Predicting the Drag on Ships with Biofouling

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Fundamental Issue

All surfaces are rough in the limit of high unit Reynolds number resulting in significant drag/performance penalties

FFG-7 at cruising speed – 15 kts

Description of Condition	ΔSP @ U_s = 7.7ms^{-1} (kW)	$\%\Delta SP$ @ U_s = 7.7ms^{-1}
hydraulically smooth surface	--	--
typical as applied AF coating	50	2%
deteriorated coating or light slime	250	11%
heavy slime	458	21%
small calcareous fouling or weed	781	35%
medium calcareous fouling	1200	54%
heavy calcareous fouling	1908	86%

Schultz (2007) *Biofouling*

Fundamental Issue

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Hull fouling results in increased fuel cost of $1 million per ship per year (2011)

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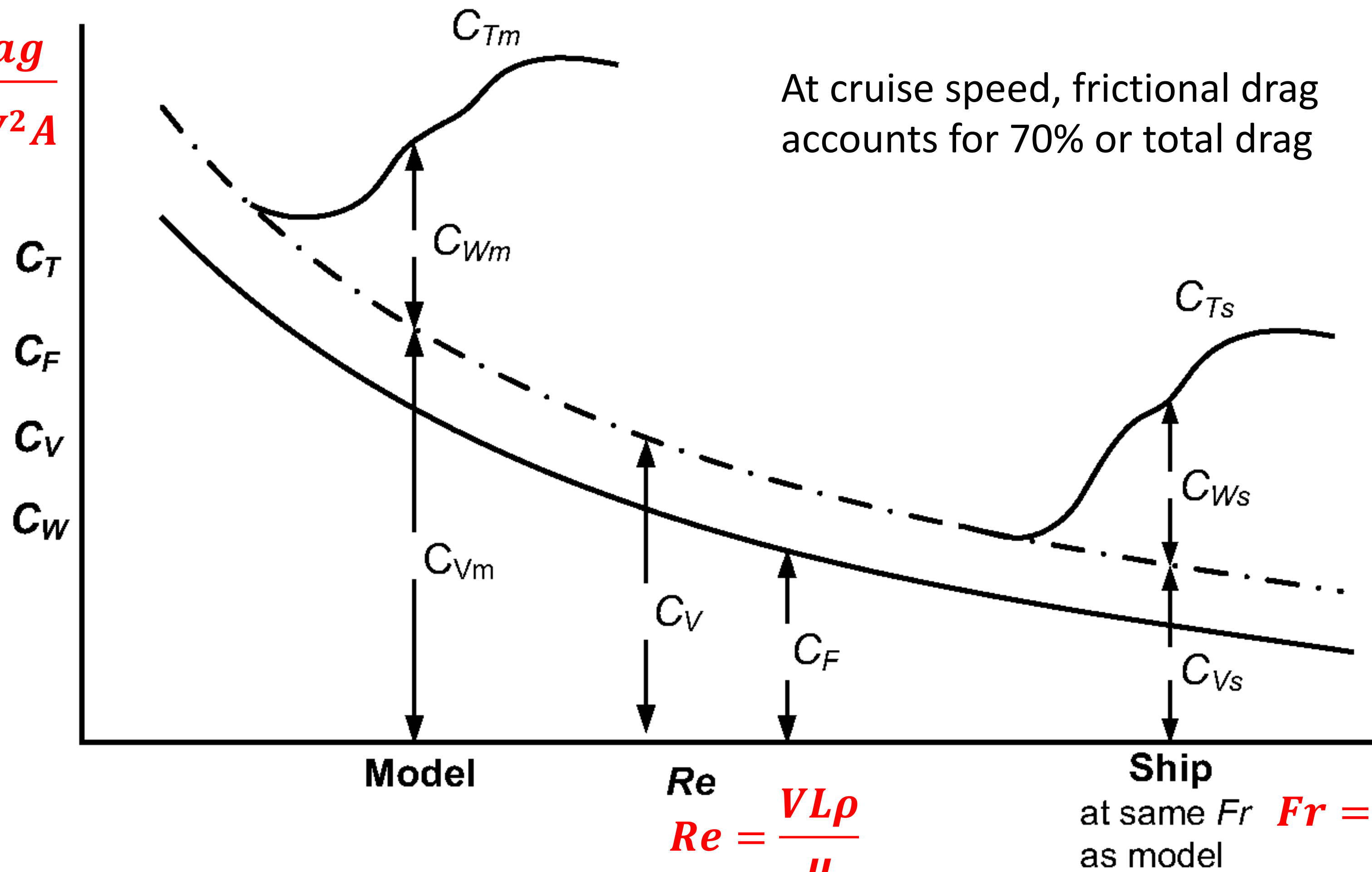
Schultz (2011) *Biofouling*

Accounting for Drag: Ship Resistance

$$C_T = \frac{Drag}{\frac{1}{2}\rho V^2 A}$$

At cruise speed, frictional drag accounts for 70% or total drag

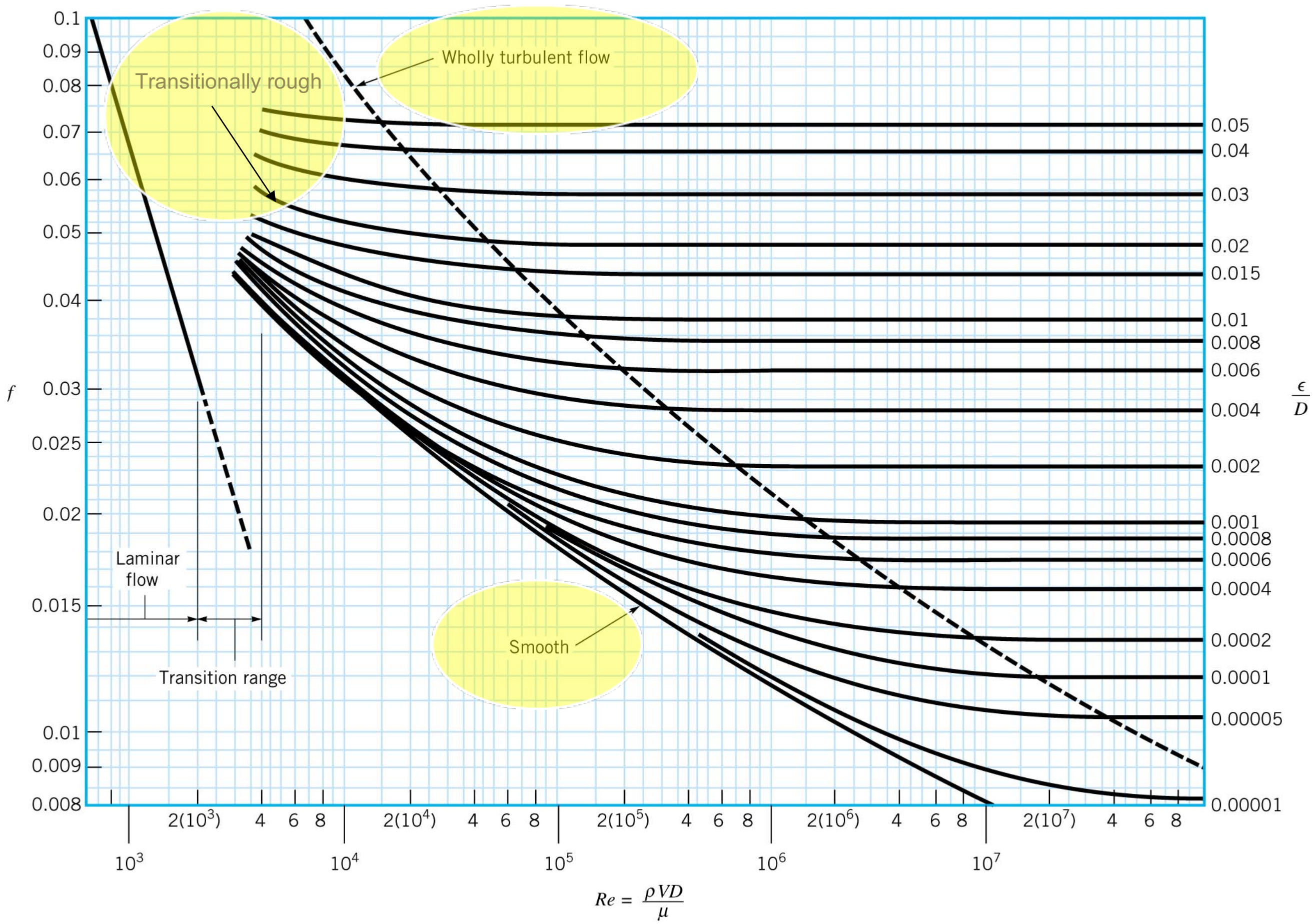


$$Re = \frac{VL\rho}{\mu}$$

$$Fr = \frac{V}{\sqrt{gL}}$$

Molland, *et al.* Ship Resistance and Propulsion, Cambridge University Press, 2017.

Accounting for Drag: Pipe Flow



Moody (1944), Colebrook (1939)

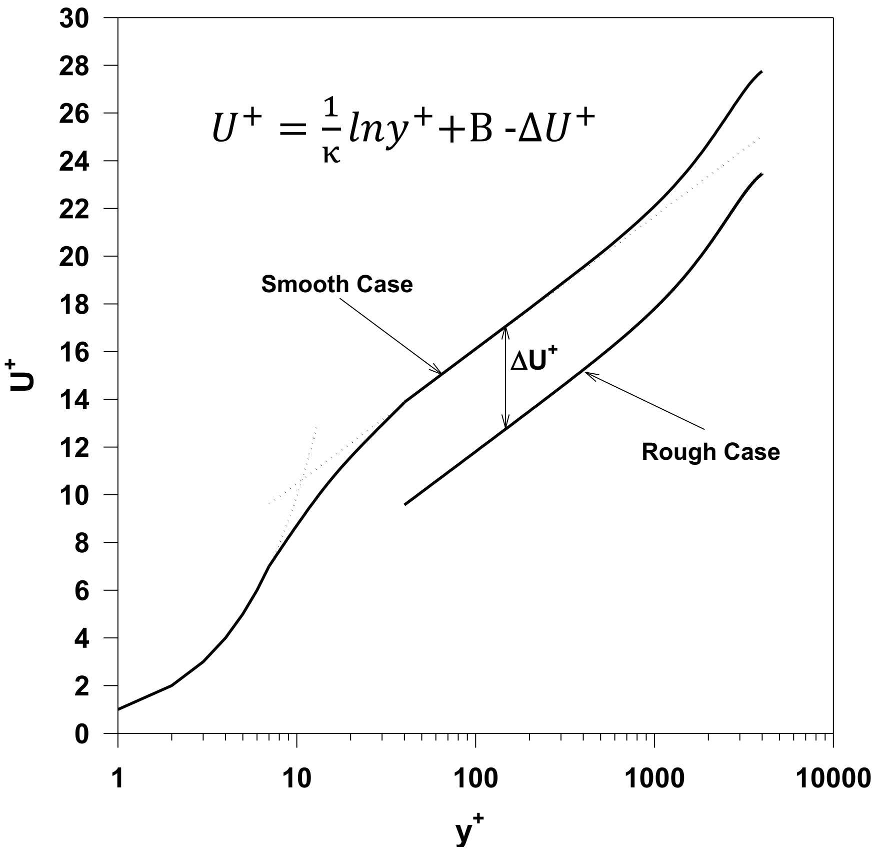
Pipe Material	Equivalent Roughness ε (mm)
Riveted steel	0.9 – 9.0
Concrete	0.3 – 3.0
Wood stave	0.18 – 0.9
Cast iron	0.26
Galvanized iron	0.15
Commercial steel	0.045
Drawn tubing	0.0015
Plastic, glass	0.0 (smooth)

