Development of NASA 2.7%-Scale Semispan and Full Span High Lift Common Research Models (CRM-HL)

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Both the 2.7%-scale semispan and full span High Lift Common Research Model (CRM-HL) were developed to support extensive experimental investigations in cryogenic facilities exploring Reynolds number trends, tunnel wall effects, and additively manufactured test articles. The 2.7%-scale CRM-HL was designed, analyzed, and fabricated as a tool to validate Computational Fluid Dynamics (CFD) code in alignment with High Lift Prediction Workshop (HLPW) objectives. The NASA 2.7%-scale CRM-HL semispan and full span models are part of the CRM-HL ecosystem of models built and tested around the world. These models are based on the same generic commercial high lift design, built at different scales, both semispan and full span, each designed to be tested in multiple configurations with the modular ability to test different part designs. The 2.7%-scale wind tunnel models were designed with modular components that enable its testing in several configurations, including takeoff and landing, as well as with and without the nacelle-pylon and landing gear. The same modular left hand wing supports testing of both the semispan and full span fuselages. The 2.7%-scale CRM-HL contains static and dynamic instrumentation. The test articles described herein will be tested in the NASA Langley Research Center (LaRC) National Transonic Facility (NTF) and will continue to be tested in other wind tunnels, such as the European Transonic Wind-tunnel (ETW), as deemed appropriate by the research community.

Nomenclature

Acronyms

AoA	=	Angle of Attack
BL	=	Butt Line
CAD	=	Computer Aided Design
CFD	=	Computational Fluid Dynamics
CRM	=	Common Research Model
CRM-HL	=	High Lift Common Research Model
DMLS	=	Direct Metal Laser Sintering
ESP	=	Electronically Scanned Pressure
HLPW	=	High Lift Prediction Workshop
HIP	=	Hot Isostatic Pressing
IB	=	Inboard
IML	=	Inner Mold Line
LaRC	=	Langley Research Center
LN2	=	Liquid Nitrogen
MAC	=	Mean Aerodynamic Chord
MS	=	Model Station
NASA	=	National Aeronautics and Space Administration
NTF	=	National Transonic Facility
OB	=	Outboard

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OML = Outer Mold Line
ReCoM = Reliance Consolidated Models
RMS = Root Mean Square
SS = Stainless Steel
WL = Water Line
WUSS = Wing Under Slat Surface

Symbols

α = Alpha / angle of attack, deg
C_L = Lift coefficient
M = Freestream Mach number
q_∞ = Dynamic pressure, psf

I. Introduction

The High Lift Common Research Model (CRM-HL) configuration was designed by Boeing in collaboration with the National Aeronautics and Space Administration (NASA) to generate open-source geometry representative of a modern commercial airplane using the high-speed CRM definition as the foundation for this effort [1, 2]. The NASA Langley Research Center (LaRC) National Transonic Facility (NTF) 2.7%-scale semispan and full span CRM-HL (full span shown in Fig. 1) are among a fleet of CRM-HL wind tunnel models that support the High Lift Prediction Workshop (HLPW) [3]. These wind tunnel models are large scale multi-year design and fabrication efforts unique to the ground testing community in their modularity, complexity, and open-source nature.

The 2.7%-scale CRM-HL is third in a series of test articles, following the 10%-scale CRM-HL and 5.2%-scale CRM-HL, designed by NASA in collaboration with Boeing for the CRM-HL Ecosystem. The 10%-scale CRM-HL [4] was intended to be used as the basis for test cases to be assessed in future AIAA CFD High Lift Prediction Workshops [3, 5] and was the foundation for the requirements development of the 5.2%-scale CRM-HL. The design of the 5.2%-scale CRM-HL [6-8] was used as the basis for the 2.7%-scale CRM-HL, third in the series, which completed fabrication by the NASA LaRC Reliance Consolidated Model (ReCoM) contractors in early 2025.

The 2.7%-scale CRM-HL serves as a test bed for improving state of the art Computational Fluid Dynamics (CFD), exploring Reynolds Number effects, wind tunnel wall effects, and advancing cutting edge technologies, such as additive manufacturing for use in cryogenic facilities. The results of these wind tunnel tests are made available to the worldwide research community, facilitating the comparison of different scale wind tunnel models tested in various configurations in multiple facilities across the globe.

