Determining the Suitability of IWT Test Facilities for Demonstrating Compliance with Certification Requirements in Appendix O Conditions

Kamel Al-Khalil, Cox & Company, Inc.

Joseph Vogel, Cox & Company, Inc.

David Parkins, American Kestrel Co., LLC

Paper # 11ICE-0097

Introduction:

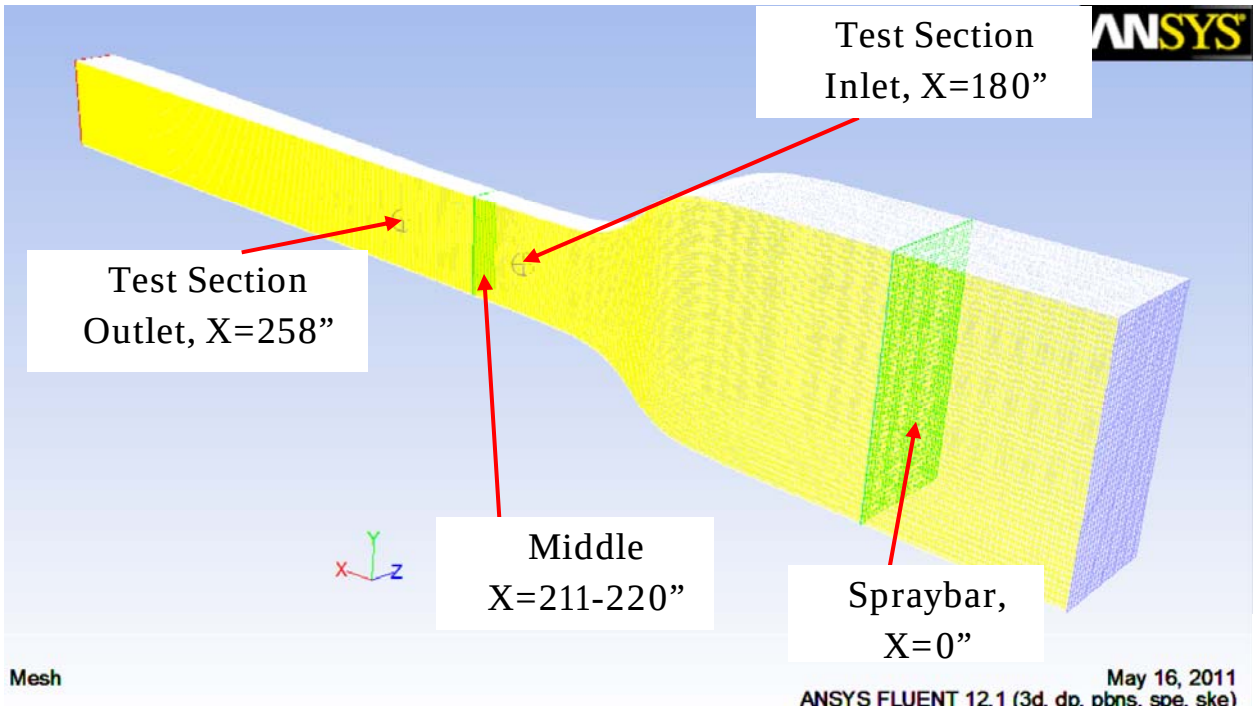
- SLD tunnel testing needed for certification
- Concern #1 – droplets not 100% super cooled
  - Short distance ➡ short residence time ➡ not enough cooling
- Concern #2 – reduced cloud size
- Issues addressed by test & analysis

Outline:

- Analysis
  - Droplet temperature (FLUENT & AEDC)
  - Ice shapes (Modified LEWICE 2D)
  - Cloud size (FLUENT)
- Icing tunnel tests
  - Cloud calibration and Ice shapes
- Conclusions
- Backup

Fluent Analysis:

- ANSYS FLUENT modeling

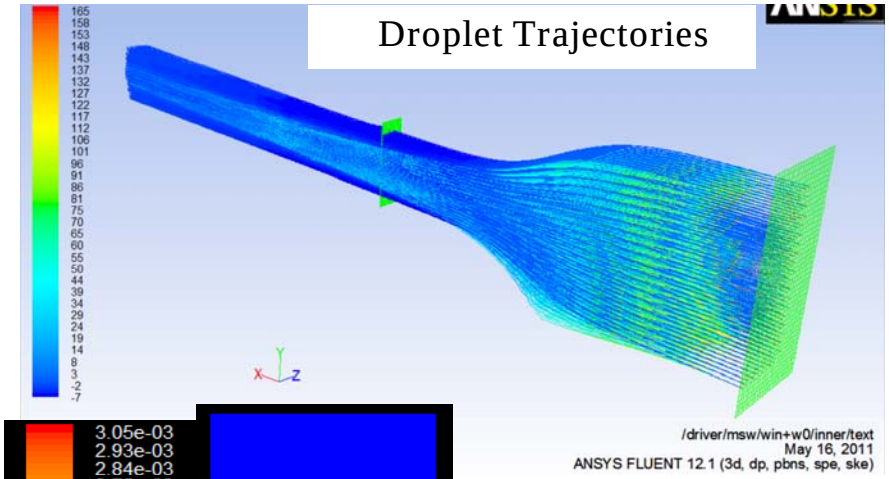


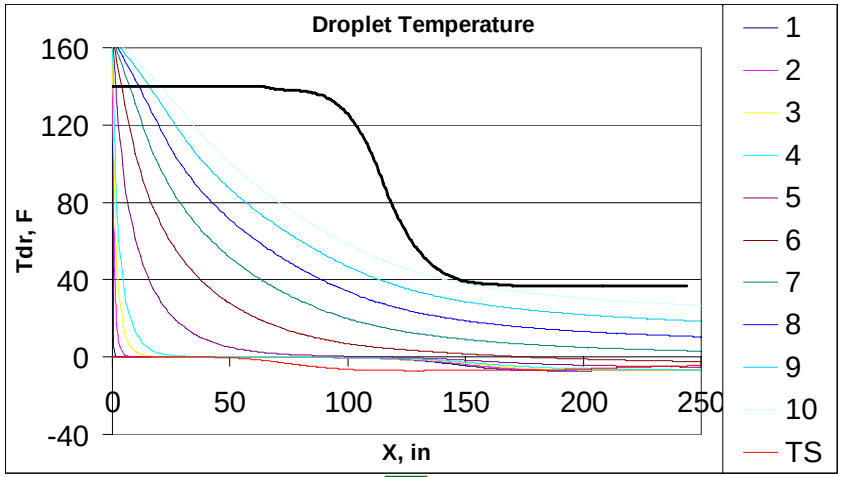
- Air Velocity & Temp field obtained
- Droplets released at Spraybar
- Tracked thru tunnel

Droplet Temperature Obtained Thru Tunnel

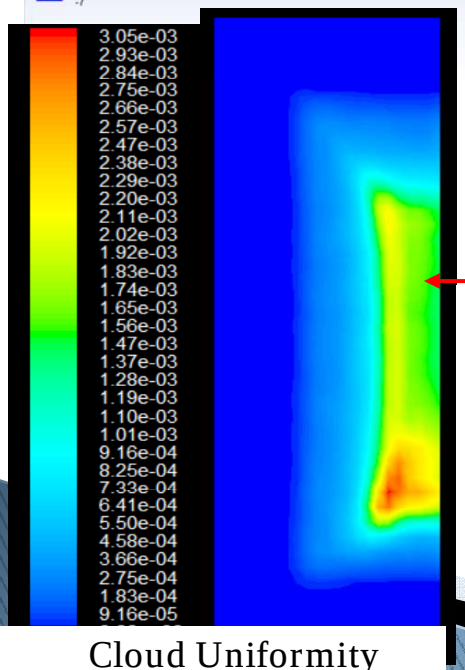
Fluent Analysis:

- Example, MVD=130 μm, T_{water}=165°F





T_{cloud} > Air Static Temperature (0.7 °F vs -6.8 °F)



Size reduced

Cloud Uniformity

Cloud Temperature & Uniformity Predicted At Test Section

Paper # 11ICE-0097

Fluent Analysis:

- Cloud supercooling results

Air: U=200 mph, Tt=28°F, Ts=20.9°F

MVD, mcr	Twater,°F	Tcloud,°F	Tcloud-Ts,°F
20	165	21.4	0.5
	36	21.4	0.5
40	165	22.4	1.5
	36	22.4	1.5
70	165	24.1	3.2
	36	23.3	2.4
100	165	24.5	3.6
	36	23.7	2.8
130	165	26.2	5.3
	36	24.3	3.4

Air: U=200 mph, Tt=0°F, Ts=-7°F

MVD, mcr	Twater,°F	Tcloud,°F	Tcloud-Ts,°F
20	165	-6.5	0.5
	36	-6.5	0.5
40	165	-5.3	1.7
	36	-5.3	1.7
70	165	-2.8	4.2
	36	-3.9	3.1
100	165	-2.2	4.8
	36	-3.5	3.5
130	165	0.7	7.7
	36	-2.1	4.9

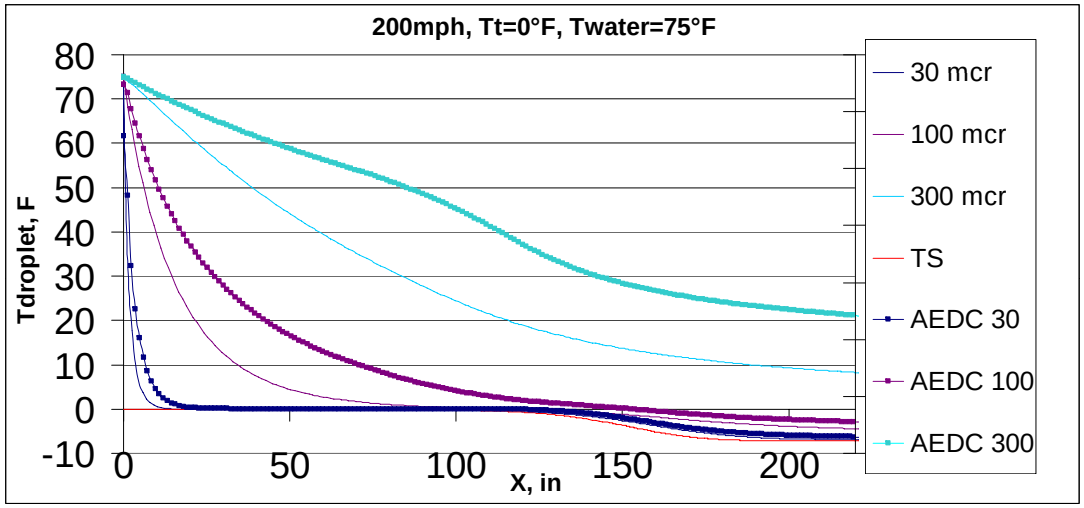
Cloud Temperature > Air T_{static}

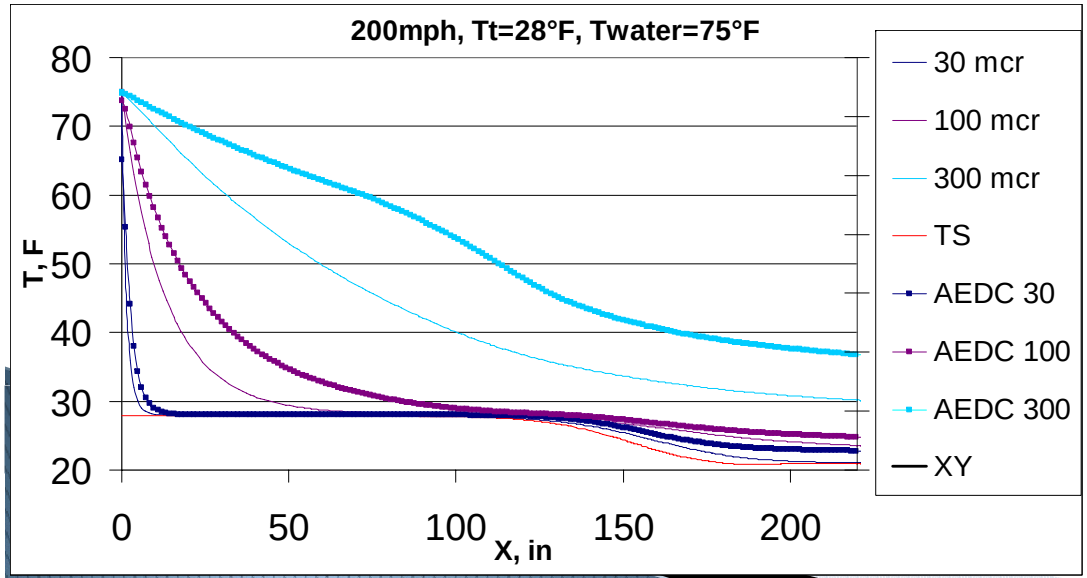
Not 100% Supercooled to T_{static}

Paper # 11ICE-0097

Fluent Analysis:

