Icing Physics Studies Using the 3D SIDRM Test Article: Ice Crystal Icing Analysis

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1. Intro
2. Ice Crystal Cloud Characterization Tests
3. Ice Crystal Accretion Tests
4. General Icing Observations
5. Leading Edge Icing Threshold
6. Surface Heat Flux Impact
7. LE Melt Contribution and Resulting Accretion Downstream
8. Conclusions and Acknowledgements

Introduction – Why Study Engine Icing

- Numerous events of power-loss and engine damage reported since the 1990's (Bravin, 2019)

- Engine icing (ice crystal icing) studied at NASA (and elsewhere)
    - Full scale engine icing tests (Honeywell LF01, LF11, HURE)
    - Component level fundamental icing physics studies

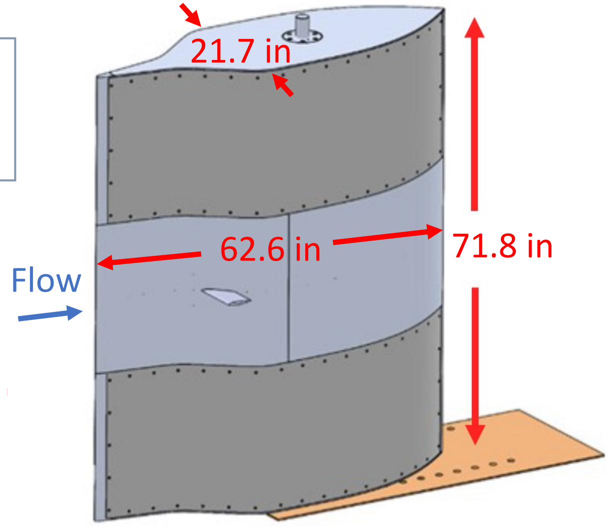
- **Goal**: Gather data to develop and validate computational icing tools (like GlennICE) to predictively assess the onset and growth of ice in current and future engines during flight, to aid certification

Testing General Details

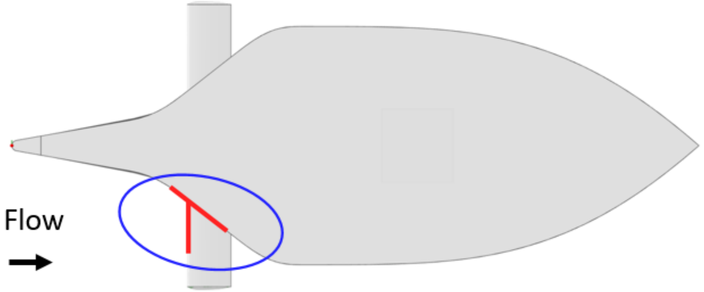
- Conducted icing tests in the NASA Icing Research Tunnel (IRT) in 2022
- Ice accretion tests used Simulated Inter-compressor Duct Research Model (SIDRM)
  - 3D geometrical features of an inter-compressor duct and strut region of a turbofan engine (curved surface w/ strut)
  - Heated surfaces
  - BUT did not fully simulate conditions
    - Different cloud: glaciated vs mixed phase
    - Different air temp: subfreezing vs heated compressed air
    - Different pressures: ~1 atm vs altitude/compressed
    - Different flow field: open vs ducted

- Tests conducted
  - Supercooled liquid ice accretion tests
  - → Ice crystal (IC) accretion tests
  - → Complementary IC cloud characterization tests (new capability)

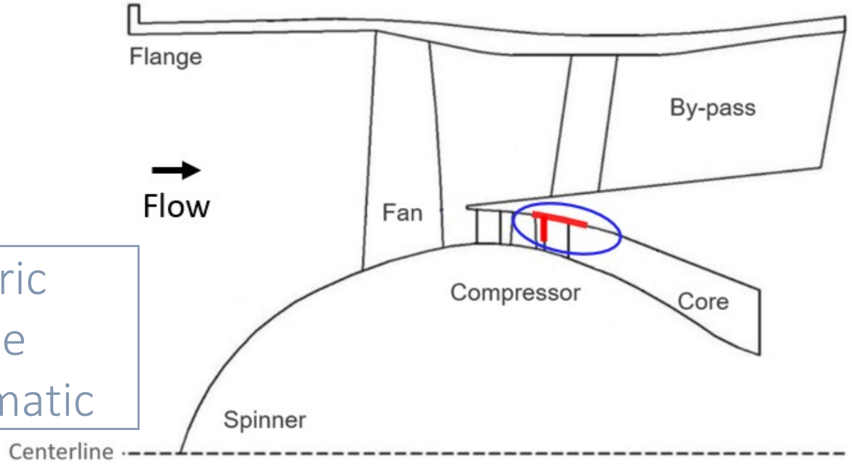
SIDRM schematic



SIDRM profile view



Generic engine schematic



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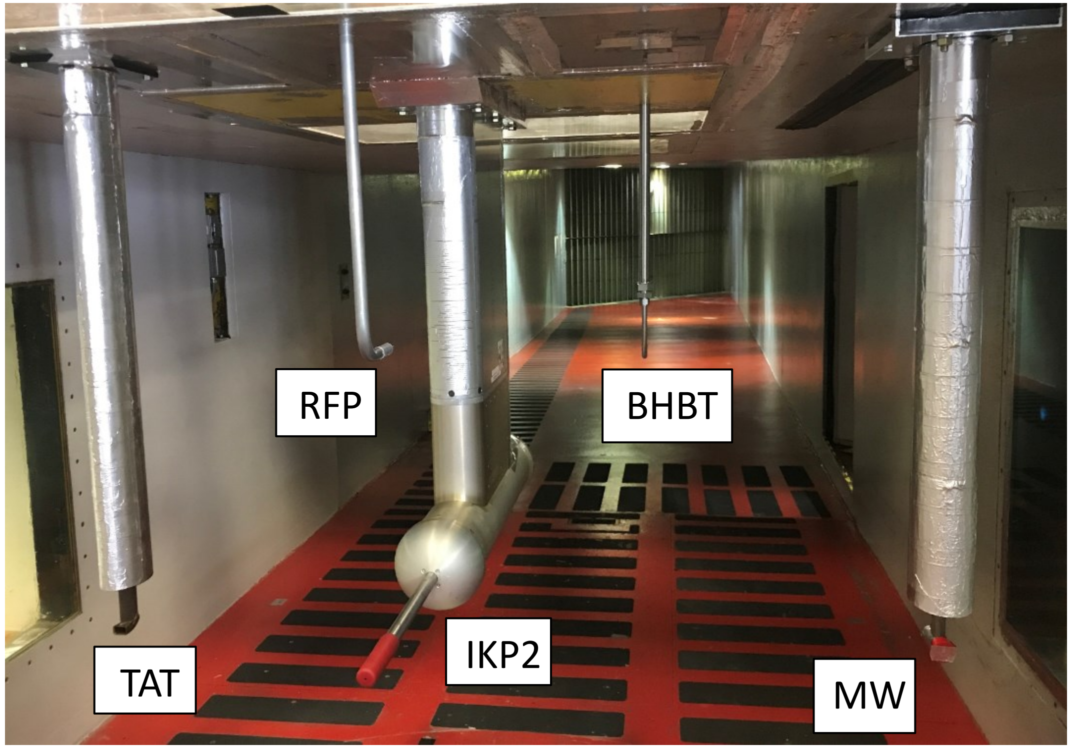
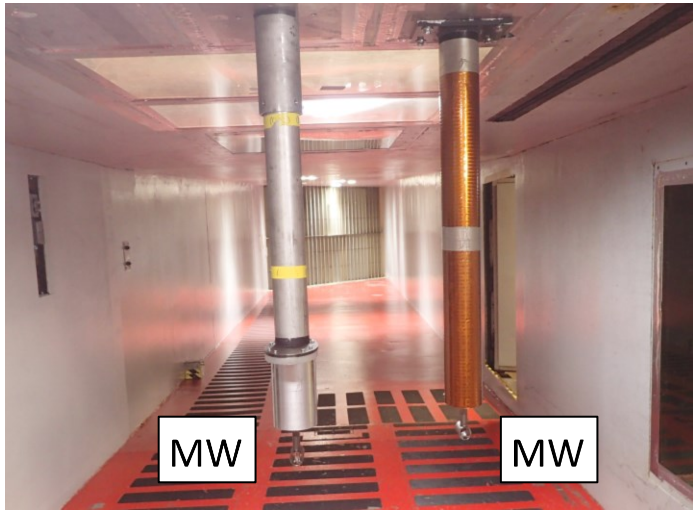
Ice Crystal Cloud Characterization Instruments



