gave approximately 2 percent higher torques than a clean smooth disk; this torque increase may be the result of roughening of residual slime or unremoved barnacle cement. The disks with only vegetation and slime on the surfaces showed a significant increase in drag, but it is possible that the primary contribution to roughness-drag was due to the surface vegetation and not the slime.

Exposure of two disks covered with antifouling paint, to salt bay water, produced thin slime layers considered free of barnacles and vegetation growth. The disk surfaces appeared to be covered by two layers of slime with embedded lumps. The thin layers remained attached to the disks and gave 52-percent increase in torque for disks P-2 and 58-percent increase in torque for disk P-12, when referenced to a smooth surface. When referenced to their own painted surfaces, the increase in torque is 42-percent for the rougher disk and 11 percent for the smoother disk. It is possible that paint flaking and/or blisters affected the torque measurements. However, it is also possible that surface waves, which increase surface drag, are being formed in the slime. If the heights of slime waves are less than the heights of initial surface roughness, surface drag may be largely governed by the initial surface roughness.

Conversely, if the heights of slime waves are greater than the heights of initial surface roughnesses, then the waves may largely control the surface drag. A definitive evaluation of slime-induced drag and the possible existence and character of surface waves should be the subject of future investigations. On the basis of the available data, it is not possible to conclude definitively that slime, by itself is a significant source of drag.

## ACKNOWLEDGEMENTS

The authors appreciates the guidance given by Dr. T. T. Huang and D. Laster when analyzing the data presented here.

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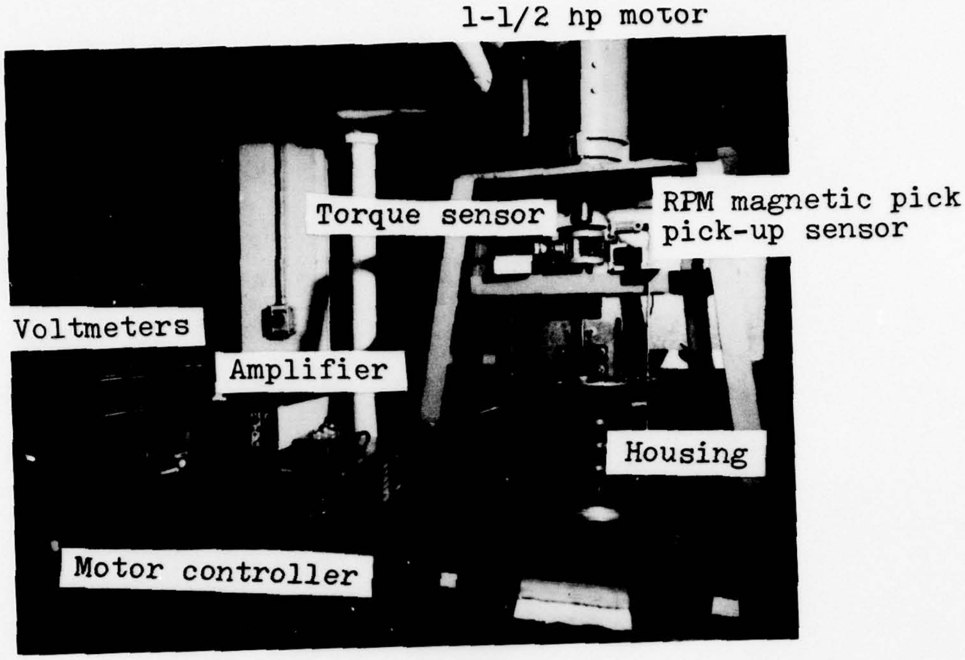
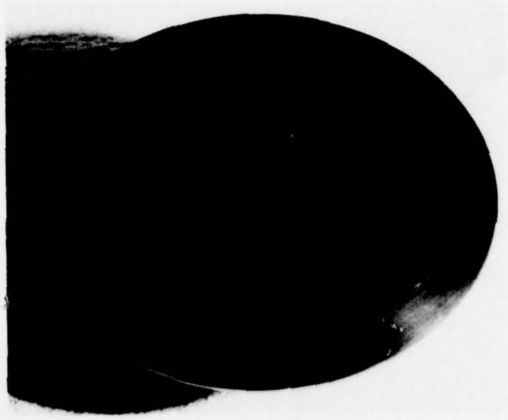
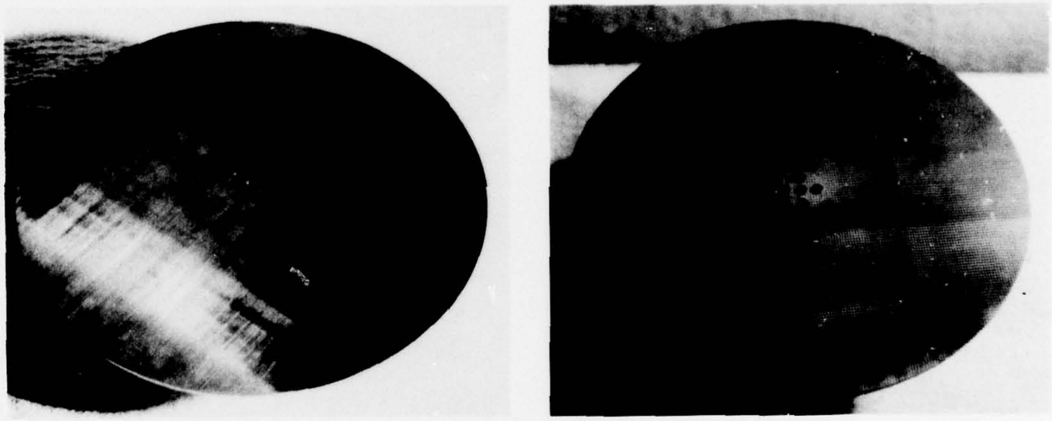


