Current Status of Scaling Methods

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Two Types of Scaling

1. **Scale Model Size**
   - **Desired Model Too Large**
2. **Scale Test Conditions**
   - **Desired MVD Outside Facility Envelope**
   - **Desired LWC Outside Facility Envelope**
   - t_{tot} **too High**

Terminology

- **Reference (Subscript *R*)**
  - **Full-Size Model**
  - **Desired Icing Conditions**
- **Scale (Subscript *S*)**
  - **Reduced-size Model**
  - **Test Conditions Found by Applying Scaling Method**

Size Scaling

Procedure for Ruff Method

Sea-Level Facility

- Reference (Known)
  - Model Geometry
  - Model Size
  - Test Conditions
- Scale
  - Model Geometry Same as Reference
  - Choose Model Size
  - Choose Velocity

Size Scaling

Procedure for Ruff Method (con't)

Remaining Scale Test Conditions

- **Match Scale Similarity Parameters to Reference:**

Test Parameter	Similarity Parameter
MVD	K_0 (or β_0)
t_{st}	ϕ
LWC	n_0
time	A_c

Size Scaling

Scale Velocity (Ruff Method)

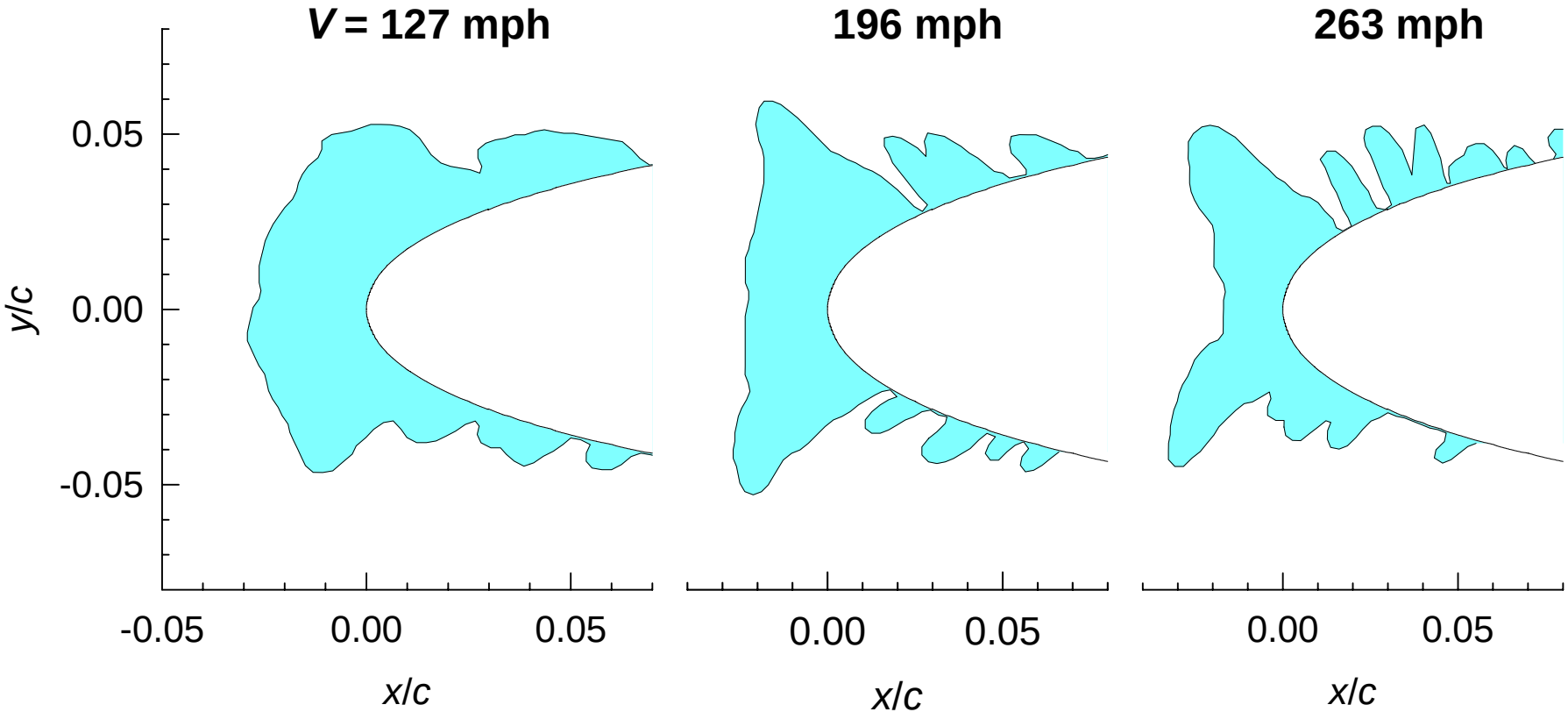
- **Choose V_S for Convenience**
- **Assume Ice Shape Independent of Velocity**

