

NASA 5.2%-Scale Semispan High Lift Common Research Model High Reynolds Number Wind Tunnel Test in the National Transonic Facility

Courtney S. Winski*, Sarah Langston*, S. Melissa Rivers[†], Miranda Ertsgaard[‡]
NASA Langley Research Center, Hampton, VA 23681, USA

A wind tunnel test was conducted at the NASA Langley National Transonic Facility (NTF) from December 2023 through May 2024 on the NASA 5.2%-scale semispan High Lift Common Research Model (CRM-HL). Eight model configurations were tested including four landing, two landing with ice shapes installed, and two takeoff configurations. The test was run in both air and in nitrogen with tunnel freestream conditions ranging from -250°F and 150°F (-156°C to 49°C), a Mach number range of 0.20 to 0.35, and chord Reynolds numbers of 1.61 million to 30 million (matching flight Reynolds number). The force and moment and pressure data from this and other CRM-HL models will be made available to the worldwide research community to allow for comparison between different wind tunnels and different configurations to improve the state-of-the-art in CFD, and to increase wind tunnel testing knowledge. This paper will give an overview of the NASA 5.2%-scale CRM-HL high Reynolds number test that was run at NTF. Some data will be presented to show repeatability and to present some basic model testing information.

*Research Aerospace Engineer, Configuration Aerodynamics Branch, Mail Stop 499, AIAA Senior Member.

[†]Reduced Life Cycle Cost (RLCC) Sub-project Manager, Transformational Tools and Technologies Project, Mail Stop 254, AIAA Associate Fellow.

[‡]Model Systems Engineer, Aeronautics Systems Engineering Branch, Mail Stop 238.

I. Nomenclature

AF	=	Axial force, balance axis
α or alpha or AoA	=	Angle of attack, deg
$\alpha_{C_{L_{max}}}$	=	Angle of attack at $C_{L_{max}}$, deg
b	=	Span of the wing
BA	=	Balance accuracy
C	=	Chord of the wing
°C	=	Degree Celsius
C_A	=	Axial force coefficient in the model body axis
C_D	=	Drag coefficient, stability axis
C_L	=	Lift coefficient, stability axis
C_{LL}	=	Rolling moment coefficient in the model body axis
C_{LLS}	=	Rolling moment coefficient in the stability axis
$C_{L_{max}}$	=	Maximum Lift Coefficient
C_m	=	Pitching moment coefficient in the stability axis
C_{LM}	=	Pitching moment coefficient in the model body axis
C_{LN}	=	Yawing moment coefficient in the model body axis
C_{LNS}	=	Yawing moment coefficient in the stability axis
C_N	=	Normal force coefficient in the model body axis
°F	=	Degree Fahrenheit
ft	=	Feet
HT	=	Horizontal tail
Hz	=	Hertz
IB	=	Inboard
in	=	Inch
kPa	=	Kilopascal
lb	=	Pound
lbf	=	Pounds force
LG	=	Landing gear
M_∞	=	Freestream Mach number
MAC	=	Mean aerodynamic chord
MB	=	Midboard
mm	=	Millimeter
MRC	=	Moment reference center
MS	=	Model station
MW	=	Megawatt
OB	=	Outboard
PSF	=	Pounds per square foot
psia	=	Pounds per square inch, absolute
Q	=	Dynamic pressure, PSF
Re_C	=	Chord Reynolds number, 10^6
S	=	Wing area
T_T	=	Test section total temperature, °F
x, y, z	=	Coordinates in model reference frame, inches

Acronyms and Abbreviations

14x22	=	14- by 22-Foot Subsonic Tunnel
CAD	=	Computer aided design
CFD	=	Computational fluid dynamics
CRM-HL	=	High Lift Common Research Model
DLR	=	German: Deutsches Zentrum für Luft- und Raumfahrt e.V.
	=	German Aerospace Center

ESP	=	Electronically Scanned Pressure
HLPW	=	High Lift Prediction Workshop
IGV	=	Inlet guide vane
IML	=	Inner mold line
LN_2	=	Liquid Nitrogen
NASA	=	National Aeronautics and Space Administration
NTF	=	National Transonic Facility
NWB	=	Niedergeschwindigkeits-Windkanal Braunschweig
	=	Low-Speed Wind Tunnel at Braunschweig, Germany
OML	=	Outer mold line
ONERA	=	Office National d'Études et de Recherches Aéronautiques
	=	National Office for Aerospace Studies and Research, France
Q5	=	QinetiQ 5-meter wind tunnel
RMS	=	Root mean square
RPM	=	Revolutions per minute
SMSS	=	Sidewall Model Support System
WUSS	=	Wing under-slat surface

II. Test Program Overview

The National Aeronautics and Space Administration (NASA) 5.2%-scale High Lift Common Research Model (CRM-HL) semispan model was tested in the National Transonic Facility (NTF) wind tunnel, located at NASA Langley Research Center in Hampton Virginia, from December, 2023 through May, 2024 (NTF Test 237). The test focused on obtaining high Reynolds number data on the open CRM-HL ecosystem design [1]. Collecting high Reynolds number force and moment data on the model with ice shapes installed was also of high priority, and is discussed in Broeren et al [2]. The NASA 5.2%-scale CRM-HL semispan model was designed by NASA as discussed in Ertsgaard and Winski [3]. Figure 1 shows pictures of the NASA 5.2%-scale CRM-HL model installed in NTF.



Fig. 1 Pictures of the NASA 5.2%-scale CRM-HL semispan model installed in the NTF [Photos: NASA].

The force and moment and pressure data from this and other CRM-HL models will be made available to the worldwide research community for Computational Fluid Dynamics (CFD) validation of high lift configurations, to allow for comparison between different wind tunnels and different configurations, to improve the state-of-the-art in CFD, and to increase wind tunnel testing knowledge.

Eight model configurations were tested, including four landing, two landing with ice shapes installed, and two takeoff configurations. 85 data runs were acquired during the test, 32 of which were within-test repeat runs. The test was run in both air and in nitrogen with tunnel freestream conditions ranging from 120°F to -250°F, a Mach number range of 0.20 to 0.35, and chord Reynolds numbers of 1.61 million to 30 million (matching flight Reynolds number).

A. High Lift Common Research Model

Currently, CFD struggles to accurately and reliably predict maximum lift, the maximum lift coefficient ($C_{L_{max}}$), as well as the complex flow physics near $C_{L_{max}}$. CFD requires wind tunnel data for high-fidelity comparisons in the development of practical modeling guidelines for predicting $C_{L_{max}}$ and assessing transition, turbulence models, and Reynolds number effects. NASA is teaming with researchers and engineers in industry, government, and academia around the world to study this area of aerodynamics in order to provide an open source wind tunnel data set to the research community to use for CFD development. The data were also used in the AIAA CFD High Lift Prediction Workshop (HLPW), currently on HLPW-5 [4].

The NASA 5.2%-scale CRM-HL semispan model is part of the CRM-HL ecosystem of models, designed using the same generic commercial high lift geometry. The outer mold line (OML) was designed by Boeing [5], and the CRM-HL design itself is an open design, representative of a high lift configuration for modern commercial transonic transports [1]. Ecosystem partners around the world have or plan to build and test wind tunnel models based on this same design, build at different scales, both semispan and full-span, and run in multiple configurations, including takeoff, landing, and cruise. The force and moment, pressure, and flow visualization data from this and other CRM-HL tests, along with the model geometry, will be made available to the worldwide research community to allow for comparison between different wind tunnels and different configurations, to improve the state-of-the-art in CFD, and to increase wind tunnel testing knowledge.

Part of the NASA 5.2%-scale CRM-HL semispan model design focused on ensuring the model is capable of supporting geometric variations of the most likely components that may be desired in future studies, including leading and trailing edge devices, wing tip, strake, and nacelle and pylon. The ecosystem of models, and the extensive testing on each model provides a relatively comprehensive understanding of the model, and the modular design of the model makes these models good platforms to test new concept designs without building an entire new model. The ability to test new designs on these "known" models also makes it easier to isolate the aerodynamic effects of the new parts.

B. National Transonic Facility

The NTF [6] and [7] is a fan-driven, closed-circuit, continuous-flow, pressurized, cryogenic wind tunnel. An aerial view of the tunnel is shown in Figure 2, and a sketch of the NTF tunnel circuit is shown in Figure 3. The facility has the ability to hold the tunnel temperature, pressure and Mach number at constant values, thus yielding independent variation of Mach number (compressibility effects), Reynolds number (flow regime), and dynamic pressure (aeroelastic considerations), within a tolerance decided on by the customer. The test section is approximately 8.2 ft (2.5 m) square and 25 ft (7.6 m) long with a cross sectional area of 66.8 ft^2 (6.2 m^2). The test section is slotted with six slots in the ceiling and six slots in the floor, 14 re-entry flaps in the top and bottom walls to prevent the flow from choking the tunnel at near-sonic conditions and a 6% openness ratio based on the wall surface area when the wall divergence is set at zero.



Fig. 2 Aerial View of the U.S. National Transonic Facility [Photo: NASA].

The NTF can be operated using air, nitrogen, or a mixture of air and nitrogen as the test medium. During air operations temperature is controlled by a large water heat exchanger, called the cooling coil, located in the settling

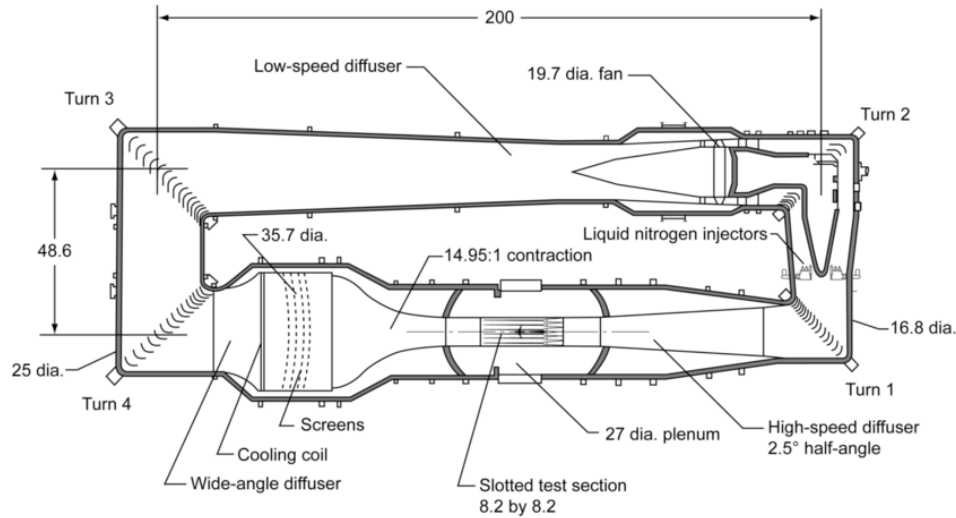


Fig. 3 National Transonic Facility tunnel circuit, dimensions in feet.

chamber which removes heat from the tunnel, thereby maintaining tunnel temperature. During nitrogen operations the temperature is controlled by evaporating liquid nitrogen (LN_2) which is dispersed into the tunnel circuit by injectors that are located just upstream of the fan. A picture of the NTF LN_2 injectors is shown in Figure 4(a). As the nitrogen is injected, it vaporizes and removes heat from the circuit. In air operations the tunnel temperature is controlled with water-fed cooling coils, located upstream of the test section in the settling chamber. These modes provide the ability to operate the tunnel between -250°F and 150°F (-156°C to 49°C). Thermal insulation that resides inside the pressure shell minimizes energy consumption. Total pressure is controlled by two large vent valves between turns 3 and 4. The facility can operate between 14.7 psia and 130 psia (101 kpa to 896 kpa), or 1 to 9 atmospheres (1.01 to 9.1 bar) in both air and in nitrogen mode.



(a) Picture of the NTF LN_2 Injectors.

(b) Picture of the NTF inlet guide vanes (IGVs) and fan blades.

Fig. 4 Photos of the NTF LN_2 injectors, IGVs and fan blades [Photos: NASA].

The Mach number is controlled by the fan revolutions per minute (RPM) and movable fan inlet guide vanes (IGV) located ahead of the fan blades. Figure 4(b) is a picture of the NTF IGVs and fan blades. The tunnel fan/drive system is powered by a variable speed motor (60 to 600 RPM) that has variable maximum torque or power output up to 360 RPM. At 360 RPM the maximum power is 100 megawatts (MW) and maintains that maximum power level up to 600 RPM. The compressor consists of a fixed pitch, single stage fan with variable inlet guide vanes. For fine Mach number control, the inlet guide vanes are varied to achieve the desired compression ratio to maintain the selected Mach number. The Mach range at NTF is 0.20 to 1.2. Table 3 lists the characteristics of the NTF tunnel.

Table 3 NTF Characteristics.

Mach Number	0.20 - 1.20
Reynolds Number	$4 \times 10^6 - 145 \times 10^6$ per foot
Pressure	15 psia - 125 psia
Temperature	$-250^\circ F - 150^\circ F$
Test Gasses	Air, Nitrogen, Air and Nitrogen
Test Section Size	8.2 ft x 8.2 ft
Test Section Length	25 ft
Test Section Area	$66.8 ft^2$
Contraction Area Ratio	15:1
Circuit Length	497 ft
Drive Power	100 Megawatts

C. Testing Procedures

Testing followed the best practices of the NTF, including the acquisition and application of weight tares, check loads, wind off zeros before and after running, instrumentation checks and calibrations throughout testing, and temperature equalization of the tunnel and the balance structures. Leak checks were done on the model pressures after initial installation, and again after any model changes on the new parts. Multiple repeat sweeps were done throughout testing, including short term and long term repeats.

It is very important to have a model that is as smooth as possible for high Reynolds number testing since the high Reynolds number flow is used to, in a sense, scale the model up from model-scale to full-scale, meaning that any small scale imperfections, roughness, or steps become amplified in the high Reynolds number flow. It is especially important to have as few non OML features as possible on the upper surface of the model. Model filler was used to fill in fastener holes and gaps on the model, and sanded down to be as flush with the model surface as possible. Atmospheric tunnels are able to use tape on the lower surface of the model since the small steps have less of an effect at lower Reynolds numbers, but those steps have a much larger effect at high Reynolds numbers seen at NTF. The model was wiped down and cleaned as a last step before closing the tunnel after model work.

A balance monitoring system was used to ensure that maximum forces and moments were not reached on the model or the balance during testing. The majority of the test was run in pitch-pause data collection mode, running alpha sweeps from the lowest angle of attack (-4°) to the highest angle of attack (22°). Most alpha sweeps were using run schedule A1, with 30 angles, and repeats were run using a reduced run schedule, A2, with 20 angles. Alpha schedules A1 and A2 are listed below, and both have a smaller delta increment near $C_{L_{max}}$. Because of model dynamics a few runs were cut off early before reaching the maximum angle of attack planned. A set of continuous sweep runs were tested to compare the continuous sweep forces and moments against the pitch-pause forces and moments, checking for potential flow setup differences on the model from pitching patterns. No difference was seen between the continuous data and the pitch-pause data.

Alpha schedule A1: -4, -2, 0, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 13.5, 14, 14.5, 15, 15.5, 16, 16.5, 17, 17.5, 18, 18.5, 19, 19.5, 20, 22

Alpha schedule A2: -4, 0, 4, 6, 8, 10, 12, 14, 14.5, 15, 15.5, 16, 16.5, 17, 17.5, 18, 18.5, 19, 20, 22

D. Model Configurations

Table 4 lists the configurations that were tested during this test entry. The nacelle chine was installed in the middle position for all nacelle-on runs. The ecosystem has defined selected baseline reference configurations that all ecosystem partners are asked to run [5] during their testing campaigns. The ecosystem baseline landing configuration, Landing - Nacelle On, is 30° slat, 40° inboard (IB) flap and 37° outboard (OB) flap with nacelle on with chine on (middle position), horizontal tail (HT) off, and the landing gear (LG) off at Mach 0.20. The ecosystem baseline takeoff configuration (TO), Takeoff - Nacelle On, is 22° slat and 25° inboard and outboard flaps with nacelle/pylon installed with chine on in the

middle position, horizontal tail off, and landing gear off at Mach 0.26.