Figure 1 - Photograph of Test Set-up For Measuring Rotating Disk Torque



Smooth Pattern



Close Crosshatch Pattern

Wide Crosshatch Pattern

Figure 2 - Photographs of Titanium Disks and Roughness Patterns

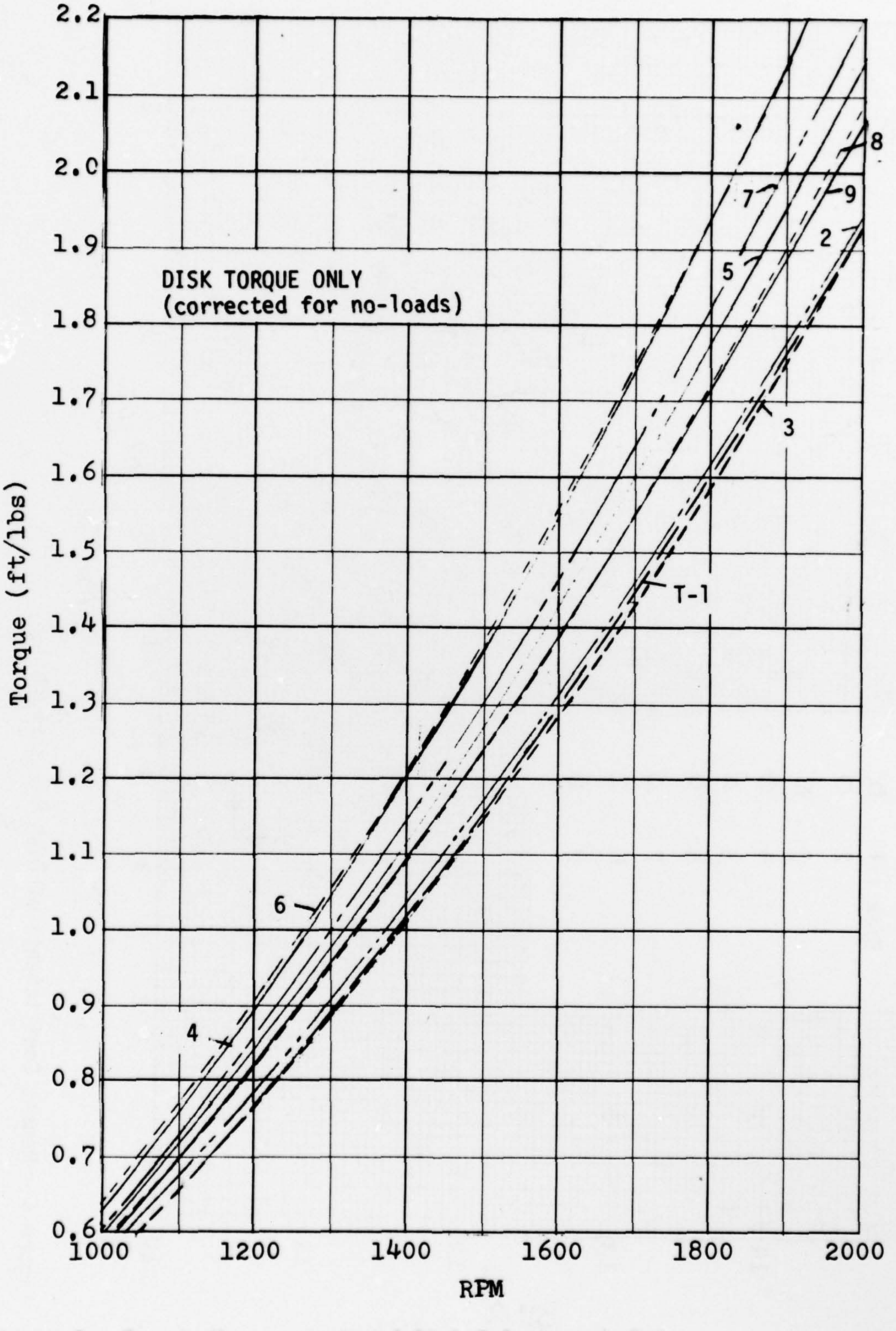


Figure 3 - Torque Measurements of Disk T-1 through T-9