Size Scaling

Effect of Velocity on Ice Shape

10.5-in-Chord NACA 0012

β_0, 85 % A_c, 1.74 n_0, 0.47 ϕ, 14.0°F

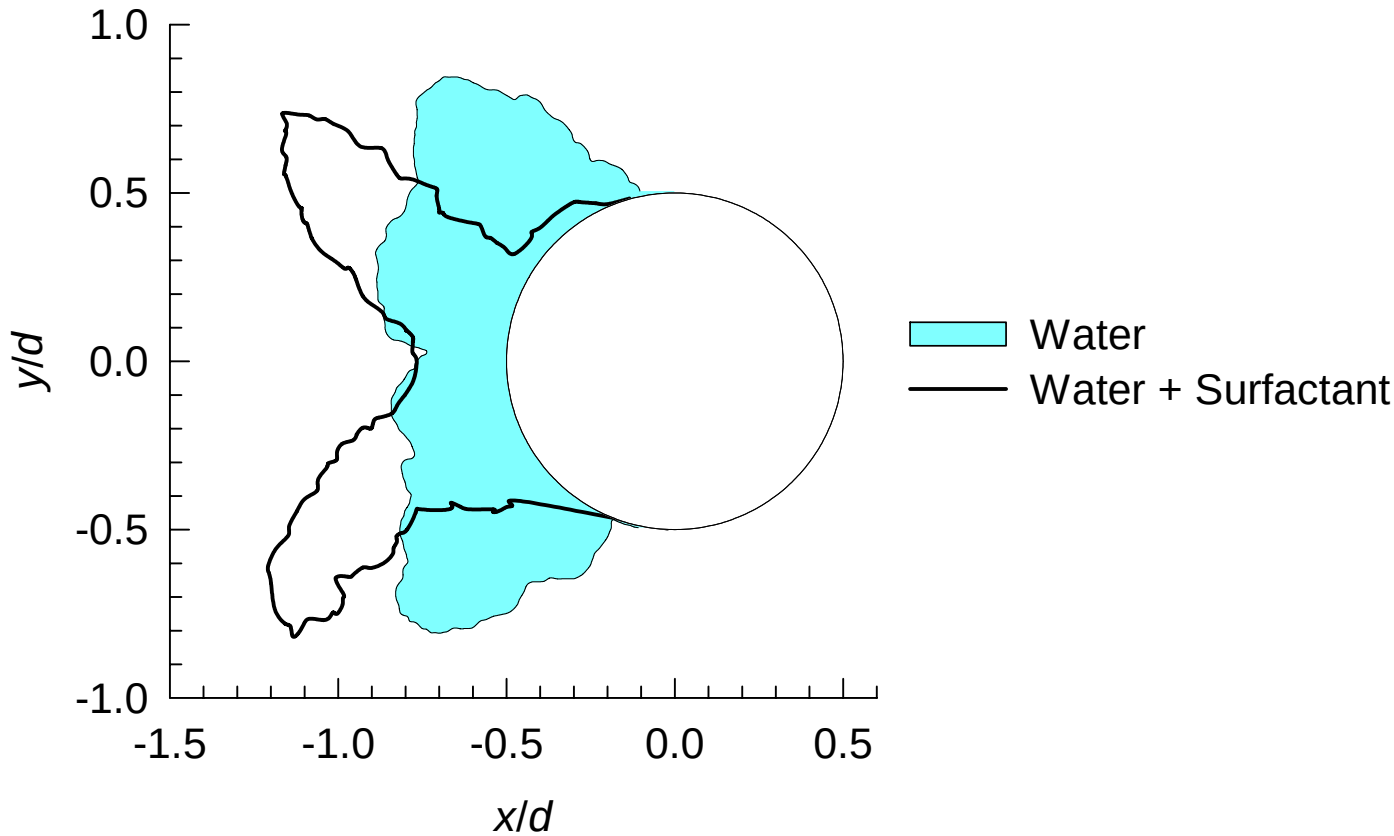


Size Scaling

Effect of Surfactant on Ice Shape

2-in-Diam Cylinder

t_{st}, °F	V, mph	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	n_0	ϕ, °F
18	105	40	1.16	16.0	66	1.13	0.28	14



Size Scaling

Supplemental Similarity Parameter

- **Weber Number Includes**
  - **Velocity, *u***
  - **Surface Tension (Surfactant), $\sigma_{w/a}$**

$$We = u^2 L \rho / \sigma_{w/a}$$

- **Need to Identify**
  - **Velocity, *u***
  - **Length, *L***
  - **Density, ρ**

Size Scaling

Probable Form of Weber Number

$$We_L = \frac{V^2 d \rho_w}{\sigma_{w/a}}$$

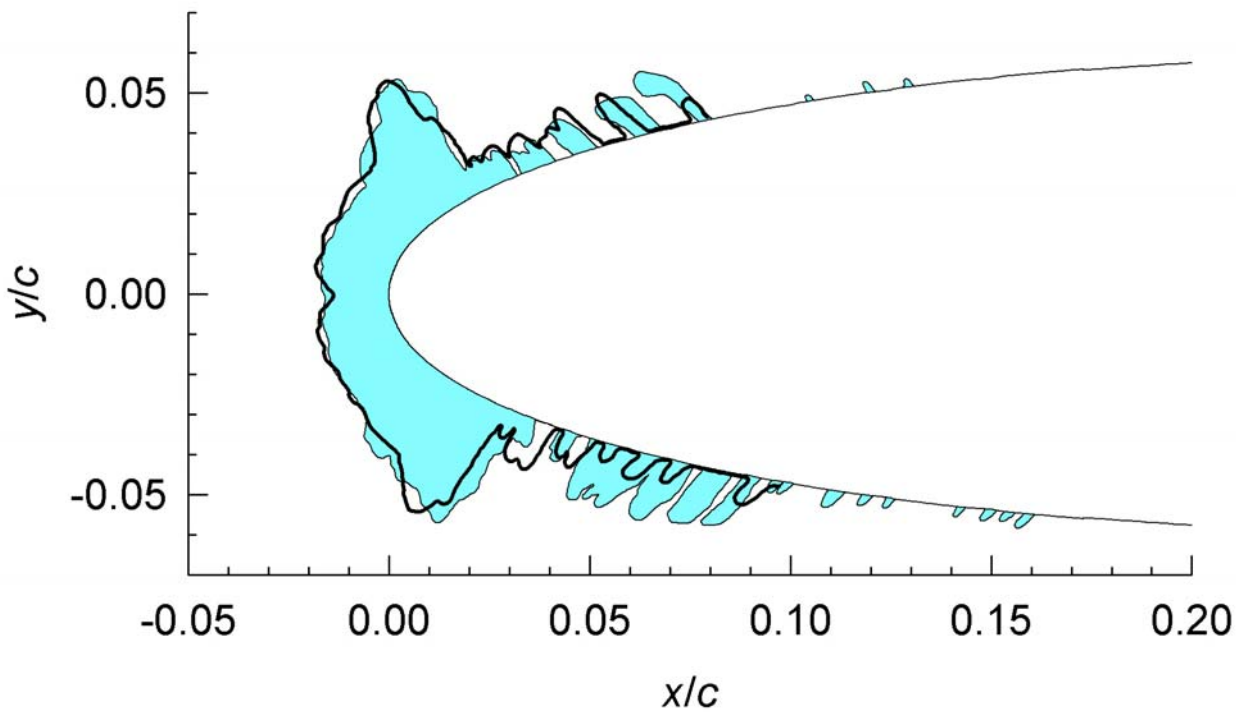
- $u = f(V)$
- $L \propto d$
- Density is Probably ρ_w