$\varepsilon = k_s$

equivalent sandgrain roughness

Modeling Roughness/Predicting Drag

Turbulent boundary layer
velocity profile



$$U^+ = \frac{U}{U_\tau}$$

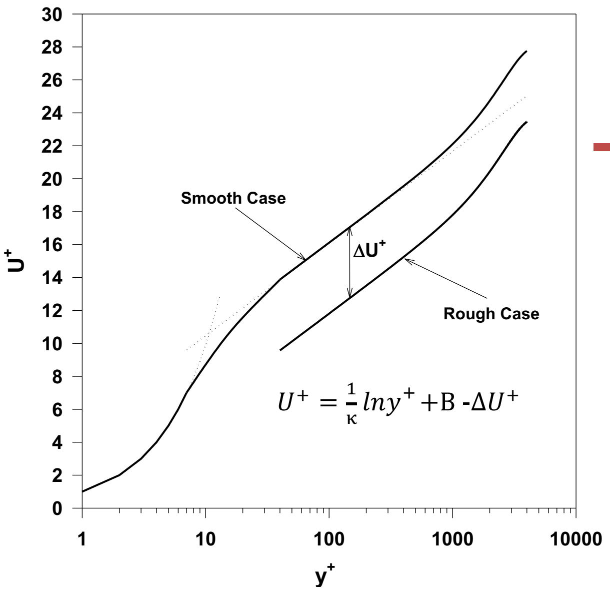
$$y^+ = \frac{yU_\tau}{\nu}$$

$$U_\tau = \sqrt{\tau_w/\rho}$$

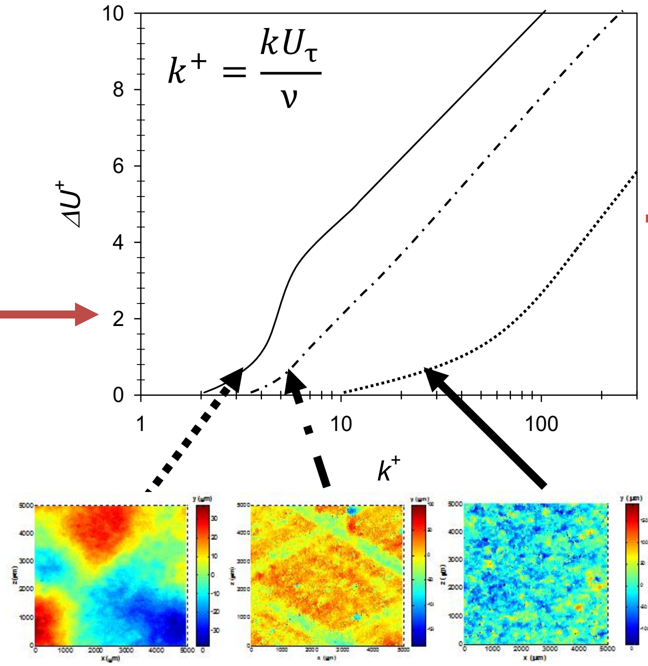
ΔU^+= Change in velocity due to drag from rough surface

Modeling Roughness/Predicting Drag

Turbulent boundary layer velocity profile



Roughness function



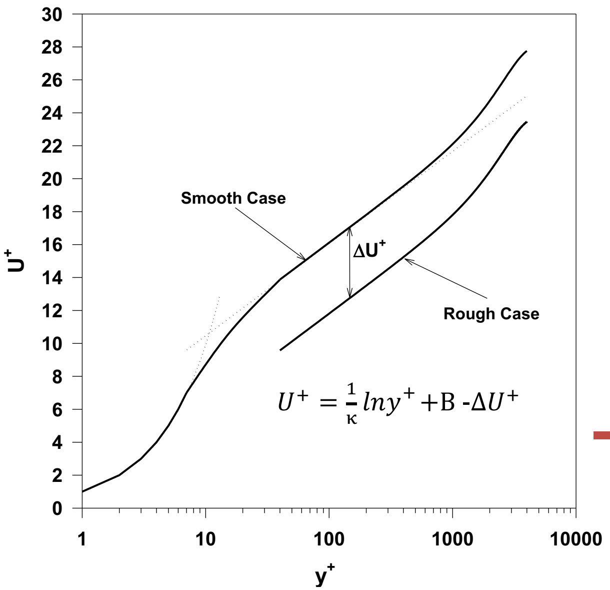
Valid for a specific roughness

$\Delta U^+ = f(k^+)$

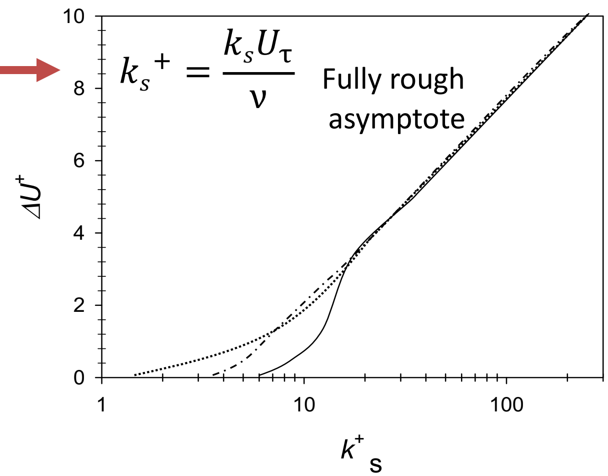
Computational models

Modeling Roughness/Predicting Drag

Turbulent boundary layer velocity profile



$$\Delta U^+ = \frac{1}{\kappa} \log k_s^+ + A - B$$



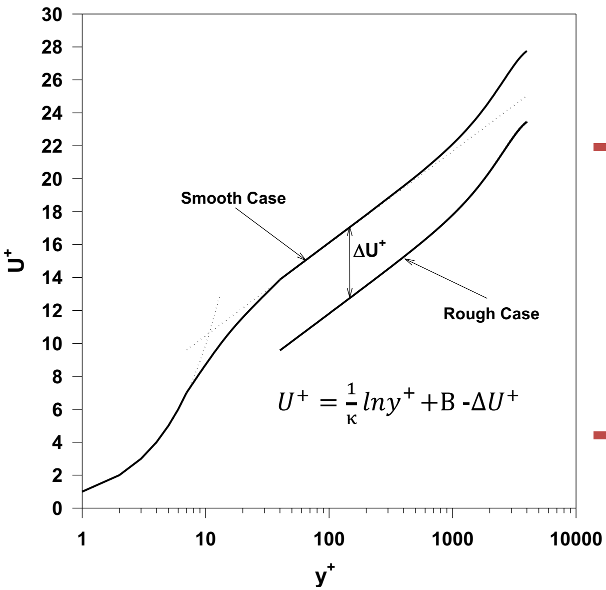
Computational models

$\Delta U^+ = f(k_s^+)$

Valid for any roughness in fully rough regime

Modeling Roughness/Predicting Drag

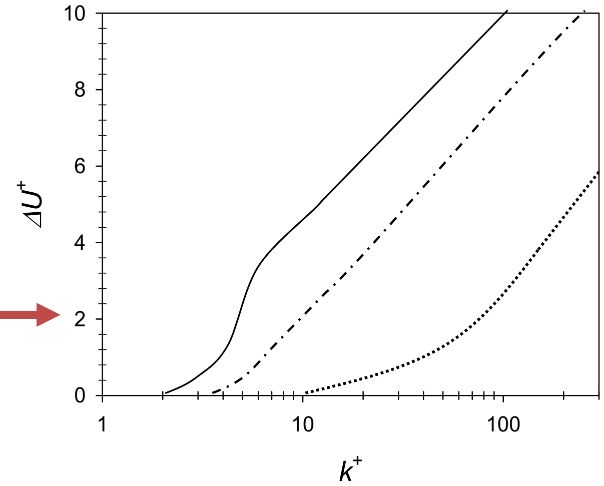
Turbulent boundary layer velocity profile