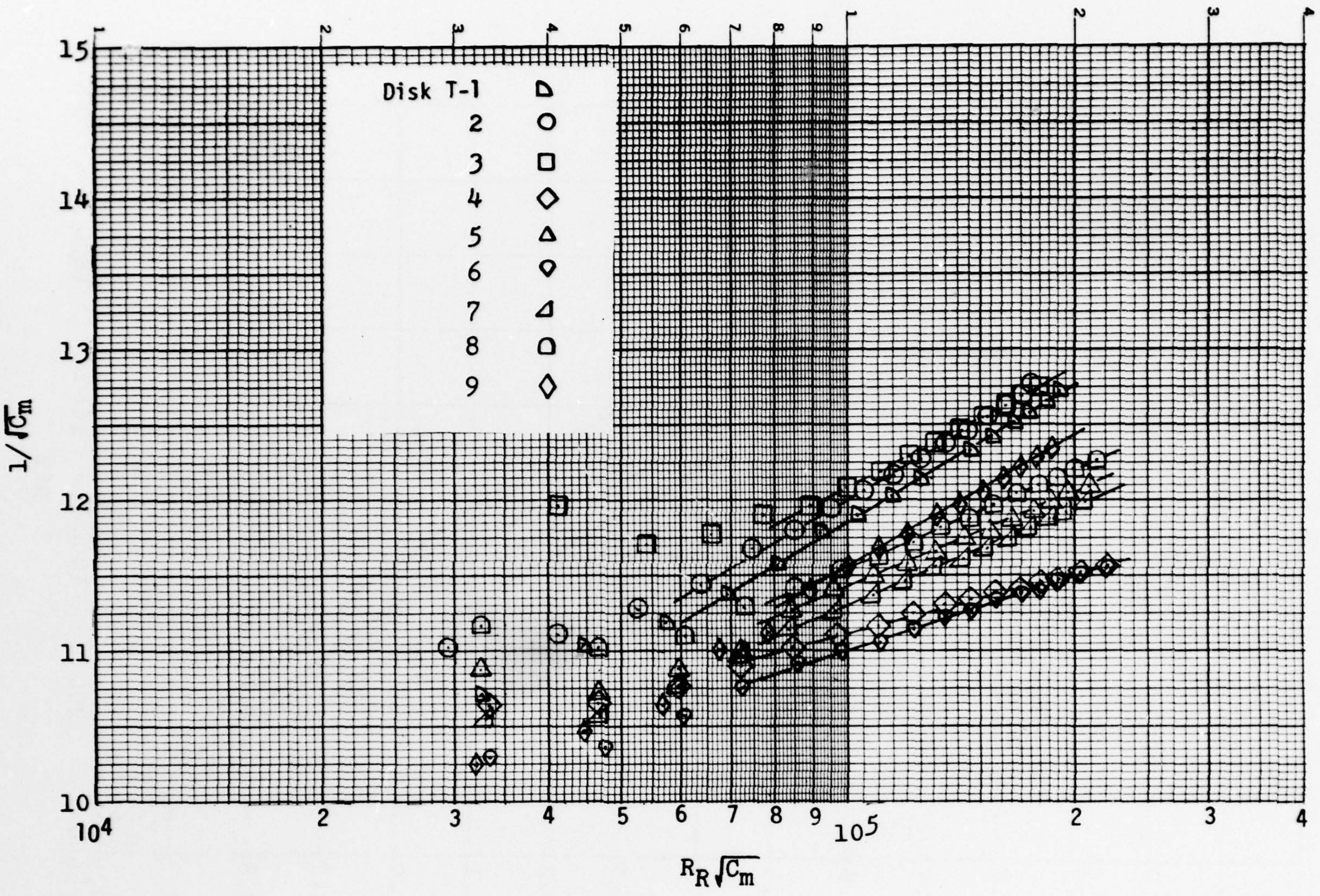


Figure 4 - Monent Coefficients of Disk T-1 through T-9

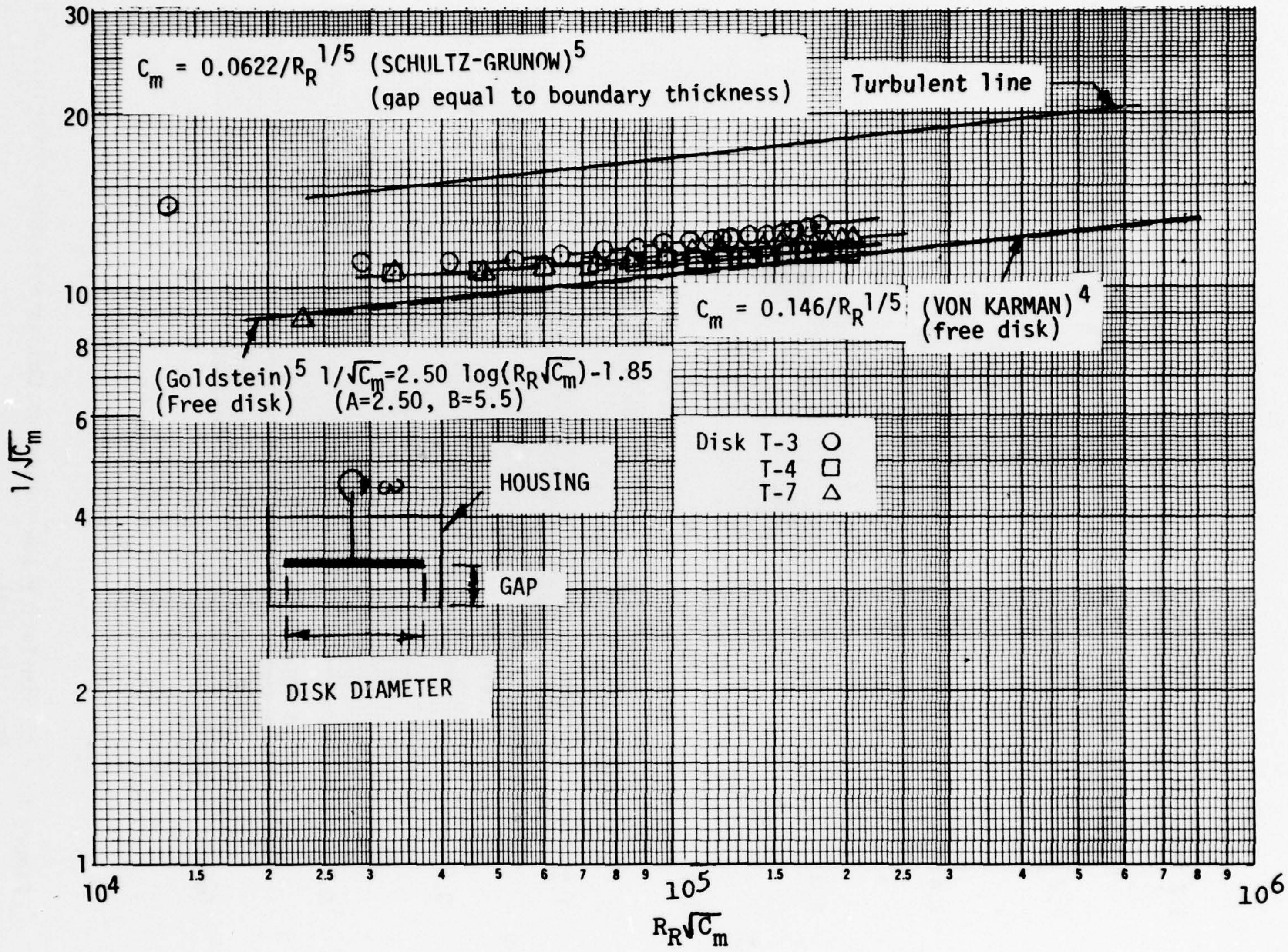


Figure 5 - Gap and Housing Diameter Effect on the Moment Coefficients for the Rotating Disk with Turbulent Flow.

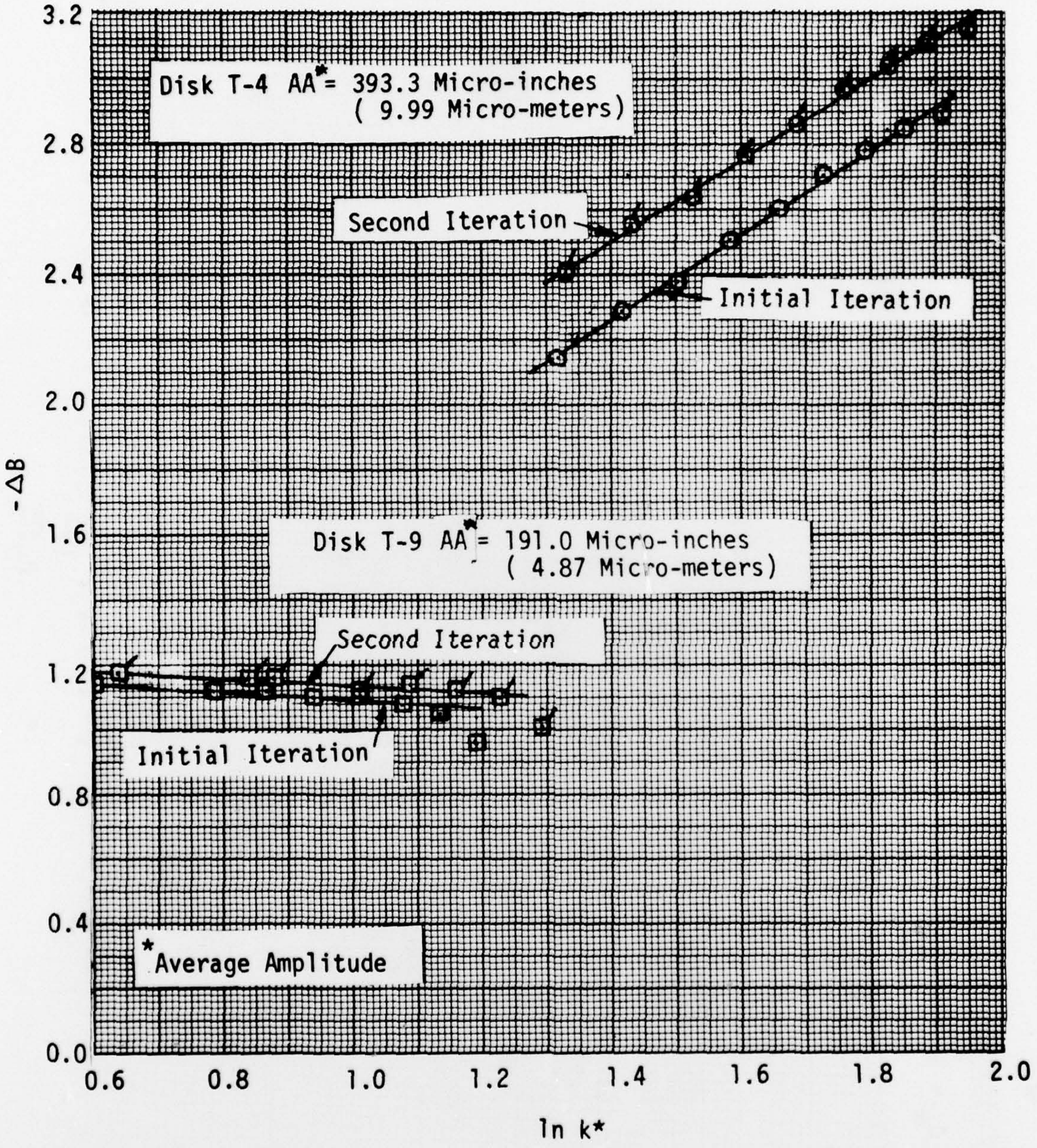
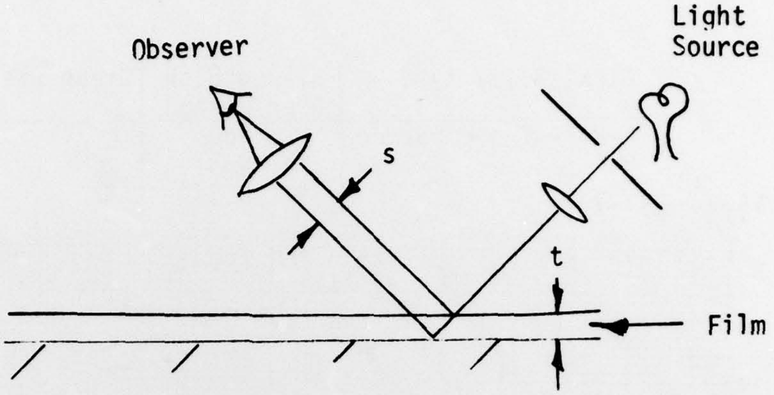