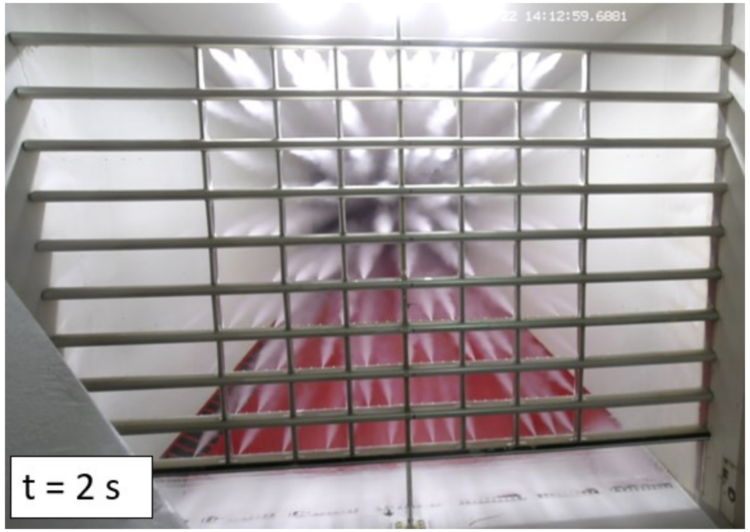
Instrument	Measurement
MW: Multiwire	Melt ratio and recirculation
IKP2: Isokinetic Probe Version 2	Total water content
RFP: Rearward Facing Probe	Air temperature and humidity
PI-IC: Particle Imaging - Ice Crystal	Particle size distribution
TAT: Total Air Temperature	Air temperature
ID: Ice Detector (not shown)	Glaciation (liquid presence)
BHBT: Background Humidity Bent Tube	Humidity

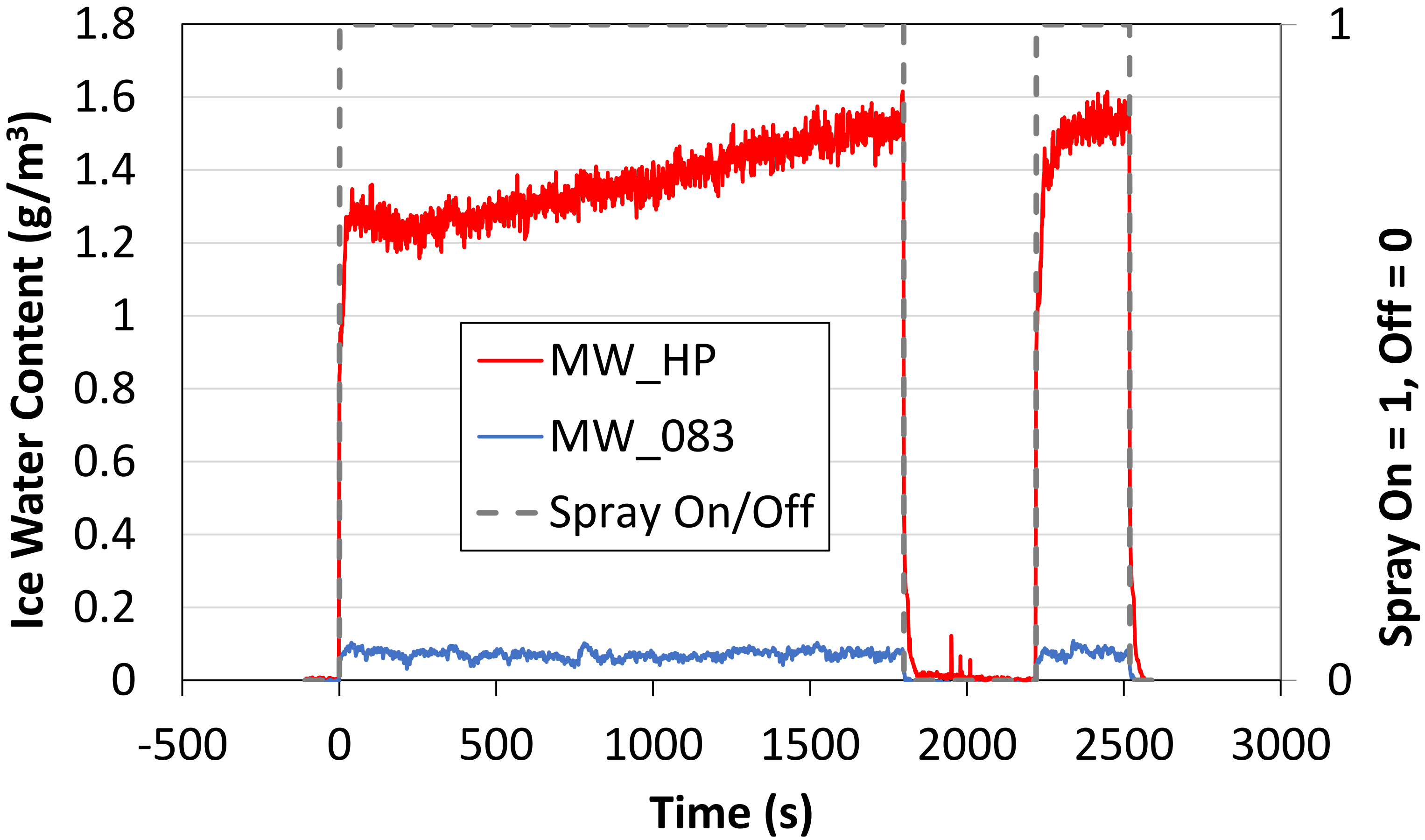


12 Icing clouds characterized

- Total Water Content (TWC)
- Particle Size Distribution (PSD)

Cloud Recirculation and Continuation





Thaw resolved issue → Tunnel raised to 10 °C for ~30 min to melt ice

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Ice Accretion Test Objectives

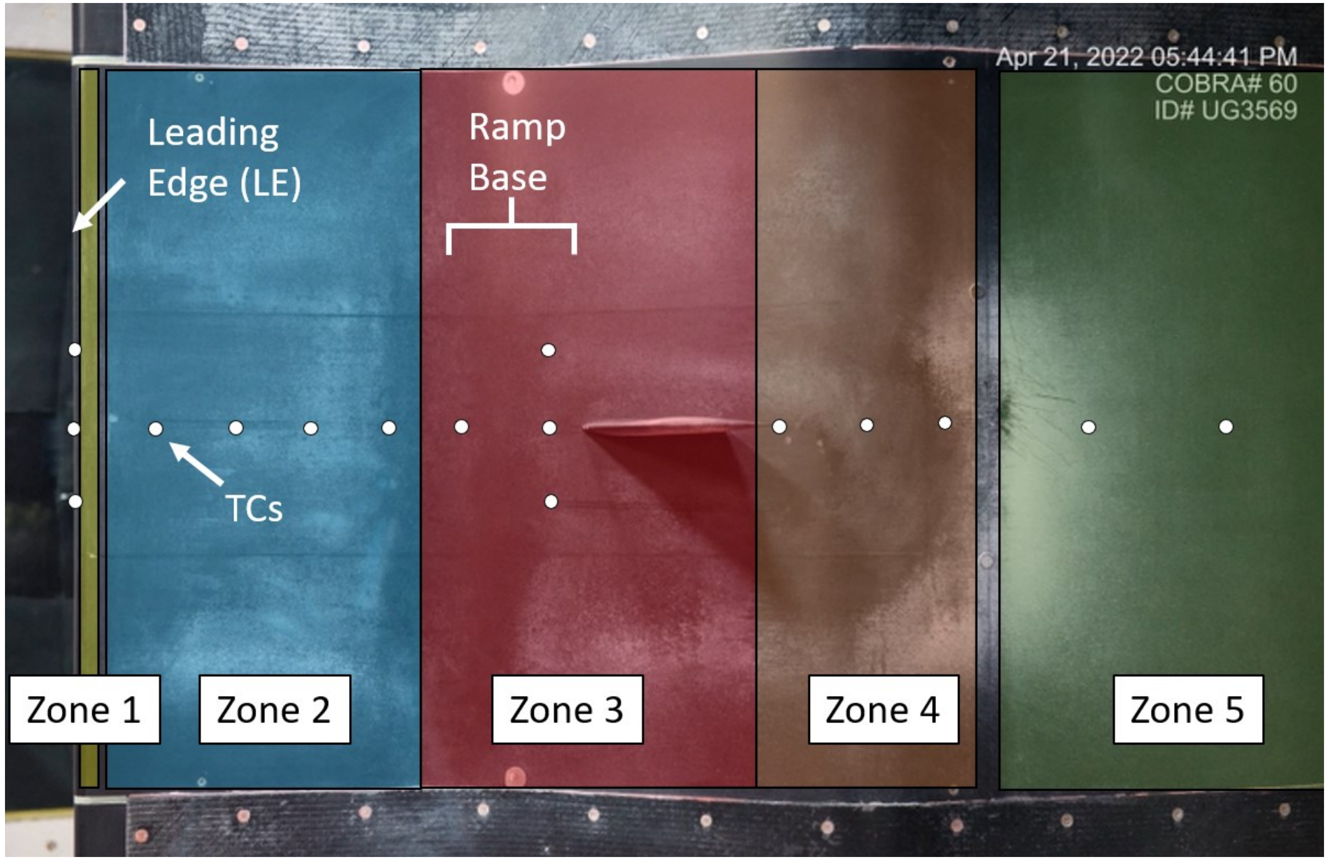
Objectives:

- Identify test parameter's impact on ice accretion mass, location, and characteristics:
  - Surface heat flux
  - AOA
  - MVD + TWC
  - Airspeed
- Investigate leading edge icing heat flux threshold
- Investigate leading edge melt contribution
- Generate accretions without shedding

Key Measurements:

- 3D laser scans (end of test)
- Ice mass (end of test)
- Heat flux (and heater power measurements)
- Surface temperature
- Video to observe icing behavior

20 test runs presented in paper



Heater Overlay

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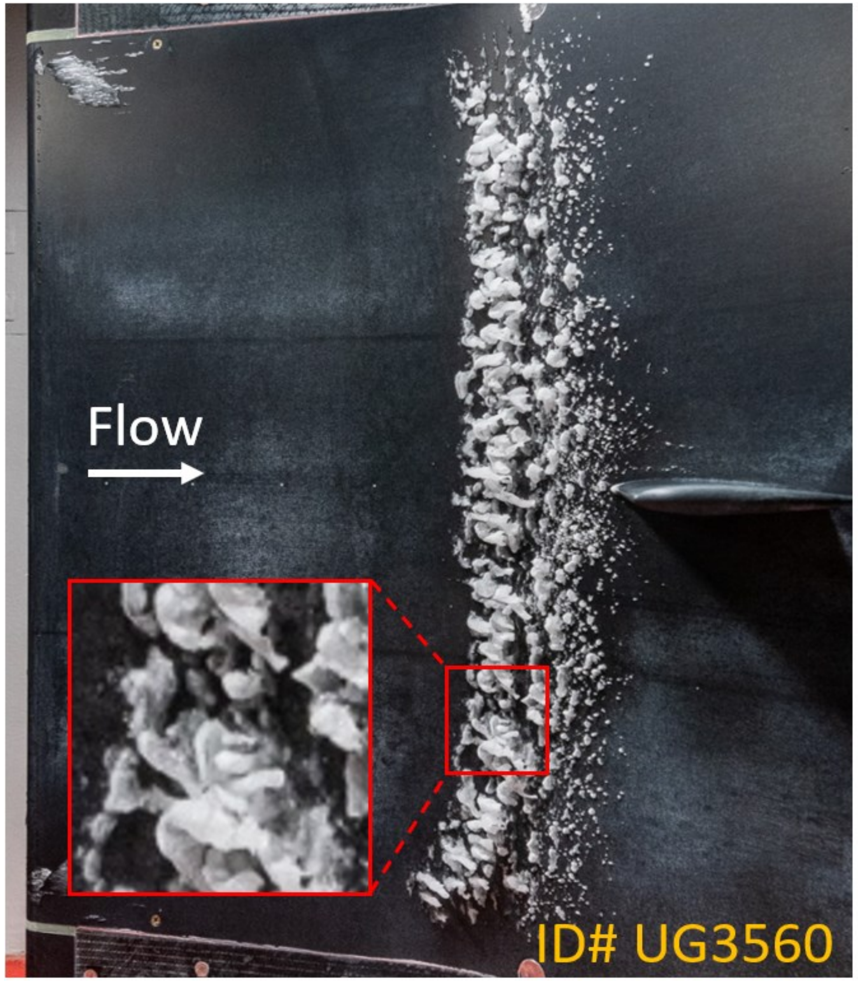
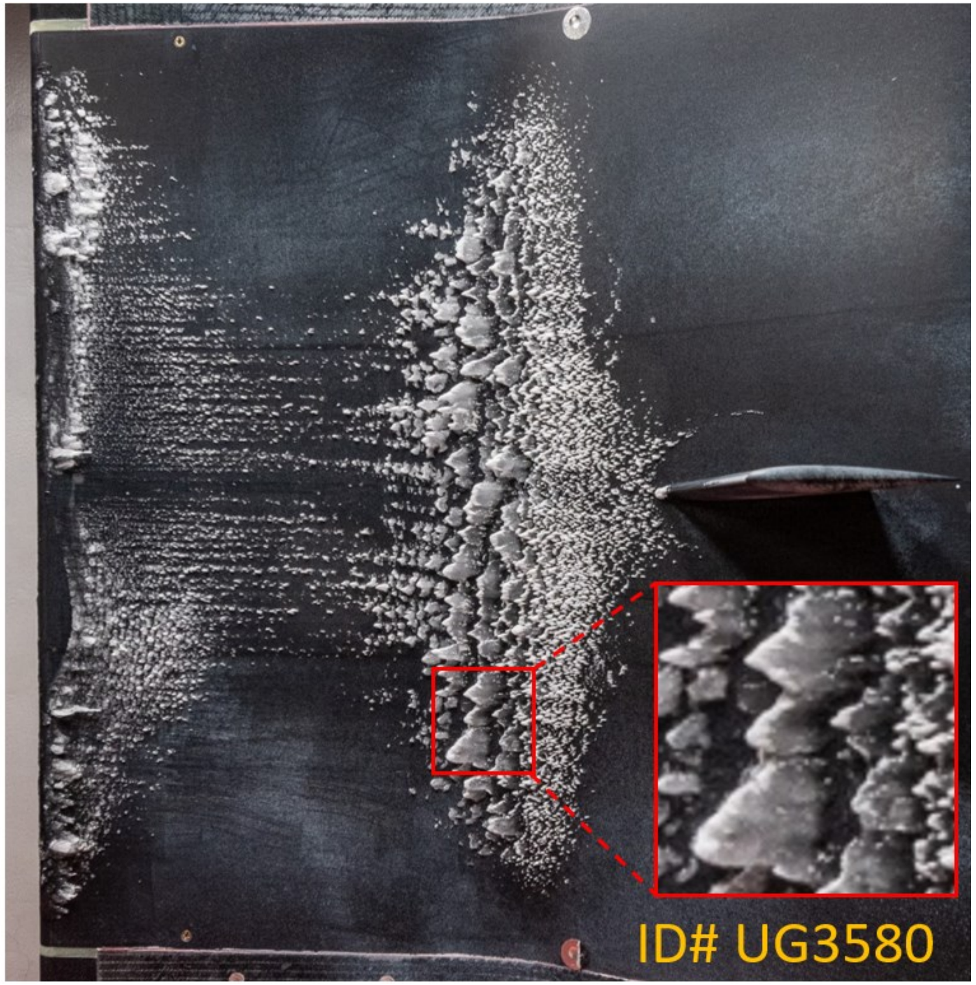
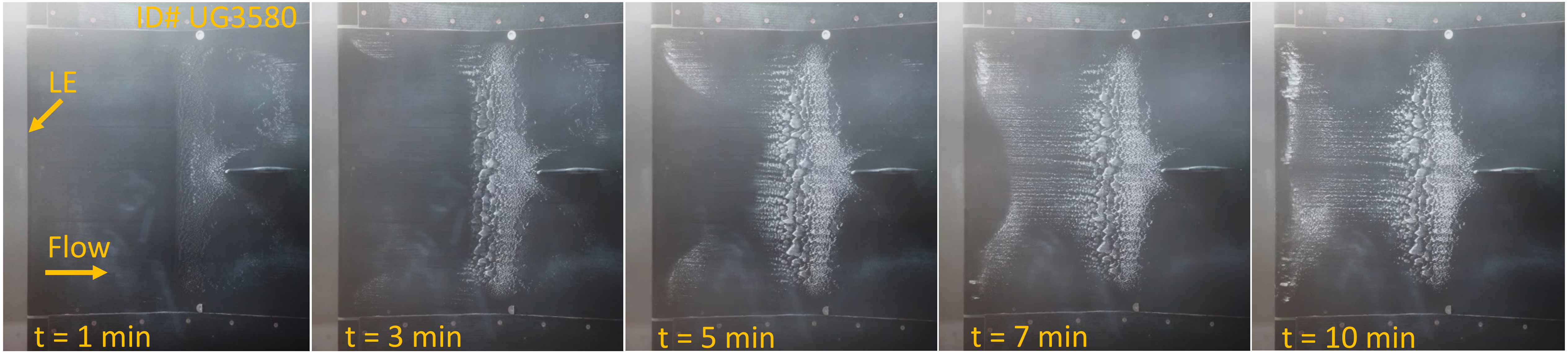
Icing Observations