- Cloud supercooling: FLUENT vs AEDC





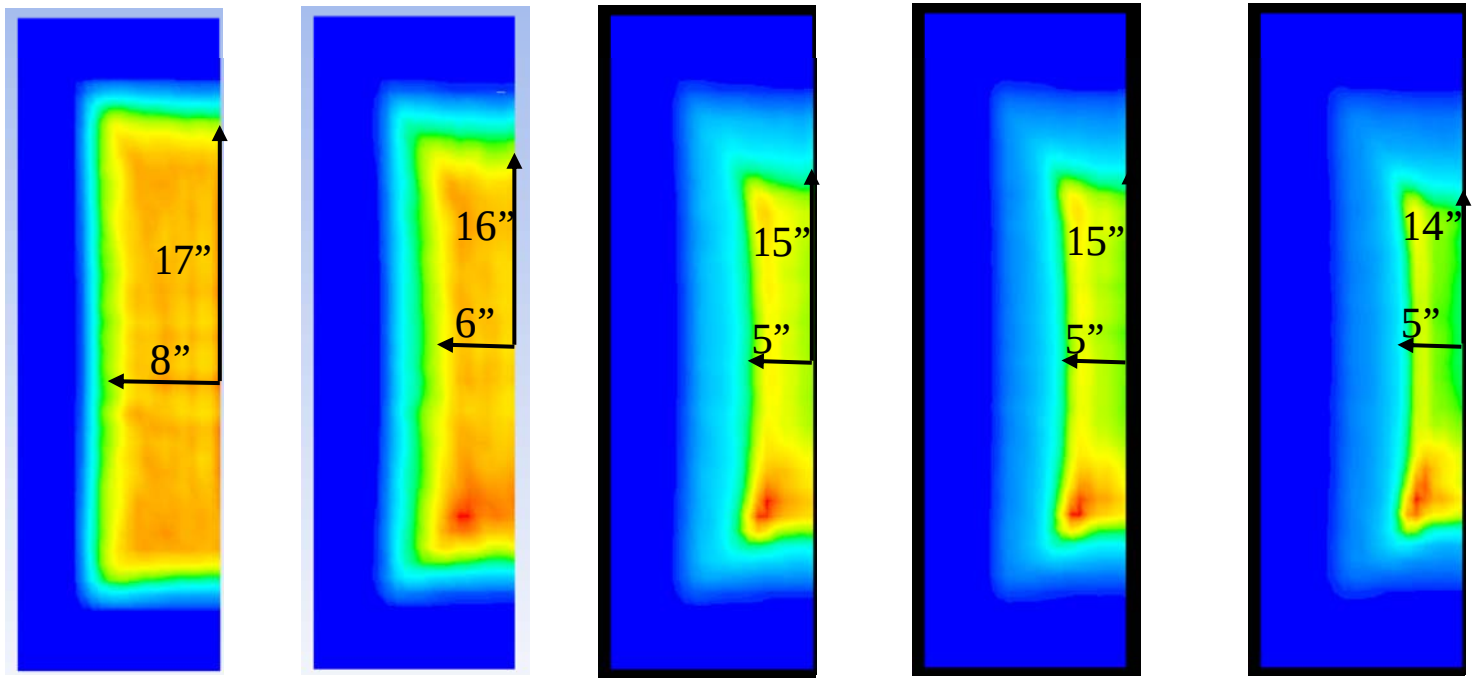
- AEDC-1D thermodynamic model
- AEDC predicts higher temperatures for larger droplets

Good overall agreement between AEDC and Fluent for Dia<200 μm (difference~5 °F)

Paper # 11ICE-0097

Fluent Analysis:

- Cloud size and Uniformity Predictions:



MVD=20 μm | MVD=40 μm | MVD=75 μm | MVD=100 μm | MVD=130 μm

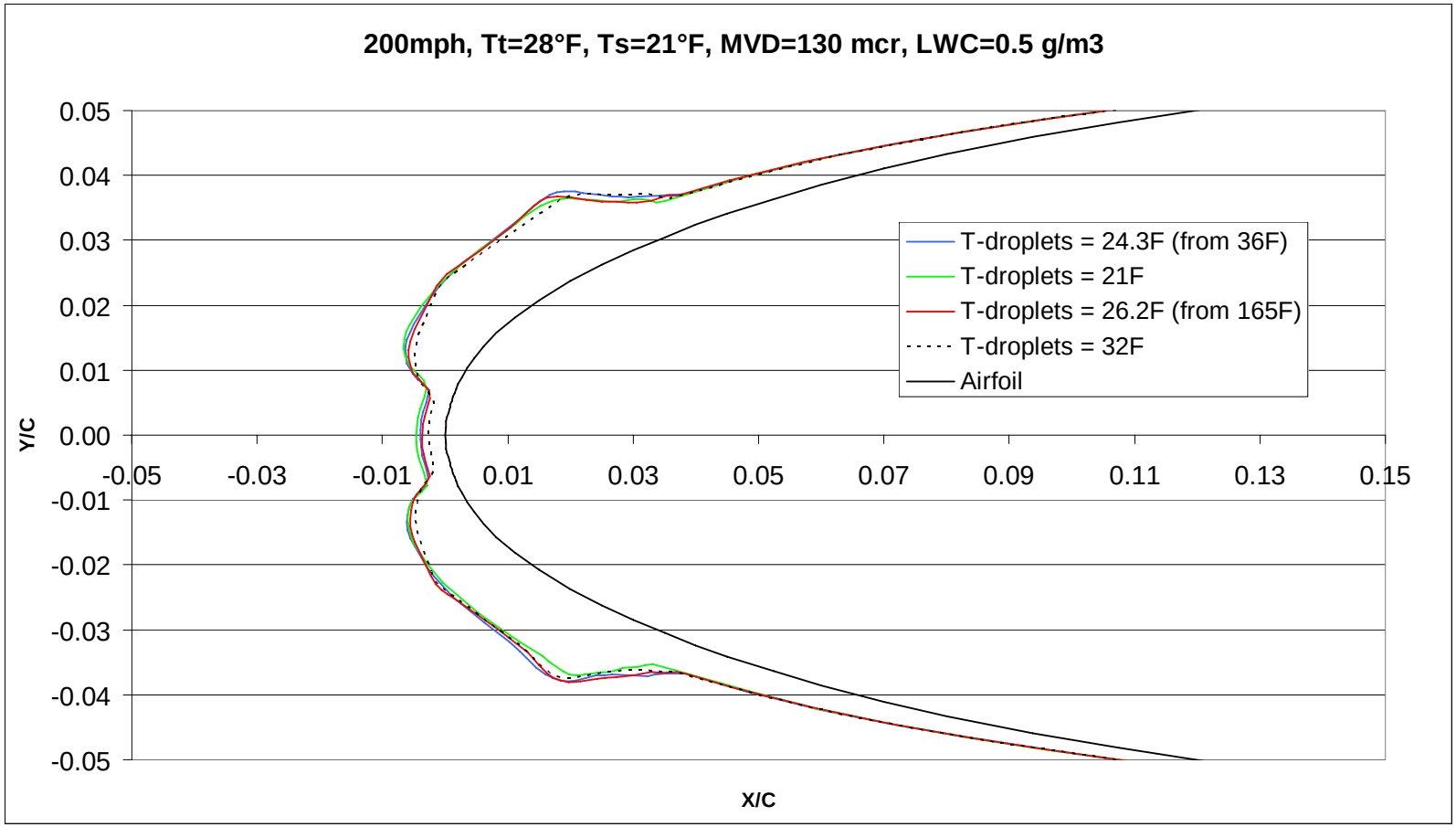
Reduced cloud with increased MVD. No significant reduction above 75 μm

Paper # 11ICE-0097

LEWICE2D Analysis:

- Does cloud need to be 100% supercooled to ambient static temperature?
  - Water droplet temperature is normally assumed at ambient static temperature
  - Two extreme cases were considered for the water droplet temperature at the nozzle release location (35°F & 165°F)
  - Water droplets in the cloud distribution were tracked from the nozzle location and individual temperatures predicted at the tunnel test section location. The bulk cloud temperature is calculated from the results at that location
  - The NASA ice shape prediction code LEWICE 2D was modified to allow user input of the water droplet temperature just before impact on the airfoil surface
  - Calculations performed on a NACA0012 3ft chord at two ambient temperatures (very warm and cold)

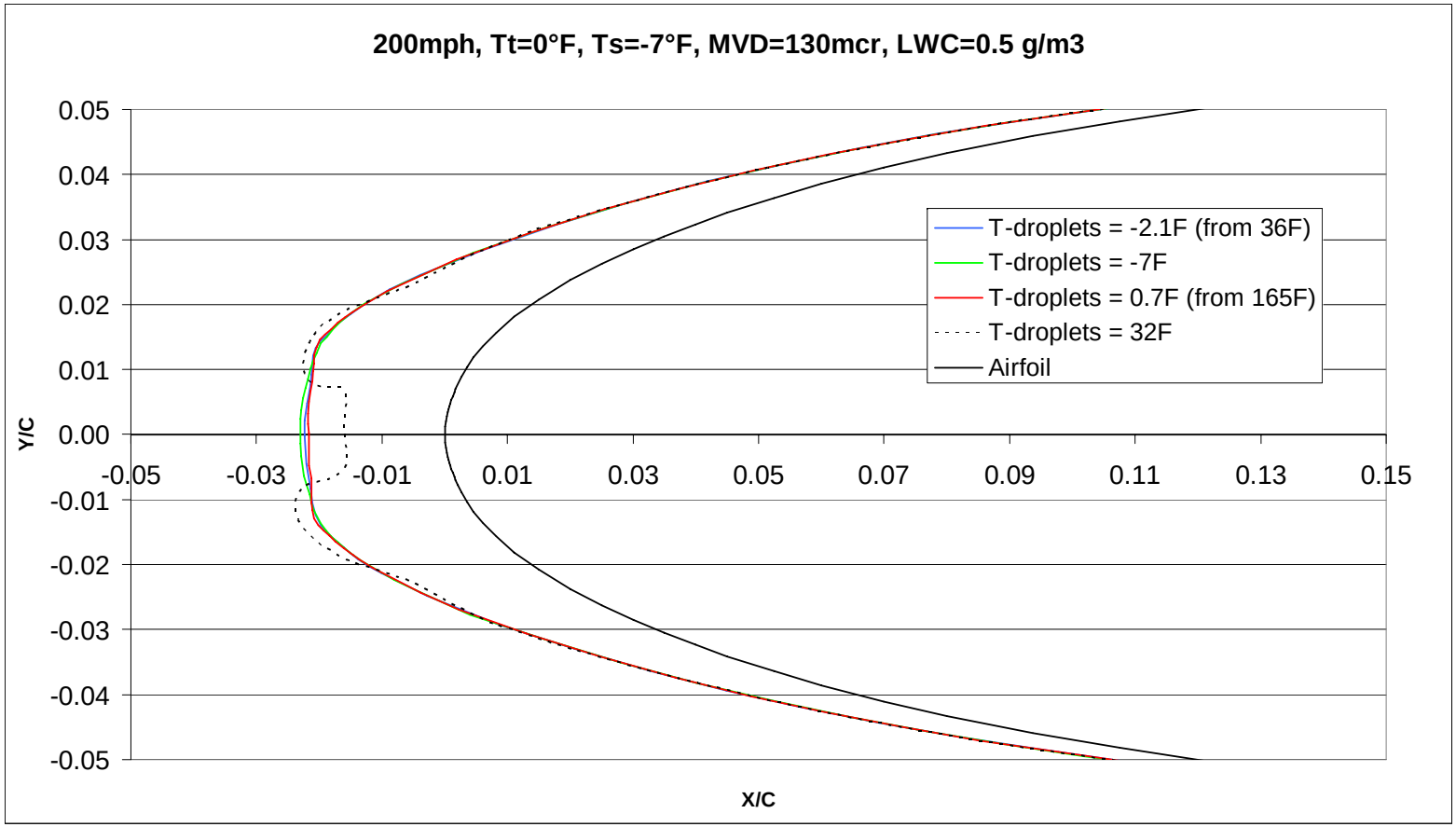
LEWICE2D Analysis (warm case):



Not 100% Supercooled – No Effect On Ice Shapes

Paper # 11ICE-0097

LEWICE2D Analysis (cold case):



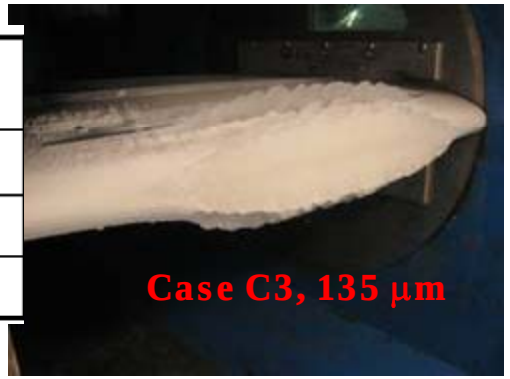
Not 100% Supercooled – No Effect On Ice Shapes

