Analysis and Prediction of Ice Shedding for a Full-Scale Heated Tail Rotor

Richard E. Kreeger - NASA Glenn
Andrew Work - Ohio Aerospace Institute
Rebekah Douglass - Ohio Northern University
Matthew Gazella - Kent State University
Zakery Koster - Virginia Tech
Jodi Turk - Cleveland State University

Outline

- Introduction
- Background
  - Overview of Shedding Models
  - Experimental Setup
- Data Analysis
  - Shedding Trajectory Analysis Tool
  - Image Processing
  - Shedding Trajectory Model
- Results
- Conclusions


UN
UNITED NATIONS

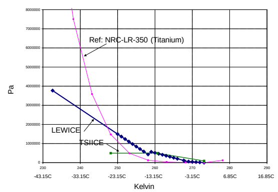
LEWICE Ice Accretion Prediction

LEWICE is a software package the predicts the size, shape, and location of ice growth on aircraft surfaces exposed to a wide range of icing conditions.

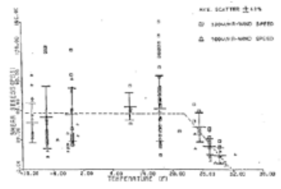
- ✓ Flow solution using potential flow or structured viscous solver
- ✓ Particle trajectory calculation, including impingement limit search for collection efficiency and multiple drop size distributions
- ✓ Integral boundary layer routine calculates heat transfer coefficient
- ✓ Quasi-steady analysis of control volume mass and energy balance in time stepping routine
- ✓ Geometry modification using density correlations to convert ice growth mass into volume allows multiple time-step solutions
- ✓ All physical effects modeled, including turbulence, bouyancy, droplet deformation, breakup and splashing
- ✓ Extensive validation against experimental data

LEWICE also models the behavior of thermal ice protection systems while exposed to the same range of icing conditions.

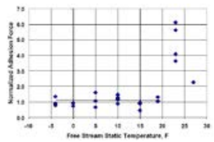
Adhesion Models



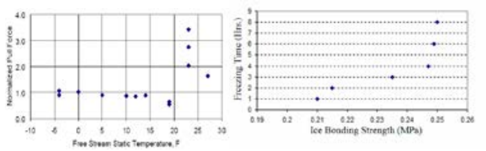
LEWICE



AIAA 94-0712

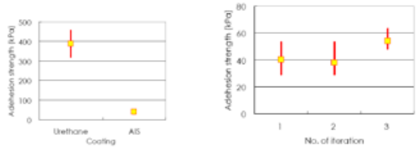


Penn State Tests

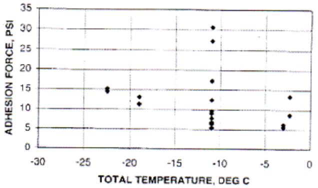


AIAA 2003-732

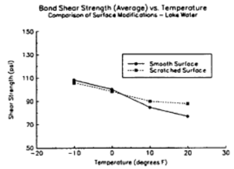
Most shedding models used today are based on empirical adhesion data, and are mainly a function of temperature…



SAE 2007-01-3315



SAE 2003-01-2093



NASA TM-107162

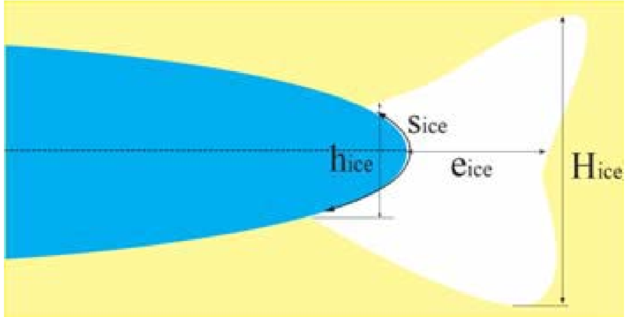
…but need to account for geometric conditions as well.

