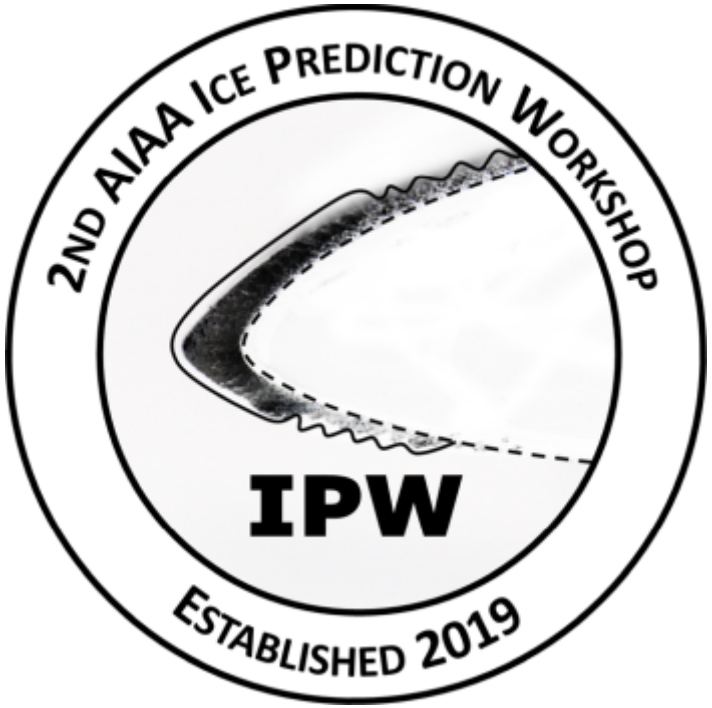

Ice Protection Workshop 2

Guy Fortin
Advanced Aerodynamics

2023-06-23

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CRM-65 MidSpan

DRAGON ICE SUITE

Flow: Reynolds Averaged Navier Stokes Solver (RANS)
k-w Turbulence Model

Heat Transfer Coefficient by Convection: Newton's law of cooling and Fourier's law
Semi-Empiric Equivalent Sand Grand Roughness Correlation for 1 layer ice shape prediction

Drop (Collection Efficiency): Euleurian Solver

Thermo (Mass and Heat Transfers): Iterative Messinger Solver
Multi-stagnation point
Runback is based on wall shears stress

Geometry: Lagrangian Node Displacement Method

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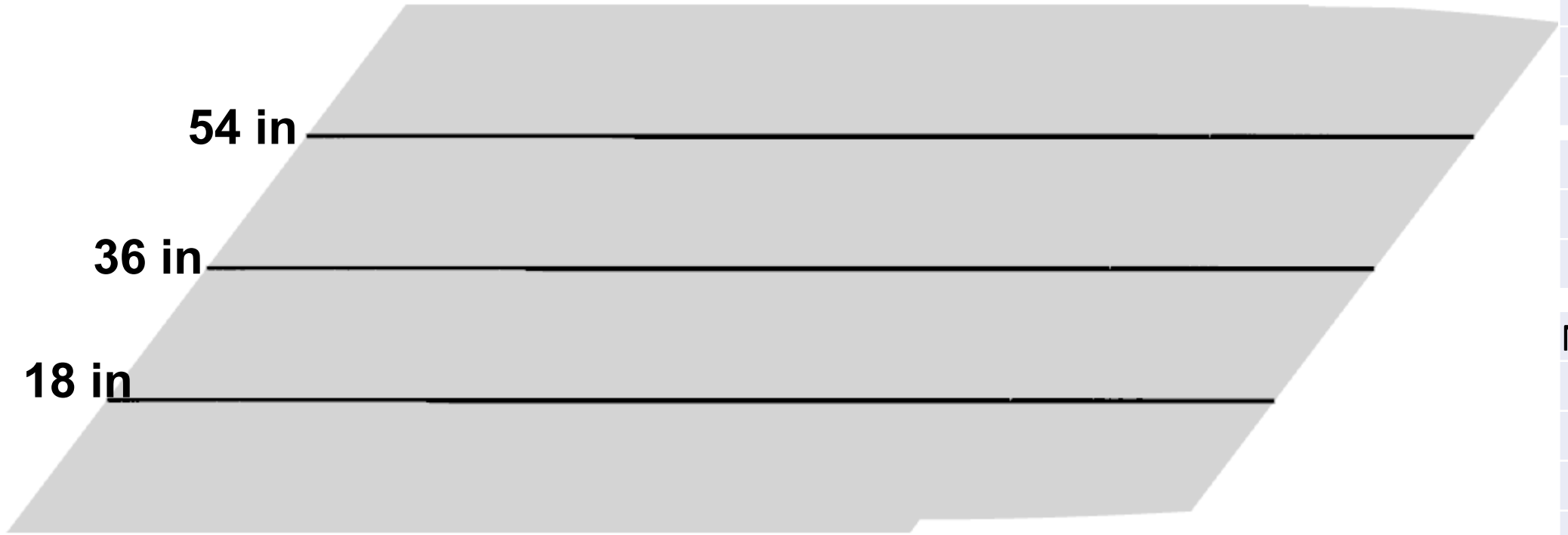
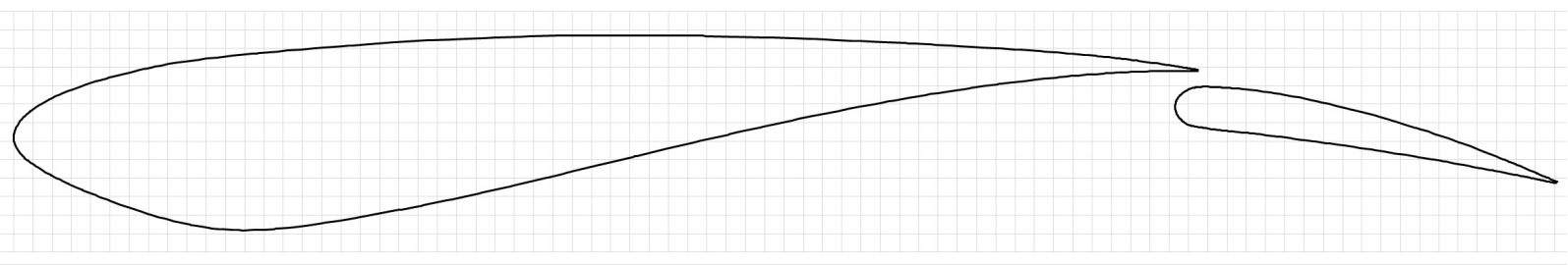
CRM-65 InBoard





AoA	3.7	deg
TAS	66.9	m/s
MVD	25	µm
LWC	1	g/m³
time	29	min
SAT	-3.6	ºC
SAT	-8.5	ºC
SAT	-26	ºC

NASA IRT	Droplet
Volume	Diameter
0.05	7.3
0.1	9.9
0.2	13.7
0.3	24.9
0.2	44.9
0.1	74.9
0.05	127.6

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CRM-65 InBoard

AoA	3.7	deg
TAS	66.9	m/s
MVD	25	µm
LWC	1	g/m³
time	29	min
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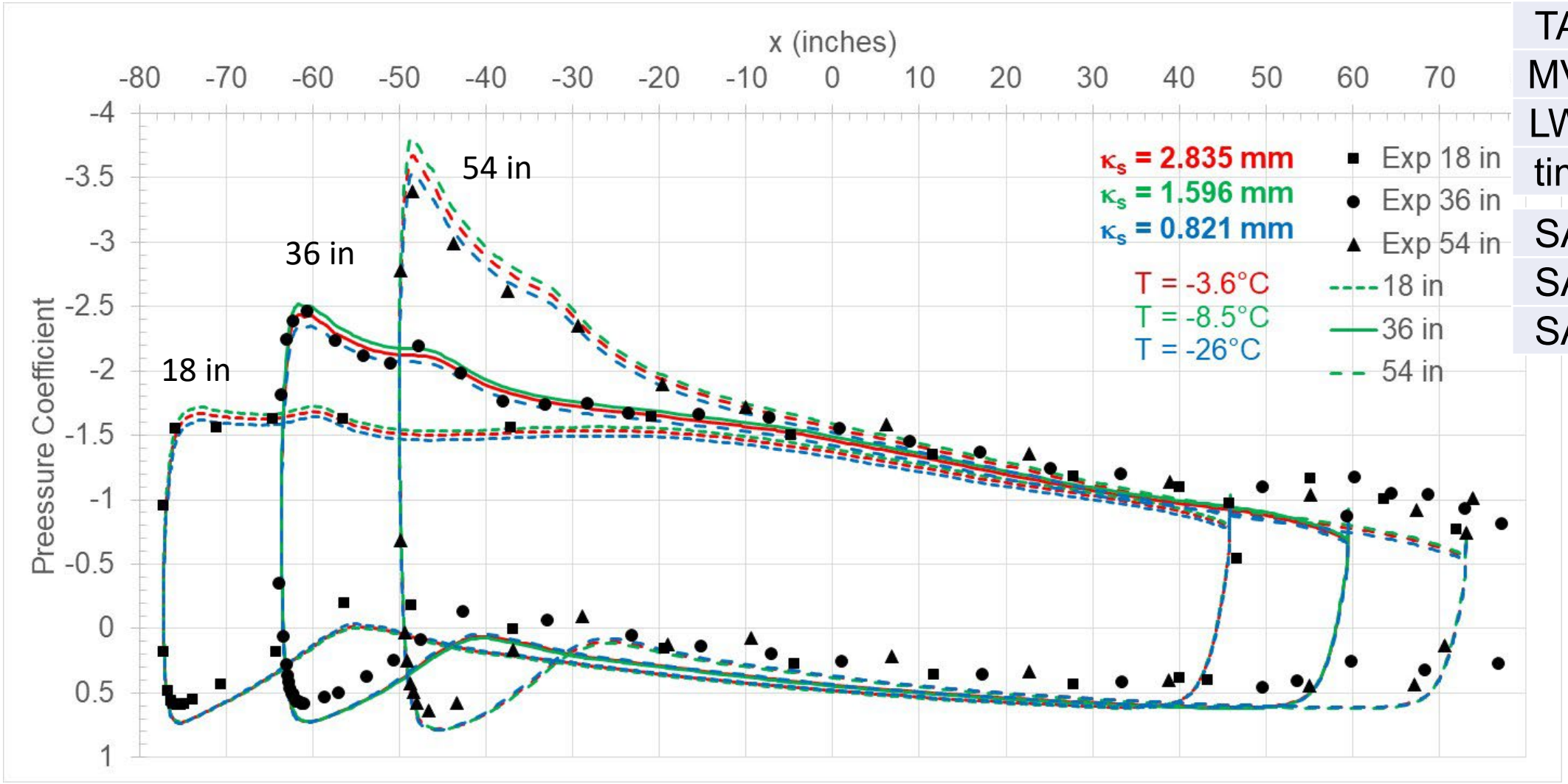
SAT	-8.5	ºC
SAT	-26	ºC



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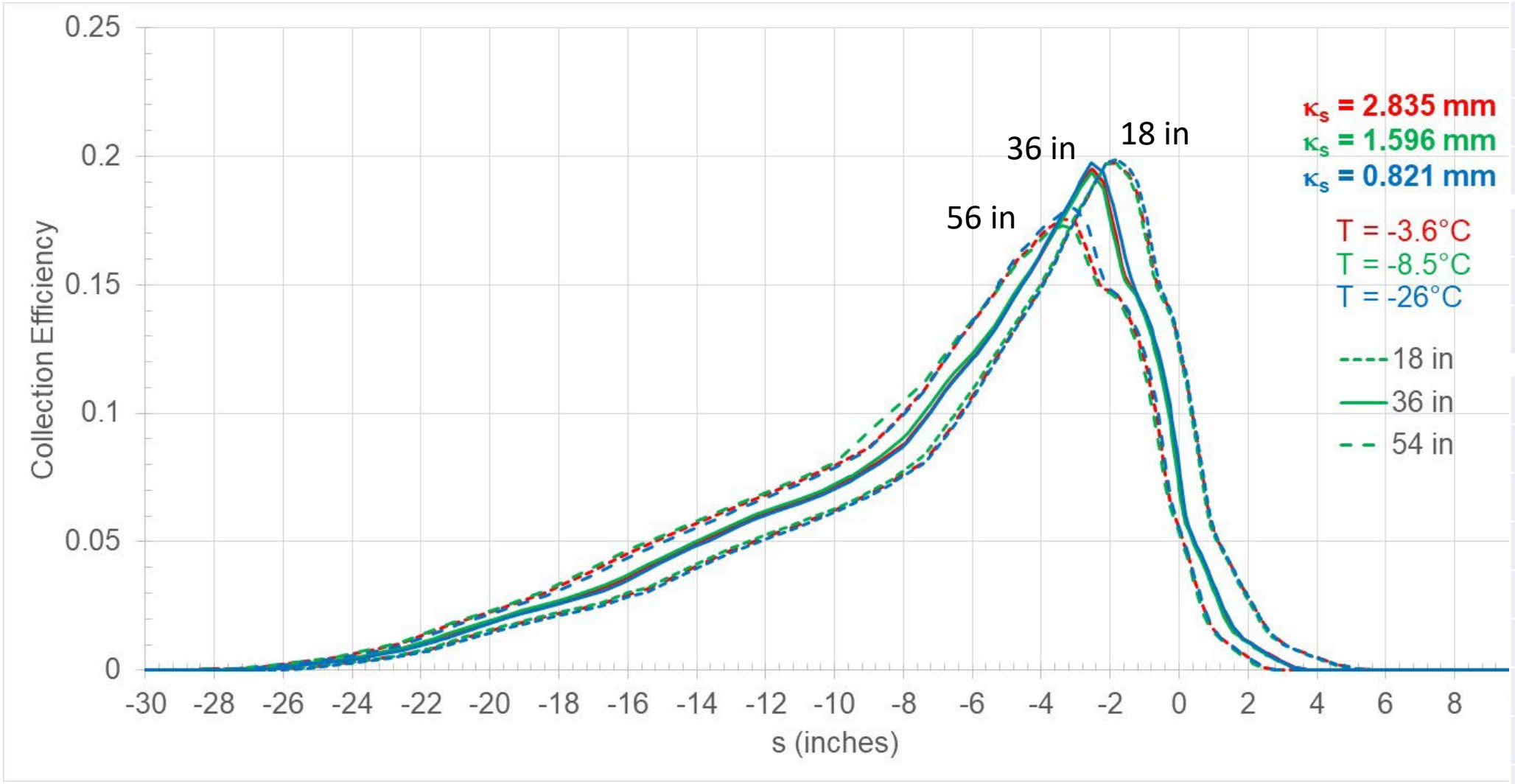
CRM-65 InBoard