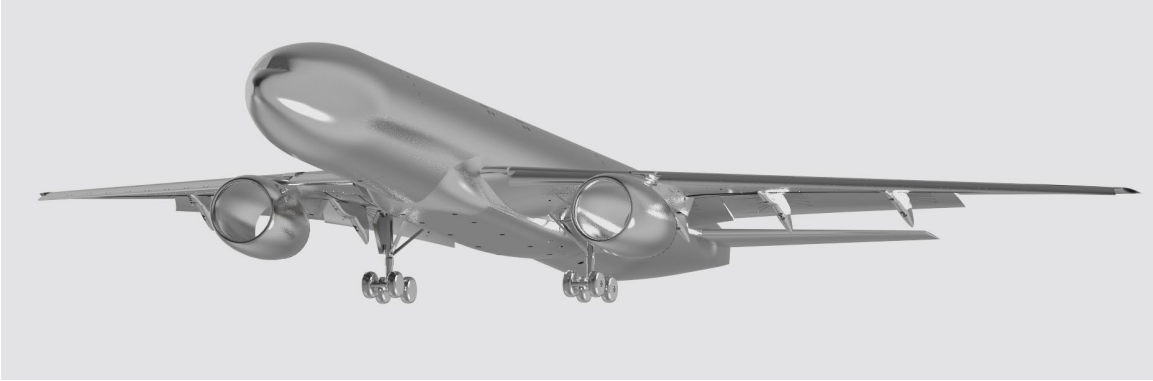


Fig. 1 As-designed 2.7%-scale Full Span CRM-HL CAD rendering in the landing configuration.

The 2.7%-scale CRM-HL models were designed, analyzed, and prototyped at NASA LaRC. The Aeronautics Systems Engineering Branch (ASEB) engineers supported requirements development, and performed the design and analysis of the wind tunnel models in accordance with NASA's Wind Tunnel Model Systems Criteria. ASEB also manages the ReCoM contract that vetted companies specialized in model design and fabrication. The fabrication

contract was competed by and awarded to Advanced Technologies Incorporated (ATI*) of Newport News, Virginia. ASEB engineers worked with ATI to ensure a quality test article was delivered at the end of the contract period.

The NASA 2.7%-scale CRM-HL full span model will be tested in two different wind tunnels: the National Transonic Facility (NTF) [9] located at the NASA LaRC and European Transonic Wind-tunnel (ETW) [Z] under an agreement between NASA and ETW.

Provided in this paper is an overview of the design, requirements, and fabrication of the 2.7%-scale semispan and full span CRM-HL wind tunnel model for testing in the NTF (shown in Fig. 2). Additional design and fabrication will be performed for testing the 2.7%-scale CRM-HL in ETW at the end of 2025. The ETW efforts will not be captured in this publication.

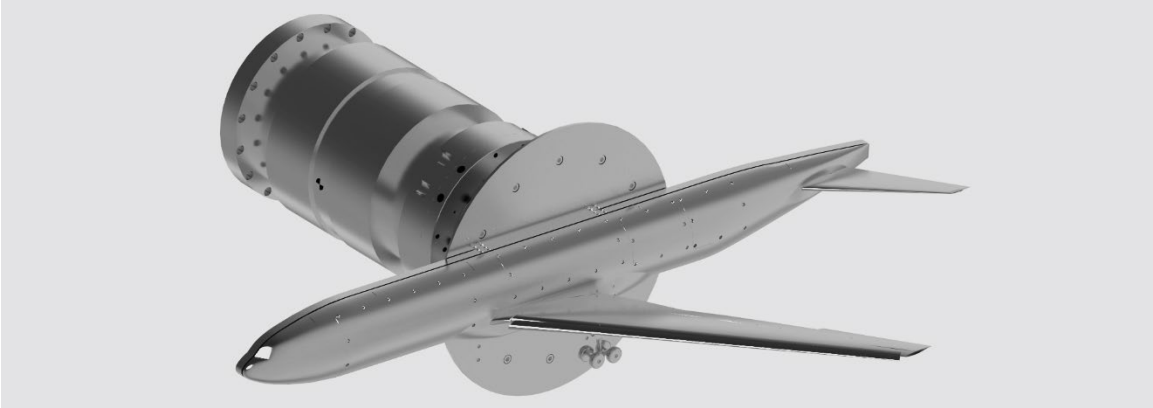


Fig. 2 As-designed 2.7%-scale Semispan CRM-HL CAD rendering in the landing configuration (no nacelle).

The CRM-HL is a 2.7%-scale semispan and full span model resembling a modern commercial airplane. The original 2.7%-scale NTF Full Span CRM test article consists of a fuselage, horizontal tail, mounting block, and Electronically Scanned Pressure (ESP) package as described below in Fig. 3. The pre-existing fuselage has been used in multiple wind tunnel testing campaigns over the years.