- Negligible strut influence
- Primary accretions near ramp base
- Amorphous runback ice vs structured sharkteeth ice

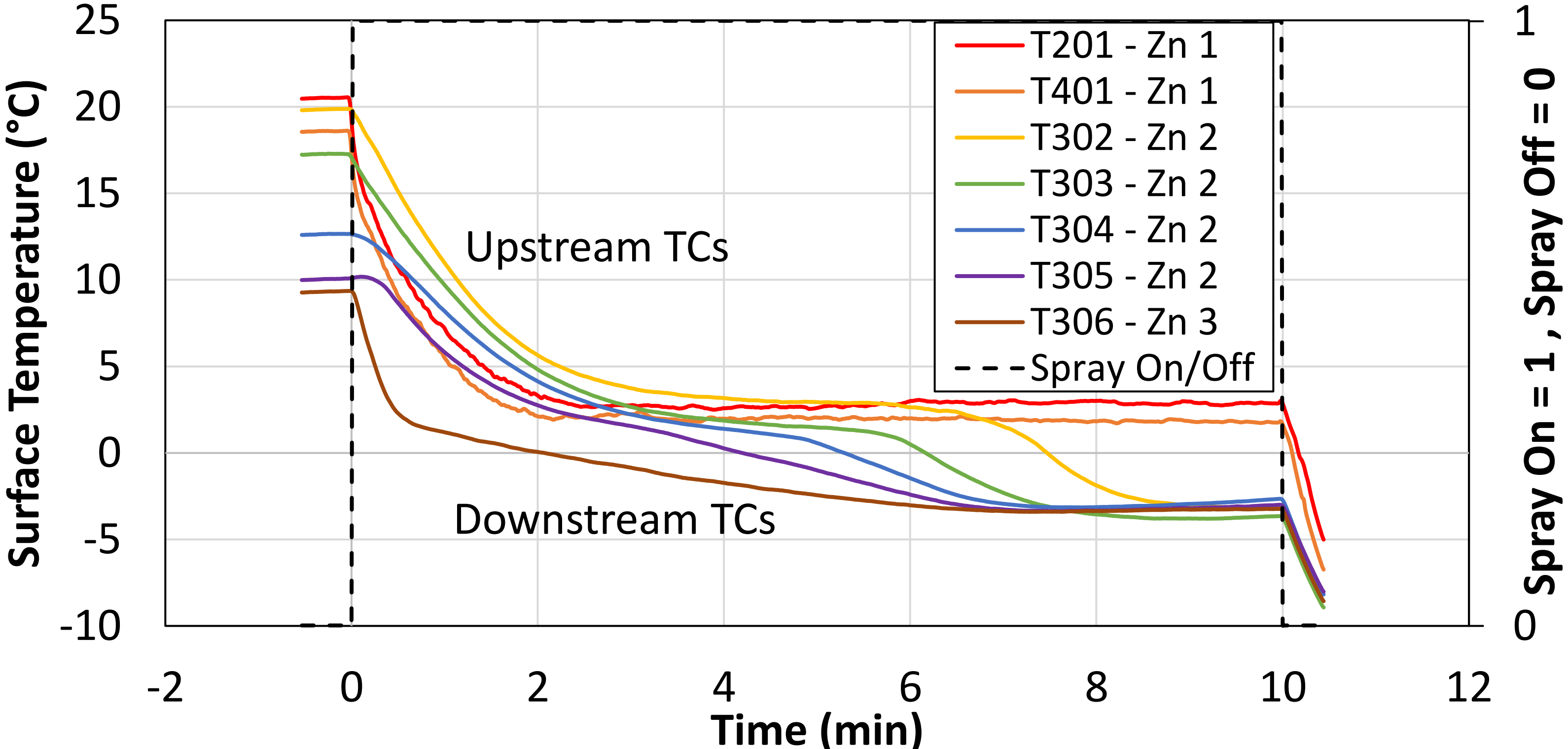




Transient Icing Behavior



- All IC accretions exhibited transient behavior
- But reached steady state once a surface reached subfreezing temperatures



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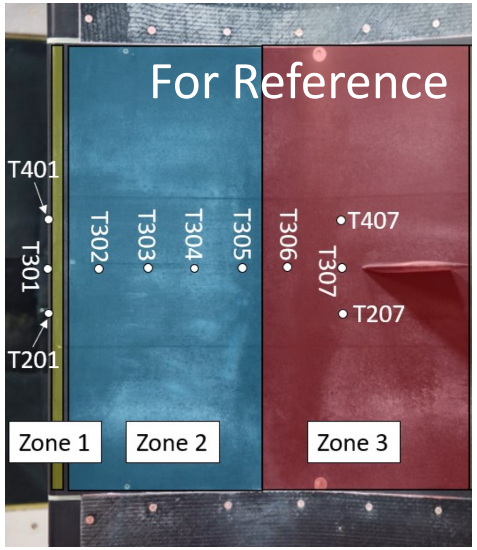
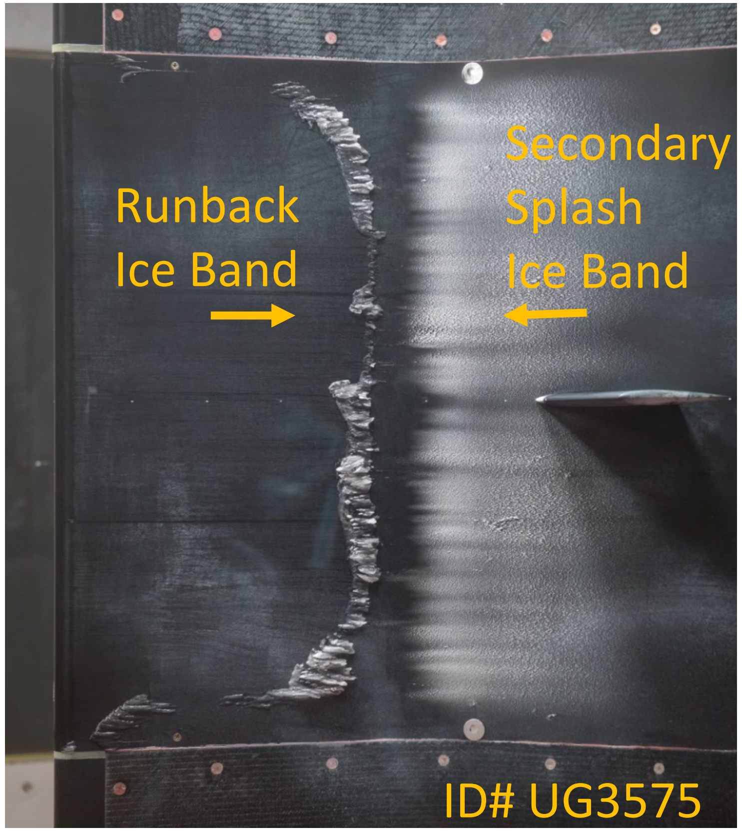
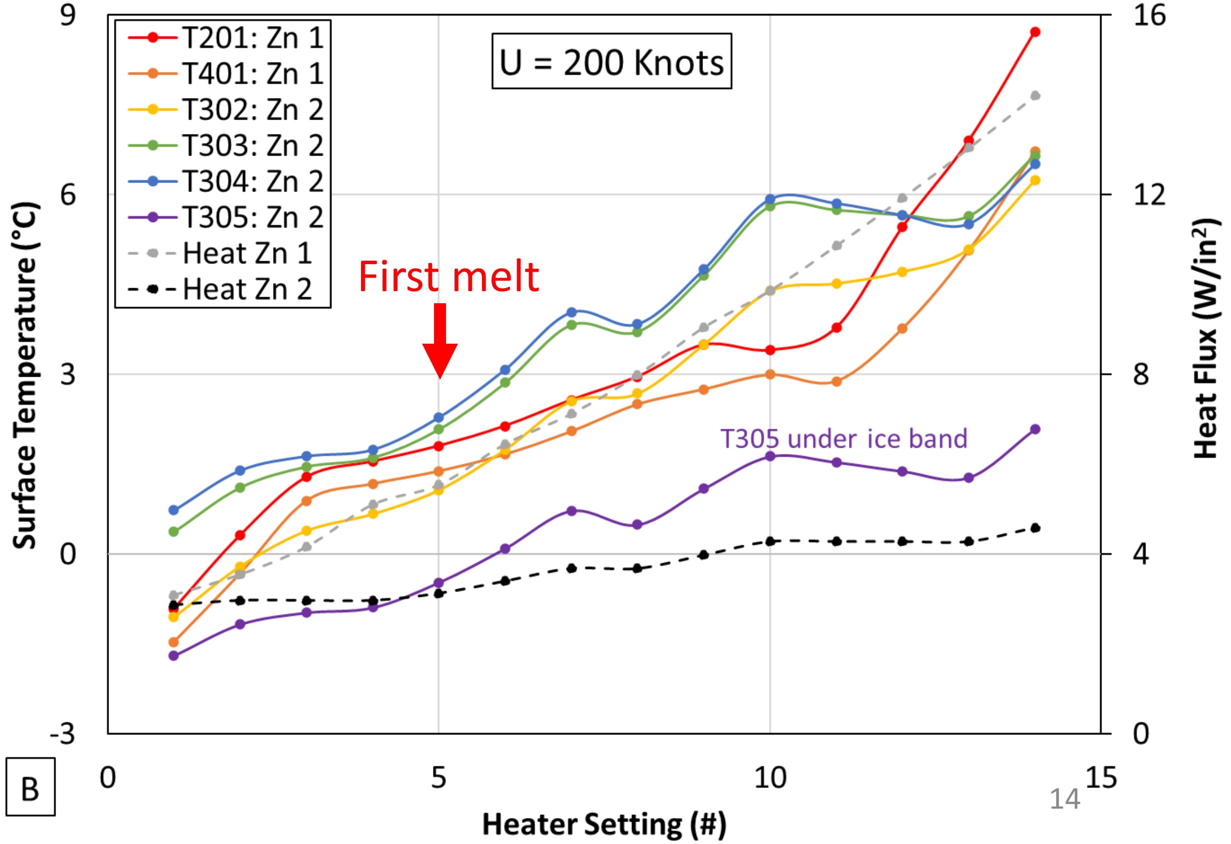
Leading Edge Icing Heat Flux Threshold