Size Scaling

Ruff Method with Constant We_L

NACA 0012, 1.7:1 Scale Ratio

	c, in	t_{st}, °F	V, mph	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	n_0	ϕ, °F	We_L
	36.0	12	115	160	1.50	9.7	95	1.70	0.30	20	1.17
	21.0	19	149	38	1.00	7.3	85	1.88	0.28	12	1.15

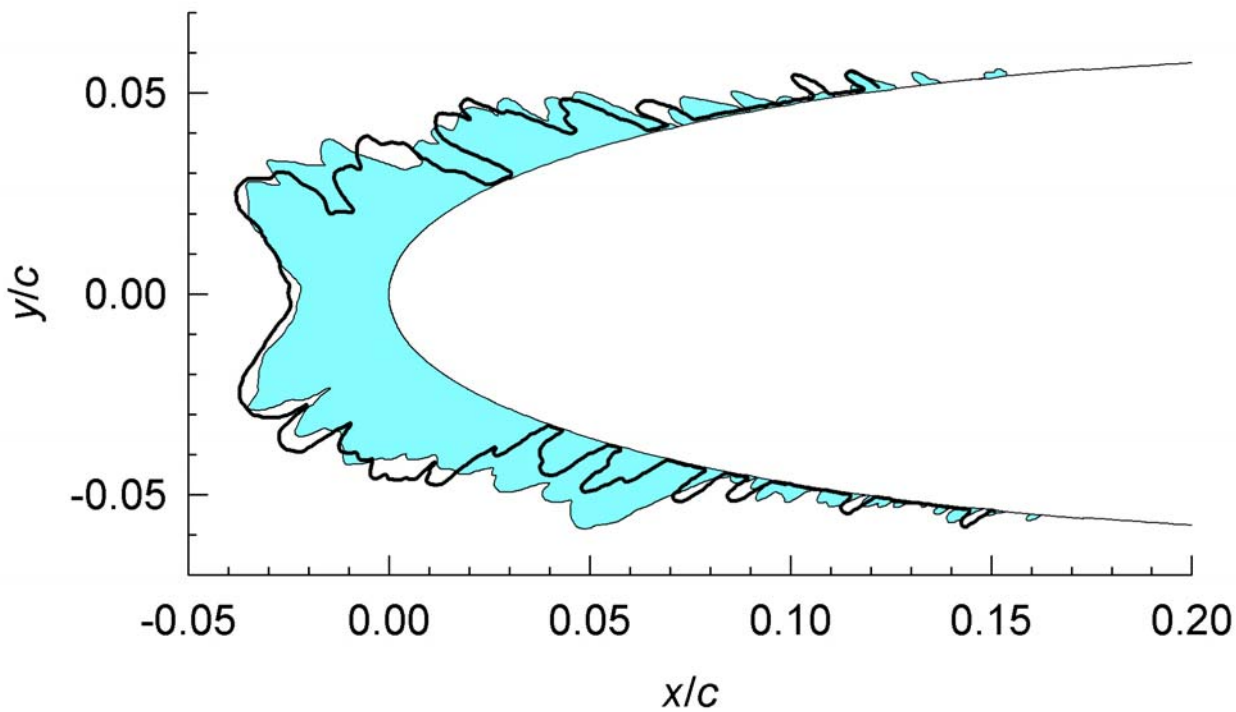


Size Scaling

Ruff Method with Constant We_L

NACA 0012, 1.7:1 Scale Ratio

	c, in	t_{st}, °F	V, mph	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	n_0	ϕ, °F	We_L
	36.0	-3	115	160	1.50	9.7	95	1.70	0.50	34	1.18
	21.0	9	150	38	0.99	7.3	85	1.88	0.52	22	1.16