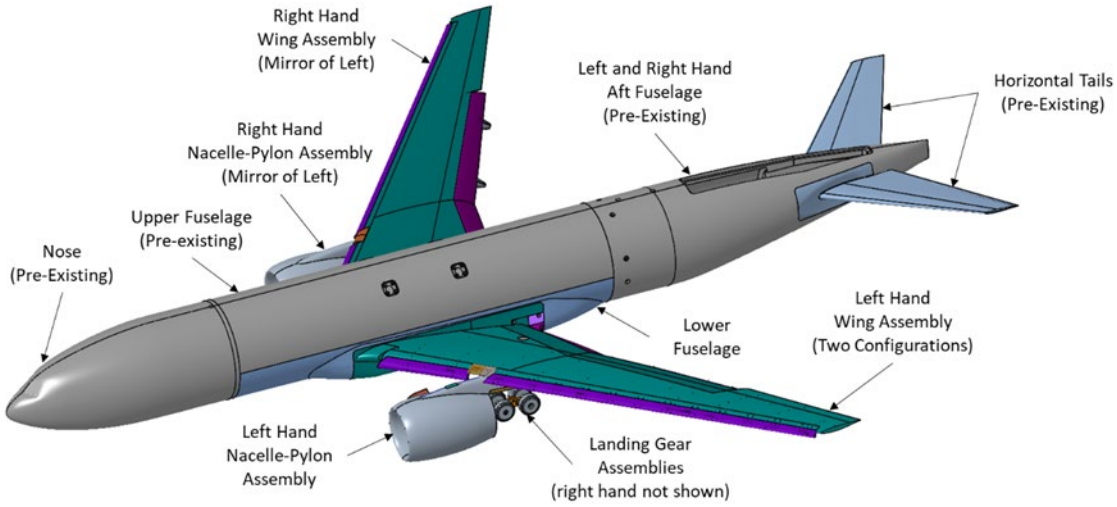


Fig. 3 CAD isometric view of the Full Span 2.7%-scale CRM-HL.

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The newly designed 2.7%-scale CRM-HL assembly includes the nacelle sub-assembly, landing gear sub-assembly, deployed leading and trailing edge sub-assemblies, and provisions for flow visualization inserts. The strake, aileron, and wing tip are integral components of the main spar. The Semispan 2.7%-scale CRM-HL is shown in Fig. 4 with the nacelle and landing gear sub-assemblies. Each of these components was designed to be interchangeable, allowing the opportunity to test a clean wing (landing gear and nacelle sub-assemblies removed) and for alternate designs to be tested on the wing in the future.

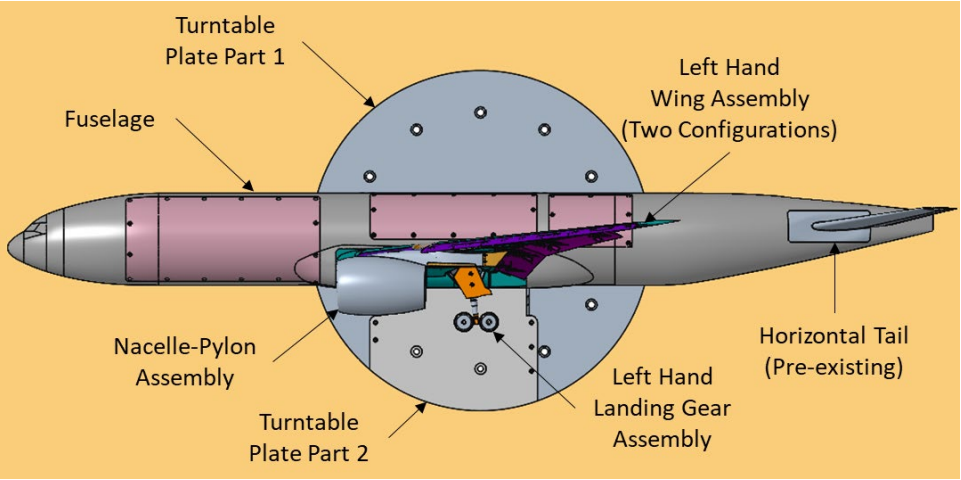


Fig. 4 CAD Butt Line (BL) station view of the Semispan 2.7%-scale CRM-HL.

II. Requirements and Development

Key model geometric reference parameters are:

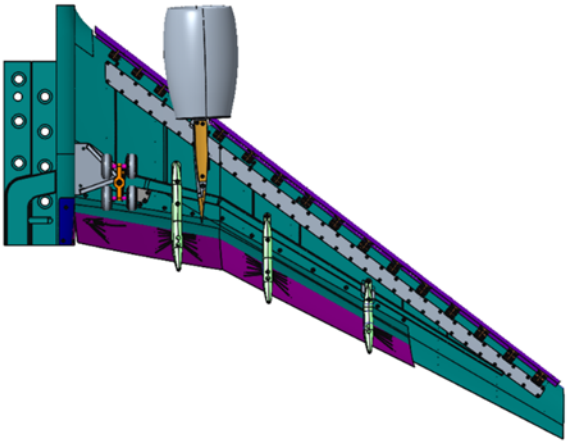
- Mean Aerodynamic Chord (MAC) 7.45 inches at butt line (BL) 12.66 inches
- Wingspan (semispan) 31.23 inches
- Reference Area 1.51 square feet
- Fuselage Length 5.56 feet

