Evaluation of Alternative Altitude Scaling Methods for Thermal Ice Protection System in NASA Icing Research Tunnel

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Outline

- Introduction
- Experimental Methods
- Results and Discussion
- Conclusion

Introduction
Motivation for Study

- Most thermal Ice Protection System (IPS) development and testing done in atmospheric icing tunnels that cannot simulate altitude effects.
- Altitude scaling is required to test IPS in atmospheric wind tunnels.
- Re-based scaling methods with empirical corrections typically used.
- A more robust scaling methods desired for development of current and future generation aircraft
- Joint NASA and NRCC research program conducted to study the issue.

Introduction
NRC AIWT Tests (2012, 2014, 2015)

- 18” chord NACA 0018 model with simple heated air IPS
- Re-based scaling method found to be inadequate
  - Airfoil surface temperatures well matched between altitude and ground conditions.
  - Accreted ice mass much larger than reference
  - Ice formed farther downstream than reference
  - Visual evidence of water re-entrainment into air flow.
- Two Weber number based method for scaling investigated.
  - One method matched We_{DW} (water density based)
  - Other method matched We_{DA} (air density based) and m_w/m_e (defined as Pi3).

Introduction
AIWT Tests (2012, 2014, 2015)

- We-based scaling methods produced ice accretions much closer in size and location to altitude reference conditions than Re-based scaling method.
- Provided means of altitude scaling based on primary physics and not empirical corrections.

Reference

Re Scaling

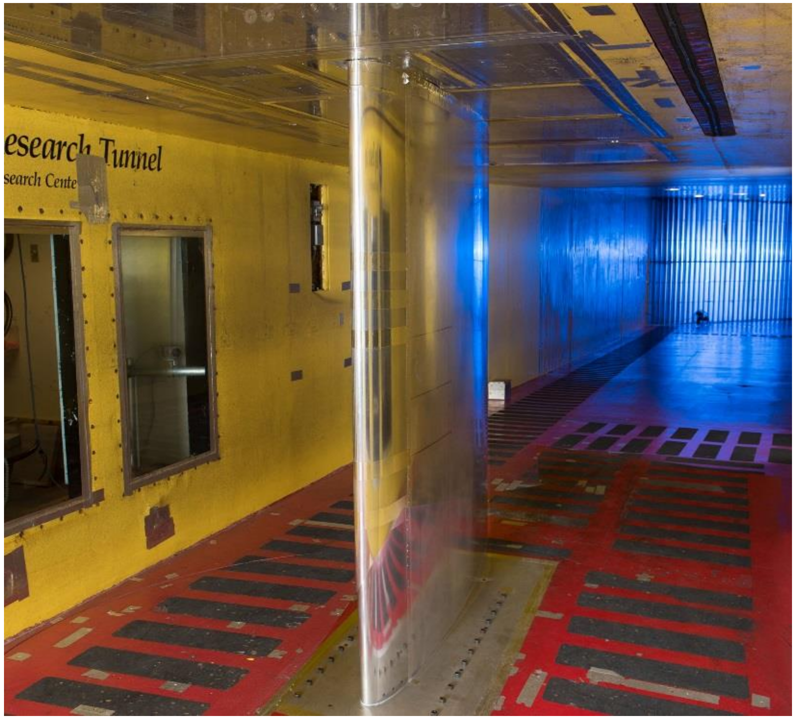
WePi3 Scaling

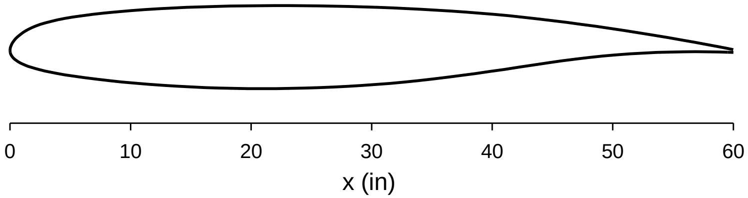
Introduction
2016 IRT Test

- Compared different scaling methods with a much larger business jet airfoil model.
- Ice protection system more similar to what is used on commercial aircraft.
- IRT cannot simulate altitude conditions.
- Results of different scaling methods can be compared to one another and trends compared to AIWT results.

Experimental Procedure

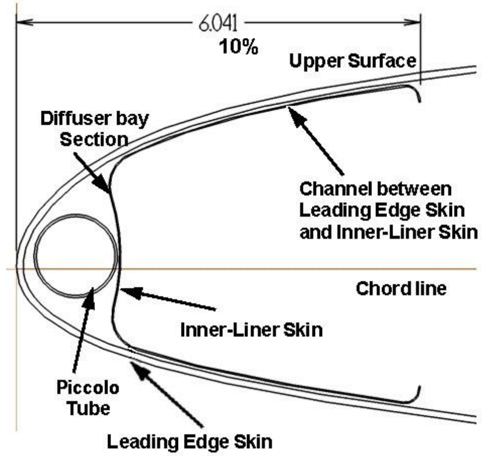
- Test conducted in Icing Research Tunnel at NASA Glenn Research Center.
- 60 in. chord model representative of modern business jet.
- Piccolo tube IPS.
- Built for 2006 Wichita State University IPS analysis and modelling study.
- Extensively instrumented with temperature and pressure sensors.