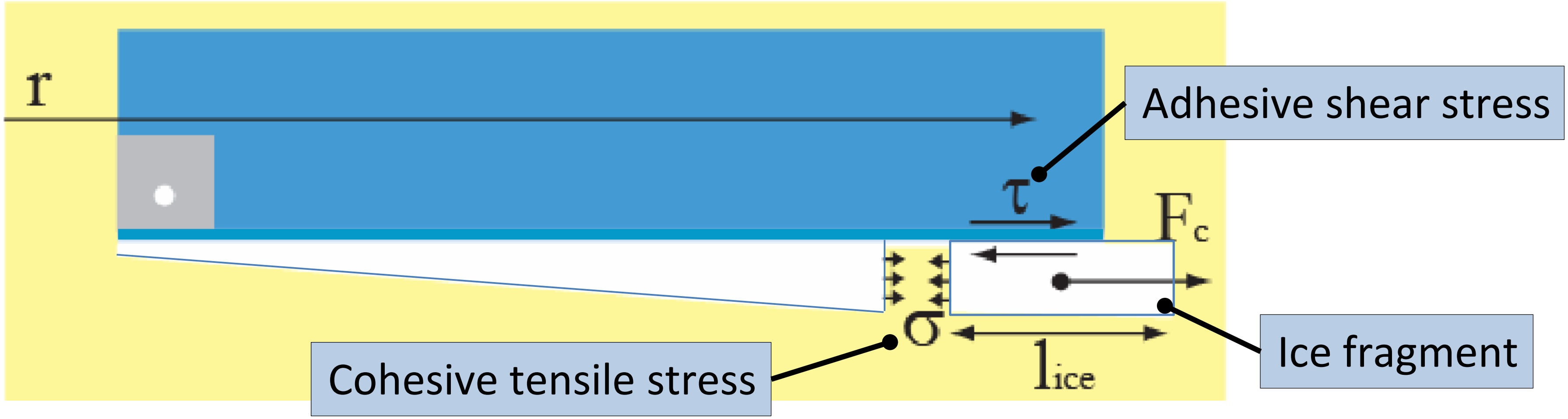
Typical Shedding Model

$$F_{Centrifugal} = F_{Adhesion} + F_{Cohesion} = m_{ice} r \Omega^2$$

$$F_{Adhesion} = \tau A_{Adhesion}$$

$$F_{Cohesion} = \sigma A_{Cohesion}$$

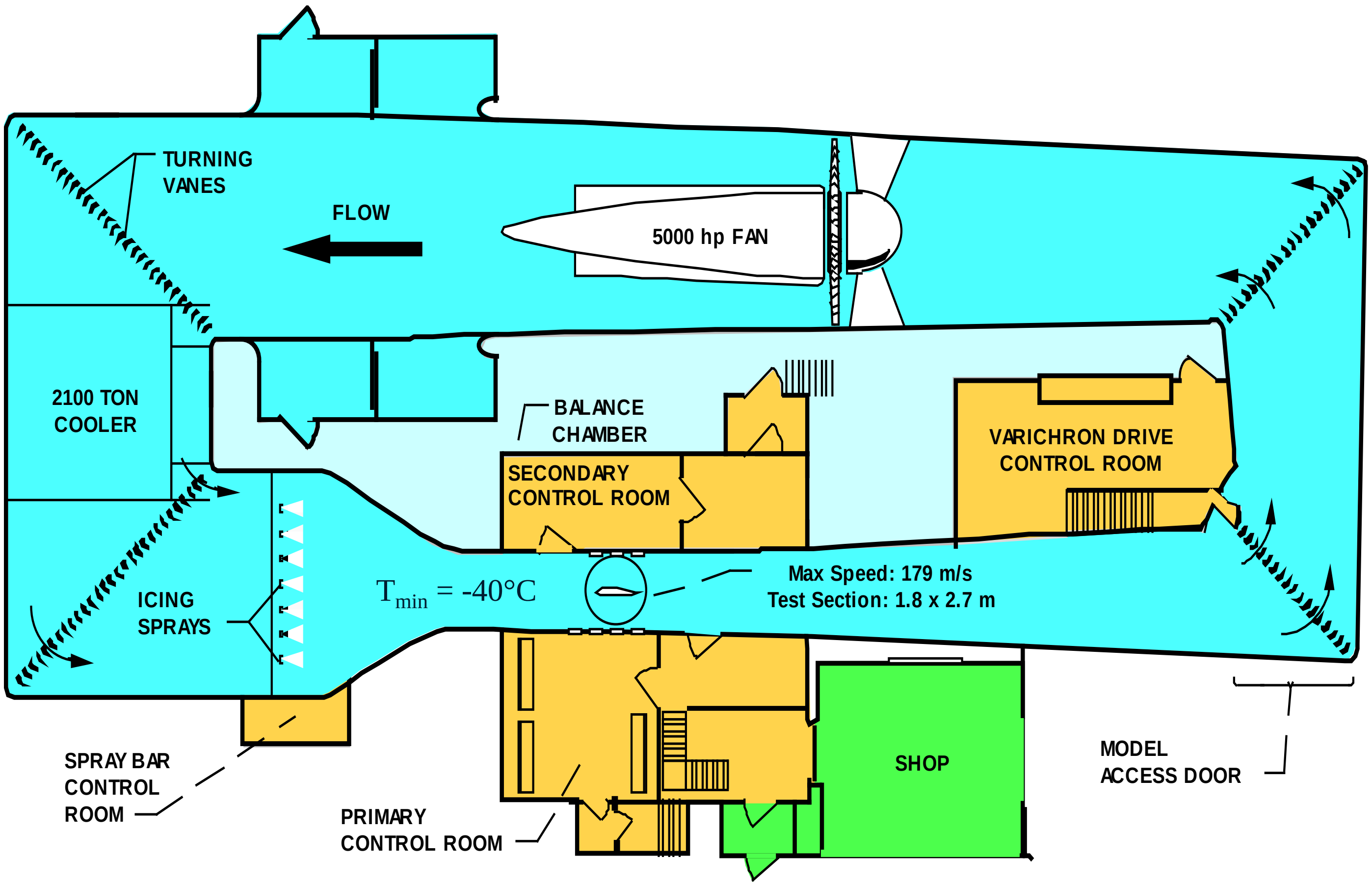




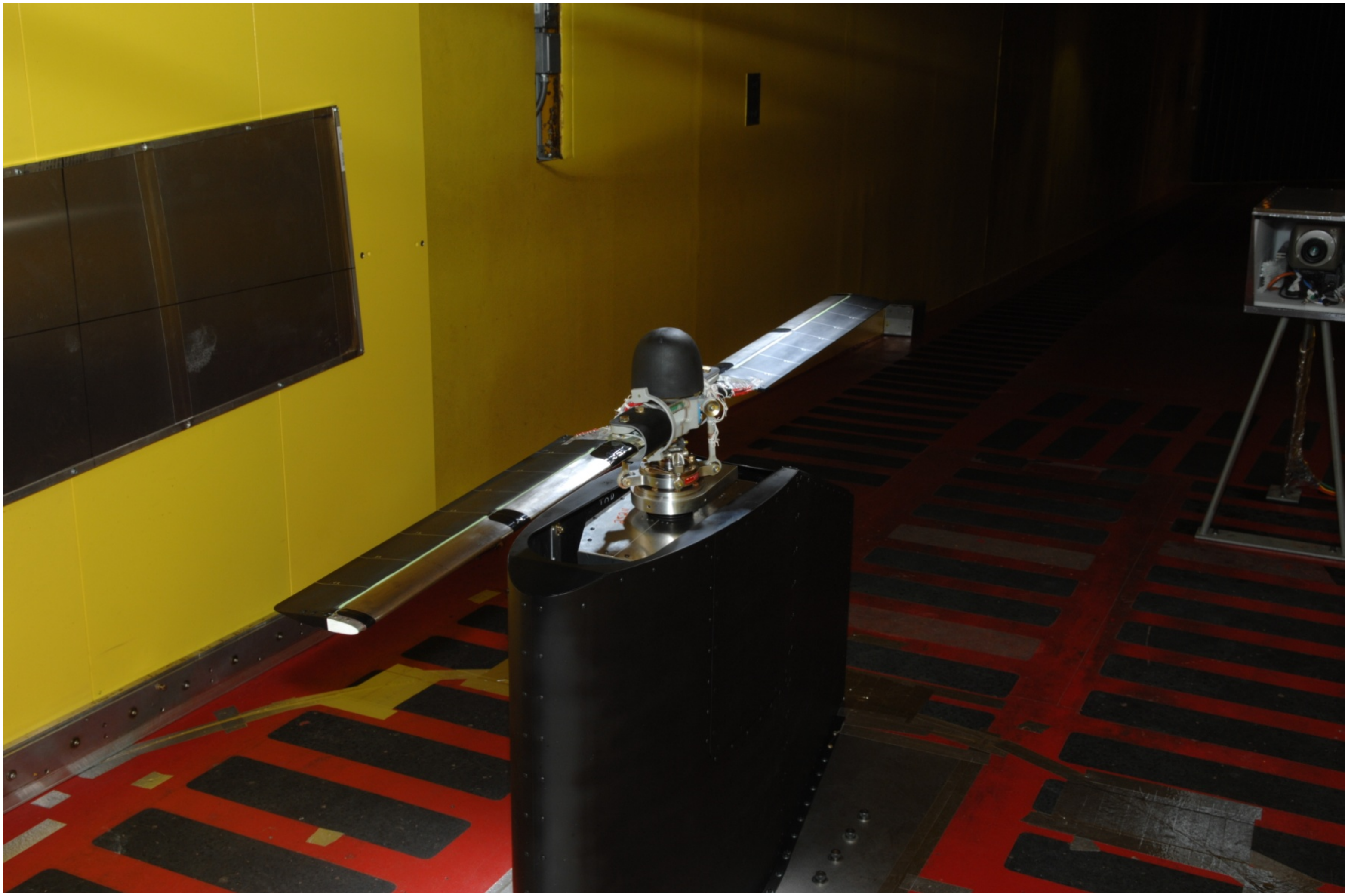
Fortin, G., and Perron, J.; "Spinning Rotor Blade Tests in Icing Wind Tunnel." AIAA 2009-4260, 1st AIAA Atmospheric and Space Environments Conference, June 22-25, 2009, San Antonio, TX.

Itagaki, K.; "Mechanical Ice Release Processes – I. Self-Shedding from High Speed Rotors." CRREL Report 83-26, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, October 1983.

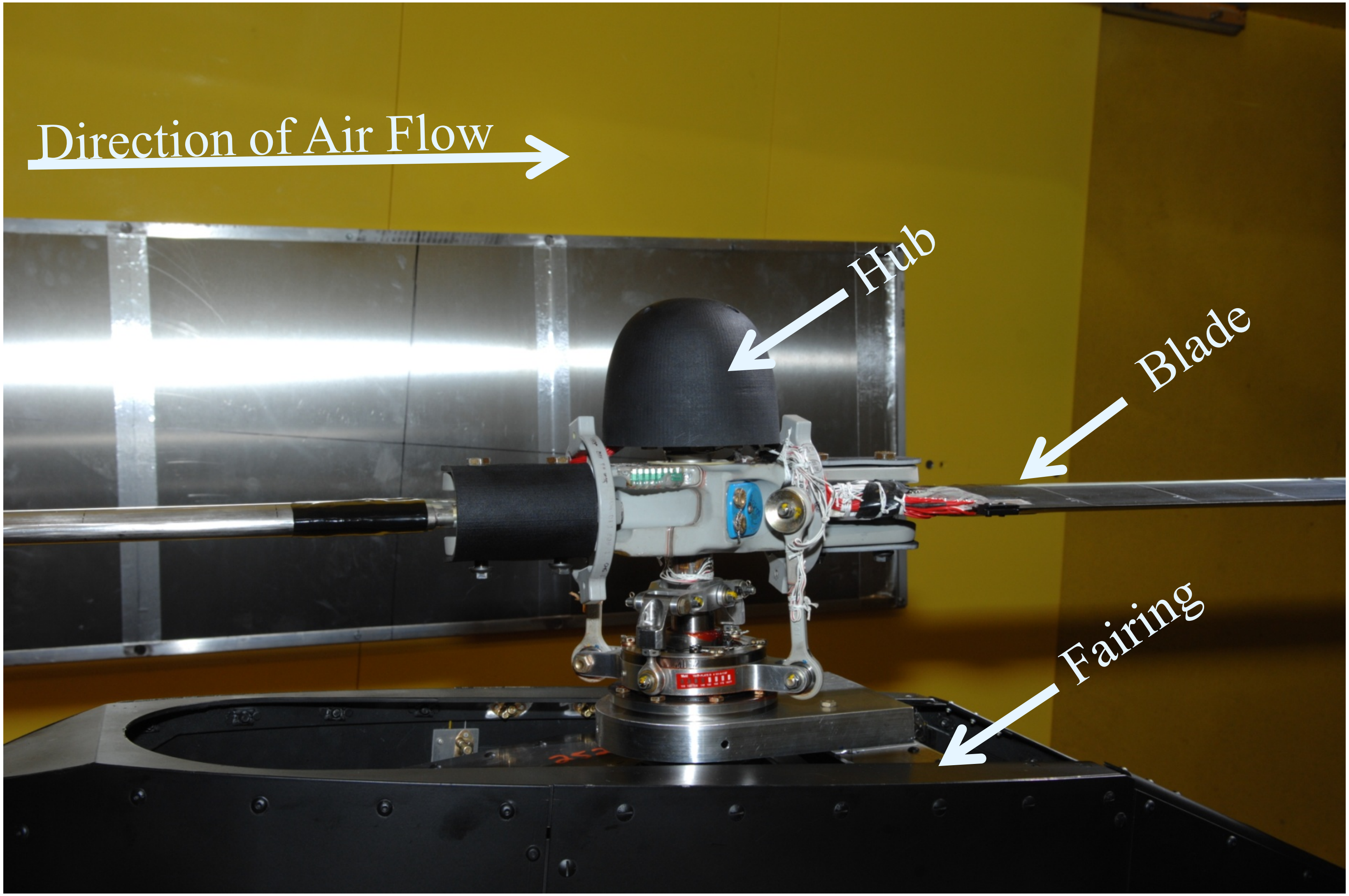
NASA Glenn Icing Research Tunnel



Rotor Model in the Icing Research Tunnel



Rotor Model in the Icing Research Tunnel



Workflow of the STAT Script

Define Parameters
- Frames per second/timestep
- Blade rotation per timestep
- 4 points for image transform
- Rotor disk diameter