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TAS	66.9	m/s
MVD	25	μm
LWC	1	g/m³
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NASA IRT Volume	Droplet Diameter
0.05	7.3
0.1	9.9
0.2	13.7
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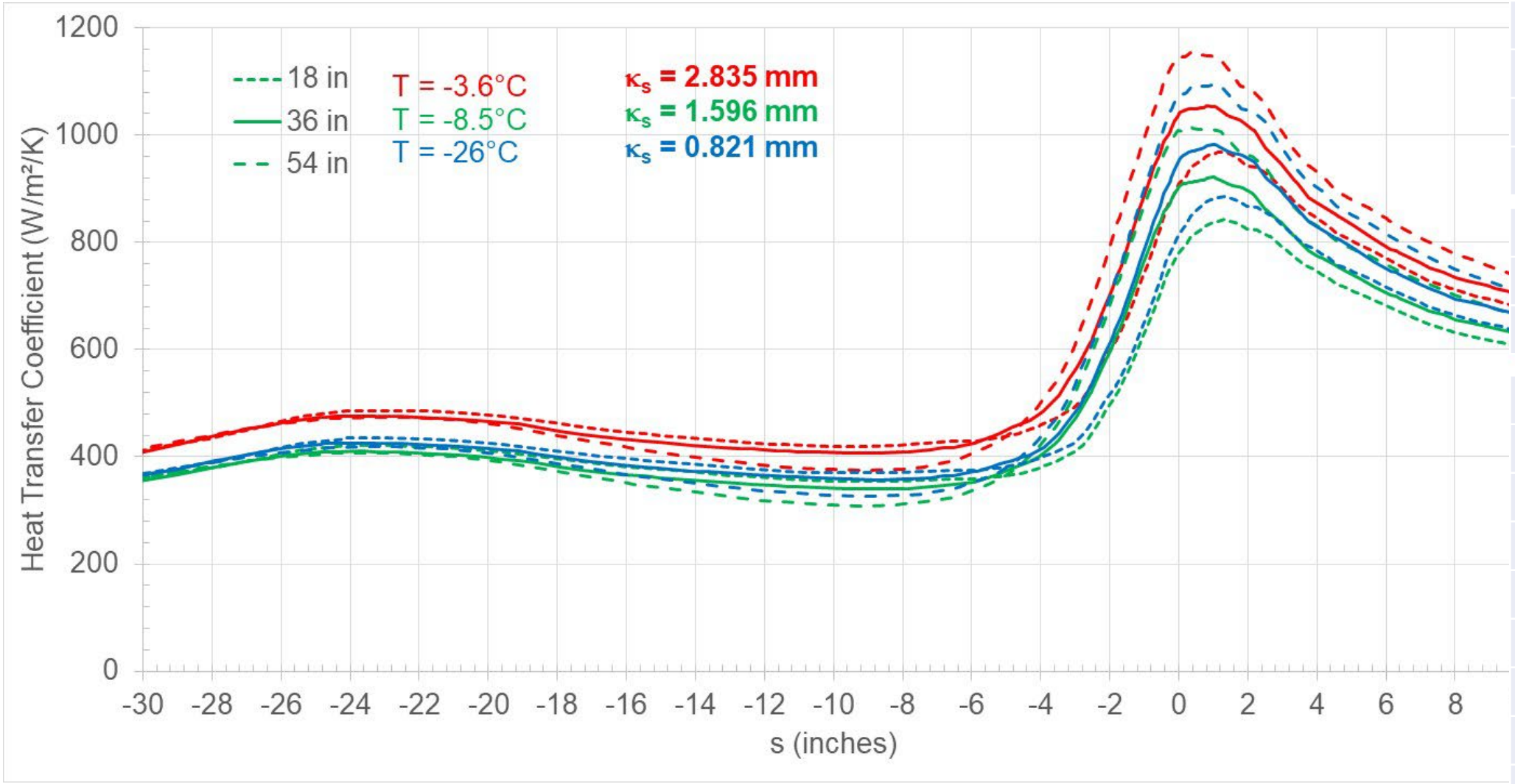
0.2	44.9
0.1	74.9
0.05	127.6

BOMBARDIER

CRM-65 InBoard



AoA	3.7	deg
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0.2	44.9
0.1	74.9
0.05	127.6

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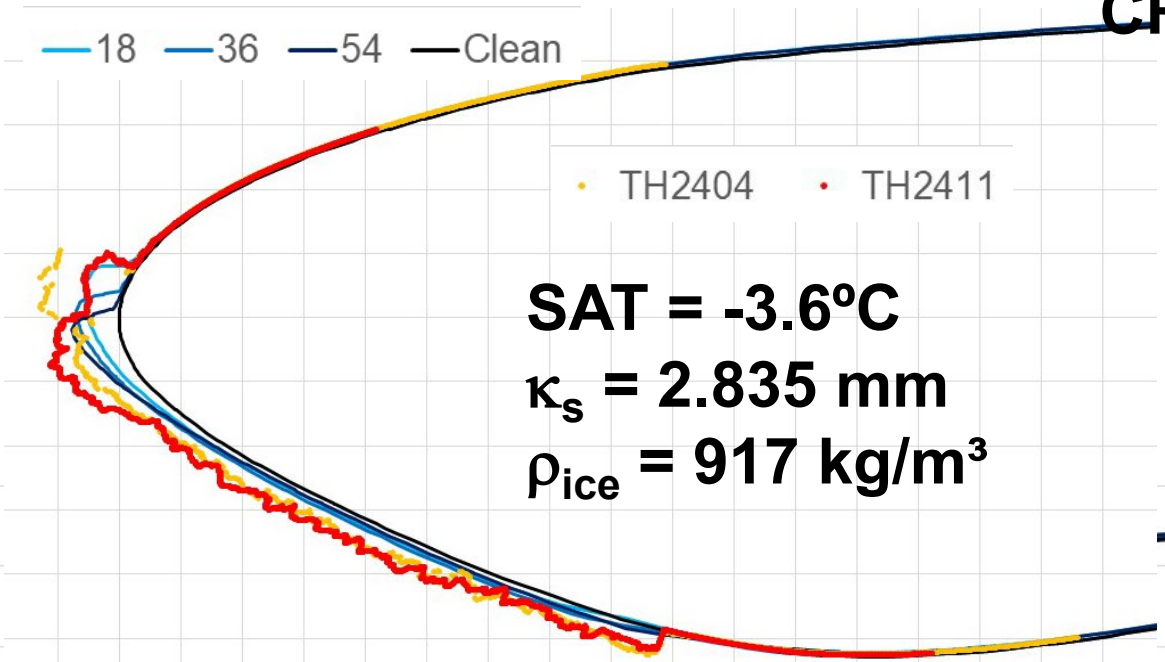
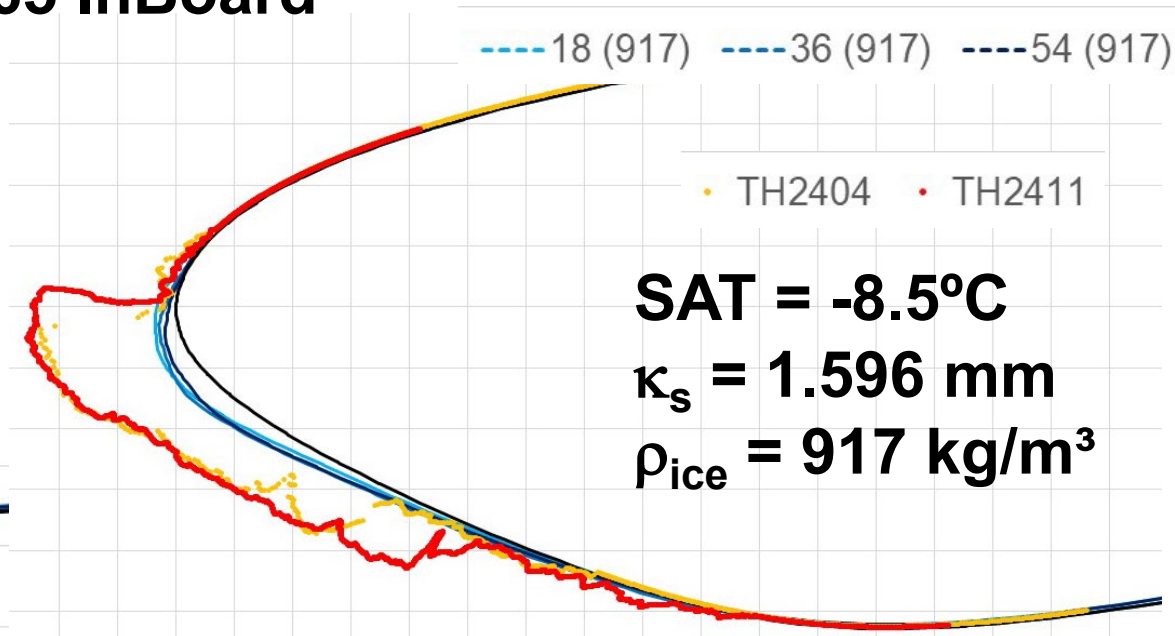
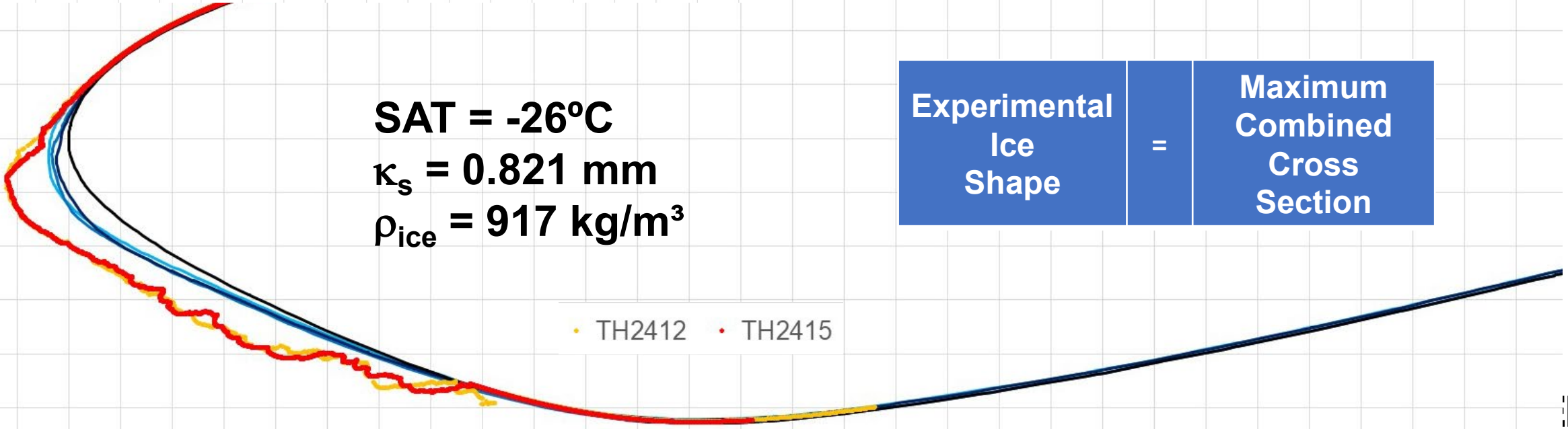
CRM-65 InBoard



SAT = -3.6ºC
κ_s = 2.835 mm
ρ_{ice} = 917 kg/m³



SAT = -8.5ºC
κ_s = 1.596 mm
ρ_{ice} = 917 kg/m³



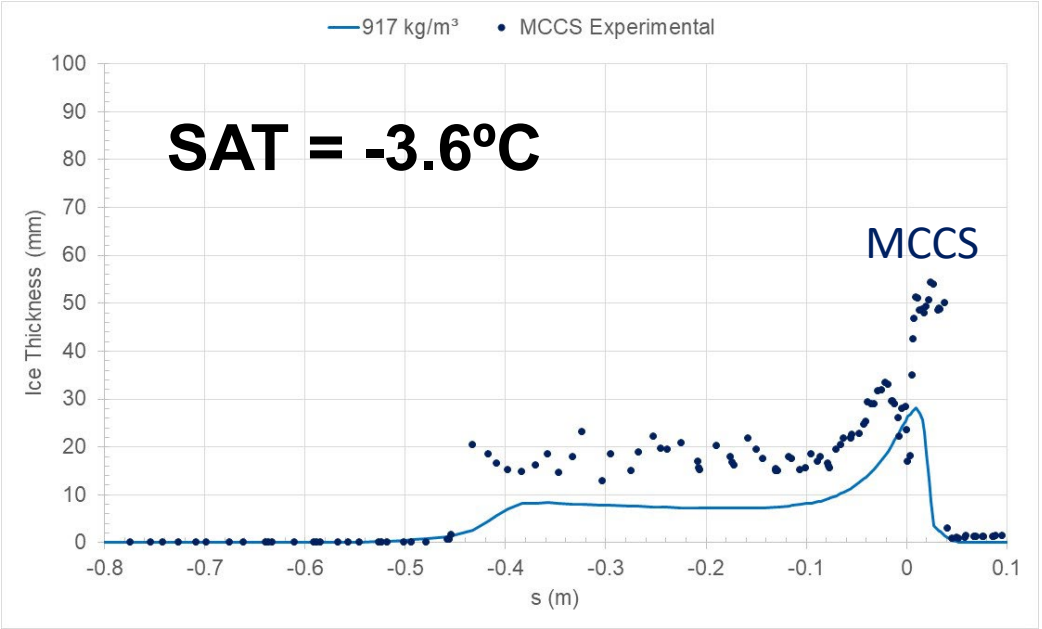
SAT = -26ºC
κ_s = 0.821 mm
ρ_{ice} = 917 kg/m³

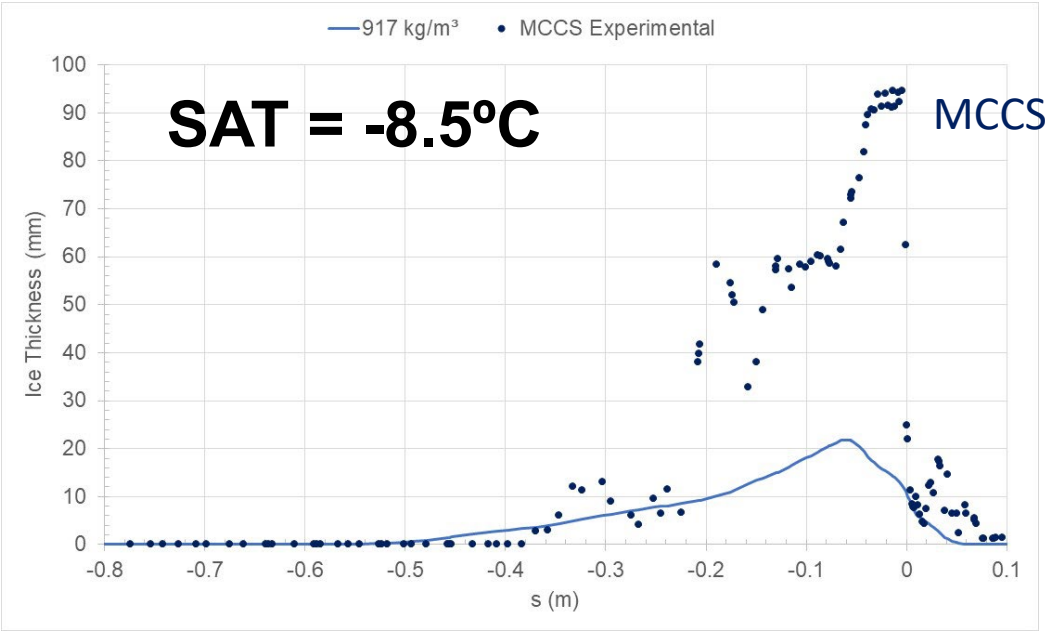
Experimental Ice Shape	=	Maximum Combined Cross Section