Figure 6 - $\Delta B$ Similarity-Law Roughness Characterization Correlation from Rotating Disk



$s \sim t$ - Separation of reflected images, s, is proportional to the film thickness, t.

Figure 7 - Transparent Film Thickness Measurement Technique

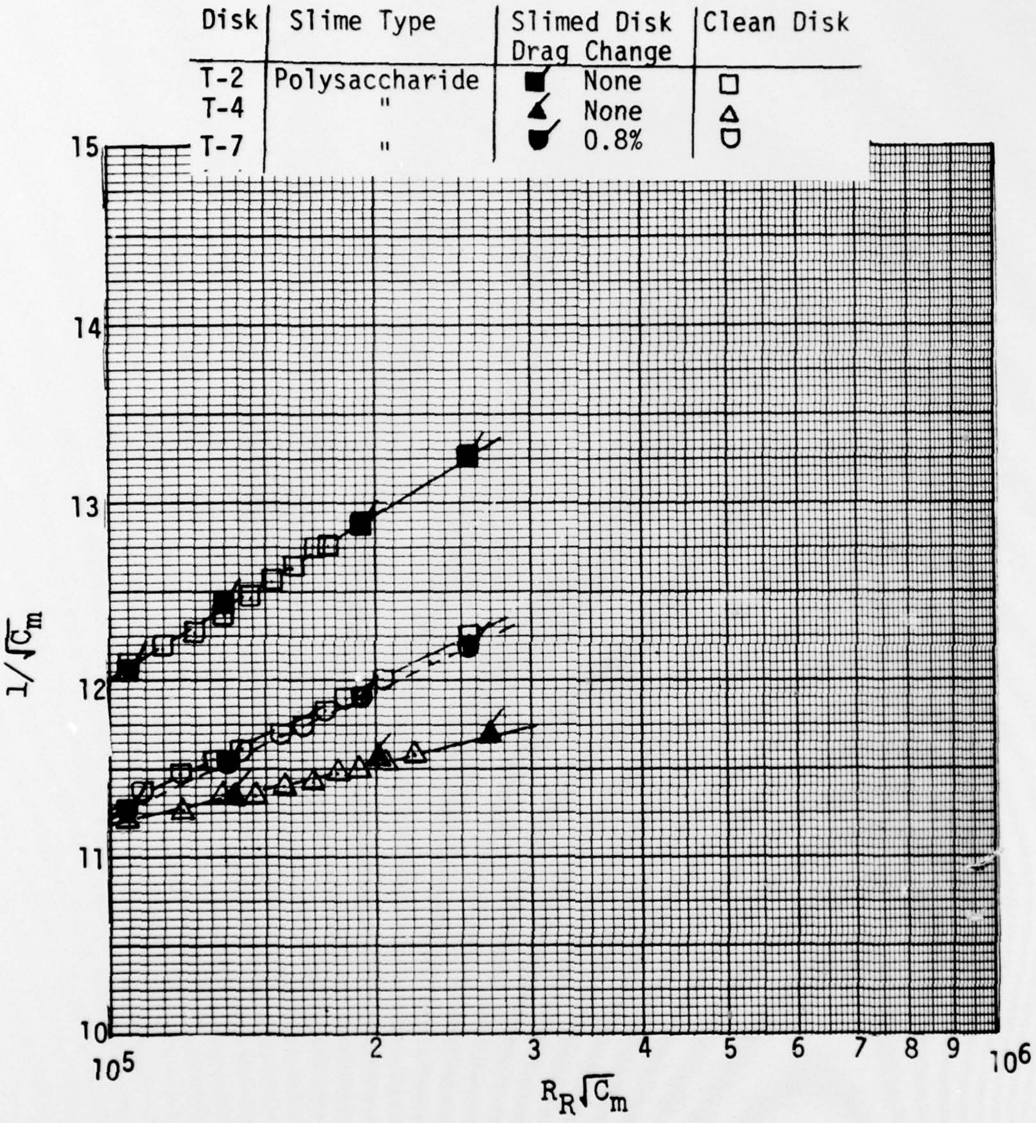
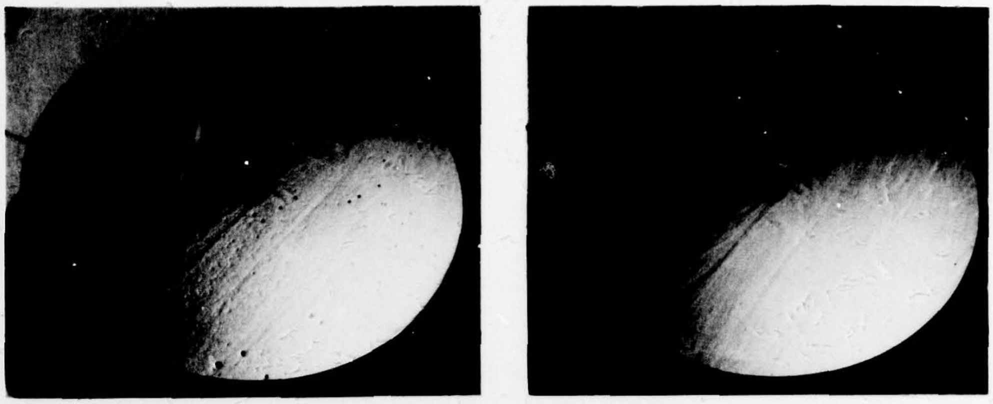