Indentify Shed Images
- Images masked to remove rotor disk
- Peaks detected in image intensity
- Images Imported

Transform Images
- Using 4-point projective plane transformation

Subtract Background
- Using median image of all shed images

Images Processed
- Masking (remove rotor disk)
- Median filtered
- Otsu threshold to create binary image
- Mask within 15 pixels of Otsu thresholded gradient image

Identify Particle Statistics
- Area determined by pixel count
- Centroid located
- Volume estimated from area

Estimate Shed Origination
- Find tangent lines to shed particles
- Identify shed angle at first tangent point

Calculate STM Fronts
- User input to fit model
- Specify break points on leading edge

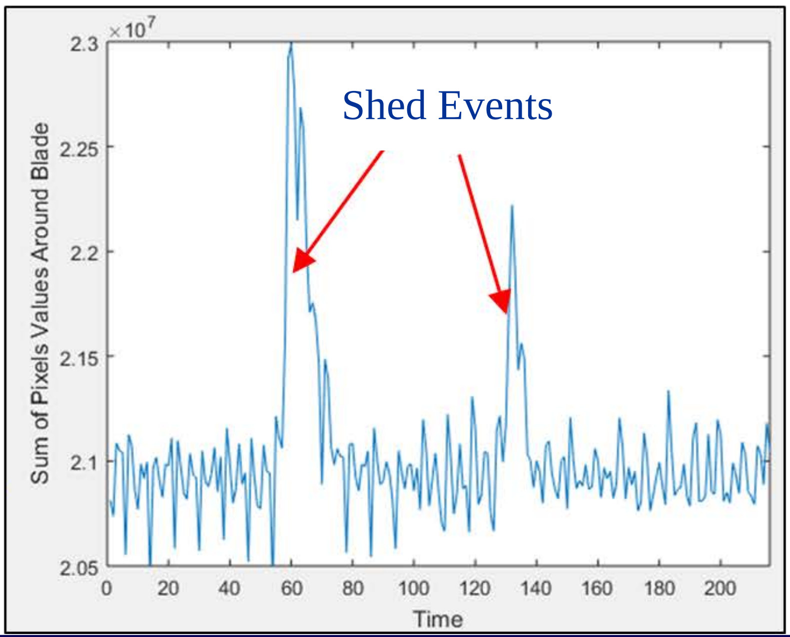
Plot Output
- Plot binarized image
- Plot STM shed fronts
- Plot rotor disk line
- Plot background subtracted rotor disk

Finding Shed Events

	Description	Rotor Speed (rpm)	Blade Pitch (deg)	Tunnel Static Temp. (°F)	Tunnel Speed (kts)	LWC (g/m³)	MVD (µm)
Run 67	Chordwise De-ice	1200	10	-4	60	0.5	15
Run 71	Spanwise De-ice	1200	5	-4	60	0.5	15

.cine
(Video)

.jpg
(1,000s of Images)



.jpg
(Shed Only,
~10 images)

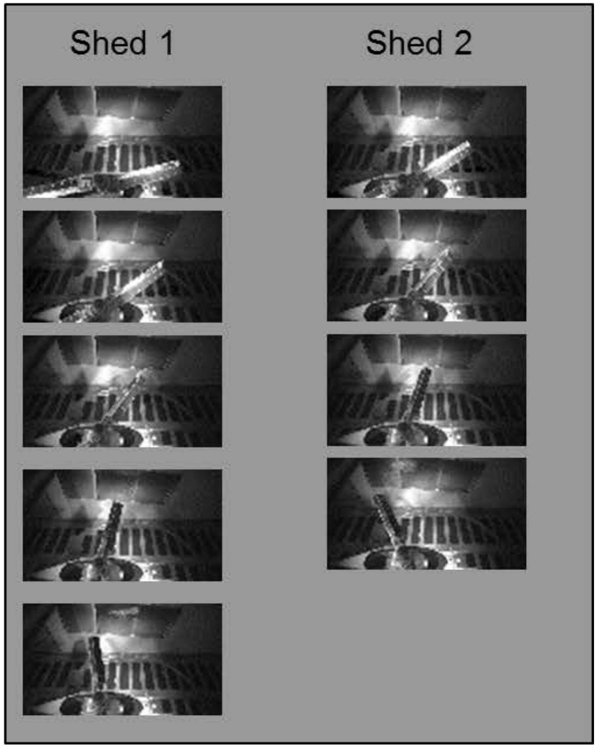
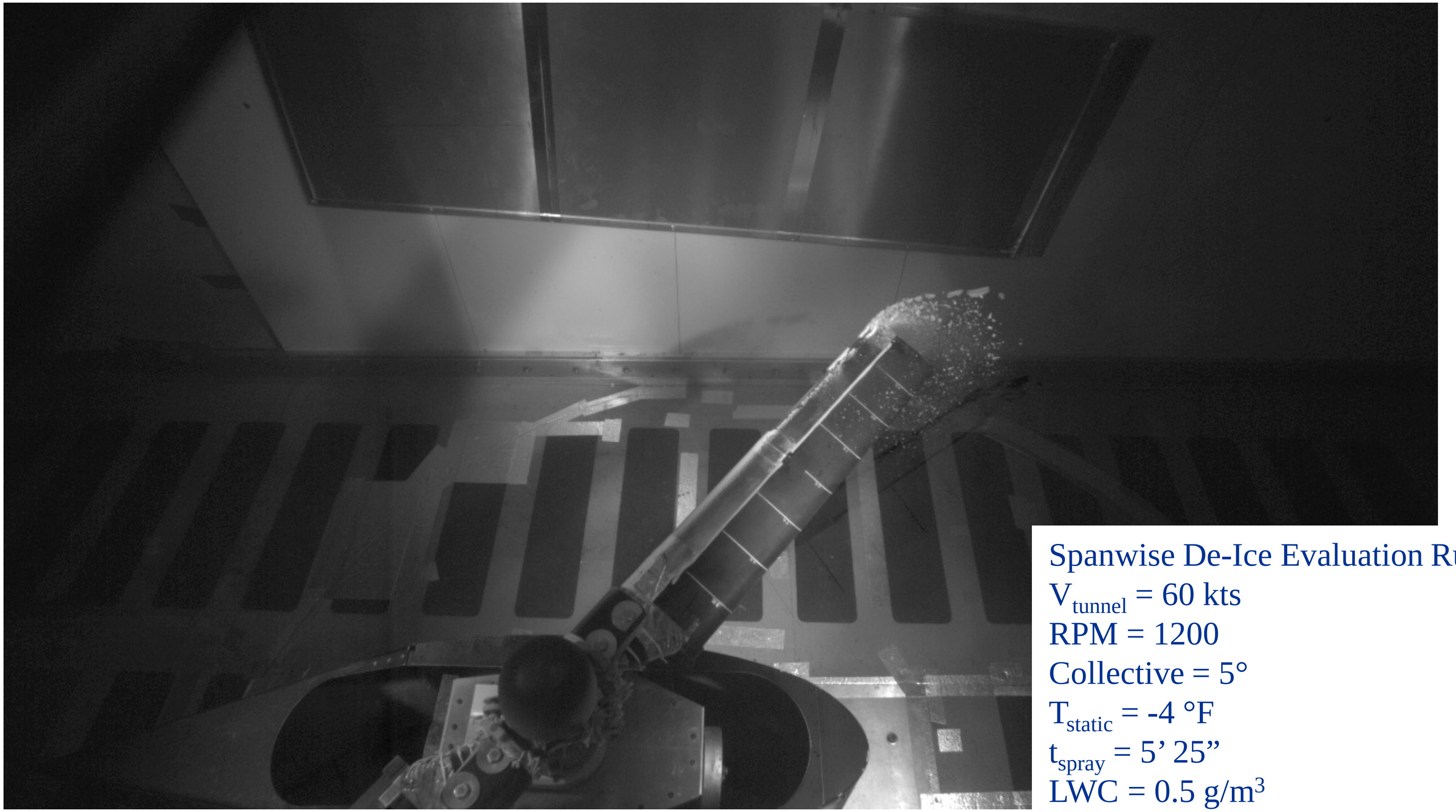