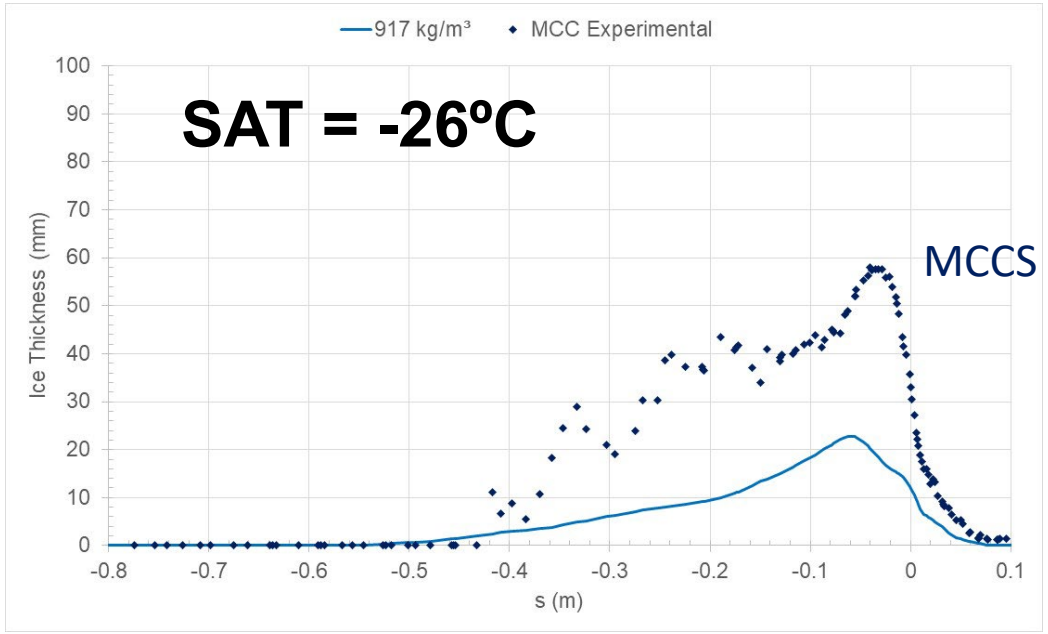
CRM-65 InBoard

SAT (º)	Surface (m²) Exp	Ice Mass (kg/m) Exp	Ice Density kg/m³
-3.6	0.013851	4.920	355
-8.5	0.019920	8.220	413
-26.0	0.019404	7.900	407

Hingewise cut







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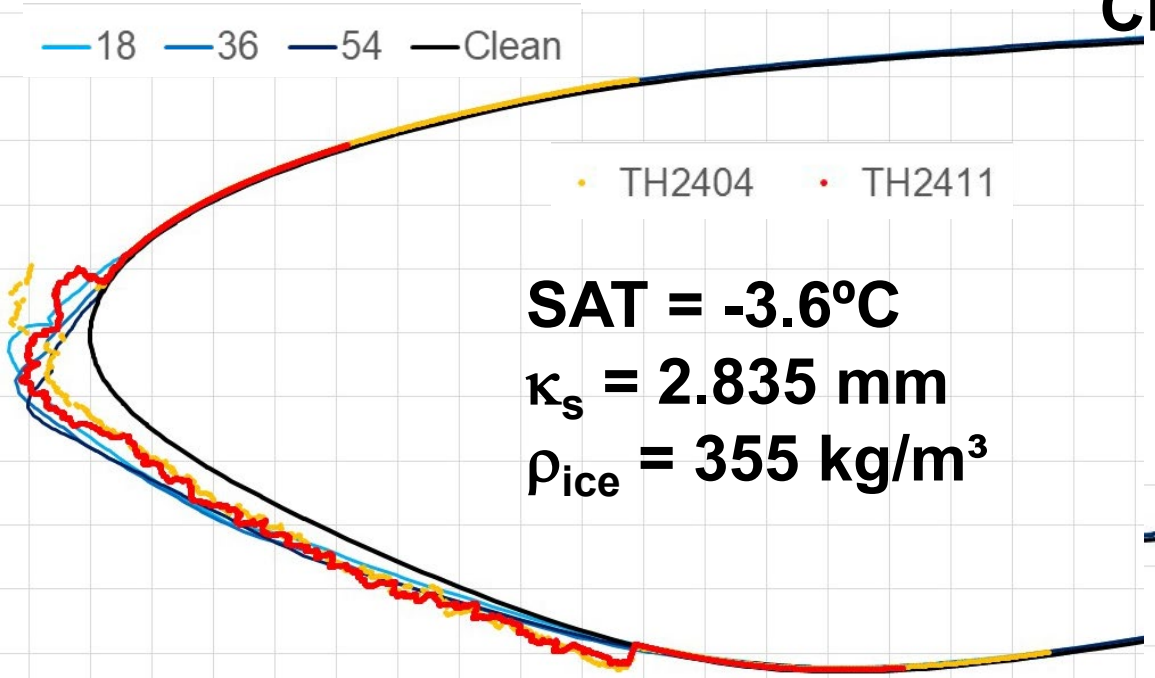
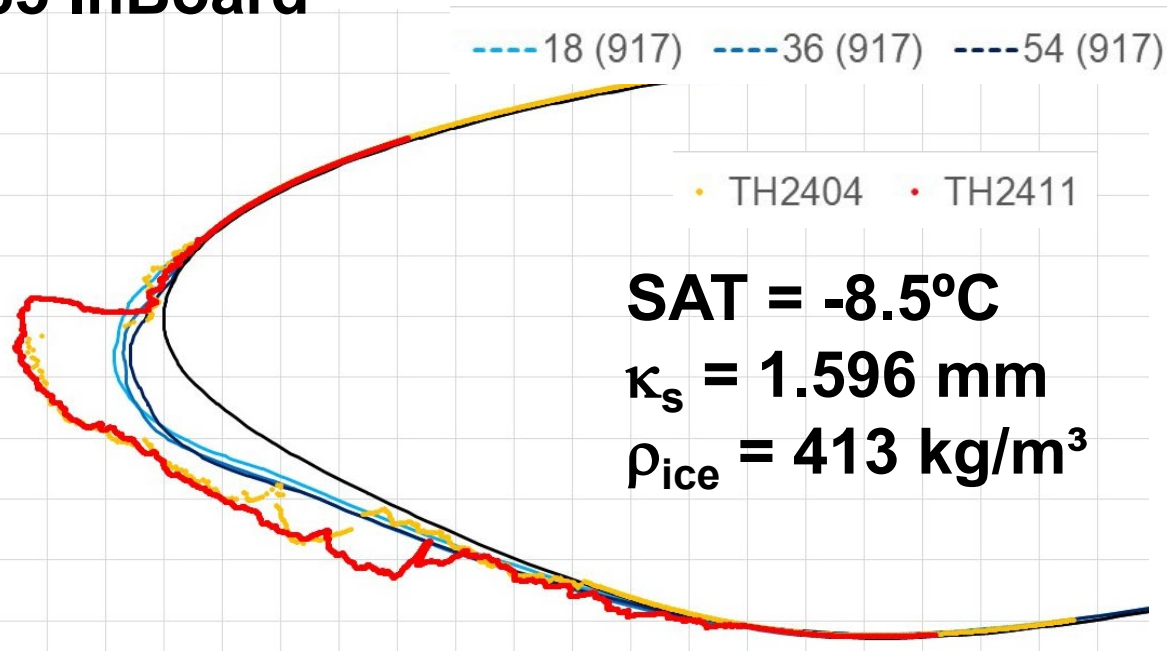
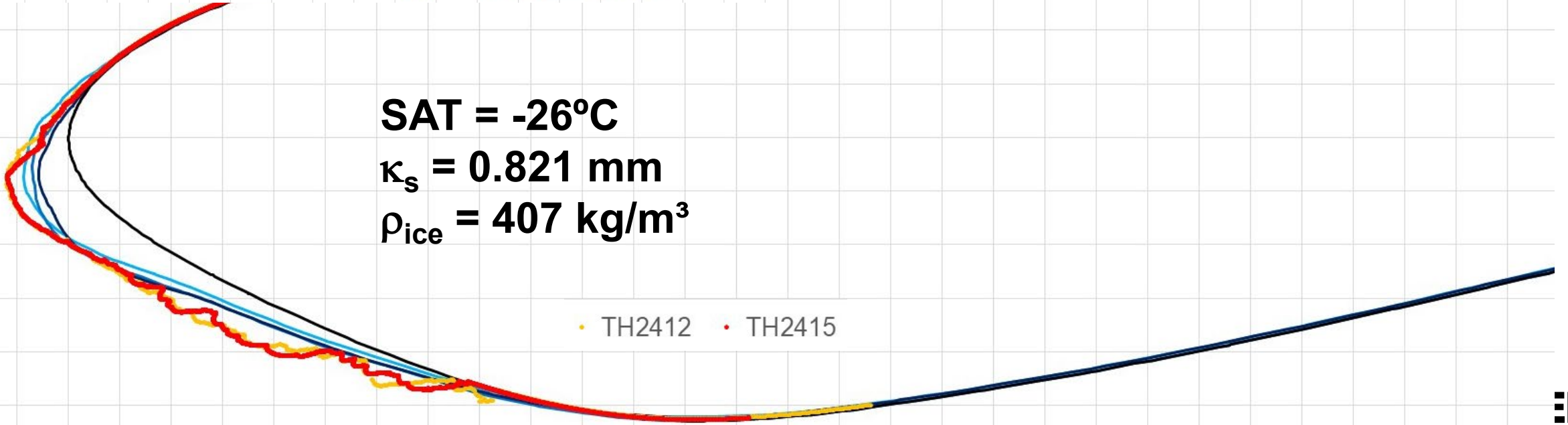
CRM-65 InBoard



SAT = -3.6ºC
κ_s = 2.835 mm
ρ_{ice} = 355 kg/m³

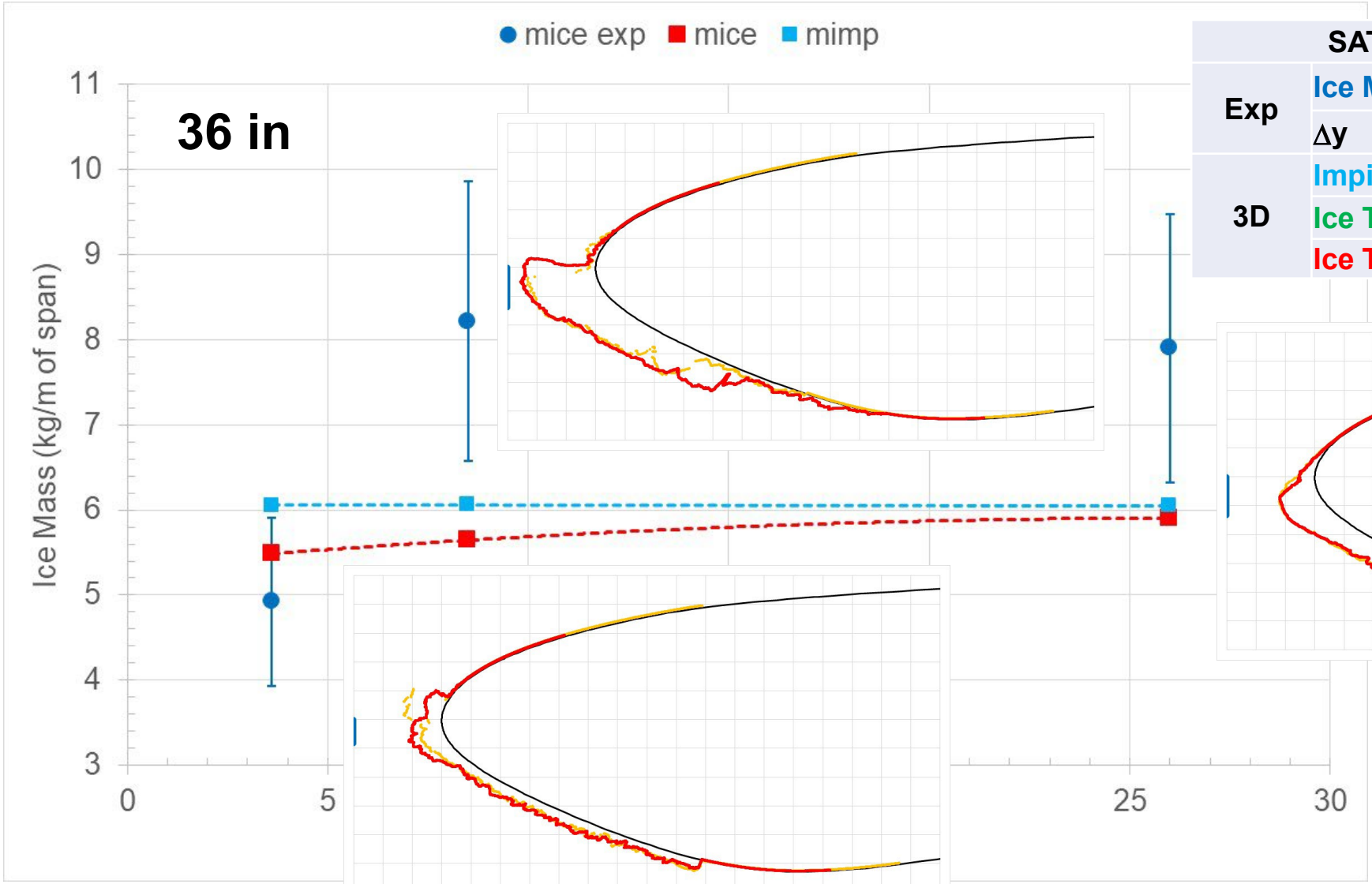


SAT = -8.5ºC
κ_s = 1.596 mm
ρ_{ice} = 413 kg/m³

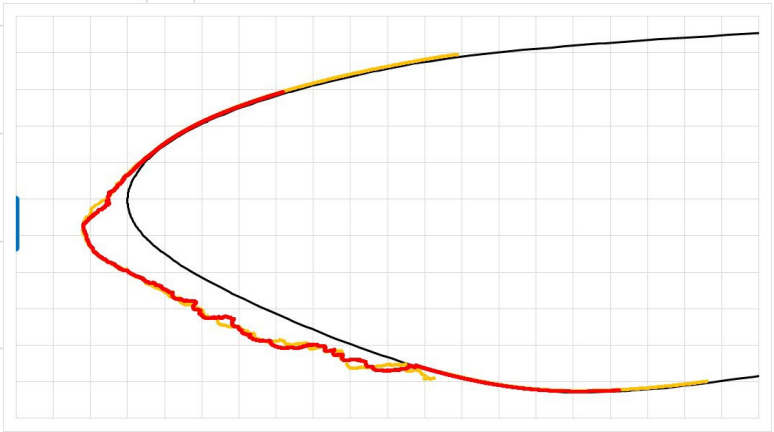


SAT = -26ºC
κ_s = 0.821 mm
ρ_{ice} = 407 kg/m³

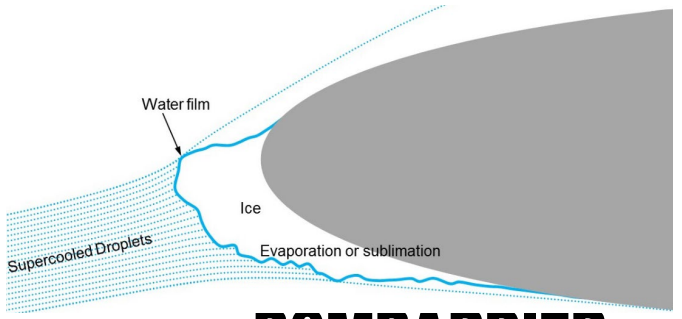
CRM-65 InBoard



	SAT	-3.6	-8.5	-26	ºC
Exp	Ice Mass	4.920	8.220	7.900	kg/m
	Δy	1.664	2.780	2.672	inches
3D	Impingment	6.050	6.067	6.044	kg/m
	Ice Thermo	5.485	5.645	5.905	kg/m
	Ice Thickness	5.229	5.492	5.687	kg/m