Table 4 Model Configurations.

Configuration	Slat	IB Flap	OB Flap	Nacelle	LG	HT	Ice Shapes
Landing - Nacelle On (L baseline)	30°	40°	37°	on	-	-	-
Landing - Nacelle On - LG	30°	40°	37°	on	on	-	-
Landing - Nacelle On - HT	30°	40°	37°	on	-	on	-
Landing - Nacelle Off	30°	40°	37°	-	-	-	-
Landing - Nacelle On - HT - Icing	30°	40°	37°	on	-	on	on
Landing - Nacelle On - Icing	30°	40°	37°	on	-	-	on
Takeoff - Nacelle On (TO baseline)	22°	25°	25°	on	-	-	-
Takeoff - Nacelle Off	22°	25°	25°	-	-	-	-

E. Testing Conditions

Table 5 lists the tunnel conditions that were run during the test. In general, landing configuration data were collected at Mach 0.20 and takeoff configuration data were collected at Mach 0.26. Conditions noted with "Rake run only" were run with a pressure rake installed on the wall in front of the model, and no model data runs were done at those conditions. Certain conditions were run for comparisons with other tunnel data on this same model, the NASA 5.2%-scale CRM-HL model check out test at NASA Langley 14- by 22-Foot Subsonic Wind Tunnel (14X22) Test 668 (2022) [8] and the test of the NASA 5.2%-scale CRM-HL model in the Niedergeschwindigkeits-Windkanal Braunschweig (Low-Speed Wind Tunnel at Braunschweig, Germany) (NWB) (2023) [9] and [10], and for comparison with other CRM-HL ecosystem models tested at other wind tunnels including the NASA 10%-scale CRM-HL test in QinetiQ 5-meter (Q5) wind tunnel (2019) [11] and the (French) Office National d'Études et de Recherches Aérospatiales (National Office for Aerospace Studies and Research) (ONERA) 5.1%-scale Large Reference Model – High-Lift model (LRM-HL) test in the ONERA F1 Pressurized Low-Speed Wind Tunnel (2022) [12] and [13]. Two runs were tested at 5.49 million Re_C , one in air operations at a dynamic pressure (Q) of 207 PSF and another run taken at a Q of 138 PSF in cryogenic operations, and two runs were taken at 16 million Re_C , one at a Q of 240 PSF, and the other at a Q of 157 PSF. These Q variation runs can be used for aeroelastic assessment of the model.

Table 5 Test Conditions.

Configuration	Mach	Re_C *10 ⁶	$T_{T,TS}$ °F	Q PSF	Notes
Landing	0.20	1.6	100	61	Match DLR & 14x22 Test 668 Re_C
	0.20	3.33	120	133	
	0.20	5.33	-50	134	Match Q5 Re_C
	0.20	5.49	95	207	High Q
	0.20	5.49	-50	138	Low Q
	0.20	5.9	-50	149	Match ONERA Re_C
	0.20	16	-180	240	High Q
	0.20	16	-250	157	Low Q
	0.20	30	-250	295	
	0.26	16	-250	202	For icing
	0.30	16	-250	232	For icing
	0.35	16	-250	268	For icing
	0.20	7	95	264	Rake run only
	0.26	5.6	120	288	Rake run only
	0.35	5.49	120	376	Rake run only
Takeoff	0.23	1.8	120	82	Match DLR Mach & Re_C
	0.26	1.97	120	101	Match 14x22 Test 668 Re_C
	0.26	4.08	120	210	

III. Model and Hardware Description

The NASA 5.2%-scale CRM-HL semispan model is part of the CRM-HL ecosystem of models, designed and constructed to match the CRM-HL reference geometry outer mold line (OML) [5] as closely as possible. The reference design is representative of a high lift configuration for transonic transports [1] and is openly available on the CRM website [14], which has a section that provides the geometry files for the CRM-HL reference OML as well as the geometry files for the as-built models within the CRM-HL ecosystem [15].

The NASA 5.2%-scale CRM-HL wing was designed at the NASA Langley Research Center from the reference OML, with details of the design process available in the paper by Ertsgaard and Winski [3], and fabricated by Advanced Technology Inc. (ATI) *. The fuselage of the model and support hardware were preexisting and have been used on a multitude of wind tunnel test campaigns over many years. The NASA 5.2%-scale CRM-HL was designed as a port semispan wing, or half model, specifically for the NTF. As noted earlier, the NTF is a high Reynolds number facility that can be run in cryogenic conditions, which creates constraints on the model design. NTF test conditions for this test ranged from temperatures -250°F and 150°F (-156°C to 49°C), and up to a maximum Q of 380 PSF (18 kPa). These extremes, coupled with the angle-of-attack range of -4° to 22° heavily influenced the model design.

The NASA 5.2%-scale CRM-HL semispan model has been tested four times in three wind tunnels. The model was first tested at the 14X22 from August 15 to September 8, 2022 for a model checkout test. Testing details are available in Winski et al. [8]. The model was then tested at the NWB [16] from May 9 to July 6, 2023, under an agreement between NASA and the German Aerospace Center (German: Deutsches Zentrum für Luft- und Raumfahrt e.V.) (DLR). Testing details are available in Pülm et al. [9] and [10] The high Reynolds number test that is the focus of this paper was run at the NTF from December 22, 2023 to May, 2024. The NASA 5.2%-scale CRM-HL was again tested in the 14x22 from September 23 to September 26, 2024 for a dedicated flow visualization test.

Semispan testing allows for a larger scale model to be tested than a full-span model of the same design which results in the ability to test at higher chord Reynolds numbers in the same conditions. Due to the scaled down nature of the wind tunnel model from full scale, certain changes needed to be made to the NASA 5.2%-scale CRM-HL model, creating variations from the reference geometry. Most notably the designs for the flap track fairings and the slat brackets had to be large enough to house pressure tubing running from the flaps and slats to the main wing spar instrumentation trough. In accordance with the ecosystem recommendations, the flap track and slat track variations from baseline are in height and not width.

The wing main spar was designed with instrumentation troughs for pressure tubing to run from the wing to the Electronically Scanned Pressure (ESP) modules in the fuselage. The upper surface of the wing was designed to be as clean as possible, minimizing pressure troughs and fasteners whenever possible. The surface finish on all flow surfaces is 8 micro-inches or less, since the effect of small amounts of roughness are exacerbated in high Reynolds number testing.

The wing was fabricated from Vascomax® C-250, a material often used in cryogenic testing because it remains dimensionally stable under a large range of temperatures and also retains its strength. The model was designed to be modular as shown in Figure 5, with changeable slat angle and IB and OB flap angles, nacelle and pylon on or off, chine at three radial locations or removed, horizontal tail on or off, and landing gear on or off. The modular design of the model also allows for the ability to test non-original parts at any of the previously mentioned locations. The model also has a removable plug near the wing root that can be used for different flow visualization techniques. One flow visualization plug will be left as is for standard clean wing testing.

A. Model Reference Dimensions

Table 1 lists the model reference dimensions used in the data reduction. Axial transfer, x , is positive moving back from in front of the nose of the aircraft towards the tail. Side transfer, y , is positive moving from the model center-line out towards the right wing tip. Normal transfer, z , is positive going from slightly below the model lower fuselage towards the roof of the plane or upper fuselage.

In model coordinates, the nose begins at model station (MS) $x=4.81$ in and the tail ends at MS $x=133.328$ in, with the fuselage being 128.52 in long. Note that the ecosystem CAD definition has its full-scale back end at $x=2562$ in ($x=133.224$ in 5.2%-scale), whereas the NASA 5.2%-scale semispan model ends at $x=133.328$ in. The mounting point of the model is at water line (WL) $z=11.287$ in of the model, and $x=59.883$ in behind the nose. Force and moment plotting was done in the model aerodynamic coordinate system set at the model's aerodynamic center, or moment reference center (MRC). These coordinate transformations as well as transformations for other CRM tests in the NTF are covered by Pomeroy, et al. in [17].

*No federal endorsement is implied.

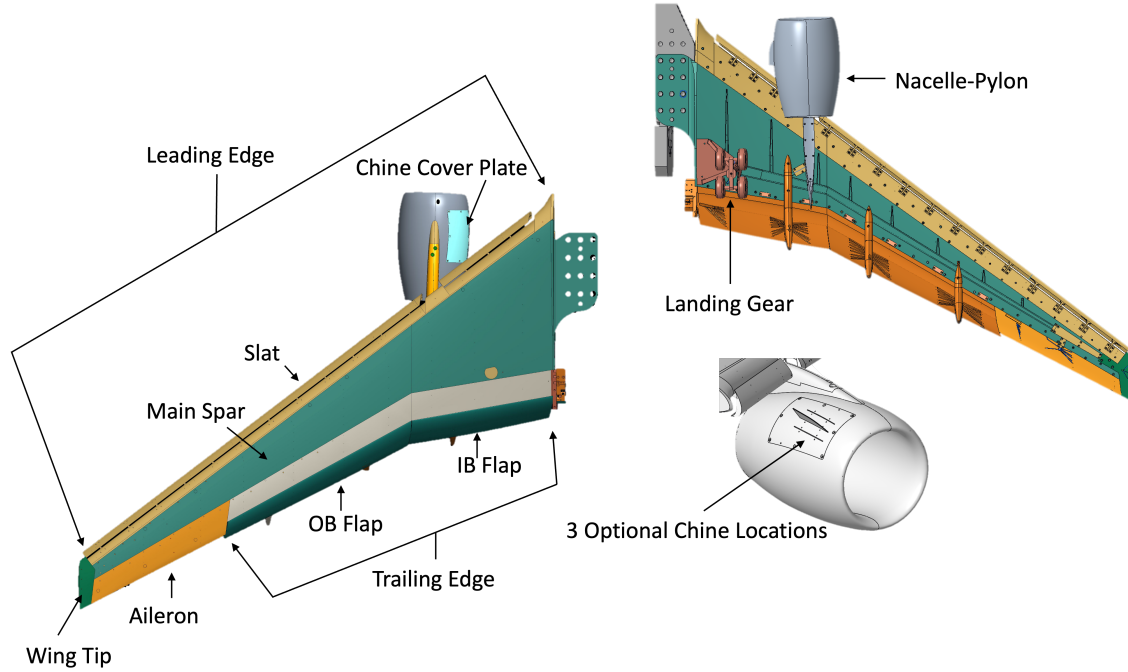


Fig. 5 5.2%-scale CRM-HL main wing assembly.

Table 1 Model Reference Dimensions.

Parameter	Variable	Full Scale	5.2%-Scale
Reference area (semispan)	S_{REF}	2065 ft^2	5.58 ft^2
Reference chord	C_{REF}	275.8 in	14.34 in
Wingspan (semispan)	b_{REF}	1156.75 in	60.15 in
Mean Aerodynamic Chord x distance	MAC x	275.8 in	14.34 in
Mean Aerodynamic Chord y distance	MAC y	468.75 in	24.35 in
X Moment Reference Center	MRC x	1325.9 in	68.95 in
Y Moment Reference Center	MRC y	0 in	0 in
Z Moment Reference Center	MRC z	177.95 in	9.25 in
Fuselage length		2059.62 ft	10.71 ft
Clean wing volume			773 in^3

B. Model Parts

The model consists of a fuselage, a horizontal tail and numerous wing interchangeable parts that attach to the wing spar (or main element). The fuselage being used on this model was preexisting, and the wing spar and wing components were designed and built for this model. See [3] by Ertsgaard and Winski for details of the wing design process and model parts. The model consists of numerous interchangeable parts allowing for the buildup of different configurations for takeoff, landing, and cruise. Figure 5 shows a computer aided drawing (CAD) view of the parts of the wing that can be changed out on the main spar. Figure 6 shows an exploded CAD view of the major wing components that attach to the wing spar (green).

1. Fuselage

The fuselage used on this model was preexisting, and had been used on numerous testing campaigns in the NTF and in other tunnels. New fuselage fairings were designed and fabricated with the wing to restore the fuselage contour and

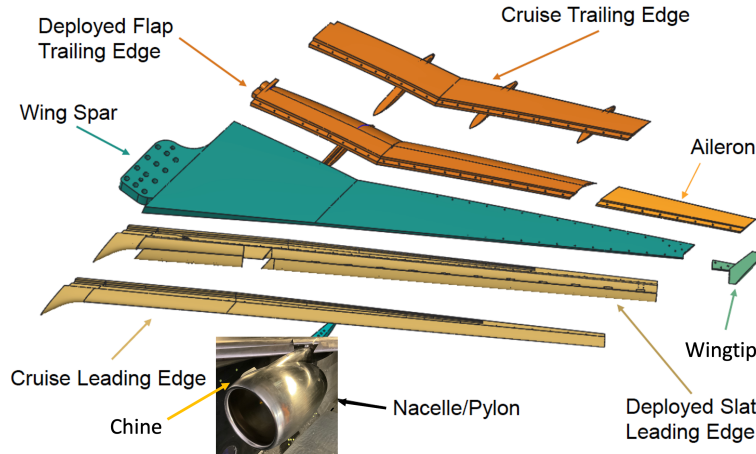


Fig. 6 5.2% CRM-HL blown up CAD view of the major wing components [Photo:NASA].

accommodate the CRM-HL wing loft and strake. Fairings on the fuselage provide access to the model block, ESP modules, and angle measurement system. The ESP modules were stored in a heater box inside of the fuselage during testing. The aft fuselage can have a horizontal tail installed, or a blank plate. There is no vertical tail on this model.

2. Wing Spar

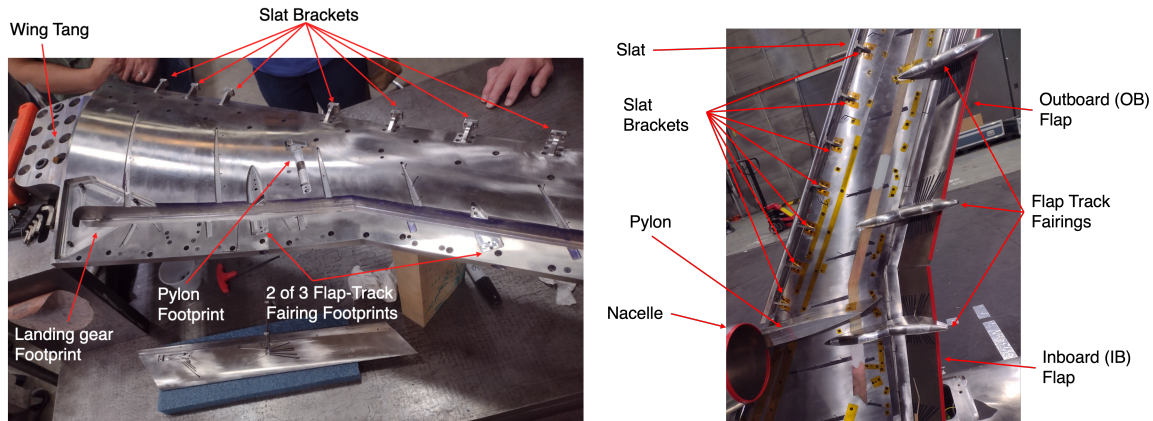
Figure 6 shows a blown up CAD view of the major wing components that attach to the wing spar (green). The wing spar is attached to the fuselage model block by the wing tang. All of the pressure instrumentation runs through the main wing spar into the fuselage. The wing tip and the aileron stay attached to the main wing spar, though they can be removed. The wing spar and all wing parts are made of Vascomax® with AAA certification and have a 8 micro-inches root mean square (RMS) surface finish on all flow surfaces unless otherwise specified.

3. Leading Edges and Trailing Edges, Slats and Flaps

The model has one set of slat and flap parts for the cruise configuration, and another set of slat and flap parts for deployed takeoff and landing configurations. The cruise leading edge is one long piece that abuts the entire leading edge of the wing spar, with no slat jutting out, and no slat brackets, just a single smooth surface. The cruise trailing edge has no deflection and abuts the wing spar to make one smooth surface with flap track fairings attached on the underside. The deployed configurations all use common slats and flaps with the brackets changed out to set each designated angle. The aileron is not deflected or removed. Figure 7(a) shows the underside of the wing spar with the slat brackets and the mounting features or footprints for the flap track fairing labeled. Figure 7(b) shows the underside of the wing with the deflected slat and deflected flaps installed.