Figure 8 - Drag Effect of Synthetic Slimes on Rough and Smooth Disk Surfaces



With Barnacles Barnacles Removed

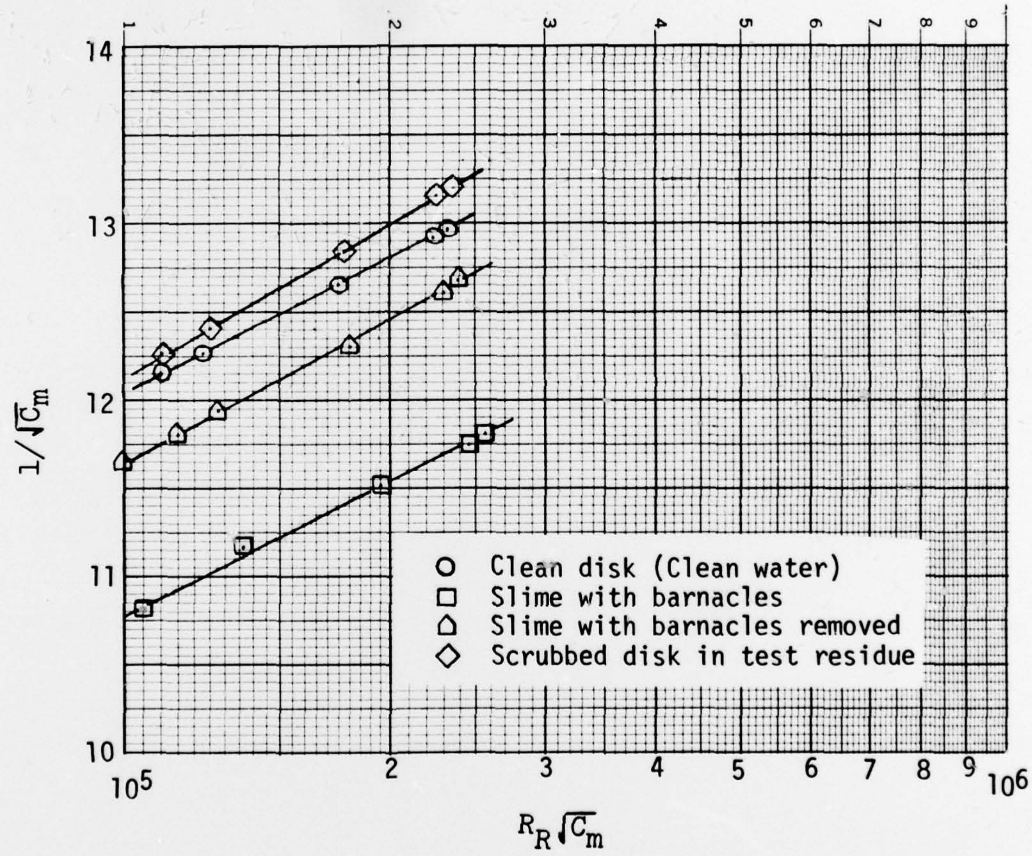
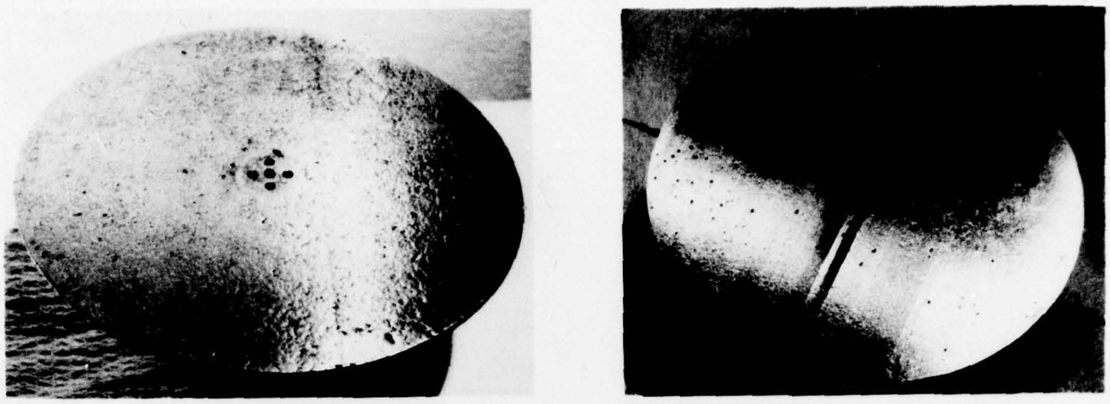


Figure 9 - Drag Effect of Natural Slime with Barnacles and Barnacles Removed from a Smooth Surface - Disk T-3