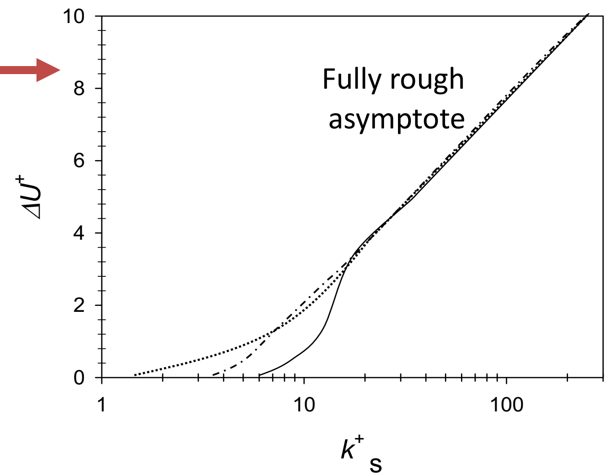


Lab Results to Full Scale

Moody Type Diagram

Roughness function





Valid for a specific roughness

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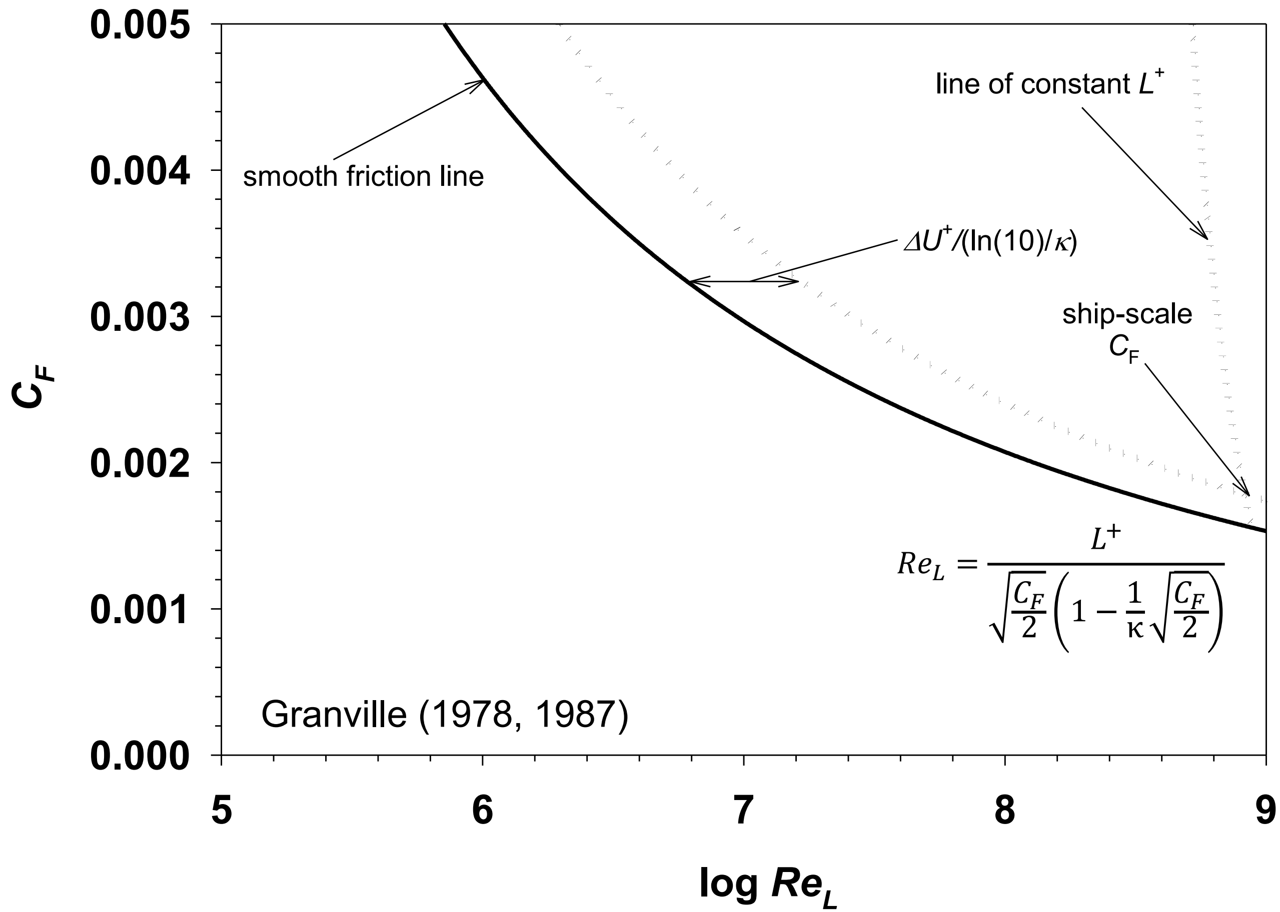
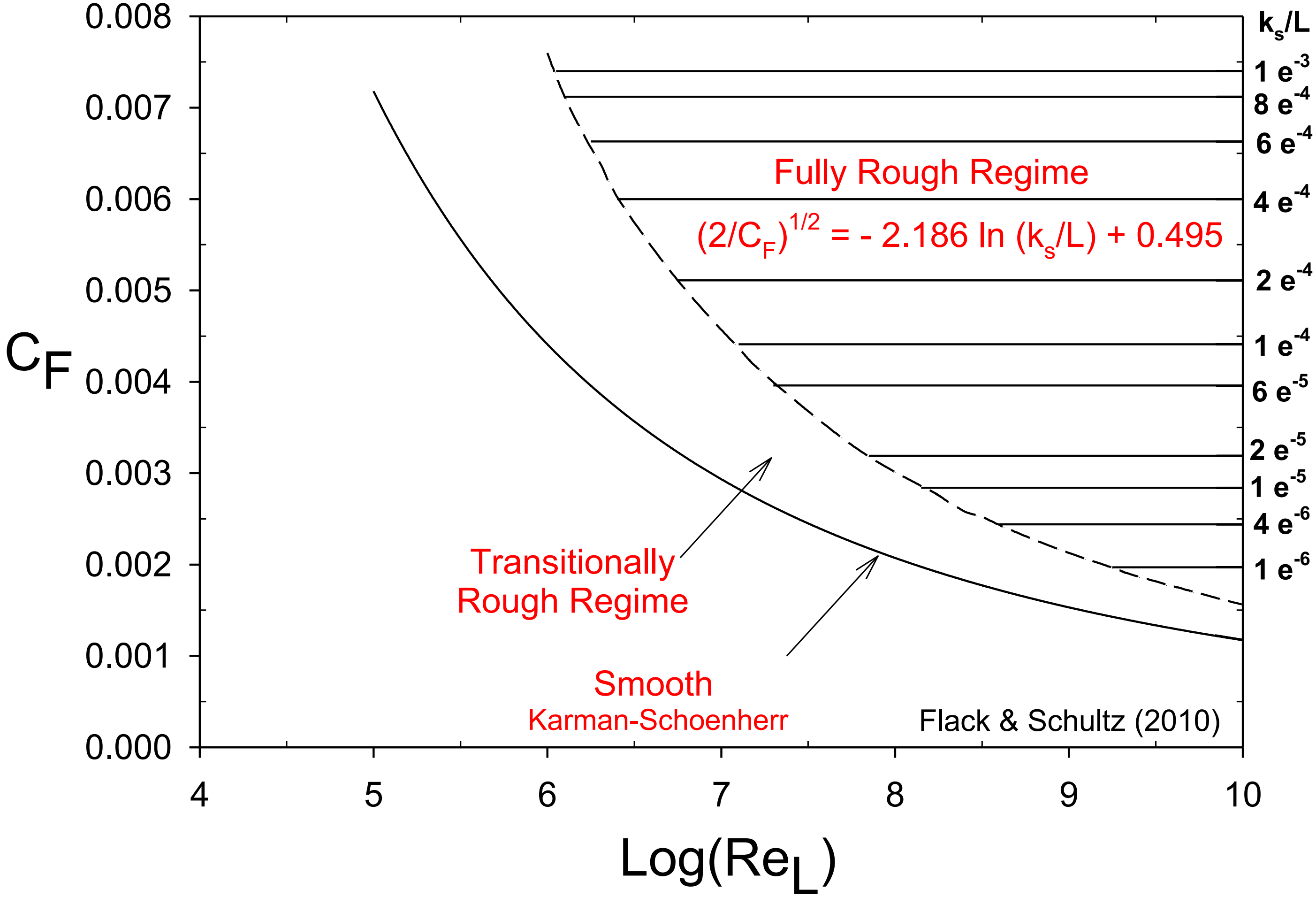
Modeling Roughness/Predicting Drag

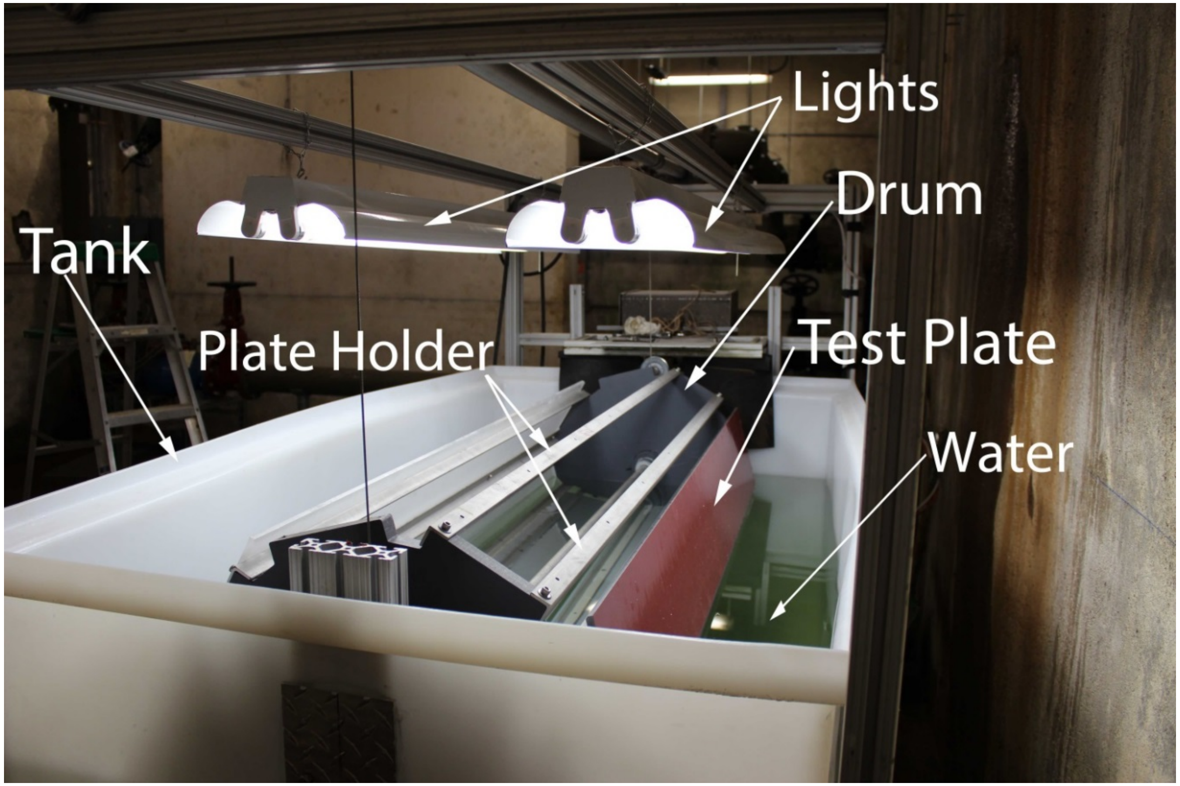


Lab Results to Ship Scale

Modeling Roughness/Predicting Drag



Biofilm Roughness



- 72” x 36” x 48” PE Tank
- horizontal axis rotation
- 24” diameter drum
- panel capacity - 8