Δy



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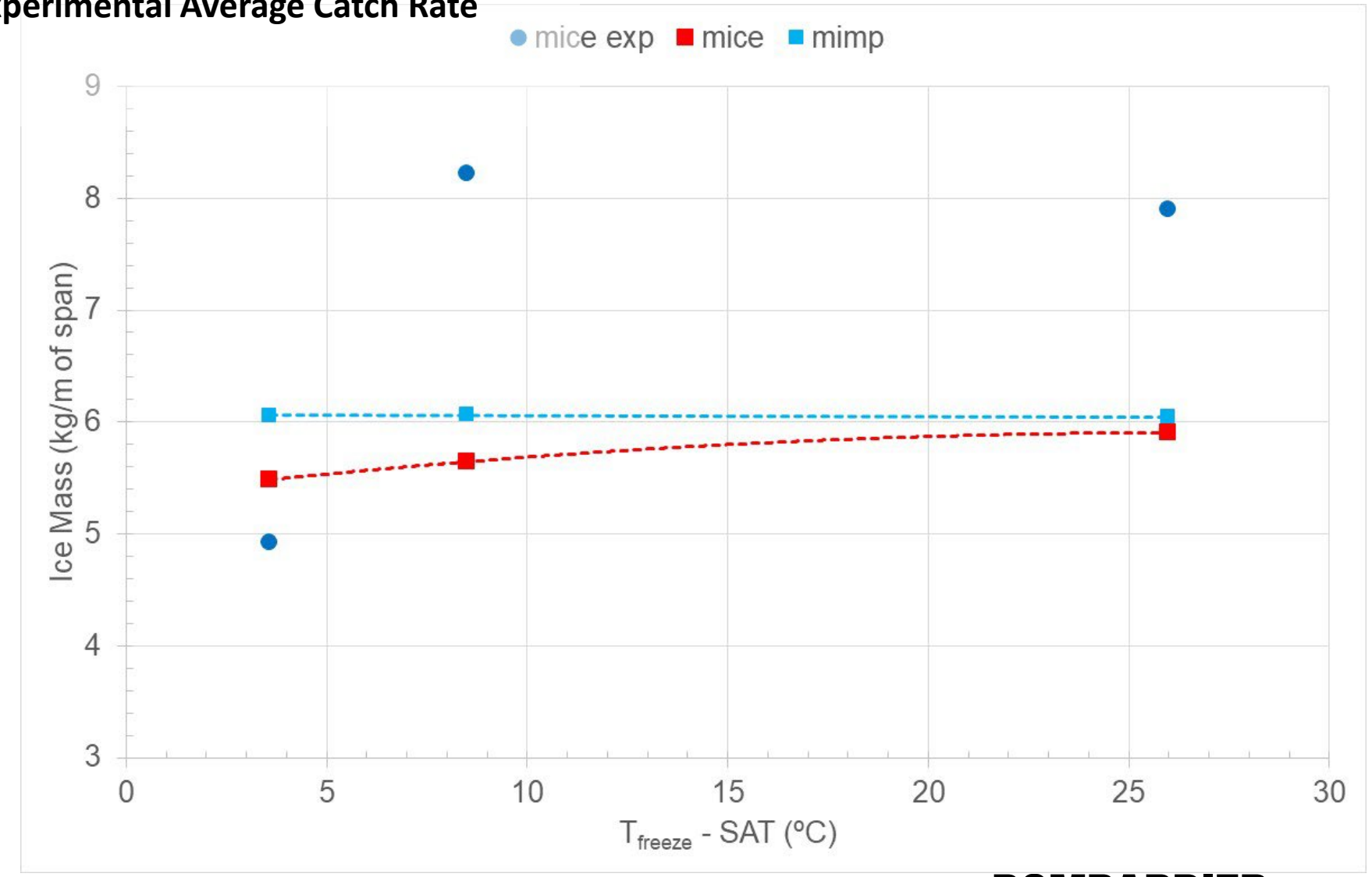
CRM-65 MidSpan

Observation: Ice Mass

Numerical Clean Catch Rate versus Experimental Average Catch Rate



BOMBARDIER

CRM-65 MidSpan

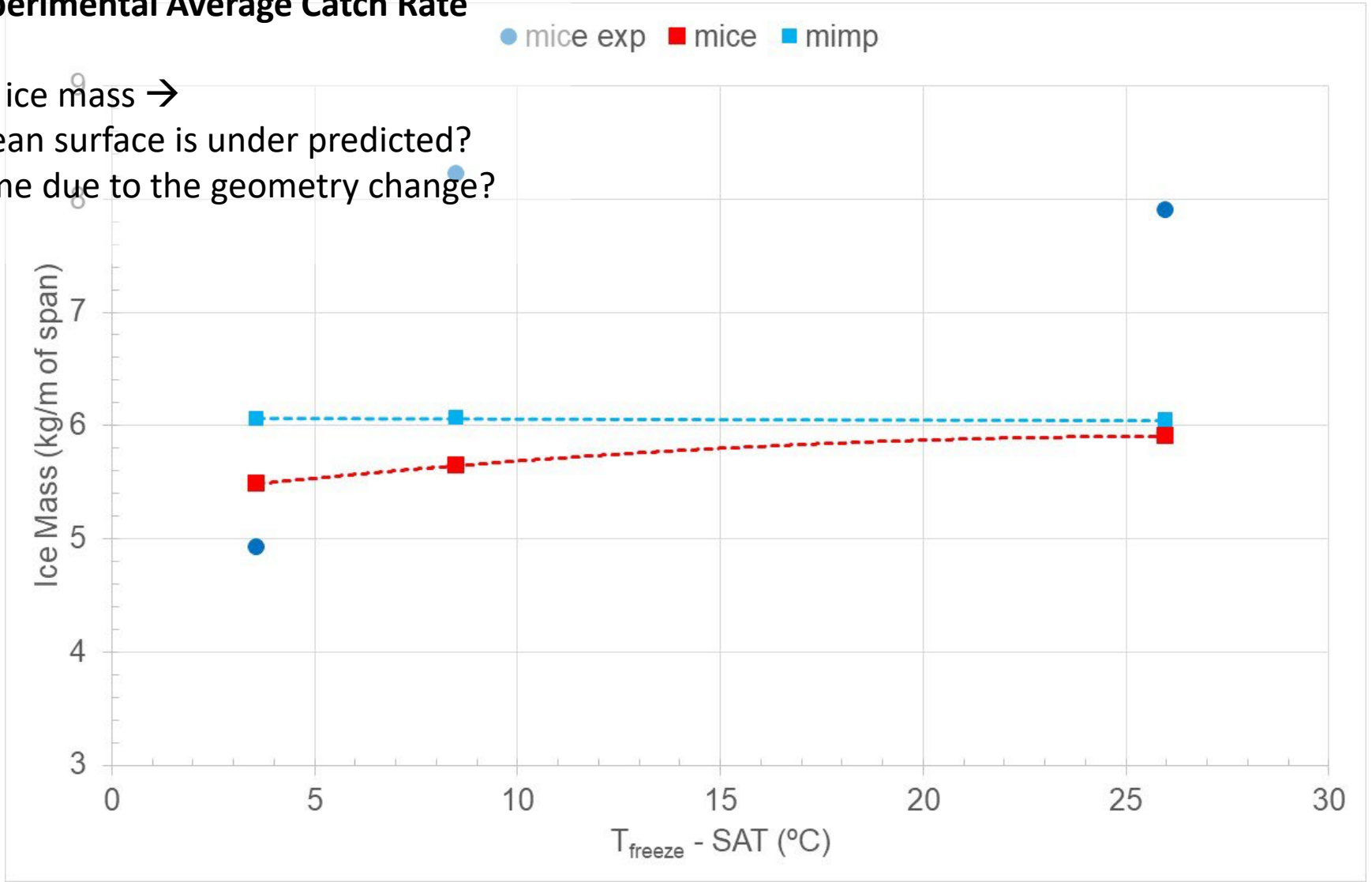
Observation: Ice Mass

Numerical Clean Catch Rate versus Experimental Average Catch Rate

Cold Case (-26°C): Under predicted the ice mass →

Do the numerical catch rate for clean surface is under predicted?

Do the catch rate increase with time due to the geometry change?



BOMBARDIER

CRM-65 MidSpan

Observation: Ice Mass

Numerical Clean Catch Rate versus Experimental Average Catch Rate

Cold Case (-26°C): Under predicted the ice mass →

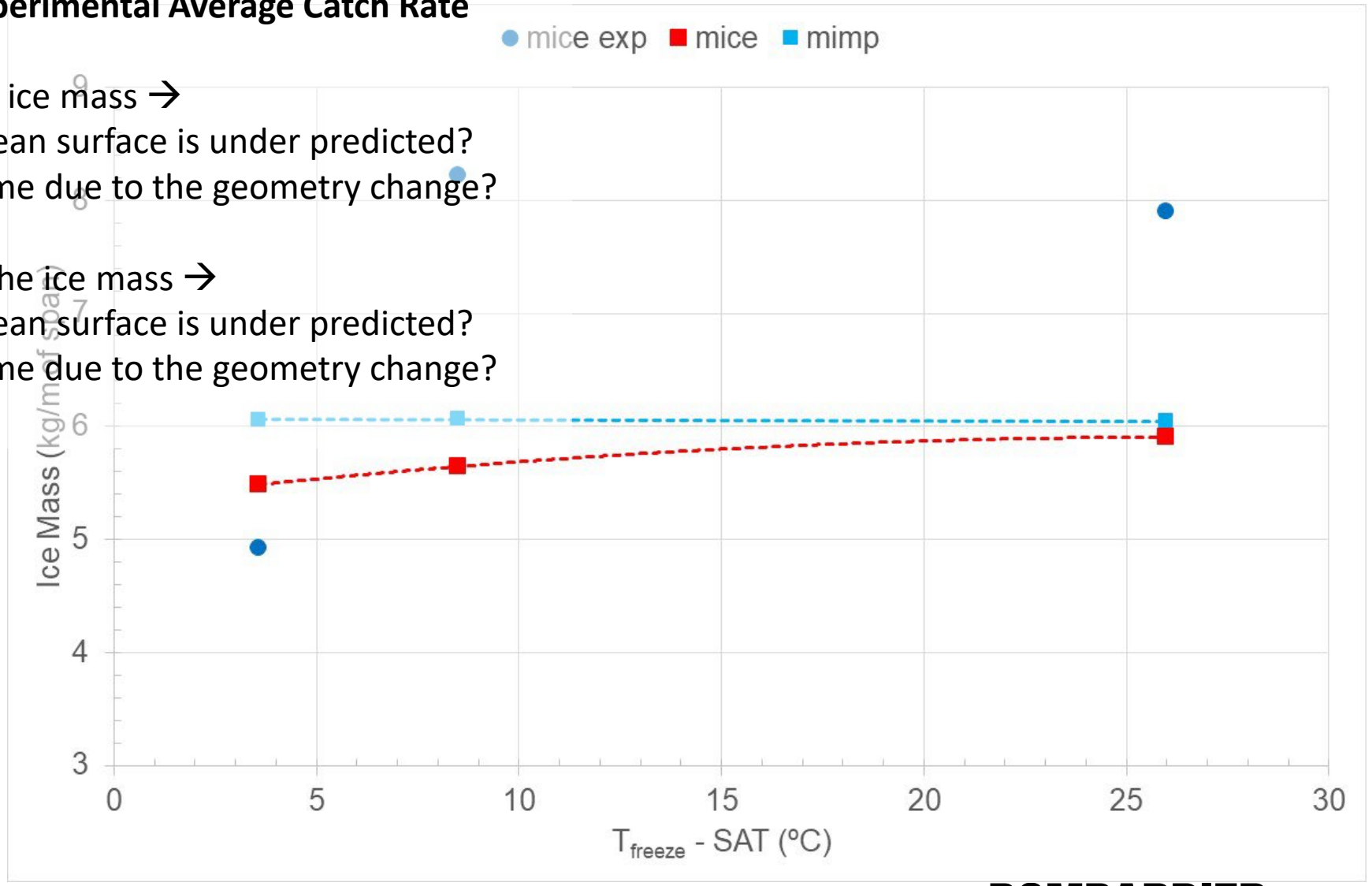
Do the numerical catch rate for clean surface is under predicted?

Do the catch rate increase with time due to the geometry change?

Mixed Case (-8.5°C): Under predicted the ice mass →

Do the numerical catch rate for clean surface is under predicted?

Do the catch rate increase with time due to the geometry change?



BOMBARDIER

CRM-65 MidSpan

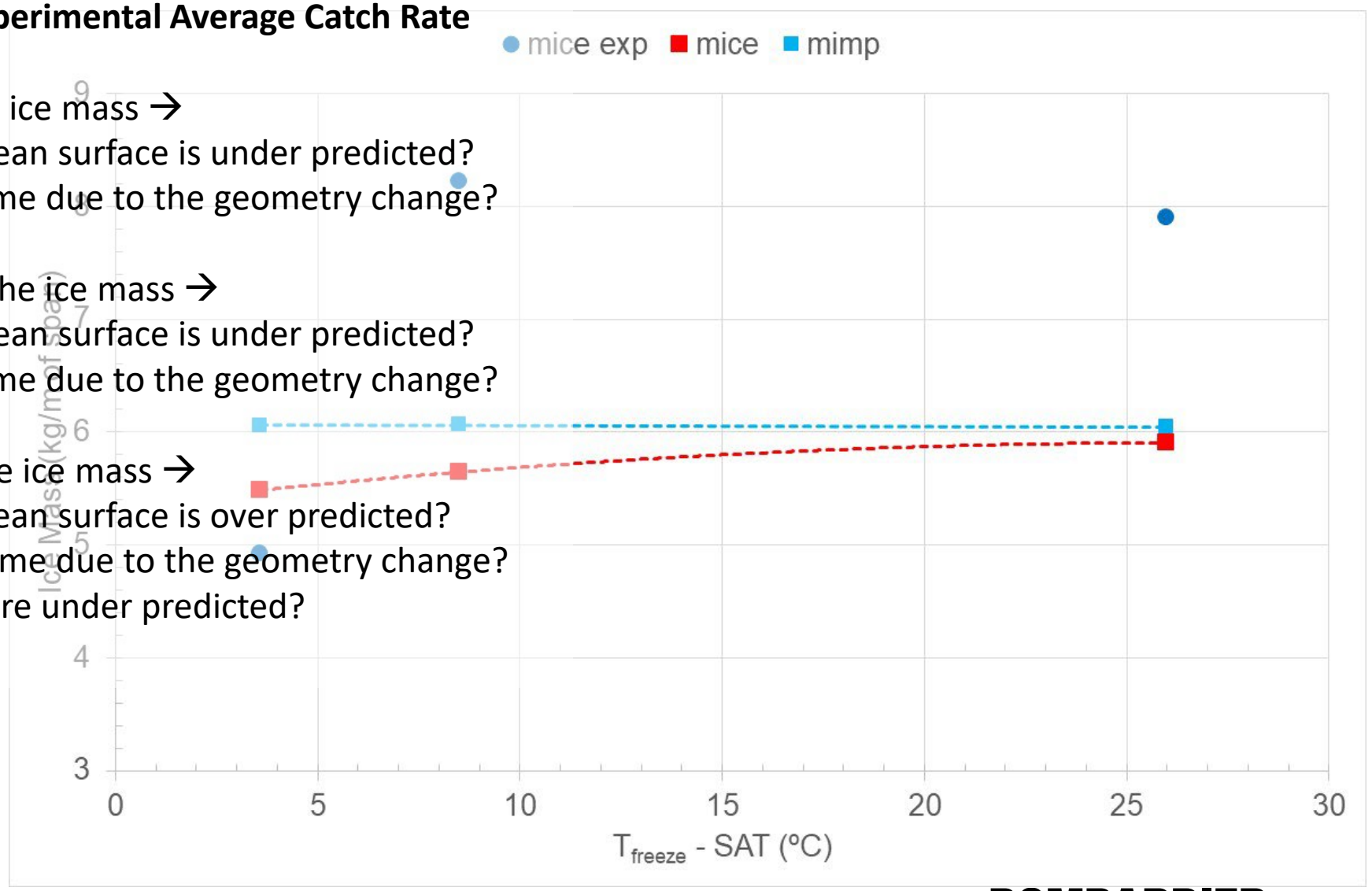
Observation: Ice Mass

Numerical Clean Catch Rate versus Experimental Average Catch Rate

Cold Case (-26°C): Under predicted the ice mass →
- Do the numerical catch rate for clean surface is under predicted?
- Do the catch rate increase with time due to the geometry change?