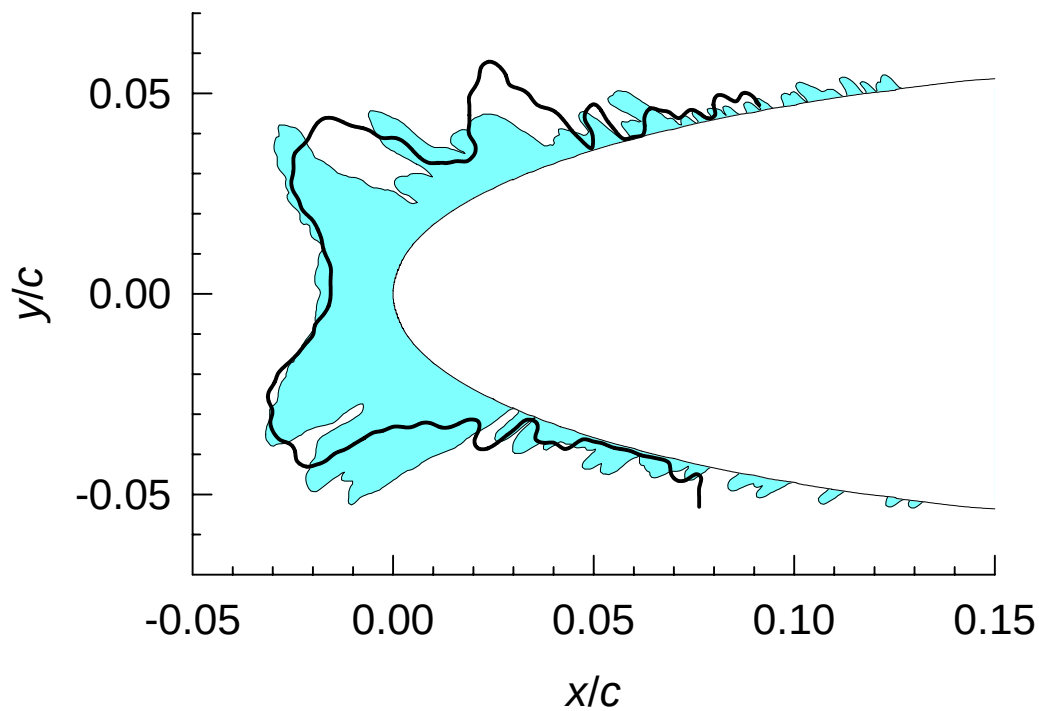


Size Scaling

Ruff Method with Constant We_L

NACA 0012, 3.4:1 Scale Ratio

	c, in	t_{st}, °F	V, mph	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	n_0	ϕ, °F	We_L
	36.0	12	150	40	1.00	13.3	79	2.04	0.40	19	1.99
	10.5	13	278	14	0.65	3.3	79	2.04	0.40	15	2.00

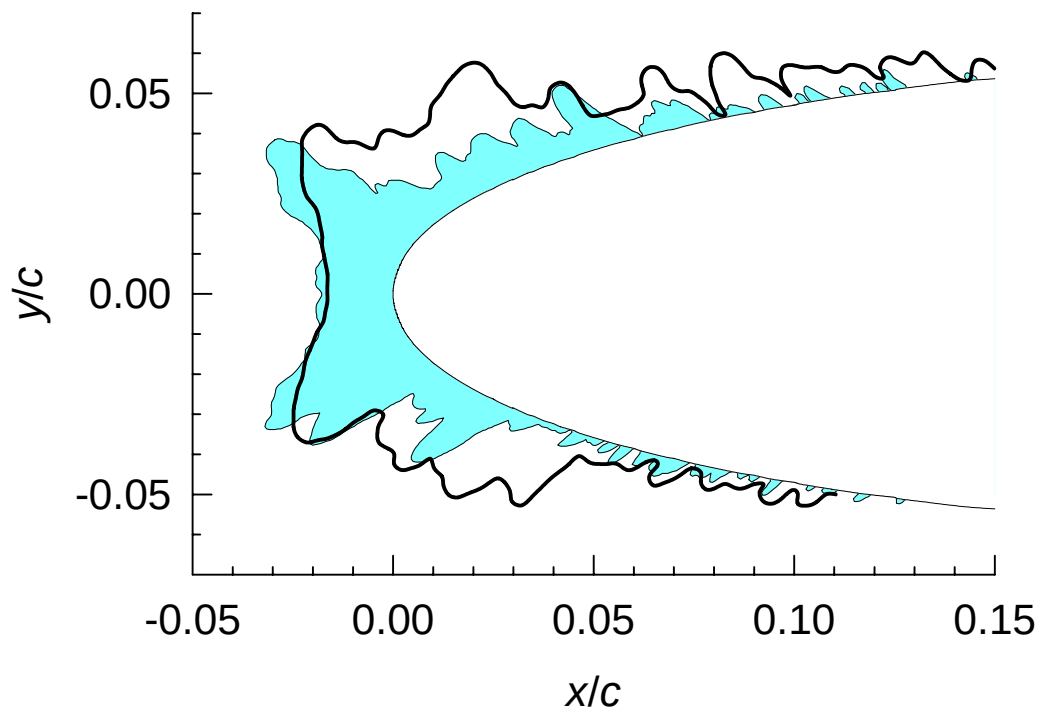


Size Scaling

Ruff Method with Constant We_L

NACA 0012, 3.4:1 Scale Ratio

	c, in	t_{st}, °F	V, mph	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	n_0	ϕ, °F	We_L
	36.0	14	150	70	0.74	16.0	89	1.80	0.40	17	2.00
	10.5	12	278	25	0.70	2.7	89	1.82	0.40	17	1.99