Image Processing – Original (Run 71)



Spanwise De-Ice Evaluation Run
V_{tunnel} = 60 kts
RPM = 1200
Collective = 5°
T_{static} = -4 °F
t_{spray} = 5’ 25”
LWC = 0.5 g/m^3
MVD = 15 micron
Frame Rate = 480 fps

Image Processing - Transformed

Image Processing – Background Subtracted

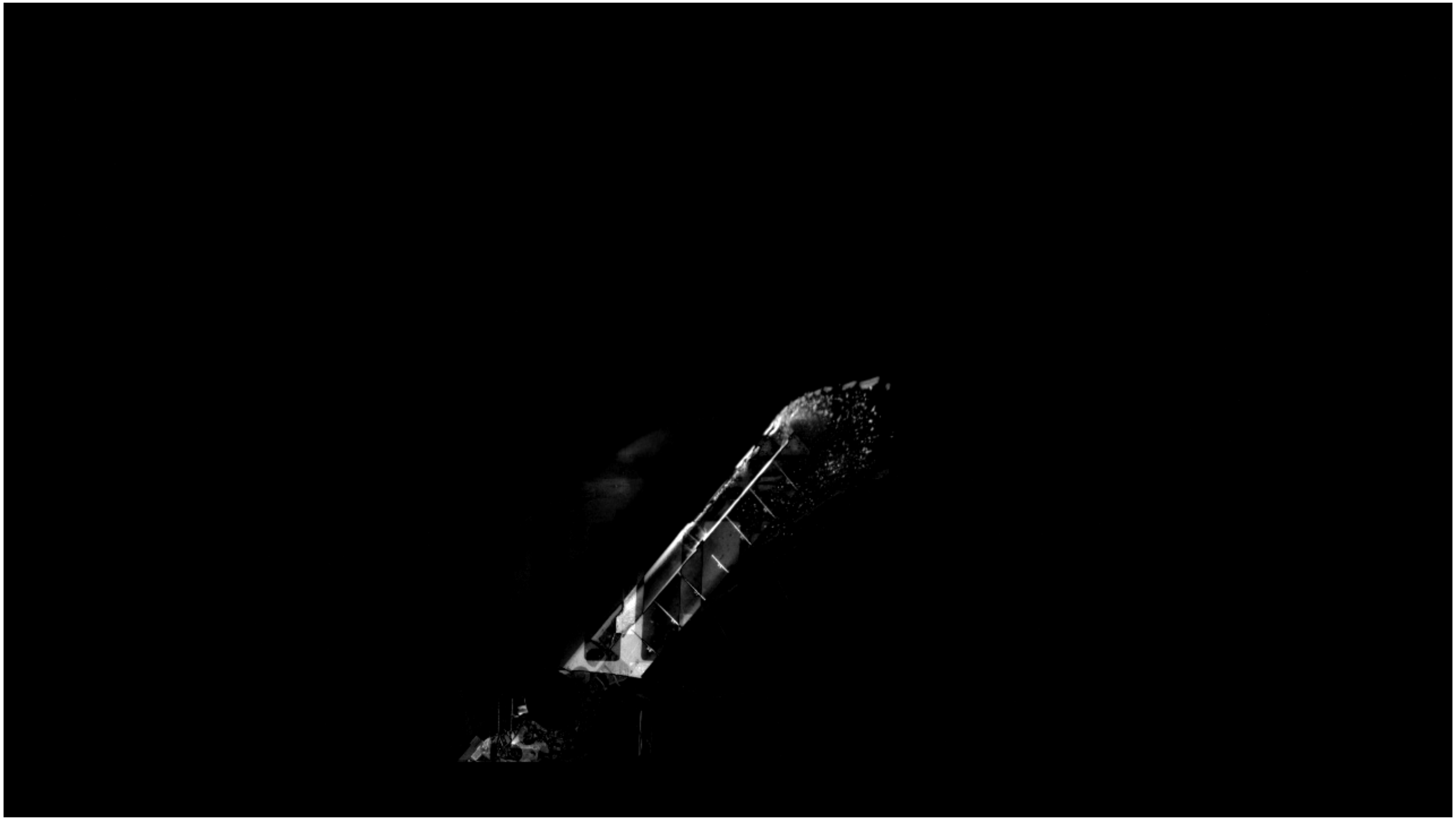


Image Processing – Background Subtracted

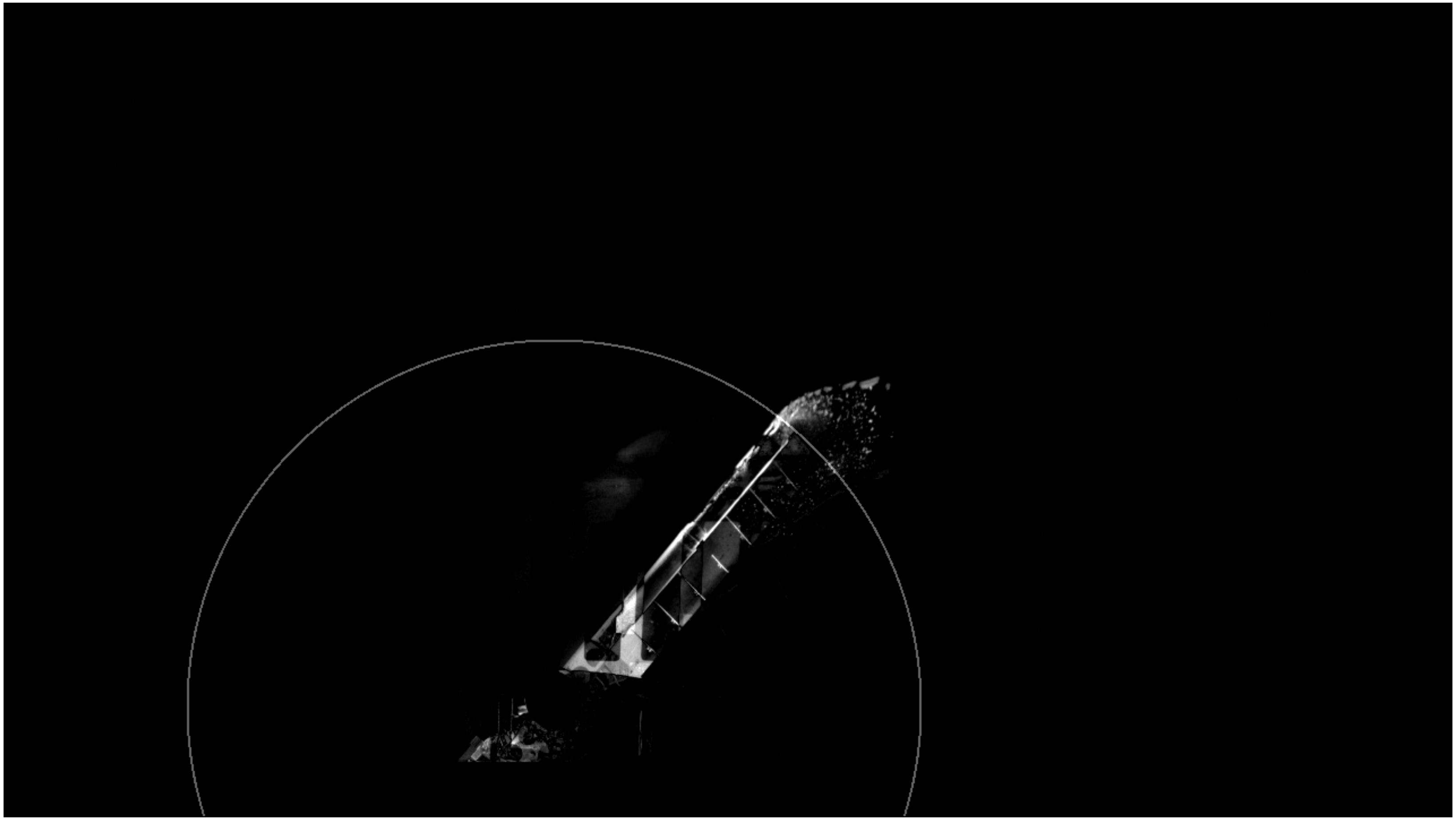
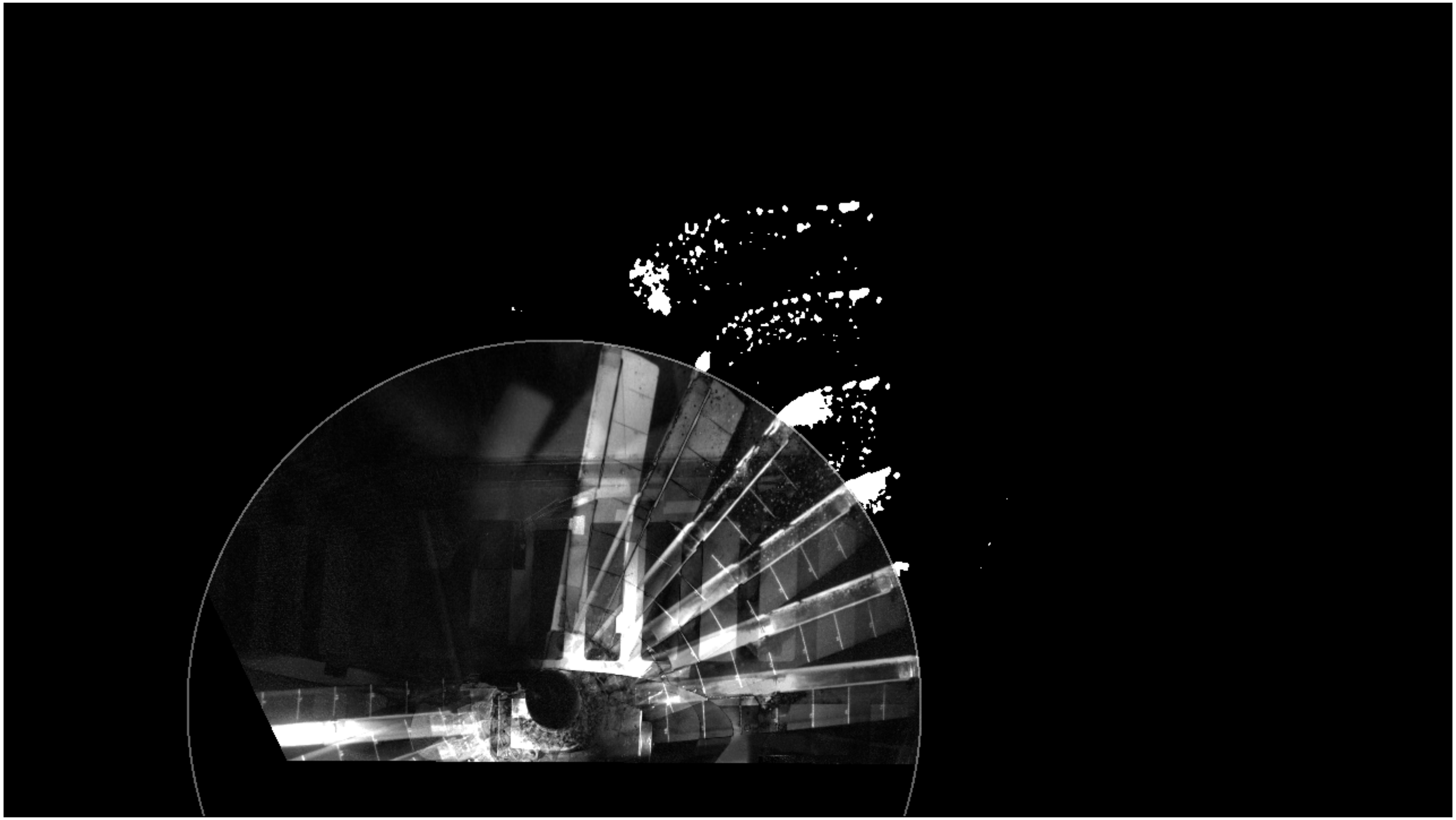