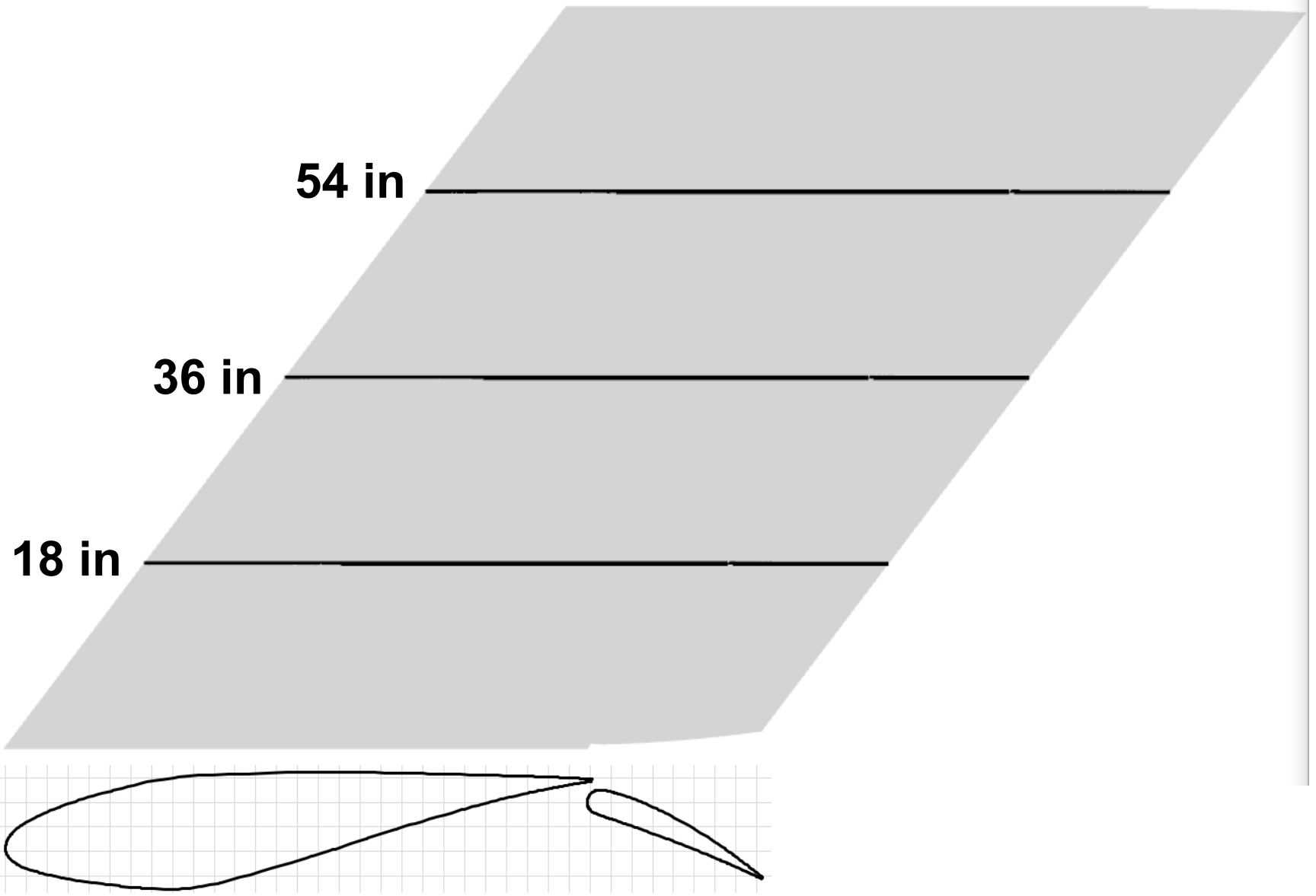
Mixed Case (-8.5°C): Under predicted the ice mass →
- Do the numerical catch rate for clean surface is under predicted?
- Do the catch rate increase with time due to the geometry change?

Mixed Case (-3.6°C): Over predicted the ice mass →
- Do the numerical catch rate for clean surface is over predicted?
- Do the catch rate decrease with time due to the geometry change?
- Do evaporation and sublimation are under predicted?
- Do water shedding occurs



BOMBARDIER

CRM-65 MidSpan



AoA	3.7	deg
TAS	66.9	m/s
MVD	25	μm
LWC	1	g/m³
time	29	min
SAT	-3.6	ºC
SAT	-8.5	ºC
SAT	-26	ºC

NASA IRT Volume	Droplet Diameter
0.05	7.3
0.1	9.9
0.2	13.7
0.3	24.9
0.2	44.9
0.1	74.9
0.05	127.6

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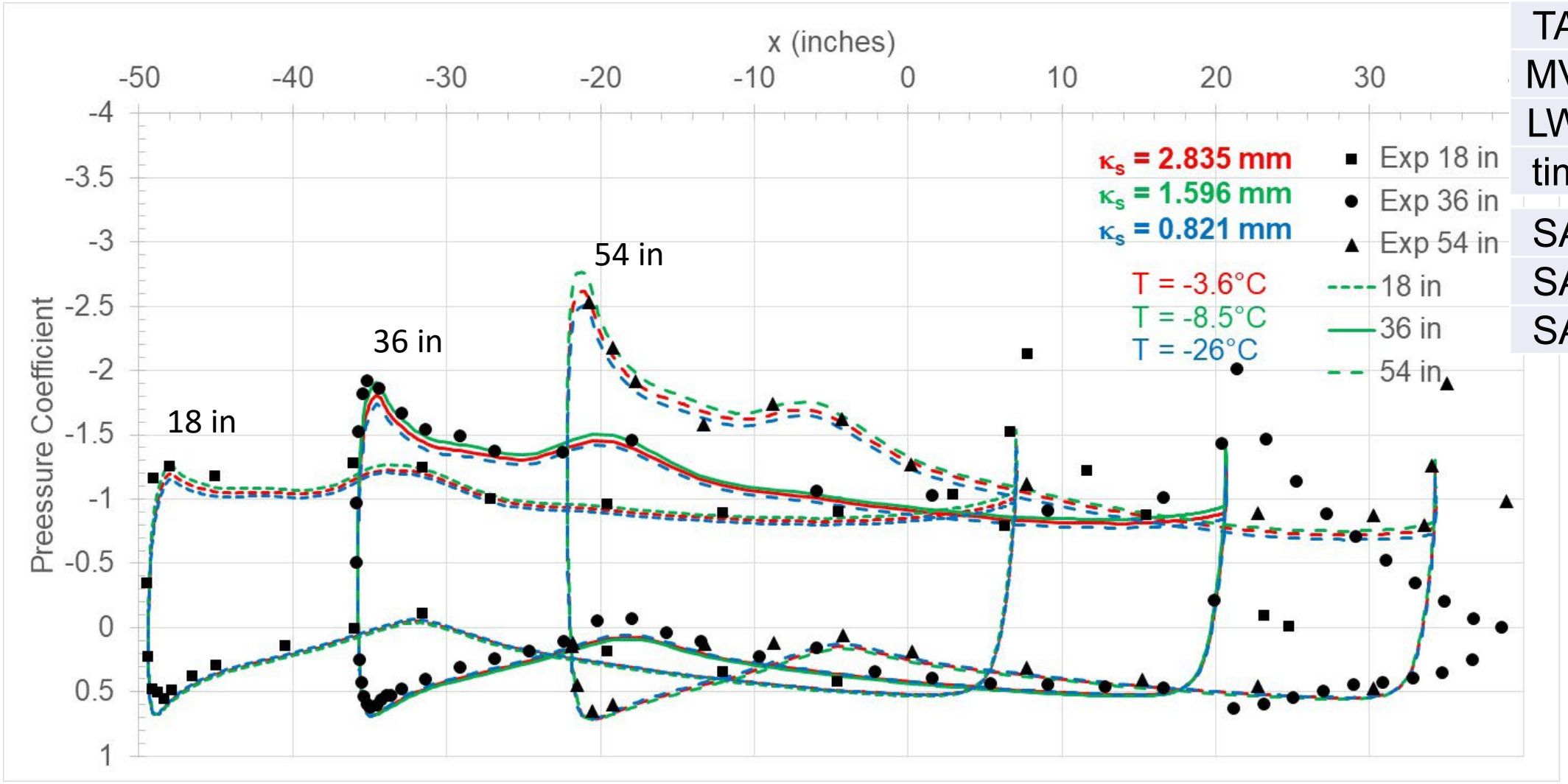
CRM-65 MidSPan

AoA	3.7	deg
TAS	66.9	m/s
MVD	25	µm
LWC	1	g/m³
time	29	min
SAT	-3.6	ºC
SAT	-8.5	ºC
SAT	-26	ºC



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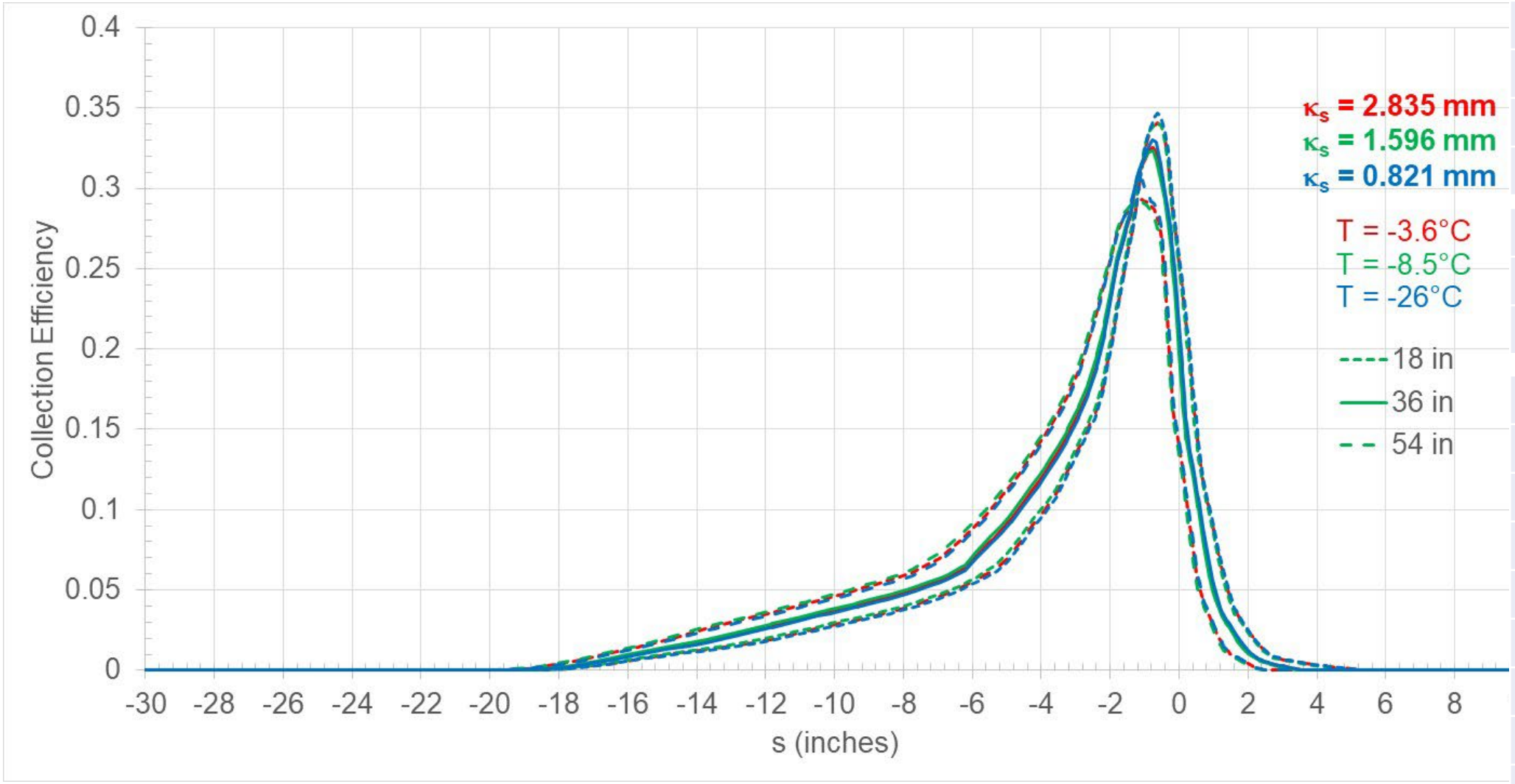
CRM-65 InBoard