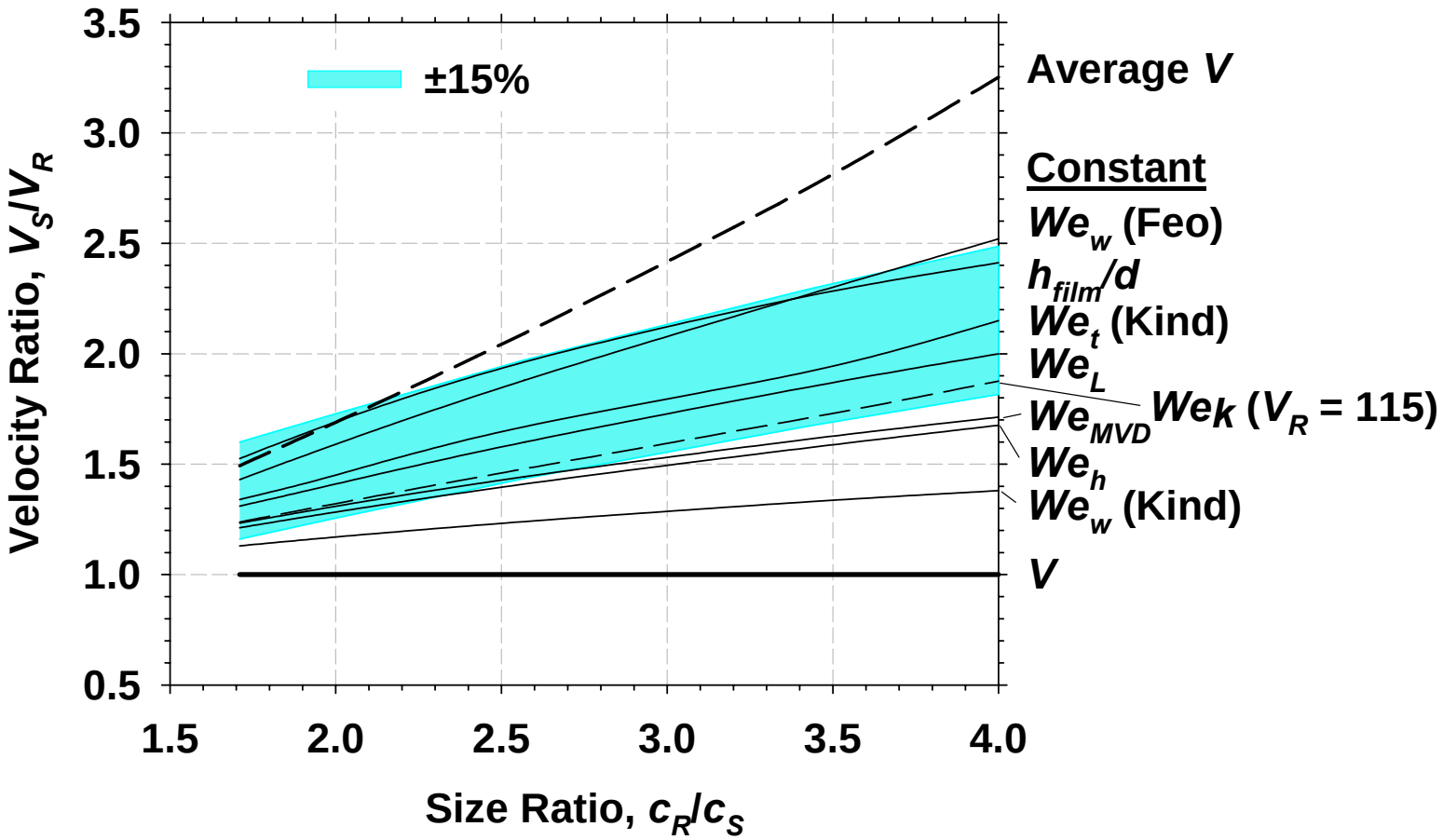


Size Scaling

Scale Velocities by Different Methods

NACA 0012; n_0 = 0.52

c_R = 36 in; V_R = 150 mph; MVD_R = 40 μm; LWC_R = 1 g/m³



Size Scaling
Recommendations

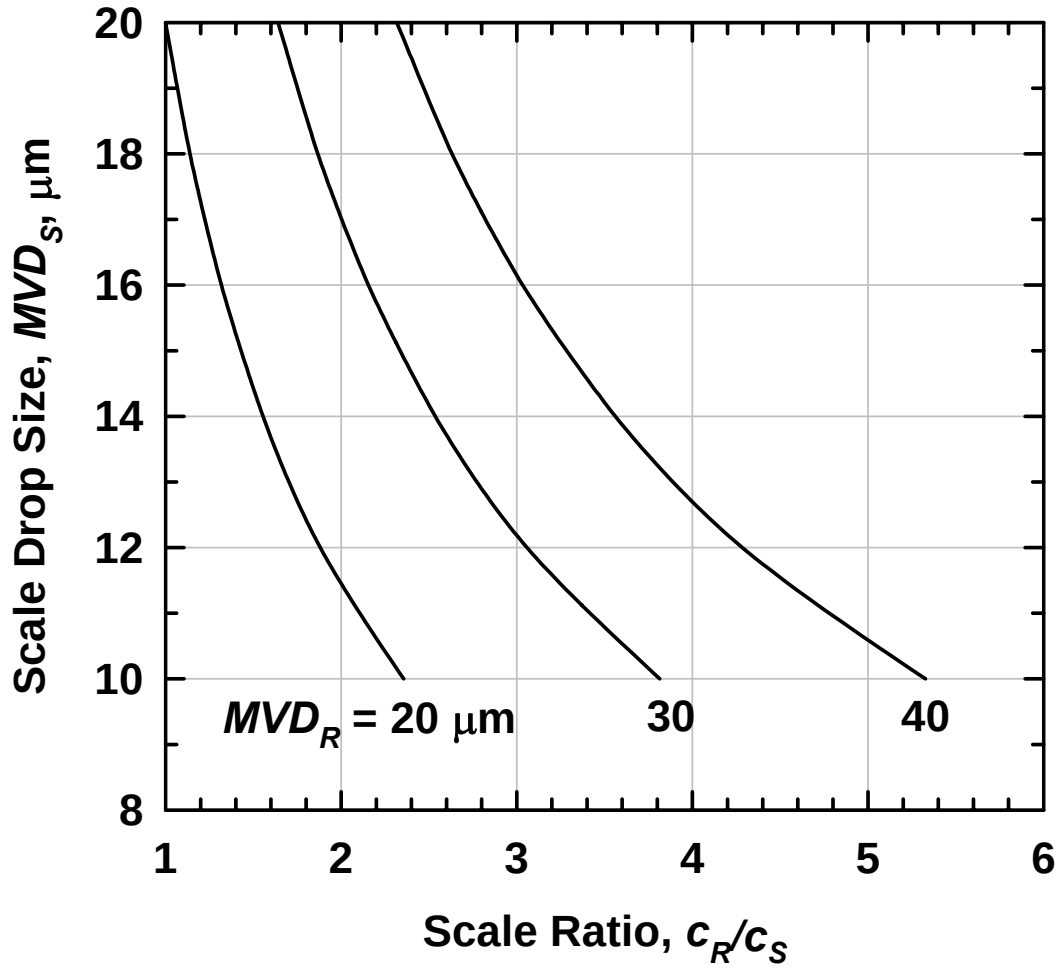
- **Ruff Method with Constant We_L**
- **Choose Scale Model Size (Same Non-dimensional Coordinates as Reference)**
- **Determine Scale Test Parameters by Matching Similarity Parameters at Stagnation:**