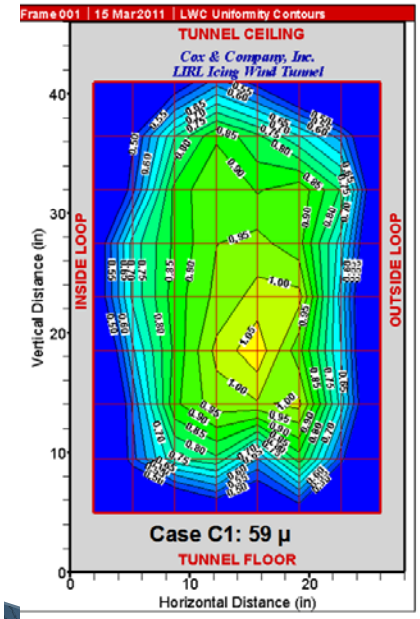
Paper # 11ICE-0097

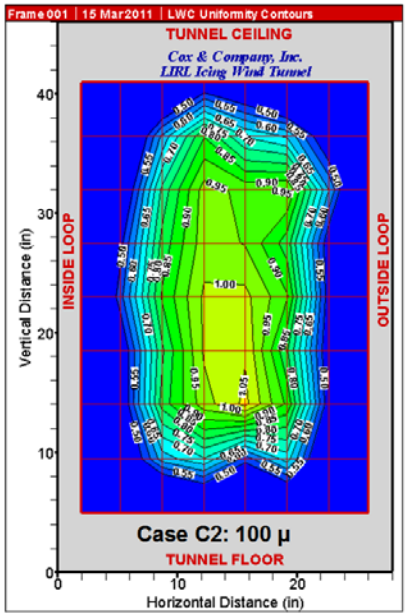
Icing Tunnel tests:

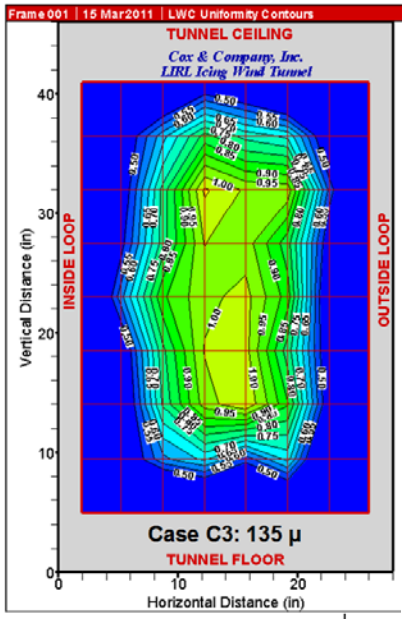
- Cloud size

Case #	True Airspeed (mph)	Total Temp (° F)	Spray time (seconds)	MVD (microns)	P air (psig)	ΔP (psi)	Water Temp (° F)	Air Temp (° F)	Measured LWC (g/m^3)	Calculated K factor
C1	150	- 5	120	59	3.0	12.5	65	90	0.74	29.5
C2	150	- 5	72	100	2.5	17.5	65	90	1.03	35.1
C3	150	- 5	30	135	2.5	25.0	65	90	1.33	39.9





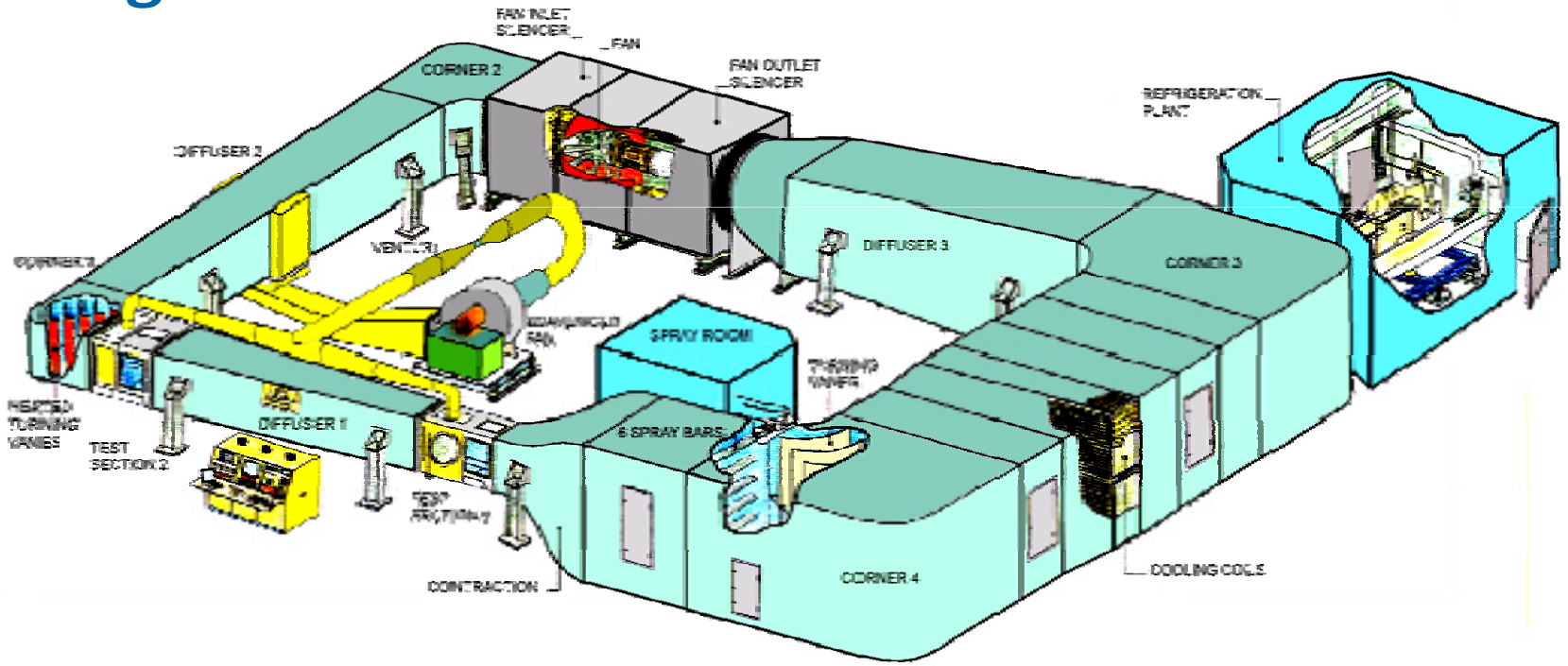




- Cloud gets smaller for bigger MVD
- Uniform Cloud size ~12”x24” for MVD=135 µm

Paper # 11ICE-0097

Icing Tunnel Tests at the Cox LIRL

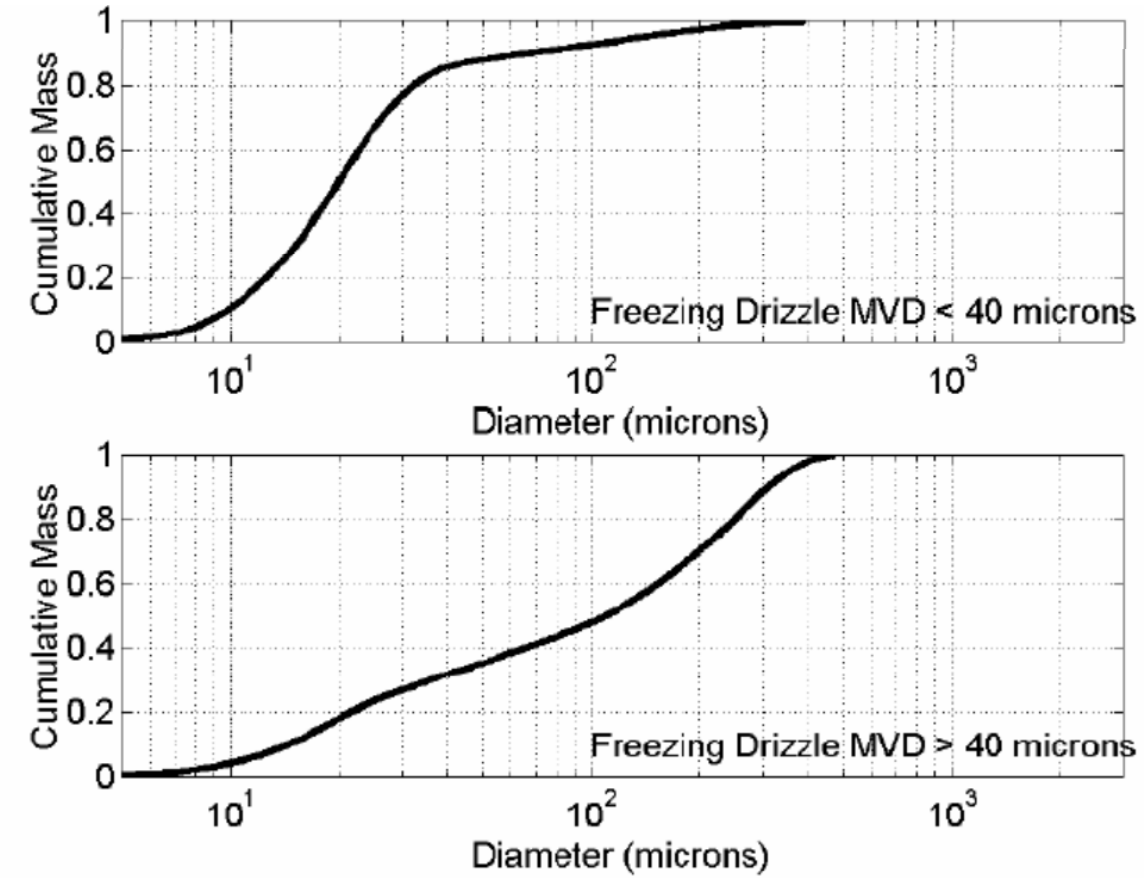


- Tests conducted in the main test section (TS-1)
- Model: NACA 0012, 3 ft chord
- AOA = 0
- Cox uses the NASA MOD-1 type nozzles
- MVD for SLD droplets assumed same as NASA's at the same water & air pressure setup

Paper # 11ICE-0097

Tunnel tests:

- Appendix O- proposed SLD distributions



- MVD~110 μm for Freezing Drizzle
- Tests done for MVD up to 135 μm

Tunnel tests:

- Ice Shapes, NACA0012, 3ft chord

Case #	Airspeed		Temperature			Cloud			Spray Settings			
	TAS kts	IAS mph	TAS mph	Total F	Static F	Time (min)	MVD* µm	LWC g/m3	Pair psig	ΔP psid	Water Temp F	Air Temp F
1	93	110	107	16.5	14.5	14.9	59	0.98	3.0	12.5	65.0	70
2	150	177	173	22.5	17.2	16.0	100	0.85	2.5	17.5	65.0	70
3	150	180	173	9.2	3.9	16.0	100	0.85	2.5	17.5	65.0	70
4	150	180	173	6.0	0.7	10.3	135	1.16	2.5	25.0	65.0	70
5	150	176	173	28.0	22.7	10.3	135	1.16	2.5	25.0	65.0	70
4a	150	180	173	6.0	0.7	10.3	135	1.16	2.5	25.0	120.0	120
5a	150	176	173	28.0	22.7	10.3	135	1.16	2.5	25.0	120.0	120
1b	93	110	107	16.5	14.5	14.9	59	0.98	3.0	12.5	35.0	70
2b	150	177	173	22.5	17.2	16.0	100	0.85	2.5	17.5	35.0	70
3b	150	180	173	9.2	3.9	16.0	100	0.85	2.5	17.5	35.0	70
4b	150	180	173	6.0	0.7	10.3	135	1.16	2.5	25.0	35.0	70
5b	150	176	173	28.0	22.7	10.3	135	1.16	2.5	25.0	35.0	70

Medium T_{water} (65°F)

High T_{water} (120°F)

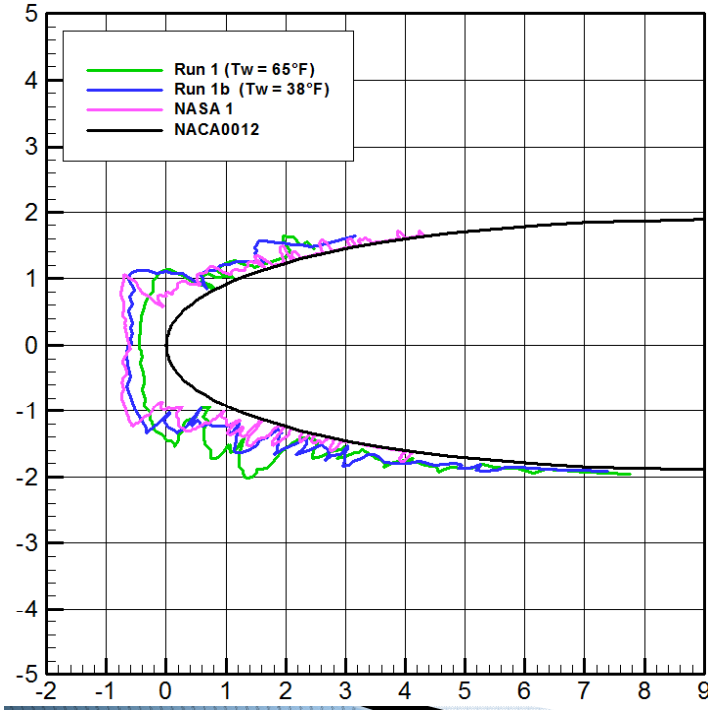
Low T_{water} (35°F)

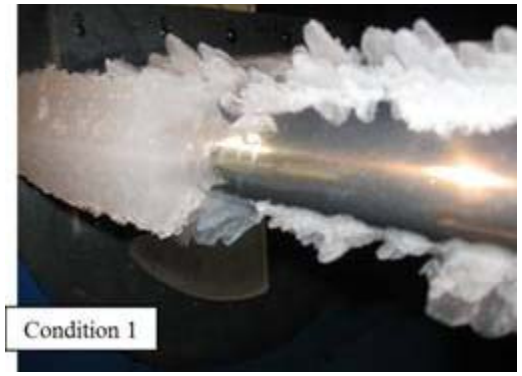
Shapes Obtained For Various MVD, OAT, & spraybar water temperature