AoA	3.7	deg
TAS	66.9	m/s
MVD	25	µm
LWC	1	g/m³
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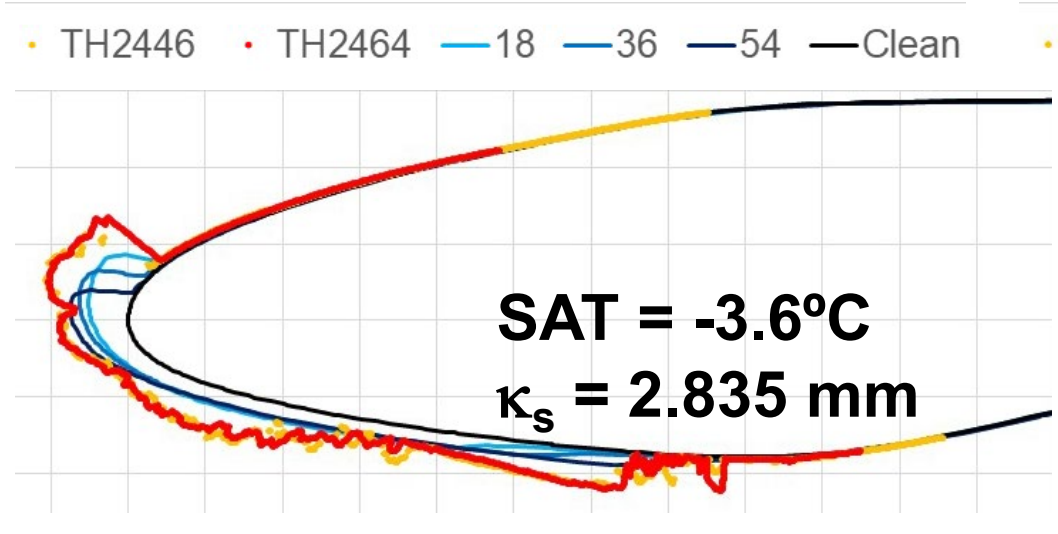
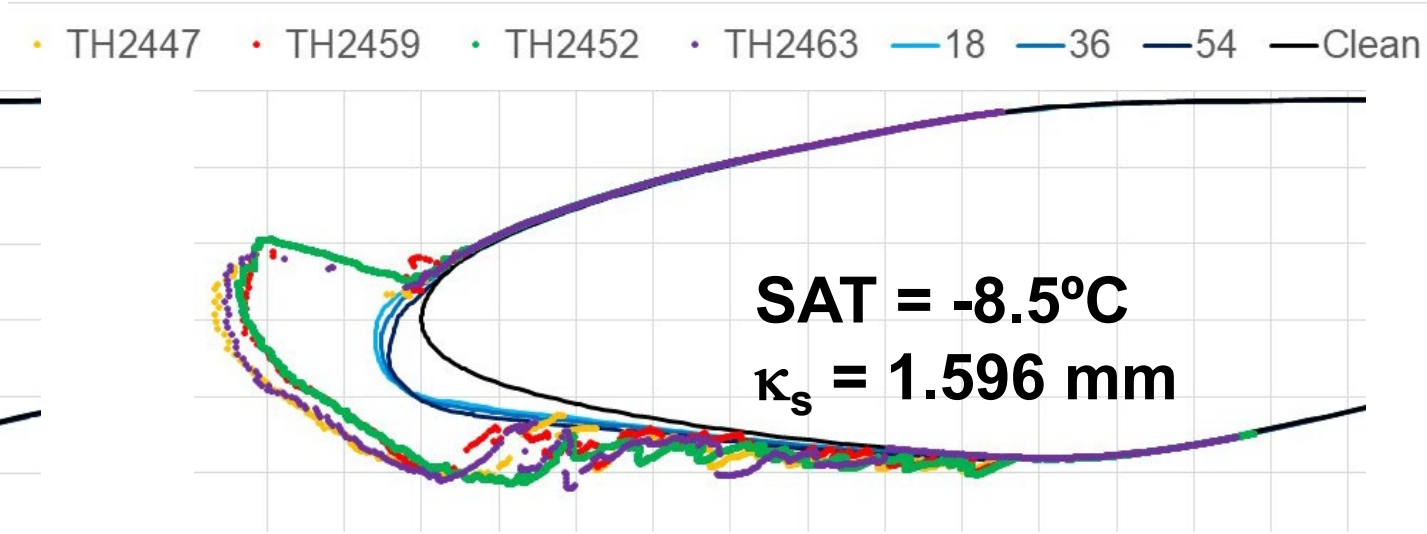
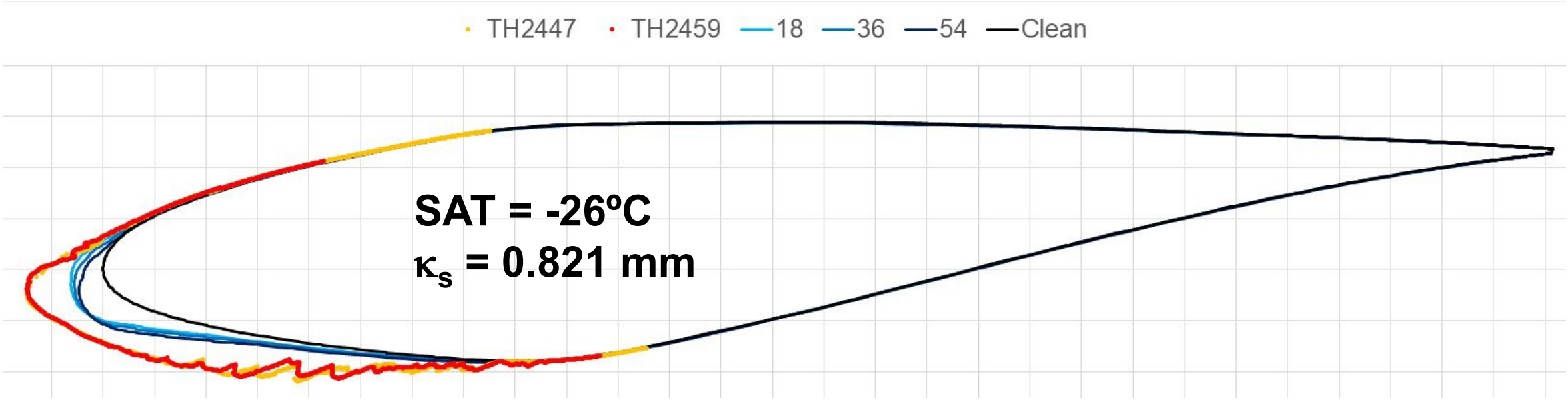
0.2	44.9
0.1	74.9
0.05	127.6

BOMBARDIER

CRM-65 MidSpan







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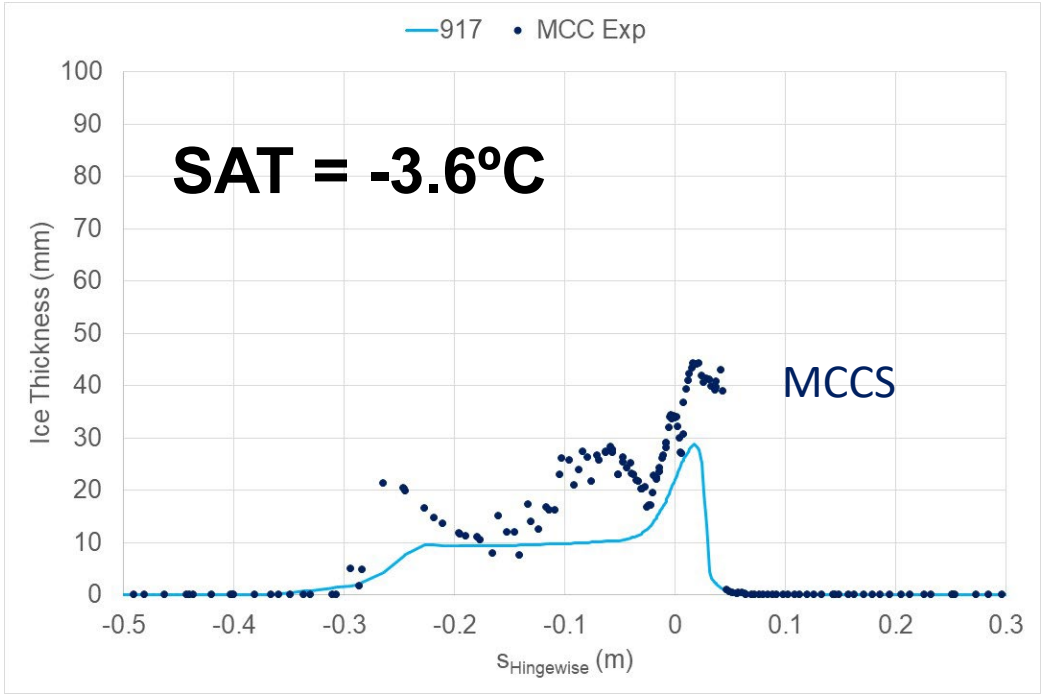
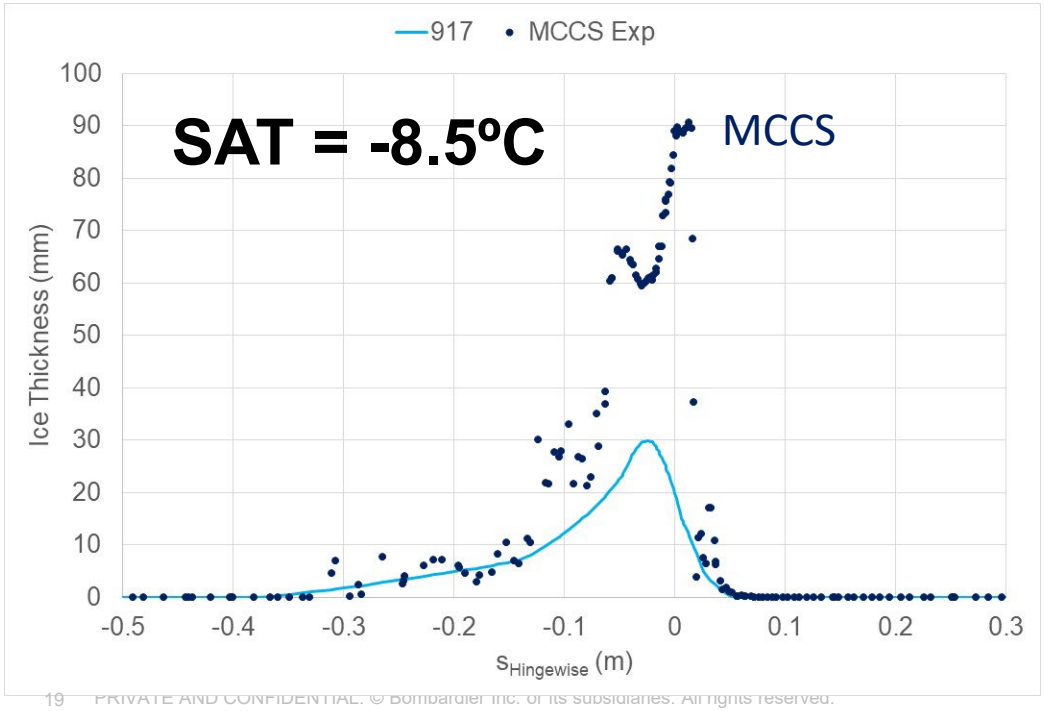
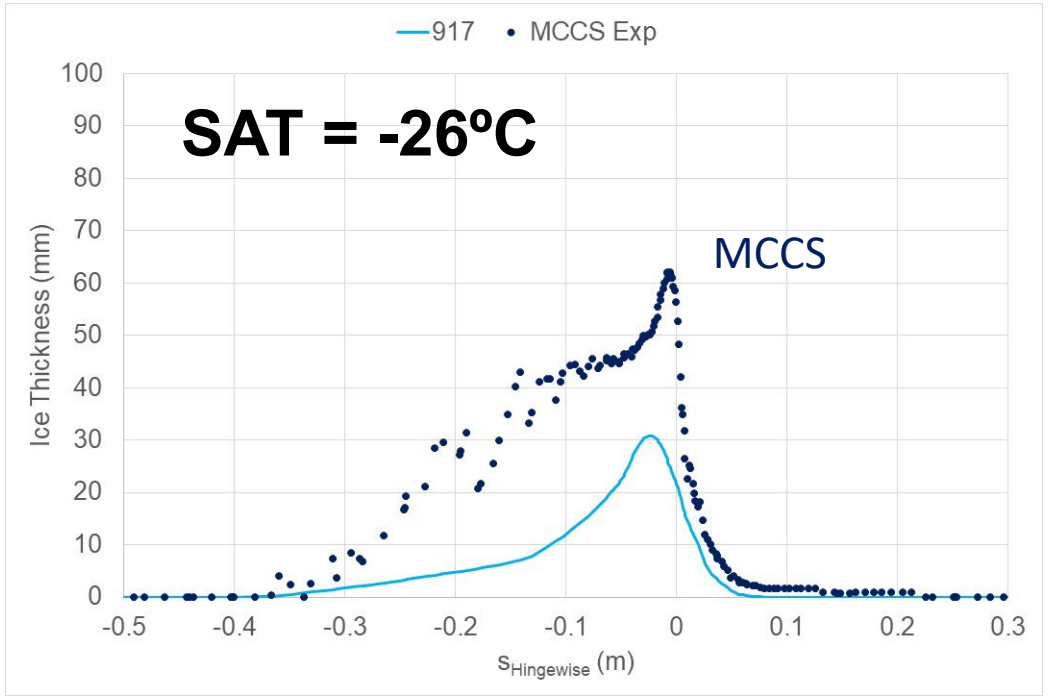
CRM-65 MidSpan

SAT (°)	Surface (m²) Exp	Ice Mass (kg/m) Exp	Ice Density kg/m³
-3.6	0.011466	4.170	364
-8.5	0.013216	6.420	486
-26.0	0.014025	6.500	463