Requirements included, but were not limited to:

- Temperature range: -250°F to 120°F
- Maximum dynamic pressure (q_∞): 525 psf
- Angle of Attack (AoA) Range: -4° to 22°
- NTF Full Span Support Hardware: NTF-118A and NTF Upper Swept Strut
- NTF Semispan Support Hardware: NTF-117S Balance and Top Hat 1
- Operations: Air or Nitrogen
- Surface: 8 micro-inches Root Mean Square (RMS) or better on all flow surfaces, maintain upper Outer Mold Line (OML), minimize leak paths
- Tolerances: +/-.003 inch surface contour, +/-.010 inch planform, .001 inch aft facing step, .003 inch joint gap, .0015 inch leading edge, +/-.005 inch orifice location, no forward facing step
- Modularity: Design for takeoff and landing configurations, and removable nacelle-pylon, chine, and landing gear
- Repeatability: Provisions for pinning interfaces (e.g. pins between flap and wing interfaces)
- Longevity: Extended life of materials (e.g. ultrasonic inspection certificate of conformance)
- Compliance: NASA Technical Standard 8719.28, Wind Tunnel Model Systems Criteria
- Existing 2.7%-scale NTF Full Span fuselage, mounting block, and horizontal tail shall be used
- Permanent model deformation targets
- 315 static pressure taps distributed across 9 span-wise wing stations and 12 dynamic transducers

- Material selection: Vascomax® C-250, A-286, 18-8 Stainless Steel (SS), 316 SS, Vascomax® C-200, or Direct Metal Laser Sintering (DMLS) Inconel 718
- Adaptable to multiple wind tunnels; NTF, ETW, etc.

The 2.7%-scale CRM-HL Main Wing Assembly (Fig. 6) consists of a wing spar with modular high lift components, including slats, flaps, and a deployed trailing edge. While the trailing edge was designed as a separate component, it is not designed to be removed. A different set of brackets was designed for two different fixed flap deflections (1 landing and 1 takeoff) and two different fixed slat deflections (1 landing and 1 takeoff). The flaps and slats were reused for each of the deployed configurations. Sub-assemblies, such as the nacelle-pylon and landing gear shown in Fig. 7, were also designed to be modular and removable to enable flexibility in performing future research. The 2.7%-scale CRM-HL was designed to allow for testing of nonoriginal parts. Additionally, the 2.7%-scale CRM-HL was designed with a new lower fuselage to restore the contour of the pre-existing 2.7%-scale Full Span Fuselage, which was also used to support testing of the High Speed (HS) CRM wings.



PART	TAKEOFF CONFIGURATION	LANDING CONFIGURATION
IB FLAP	25°	40°
OB FLAP	25°	37°
IB & OB SLATS	22°	30°

Not Shown: Landing gear off plate and nacelle-pylon filler

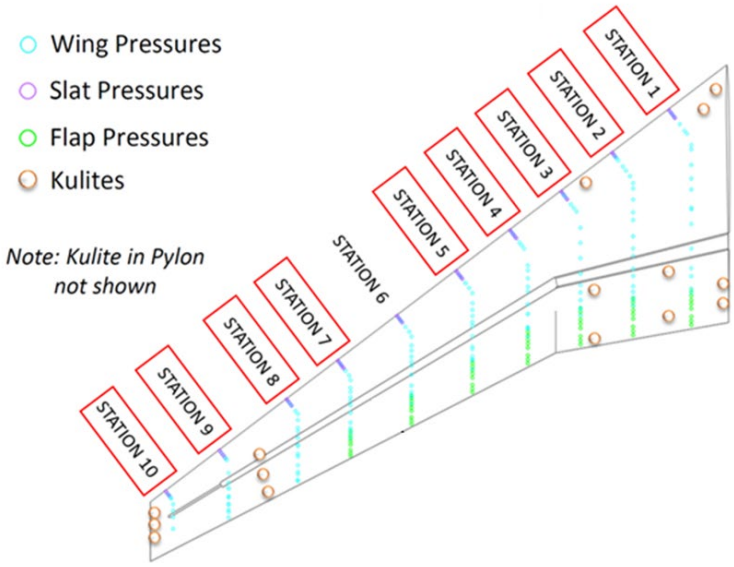
Fig. 5 NASA 2.7%-scale CRM-HL assembly configurations.



Fig. 6 Picture of additively manufactured 2.7%-scale CRM-HL landing gear and nacelle in machine shop.