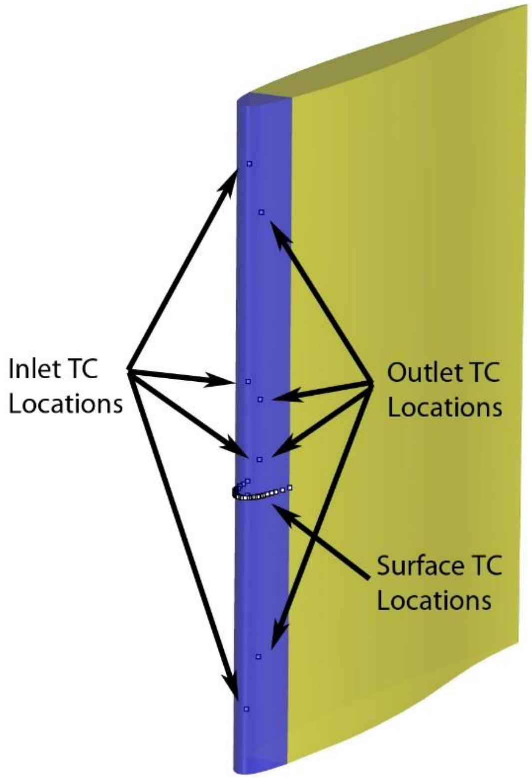


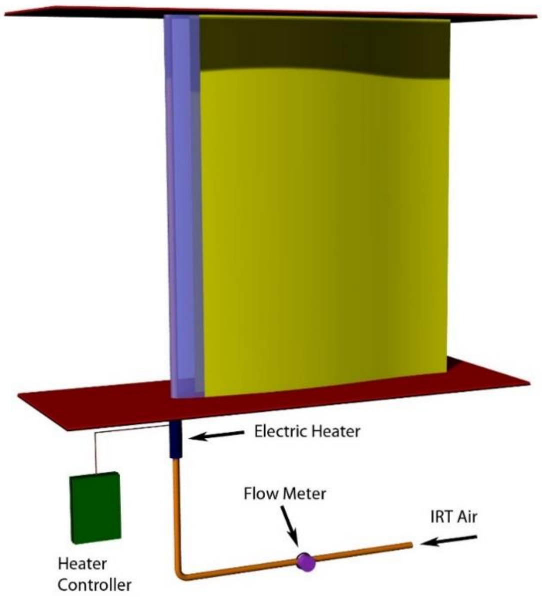


Experimental Procedure

- Surface temperatures (32 TCs)
- 4 TCs in piccolo tubes (Inlet T)
- 4 TCs in diffuser liner (Outlet T)







Reference Conditions

Flight Phase	Altitude (ft)	V (kts)	α (deg)	T_s (deg C)	T_t (deg C)	LWC (g/m^2)	MVD (μm)
Descent	10000	180	-1	-14.2	-10	0.35	19.1
Cold Hold	15000	180	3	-20.1	-15.8	0.24	17.5
Warm Hold	15000	180	3	-8.6	-4.3	0.49	17.4

Scaling Parameters

Scaling Method	Scaling Parameters Held Constant			
Re	Re_{2r}	m_w	K_0	T_r
WePi3	WeDA	Pi3	K_0	T_r
WeDW	WeDW	m_w	K_0	T_r

- Required 2 step process to obtain scaled conditions
  - Run at Re-scaled conditions to obtain L.E. temperatures.
  - Run at We-scaled conditions with IPS adjusted to match the L.E. temperatures obtained at Re-scaled conditions.