Hingewise cut

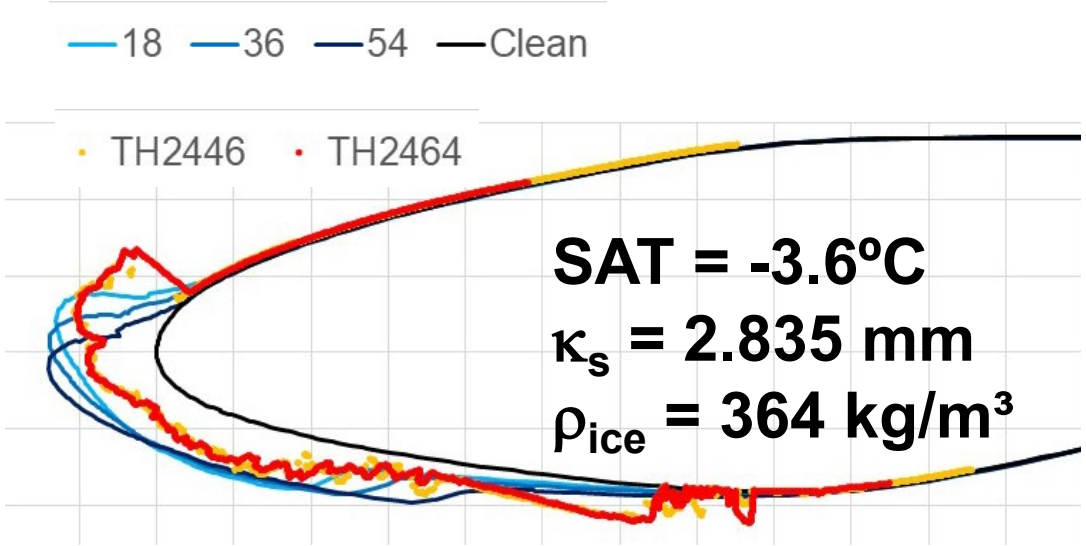


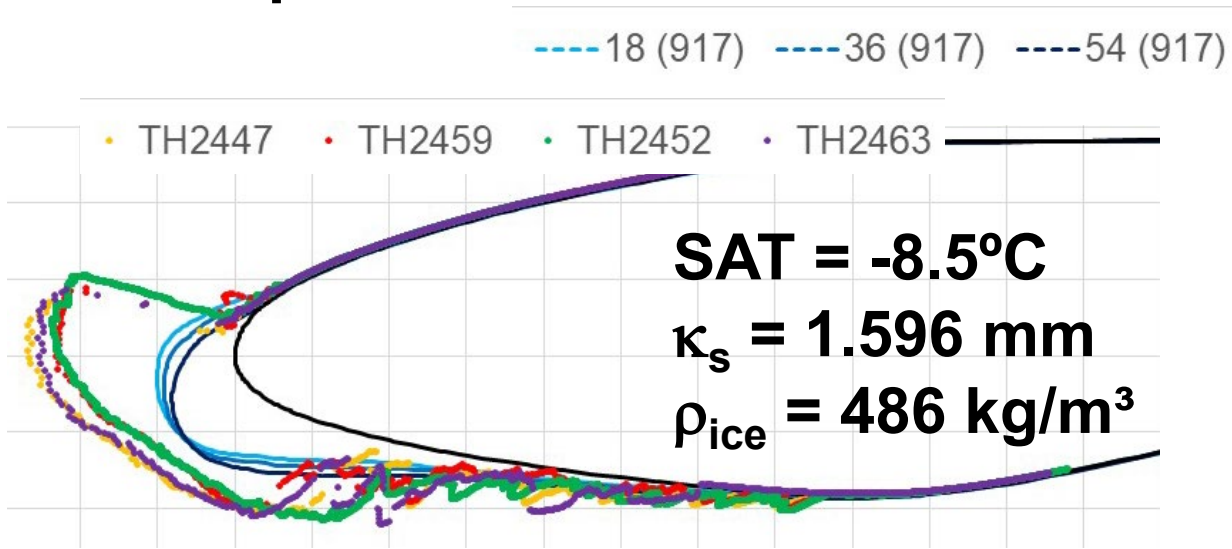


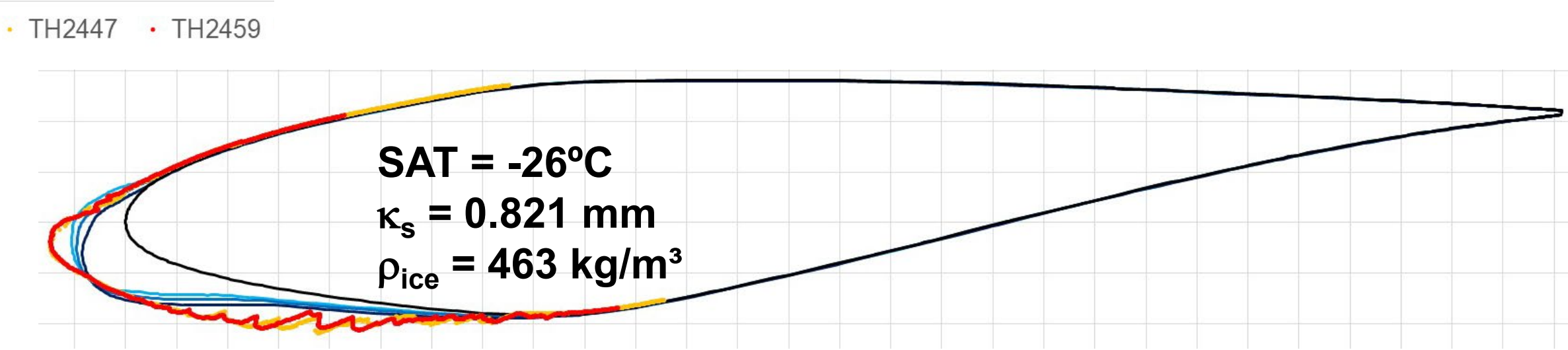


BOMBARDIER

CRM-65 MidSpan







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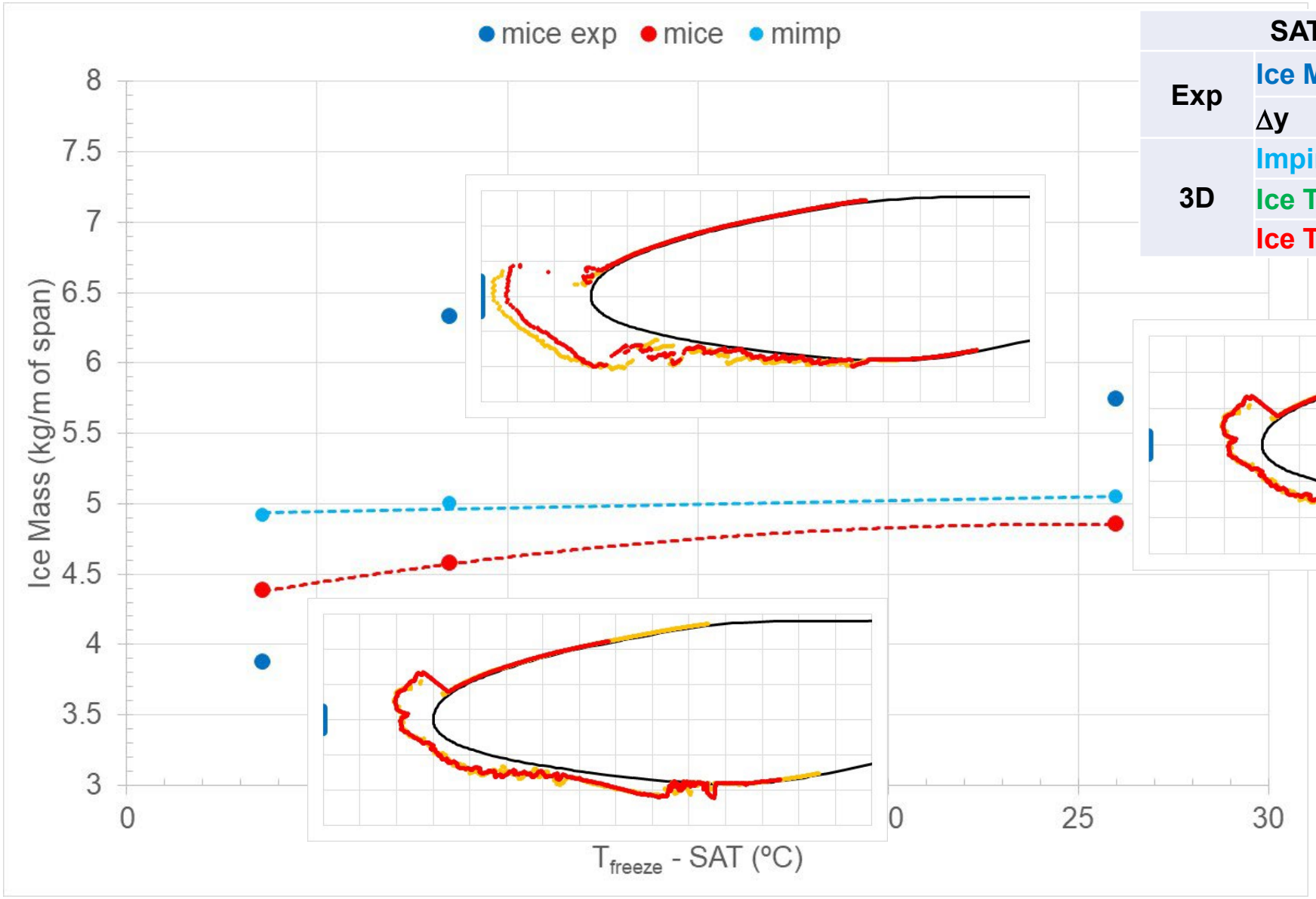
CRM-65 MidSpan



	SAT	-3.6	-8.5	-26	°C
Exp	Ice Mass	3.873	6.420	5.743	kg/m
	Δy	1.310	2.141	1.942	inches
3D	Impingment	4.915	4.999	5.049	kg/m
	Ice Thermo	4.379	4.572	4.853	kg/m
	Ice Thickness	4.163	4.420	4.248	kg/m

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CRM-65

Conclusion: 3D Ice Shape Simulation

1 layer ice simulation

- Need an equivalent ice density to match the Maximum Combined Cross Section
- If evaporation is under estimated that is due to Test Section Relative Humidity or to the evaporation model
- Artificial Ice Density based on MCCS volume to match ice shape

Multi-Layer Simulation

- Need Catch Rate or Collection Efficiency on
  - clean surface
  - intermediary iced surface
- Need Ice mass
  - few minute after ice accretion start
  - at intermediary time
  - at final time
- Local Ice Roughness Coefficient
- Local Ice Density

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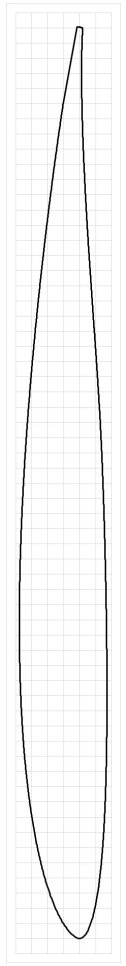
RG-15



AoA	4	deg
TAS	25	m/s
MVD	23	µm
LWC	0.44	g/m³
time	20	min

SAT	-2	ºC
SAT	-4	ºC
SAT	-10	ºC

VTT Icing Wind Tunnel	
Volume	Diameter
0.05	6.5
0.1	11.2
0.2	15.7
0.3	22.7
0.2	32.9
0.1	59.5
0.05	96.7

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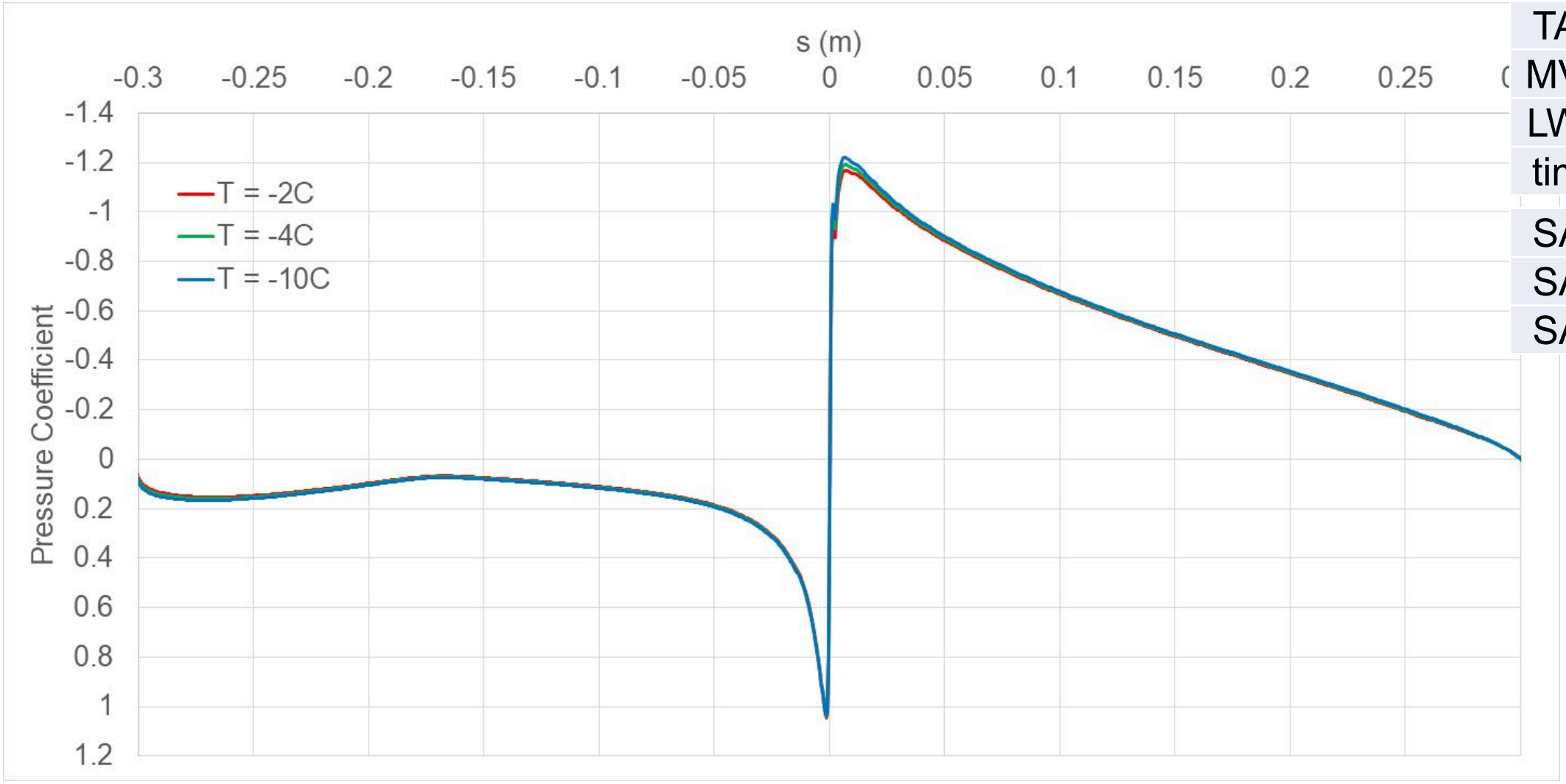
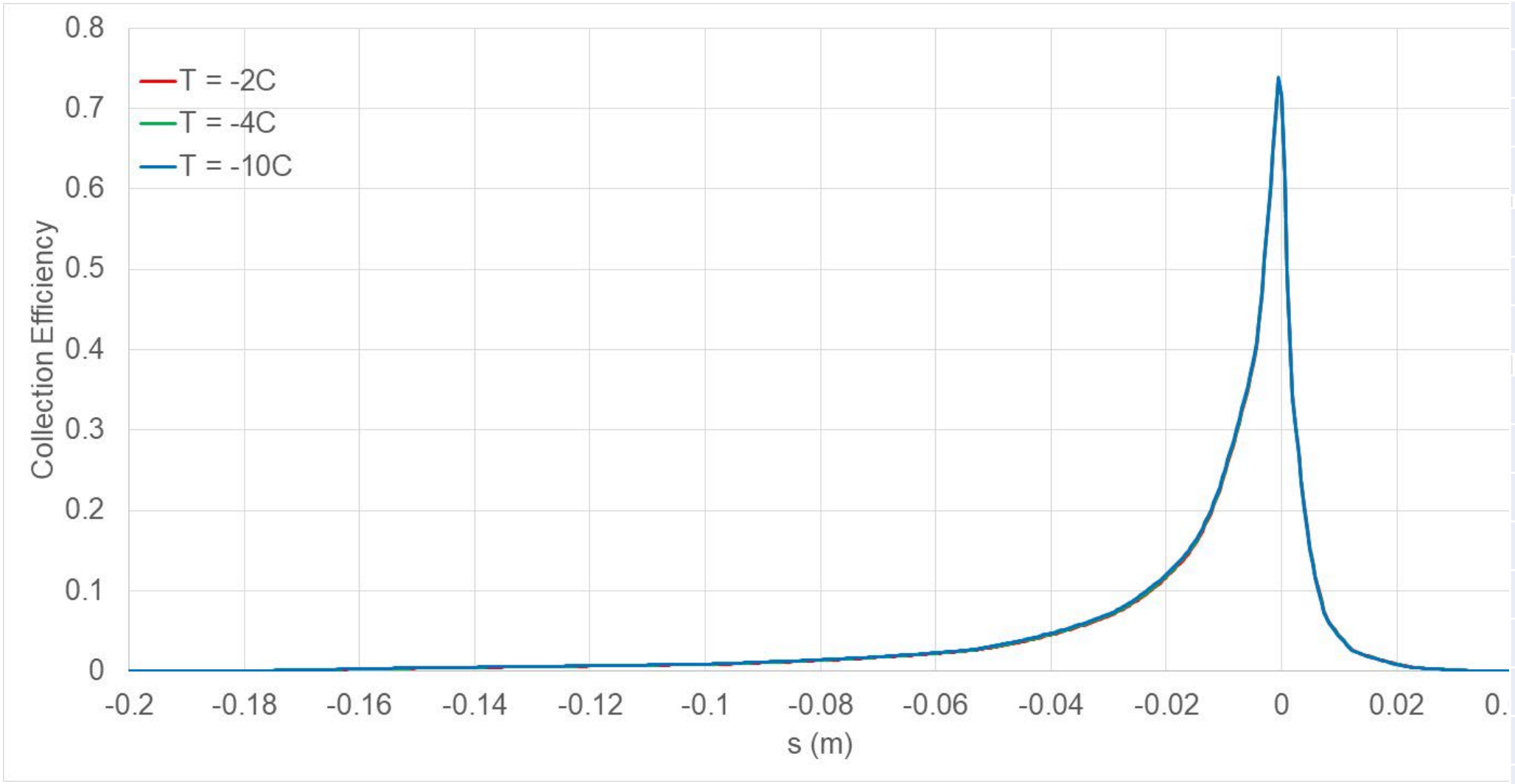
RG-15