Scale Test Parameter	Similarity Parameter
V	We_L
t_{st}	ϕ
MVD	K_0 (or β_0)
LWC	n_0
time	A_c

Size Scaling Limits

Effect of Scale Ratio on Scale Drop Size

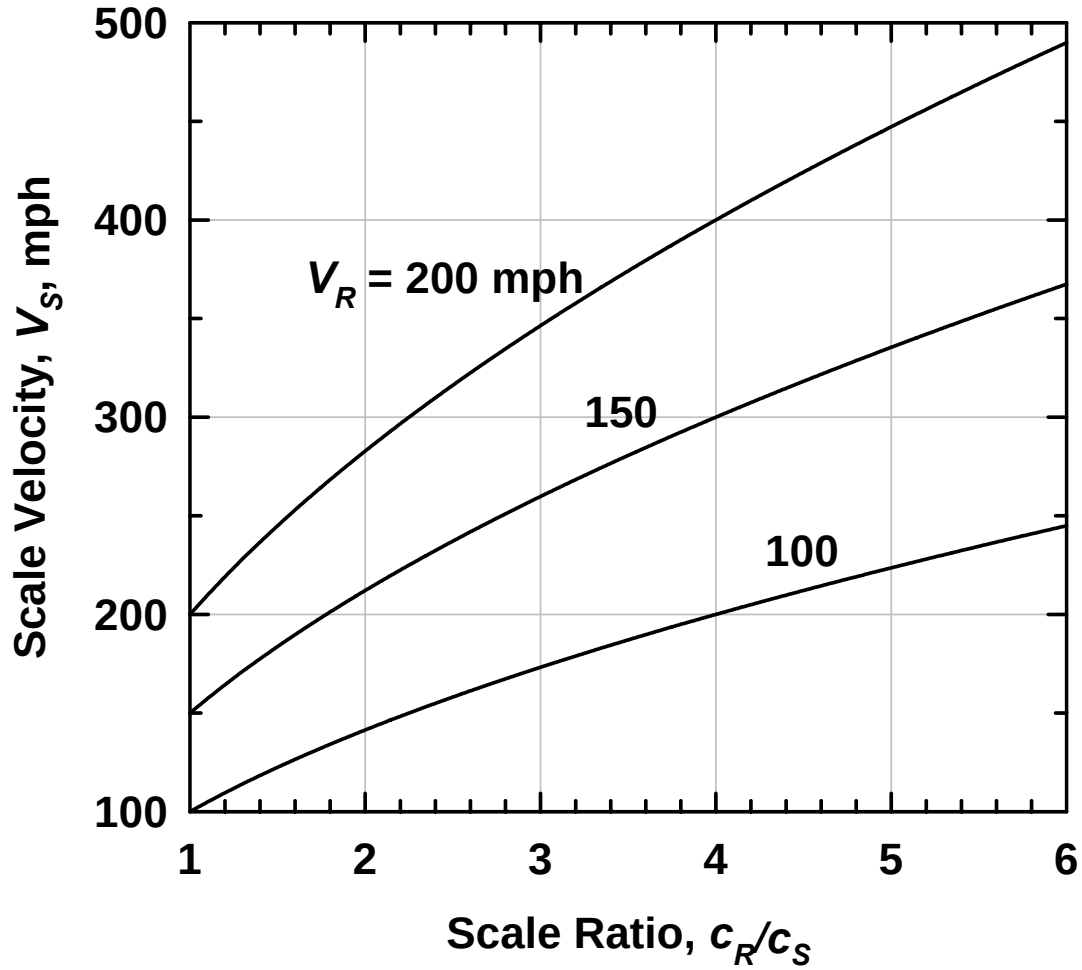
Ruff Method with Constant We_L



Size Scaling Limits

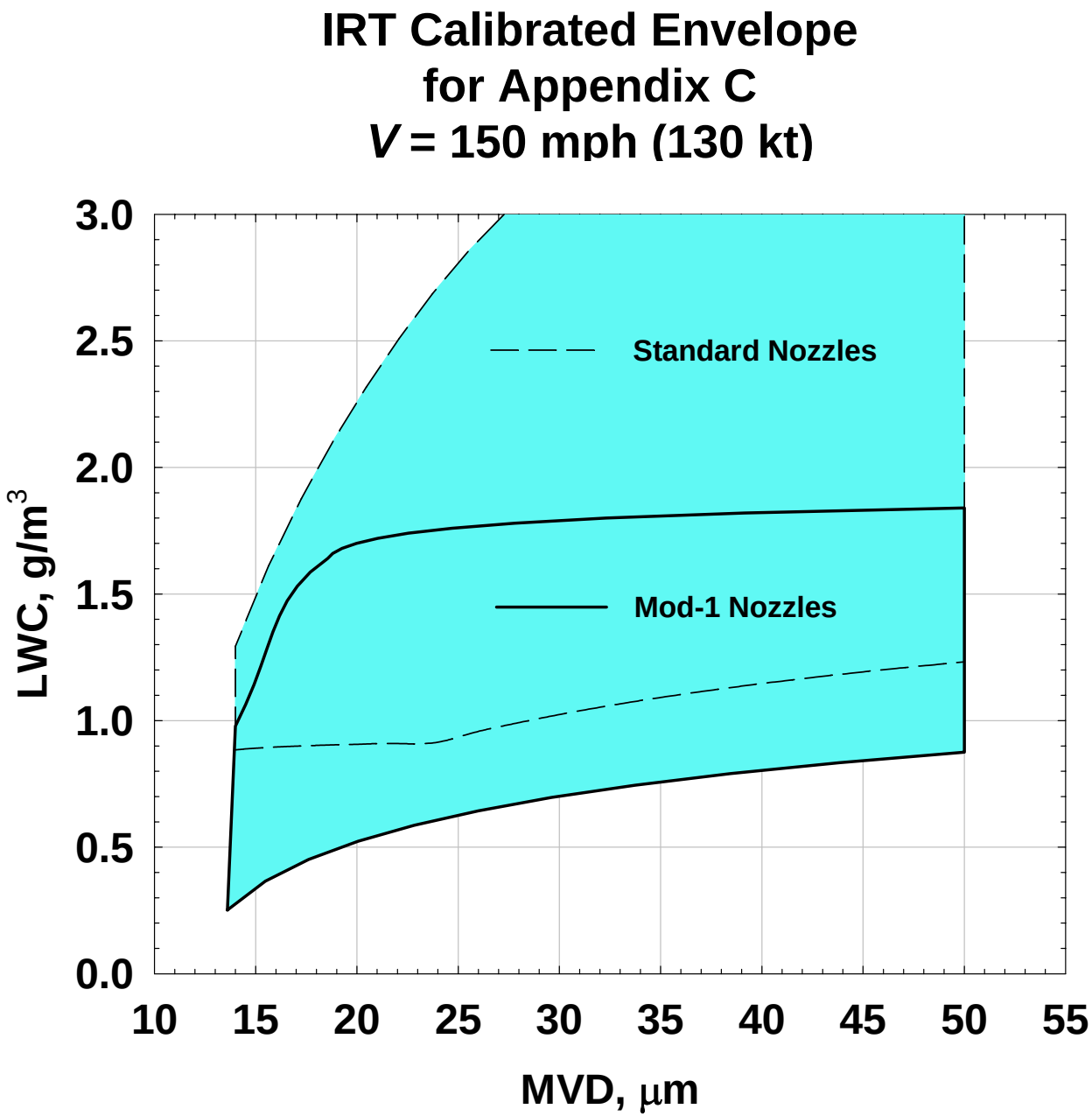
Effect of Scale Ratio on Scale Velocity

Ruff Method with Constant We_L



Test-Condition Scaling

- **Desired *MVD* Outside Facility Calibrated Envelope**
- **Desired *LWC* Outside Facility Calibrated Envelope**
- **Computed Scale Temperature too High (Size Scaling)**
  - **Total Temperature Above Freezing**