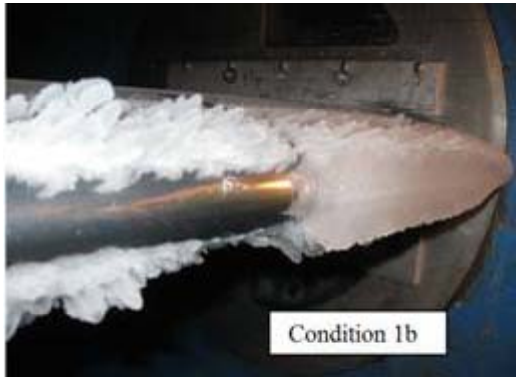
Paper # 11ICE-0097

Tunnel tests:

- Condition 1: MVD=59 μm, LWC=0.98 g/m^3, Time=14.9 min, T_{total}=16.5°F, KTAS=93
- NASA: Same



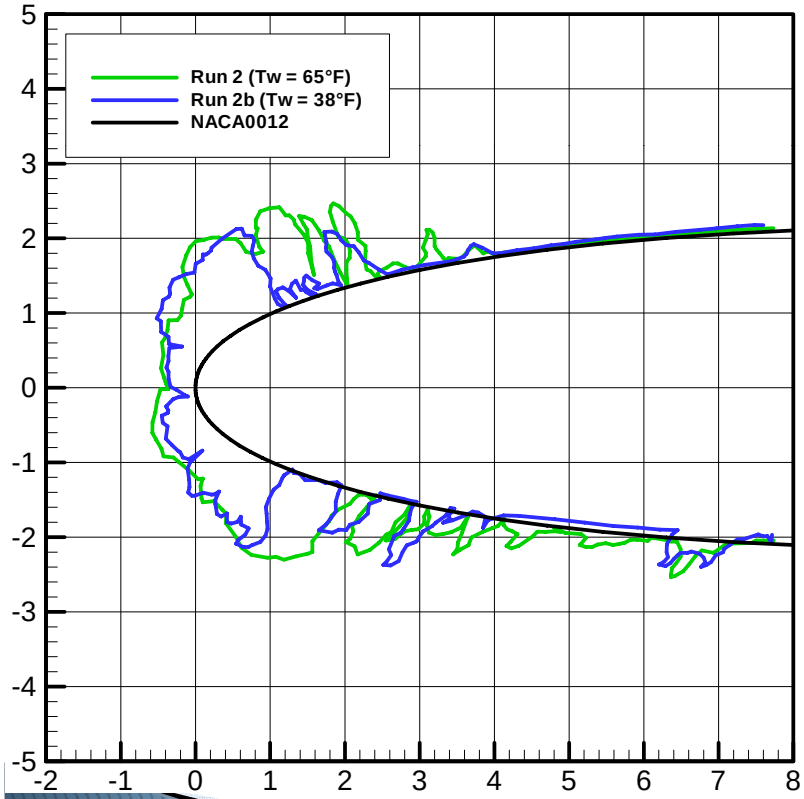


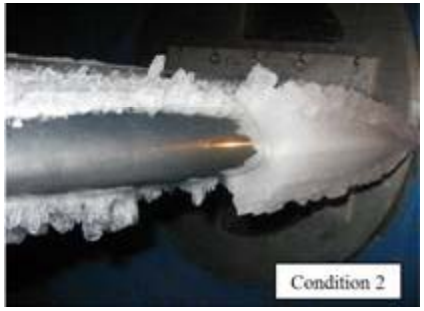


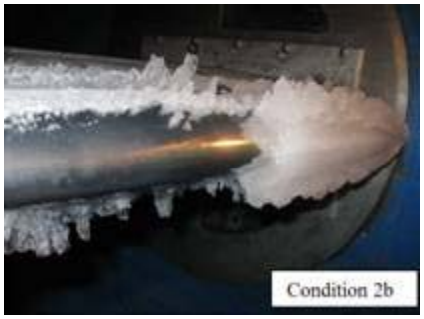
- Little variation with Twater
- Supercooling level has little effect on ice shape
- Good match with NASA

Tunnel tests:

- Condition 2: MVD=100 μm, LWC=0.85 g/m^3, Time=16 min, T_{total}=22.5°F, KTAS=150



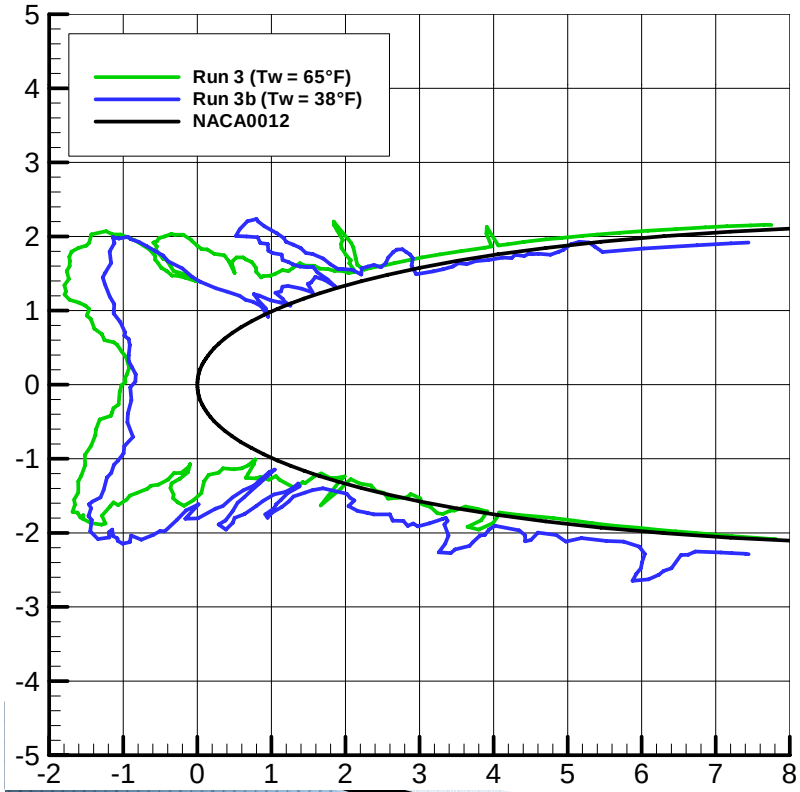


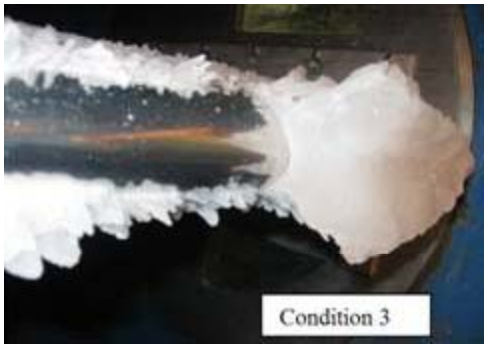


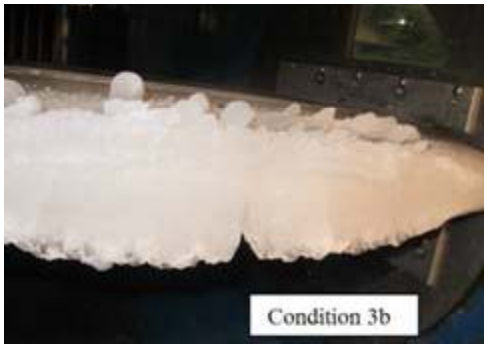
- Little variation with Twater
- Supercooling level has little effect on ice shape

Tunnel tests:

- Condition 3: MVD=100 μm, LWC=0.85 g/m^3, Time=16 min, T_{total}=9.2°F, KTAS=150





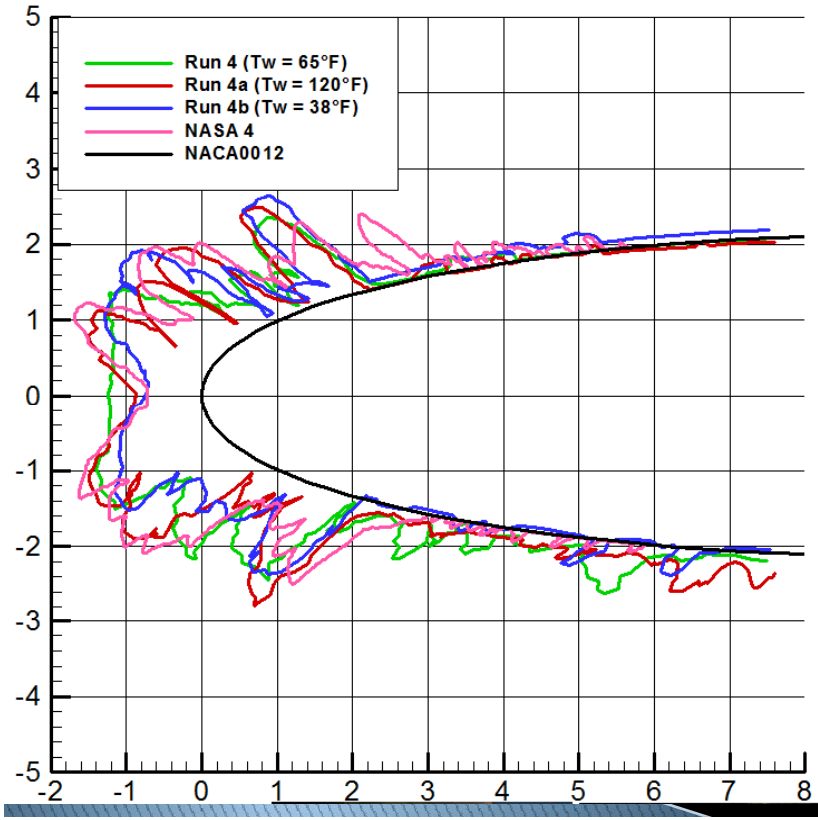


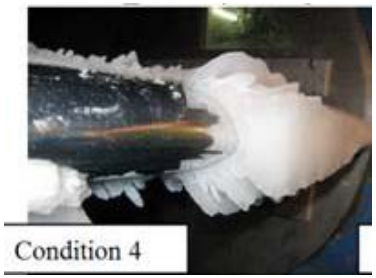
- Little variation with T_{water}
- Supercooling level has little effect on ice shape

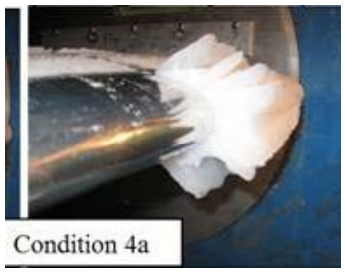
Paper # 11ICE-0097

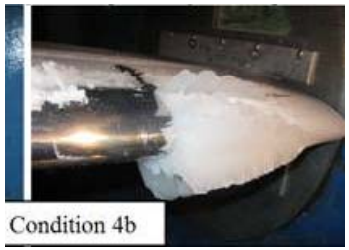
Tunnel tests:

- Condition 4: MVD=135 μm, LWC=1.2 g/m^3, Time=10.3 min, T_{total}=6.0°F, KTAS=150
- NASA: MVD=135 μm, LWC=1.1 g/m^3, Time=10.3 min, T_{total}=6.0°F, KTAS=150







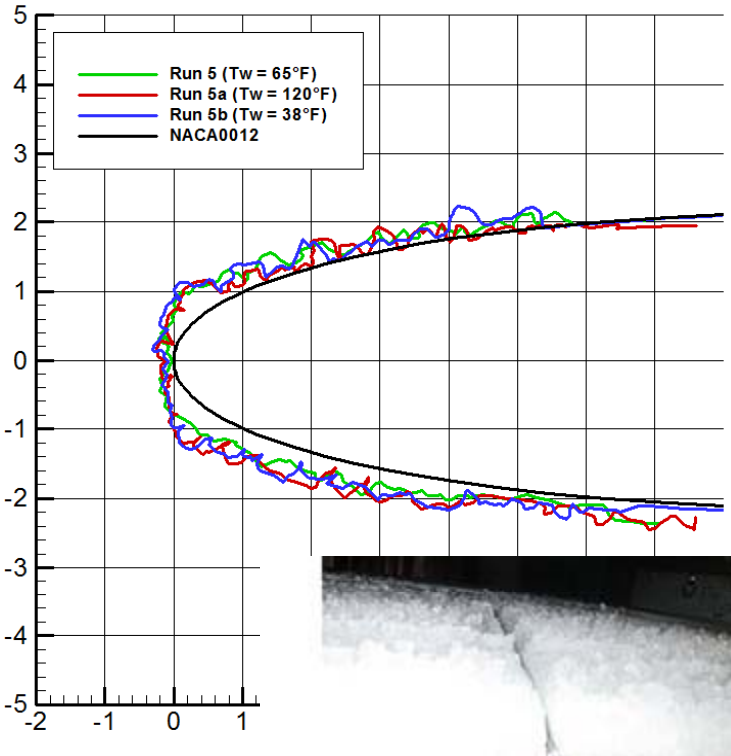


- Little variation with Twater
- Supercooling level has little effect on ice shape
- Good match with NASA