Before Test

After Test

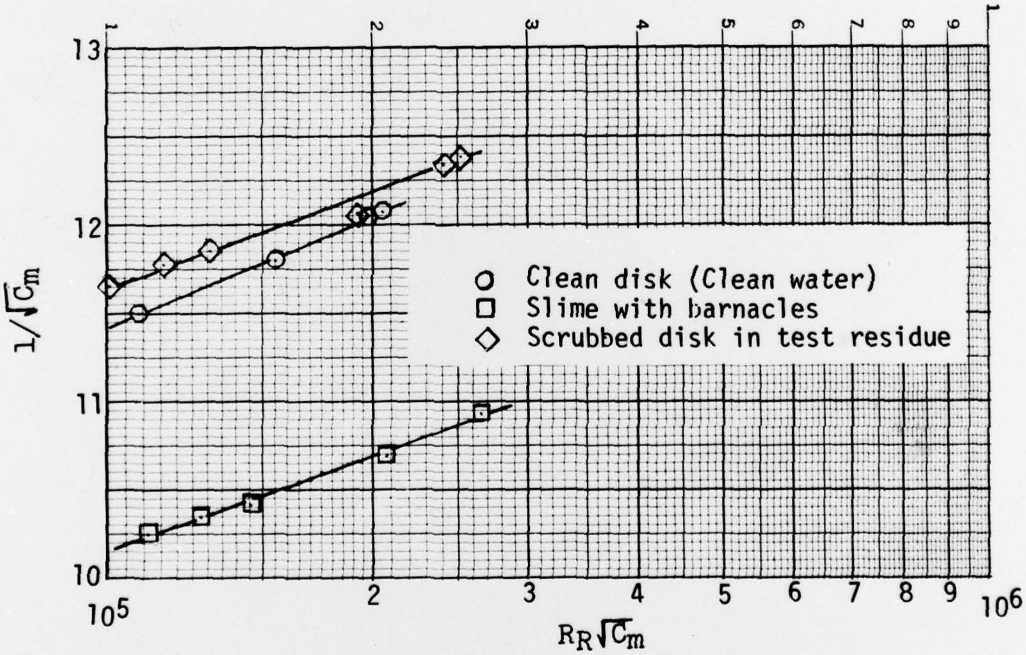
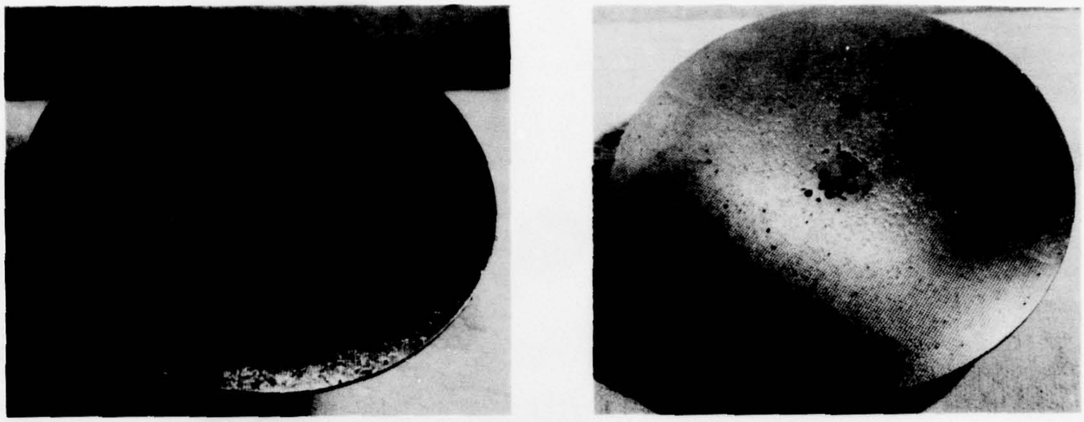


Figure 10 - Drag Effect of Natural Slime with Barnacles on a Rough Surface - Disk T-5



Before Test

After Test

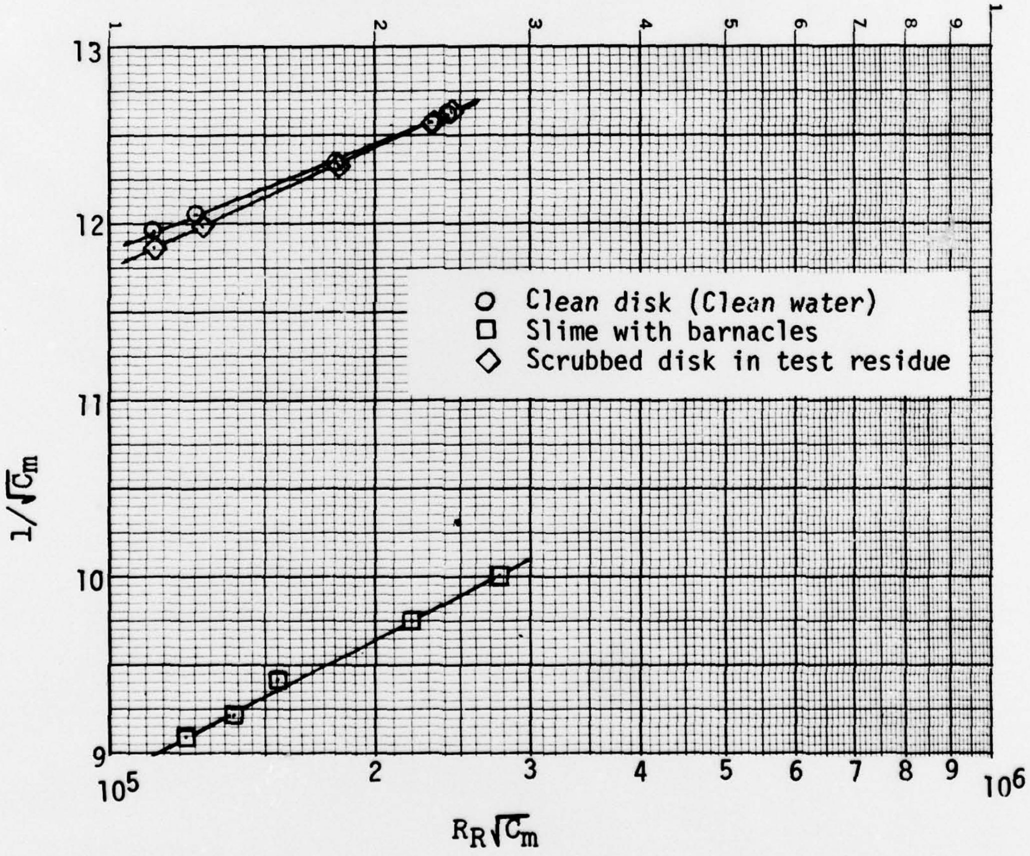


Figure 11 - Drag Effect of Natural Slime with Barnacles on a Rough Surface - Disk T-8

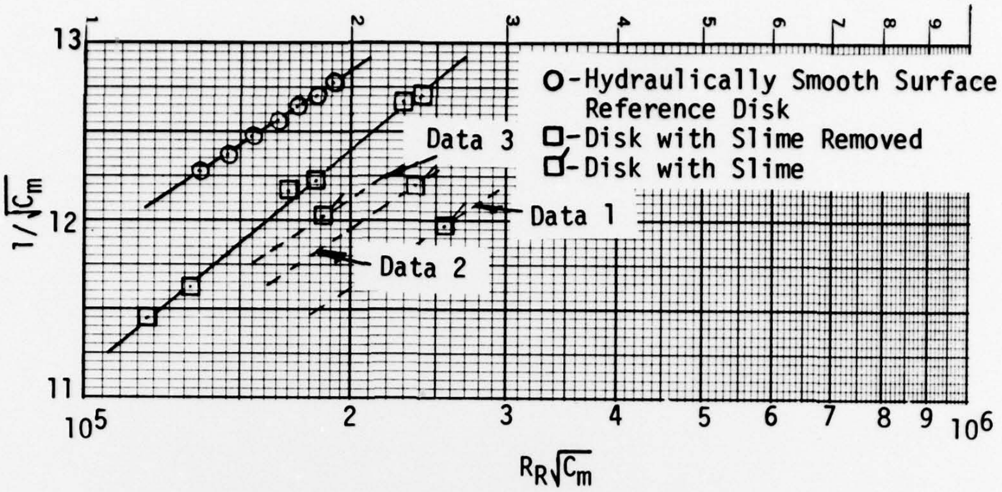


Figure 12 - Drag Effect of Theaodactylum Tricornutum Algae on a Smooth Surface - Disk T-1

Figure 13 - Photograph of Typical Slime Vegetation Growth Observed on the Titanium Disk Surface