  - **Total Temperature Above 27°F**


IRT Calibrated Envelope
for Appendix C
V = 150 mph (130 kt)
Standard Nozzles
Mod-1 Nozzles
LWC, g/m3
MVD, μm
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10
15
20
25
30
35
40
45
50
55

LWC Scaling

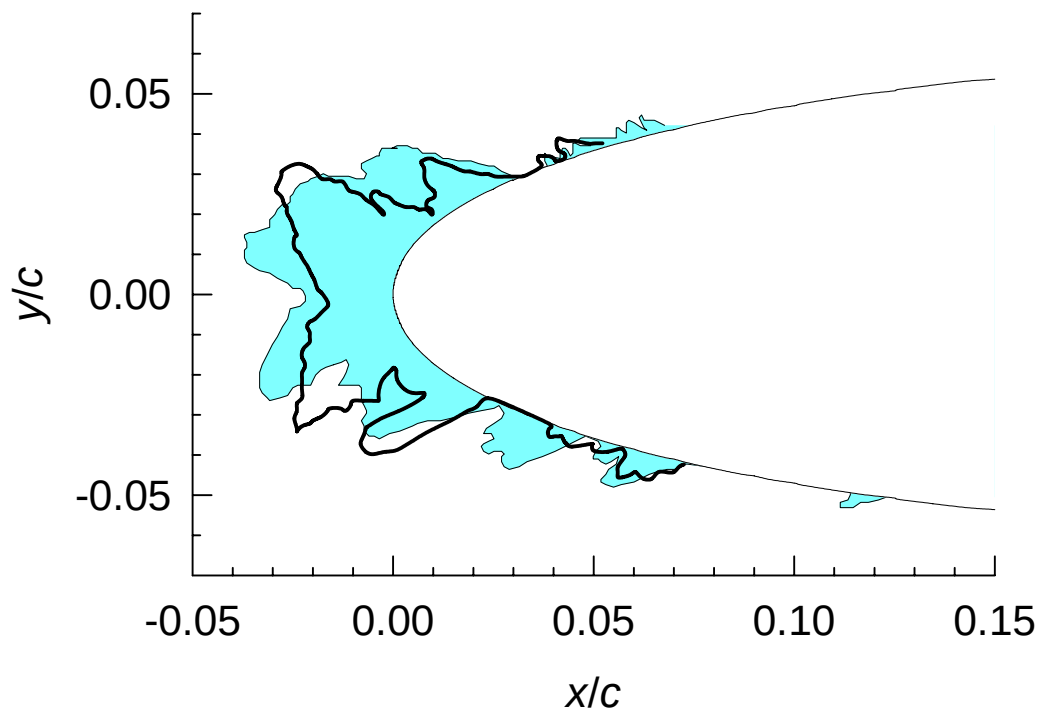
c, *V*, *MVD* = Constant

- *LWC* × Time = Constant
  - Conditions Satisfy $\beta_{0,S} = \beta_{0,R}$
  - Method Requires
    - $A_{c,S} = A_{c,R} = \dfrac{V_R\, LWC_R\, \tau_R}{d_R\, \rho_i}$
    - $t_{st,S} = t_{st,R}$
  - Procedure
    - Choose LWC_S
    - Calculate $\tau_S = LWC_R \times \tau_R / LWC_S$