Descent Scenario

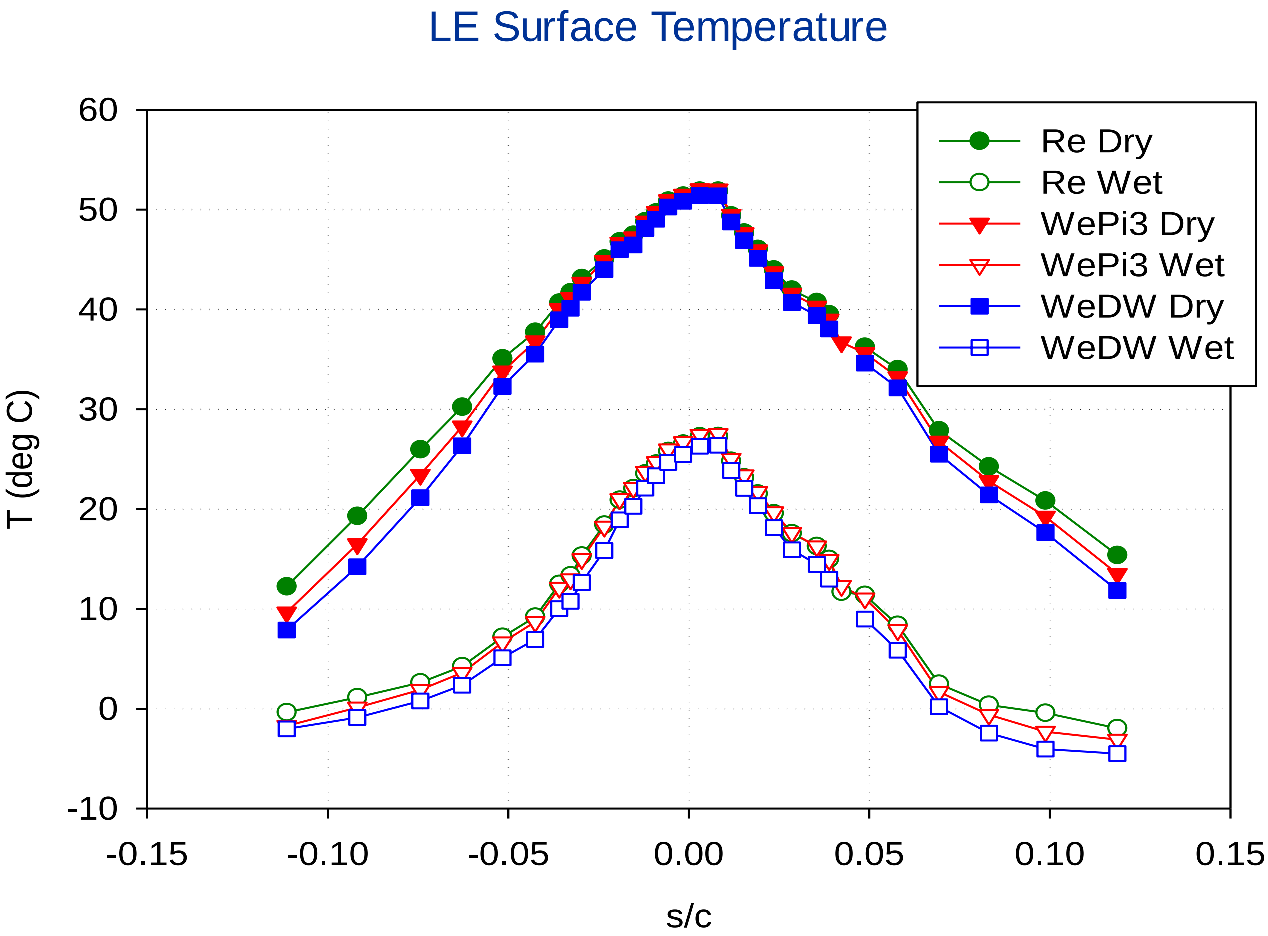
Scale Method	Alt (ft)	V (kts)	T_s (deg C)	LWC (g/m^3)	MVD (μm)	m_w (g/m^2s)	Re_{2r} ($x10^6$)	WeDA	Pi3	WeDW ($x10^6$)	Ice Mass (g)
Referenc	*10000*	*180*	*-14.2*	*0.35*	*19.1*	*17.6*	*0.224*	*5814*	*1.6*	*6.21*	***N/A***
Re	1066	133	-12.7	0.48	22.8	17.6	0.224	4315	2.24	3.38	**20**
WePi3	1439	159	-13.5	0.35	19.4	14.4	0.265	5814	1.62	4.84	**8.5**
WeDW	1782	180	-14.2	0.34	21.6	17.6	0.297	7769	1.88	6.21	**12.7**

Re Scaling

WePi3 Scaling

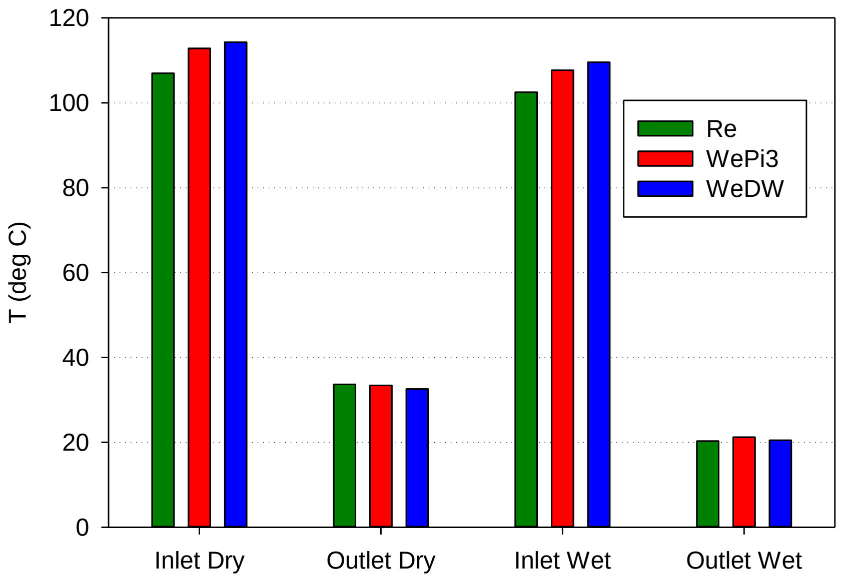
WeDW Scaling

Descent Scenario

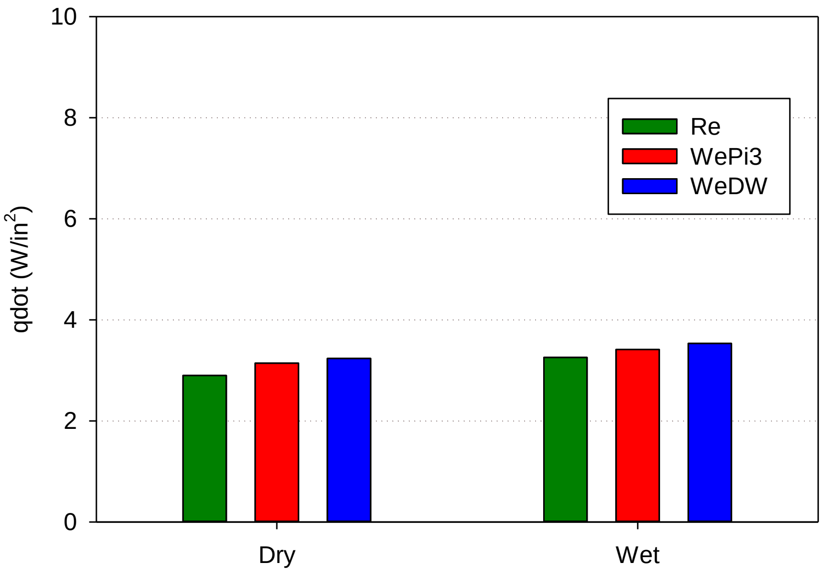


Descent Scenario

Heated Air Temp.