A. Instrumentation

The 2.7%-scale CRM-HL was designed to support 315 static pressure ports (189 left hand and 126 right hand) distributed in streamwise rows at 9 discrete spanwise stations in all of its configurations. These pressure stations were down selected from the ten 5.2%-scale CRM-HL stations described in Fig. 7. The rows of static pressures on the leading edge of the 5.2%-scale CRM-HL changed direction [6]. Rather than following the streamwise station, the static pressures on the leading edge of the wing (starting at the quarter-chord) were transposed each following a plane normal to the leading edge [6], shown in Fig. 7. The decision to down select instrumentation from the 5.2%-scale CRM-HL was made during the design phase of the 2.7%-scale CRM-HL in collaboration between Boeing and NASA. Additionally, there were 12 dynamic transducers in the 2.7%-scale CRM-HL as shown in Fig. 7. Identifying the coordinates for these locations aided the CRM-HL ecosystem in prioritizing the reference transducer locations for the smaller scale test articles in the ecosystem.



CRM-HL Station	eta
1	0.160
2	0.251
3	0.333
4	0.415
5	0.501
6	0.596
7	0.692
8	0.774
9	0.882
10	0.968

Fig. 7 Down selection of instrumentation locations at 9 of 10 discrete streamwise stations.

Additionally, there were 12 dynamic transducers, 6 on each wing, in the 2.7%-scale CRM-HL described in Fig. 8. Down selecting and identifying the coordinates for these locations aided the CRM-HL ecosystem in prioritizing the reference transducer locations, especially for the smaller scale test articles, in the ecosystem.

Priority	Kulite	Length	MS	BL	Surface
1	A.2	0.500"	28.923	4.346	IB LE
2	A.6	0.100"	*13.823	*6.108	IB Flap
9	C.2	0.100"	46.735	25.814	OB Wing
4	B.2	0.100"	32.501	10.120	Slat Filler
5	A.4	0.100"	37.406	3.465	IB TE
6	D.2	0.100"	49.169	31.112	Wing Tip

Kulite MS and BL dimensions retrieved and scaled down from 5.2% CRM-HL drawing 1299897 Rev. A

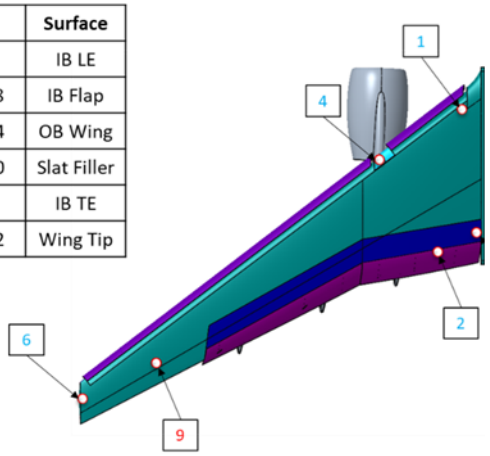
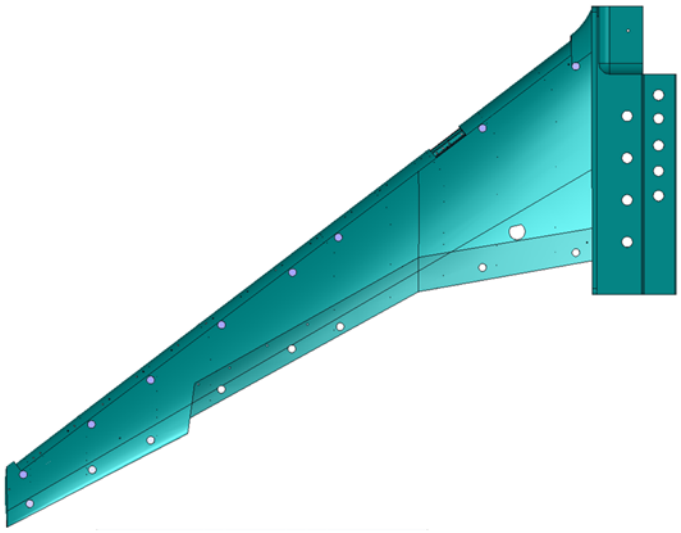


Fig. 8 Instrumentation locations at 9 discrete streamwise stations.

There were 16 deformation targets designed into the upper surface of each wing identified by required locations in Fig. 9. The coordinates captured describe the deformation targets on the left-hand wing only. The right-hand wing deformation targets are at the same locations, mirrored across the BL-plane. The intent of machining these deformation

targets into the upper surface was to ensure repeatability and higher contrast imaging. Previous models used fluorescent paint directly on the surface of the wing, which is then hand worked to contour to avoid tripping the flow during testing, compromising the visibility of the paint. As a result of the findings during the model preparation of the 5.2%-scale CRM-HL, the 2.7%-scale CRM-HL deformation targets were machined at a diameter of 3/8" and maintained a hole depth of .005 inch or less.