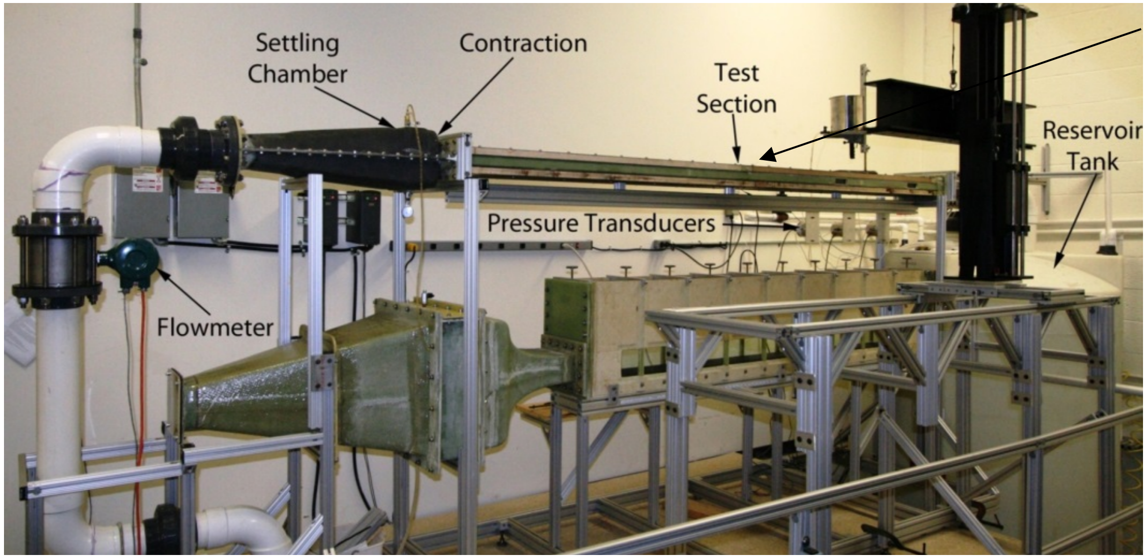
- test panels mount along the length of the drum
- rotational speeds of 60 & 120 rpm (4 & 8 knots)
- timed lighting (18h light / 6h dark) & temperature control (25º C)
- inoculated with diatoms collected from Florida bottom paints

Biofilm Roughness

Diatom genera present in biofilms: *Amphora*, *Achnanthes*, *Entomoneis* and *Navicula*

Designation	Description
Specimen A	Silicone Fouling-Release System
Specimen B	Fluoropolymer Fouling-Release System
Specimen C	Fluoropolymer Fouling-Release System (Slime Release)

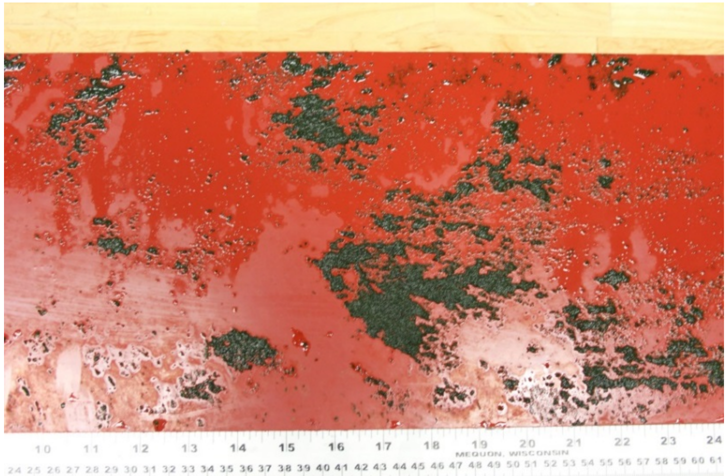
High Reynolds number channel



Bio-fouled plate on top and bottom wall

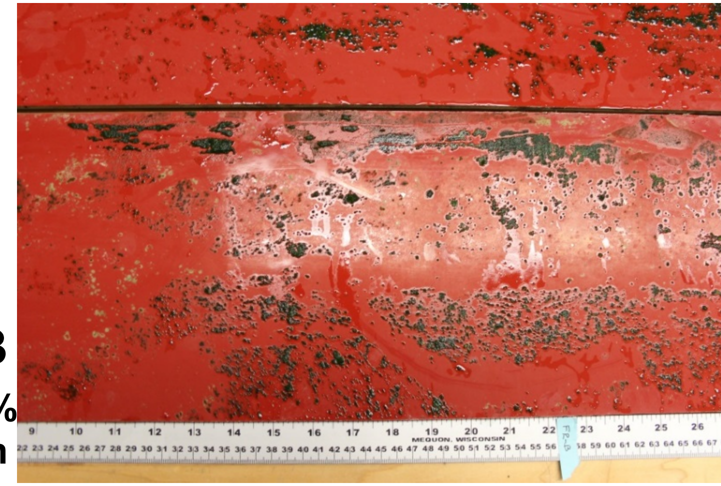
- 2.5cm (*H*) x 20.3cm (*W*) x 3.25m (*L*)
- U_e = 0.5 – 11.0 m/s
- $Re_m = 1.2 \times 10^4 - 3.1 \times 10^5$
- Re_τ = 350 – 6,100 (smooth wall)
- 90*H* Development Region
- 10 pressure taps in fully developed region (τ_w +/- 1%)
- 6 replicate runs

Biofilm Roughness



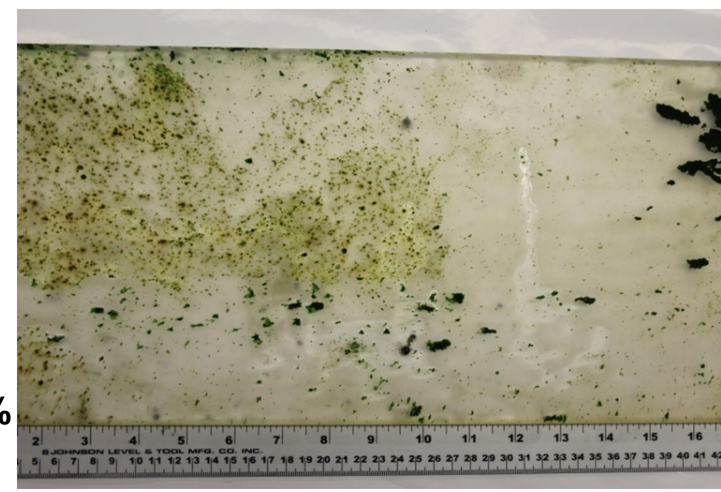
Specimen A
coverage = 19.6%
thickness, *k* = 545 μm

Specimen B
coverage = 11.8%
thickness, *k* = 433 μm



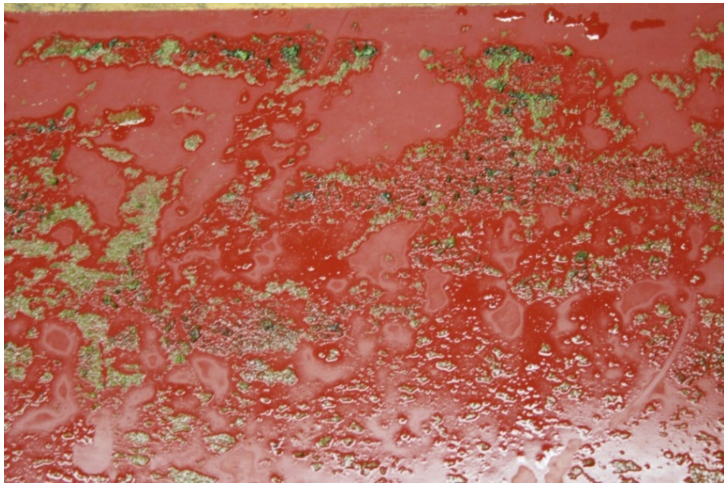
Specimen C
coverage = 6.4%
thickness, *k* = 574 μm

Acrylic Control
coverage = 18.1%
thickness, *k* = 527 μm



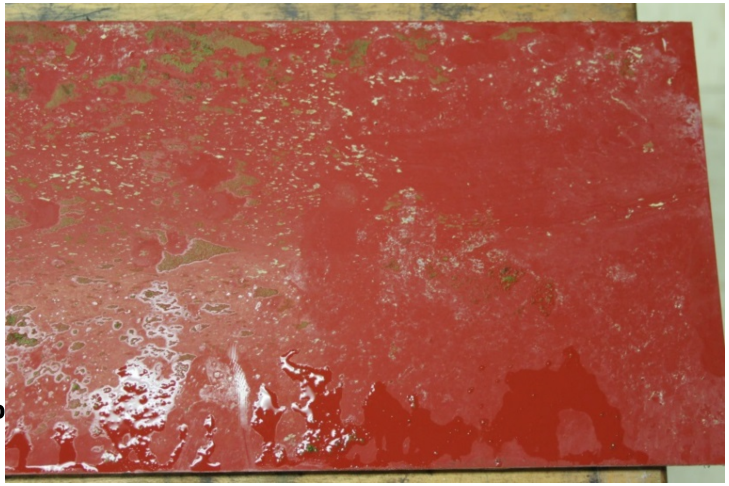
3 months exposure

Biofilm Roughness



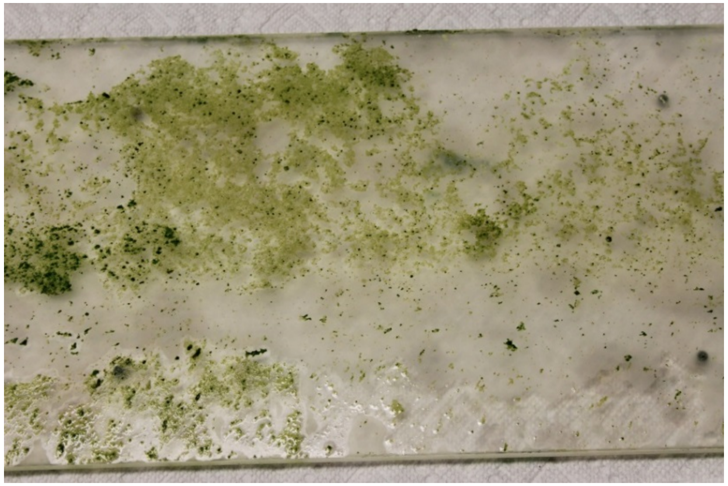
Specimen A
coverage = 14.2%
thickness, k = 520 μm