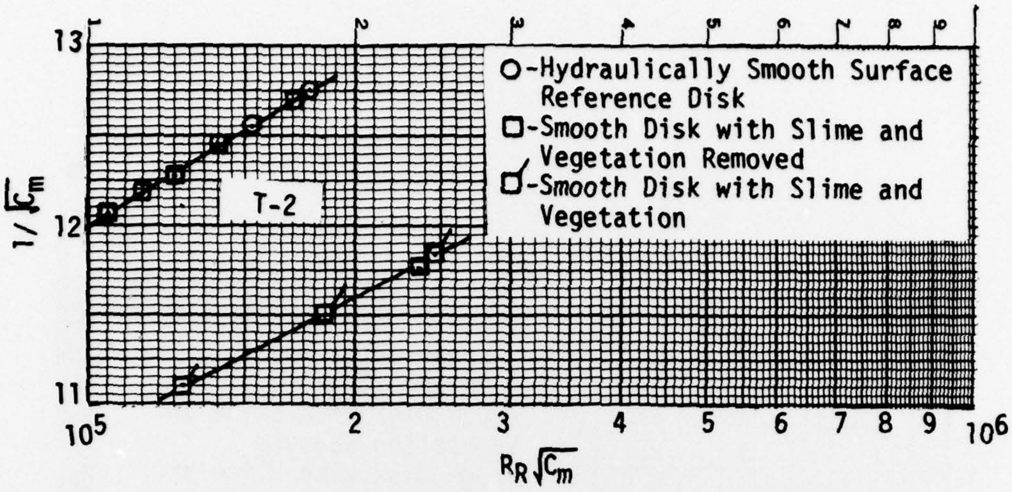


Figure 14 - Drag Effect of Natural Slime with Vegetation - Disk T-2

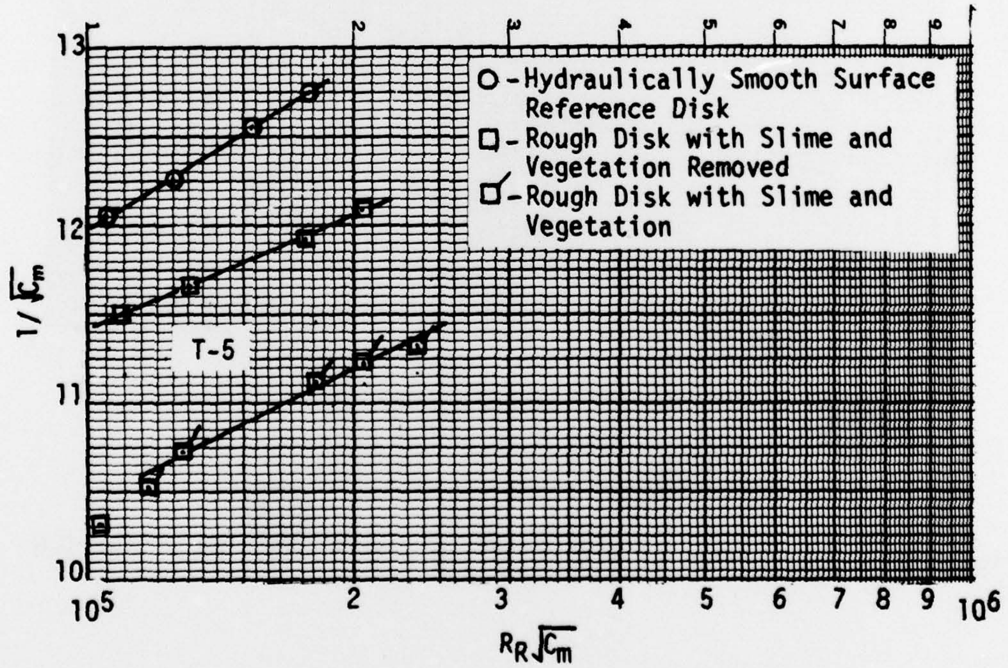


Figure 15 - Drag Effect of Natural Slime with Vegetation - Disk T-5

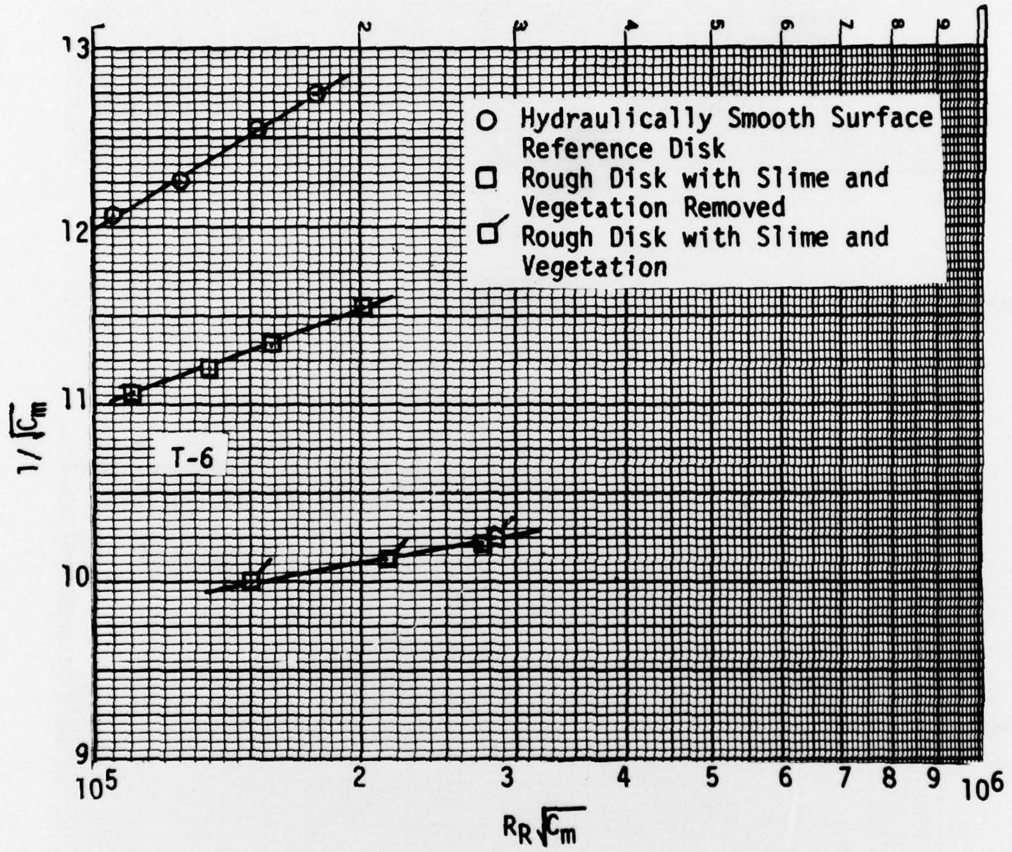


Figure 16 - Drag Effect of Natural Slime with Vegetation - Disk T-6