CAD Label	MS	BL	WL
PNT0	29.010	4.003	On Upper Surface of Wing
PNT1	31.963	8.466	
PNT2	37.162	15.365	
PNT3	38.833	17.555	
PNT4	41.328	20.950	
PNT5	43.956	24.344	
PNT6	46.173	27.328	
PNT7	48.262	30.135	
PNT8	37.889	4.004	
PNT9	38.599	8.467	
PNT10	41.468	15.376	
PNT11	42.476	17.589	
PNT12	44.404	20.960	
PNT13	46.828	24.341	
PNT14	48.387	27.336	
PNT15	49.852	30.124	

Fig. 9 Required deformation target locations.

B. Model – Tunnel Interface

The pre-existing 2.7%-scale CRM Full Span Model Assembly, shown in Fig. 10, was designed for testing in the NTF. The 2.7%-scale CRM NTF Fuselage is a five-piece metric assembly with fasteners used to secure the nose and aft fuselage to the mid-section of the fuselage. The tail of the fuselage consists of two parts assembled on either side of the balance adaptor and upper swept strut similar to a clam shell. The center section of the fuselage is also two pieces, upper and lower. The lower fuselage is captured between the wings and the pre-existing 2.7%-scale NTF Full Span Mounting Block and ultimately the NTF 118A Balance.

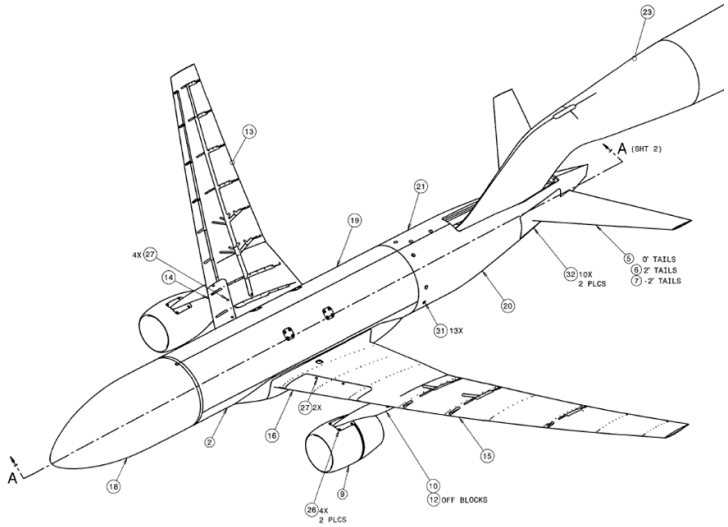


Fig. 10 Legacy Full Span 2.7%-scale CRM mounted to Upper Swept Strut.

The NTF 118A Balance is a 6-component balance mounted to the upper swept strut through the balance adaptor. The 2.7%-scale CRM-HL Wing Assembly is also metric and was mounted through the lower fuselage to the 2.7%-scale NTF Full Span Mounting Block (shown in Fig. 11) similar to the original 2.7%-scale CRM Wing Assembly. After the lower fuselage and wing assemblies are installed, the 2.7%-scale CRM-HL upper fuselage, nose, aft fuselage, and cover are installed to complete the fuselage contour.

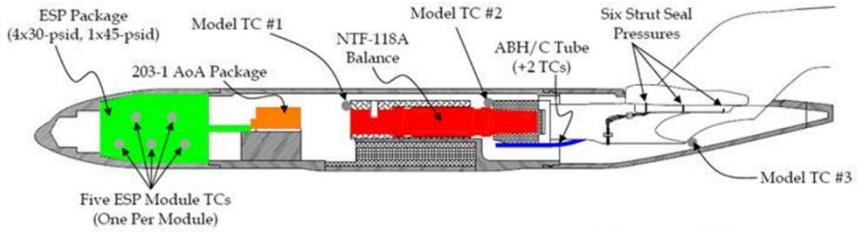


Fig. 11 Legacy Full Span 2.7% CRM mounted to NTF Balance 118A and interface.

The 2.7%-scale semispan fuselage and standoff were designed and fabricated as part of this effort. The semispan fuselage was designed as one continuous part from nose to tail. The four-piece standoff, shown in Fig. 12, was used to offset the fuselage one inch off the tunnel wall with as little flow getting in behind the fuselage as possible, is nonmetric, and was attached to the turntable with a Teflon seal. Together, the fuselage and the standoff create a labyrinth seal between their interfaces. Design efforts of the semispan were performed in tandem with the design of the 2.7%-scale full span to ensure both semispan and full span fuselages were compatible with the 2.7%-scale left hand wing assembly.