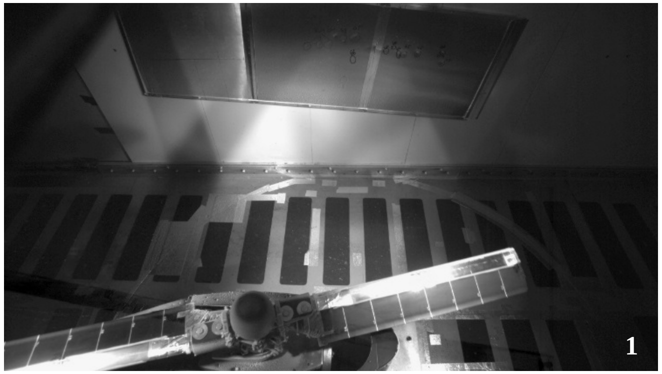
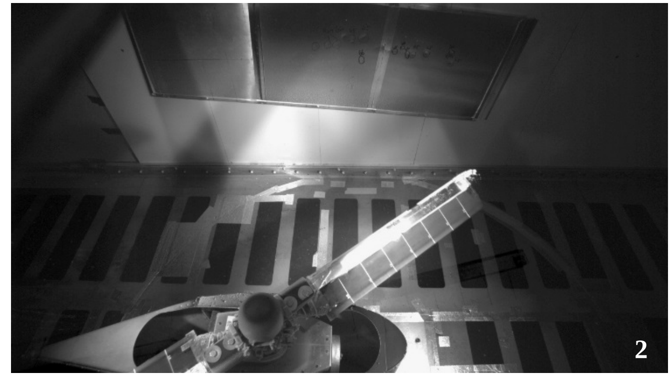


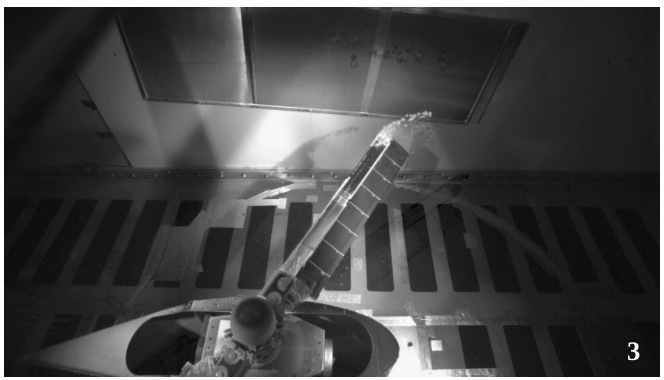
Image Processing – Final Stage

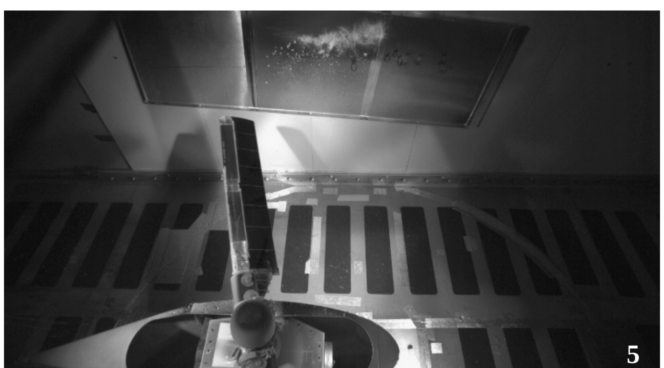


Run 67 Shed Event









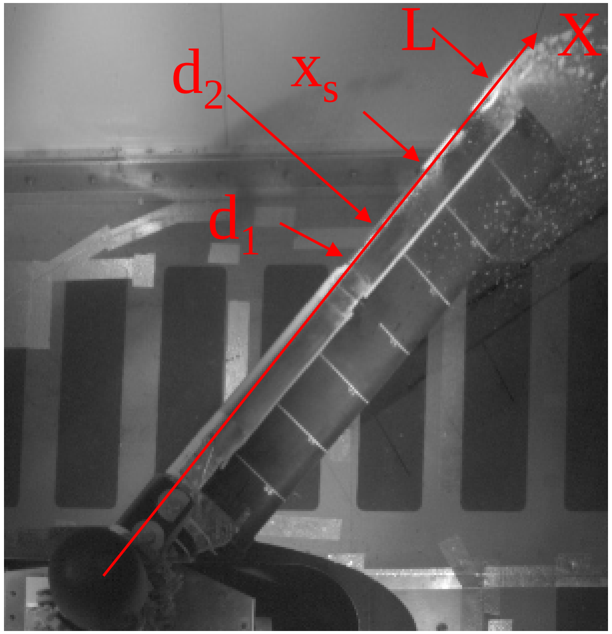
Chordwise De-Ice Evaluation Run
V_{tunnel} = 60 kts
RPM = 1200
Collective = 10°
T_{static} = -4 °F
t_{spray} = 6’ 49”
LWC = 0.5 g/m^3, MVD = 15 micron
Frame Rate = 320 fps