LWC Scaling

Scaling with *LWC* × Time = Constant

	c, in	t_{st}, °F	V, mph	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	n_0	ϕ, °F	We_L
	21.0	11	150	30	0.80	9.1	80	1.90	0.59	20	1.16
	21.0	11	150	30	1.40	5.2	80	1.90	0.40	20	1.17



LWC Scaling

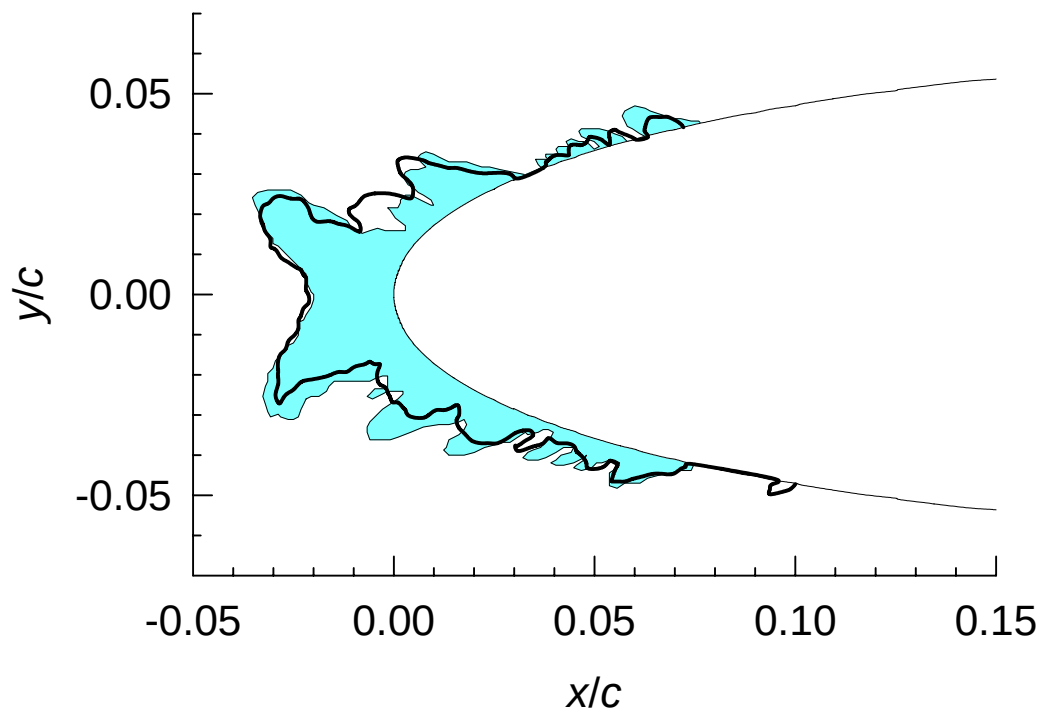
c, *V*, *MVD* = Constant

- **Olsen Method**
  - **Conditions Satisfy $\beta_{0,S} = \beta_{0,R}$**
  - **Method Requires**
    - $A_{c,S} = A_{c,R} = \dfrac{V_R\, LWC_R\, \tau_R}{d_R\, \rho_i}$
    - $n_{0,S} = n_{0,R}$
  - **Procedure**
    - **Choose LWC_S**
    - **Calculate $\tau_S = LWC_R \times \tau_R / LWC_S$**
    - **Calculate t_{st} Such That $n_{0,S} = n_{0,R}$**

LWC Scaling

Scaling with Olsen Method

	c, in	t_{st}, °F	V, mph	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	n_0	ϕ, °F	We_L
	21.0	13	150	30	0.80	9.1	80	1.90	0.52	18	1.17
	21.0	4	150	30	1.40	5.2	80	1.90	0.52	27	1.17



Recommended Scaling Methods
Size Scaling

- **Size Scaling**
  - **Ruff Method**
  - **Supplemented with $We_{L,S} = We_{L,R}$ to find Scale Velocity**

Recommended Scaling Methods
Test-Condition Scaling

- ***MVD*** **Scaling: Pending**
- ***LWC*** **Scaling: Olsen Method**
  - ***LWC*** **Chosen**
  - $t_{st,S}$ **Calculated so that** $n_{0,S} = n_{0,R}$
  - $\tau_S = LWC_R \times \tau_R / LWC_S$
- **Temperature Scaling: Olsen Method**
  - $t_{st,S}$ **Chosen**
  - LWC_S **Calculated so that** $n_{0,S} = n_{0,R}$
  - $\tau_S = LWC_R \times \tau_R / LWC_S$

Concluding Remarks

- **Methods to Scale Size and Test Conditions Demonstrated**
- **Size Scaling Limitations**
  - **Minimum Drop Size**
  - **Maximum Velocity**
  - **½ to ¼ Scale Reasonable (Depending on Ref. Conditions)**
- **Further Testing**
  - **Confirm Effect of *MVD***
  - **Better Understand Effect of *V***
  - **Ruff + Constant-We_L Scaling at AOA**