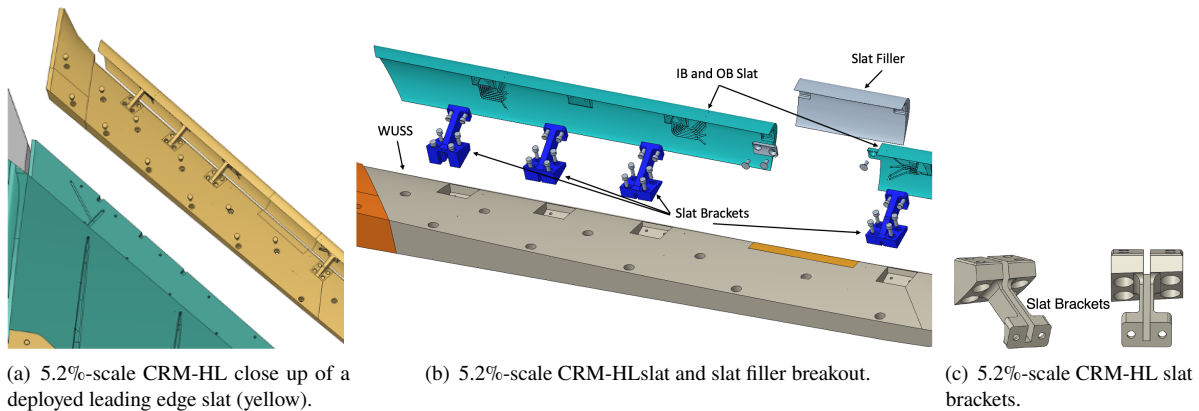
Figure 8 shows CAD snapshots of the deployed leading edge parts. The deployed configuration incorporates model hardware along the length of main spar which completes the main spar leading edge, called the wing under-slat surface (WUSS), which is shown broken out in yellow with the slat attached in Figure 8(a). The slat is in three lengthwise pieces as can be seen in Figure 8(b), an inboard slat, a small slat filler insert which is only used when running without the nacelle-pylon, and an outboard slat. The jetted out, deflected, slats connect to the WUSS with slat brackets, shown in Figure 8(c).

There are 15 slat brackets connecting the deployed slat to the WUSS leading edge, three on the inboard slat and 12 on the longer outboard slat. Pressure tubing running from the slat to the leading edge and then to the wing spar is routed through the slat brackets. The slat brackets are therefore larger in height than the ecosystem design to accommodate the tubing. The model has two sets of slat brackets, allowing the deployed slat to be set to 22° or 30° using the common slat pieces, and the slat brackets are changed out to change between angles. The 22° slat brackets are shorter with a shallower angle and the 30° slat brackets are longer with a steeper angle. When the slat angles are changed the pressure tubing remains connected to translate inside the deployed leading edge and the slat brackets are switched out over top of the pressure tubing.



(a) 5.2%-scale CRM-HL underside of the wing with slat brackets (b) 5.2%-scale CRM-HL underside of the wing with the slats, slat installed and mounting features for the flap track fairings and landing brackets, flaps and flap brackets installed.

Fig. 7 Pictures of the NASA 5.2%-scale CRM-HL underside of the wing [Photos: NASA].



(a) 5.2%-scale CRM-HL close up of a deployed leading edge slat (yellow).

(b) 5.2%-scale CRM-HLslat and slat filler breakout.

(c) 5.2%-scale CRM-HL slat brackets.

Fig. 8 NASA 5.2% CRM-HL CAD of the slat and slat parts.

Like the deflected slats, there is only one set of deflected flap parts, and the flap track fairings, which serve as integral flap brackets, are changed out to set the flap deflections to different angles. Figure 9 shows example CAD snapshots of the flap track fairings. Note that while these images demonstrates the correct flap track fairing OML (orange) they are not representative of the final as-built wing hardware (gray). Figure 9(a) shows the difference between a cruise flap bracket, and one of the deployed flap brackets. The inboard (IB) deflected flap can be set to 25° (takeoff), 37°, 40°, or 43° (landing). The outboard (OB) flap can be set to 25° (takeoff), 34°, 37°, or 40° (landing).

For the deflected flap configurations, the two flaps are attached to the trailing edge of the wing spar with the flap track fairings. The IB flap has one flap-track fairing per configuration or angle and the OB flap has two flap-track fairings per configuration or angle. The fairings double as a structural bracket for holding the flaps to the wing spar. Pressure tubes are routed through pockets in the flap-track fairings from the flaps to the main spar instrumentation trough, as can be seen in Figure 9(b). To accommodate the tubing the flap-track fairings are larger in height, but not in width, than the ecosystem OML.

The high-lift configurations of the model have a gap between the IB and OB flaps, seen in Figure 10. The model could not be designed to have that gap closed because of the different deflection angles the flaps are tested at. The ecosystem calls for this flap gap to be partially filled as discussed in Section III.B.4.

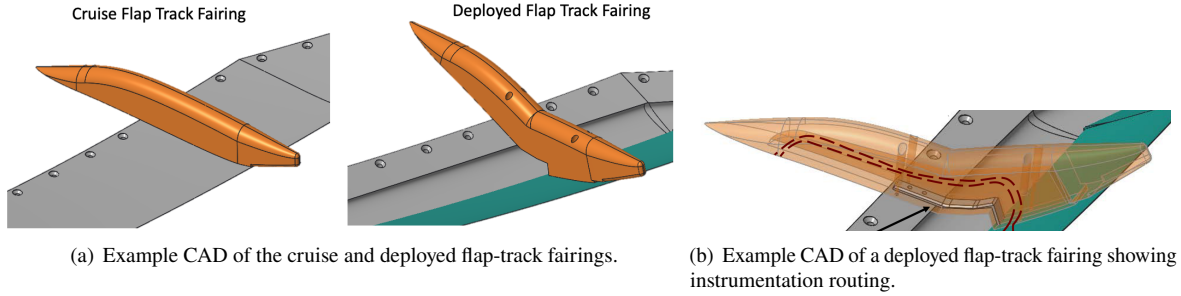


Fig. 9 NASA 5.2% CRM-HL CAD of the flap track fairings.

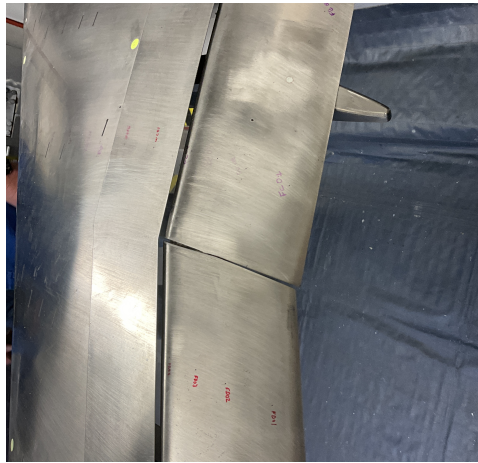


Fig. 10 Zoomed-in view of the gap between the IB and OB flaps on the NASA 5.2%-scale CRM-HL model [Photo: NASA].

4. Flap Gap Filling

As stated above, the non-cruise configurations of the model have a flap-to-flap gap at the trailing edge, however CFD will be run with that gap closed. A portion of this gap was filled following the measurements used on the NASA 10%-scale CRM-HL model at QinetiQ. The filler starts at the leading edge between the two flaps. In the landing configuration the gap was filled to 2.4 in forward of the IB flap trailing edge (42 in full scale). In the takeoff configuration the gap was filled to 1.4 in forward of the IB flap trailing edge (24 in full scale). Figure 11 shows the filler used at NTF during the landing runs. Filler was used in the gap, and tape was used on the under surface to help keep the filler in place.

5. Nacelle-Pylon

The model can be run with the nacelle-pylon on or off. When the nacelle-pylon is off, a blank plate is installed to fill in the pylon interface on the underside of the wing, and a slat filler piece is installed on the leading edge to make the slat one long uninterrupted feature, as seen in Figure 6. The chine on the nacelle is removable, and can be replaced by a blank plate. The chine can also be moved to three different azimuthal locations on the nacelle. The entire test was run with the chine on, in the middle position. Figure 12 shows a picture of the nacelle attached to the wing spar, with the chine in the middle location.

The nacelle has 17 pressure ports that were built into the design, the inclusion of which were enabled by three dimensional (3D) printing the nacelle. Figure 13(a) shows the built in internal features of the nacelle, Figure 13(b) shows a CAD view of the nacelle with pressure tap locations labeled, and Figure 13(c) shows a picture of the nacelle alone with pressure tubing coming out where the pylon attaches. For more information about the additive manufacture of the nacelle see Ertsgaard and Winski [18].

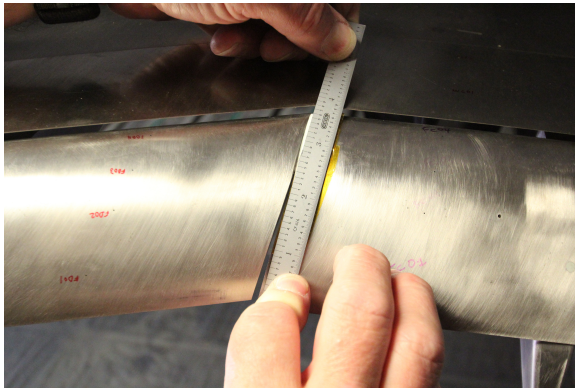
The nacelle was additively manufactured out of Inconel 718 and then hand worked to the correct OML and inner mold line (IML) and to achieve the correct surface finish (8 micro-inches RMS on flow surfaces). The pylon was made



(a) Flap gap filler, zoomed out view.



(b) Flap gap filler, zoomed in view.



(c) Flap gap filler with ruler.



(d) Flap gap filler, under wing view.

Fig. 11 Flap gap filler between the inboard and the outboard flaps, landing configuration [Photos: NASA].



Fig. 12 Picture of the 5.2%-scale CRM-HL nacelle [Photo: NASA].

using standard manufacturing techniques, not additive manufacturing. The build of the nacelle took four attempts to achieve acceptable tolerances, but lessons were learned for the future on how to additively manufacture such a large part, including where to thicken the part to account for shrinkage during heat treating post build.

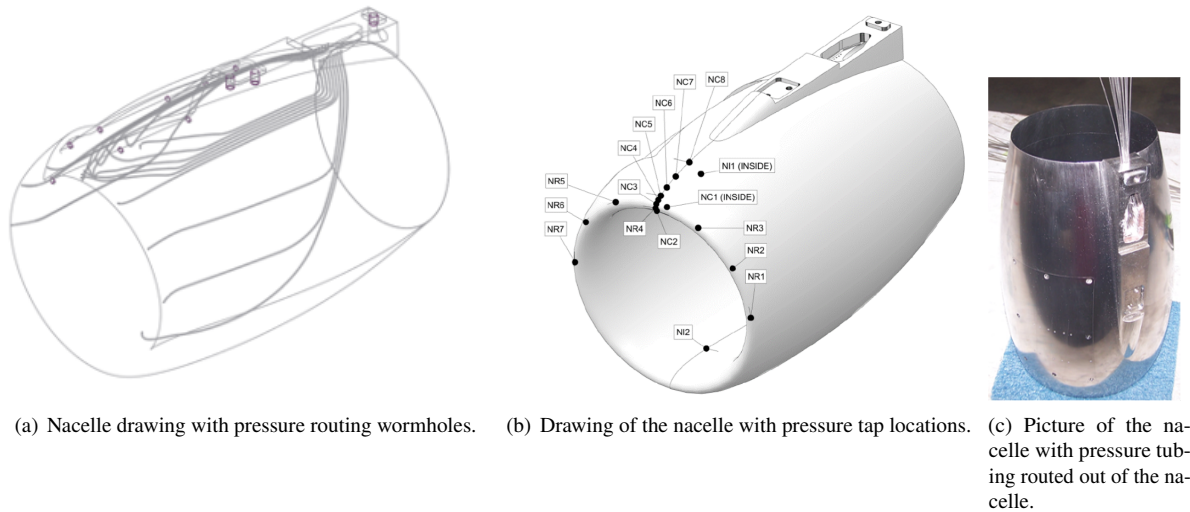


Fig. 13 NASA 5.2%-scale CRM-HL nacelle pressure port design [Photo: NASA].

The ecosystem nacelle lip was redesigned after testing of the NASA 10%-scale CRM-HL model, therefore the NASA 5.2%-scale model nacelle-pylon does not match the NASA 10%-scale nacelle-pylon. Because of unexpected shrinkage mechanics during heat treat of the NASA 5.2%-scale nacelle, the IML of the nacelle does not match design, but the forward portion, back portion and the minimum were maintained, allowing the flow to be as unaffected as possible.

6. Landing Gear

The model can be run with the landing gear on, or without the landing gear and a cover plate in it's place. The landing gear strut, shown in Figure 14(a), was additively manufactured [18] out of Inconel 718 and then hand worked to the correct OML and surface finish (32 micro-inches RMS). The surface finish was less critical for the landing gear strut than it was for the nacelle and the rest of the model because the strut itself is a large protuberance that will create turbulent flow independent of surface roughness. The landing gear wheels and door were fabricated separately from the landing gear using standard machining practices. The wheels were fixed to the strut with a pin, and were therefore not free to rotate. Figure 14(b) shows a picture of the landing gear installed on the wing spar.

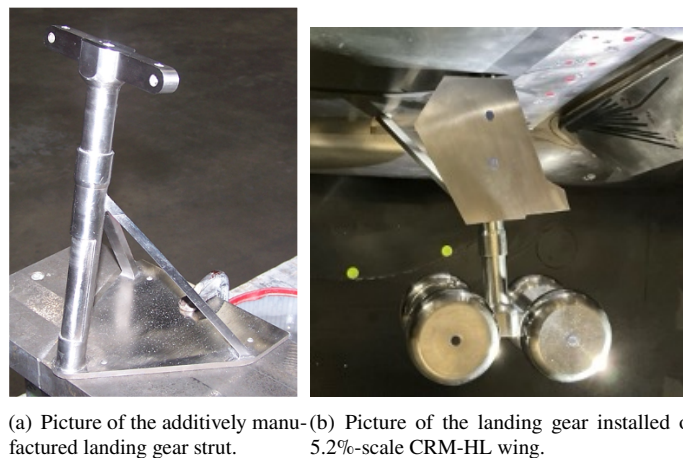


Fig. 14 Pictures of the 5.2%-scale CRM-HL landing gear [Photos: NASA].

The ecosystem OML calls for a larger landing gear bay than what could be accommodated on this model, and as a compromise the landing gear wing interface plate is not flush to the wing, but is a step down into the wing surface by

design, as seen in Figure 15.

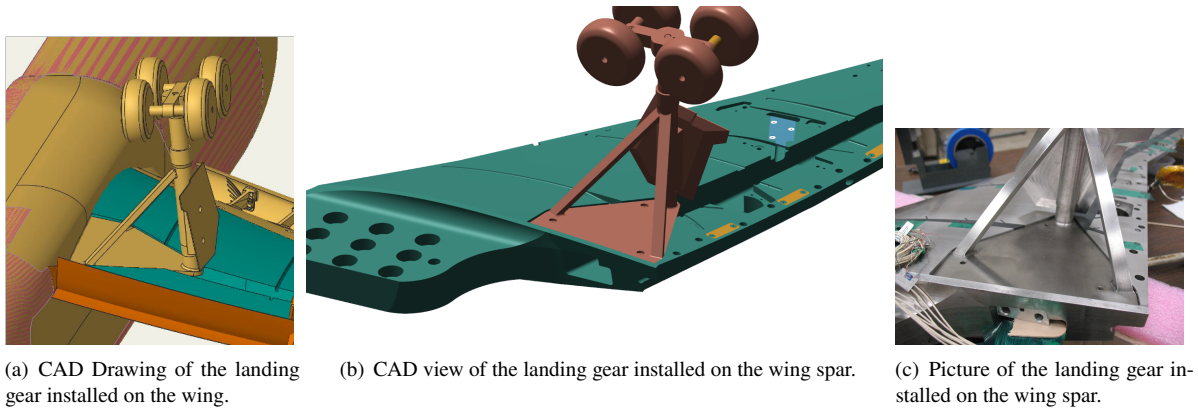


Fig. 15 Landing gear installation on the NASA 5.2%-scale CRM-HL wing [Photo: NASA].