Run 67 Shed Frame -4379

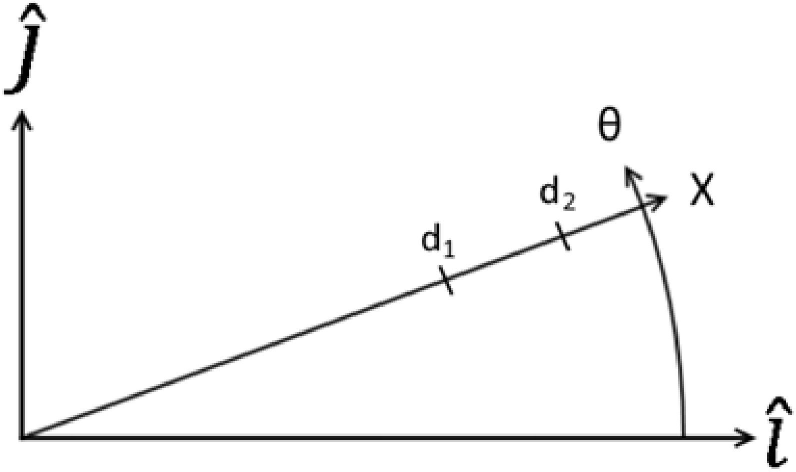
SHEDDING TRAJECTORY MODEL (STM)

Terms (1/2)

- L = rotor disc radius
- d_1 = start of shed ice
- d_2 = end of shed ice
- x_s = radial position of shed ice, inner edge
- θ = rotational position of the rotor,
  - Typically $\theta_i = 0$ at shed start
  - θ_i can be adjusted to correct STAT's automatically identified shed start
- $Z = L - d_2 + d_1$
  - When ice reaches blade tip and breaks off

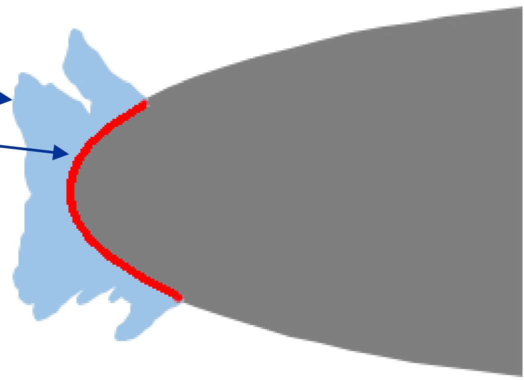


- **Shown on next slide:**
- A = cross-sectional area of ice, normal to X
- W = width of A at interface

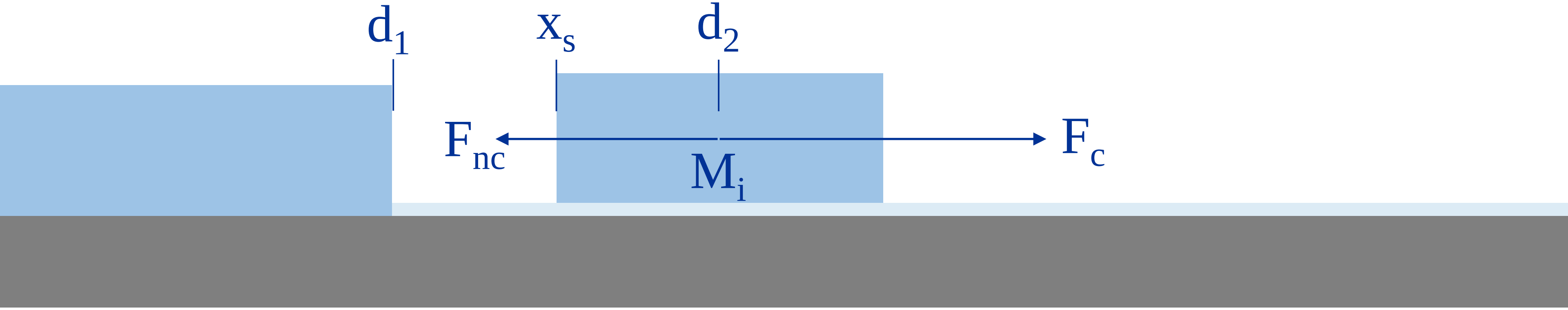


Terms (2/2)

- A is the blue area
- W is the length of the red line



- M_i is the mass of the ice
- F_c is the centrifugal force on the ice
- F_{nc} are the non-conservative forces
  - b is coefficient for viscous damping
  - F_f' is coefficient for friction (per unit length)
- $F_i = F_{nc} + F_c$



On-Rotor Position Calculation

$$F_i(x_s) = \begin{cases} \overbrace{\rho A(d_2 - d_1)}^{\text{Mass}} \overbrace{\left(x_s + \frac{(d_2 - d_1)}{2}\right)}^{\text{Centroid Position}} \omega^2 - \overbrace{(d_2 - d_1)}^{\text{Interfacial Area}}\left(Wb\dot{x}_s + F_f{}'\right), x_s < z \\ \underbrace{\rho A \frac{(L^2 - x_s^2)}{2} \omega^2}_{\text{Inertial Term}} - (L - x_s)\left(\underbrace{\dot{x}_s bW}_{\text{Damping Term}} + \underbrace{F_f{}'}_{\text{Friction Term}}\right), x_s \geq z \end{cases}$$

$$M_i(x_s) = \begin{cases} \rho A(d_2 - d_1), x_s < z \\ \rho A(L - x_s), x_s \geq z \end{cases}$$

$$a_i(x_s) = \frac{F_i(x_s)}{M_i(x_s)} = \begin{cases} \frac{\omega^2}{2}\left(2x_s + (d_2 - d_1)\right) - \frac{\left(\dot{x}_s bW + F_f'\right)}{\rho A}, x_s < z \\ \frac{\omega^2}{2}(L + x_s) - \frac{\left(\dot{x}_s bW + F_f'\right)}{\rho A}, x_s \geq z \end{cases}$$

On-Rotor Position Calculation

The on-rotor position is necessary to get initial velocity of ice leaving the rotor

$$B = \frac{bW}{\rho A}$$

$$F = \frac{F_f'}{\rho A \omega^2}$$

Problem:

$$\begin{cases} \ddot{x}_s + B\dot{x}_s - \omega^2 x_s = \dfrac{w^2(d_2 - d_1 - 2F)}{2}, x_s < z \\ \ddot{x}_s + B\dot{x}_s - \dfrac{\omega^2}{2} x_s = \dfrac{w^2(L - 2F)}{2}, x_s \geq z \end{cases}$$

$$r_{1,2} = \frac{\left(-B \pm \sqrt{B^2 + 4\omega^2}\right)}{2}$$

$$r_{3,4} = \frac{\left(-B \pm \sqrt{B^2 + 2\omega^2}\right)}{2}$$

Solution:

$$x_s(t) = \begin{cases} c_1 e^{r_1 t} + c_2 e^{r_2 t} + F - \dfrac{d_2 - d_1}{2}, x_s < z \\ c_3 e^{r_3 t} + c_4 e^{r_4 t} + 2F - L, x_s \geq z \end{cases}$$

$$c_1 = \frac{d_1 + d_2 - 2F}{2(1 - \frac{r_1}{r_2})}$$

$$c_2 = \frac{d_1 + d_2 - 2F}{2(1 - \frac{r_2}{r_1})}$$

$$c_3 = \frac{V_{1f} - r_4(2L - 2F - d_2 + d_1)}{r_3 - r_4}$$

$$c_4 = \frac{V_{1f} - r_3(2L - 2F - d_2 + d_1)}{r_4 - r_3}$$

Off-Rotor Position Calculation

$$x_i = L\cos(\omega t + \theta_i)\,\hat{\imath} + L\sin(\omega t + \theta_i)\,\hat{\jmath}$$

$$V_t = \omega L$$

$$\dot{x_s}(t) = \mathrm{V}_r = \begin{cases} c_1 r_1 e^{r_1 t} + c_2 r_2 e^{r_2 t}, x_s < z \\ c_3 r_3 e^{r_3 t} + c_4 r_4 e^{r_4 t}, x_s \geq z \end{cases}$$