Run ID #	Spray Duration min	T_0 °C	*U* knots	*AOA* °	*MVD* µm	*TWC* g/m^3	Zone 1 Heat Flux W/in^2	Zone 2 Heat Flux W/in^2	Zone 3 Heat Flux W/in^2	Zone 4 Heat Flux W/in^2	Zone 5 Heat Flux W/in^2	Zone 6 Heat Flux W/in^2
UG3575	N/A	-15	200	0	27.9	1.98	3.1 - 14.2	2.9 - 4.6	0.0	0.0	0.0	0.0

- Insufficient heat, no ice
- Runback ice and Splash ice
- First ice at Heater Setting #5
- Decrease in downstream temps with increased Zone 1 heat flux (Heater Settings # 8, 11-13)





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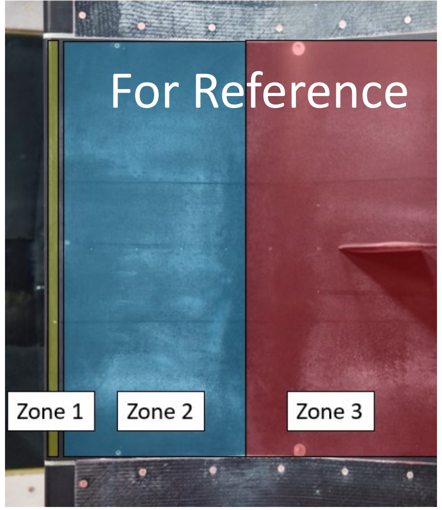
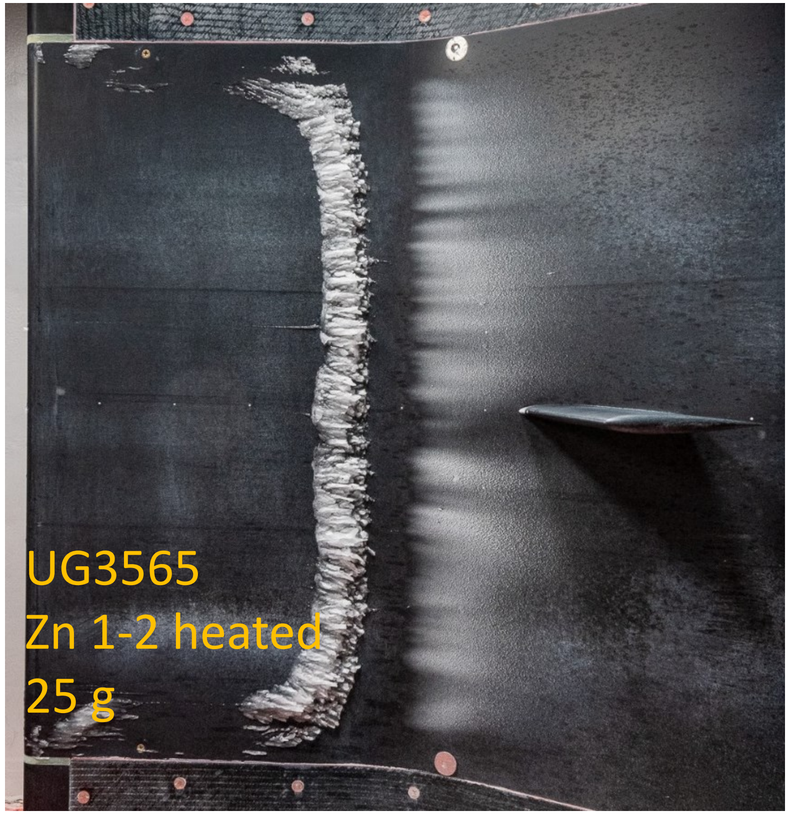
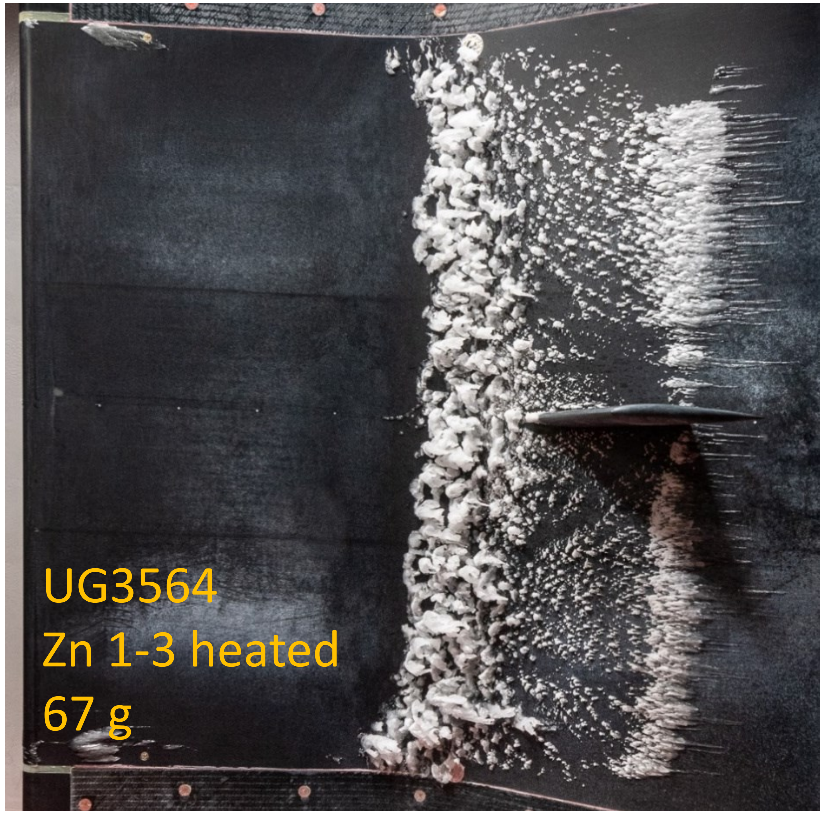
Heated Zone 3 Impact on Ice Mass and Location



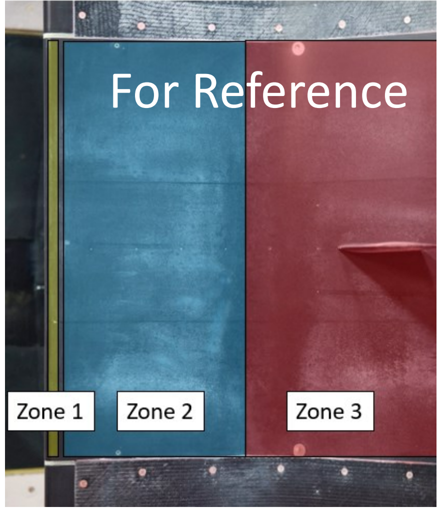
Run ID #	Spray Duration min	T_0 °C	*U* knots	*AOA* °	*MVD* µm	*TWC* g/m^3	Zone 1 Heat Flux W/in^2	Zone 2 Heat Flux W/in^2	Zone 3 Heat Flux W/in^2	Zone 4 Heat Flux W/in^2	Zone 5 Heat Flux W/in^2	Zone 6 Heat Flux W/in^2	South Casing g	North Casing g	Leading Edge g	Total g
UG3565	10	-15	150	0	26.6	1.93	8.9	3.4	0.0	0.0	0.0	0.0	25	24		49
UG3564	10	-15	150	0	26.6	1.93	9.5	3.6	3.9	0.0	0.0	0.0	67	22 (sh)		89