7. Horizontal Tail

The model can be run with or without the horizontal tail. Figure 16(a) shows a close up of the horizontal tail, and Figure 16(b) is a picture of the model installed in the NTF with the horizontal tail on. There are four incidence blocks allowing the horizontal tail to be set to 0° , 4° , 8° , or 12° , but only the 0° incidence block, with the elevator set to 0° was used during this test.

Most testing was done with no horizontal tail, with a blank plate in place of the horizontal tail as seen in Figure 16(c). The horizontal tail was used for only a small portion of cryo operations because the model access housing can not go around the horizontal tail in a safe manner, therefore the tunnel needs to be fully switched over to air mode to do a model change with the tail on. Figure 16(d) shows the access housing installed around the 5.2%-scale CRM-HL semispan model, with the model cutout portion hitting the rear fuselage in the location the horizontal tail would be if it were installed on the model. There are pressures and a Kulite on the tail, but they were not hooked up for this test campaign.

8. Deformation Targets

The wing was designed with deformation targets built into two spanwise rows along the wing. The deformation targets are shallow indentations that are filled with fluorescing paint to be used by the NTF Theia system [19] to measure wing bending and twist. In previous testing, deformation targets were painted onto the surface of the model, while in the tunnel, with a fluorescent pen, however the model deformation targets were not able to be sanded down enough to take away all the height introduced by the fluorescent paint pen, creating a forward facing step on the model. Also, every time that targets had to be repainted, a new calibration needed to be done because the dots were never painted in the exact same location. Having a built in location for the targets eliminates the location shift when targets are repainted and allows the targets to be flush with the model surface instead of on top of the model surface with a step.

Figure 17(a) shows the location of the deformation targets on the wing. The five targets shown in yellow were painted on, because those locations were missed during the model build, resulting in 11 built in targets instead of the planned 16. Figure 17(b) shows pictures of the deformation targets on the wing and on the tunnel wall which were reference targets for the Theia system.



Fig. 16 Pictures of the horizontal tail installation on the NASA 5.2%-scale CRM-HL model [Photos: NASA].

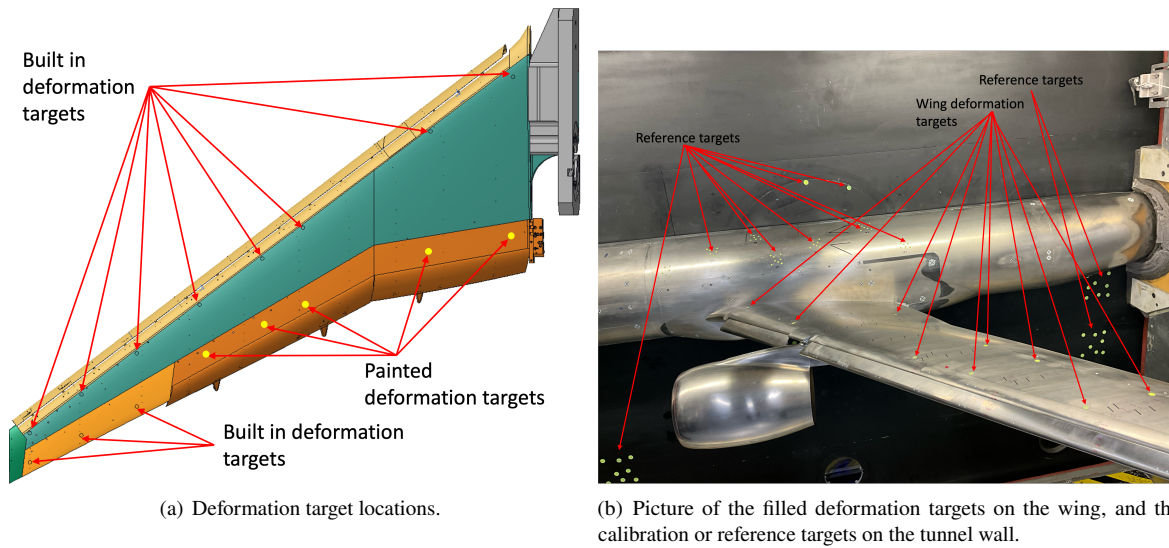


Fig. 17 Deformation target locations on the NASA CRM-HL 5.2%-scale model, used for wing bending and twist calculations [Photo: NASA].

C. Trip Dots

Trip dots, used to force transition of the flow from laminar to turbulent, were applied to the model following the ecosystem location definition. Figure 18 shows the layout of the transition strips, in red, on the NASA 5.2%-scale CRM-HL model in the NTF, the 14x22 and the NWB. The flow is expected to transition to turbulent on its own in high Reynolds number flow, so the trip dots on the wing were removed for cryogenic (high Reynolds number) runs, but were left on the nacelle and on the model nose and standoff nose.

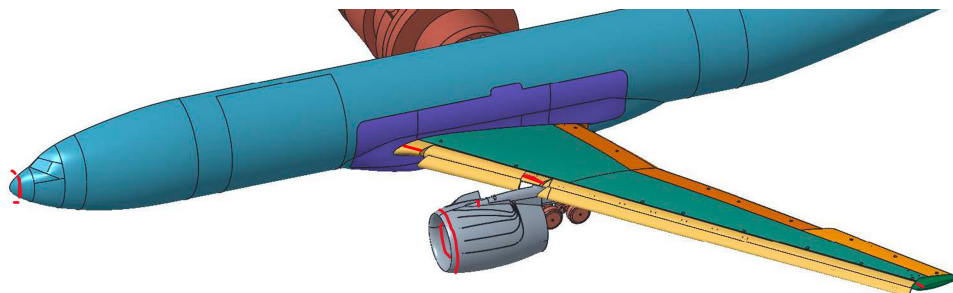


Fig. 18 Trip dot locations (bright red) on the NASA 5.2%-scale CRM-HL model in the 14x22, the NWB, and in the NTF (low RE runs).

Table 2 lists the locations on the model where trip dots were applied. Trip dot location is measured to/from the center of the trip dot [20]. Trip dots for all locations on the model were 0.005 in high (5 thou, 0.127mm), with a 0.050 in diameter (1.27mm), and a 0.10 in (2.54mm) center to center spacing.

D. Model Installation

The semispan model was mounted in the NTF tunnel on the far wall of the tunnel (right wall while facing forward toward the contraction into the flow), midway between the floor and ceiling, at tunnel station 13, which is 13 feet downstream of the start of the test section and midway up the wall, approx 43.5 inches above the top of the floor fillet. Table 3 lists the installation hardware for the semispan assembly.

Figure 19 shows the attachment assembly between the model and the balance. The balance was located outside of the model in the Sidewall Model Support System (SMSS), which was attached to the backside of the test section wall. A top hat, a model adapter and a model adapter spacer were used to attach the fuselage, using the fuselage mounting block, to the balance at the correct distance off of the tunnel wall. The wing tang, at the root of the wing, mates to the fuselage at the fuselage mounting block. The fuselage mounting block can be removed from the fuselage, whereas the wing tang is part of the wing. All of these parts were metric, meaning that the balance felt the weight of the parts. A 1" thick phenolic spacer was installed between the top hat and the balance to provide thermal insulation between the balance and the model hardware, which could get very cold during cryogenic operations. Keys were used between the top hat and model adapter, and between the model adapter and the adapter spacer to prevent the assembly from rotating. The wing tang attached the wing to the fuselage mounting block.

Figure 20 shows the attachment assembly between the model and the tunnel wall. Note that while the figure shows the NASA 2.7%-scale fuselage the assembly is the same for the NASA 5.2%-scale fuselage. A standoff or peniche is a plate that follows the contours of the semispan fuselage that abuts up to the tunnel wall, but is not part of, or attached to the model. The standoff is used to offset the model from the tunnel wall to get the model out of the wall boundary layer. The standoff is non-metric and mounts to the turntable which attaches to the balance housing (both non-metric). The turntable becomes part of the tunnel wall. There is a single model attitude drive that attaches to and controls the balance and the balance housing. This allows the balance housing, the turntable and the standoff to rotate with the balance and the model as model attitude is set and maintains a suitable fuselage to standoff alignment.

The 2 in standoff for the fuselage was used for the installation of the NASA 5.2%-scale CRM-HL model in the NTF, and a gap between the standoff and the fuselage of 0.25 in was set all around. The 2 in standoff itself is not 2 in thick, but with the 0.25 in gap the resulting distance from the wall to the fuselage is 2 in. Both the standoff and the model have tongue and groove or puzzle like lips, forming a labyrinth seal between the standoff (non-metric) and the fuselage (metric) to prevent airflow between the two while also keeping them far enough apart to prevent fouling [21]. The seal is part of the back of the fuselage, it is a slot cut into the standoff in a tongue and groove arrangement. The labyrinth seal

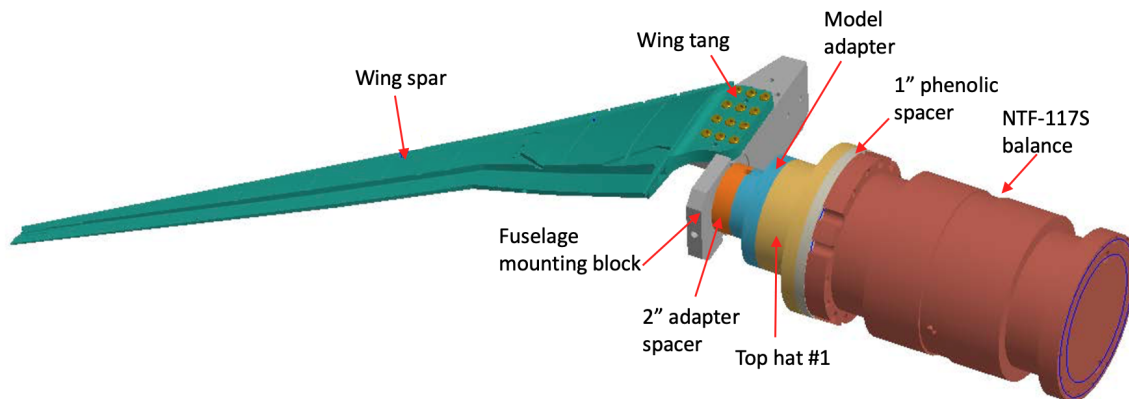


Fig. 19 NTF-117S balance attachment assembly to the 5.2%-scale CRM-HL.

Not Shown:

- Mounting Block
 - Fuselage to the balance
- Wing Tang
 - Wing to the fuselage

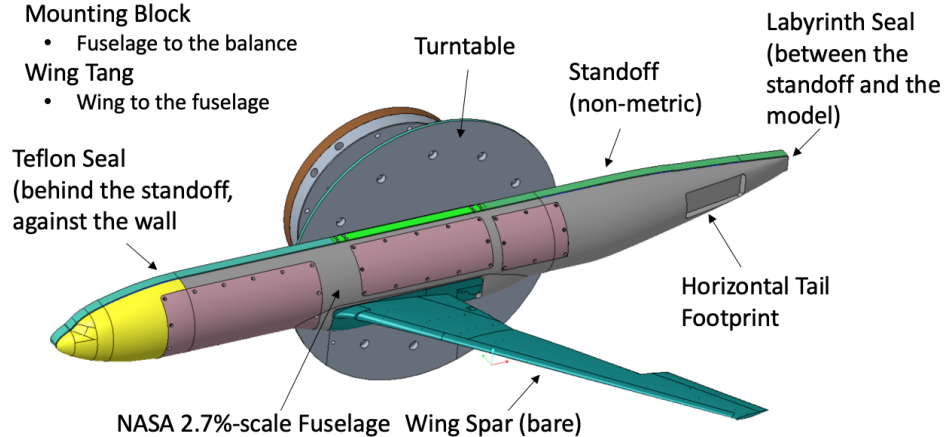


Fig. 20 Semispan attachment assembly to the tunnel.

Table 2 Trip Dot Locations.

Component		Position (in)	Note
Wing	Upper	In between slats only	
		IB 0.8 in	0.8 in from the Leading Edge of the inboard section of the wing (strake). Measured perpendicular to the leading edge
		MB 0.6 in	0.6 in from the Leading Edge of the midboard (MB) section of the wing (over nacelle). Measured perpendicular to the leading edge
		OB 0.6 in	0.6 in from the Leading Edge of the outboard section of the wing (tip). Measured perpendicular to the leading edge
	Lower	None	
Fuselage	Nose	1 in	Ring around the nose 1.0" aft of hilite, measured parallel to direction of body stations (streamwise)
Standoff	Nose	1 in	Nose of standoff 1.0 in aft of hilite, measured parallel to direction of body stations (streamwise), both upper and lower surfaces.
Nacelle	Outer	0.4 in	0.4 in aft of leading edge
	Inner	0.9 in	0.9 in aft of leading edge
Pylon	Top	0.3 in	0.3 in aft of juncture with nacelle
	Side	None	
HT	Upper		10% chord
	Lower		10% chord

Table 3 Installation Hardware.

Item	Metric
SMSS	non-metric
Balance, NTF-117S	metric
1-inch thick phenolic spacer	metric
Top Hat #1	metric
Model adapter	metric
2-inch Spacer	metric
Turntable	non-metric
Teflon Seal - behind the standoff against the wall	non-metric
Backing Plate	non-metric
Standoff or Peniche, 2 in	non-metric
Labyrinth Seal - between standoff and model	non-metric
Mounting block - fuselage to balance	metric
Wing tang - wing to fuselage	metric

was designed to have a large enough gap between the model and the standoff to not foul (the standoff is non-metric and the model is metric), but a small enough gap to restrict as much airflow as possible.

The model and the standoff hang past the turntable so a spring-loaded Teflon seal (or wall seal) is attached in a groove on the back of the standoff with Teflon clips to act as springs, to help the standoff move more smoothly against the tunnel wall to maintain a constant contact between the wall and the standoff, sealing off the back from airflow, which would cause forces on the model unrelated to what we are testing. Because the seal and the standoff are non-metric, the seal is meant to be just loose enough to allow the springs to move and keep the seal in contact with the wall.

IV. Instrumentation

Several types of instrumentation were used to obtain quantitative data during the test. Details about the types of measurements made during the test and the instrumentation that was used to obtain the data are outlined below.

A. Model Force and Moment Measurements

The NTF-117S semispan balance resides outside of the model, housed within the SMSS in a heated enclosure. The balance is a “hot balance,” meaning that it is kept warm at a constant temperature, between $95^{\circ}F$ and $100^{\circ}F$, no matter the temperature of the test section or the model. The NTF-117S was last calibrated on 06/30/2009. The calibration load and the quoted 95% confidence balance accuracy (BA) of each component, obtained from the balance calibration report, are below in Table 4. Because of the nature of a semispan model there is no side-force gauge, so there are only five balance components.

Table 4 NTF-117S Balance Design Loads and Accuracy.