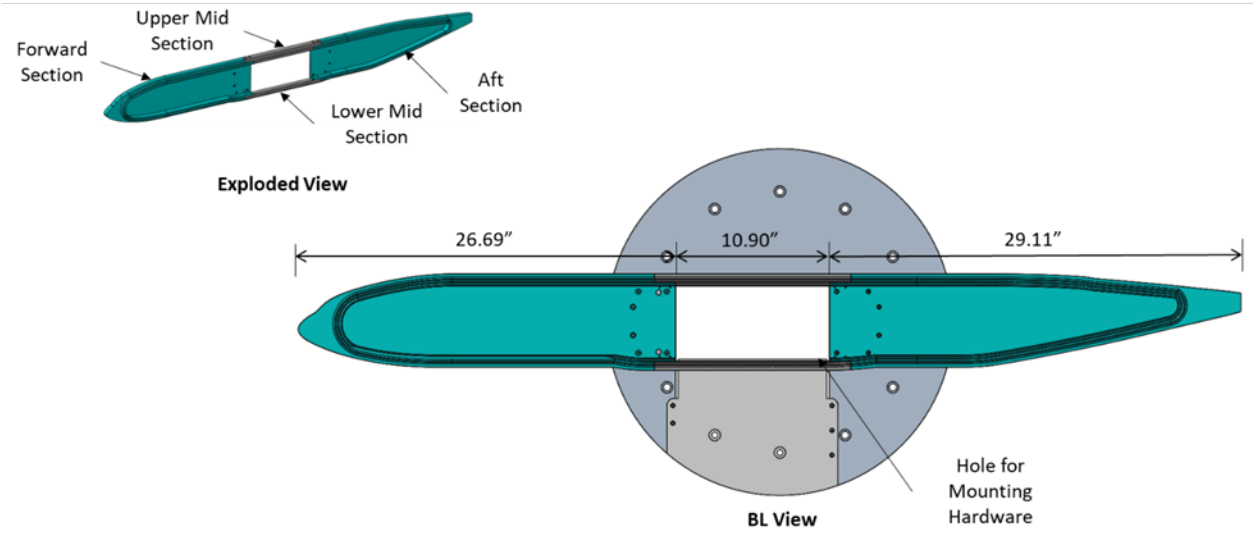


Fig. 12 Semispan 2.7% CRM-HL Standoff and Turntable geometry.

The semispan 2.7%-scale CRM-HL model support hardware was designed for integration with the semispan NTF Balance 117S. A new ESP Package, Spool, Mounting Block, and two-piece Turntable (shown in Fig. 12) were designed for integration into the installation assembly, as shown in Fig. 13. Similar to previous NTF installation hardware, the Mounting Block was fabricated from 13-8 SS H1150M and the Spool was fabricated from Vascomax® C-200. The new adapters were analyzed in accordance with NASA STD 8719.28.

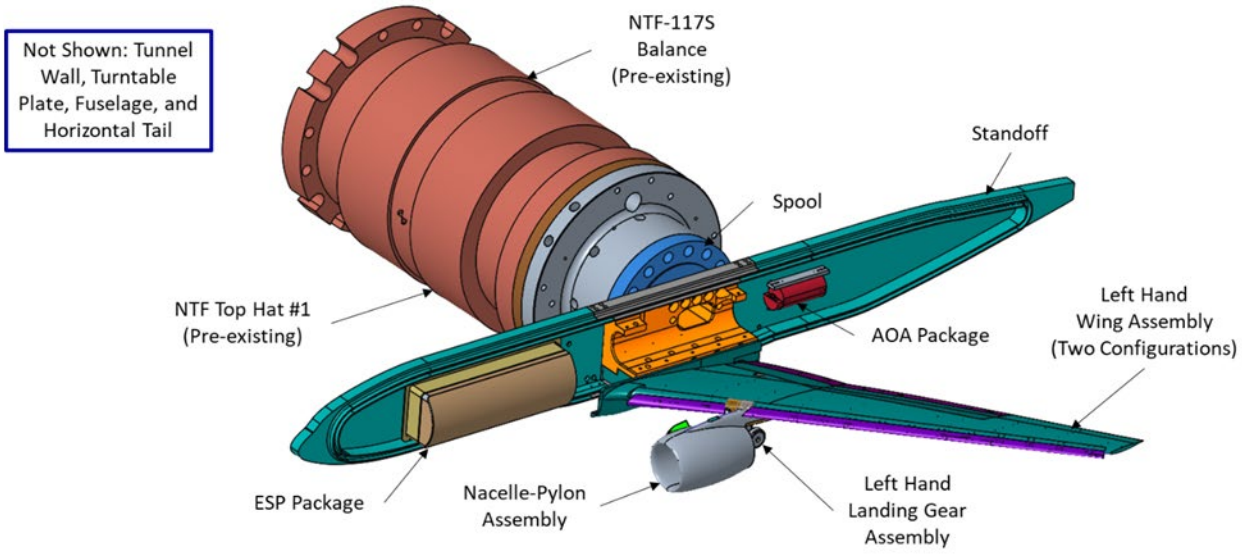


Fig. 13 2.7%-scale CRM-HL Semispan installation assembly.