- By heating Zone 3, the runback remains liquid into Zone 3
- Greater collision efficiency in Zone 3 (near ramp base)
- Liquid runback helps capture the incoming ice crystals, which increases the collection efficiency
- Greater ice mass heating Zone 3



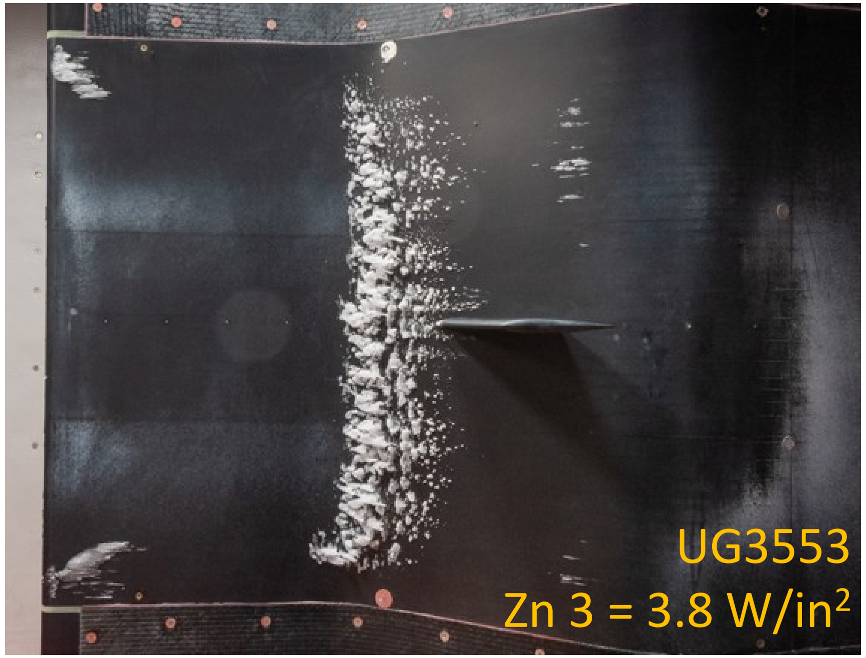


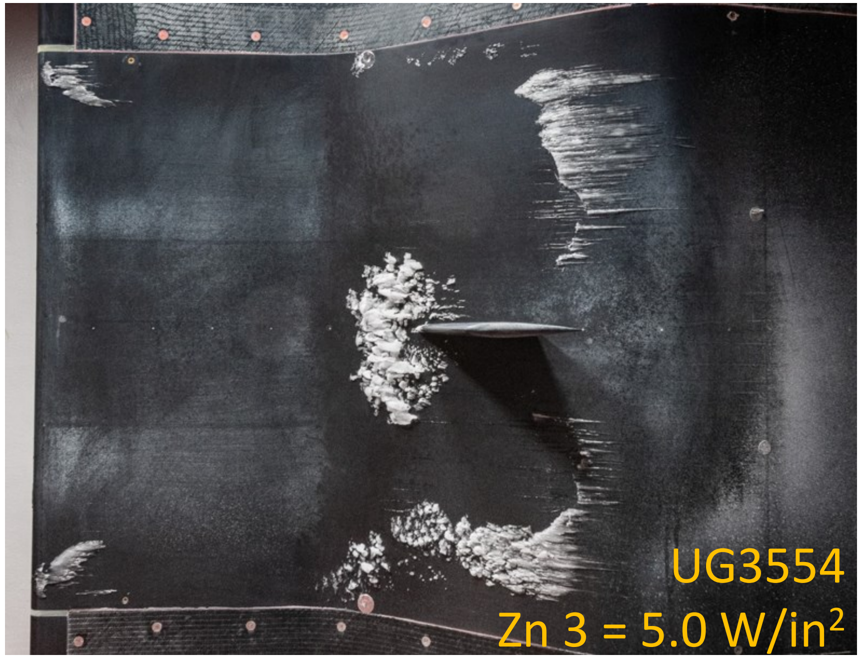
Elevated Zone 3 Heat Flux Impact on Location



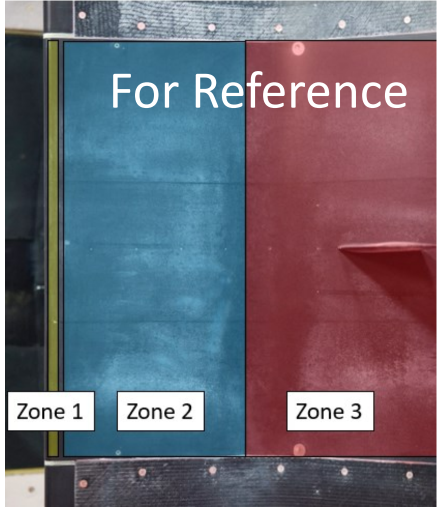
Run ID #	Spray Duration min	T_0 °C	*U* knots	*AOA* °	*MVD* µm	*TWC* g/m³	Zone 1 Heat Flux W/in²	Zone 2 Heat Flux W/in²	Zone 3 Heat Flux W/in²	Zone 4 Heat Flux W/in²	Zone 5 Heat Flux W/in²	Zone 6 Heat Flux W/in²	South Casing g	North Casing g	Leading Edge g	Total g
UG3553	10	-20	150	0	26.3	2.16	8.9	3.7	4.3	4.0	7.5	4.5	32	33		65
UG3554	10	-20	150	0	26.3	2.16	8.9	3.7	5.6	4.0	7.5	4.5	29 (sh)	35 (sh)		64 (sh)

- Higher Zone 3 heat flux moved accretion farther downstream
- Higher heat flux setting resulted in multiple ice build and sheds
- Honeywell LF11 full scale icing test: Increased fan speed increased the temperature in the core flowpath and suppressed accretion and suppressed engine rollback