Paper # 11ICE-0097

Tunnel tests:

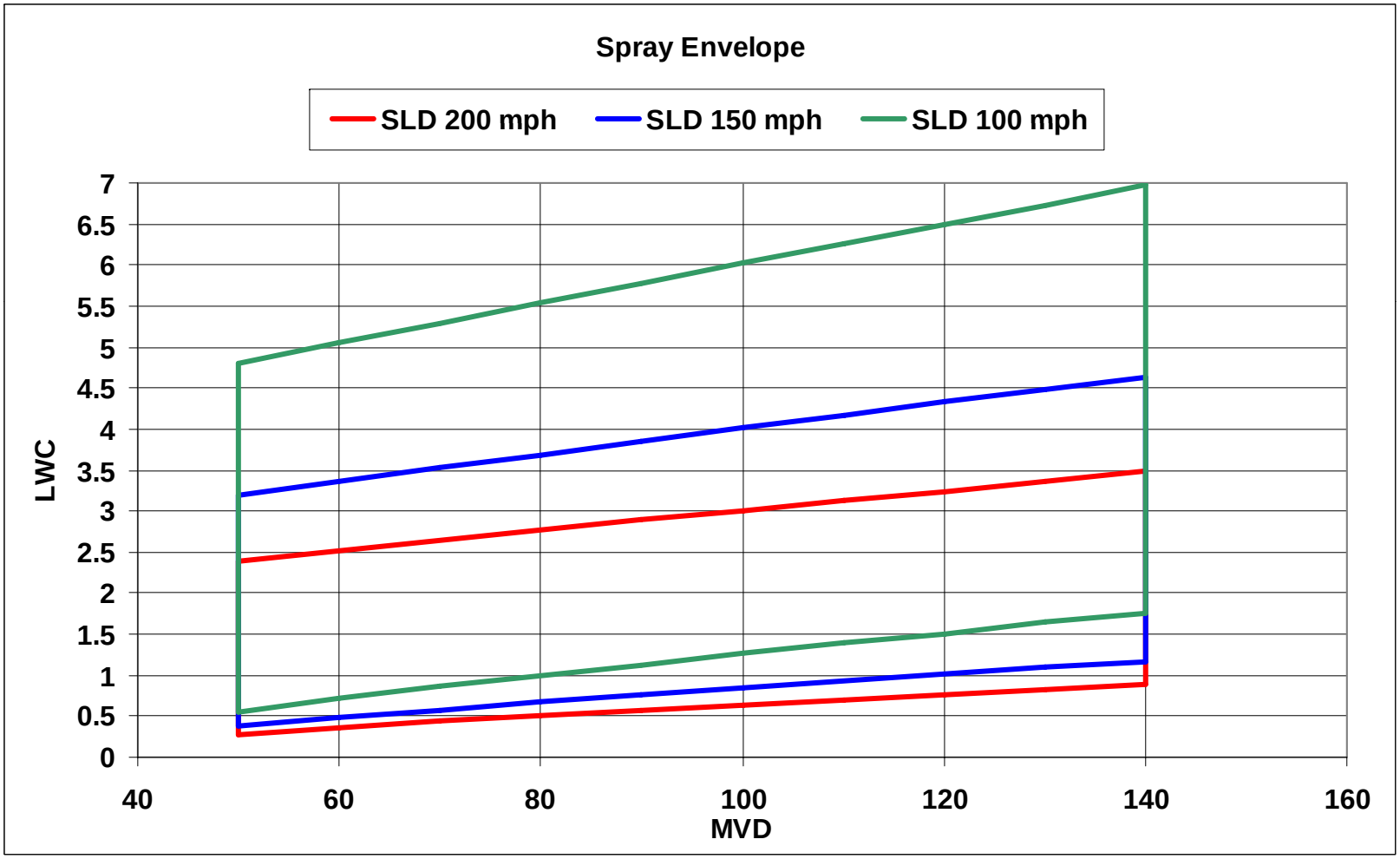
- Condition 5: MVD=135 μm, LWC=1.1 g/m^3, Time=10.3 min, T_{total}=28°F, KTAS=150



- Little variation with T_{water}
- Supercooling level has little effect on ice shape

Paper # 11ICE-0097

Cox Tunnel SLD Envelope



Paper # 11ICE-0097

Conclusions

- Large droplets do not supercool 100% to T_{static}
- No or little effect on ice shapes
- Effective test section size is reduced

- Tunnels relatively smaller than NASA IRT are also suitable for SLD testing up to a specifically defined/demonstrated MVD

Acknowledgement

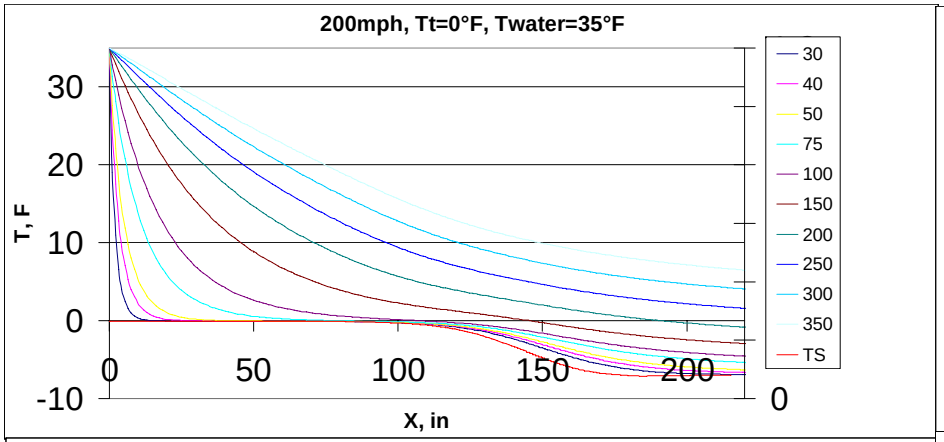
- The authors would like to recognize Dr. Pavel Shamara of Cox & Company for providing the Fluent analytical predictions in support of the current study

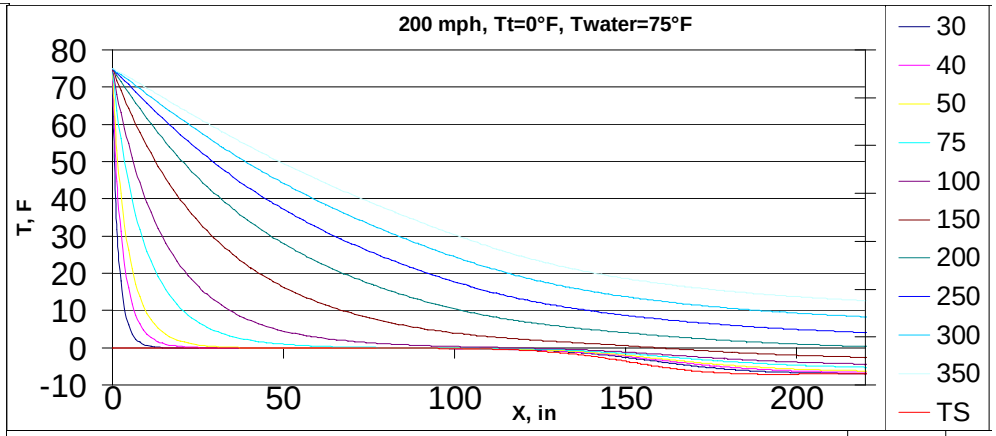
Backup

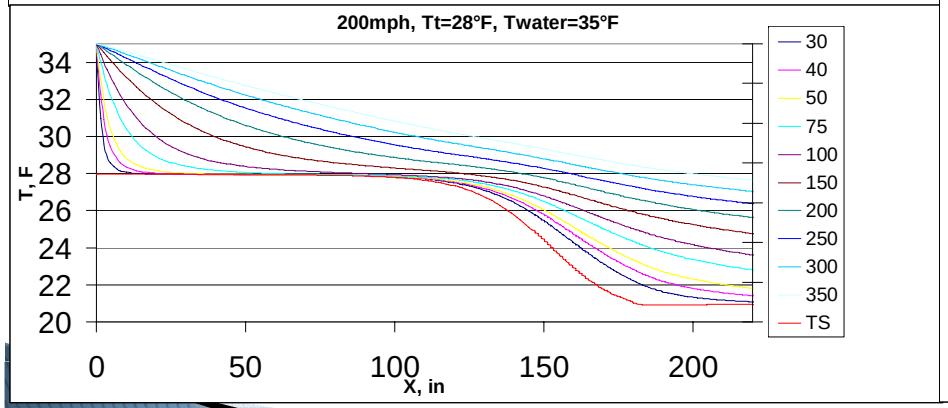
Paper # 11ICE-0097

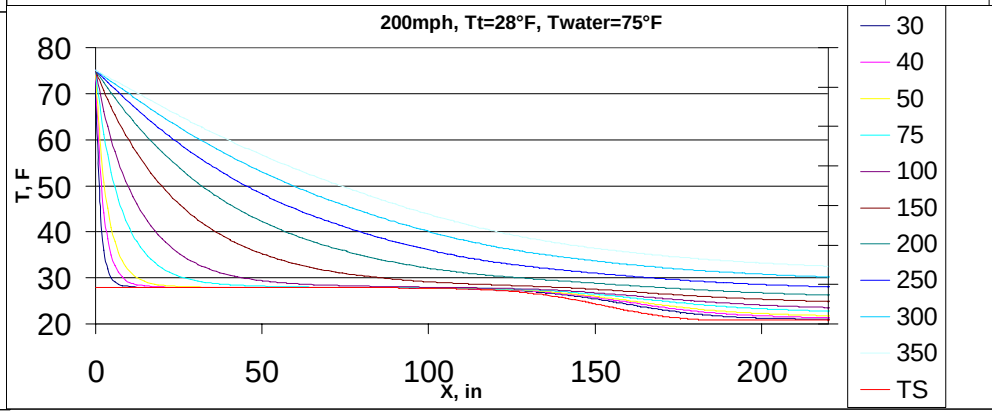
Analysis (FLUENT)

- Droplet temperature vs distance traveled (specific droplet sizes)