Component	Full Scale (Calibration)	% Full Scale Accuracy (95% conf)	Effective Balance Accuracy (BA)
Axial Force (AF)	$\pm 1,800$ lb	0.14	2.25 lb
Side Force (SF)	-	-	-
Normal Force (NF)	$\pm 12,000$ lb	0.05	6 lb
Rolling Moment (RM)	$\pm 669,000$ in-lbf	0.12	802.8 in-lbf
Pitching Moment (PM)	$\pm 90,000$ in-lbf	0.16	144 in-lbf
Yawing Moment (YM)	$\pm 100,350$ in-lbf	0.09	90.3 in-lbf

1. 95% Balance Coefficient Accuracy

The equations to compute the balance accuracies are provided in Equations 2 to 3. Table 5 presents the balance force and moment coefficient accuracies at each Q that were run during the test. These accuracies are based on a reference area (S_{REF}) of 5.58 ft^2 , a reference span (b_{REF}) of 60.15 in. , a reference chord (C_{REF}) of 14.34 in. , and the 95% balance accuracy (BA), shown in Table 4. Note that the force and moment coefficient balance accuracies are presented in the body/model axis system, where the body axis coefficients are Axial Force Coefficient, C_A , Normal Force Coefficient, C_N , Rolling Moment Coefficient, C_{LL} , Pitching Moment Coefficient, C_{LM} , and Yawing Moment Coefficient, C_{LN} .

$$\text{BalanceAccuracy}_{\text{AxialForceCoeff}} = BA_{C_A} = \frac{BA_{AF}}{Q * S_{REF}} \quad (1)$$

$$\text{BalanceAccuracy}_{\text{NormalForceCoeff}} = BA_{C_N} = \frac{BA_{NF}}{Q * S_{REF}} \quad (2)$$

$$\text{BalanceAccuracy}_{\text{RollingMomentCoeff}} = BA_{C_{LL}} = \frac{BA_{RM}}{Q * S_{REF} * b_{REF}} \quad (3)$$

$$\text{BalanceAccuracy}_{\text{PitchingMomentCoeff}} = BA_{C_{LM}} = \frac{BA_{PM}}{Q * S_{REF} * C_{REF}} \quad (4)$$

$$\text{BalanceAccuracyYawingMomentCoeff} = BA_{CLN} = \frac{BA_{YM}}{Q * S_{REF} * b_{REF}} \quad (5)$$

Table 5 NTF-117S 95% Balance Accuracy of the Force and Moment Coefficients in the Model Axis.

Q PSF	BA_{CA}	BA_{CN}	BA_{CLL}	BA_{CLM}	BA_{CLN}
61	0.0074	0.0176	0.0392	0.0295	0.0044
82	0.0055	0.0131	0.0292	0.0219	0.0033
101	0.0045	0.0106	0.0237	0.0178	0.0027
133	0.0034	0.0081	0.0180	0.0135	0.0020
134	0.0034	0.0080	0.0178	0.0134	0.0020
138	0.0033	0.0078	0.0173	0.0130	0.0019
149	0.0030	0.0072	0.0161	0.0121	0.0018
157	0.0029	0.0068	0.0152	0.0115	0.0017
202	0.0022	0.0053	0.0118	0.0089	0.0013
207	0.0022	0.0052	0.0116	0.0087	0.0013
210	0.0022	0.0051	0.0114	0.0086	0.0013
232	0.0019	0.0046	0.0103	0.0078	0.0012
240	0.0019	0.0045	0.0100	0.0075	0.0011
264	0.0017	0.0041	0.0091	0.0068	0.0010
268	0.0017	0.0040	0.0089	0.0067	0.0010
288	0.0016	0.0037	0.0083	0.0062	0.0009
295	0.0015	0.0036	0.0081	0.0061	0.0009
376	0.0012	0.0029	0.0064	0.0048	0.0007

B. Model Angle of Attack

Model angle of attack was measured using an Angle of Attack (AoA) package installed in the aft of the fuselage shown during model build up in the NTF model preparation area (MPA) in Figure 21. The accuracy of the AoA is quoted at $\pm 0.002^\circ$ [22].

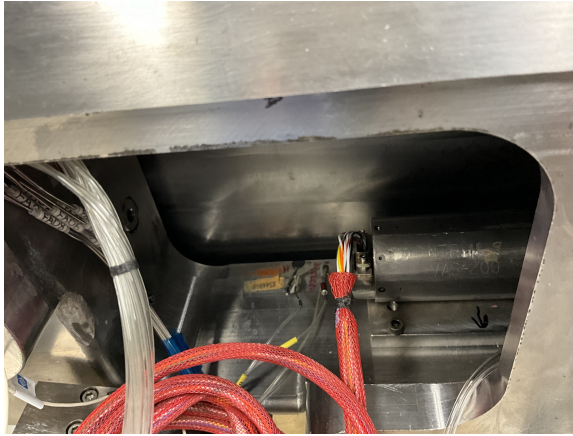
C. Wing Static Pressure Measurements

Electronically Scanned Pressure (ESP) sensors were used to measure the static pressures on the model. There are a maximum number of 309 total ports on the wing, and sometimes fewer, depending upon the configuration. The pressure taps on the wing were pared down from the locations defined by the CRM-HL ecosystem, distributed between 10 wing chord stations and the nacelle. Figure 22 shows a visual of where the pressure port stations are on the wing. Note there is a "kink" in the pressure stations at the quarter chord of the wing. The pressure ports are perpendicular to the highlight of the leading edge and angled to the streamwise direction ahead of the 25% local wing chord.

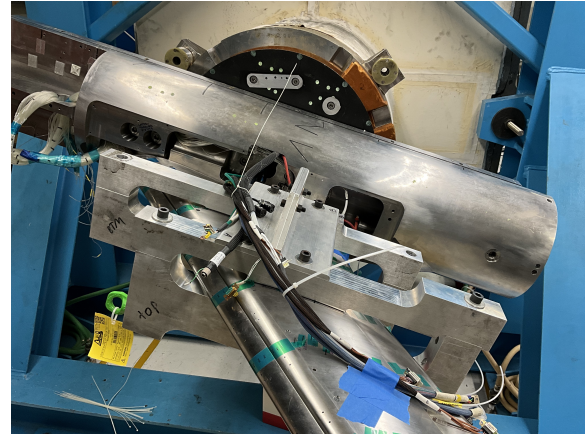
The wing static pressure measurements were distributed between one 5 psia ESP module, one 15 psia ESP module, one 30 psia ESP module, and two 45 psia ESP modules. The model ESPs were installed in the forward part of the semispan fuselage distributed in two heater boxes, shown in Figure 23. All of the pressure tubing from the wing was run to the modules and data cables were run from the ESPs out the heater boxes, through the SMSS instrumentation pass through to the data system.

D. Fouling Circuits

Fouling strips were installed on the standoff side of the labyrinth seal, in the 4 locations the fuselage was most likely to foul against the standoff shown in Figure 24. Fouling occurs when a metric (measured by the balance) part comes in contact with something that is not metric (not measured by the balance), causing forces to be transferred from the metric



(a) AoA Installed in the Fuselage



(b) Fuselage Installed on the SMSS in the MPA With the AoA Installed in the Rear Fuselage Access

Fig. 21 Model AoA package [Photos: NASA].

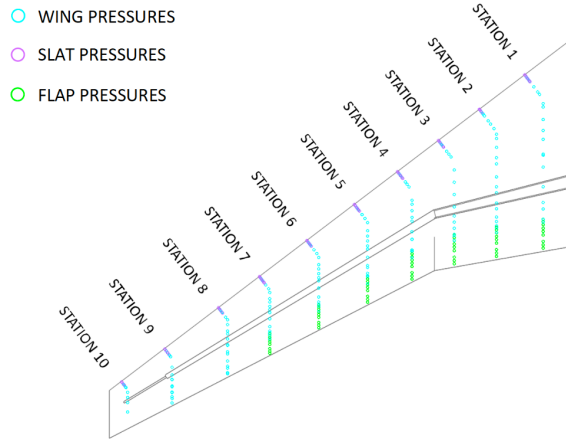


Fig. 22 Pressure Port Stations on the Wing.

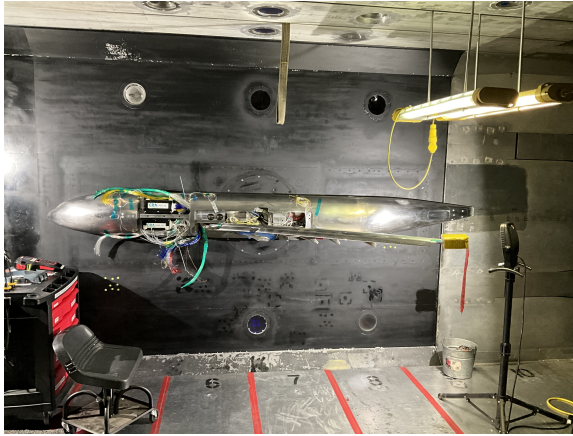
part to the non-metric part, or the forces from the non-metric part to be transferred to the metric part, resulting in the balance not accurately capturing the actual loads on the model. The fouling circuits cause an alarm to sound in the control room and a flag to appear in the data file if the model was to foul against the standoff. Any data taken during model fouling would have been labeled bad, but no fouling was detected during testing.

V. Data Acquisition and Processing

All data acquisition and processing was performed using standard NTF processes. Classical wall corrections [23] were applied to the data. Tunnel calibration to Mach number, buoyancy correction to drag, and thermal expansion corrections were applied to the final reduced data. Flow angularity corrections were not applied since the model did not lend itself to doing flow angularity measurements. No type of base pressure correction was applied to the data.

A. Facility Parameter Tolerances

Table 6 lists facility parameter tolerances used during testing for taking data. Note that these are set point tolerances, not accuracy of the reading. The NTF automated test taking system was used to set the tunnel conditions and the model angle of attack, and to assure that data were taking with all parameters within the set tolerances. Tolerances can be set tighter, however that can increase time per point. The tunnel parameters needed to be inside of the in-limit tolerance for

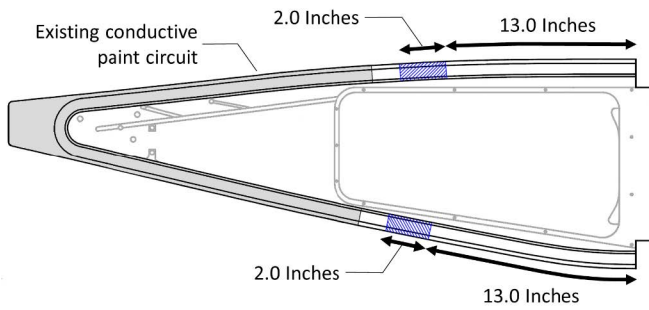


(a) Zoomed out view of the ESP heater boxes mid-installation.

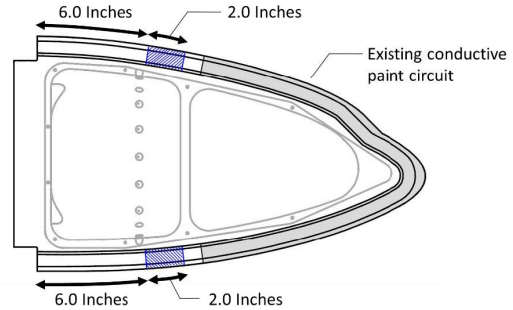


(b) Close up view of the ESP heater boxes in the fuselage, mid-installation.

Fig. 23 ESP heater boxes during installation in the NASA 5.2%-scale CRM-HL model [Photos: NASA].



(a) Aft standoff fouling strip placement.



(b) Forward standoff fouling strip placement.

Fig. 24 Fouling strip placement on the standoff.

the on-point timer to be started. If the parameter went outside of the out-of-limit tolerance, the timer would reset and the system would continue to wait until the tunnel was on condition. In general, data were not taken when the tunnel conditions were outside of these tolerance ranges. If achieving a condition became too time consuming a data point could be taken manually, at the test engineer's discretion, with the tunnel conditions outside of the selected tolerances. This was rarely done.

Table 6 Tolerances for Facility Parameters.

Parameter	In-Limit Tolerance	Out-of-Limit Tolerance	On-Point Timer
Mach Number	± 0.0010	± 0.0015	1.0 seconds
Total Pressure	± 0.03 psi	± 0.04 psi	1.0 seconds
Total Temperature	$\pm 2.0^{\circ}F$	$\pm 2.5^{\circ}F$	1.0 seconds
Model Angle of Attack	$\pm 0.09^{\circ}$	$\pm 0.10^{\circ}$	0.1 seconds

B. Data Acquisition Rates

Table 7 lists the rates and times used for collecting data during testing for the Data Acquisition System (DAS).

Table 7 Data Acquisition Rates.

Acquisition	Rate/Time
Acquisition Rate	40 Hz
Acquisition Time	4 sec
Filter Frequency	1 Hz
ESP Scan Rate	10 Hz

C. Axis System

The data presented within this paper are in the stability axis system, namely drag coefficient (C_D), lift coefficient (C_L), and pitching moment coefficient (C_m). Equations 7 to 8 show how the data are transferred to the stability axis from the model body axis by the angle of attack angle, α . Figure 25 shows a visual representation of the model to stability axis transformation.

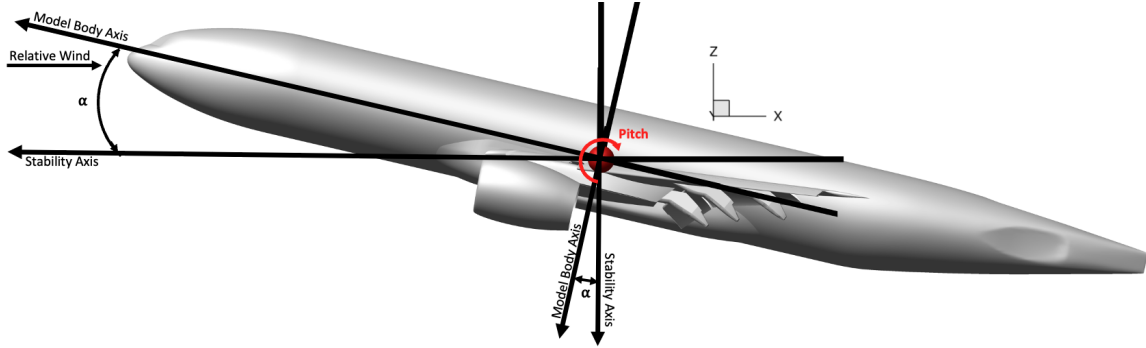
$$\text{Drag Coefficient} = C_D = C_A * \cos(\alpha) + C_N * \sin(\alpha) \quad (6)$$

$$\text{Lift Coefficient} = C_L = C_N * \cos(\alpha) - C_A * \sin(\alpha) \quad (7)$$

$$\text{Rolling Moment Coefficient Stability Axis} = C_{LLS} = C_{LL} * \cos(\alpha) + C_{LN} * \sin(\alpha) \quad (8)$$

$$\text{Pitching Moment Coefficient Stability Axis} = C_m = C_{LM} \quad (9)$$

$$\text{Yawing Moment Coefficient Stability Axis} = C_{LNS} = C_{LN} * \cos(\alpha) - C_{LL} * \sin(\alpha) \quad (10)$$

**Fig. 25 Axis system.**

VI. Test Results and Discussion

This section is not meant to be a comprehensive analysis of the data, but to provide an overview of the test data. The scope of this paper is a documentation of the test, and not an examination of the data, as data analysis are presented in other papers. A more in depth analysis of the Reynolds number effects in this test is available in Langston et al [24]. An analysis of the pressure data from this test is available in Langston et al [25]. An analysis of select model configuration trends from the test of this same model in the 14x22 can be found in Winski et al [8]. Analysis of the data from this model being tested at the NWB tunnel is available in Puelm et al. [9] and [10]. Force and moment are presented in the stability axis.

A. Repeatability

Repeat runs were conducted throughout testing to provide confidence in the model, the instrumentation, and in the data set. Two sets or repeat plots are provided herein, both run on the baseline landing configuration, Landing - Nacelle On, one set run in air operations at Re_C 3.33 million, and one set of repeats all run in cryogenic operations at Re_C 30 million.

Figure 26 plots for three runs with the model in the Landing - Nacelle On configuration run in air mode at Mach 0.20, Re_C 3.33 million, and Q 133 PSF. These plots include C_L , C_D , and C_m as a function of alpha; a drag polar is also depicted. Error bars on the force and moment plots show the 95% balance accuracy from Table 5. Runs 37 (blue) and 38 (red) were run one after the other for short term repeatability. Run 66 (orange) was run more than 7 weeks later after 4 separate model changes had occurred, providing long term repeatability comparison data. Run 38 was a reduced alpha polar with fewer points taken than the alpha polars for runs 37 and 66, this reduced resolution can most clearly be seen in the drag polar plot (bottom left) in the lower C_D , lower C_L range, where the red line misses a portion of the curve. The repeatability is well within the balance accuracy for short term and long term repeat runs. $C_{L_{max}}$ was between 2.357 and 2.365 for the three runs, occurring between 17° and 17.5° alpha. It can be hard to pinpoint $C_{L_{max}}$ when taking discrete data points at 0.5° increments near $C_{L_{max}}$, but the data still do repeat well.