AoA	3.7	deg
TAS	66.9	m/s
MVD	25	µm
LWC	1	g/m³
time	29	min
SAT	-3.6	ºC
SAT	-8.5	ºC
SAT	-26	ºC

BOMBARDIER

RG-15



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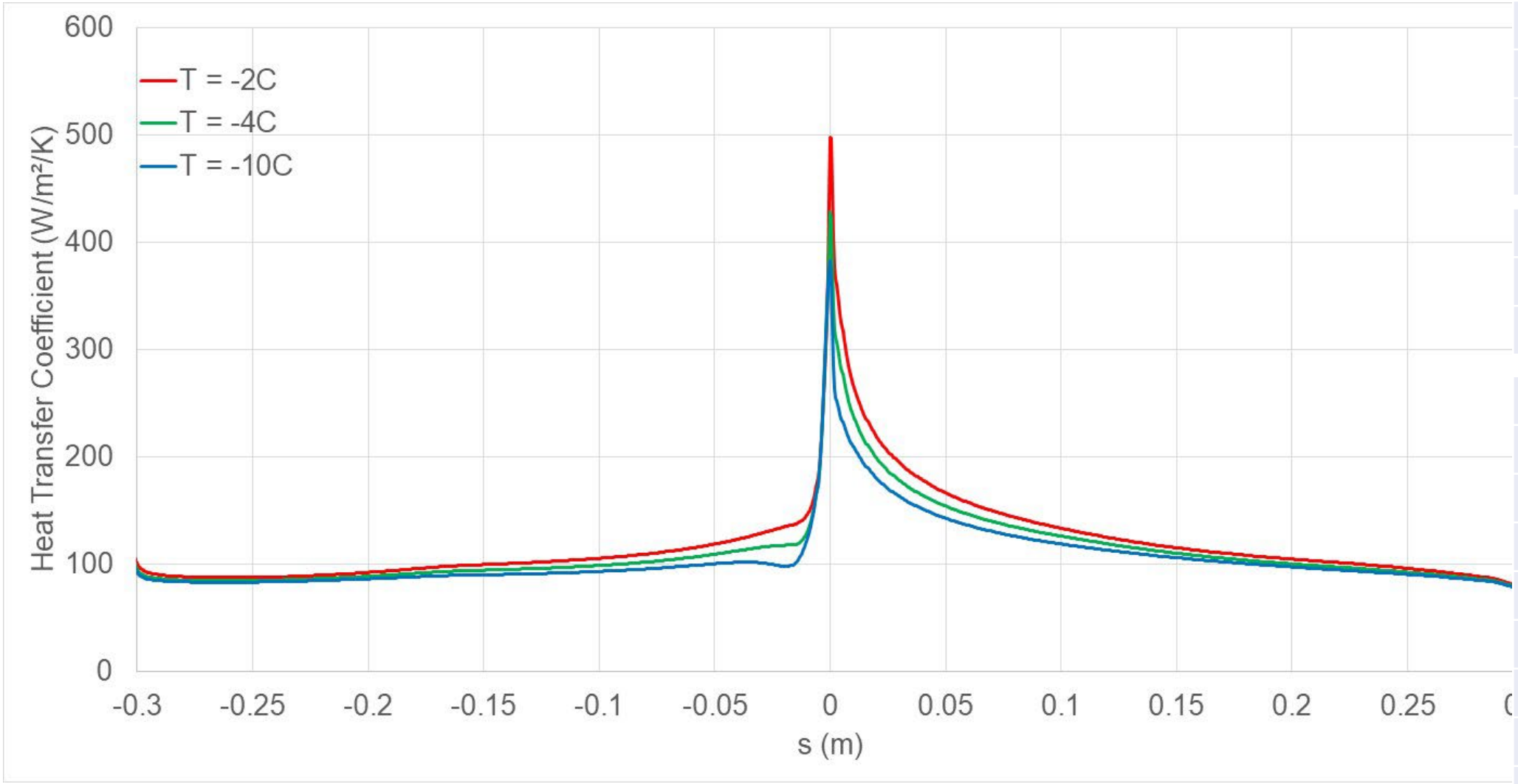
BOMBARDIER

CRM-65 InBoard



AoA	3.7	deg
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SAT	-8.5	ºC
SAT	-26	ºC

NASA IRT Volume	Droplet Diameter
0.05	7.3
0.1	9.9
0.2	13.7
0.3	24.9
0.2	44.9
0.1	74.9
0.05	127.6

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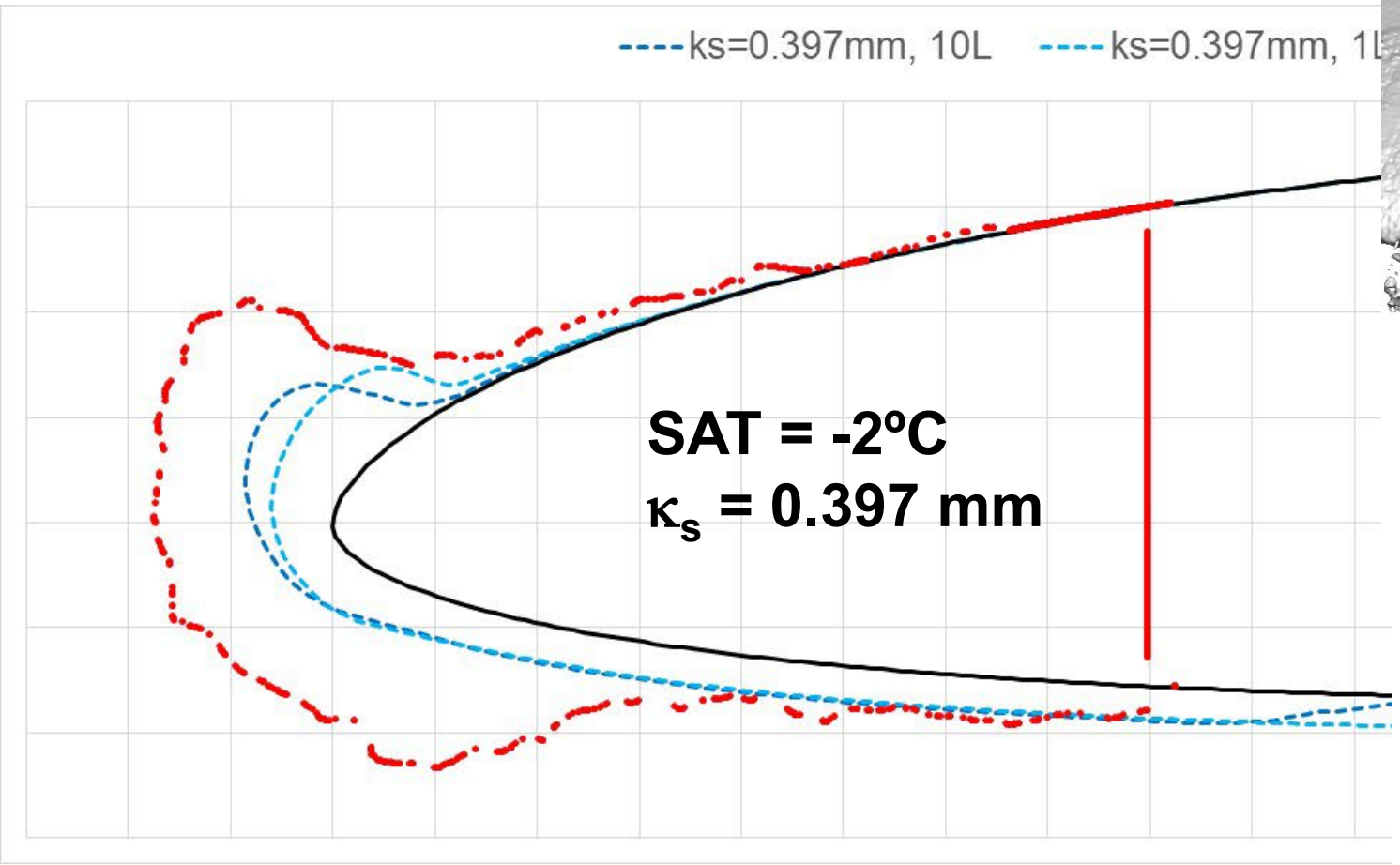
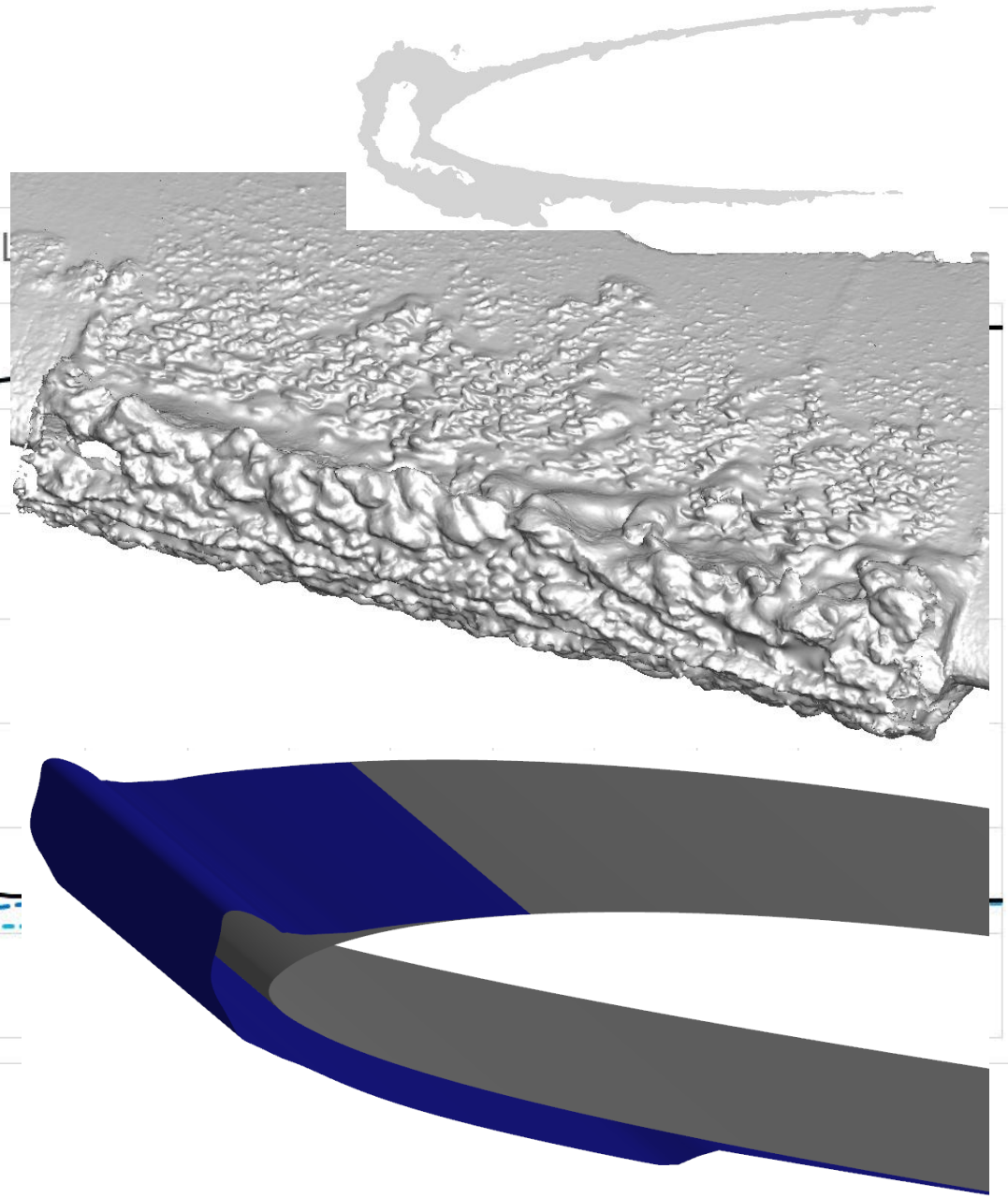
RG-15





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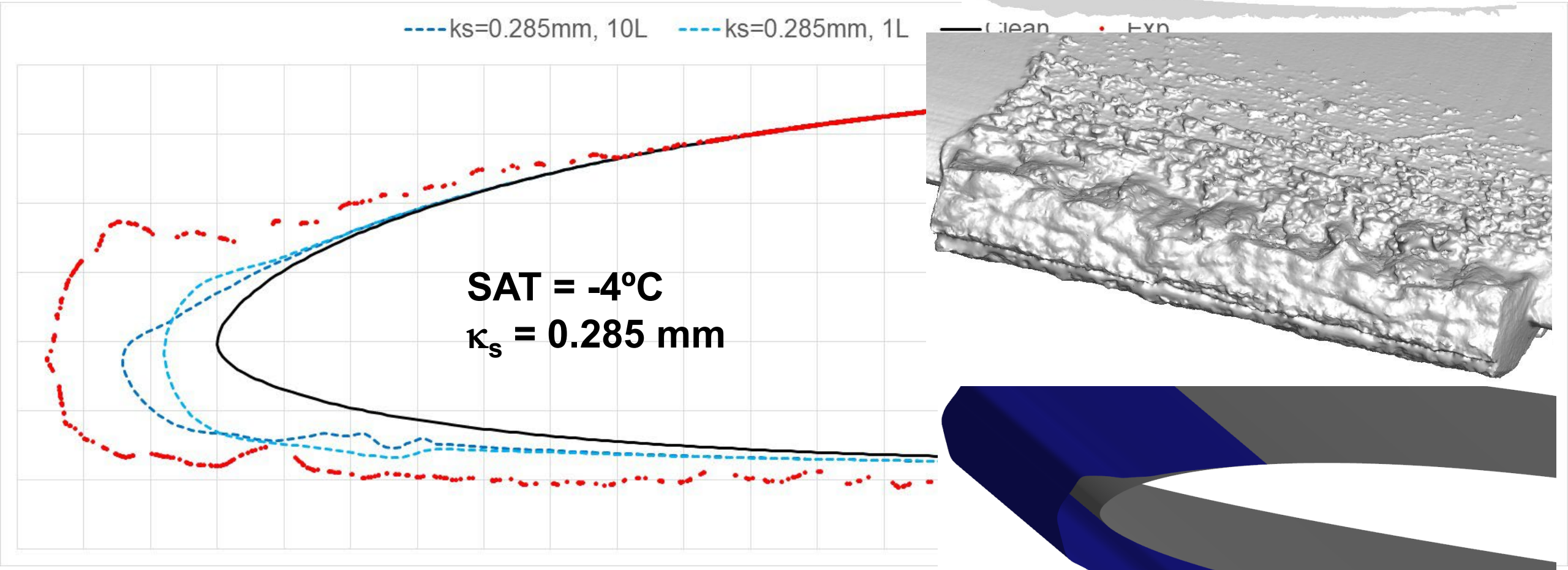

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