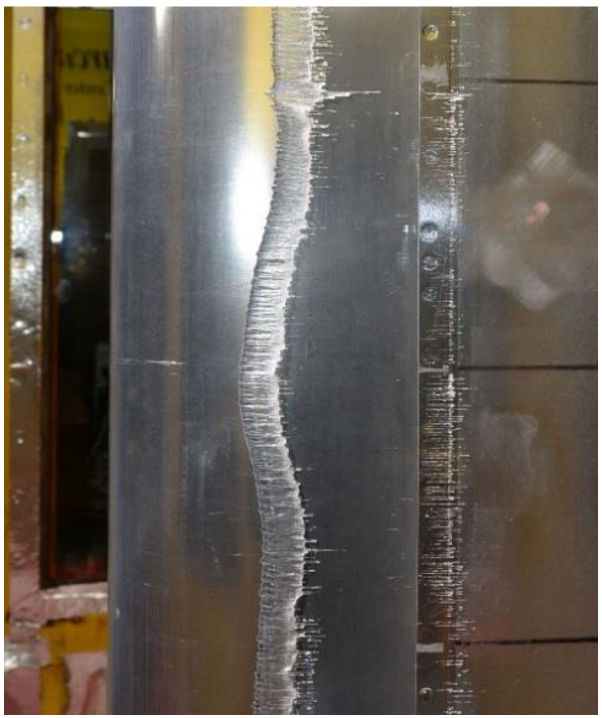


Heated Air Energy Input



Cold Hold Scenario

Scale Method	Alt (ft)	V (kts)	T_s (deg C)	LWC (g/m^3)	MVD (μm)	m_w (g/m^{2}s)	Re_{2r} (x10^6)	WeDA	Pi3	WeDW (x10^6)	Ice Mass (g)
Reference	*15000*	*185*	*-20.1*	*0.31*	*14.6*	*13.4*	*0.193*	*5147*	*1.06*	*6.54*	***N/A***
Re	976	109	-16.4	0.52	20.1	13.4	0.193	3065	1.87	2.27	**54.2**
WePi3	1495	149	-16	0.28	16.9	9.5	0.253	5147	1.06	4.22	**5.0**
WeDW	2087	185	-15.7	0.27	18.9	13.3	0.31	8346	1.37	6.54	**16.4***