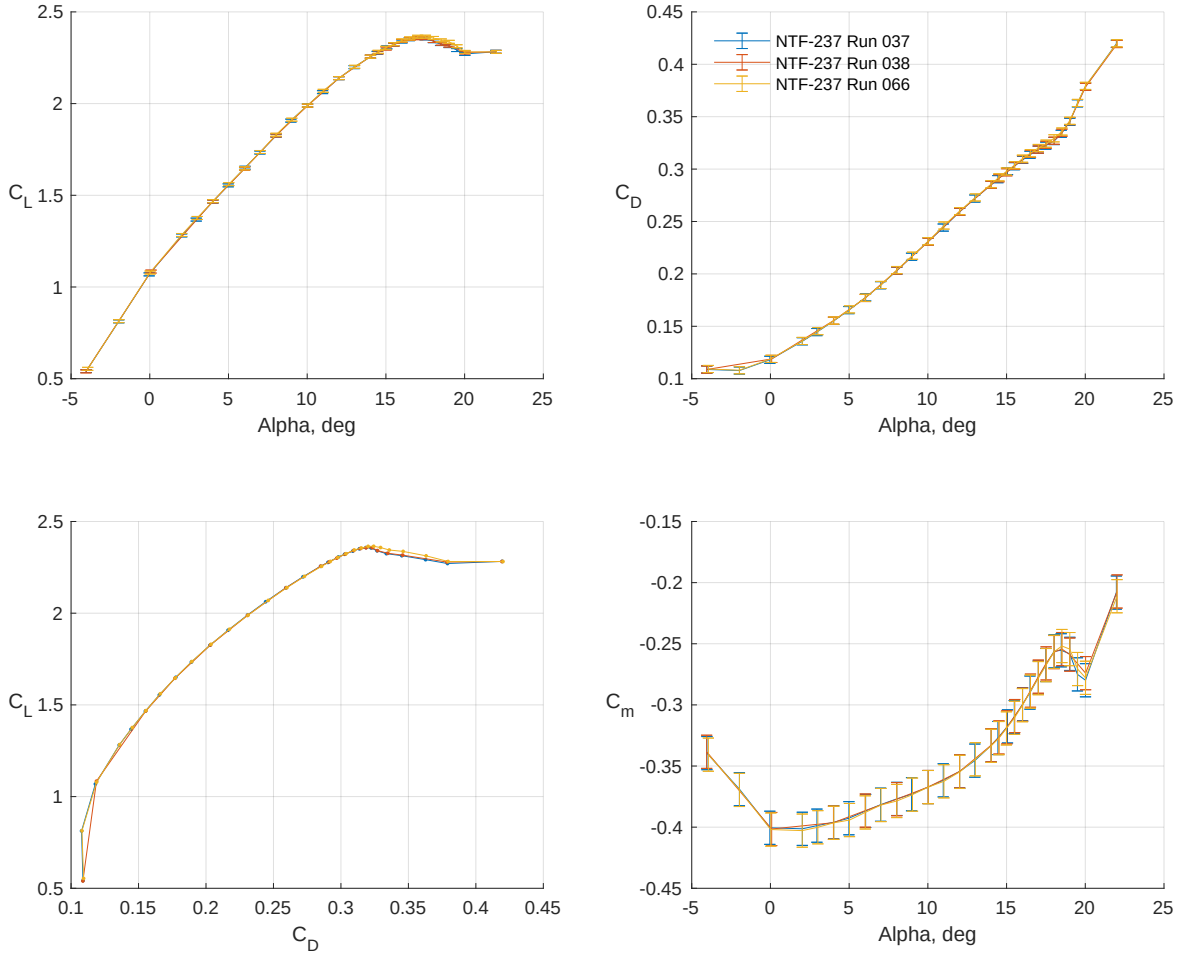


Fig. 26 Force and moment repeat plots for the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20, Re_C 3.33 million, with bars representing the 95% balance accuracy.

Example residual calculations are shown in Equations 11 to 13, where i is for an individual run, and n is the number of runs being averaged. Plotting the residuals gives a visual representation of the repeatability of the data, showing each point's deviation from the average of all the points at a specific condition. Figure 27 is a plot of the C_L , C_D , and C_m residuals for the same runs shown in Figure 26, with the 95% balance accuracy shown in green. At the lower angles of attack the drag coefficient from run 38 trends slightly off from runs 37 and 66. The lift coefficient is more scattered at alphas post stall, which is normal and expected due to the more dynamic flow physics seen post stall.

$$\text{Lift Coefficient Residual} = \Delta C_{L_i} = C_{L_i} - \frac{\sum C_{L_{1:n}}}{n} \quad (11)$$

$$\text{Drag Coefficient Residual} = \Delta C_{D_i} = C_{D_i} - \frac{\Sigma C_{D_{1:n}}}{n} \quad (12)$$

$$\text{Pitching Moment Coefficient Residual} = \Delta C_{m_i} = C_{m_i} - \frac{\Sigma C_{m_{1:n}}}{n} \quad (13)$$

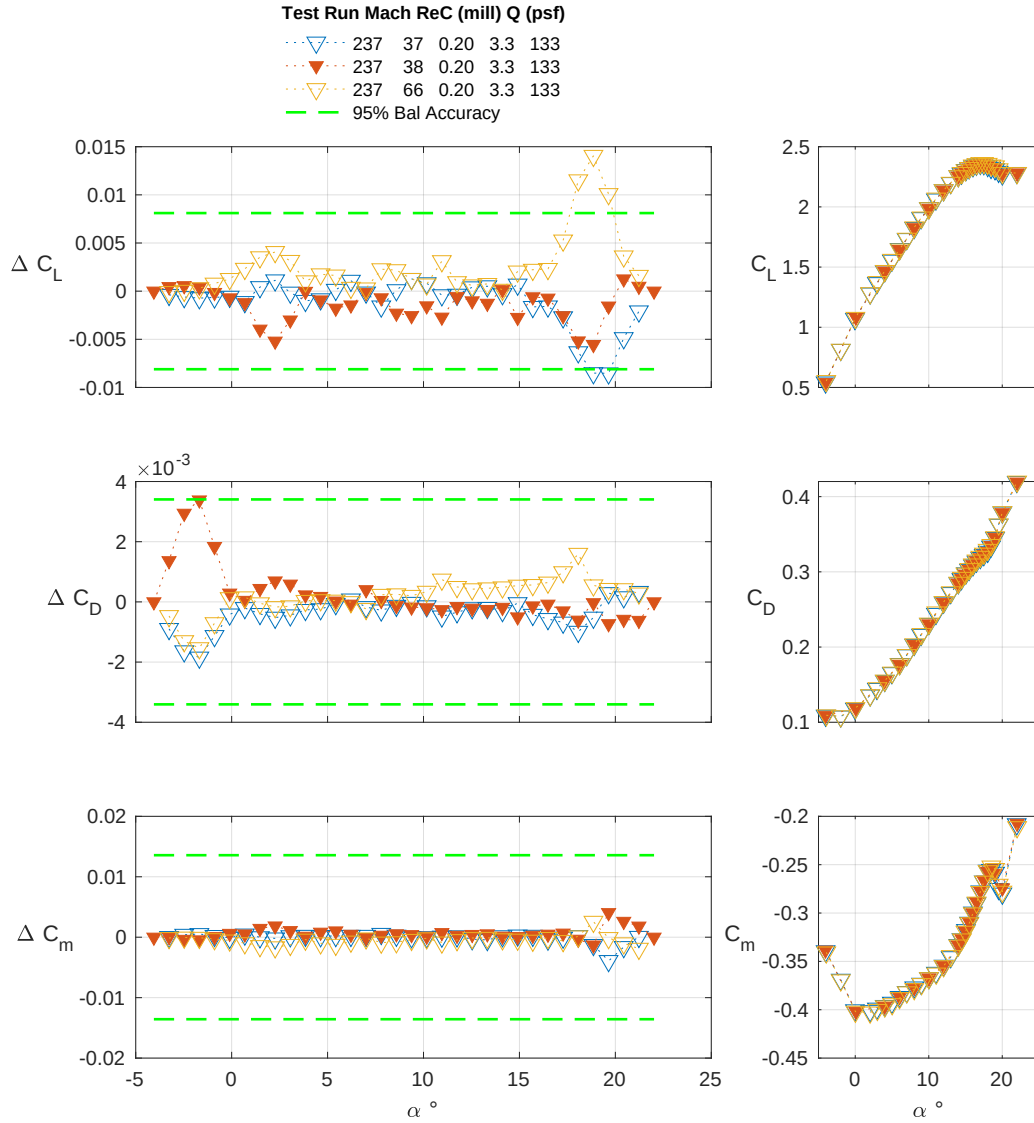


Fig. 27 Force and moment residual plots for repeat runs of the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20, Re_C 3.33 million.

Figures 28 and 29 are the same parameters as Figures 26 and 27, but run in cryogenic operations at a tunnel temperature of -250°F to achieve a Re_C of 30 million. Figure 28 plots for three runs with the model in the Landing - Nacelle On configuration run in nitrogen (N_2) at Mach 0.20, Re_C 30 million, and Q 294 PSF. These plots include C_L , C_D , and C_m as a function of alpha; a drag polar is also depicted. Error bars on the force and moment plots show the

95% balance accuracy from Table 5. Runs 96 and 99 are considered short term repeats, as they were run on the same day with no model changes occurring between the runs, but there were two tunnel condition changes between the runs. Run 99 (red) was a reduced alpha polar with fewer points taken than the alpha polar for runs 96 (blue), this reduced resolution can most clearly be seen in the drag polar plot (bottom left) in the lower C_D , lower C_L range, where the red line misses a portion of the drag polar curve. C_L and C_D trend very closely together, while C_m trends similarly between the runs, but there is more variability seen between the runs. $C_{L_{max}}$ was 2.43 for both runs, occurring at 17.5° and 18° alpha respectively.

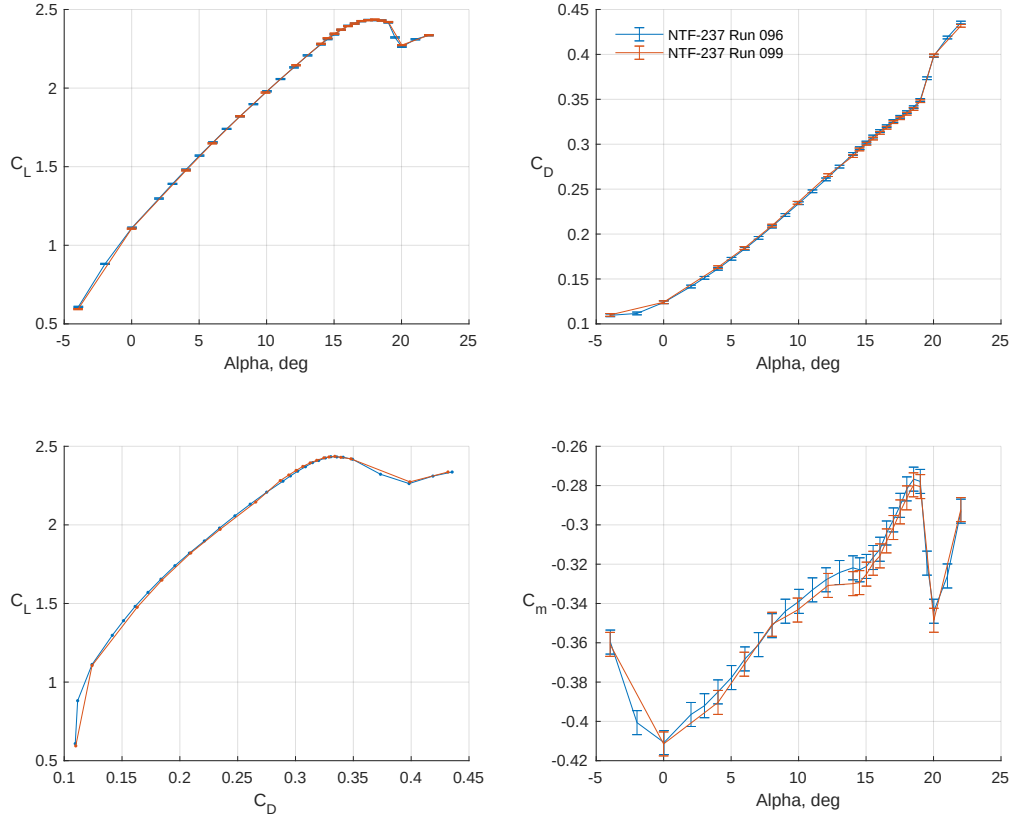


Fig. 28 Force and moment repeat plots for the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20, Re_C 30 million, with bars representing the 95% balance accuracy.

Figure 29 is a plot of the residuals for the same runs shown in Figure 28, with the 95% balance accuracy shown in green. C_L , C_D and C_m have some divergence at negative angles of attack, with a few points falling outside of the 95% balance accuracy. Both C_L and C_D have a single residual point that falls outside of the 95% balance accuracy post stall, which is not unexpected because of the more dynamic flow physics seen post stall.

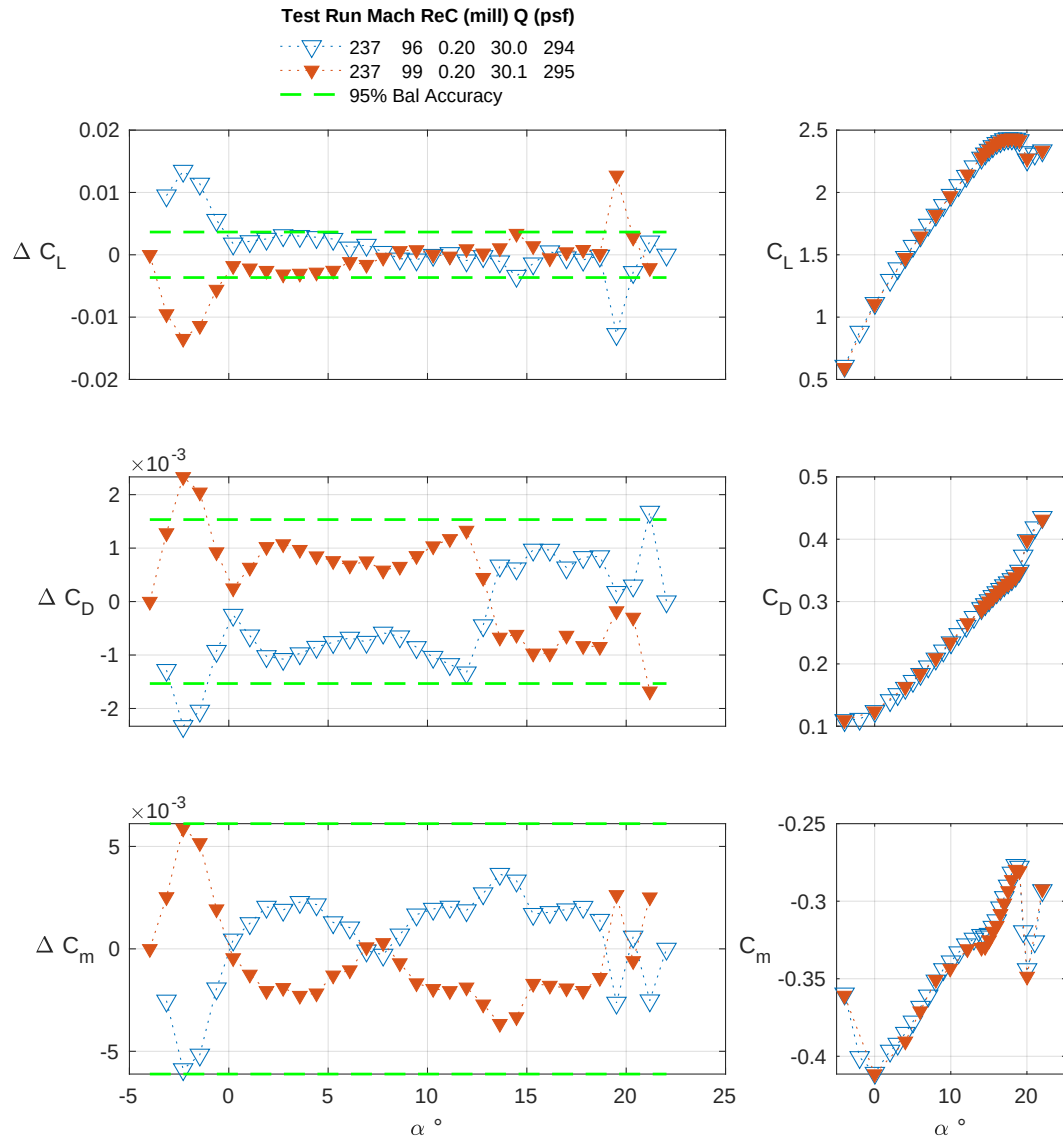


Fig. 29 Force and moment residual plots for repeat runs of the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20, Re_C 30 million.