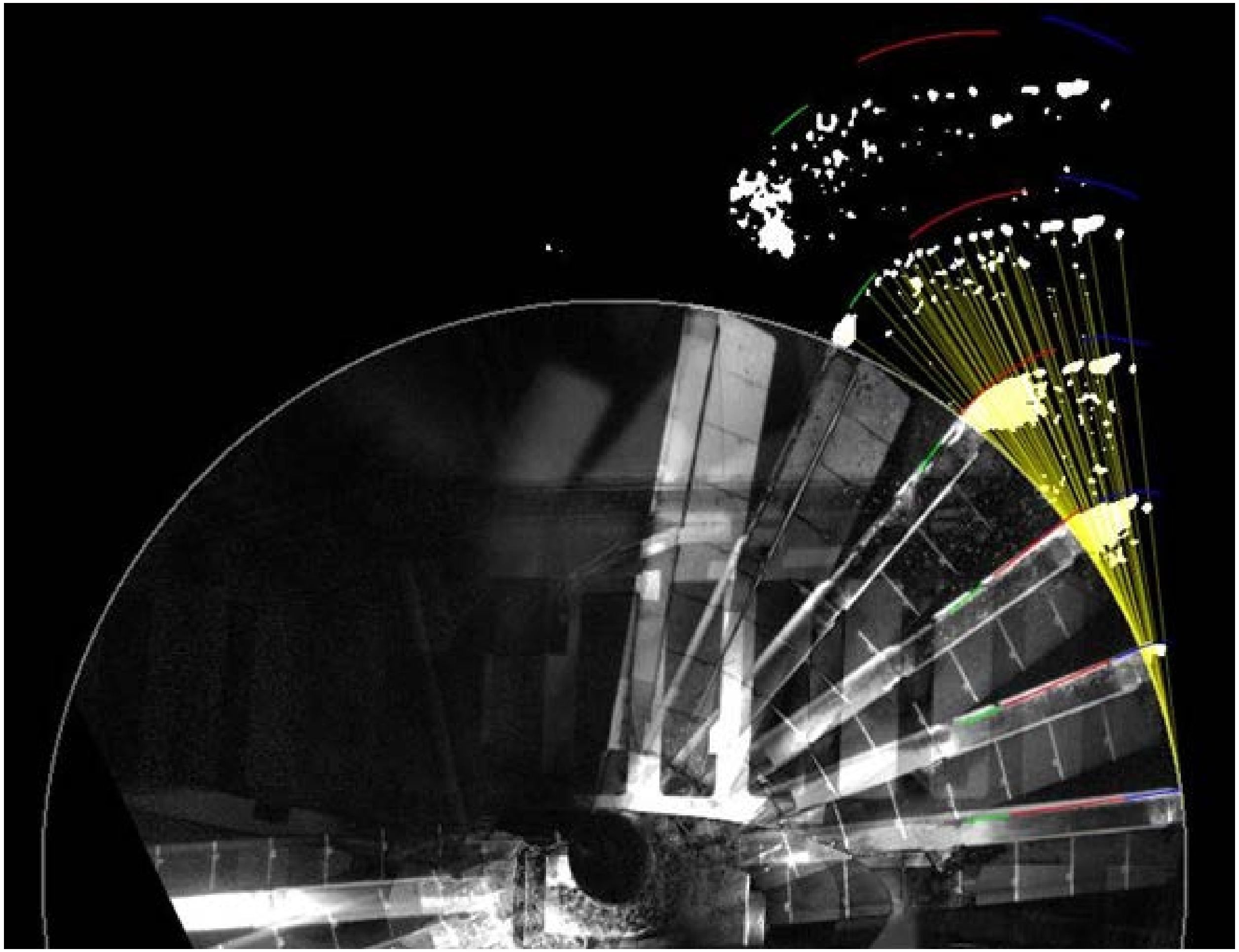
$$\begin{aligned} V_i(B,F) = &\,(V_r(B,F)\cos(\omega t + \theta_i) - V_t \sin(\omega t + \theta_i))\hat{\imath} \\ &+(V_r(B,F)\sin(\omega t + \theta_i) + V_t \cos(\omega t + \theta_i))\hat{\jmath} \end{aligned}$$

Predicted position of shed ice with quadratic drag (c is the drag term):

$$x_2(t,B,F,c) = \frac{m}{c}\ln\left(1 + \frac{cV_i(B,F)t}{m}\right) + x_i$$

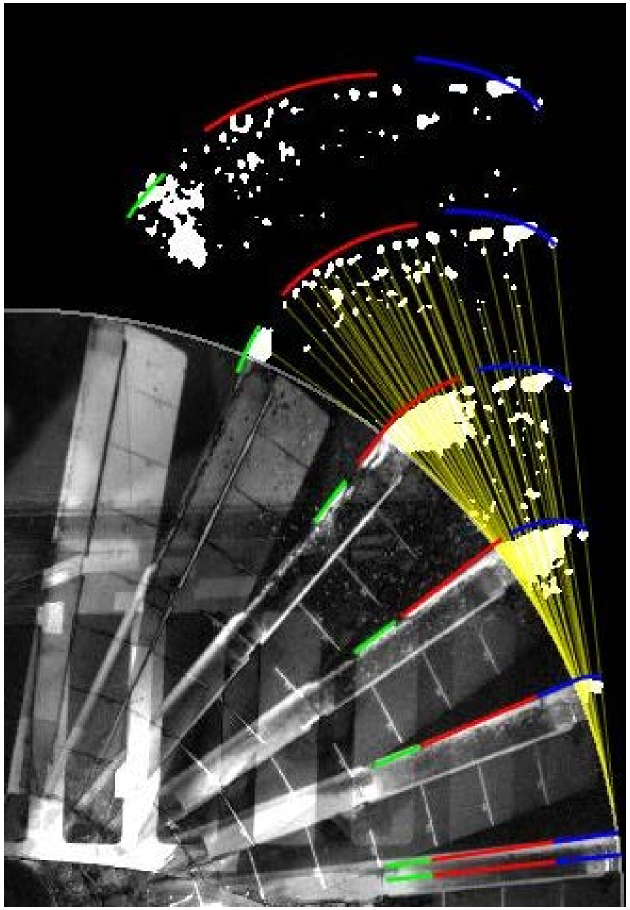
$$c = \frac{c_d A_p \rho_a}{2m}$$

RESULTS

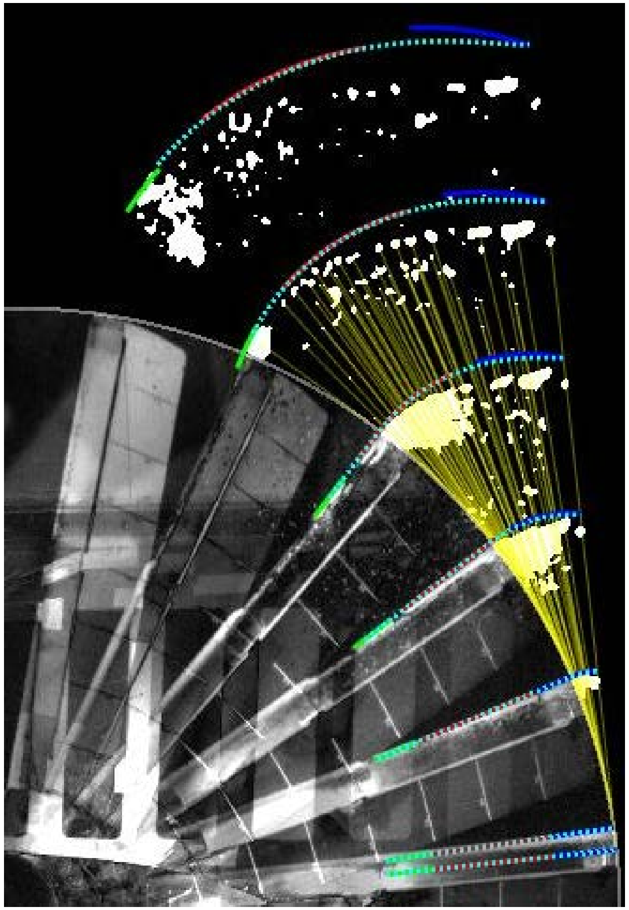


F = 0, B = 0, c = 0, θ = 0

Shed Ice Images Compared to Unfit STM, Run 71.