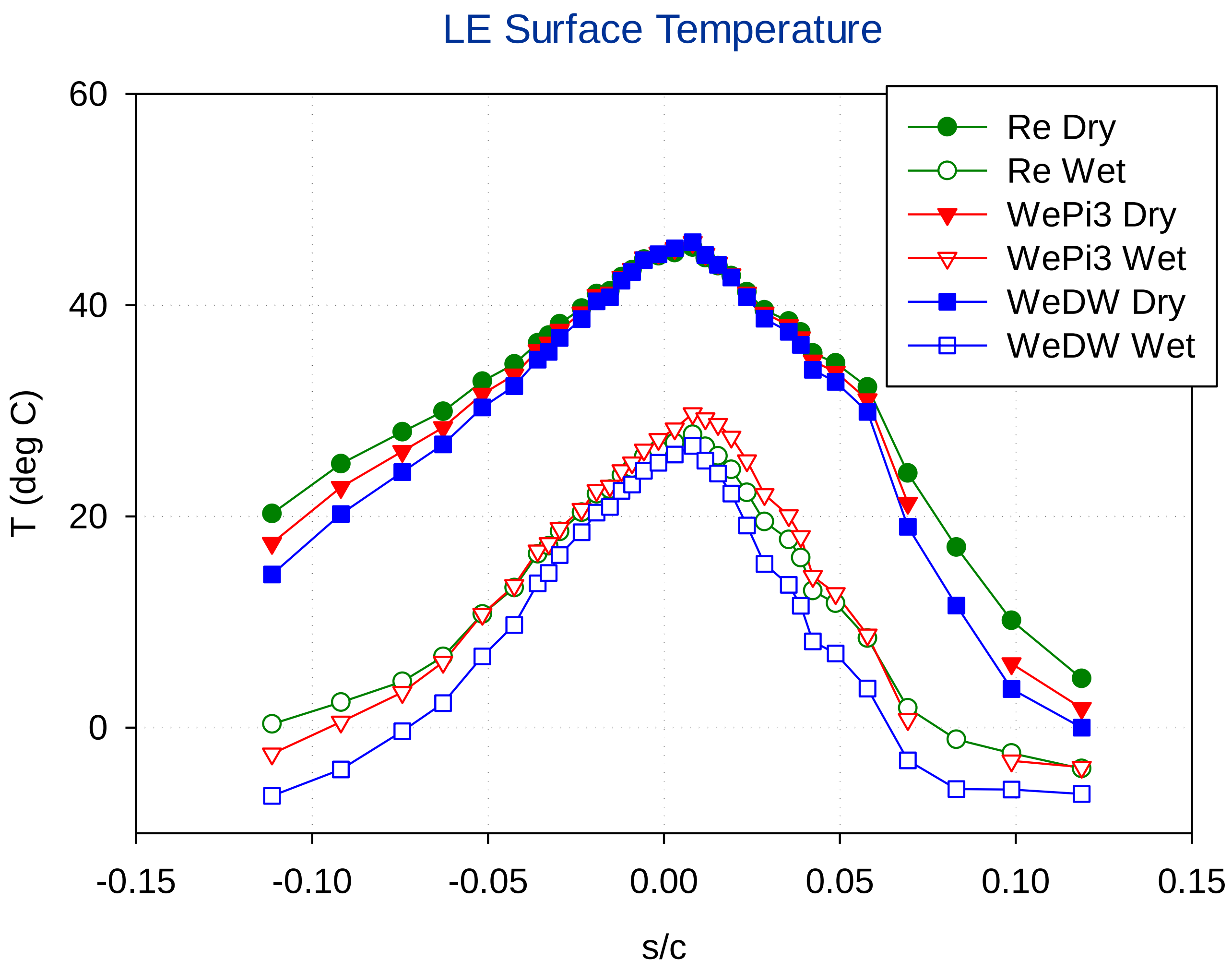


Re Scaling

WePi3 Scaling

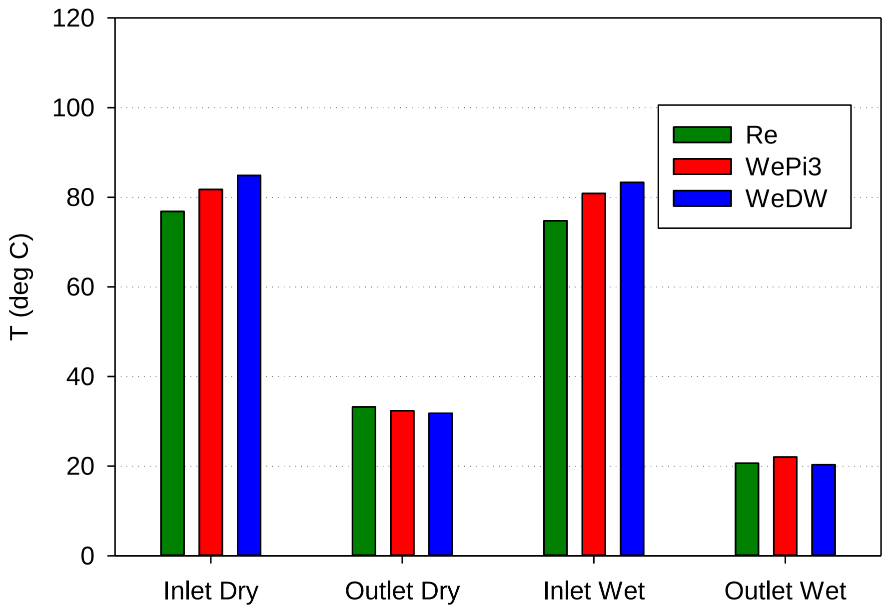
WeDW Scaling

Cold Hold Scenario

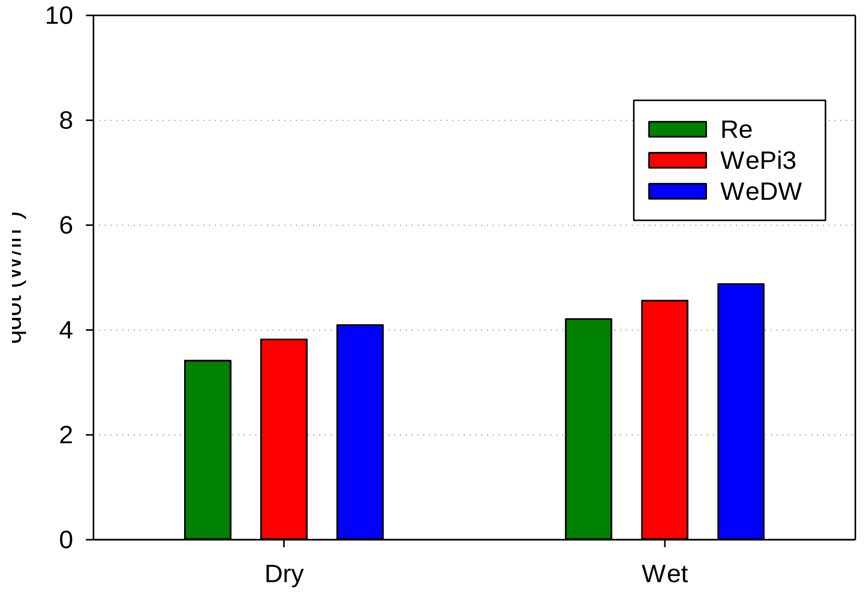


Cold Hold Scenario

Heated Air Temp.