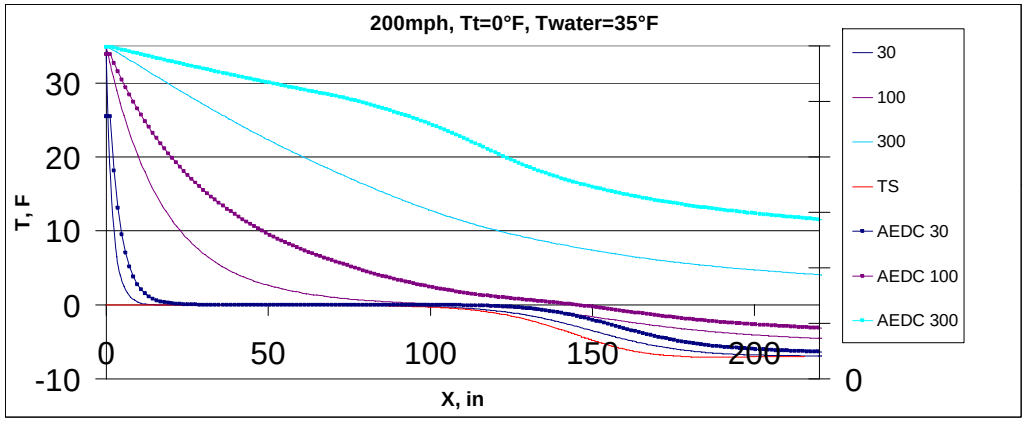


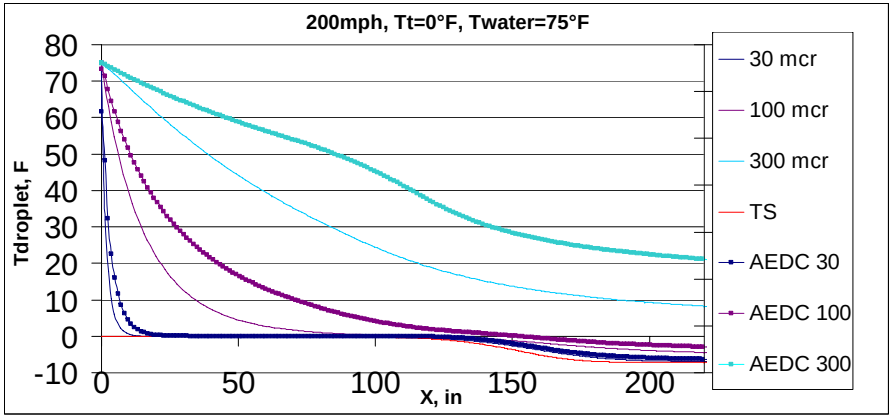


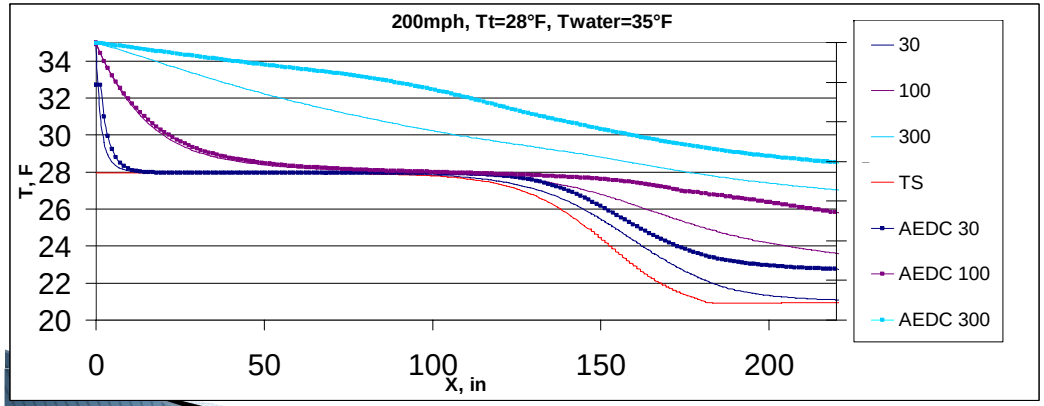
Paper # 11ICE-0097

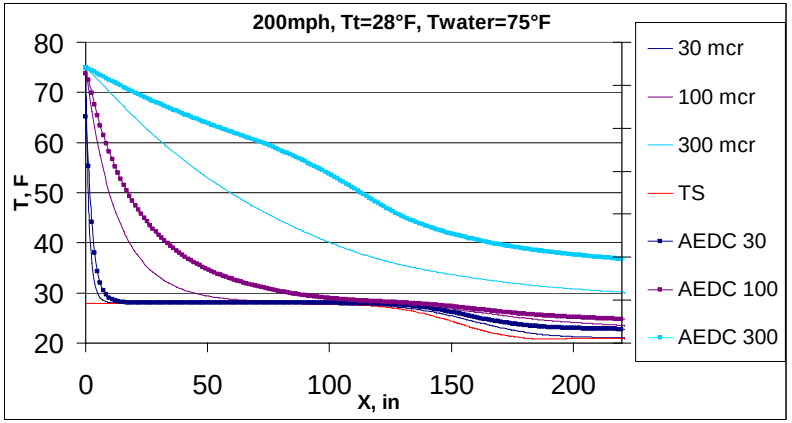
Analysis (FLUENT vs AEDC)

- Droplet temperature vs distance traveled (specific droplet sizes)









Paper # 11ICE-0097

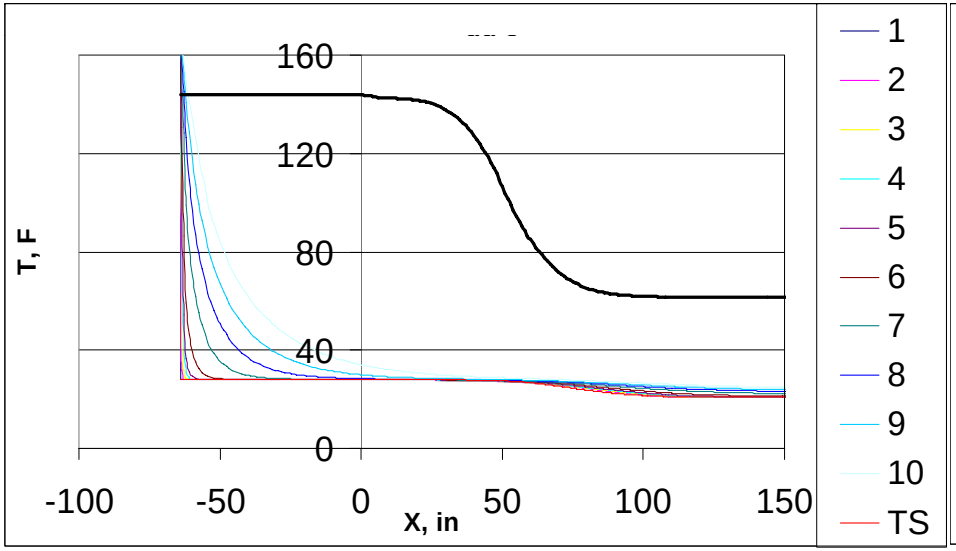
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=28°F, T_{static}=21.1°F, MVD=20μm, RH=100%

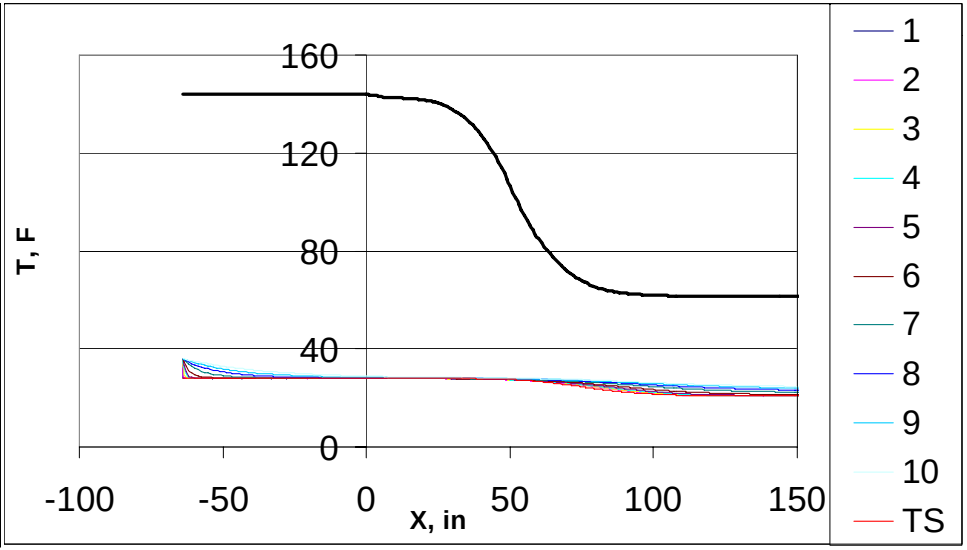
#	1	2	3	4	5	6	7	8	9	10
D, mcr	4.4	9.4	14.4	19.4	24.4	37.5	62.5	87.5	112.5	141.7
%	7.7	14.0	14.9	17.5	9.8	17.5	10.8	4.9	2.2	0.8

T_{water}=165°F



Tcloud=21.4 F

T_{water}=36°F



Tcloud=21.4 F

Paper # 11ICE-0097

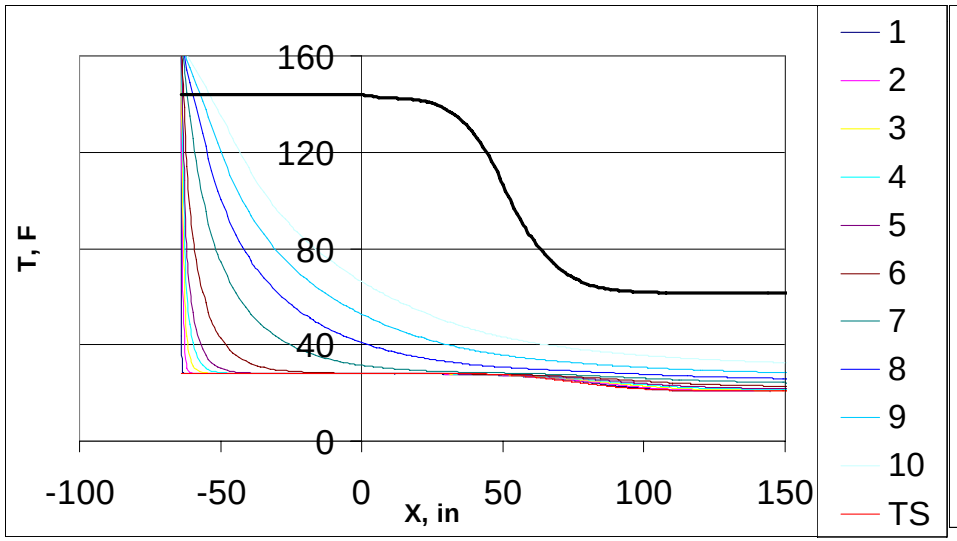
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=28°F, T_{static}=21.1°F, MVD=40μm, RH=100%

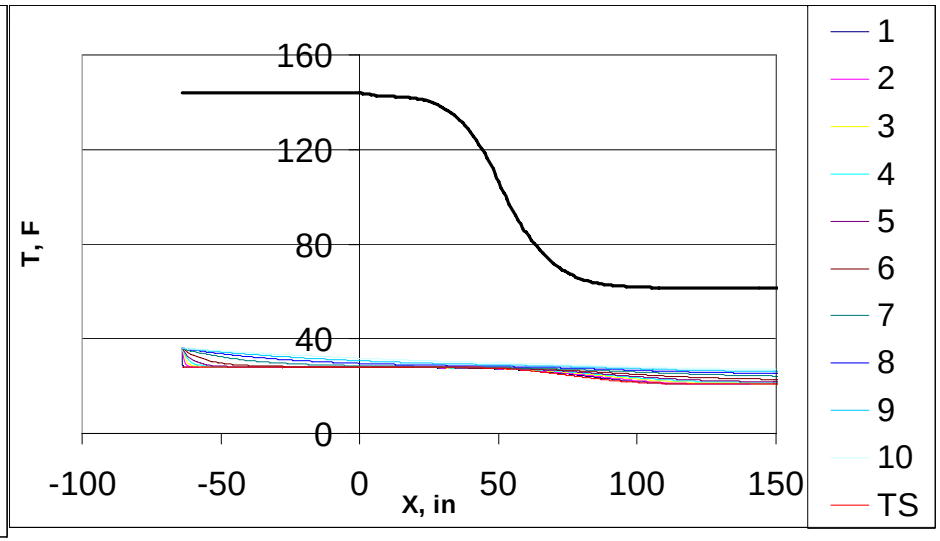
#	1	2	3	4	5	6	7	8	9	10
D, mcr	8.9	18.9	28.9	38.9	48.9	75.1	125.0	175.0	225.0	283.3
%	7.7	14.0	14.9	17.5	9.8	17.5	10.8	4.9	2.2	0.8

T_{water}=165°F



Tcloud=22.4 F

T_{water}=36°F



Tcloud=22.3 F

Paper # 11ICE-0097

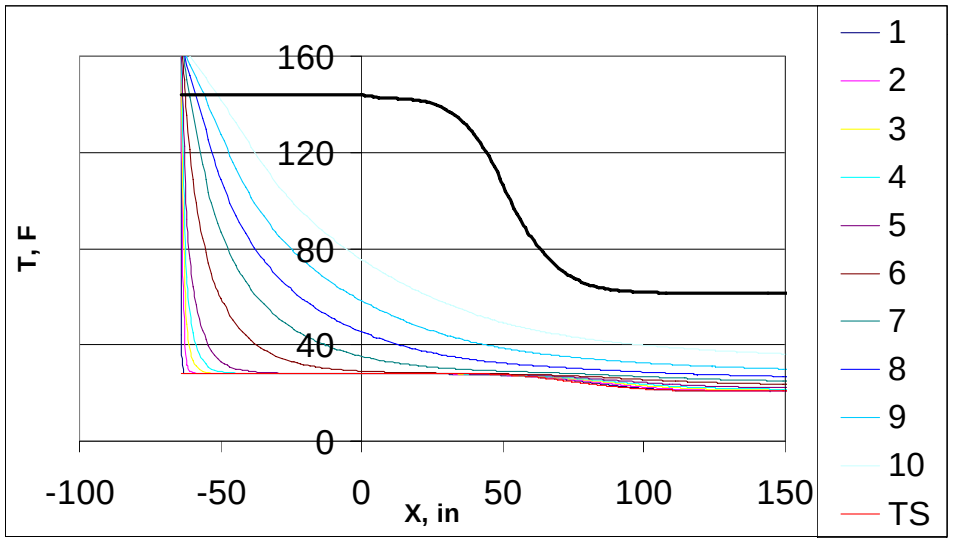
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=28°F, T_{static}=21.1°F, MVD=70μm, RH=100%

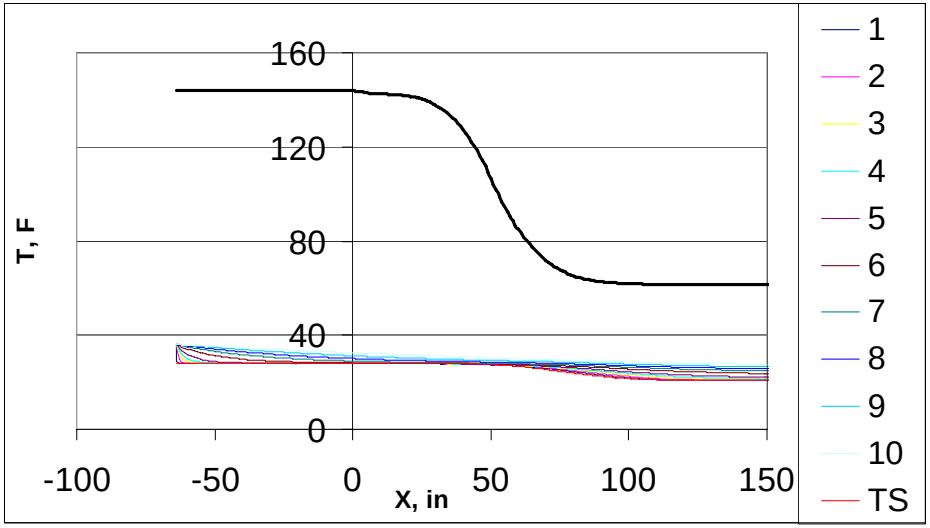
#	1	2	3	4	5	6	7	8	9	10
D, mcr	9.8	20.7	31.6	42.5	57.7	101.0	147.6	194.2	248.5	326.2
%	5.7	7.4	18.6	8.9	9.4	13.4	11.7	12.7	8.0	4.2