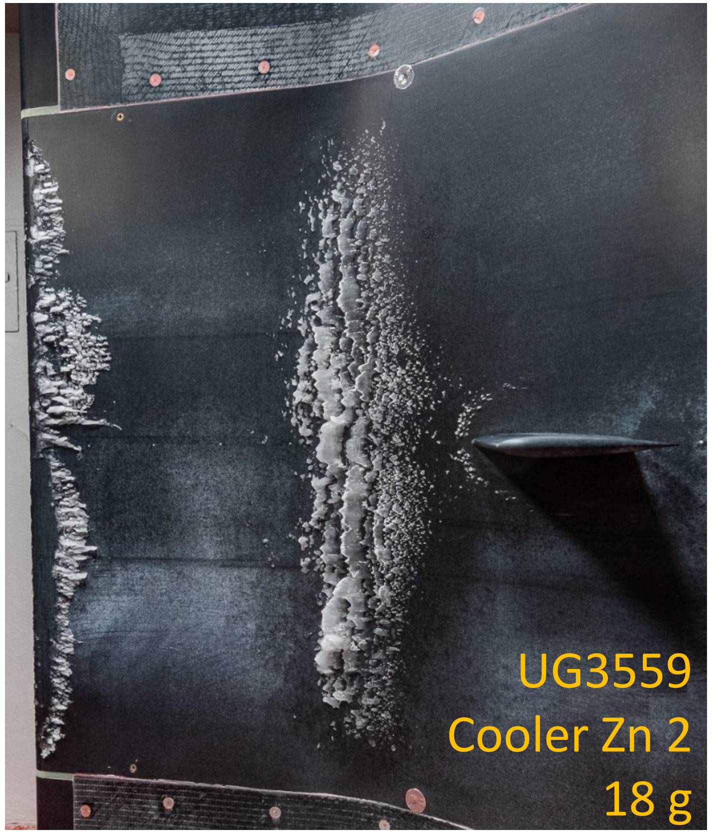


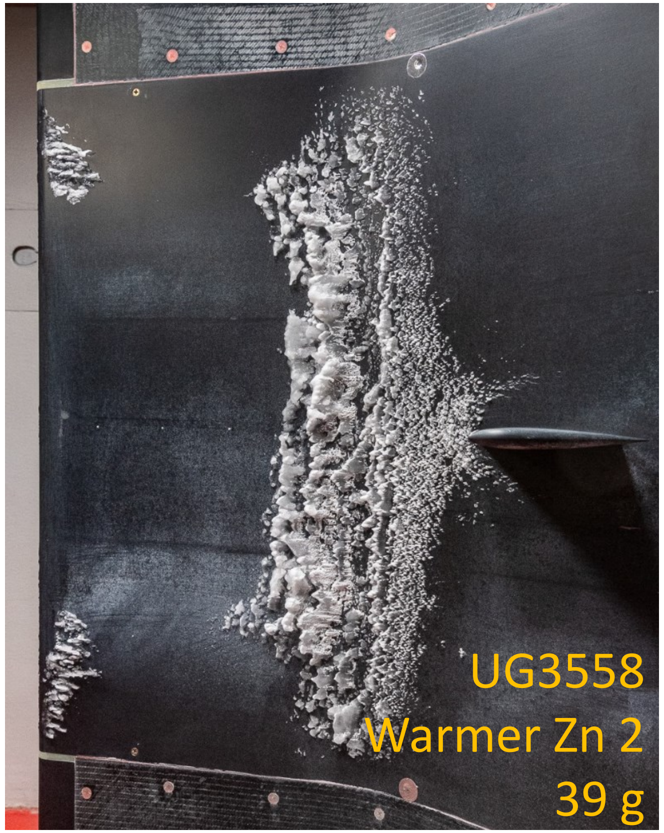
Warm Leading Edge Impact on Ice Mass



Run ID #	Spray Duration min	T_0 °C	*U* knots	*AOA* °	*MVD* µm	*TWC* g/m³	Zone 1 Heat Flux W/in²	Zone 2 Heat Flux W/in²	Zone 3 Heat Flux W/in²	Zone 4 Heat Flux W/in²	Zone 5 Heat Flux W/in²	Zone 6 Heat Flux W/in²	South Casing g	North Casing g	Leading Edge g	Total g
UG3559	10	-20	150	4	26.3	2.16	8.9	3.1	3.3	4.0	7.5	4.5	18		14 (sh)	32 (sh)
UG3558	10	-20	150	4	26.3	2.16	8.9	3.7	3.3	4.0	7.5	4.5	39 (sh)	2		41 (sh)

- Higher heat flux setting kept the leading edge warm and clear of ice, providing a continues supply of liquid melt to the ramp base, resulting in greater ice mass accretion
- Honeywell LF11 full scale icing test: Upstream heat sources provided additional melt, promoting accretion within the compressor core and quicker engine rollback





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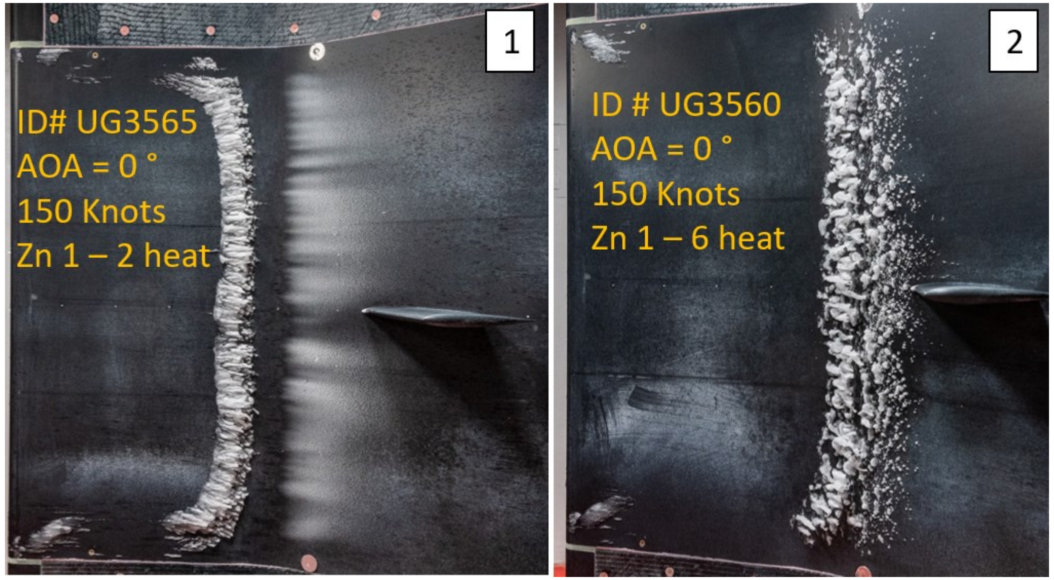
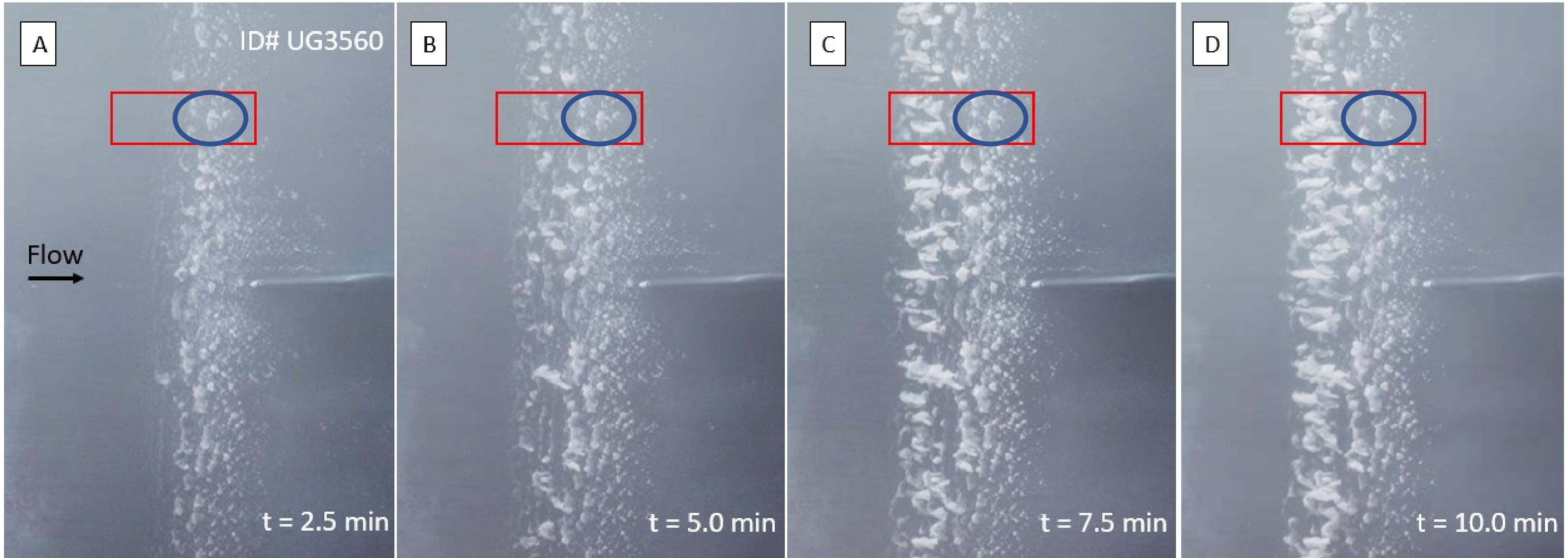
Runback Dominated Melt

Run ID #	Zone 1 Heat Flux W/in^2	Zone 2 Heat Flux W/in^2	Zone 3 Heat Flux W/in^2	Zone 4 Heat Flux W/in^2	Zone 5 Heat Flux W/in^2	Zone 6 Heat Flux W/in^2
UG3565	8.9	3.4	0.0	0.0	0.0	0.0
UG3560	7.1	2.8	3.3	3.2	6.0	3.9

- Isolated LE melt contribution test suggests runback dominant melt
- Red boxes show ice accretion moved upstream or grew in greater amounts in the same location at the front edge.
- Upstream ice stopped ice growth just aft (blue oval)