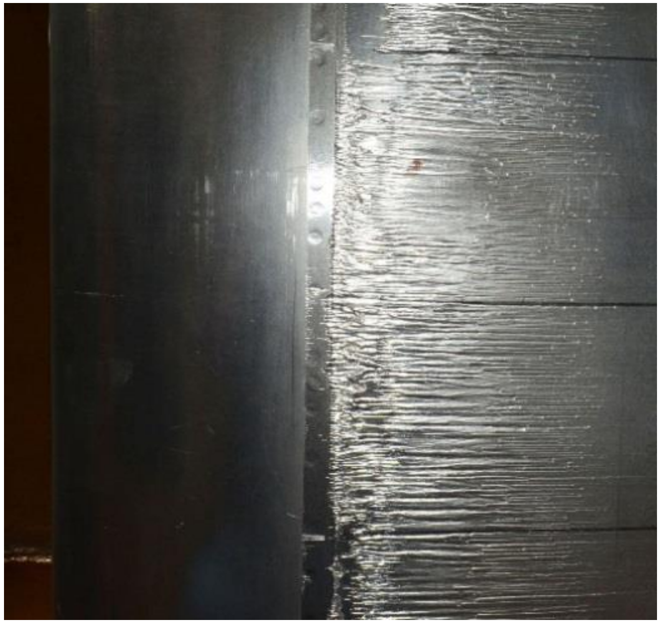


Heated Air Energy Input

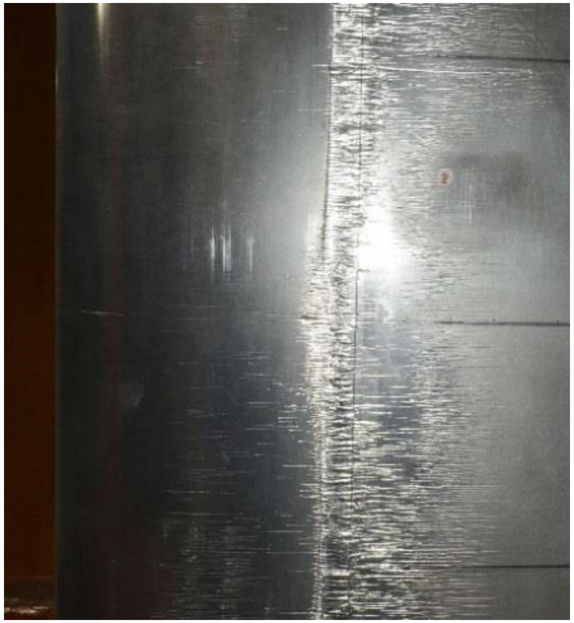


Warm Hold Scenario

Scale Method	Alt (ft)	V (kts)	T_s (deg C)	LWC (g/m^3)	MVD (μm)	m_w (g/m^{2}s)	Re_{2r} (x10^6)	WeDA	Pi3	WeDW (x10^6)	Ice Mass (g)
Reference	*15000*	*185*	*-8.6*	*0.39*	*18.3*	*20.0*	*0.186*	*4922*	*1.74*	*6.55*	***N/A***
Re	1336	109	-6.3	0.66	25.4	20.0	0.186	2923	3.09	2.26	**207.5**
WePi3	1814	147	-7.3	0.36	19.6	13.6	0.241	4922	1.74	4.12	**64.5**
WeDW	2454	184	-8.6	0.37	22	20.0	0.299	8005	2.24	6.55	**138.8**