Specimen B
coverage = 13.7%
thickness, k = 433 μm



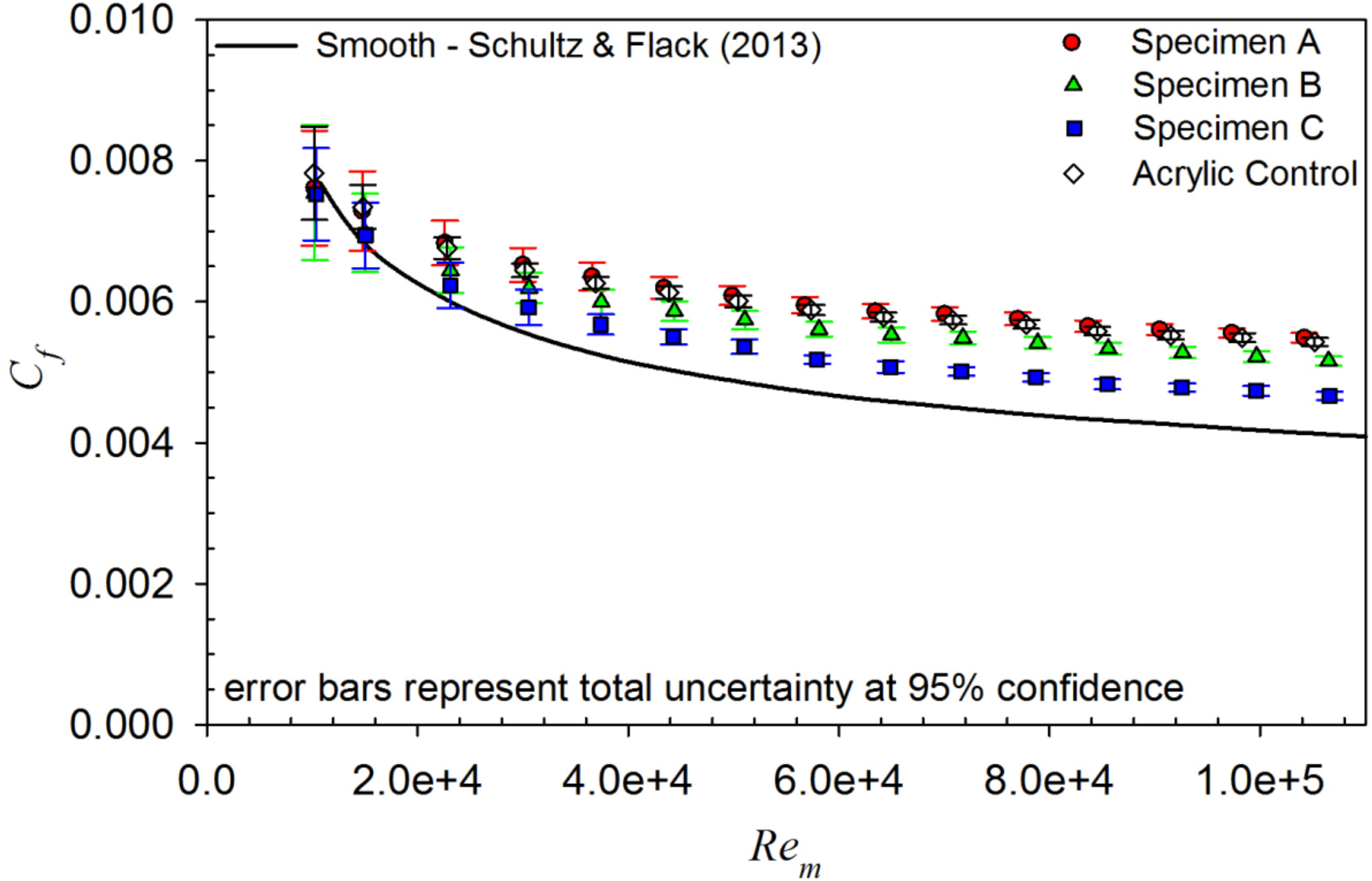
Specimen C
coverage = 49.2%
thickness, k = 98 μm