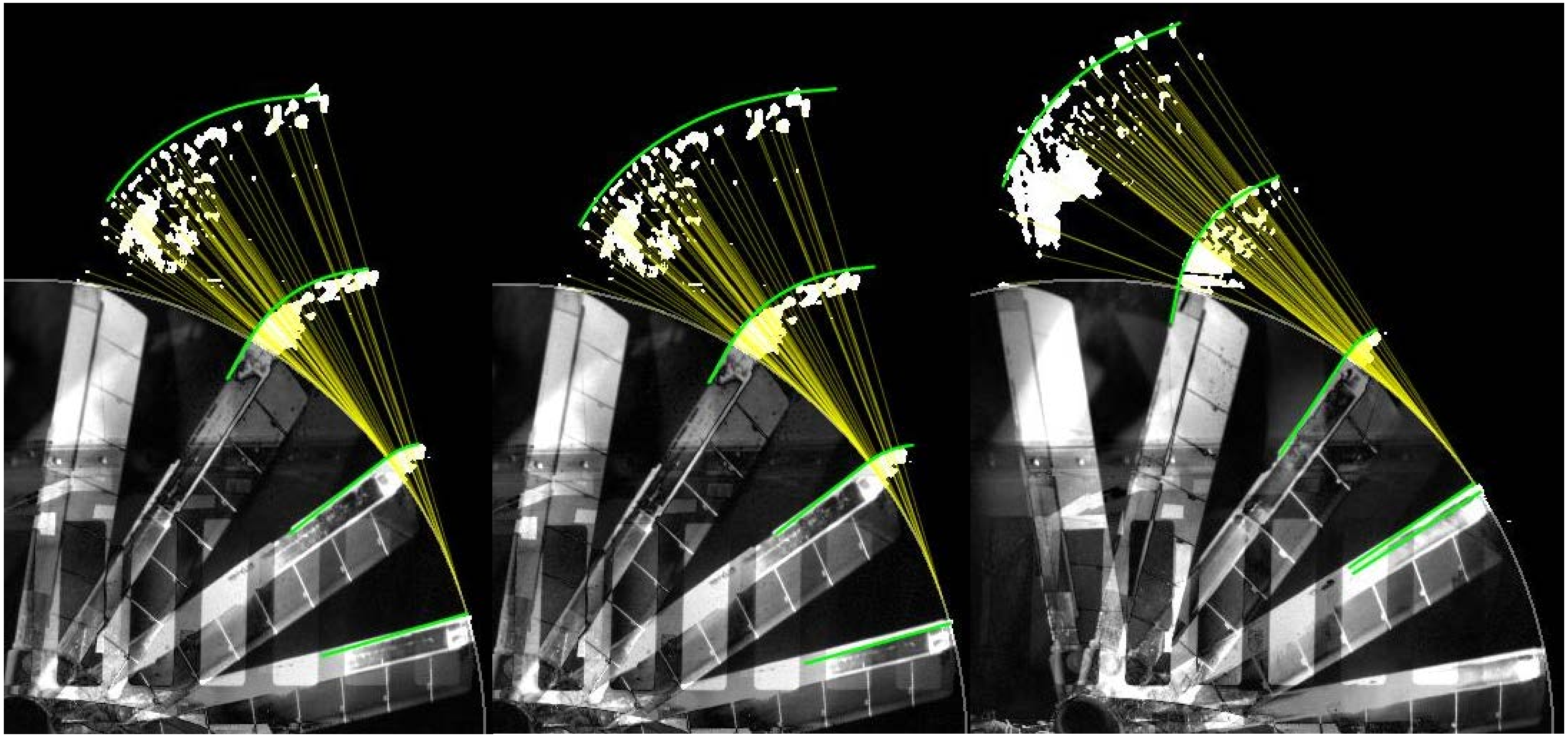


F = 0, B = 60, c = 0.0004, θ = 0



F = 0, B = 60, c = 0, θ = 0
Dotted cyan line is prediction for singular shed

Shed Ice Images Compared to Fit STM, Run 71.



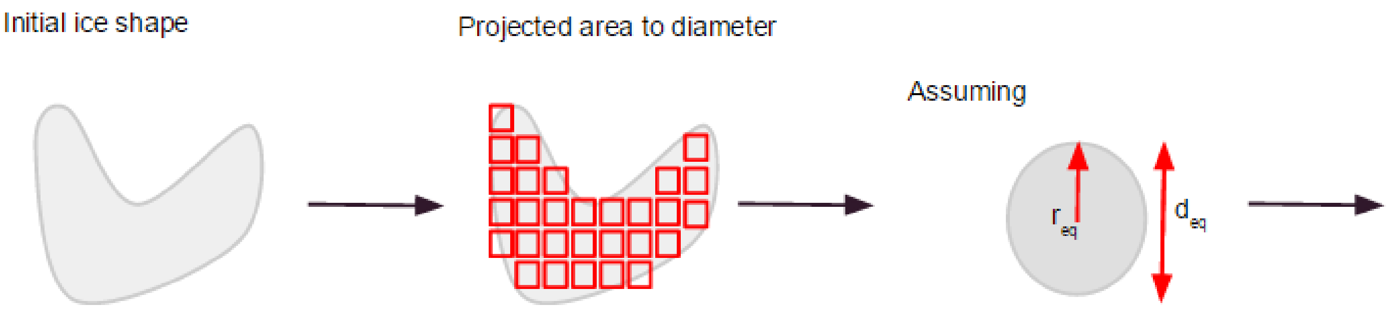
F = 0, B = 60, c = 0, θ = 0
Shed 1

F = 0, B = 140, c = 0, θ = 4
Shed 1

F = 0, B = 60, c = 0, θ = 0
Shed 2

Shed Ice Images Compared to Fit STM, Run 67.

Estimated Shed Ice Mass for High Speed Impact Analysis

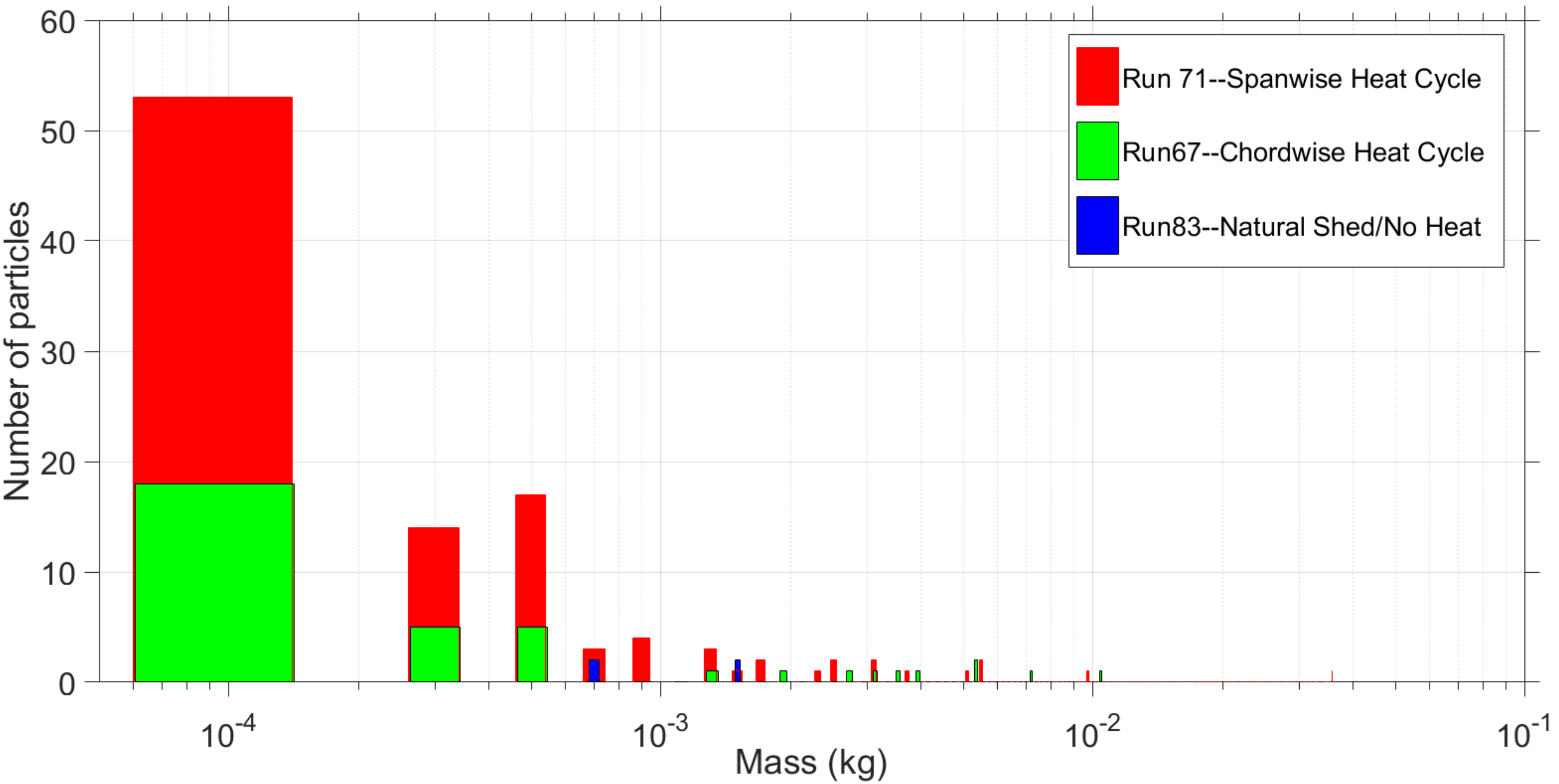


$$A = \pi r_{eq}^2 = \frac{\pi d_{eq}^2}{4}$$

$$V_2 = \frac{4}{3}\pi\left(\frac{A}{\pi}\right)^{\frac{3}{2}}$$

	Total mass shed (kg)	No. particles	Avg particle mass (kg)	St. dev. of masses (kg)
Run 67 (chordwise)	0.0511	38	0.00134	0.0023
Run 71 (spanwise)	0.1064	108	0.00099	0.0037
Run 83 (natural)	0.0045	4	0.00113	0.0006

Estimated Mass Distribution



Conclusions

- Two runs consisting of three shed events were analyzed
- The STAT tool was developed to post-process the data
- A model (STM) to predict the trajectory of a shed front was developed
  - Viscous forces at the interface between the ice and the rotor are significant
  - B is the most important fit parameter, B = 60 provides current best fit
  - There is insufficient data to estimate the importance of the c term
  - Interstitial breaks increase the shed fan angle
- The mass distribution of shed ice was estimated

Questions?