B. Tunnel Conditions

As noted in Section V.A, data are taken when the tunnel conditions are within a certain tolerance of the set condition, listed in Table 6, to increase data quality. Figures 30 and 31 show plots of the tunnel Mach and tunnel total temperature (T_T) for the repeat runs plotted in Figures 26, at Re_C 3.33 million, and 28, Re_C 30 million, respectively. It can be seen that while a few data points were taken with the tunnel conditions slightly outside of the in-limit tolerance noted in Table 6, both Mach and temperature were held relatively constant during data taking.

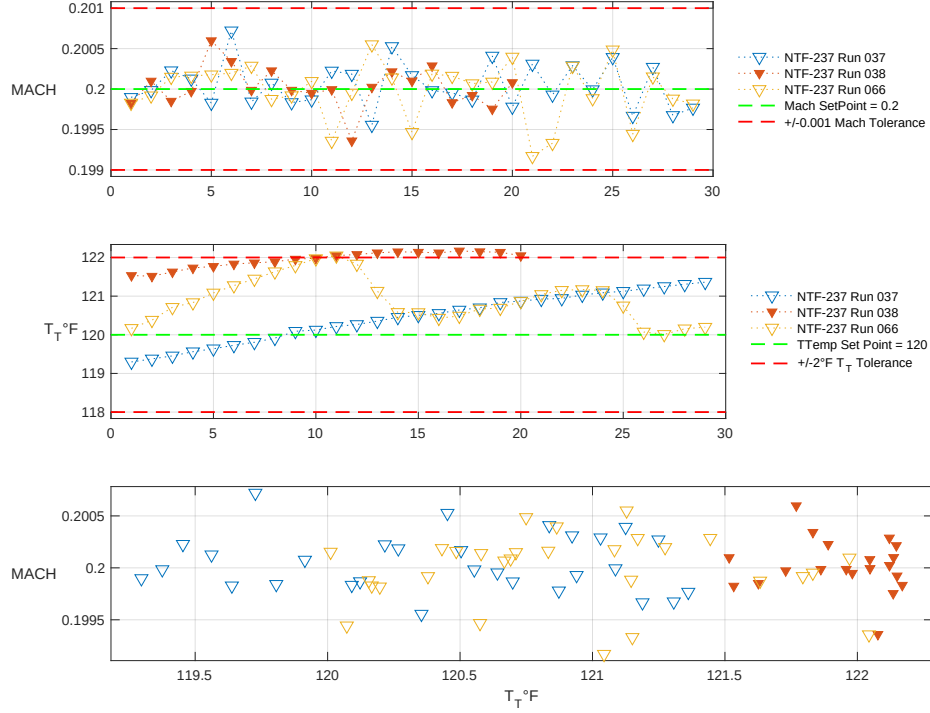


Fig. 30 Tunnel condition repeat plots for the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20, Re_C 3.33 million.

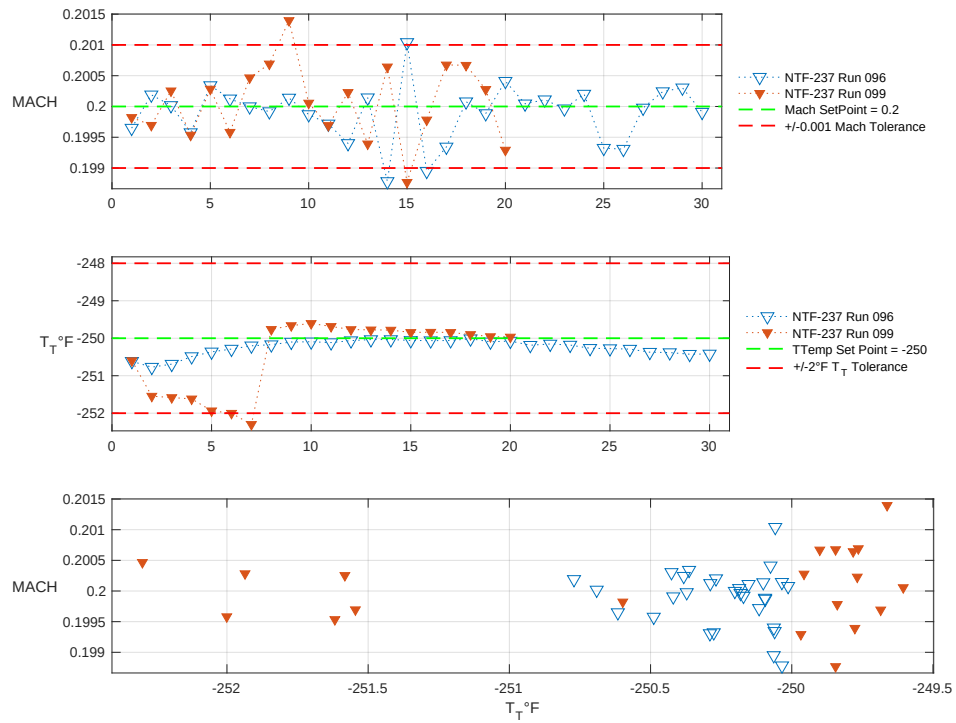


Fig. 31 Tunnel condition repeat plots for the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20, Re_C 30 mill.

C. Reynolds Number Trends

Collecting high Reynolds number data on the ecosystem CRM-HL was the main focus of this test. While a more in depth look into the Reynolds number effects is discussed in Langston et al. [24], a short overview is worthy of discussion in this paper. Figure 32 is a log plot of $C_{L_{max}}$ for the model in the baseline landing configuration, Landing - Nacelle On, at Re_C between 1.6 million and 30 million. Error bars on the $C_{L_{max}}$ values show the 95% balance accuracy from Table 5. $C_{L_{max}}$ increases as Re_C increases, as expected. $C_{L_{max}}$ level out (reduced slope) more quickly at the lower Reynolds numbers, and begins to even out at the higher Reynolds numbers. Runs at Re_C of 5.49 million and 16 million have $C_{L_{max}}$ plotted for runs at different Qs. For both Q comparison sets the run at the higher Q had the higher $C_{L_{max}}$, though the variation was within the 95% balance accuracy. Note that Q affects the calculation for balance accuracy in terms of the coefficients, so runs at the same Reynolds number, but at different Qs will have different quoted 95% balance accuracy.

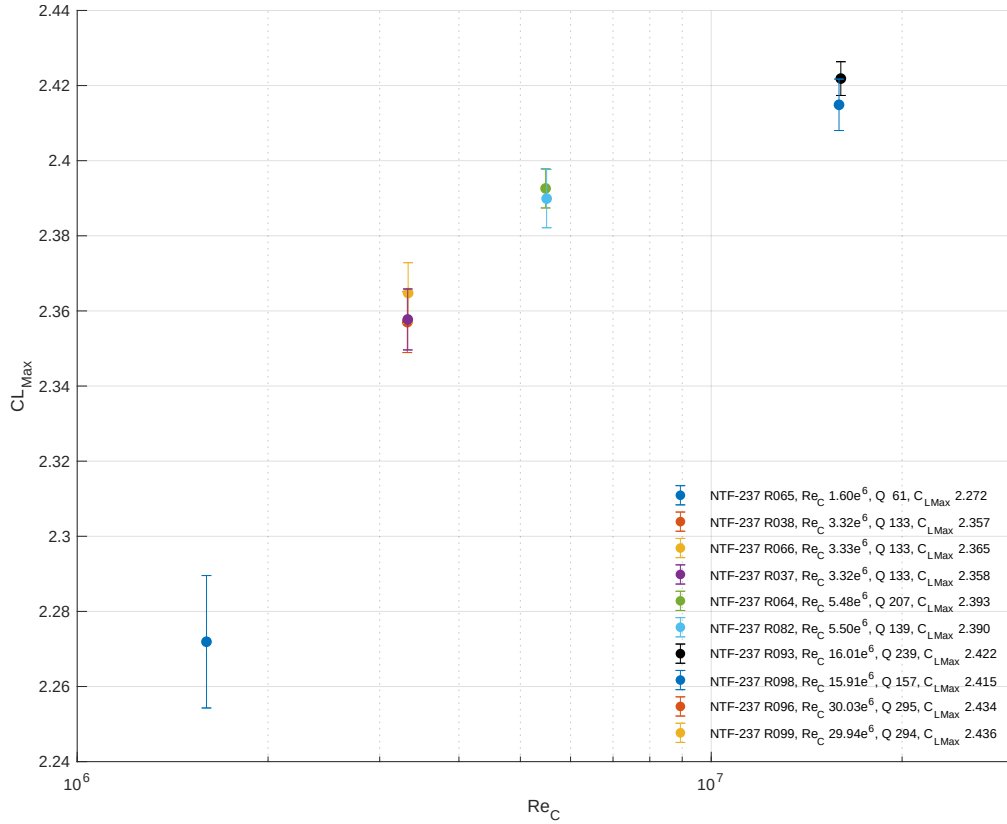


Fig. 32 $C_{L_{max}}$ vs. Re_C for the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20 at varying Re_C 's in the NTF.

Figure 33 shows plots for a select set of runs plotted in Figure 32 with the model in the Landing - Nacelle On configuration run at Mach 0.20, at Re_C 's between 1.6 million and 30 million. These plots include C_L , C_D , and C_m as a function of alpha; a drag polar is also depicted. $C_{L_{max}}$ increases as Re_C increases, as expected. Table 8 lists the $C_{L_{max}}$ for each run shown in Figures 32 and 33 as well as the run conditions and the alpha at which $C_{L_{max}}$ occurred, $alpha_{C_{L_{max}}}$.

D. Taping Runs, Leak Path Check

During the NTF test a set of five runs were done, each with an increasing amount of tape on the wing, on both the lower and upper surface. Areas of the wing that were carefully taped or filled included all cover plates, the spoiler to spar seam, the strake to wing seam at the leading edge, the WUSS insert, the wing to fuselage junction, and the flap to fuselage junction. Of note is that the cavities in the wing were filled with instrumentation and epoxy, which would also block any airflow if there were open seams, and most joints on the model were lap joints which greatly reduce the

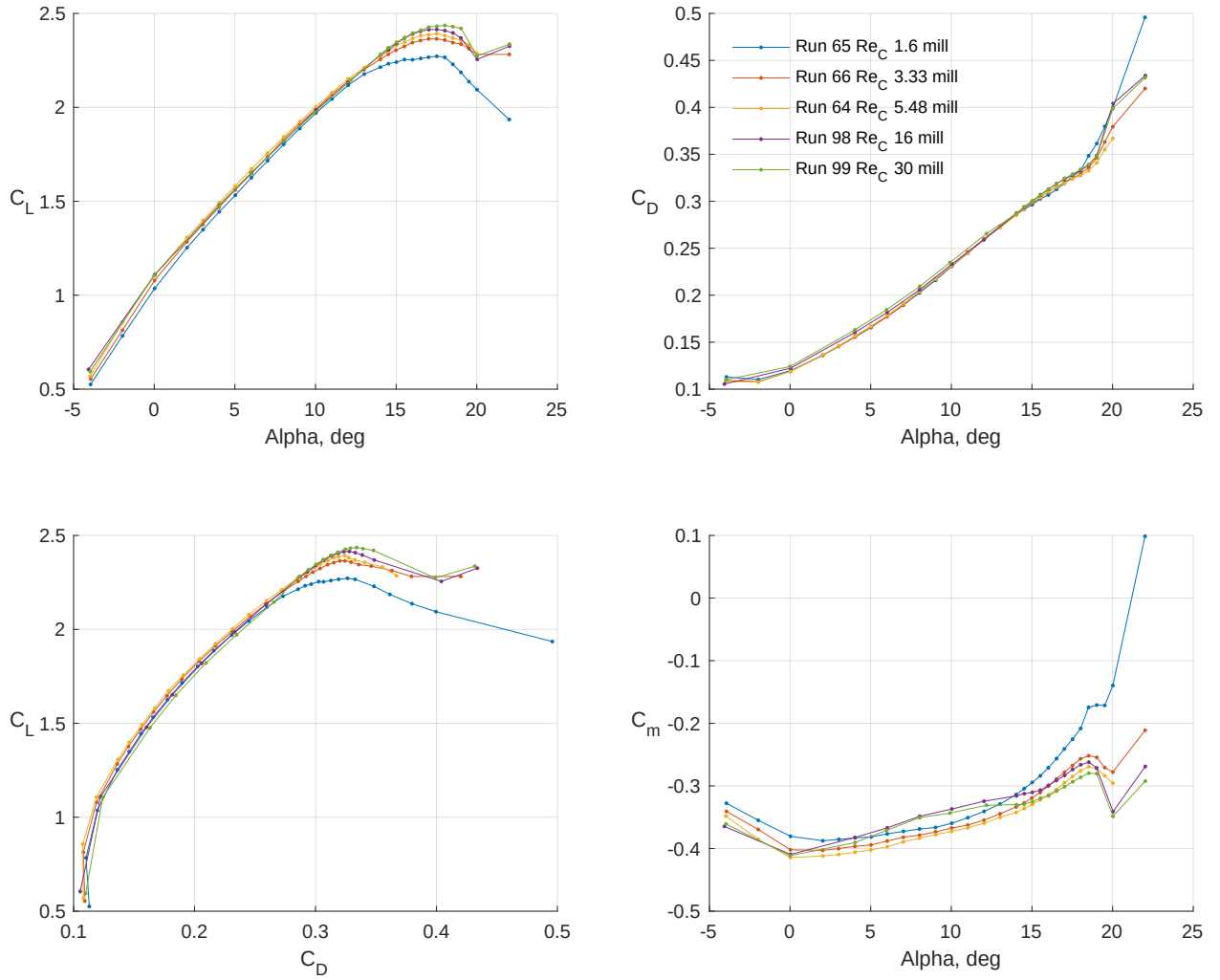


Fig. 33 Force and moment plots for the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configuration, Mach 0.20 at varying Re_C 's in the NTE.

Table 8 $C_{L_{max}}$ for the NASA 5.2%-scale CRM-HL Model, Landing - Nacelle On configuration, Mach 0.20 for the Re_C Variation Plots, Figures 32 and 33.

Test	Run	Re_C (10^6)	Q (PSF)	$\alpha_{C_{L_{max}}}$	$C_{L_{max}}$
237	65	1.60	61	17.5°	2.272
237	38	3.33	133	17.5°	2.357
237	66	3.33	133	17.5°	2.365
237	37	3.33	133	17.0°	2.358
237	64	5.49	207	17.5°	2.393
237	82	5.49	138	17.0°	2.390
237	93	16	239	17.5°	2.422
237	98	16	157	17.5°	2.415
237	96	30	294	17.5°	2.434
237	99	30	295	18.0°	2.436

chance of air flowing through the joints. All seams were taped for the final taping run. Figure 34 shows pictures of the upper and lower surface of the wing with tape (silver tape) over all of the seams for the leak path check runs.

Figure 35 is a plot of C_L for the wing taped runs versus a clean wing (blue). Table 9 lists the taping scheme for each of the runs plotted in the figure. No increase in lift or $C_{L_{max}}$ was seen with the wing taped on all seams (green) vs. the clean wing (blue). $C_{L_{max}}$ ranged from 2.390 (Run 156) to 2.395 (Run 157) for the five runs, with the clean wing $C_{L_{max}}$ of 2.393 (Run 64) and the fully taped wing $C_{L_{max}}$ of 2.392 (Run 158). From this study, the team concluded that there are no significant leak paths on the NASA 5.2%-scale CRM-HL wing.