Acrylic Control
coverage = 27.8%
thickness, k = 392 μm



6 months exposure

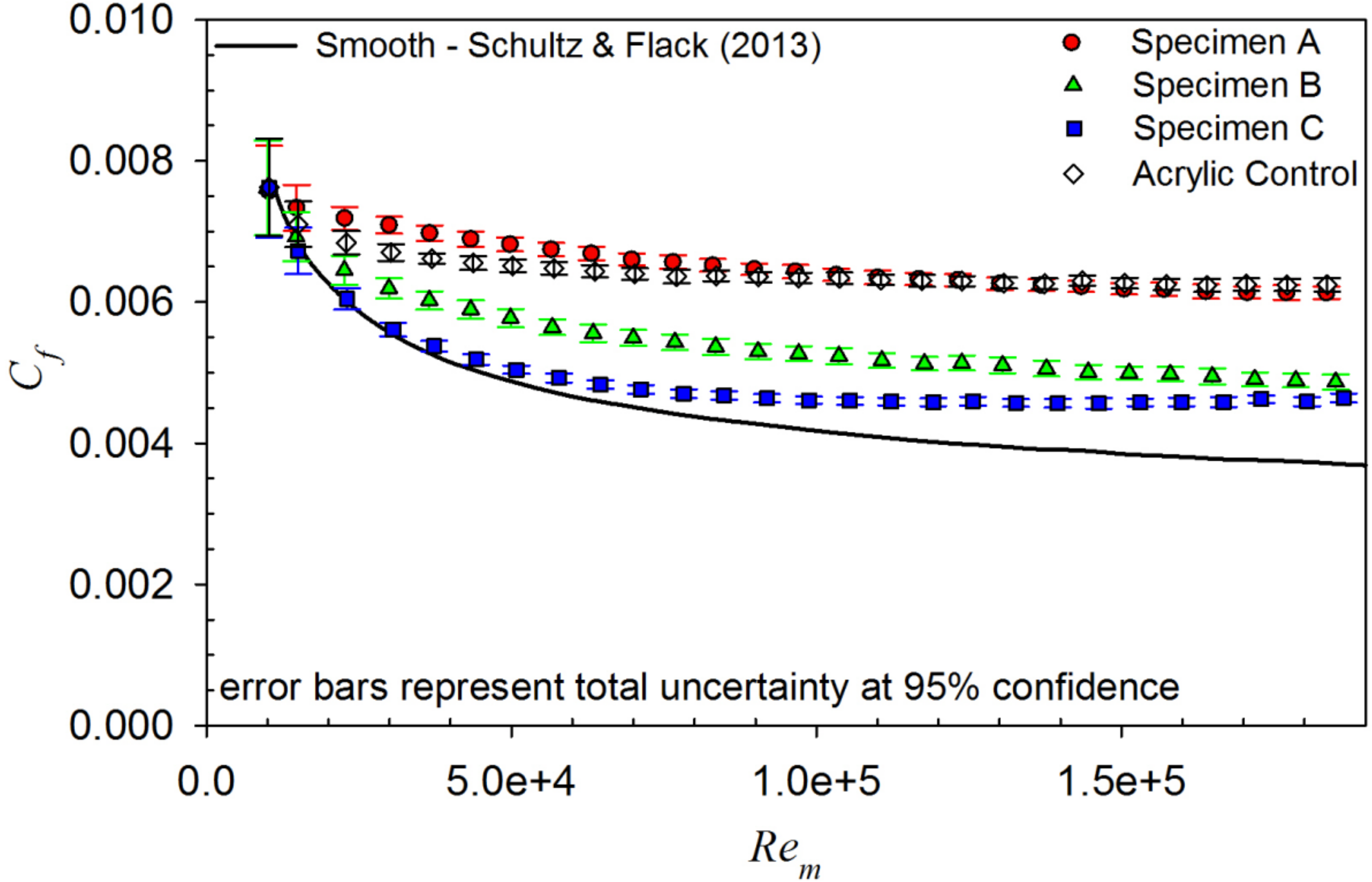
Biofilm Roughness



Schultz, Walker, Steppe & Flack (2015) *Biofouling* 31: 759

3 months exposure

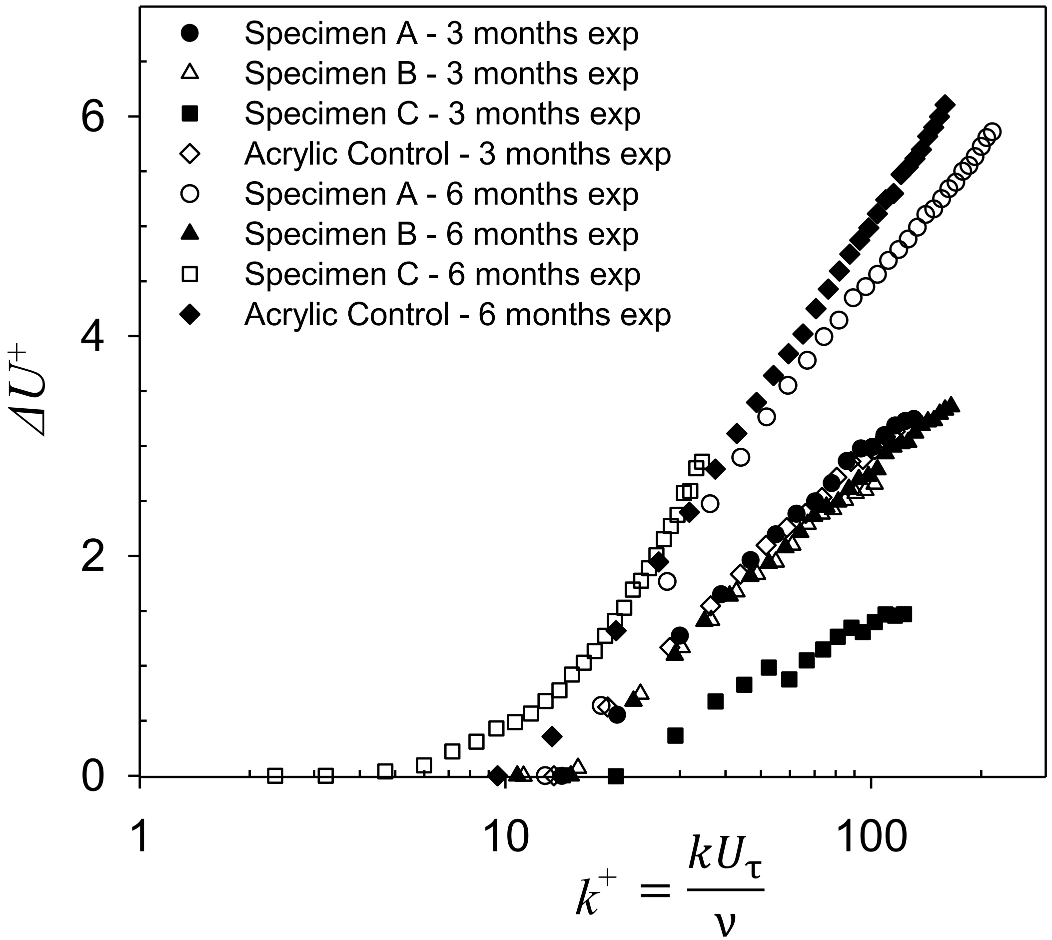
Biofilm Roughness



Schultz, Walker, Steppe & Flack (2015) *Biofouling* 31: 759

6 months exposure

Biofilm Roughness

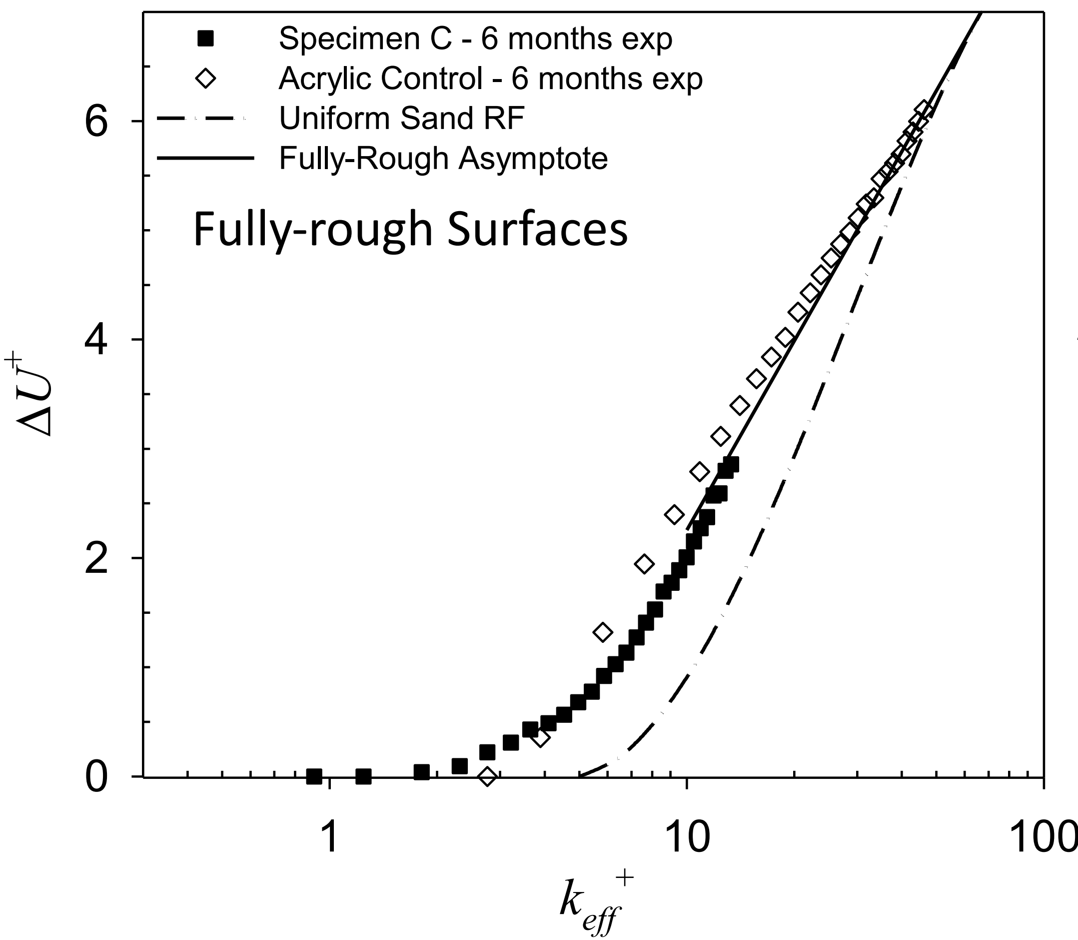


k not effective by itself in collapsing the roughness function

Significant variability in roughness function behavior

Schultz, Walker, Steppe & Flack (2015) *Biofouling* 31: 759

Biofilm Roughness

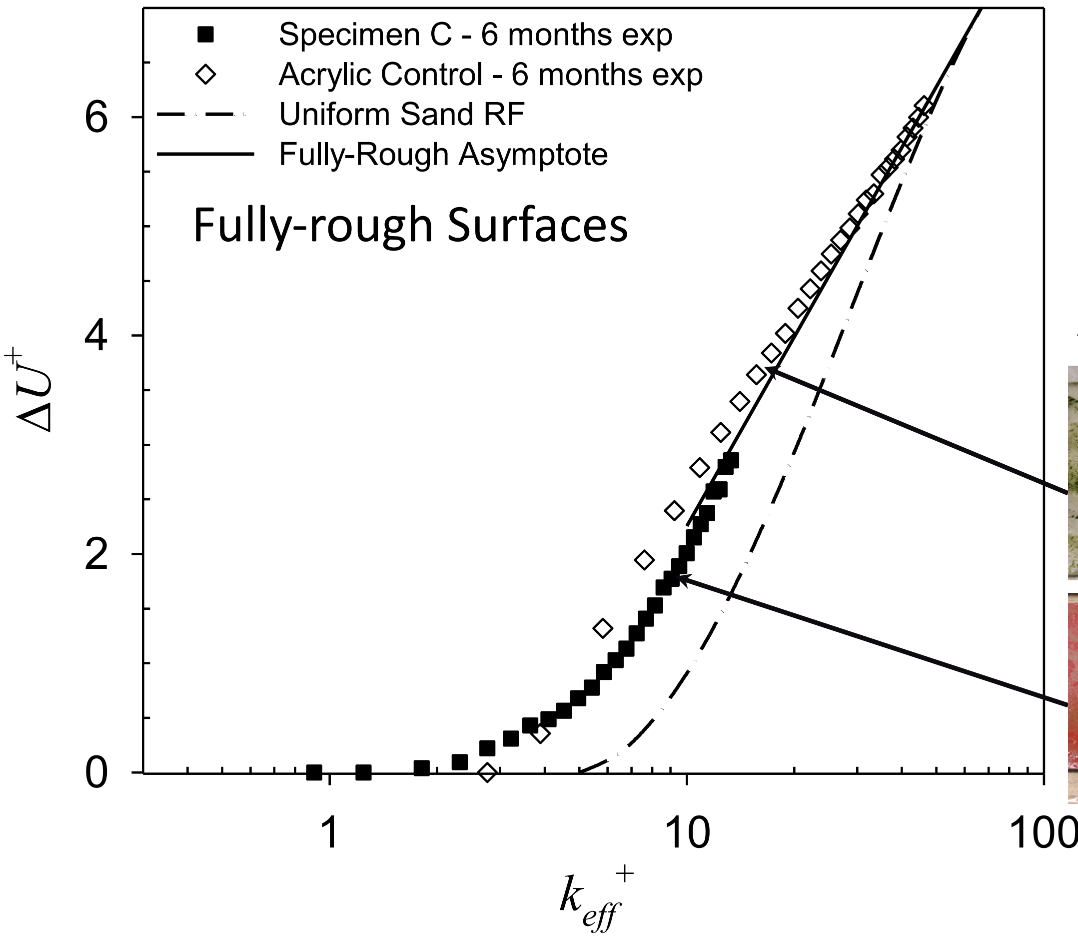


Effective hydraulic length scale appears to be related to biofilm thickness and % cover

$$k_s \approx k_{eff} = 0.055k(\%\,\text{cover})^{\frac{1}{2}}$$

Schultz, Walker, Steppe & Flack (2015) *Biofouling* 31: 759

Biofilm Roughness



Effective hydraulic length scale appears to be related to biofilm thickness and % cover

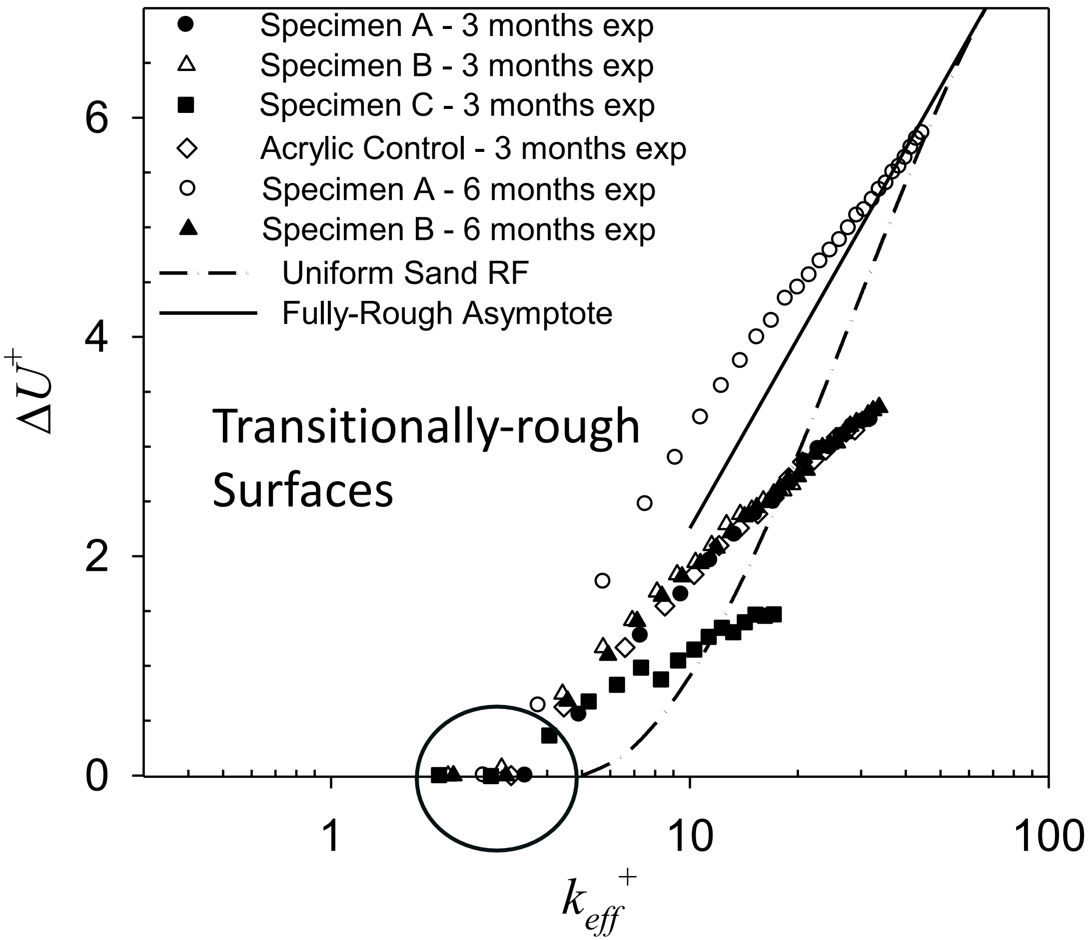
$$k_s \approx k_{eff} = 0.055k(\%\,\text{cover})^{\frac{1}{2}}$$