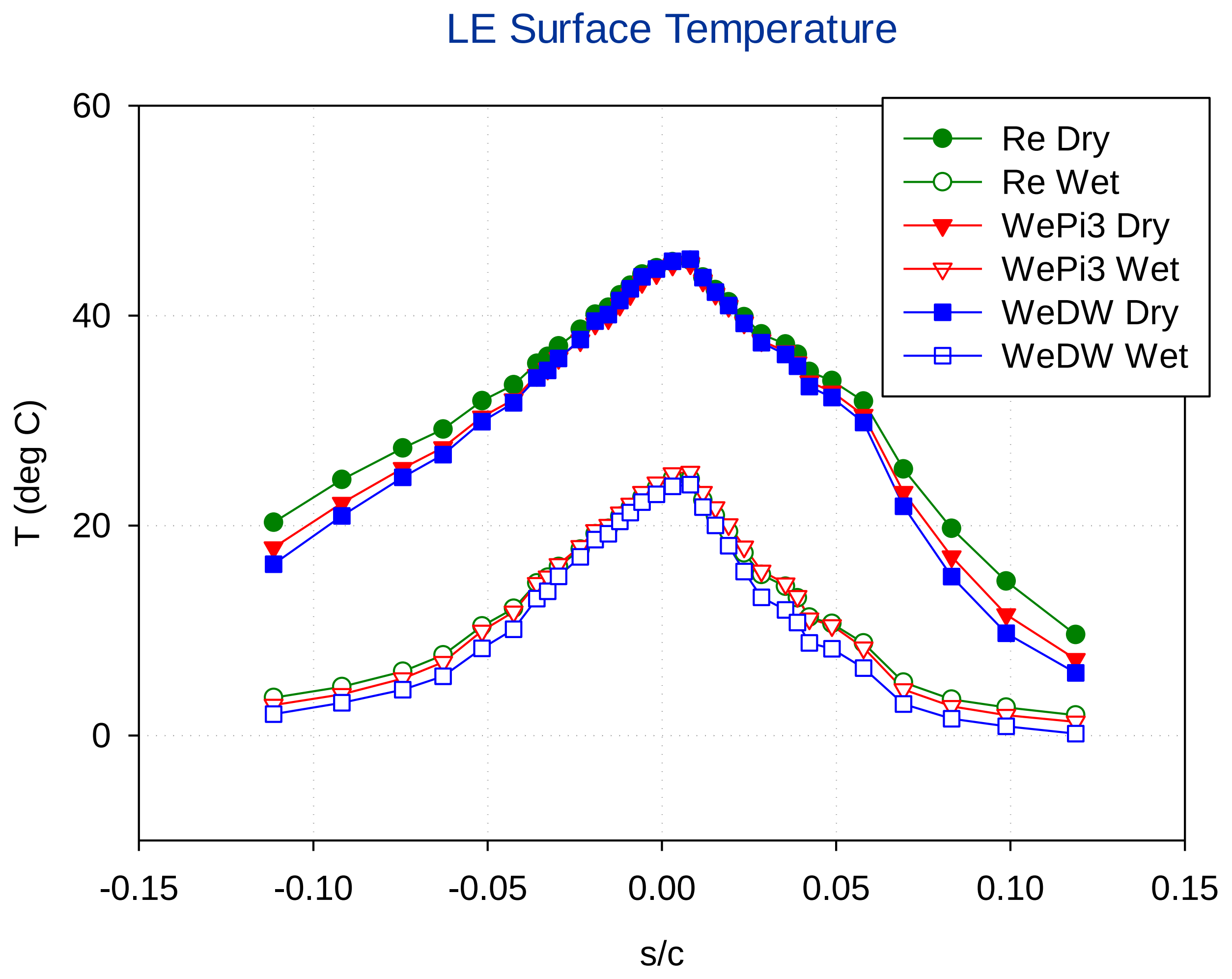
Re Scaling



WePi3 Scaling

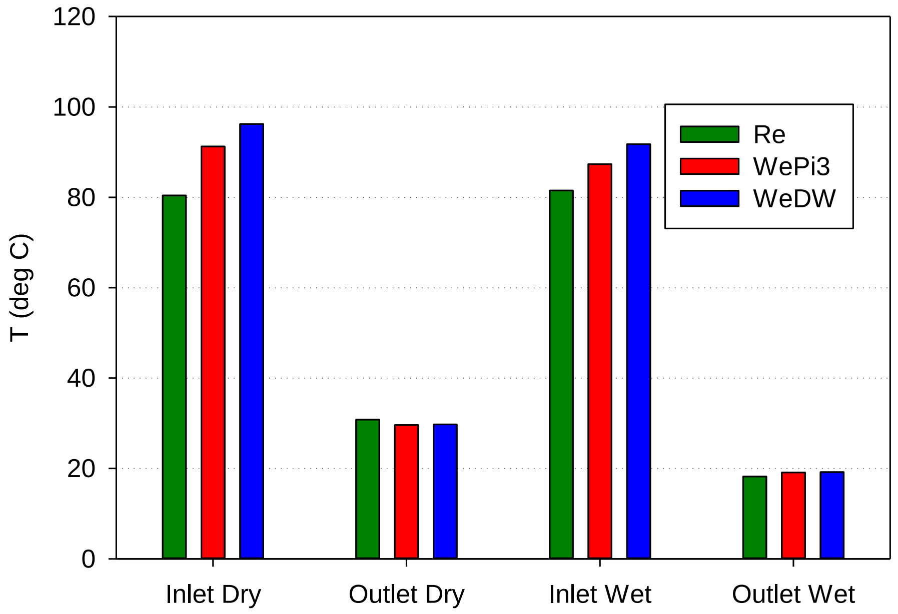
WeDW Scaling

Warm Hold Scenario

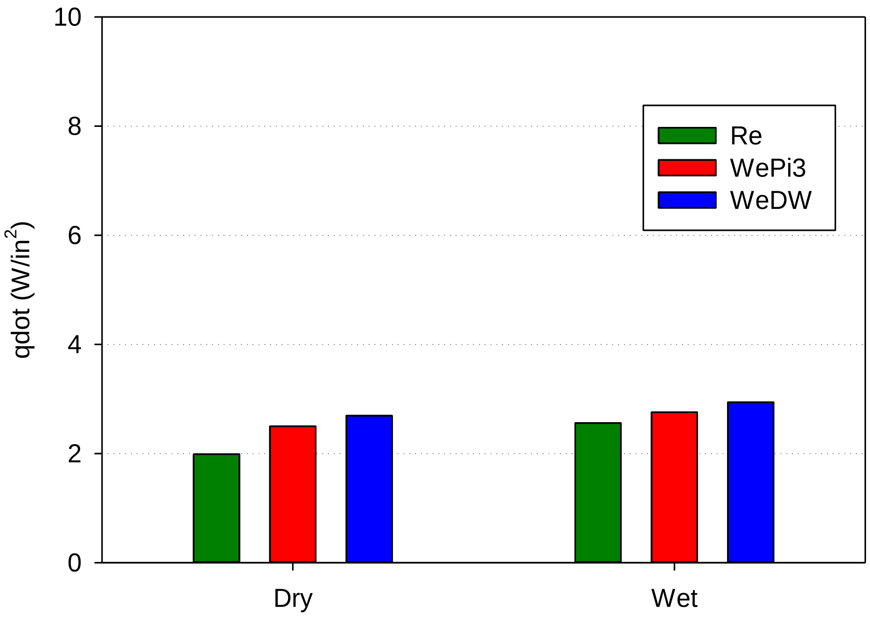


Warm Hold Scenario

Heated Air Temp.