T_{water}=165°F



Tcloud=24.1 F

T_{water}=36°F



Tcloud=23.3 F

Paper # 11ICE-0097

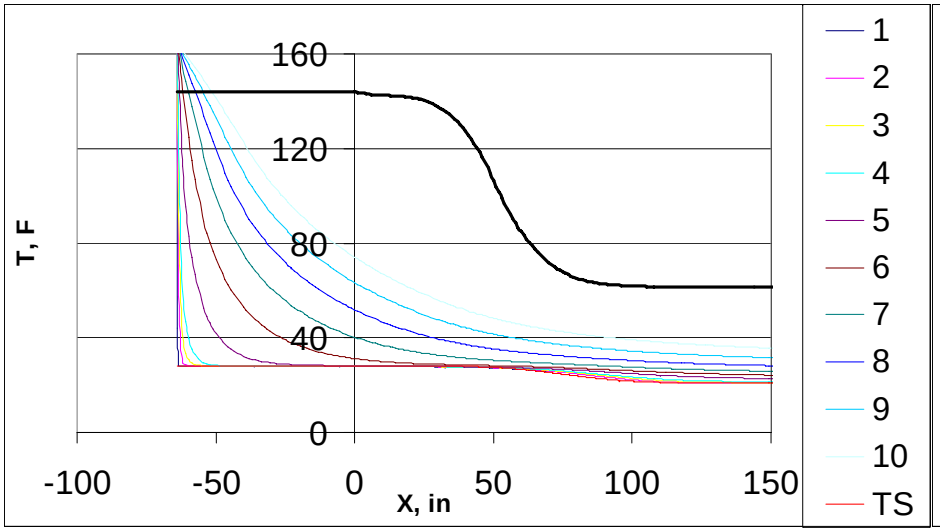
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=28°F, T_{static}=21.1°F, MVD=100μm, RH=100%

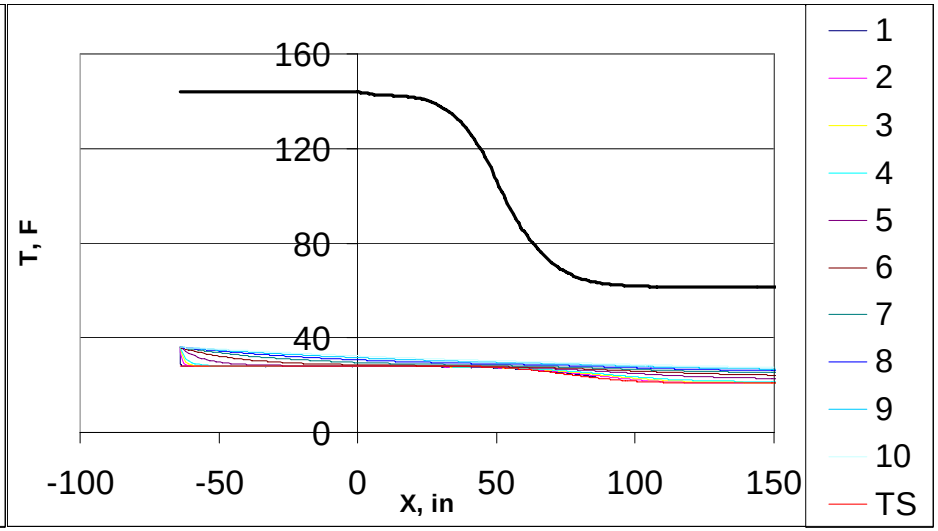
#	1	2	3	4	5	6	7	8	9	10
D, mcr	7.8	17.6	27.5	37.8	73.8	123.0	172.1	221.3	270.5	319.7
%	3.3	8.0	14.6	7.9	14.0	15.7	16.6	11.8	5.6	2.6

T_{water}=165°F



Tcloud=24.5 F

T_{water}=36°F



Tcloud=23.4 F

Paper # 11ICE-0097

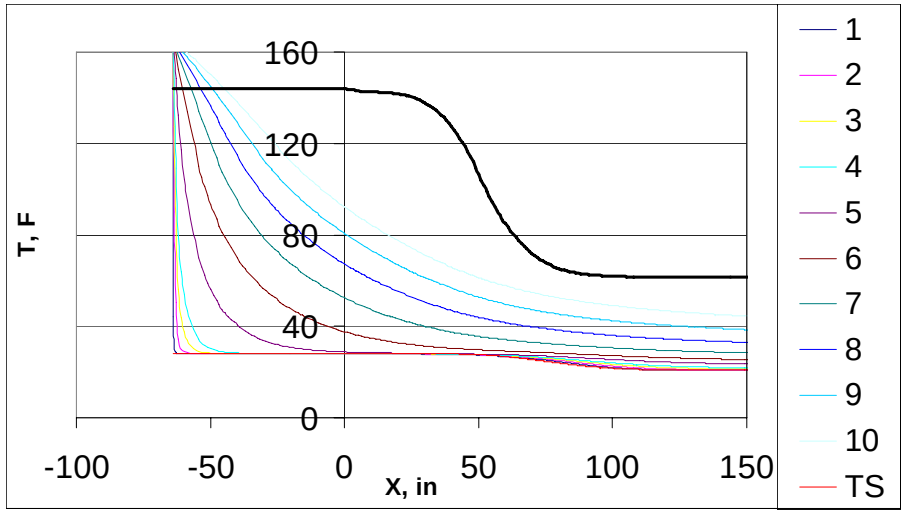
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=28°F, T_{static}=21.1°F, MVD=130μm, RH=100%

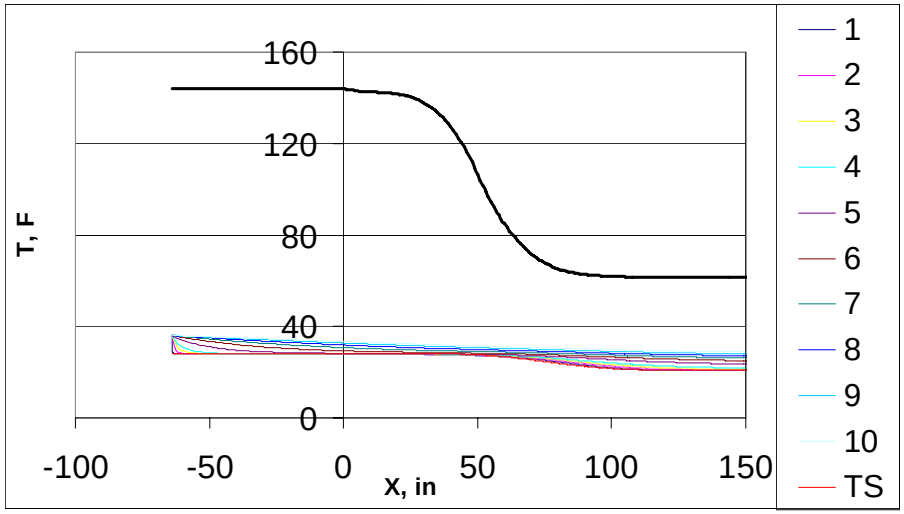
#	1	2	3	4	5	6	7	8	9	10
D, mcr	10.1	22.9	35.7	49.2	95.9	159.8	223.8	287.7	351.6	415.6
%	3.3	8.0	14.6	7.9	14.0	15.7	16.6	11.8	5.6	2.6

T_{water}=165°F



Tcloud=26.2 F

T_{water}=36°F



Tcloud=24.2 F

Paper # 11ICE-0097

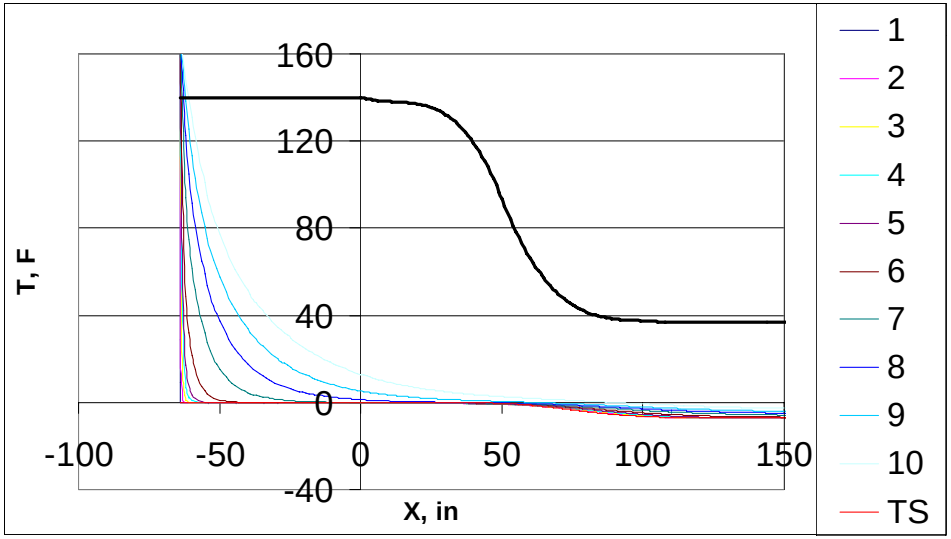
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=0°F, T_{static}=-6.9°F, MVD=20μm, RH=100%

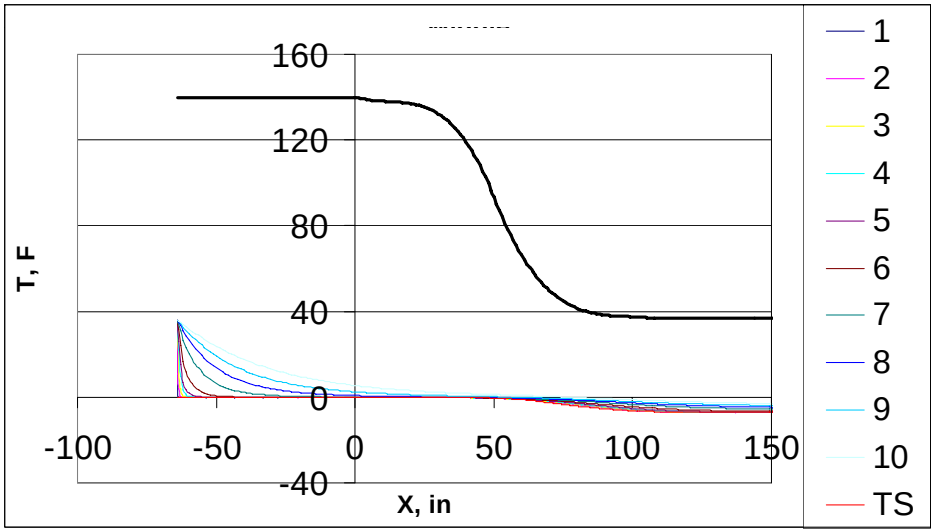
#	1	2	3	4	5	6	7	8	9	10
D, mcr	4.4	9.4	14.4	19.4	24.4	37.5	62.5	87.5	112.5	141.7
%	7.7	14.0	14.9	17.5	9.8	17.5	10.8	4.9	2.2	0.8

T_{water}=165°F



Tcloud=-6.6 F

T_{water}=36°F



Tcloud=-6.5 F

Paper # 11ICE-0097

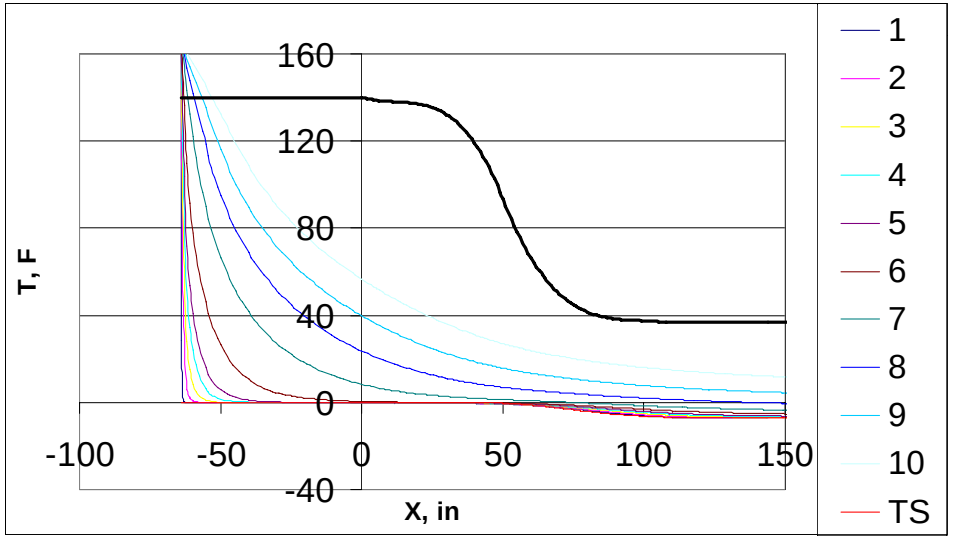
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=0°F, T_{static}=-6.9°F, MVD=40μm, RH=100%