coverage = 27.8%
thickness, k = 392 μm
k_s = 115 μm

coverage = 49.2%
thickness, k = 98 μm
k_s = 35 μm

Schultz, Walker, Steppe & Flack (2015) *Biofouling* 31: 759

Biofilm Roughness



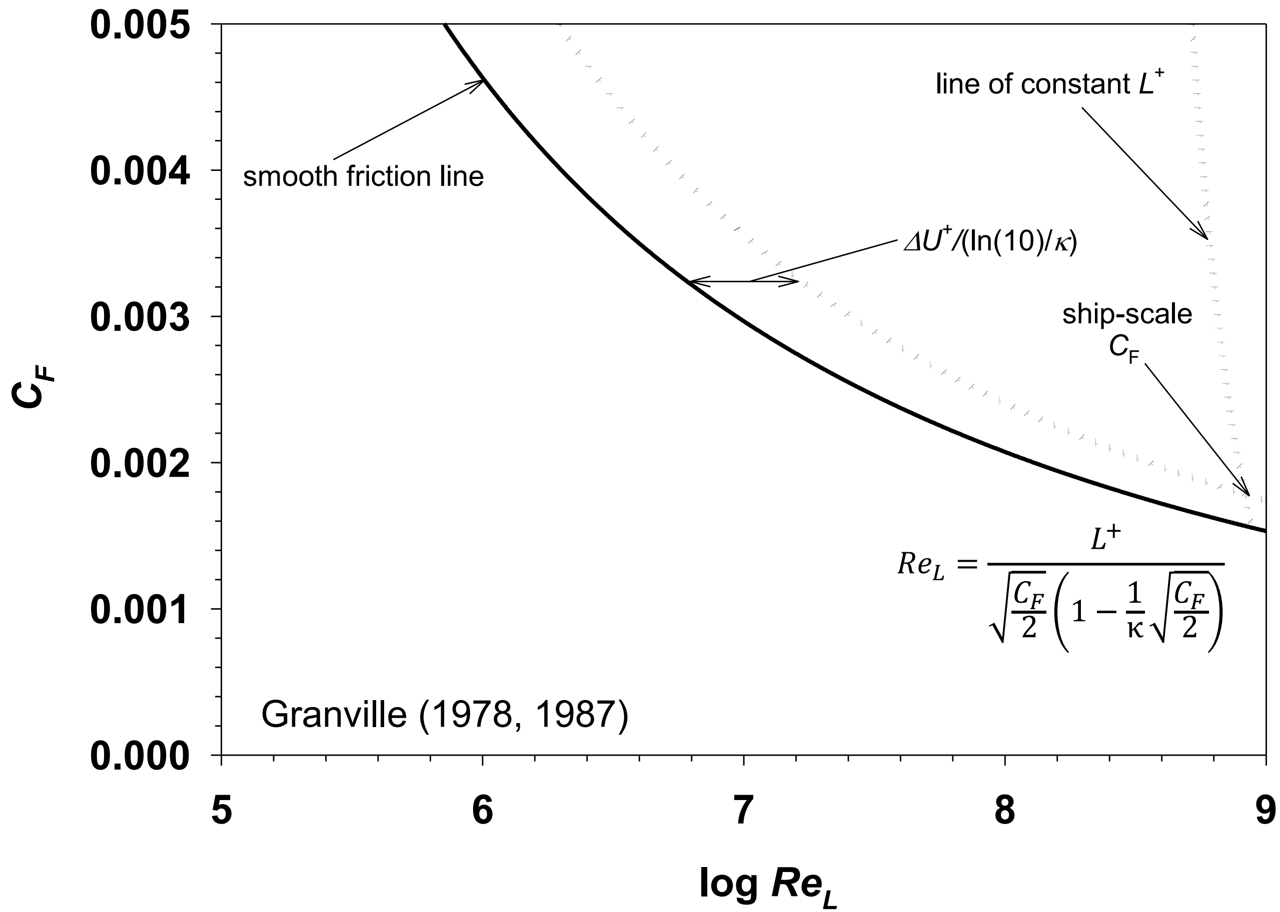
Onset of roughness effects seems to occur at k_{eff}^+ ~ 2-3

Roughness functions don't exhibit the typical asymptotic behavior

% Coverage < 25%?

Schultz, Walker, Steppe & Flack (2015) *Biofouling* 31: 759

Modeling Roughness/Predicting Drag



Lab Results to Ship Scale

Biofilm Roughness

Scale Up of Results – 3 Months Exposure*

Surface	ΔSP (%) at 15 kts
Specimen A	6.3
Specimen B	4.8
Specimen C	1.5
Acrylic Control	6.2

*changes in shaft power are calculated with respect to the hydraulically-smooth condition

Predicted Increase in Shaft Power for *DDG-51*@ 15 knots

Biofilm Roughness

Scale Up of Results – 6 Months Exposure*

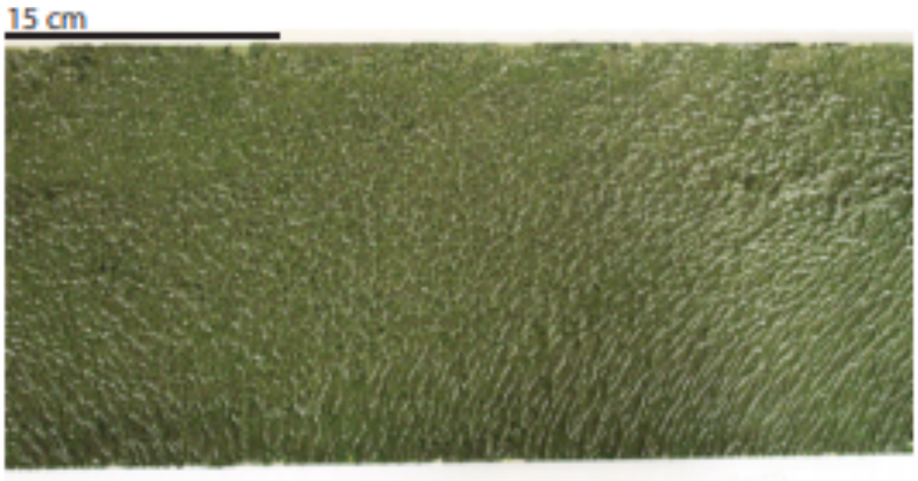
Surface	ΔSP (%) at 15 kts
Specimen A	10.1
Specimen B	5.3
Specimen C	2.3
Acrylic Control	10.1

*changes in shaft power are calculated with respect to the hydraulically-smooth condition

Predicted Increase in Shaft Power for *DDG-51*@ 15 knots

Modeling Roughness/Predicting Drag

Heavy slime fouling



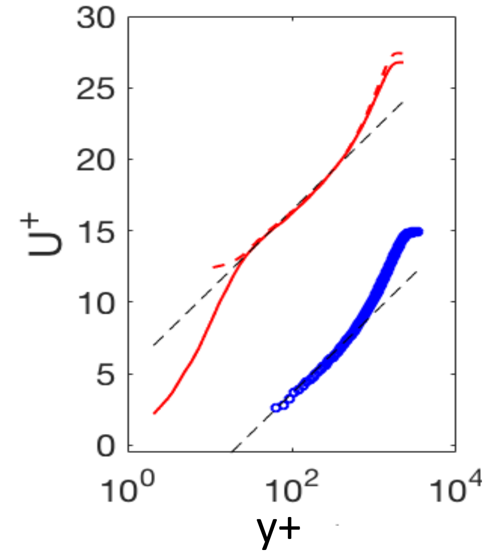


Table 1. Roughness parameters of the biofilm-fouled plate and the smooth plate.

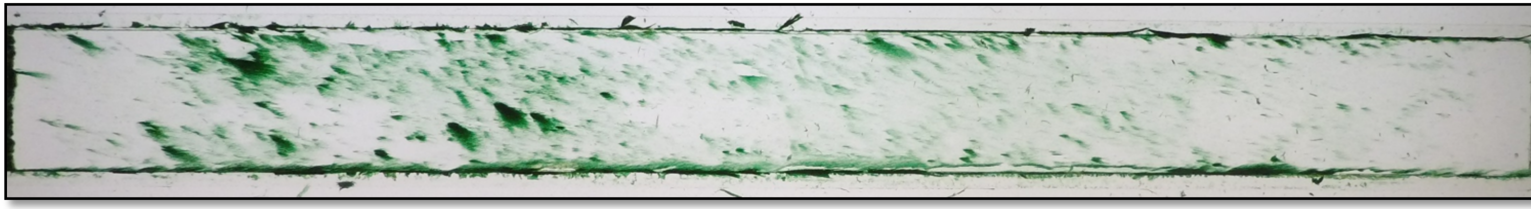
	U_e (m s^{-1})	δ (mm)	$Re_\tau = \delta^+ = \delta U_\tau / \nu$	U_τ (m s^{-1})	ΔU^+	k_s^+	k_s (mm)	C_f
Smooth	1.2	33.5	1.64×10^3	0.047	–	–	–	2.9×10^{-3}
Biofilm	1.1	30.0	2.5×10^3	0.076	12.8	736	8.8	9.0×10^{-3}

δ^+ is the friction Reynold number.

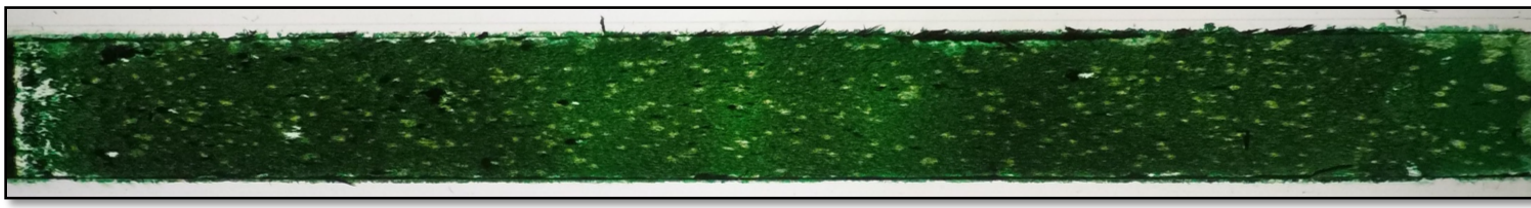
Murphy, *et al.* Biofouling (2019)