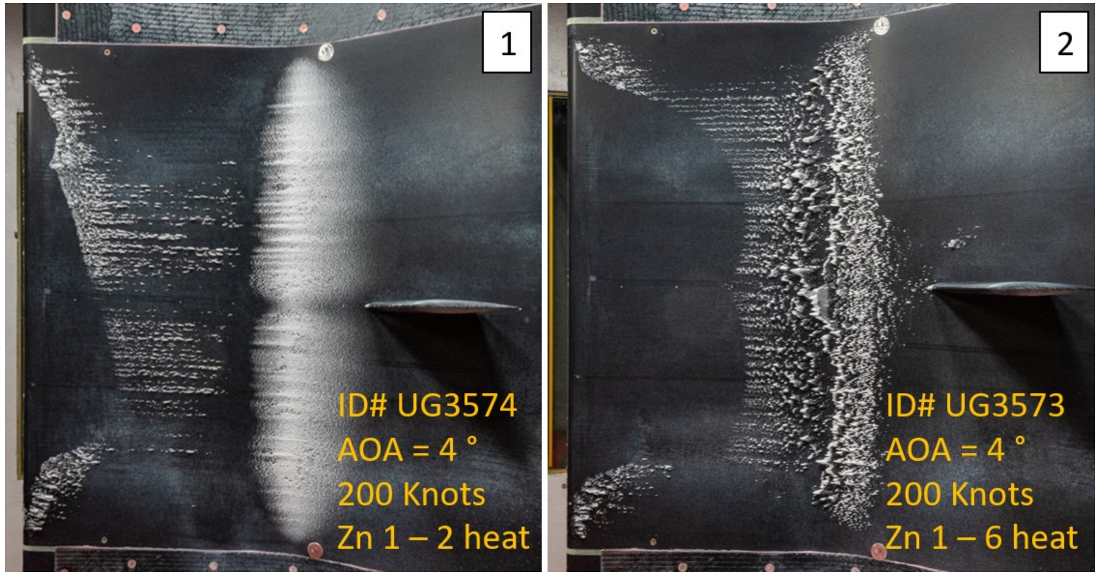


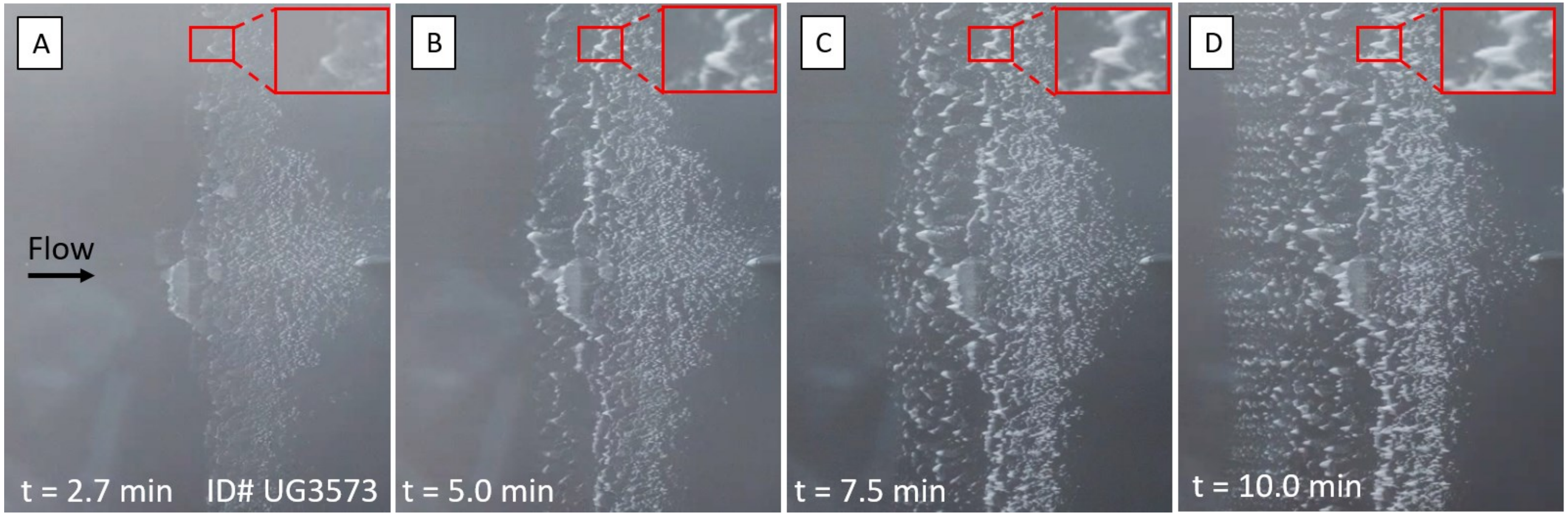


Splash Dominated Melt

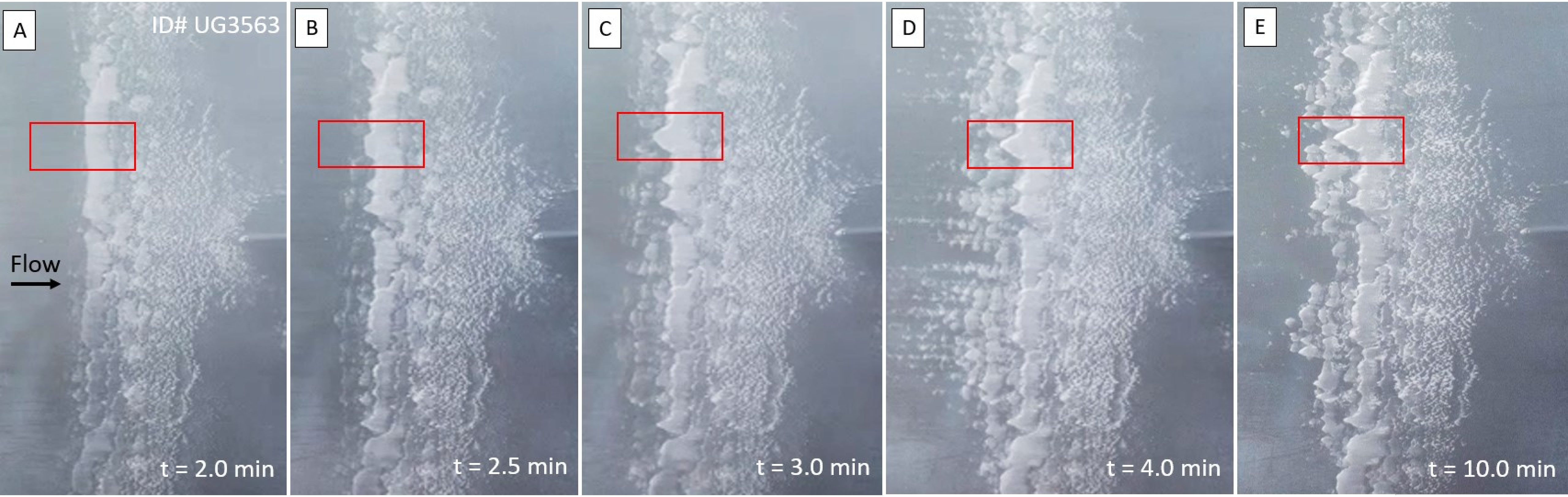
Run ID #	Zone 1 Heat Flux W/in^2	Zone 2 Heat Flux W/in^2	Zone 3 Heat Flux W/in^2	Zone 4 Heat Flux W/in^2	Zone 5 Heat Flux W/in^2	Zone 6 Heat Flux W/in^2
UG3574	9.9	3.1	0.0	0.0	0.0	0.0
UG3573	9.9	3.1	3.3	4.3	7.2	5.1

- Isolated LE melt contribution test suggests splash dominant melt (no prominent runback band)
- Despite upstream ice, the ice within red boxes grew
- Sharkteeth grew longer and pointier throughout test
- Locally higher collection eff. reinforces pointier shape





(Evidence of) Runback Dominated Melt



A (t = 2.0 min)

- Flat ridge inside the red box
- Upstream is clear
- Uniform access to liquid runback

B (t = 2.5 min)

- Plateau-shaped ridge
- Small ice forming upstream along the sides of red box, corresponding to valleys of the plateau
- Liquid runback limited to peak of plateau

C (t = 3.0 min)

- Blunt sharktooth
- More ice forming upstream along the sides of red box
- Liquid runback pinched off even more limited to narrow channel creating pointy peak

D (t = 4.0 min)

- Pointy sharktooth
- Upstream is fully covered with ice
- No more liquid runback reaching the ridge/teeth

E (t = 10.0 min)

- Limited sharktooth growth from potentially limited splash melt

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Conclusions

- Ice crystal cloud characterization tests conducted
  - Tunnel thaws reduced the impact of particle recirculation
- Successfully generated ice accretions on a test article in a fully glaciated cloud
  - Provided insight into icing physics observed
  - Produced quantitative dataset for model development and validation
- Explored minimum surface heat flux required to melt impinging IC near LE
- Discussed how surface heat flux impacted ice mass, location, and accretion characteristics
- Liquid melt generated at LE transported downstream via runback and splash
  - Discussed how runback melt and splash melt impacted accretion behavior downstream
- Discussed mechanisms that generated sharkteeth ice, but likely different than full scale engine icing tests

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