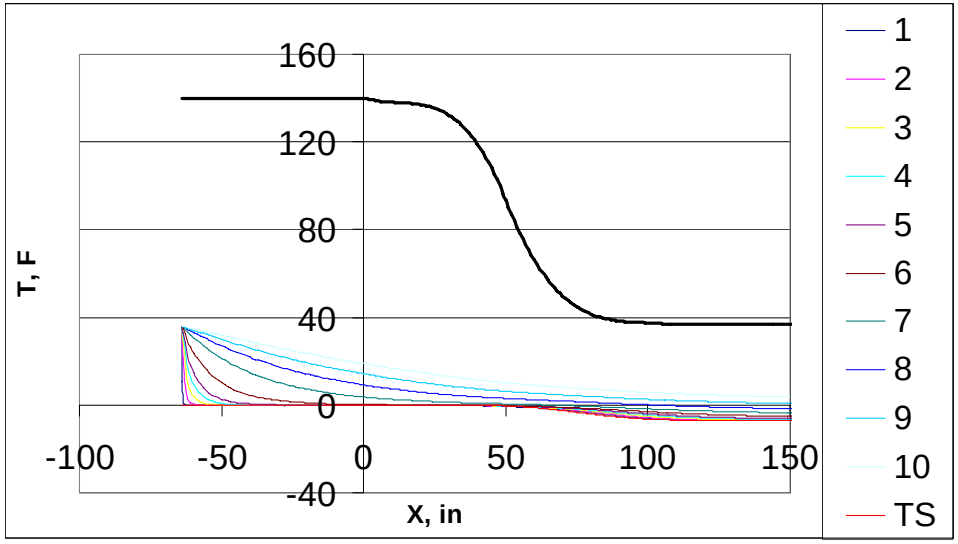
#	1	2	3	4	5	6	7	8	9	10
D, mcr	8.9	18.9	28.9	38.9	48.9	75.1	125.0	175.0	225.0	283.3
%	7.7	14.0	14.9	17.5	9.8	17.5	10.8	4.9	2.2	0.8

T_{water}=165°F



Tcloud=-5.3 F

T_{water}=36°F



Tcloud=-5.5 F

Paper # 11ICE-0097

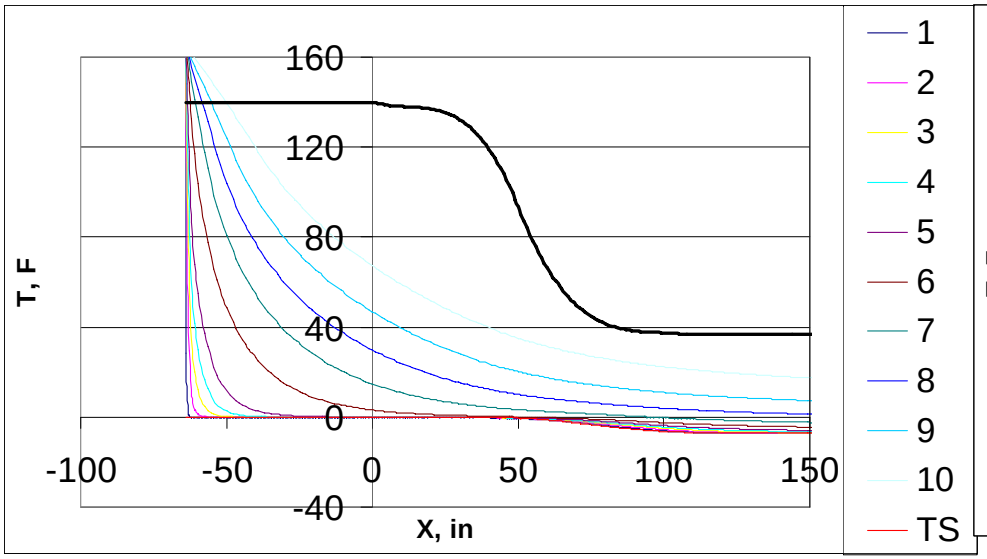
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=0°F, T_{static}=-6.9°F, MVD=70µm, RH=100%

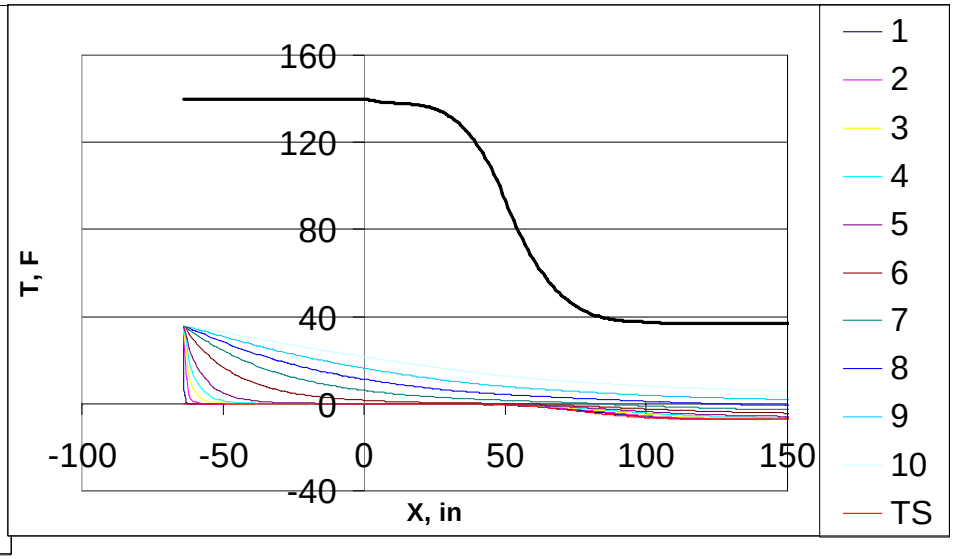
#	1	2	3	4	5	6	7	8	9	10
D, mcr	9.8	20.7	31.6	42.5	57.7	101.0	147.6	194.2	248.5	326.2
%	5.7	7.4	18.6	8.9	9.4	13.4	11.7	12.7	8.0	4.2

T_{water}=165°F



Tcloud=-2.8 F

T_{water}=36°F



Tcloud=-3.9 F

Paper # 11ICE-0097

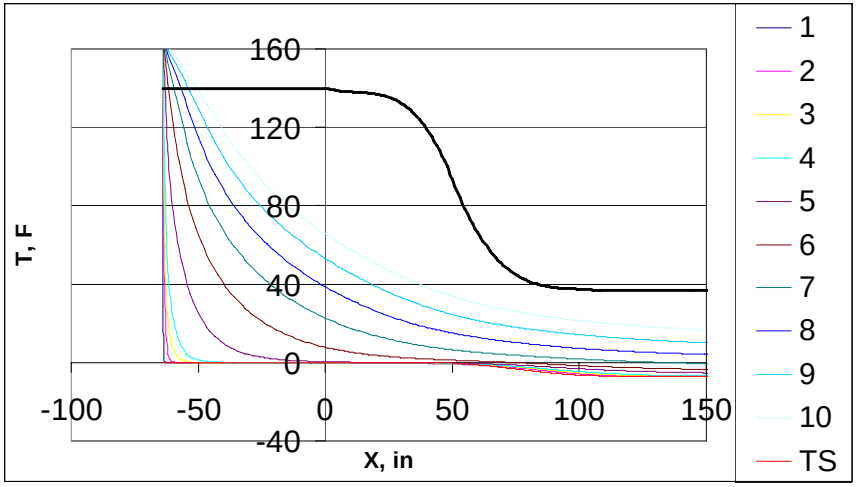
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=0°F, T_{static}=-6.9°F, MVD=100μm, RH=100%

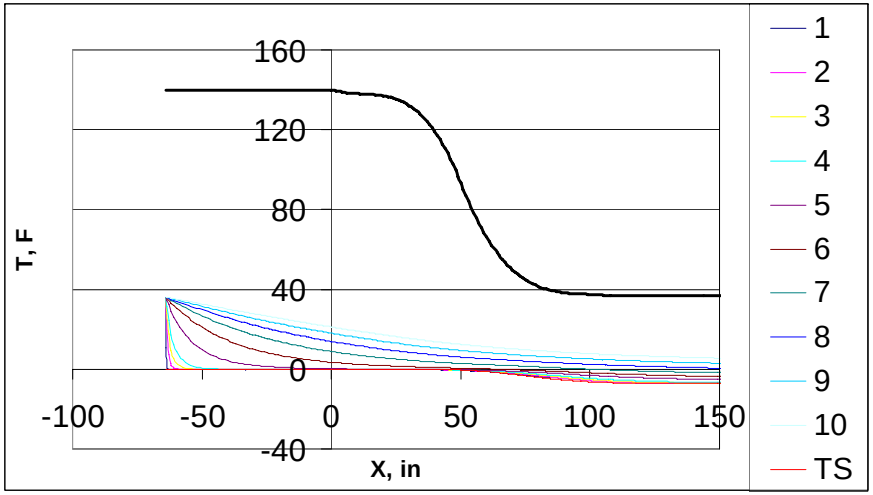
#	1	2	3	4	5	6	7	8	9	10
D, mcr	7.8	17.6	27.5	37.8	73.8	123.0	172.1	221.3	270.5	319.7
%	3.3	8.0	14.6	7.9	14.0	15.7	16.6	11.8	5.6	2.6

T_{water}=165°F



Tcloud=-2.2 F

T_{water}=36°F



Tcloud=-3.5 F

Paper # 11ICE-0097

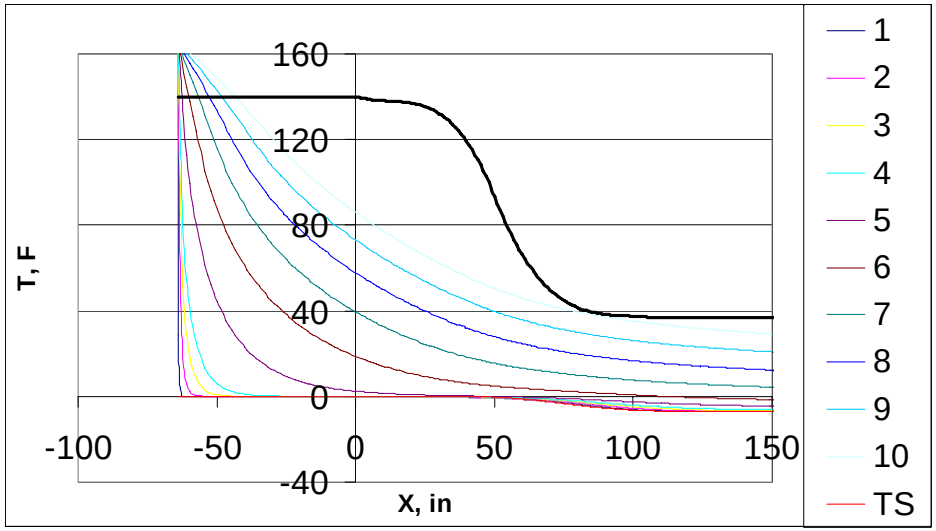
Analysis (FLUENT)

- Droplet & lump cloud temperatures (specific MVD)

200mph, T_{total}=0°F, T_{static}=-6.9°F, MVD=130μm, RH=100%

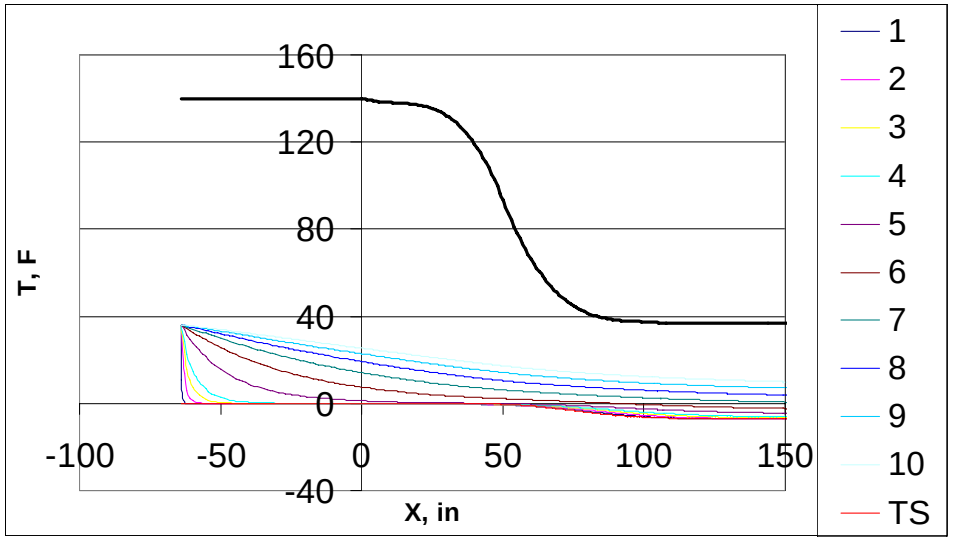
#	1	2	3	4	5	6	7	8	9	10
D, mcr	10.1	22.9	35.7	49.2	95.9	159.8	223.8	287.7	351.6	415.6
%	3.3	8.0	14.6	7.9	14.0	15.7	16.6	11.8	5.6	2.6

T_{water}=165°F



Tcloud=0.7 F

T_{water}=36°F



Tcloud=-2.1 F

Paper # 11ICE-0097