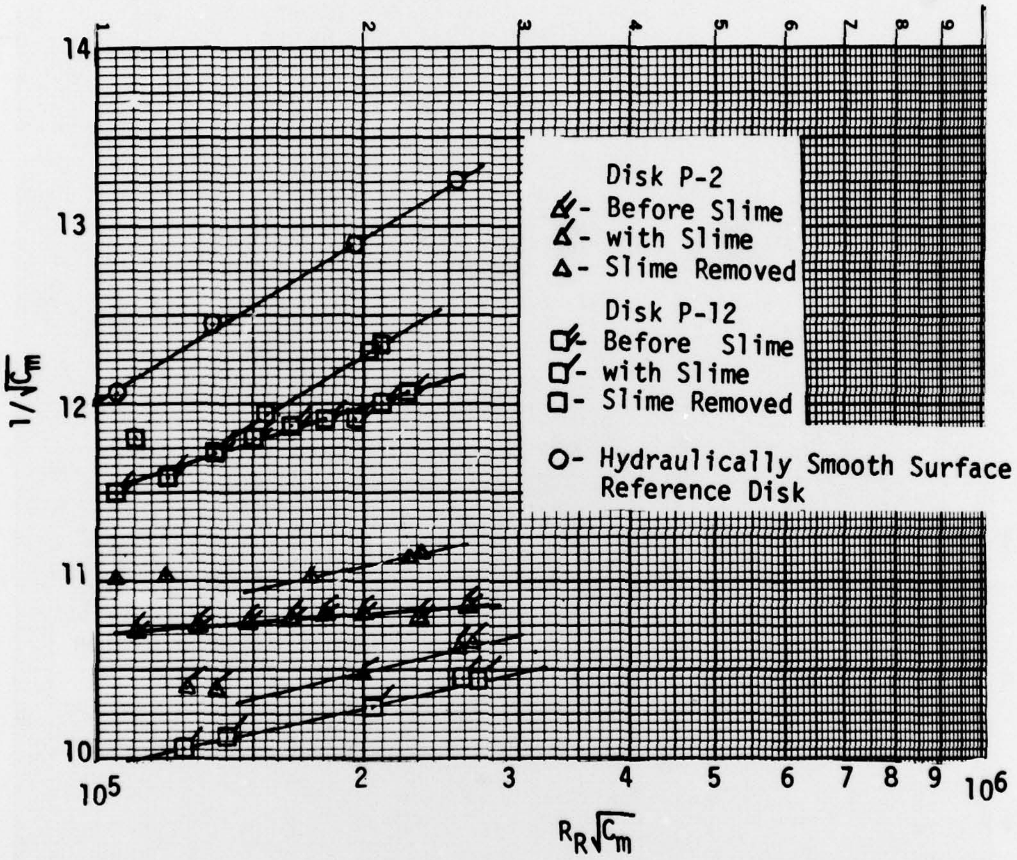


Figure 17 - Drag Effect of Natural Slime on Antifouling Paint Surfaces - Rough and Smooth Disk Surfaces.

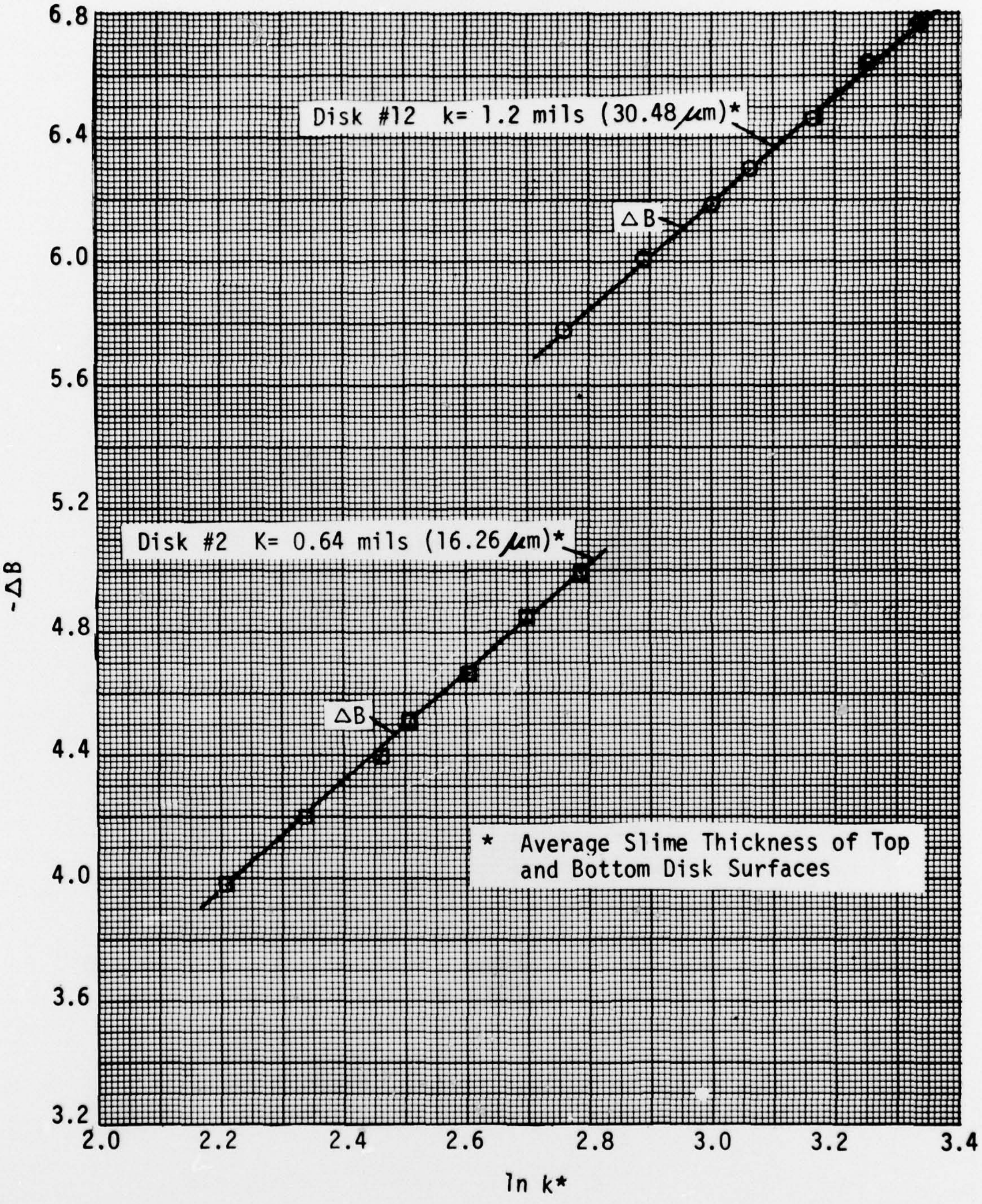


Figure 18 - Increased Disk Roughness Correlation Due to Slime on Antifouling Paint Surfaces Using ΔB Similarity-Law

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