Table 9 Model Taping Scheme for Runs in Figure 35.

Legend Label	Data Color	Taping Scheme
Clean Wing	Blue	No tape
Taped Wing Scheme 1	Red	Taped over eight cover plates on the trailing edge on the underside of the wing
Taped Wing Scheme 2	Yellow	Above tape plus Tape over the WUSS to wing junction on the underside of the wing Tape around the flow visualization plug blank on the under side of the wing
Taped Wing Scheme 3	Purple	Above tape plus Taped any previously un-taped seams on the underside of the wing Added filler all the way around the wing-to-fuselage intersection
All Wing Seams Taped	Green	Above tape plus Taped all seams on the upper surface of the wing

E. Wing Bending and Twist

The CRM-HL baseline OML was designed to match the OML of an airplane in loading from flight, not while it is sitting on the ground. While wind tunnel models are relatively stiff compared to a full-scale airplane, they do still bend and twist slightly while under load during testing. This deformation of the wing changes the wing OML, which changes the wing loading and may cause significant deviations in the results. The Theia system at NTF [19] was used throughout testing to measure wing bending and wing twist using deformation targets on the wing, shown in Figure 17.

The wing bending and wing twist were calculated along the span of the wing on the elastic axis. The elastic axis is defined as the spanwise line on the wing where loading would produce only bending of the wing, no twist, and it is the axis on the wing about which the wing twists. A line was drawn between each of the 8 leading-edge and trailing edge deformation target pairs and the deformations calculations are applied at the intersection of each of these 8 lines with



Fig. 34 Taping of the wing for leak path checks [Photos: NASA].

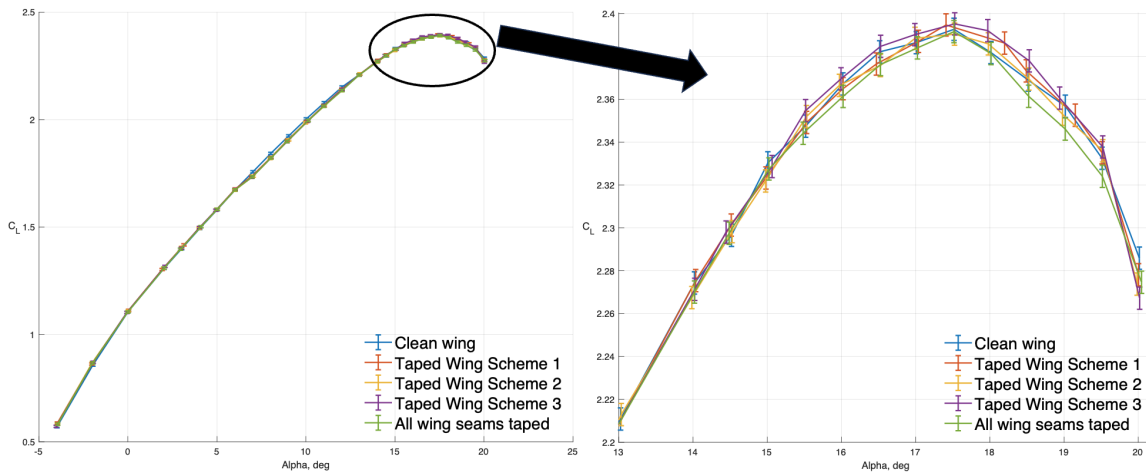


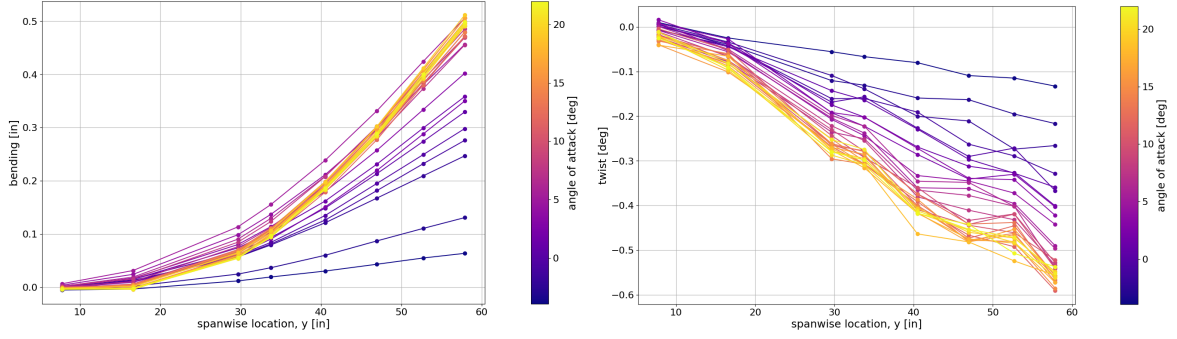
Fig. 35 NASA 5.2%-scale CRM-HL, Landing - Nacelle On, Mach 0.20, Re_C 5.5 million. C_L vs. alpha plot of the NASA CRM-HL model clean wing vs. taped wing.

the elastic axis.

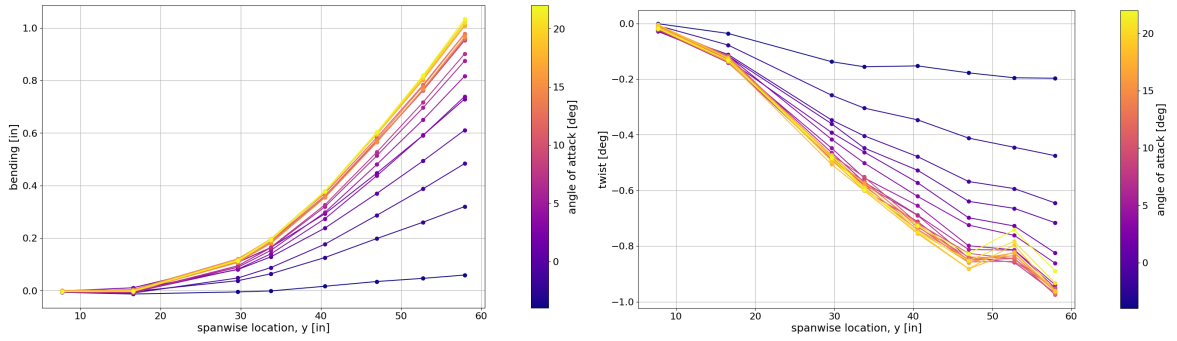
Figure 36 shows representative Theia results for two runs of the NASA 5.2%-scale CRM-HL model during testing in the NTF. These data are for the model in the Landing - Nacelle On configuration, at Mach 0.20. The X-axis is the spanwise location of the elastic axis on the wing, starting inboard moving outboard where the wing bending and wing twist were calculated. Figures 36(a) and 36(b) are the wing bending and wing twist from run 82 at Re_C 5.49 million. The maximum bending recorded for this run was 0.51 inches near the tip of the wing at alpha 19.5°, the maximum twist for this run was -0.59° near the tip of the wing at alpha 15°. Figures 36(c) and 36(d) are the wing bending and wing twist from run 99 at Re_C 30 million. The maximum bending recorded for this run was 1.03 inches near the tip of the wing at alpha 22°, the maximum twist for this run was -0.97° near the tip of the wing at alpha 15°.

The maximum recorded wing bending during testing was a 1.11 inch deflection near the wing tip with the model in

the clean landing configuration, Landing - Nacelle Off, at alpha 18.5°, Mach 0.20, Re_C 30 million, and Q 295 PSF. The maximum recorded wing twist during testing was -1.07° in incidence near the tip of the wing at alpha 16° during the same run on which the maximum wing bending was recorded. As expected, both wing bending and wing twist increased, moving from inboard to outboard over the span of the wing, and both also increased as Q increased. Wing bending tended to increase from the lowest alphas to slightly past C_{Lmax} , before slightly decreasing. Wing twist tended to increase (in the negative direction) from lower alphas to alpha angles slightly below C_{Lmax} , before slightly decreasing.



(a) NTF Test 237 Run 82, Re_C 5.49 million, wing bending measurement. (b) NTF Test 237 Run 82, Re_C 5.49 million, wing twist measurement.



(c) NTF Test 237 Run 99, Re_C 30 million, wing bending measurement. (d) NTF Test 237 Run 99, Re_C 30 million, wing twist measurement.

Fig. 36 Theia wing bending and wing twist measurements on the NASA 5.2%-scale CRM-HL model, Landing - Nacelle On configurations, Mach 0.20.

VII. Concluding Remarks

A wind tunnel test of the NASA 5.2%-scale CRM-HL model was conducted in the NASA Langley National Transonic Facility wind tunnel. This test acquired valuable high Reynolds number data for the CRM-HL ecosystem. The NASA 5.2%-scale CRM-HL model was built and designed to match the CRM-HL ecosystem reference geometry. The model was tested in eight different configurations, including four landing, two landing with ice shapes installed, and two takeoff configurations. The test was run in both air and in nitrogen with tunnel freestream conditions ranging from 120°F to -250°F, a Mach number range of 0.20 to 0.35, and chord Reynolds numbers of 1.61 million to 30 million (matching flight Reynolds number). Repeatability plots and residual plots show good within test repeatability, within the balance accuracy for most points, giving confidence in the data. The tunnel was run using best tunnel practices, including holding tight tolerances on the tunnel Mach number and total temperature while taking data. $C_{L_{max}}$ is shown to increase with increasing Re_C , as expected. Taping runs concluded that the model did not have any leak paths from the lower surface to the upper surface of the wing. Wind bending and twist were measured throughout testing, some representative results were shown.

Acknowledgments

The authors would like to thank the NASA Transformational Tools and Technologies (TTT) Project of the Transformative Aeronautics Concepts Program (TACP) and the NASA Aerosciences Evaluation and Test Capabilities (AETC) office, both under the Aeronautics Research Mission Directorate (ARMD), for their funding and support of this work. The authors would also like to thank and acknowledge the NTF staff for their hard work during the test.

References

- [1] Lacy, D. S., and Sclafani, A. J., "Development of the High Lift Common Research Model (HL-CRM): A Representative High Lift Configuration for Transonic Transports," 2020 AIAA Aviation Forum, 2020-2772, AIAA, Virtual Event, 2020.
- [2] Broeren, A. P., Ozoroski, T. A., Porter, C. E., and Hood, K. K., "Aerodynamic Effect of Artificial Ice Shapes on the 5.2% Scale Semispan High-Lift Common Research Model in the NASA National Transonic Facility," 2025 AIAA Aviation Forum, 2025-XXXX, AIAA, Las Vegas, Nevada, 2025.
- [3] Ertsgaard, M. L., and Winski, C. S., "Development of NASA 5.2%-Scale Semispan High Lift Common Research," 2025 AIAA SciTech Forum, 2025-1127, AIAA, Orlando Florida, 2025.
- [4] NASA, "5th AIAA CFD High Lift Prediction Workshop (HLPW-5)," Webpage, 2024. URL <https://hiliftpw.larc.nasa.gov/>.
- [5] Lacy, D., and Clark, A. M., "Definition of Initial Landing and Takeoff Reference Configurations for the High Lift Common Research Model (CRM-HL)," AIAA Aviation Forum 2020, 2020-2771, AIAA, Virtual Event, 2020.
- [6] NASA, "NASA National Transonic Facility," Webpage, 2024. URL <https://www.nasa.gov/directorates/armd/aetc/national-transonic-facility-ntf/>.
- [7] NTF, "NTF User Guide," NP 2012-12-354-LaRC, NASA, Dec. 2012.
- [8] Winski, C. S., Langston, S. L., and Rivers, S. M., "NASA 5.2% Semispan High Lift Common Research Model Wind Tunnel Test at the 14- by 22-Foot Subsonic Wind Tunnel," 2025 AIAA SciTech Forum, 2025-0249, AIAA, Orlando Florida, 2025.
- [9] Puelm, S., Schmidt, F. N., Rudnik, R., and Winski, C. S., "Low-Speed Testing of the 5.2% Semi-Span CRM-HL in the DNW-NWB Wind Tunnel," 2024 AIAA Aviation Forum, 2024-3516, AIAA, Las Vegas, Nevada, 2024.
- [10] Puelm, S., Schmidt, F. N., Rudnik, R., Schmidt, M., and Wolff, J., "Low-Speed Testing of Variations of the 5.2% CRM-HL With an UHBR Nacelle and a Krueger Flap in the DNW-NWB Wind Tunnel," AIAA SciTech 2025, 2025-0023, AIAA, Orlando Florida, 2025.
- [11] Evans, A., Lacy, D., Smith, I., and Rivers, M., "Test Summary of the NASA Semi-Span High-Lift Common Research Model at the QinetiQ 5-Metre Low-Speed Wind Tunnel," 2020 AIAA Aviation Forum, 2020-2770, AIAA, Virtual Event, 2020.
- [12] Mounton, S., Charpentier, G., and Lorenski, A., "Test Summary of the Full Span High Lift Common Research Model at the ONERA F1 Pressurized Low Speed Wind Tunnel," 2023 AIAA SciTech Forum, 2023-0823, AIAA, San Diego, California, 2023.
- [13] Mounton, S., Charpentier, G., and Lorenski, A., "Testing the Full Span High Lift Common Research Model at the ONERA F1 Pressurized Low Speed Wind Tunnel," AIAA Aviation Forum and Ascend 2024, 2024-3512, AIAA, Las Vegas, Nevada, 2024.
- [14] NASA, "Common Research Model," Website, 2025. URL <https://commonresearchmodel.larc.nasa.gov/>.
- [15] NASA, "CRM-HL Reference Geometry Files," Webpage, 2023. URL <https://commonresearchmodel.larc.nasa.gov/crm-hl-reference-geometry/>.
- [16] NWB, "NWB Tunnel," Webpage, 2023. URL <https://www.dnw.aero/wind-tunnels/nwb/>.
- [17] Pomeroy, B., Rivers, M. B., Walker, E. L., Brynildsen, S. E., Farr, N. L., Rider, B. J., and Hosseini, S. S., "National Transonic Facility Public Geometry Release and Summary," 2025 AIAA Aviation Forum, 2025-XXXX, AIAA, Las Vegas, Nevada, 2025.
- [18] Ertsgaard, M., and Winski, C. S., "Additive Manufacturing for NASA High Lift Common Research Models (CRM-HL) in Cryogenic Facilities," 2025 AIAA Aviation Forum, 2025-XXXX, AIAA, Las Vegas, Nevada, 2025.
- [19] Fahringer, T., Tran, L., and Keck, D., "Development of the model deformation system at the National Transonic Facility," AIAA SciTech Forum 2024, 2024-2573, AIAA, Orlando, FL, 2024.
- [20] "Trip Dot Pricing & order form 092022.docx for Web Industries, <https://www.webindustries.com/products/>," , 2022.
- [21] Gatlin, G., Parker, P., and Owens, L., "Development of a semi-span test capability at the National Transonic Facility," AIAA Aerospace Sciences Meeting 2001, 2001-0759, AIAA, Reno, NV, 2001.
- [22] "LaRC Calibration T.D. Record Form - T237 LF231 AOA Calibration Report Signed," , 2023.

- [23] Iyer, V., "A Wall Correction Program Based on Classical Methods for the National Transonic Facility (Solid Wall or Slotted Wall) and the 14x22-Ft Subsonic Tunnel at NASA LaRC," CR 2004-213261, NASA, Oct. 2004.
- [24] Langston, S. L., Winsk, C. S., and Rivers, S. M., "Reynolds Number Effects on a 5.2%-Scale High Lift Common Research Model," 2025 AIAA SciTech Forum, 2025-1514, AIAA, Orlando Florida, 2025.
- [25] Langston, S., Winski, C. S., and Rivers, M., "Reynolds Number Effects on the Surface Pressures on a 5.2%-Scale High Lift Common Research Model," 2025 AIAA Aviation Forum, 2025-XXXX, AIAA, Las Vegas, Nevada, 2025.