Modeling Roughness/Predicting Drag

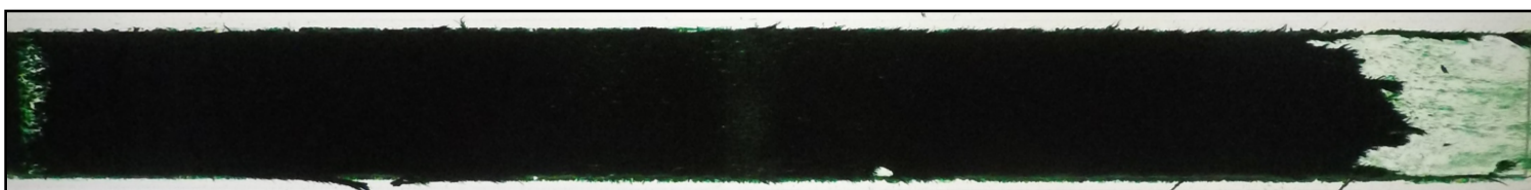
Heavy slime fouling



Three week biofilm, slight growth – Trial 3W3



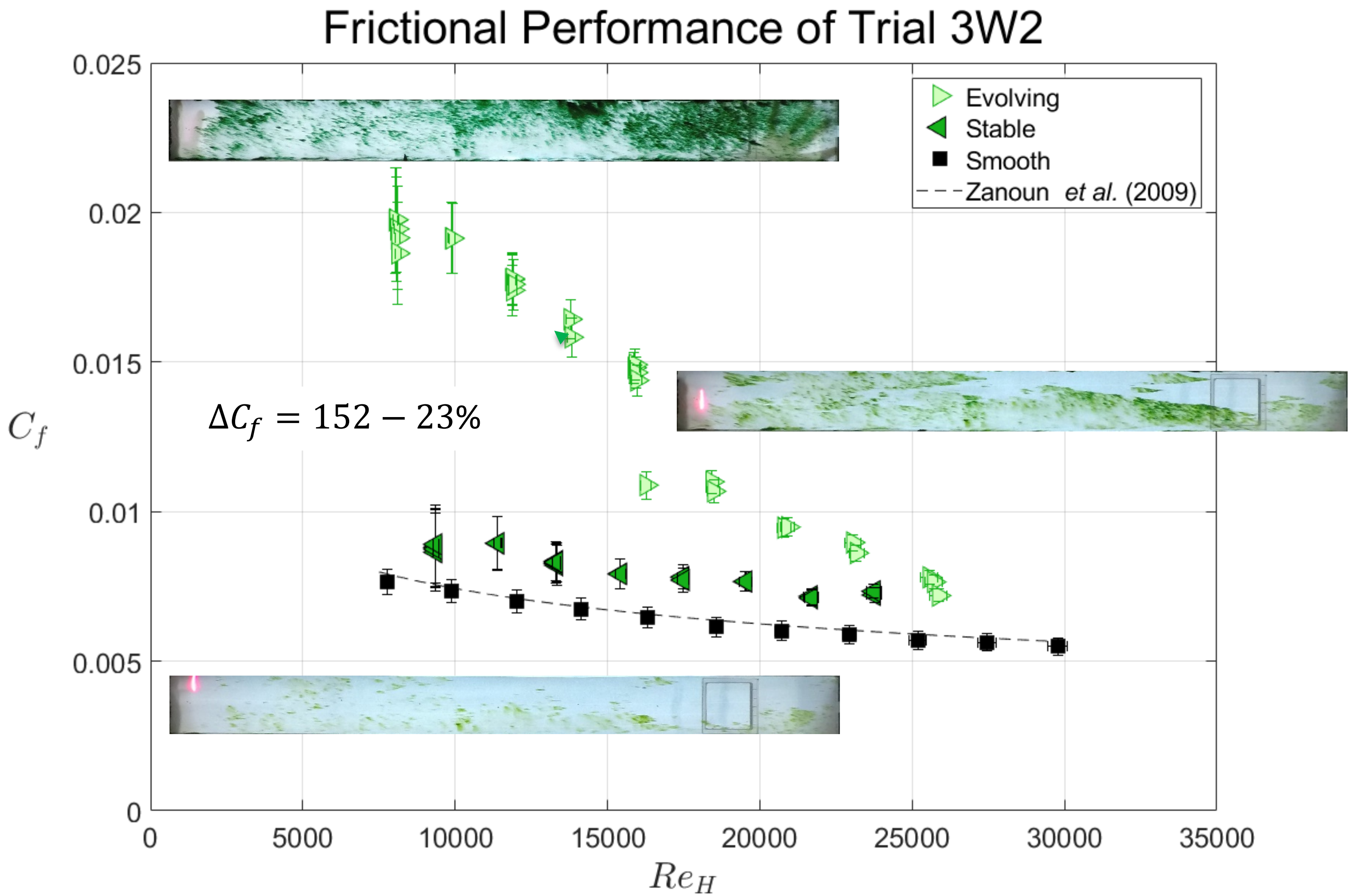
Five week biofilm, moderate growth – Trial 5W3



Ten week biofilm, heavy growth – Trial 10W2

Ceccio, *et al.* ONR Program review 2019

Modeling Roughness/Predicting Drag



Ceccio, *et al.* ONR Program review 2019

Modeling Roughness/Predicting Drag

Light calcareous tubeworm fouling

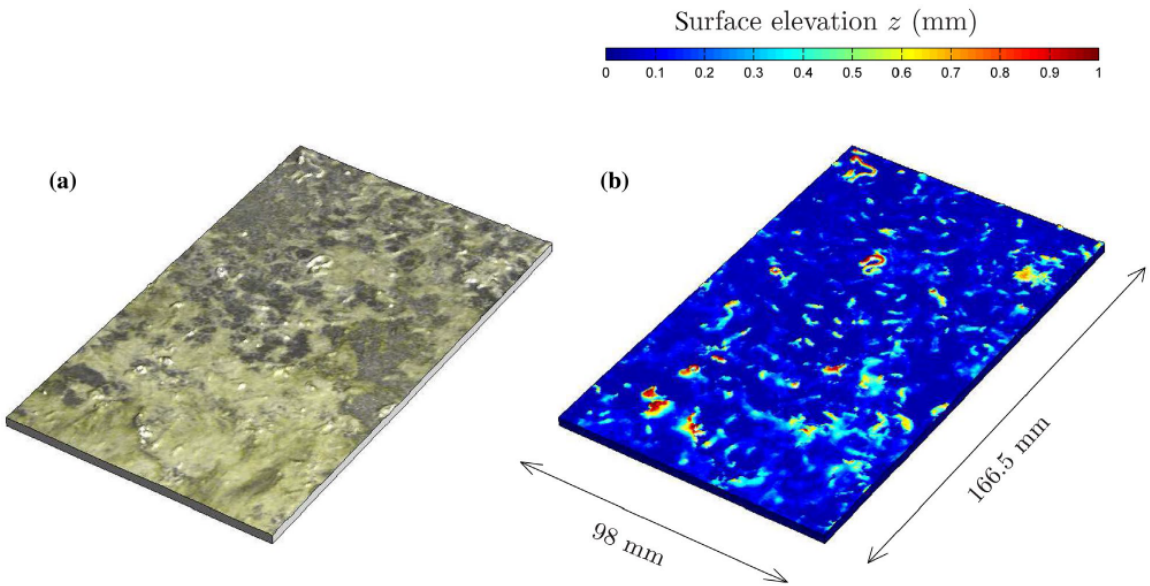


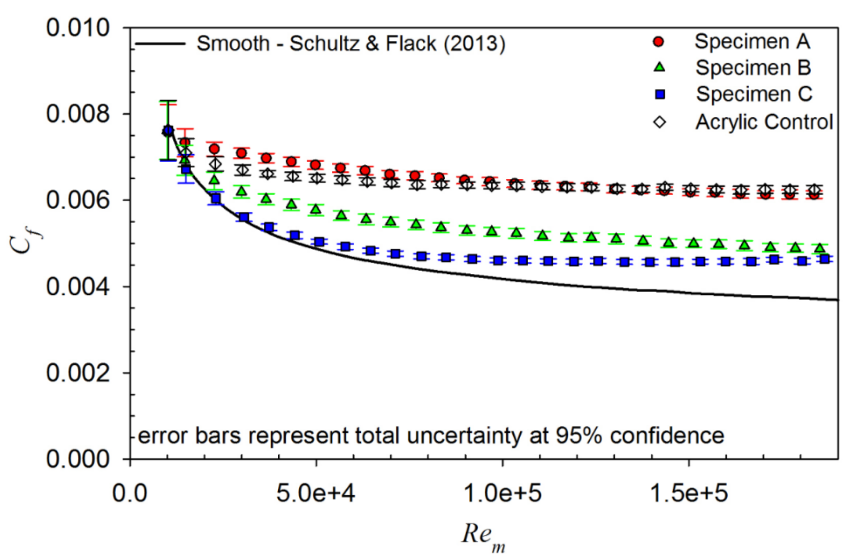
Table 2. Tabulated data on the FFG-7 Oliver Perry class frigate (Schultz 2007). Data in the shaded columns are calculated for the tube-worm fouling.

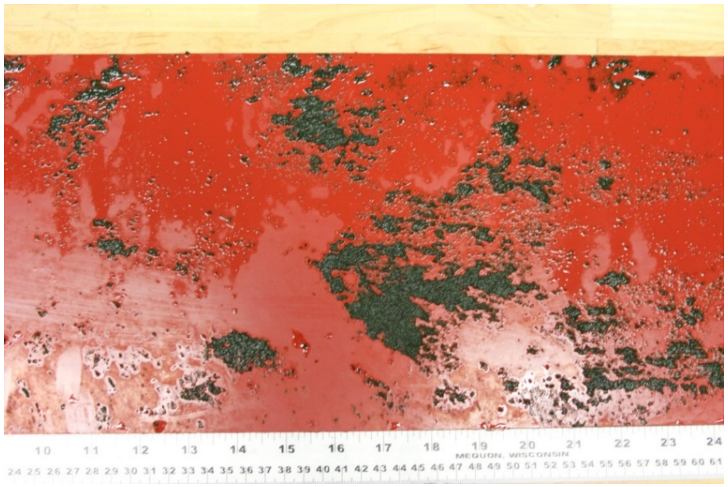
Length(m)	ν(m^{2}s^{-1})	C_A	U(m s^{-1})		Fr	Re	$\bar{C}_f/C_R$	$\%\Delta\bar{C}_f$	$\%\Delta R_T$
124	8.97×10^{-7}	0.0004	Cruising	7.7	0.22	1.06×10^9	~0.7	46%	23%
			Full-speed	15.4	0.44	2.13×10^9	~3.3	59%	13%

Monty, *et al.* Biofouling (2016)

Conclusions

- Bio-films cause a significant drag penalty
  - ~10% increase in ship power for light slime
  - ~20% increase in ship power for heavy slime
- What else is needed to address questions
  - Additional lab experiments and numerical simulations of realistic ship hull roughness
  - Methods of in-situ measurements of ship hull roughness
  - Shear stress/boundary layer measurements over full scale ships with accurate documentation of surface roughness





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- USNA Hydromechanics Lab
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- Many roughness collaborators

Questions?