Heated Air Energy Input



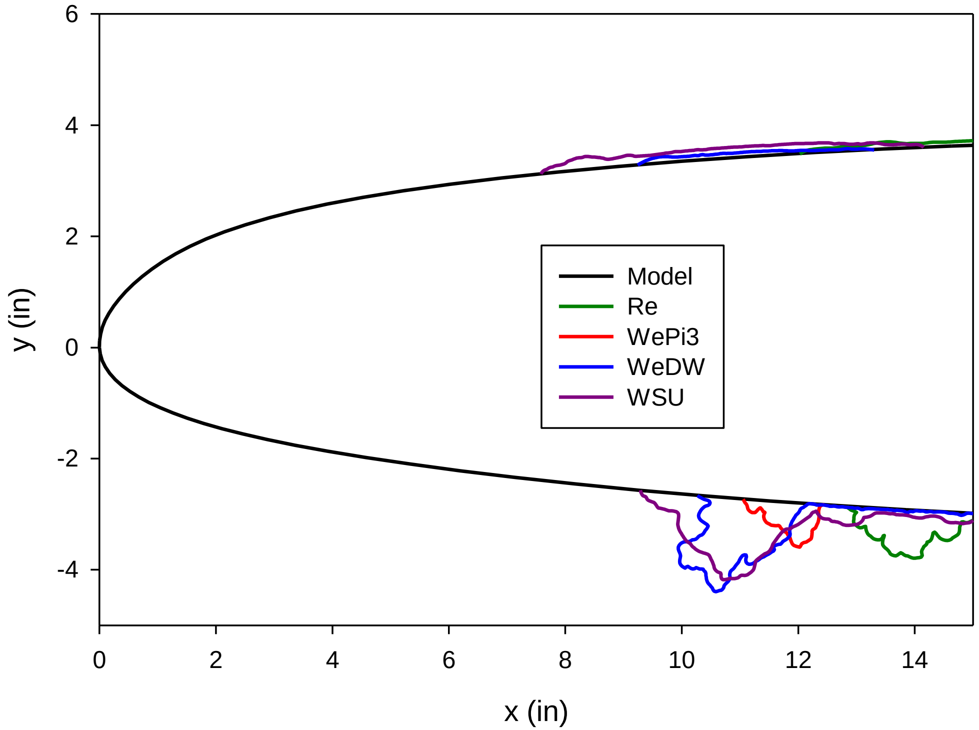
Conclusion

- Test conducted at NASA Icing Research Tunnel to evaluate new altitude scaling methods for thermal ice protection systems.
- Two Weber number-based scaled methods developed during a series of joint NASA and NRCC tests at AIWT.
- Results from IRT generally agreed with and supported the results from previous tests in NRCC.
- We-based scaling methods resulted in smaller ice accretion that formed farther upstream than the Re-based scaling methods.
- Additional tests required in altitude capable tunnels using full-scale models to better define the limits of physical relationships used to develop these scaling methods.

Extra Slides

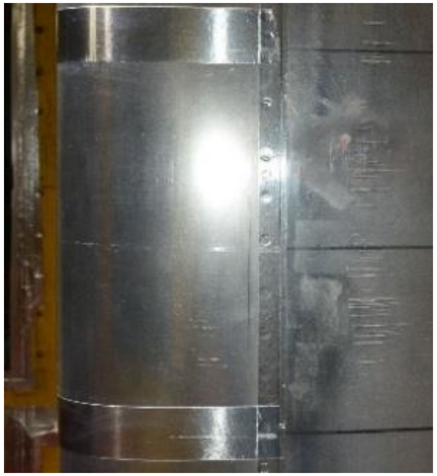
WSU Warm Hold Scenario

Scale Method	Alt (ft)	V (kts)	T_s (deg C)	LWC (g/m^3)	MVD (μm)	m_w (g/m^2s)	Re_{2r} ($x10^6$)	WeDA	Pi3	WeDW ($x10^6$)	Ice Mass (g)
Reference	*15000*	*205*	*-9.4*	*0.5*	*20*	*31.1*	*0.205*	*6065*	*1.73*	*8.04*	***N/A***
Re	1312	126	-6.3	0.82	27.2	31.1	0.205	3769	2.98	3.01	**236.5**
WePi3	1835	164	-7.6	0.43	24	21.0	0.264	6065	1.73	5.13	**68.9**
WeDW	2446	205	-9.2	0.5	22.4	31.1	0.324	9715	2.23	8.04	**266.2**
WSU	1191	115	-9.4	0.87	29	30.8	0.192	3229	3.03	2.53	**483.3**



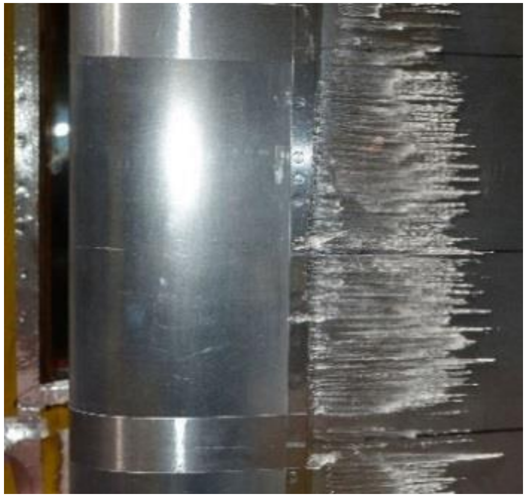
WSU Warm Hold Scenario

Re Scaling



WePi3 Scaling

WeDW Scaling



WSU Scaling

WSU Warm Hold Scenario