Similar to the 5.2%-scale CRM-HL, the notional test plan for the NTF test was at Mach (*M*) .2 and .26, at a tunnel total pressure of 100 psia, and a maximum q_∞ at 582 psf at M .26. After discussions with NTF personnel, a decision was made to limit tunnel total pressure to 80 psia due to tunnel limitations, which lowered the highest q to 525 psf. This information was then used to generate tail-off load conditions[†] shown in Fig. 14 using the same method of determining loads as the 10%-scale CRM-HL[‡].

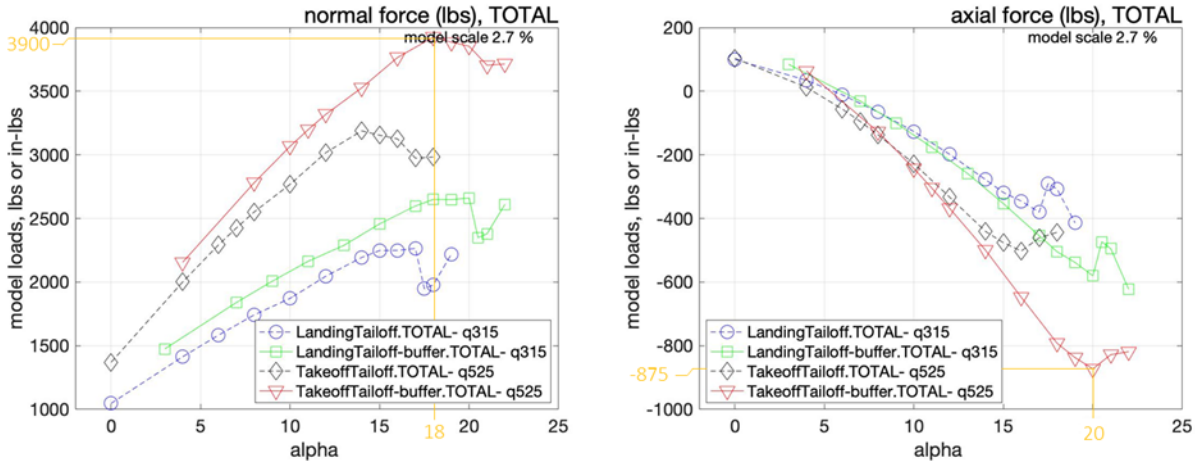


Fig. 14 Total calculated normal force (left) and axial force (right).

The design team used the load graphs and pixel ratioing to define the maximum load cases shown in Fig. 14 prior to distributing the total load across both wings. These maximum loads were used in the analysis of the structural joints throughout the model informing material selection and joint designs. Material selection was also influenced by the NTF's historical precedence with regard to thermal considerations and acceptable materials in the cryogenic testing environment. The NTF described an 11.6% increase in q_∞ (up to 586 psf) for conditioning at 0° AoA. That load case was used to inform the design of the 2.7%-scale CRM-HL.

[†] Rivers, S. M., "Determining Loads for NTF Cryogenic Models_v2", 2020. (Internal project document)

[‡] Hannon, J. A., "Estimate of maximum model loads for the 10% Common Research Model – High Lift in the 14x22", 2016. (Internal project document)

Maximum Loads				
Component	**Normal Force (lbs)**	**α_{NF} (°)**	**Axial Force (lbs)**	**α_{AF} (°)**
Total	3900	18	-875	20
Wing	2550	18	-300	20
Body	505	22	-32	22
IB Slat	105	18	-143	20
OB Slat	360	20	-455	22
IB Flap	142	8	59.5	4
OB Flap	178	11	57	7
Nacelle/Pylon	161	20	-45	20

Fig. 15 Maximum calculated loads by component.

C. Fuselage Assembly

The pre-existing 2.7%-scale NTF Full Span Model Fuselage Assembly will be used for testing the 2.7%-scale CRM-HL. The only intended change to this assembly was the lower section of the mid body, shown in Fig. 16. This decision was made because the integral strake on the wing extended too far forward to use the pre-existing fuselage without modification to the hardware. Since a new fuselage needed to be fabricated, the decision to create a cavity aft of the wing assemblies was made to facilitate instrumentation routing from the trailing edge. This allowed the instrumentation to be routed aft of the balance and ultimately over the mounting block to the ESP package, similar to the 5.2%-scale CRM-HL, which permitted the major instrumentation troughs to reside in similar locations [6]. This decision was made to ensure the bending of each wing was as similar as possible between the two different scale models. This also required the lower cover be extended to restore the fuselage contour.

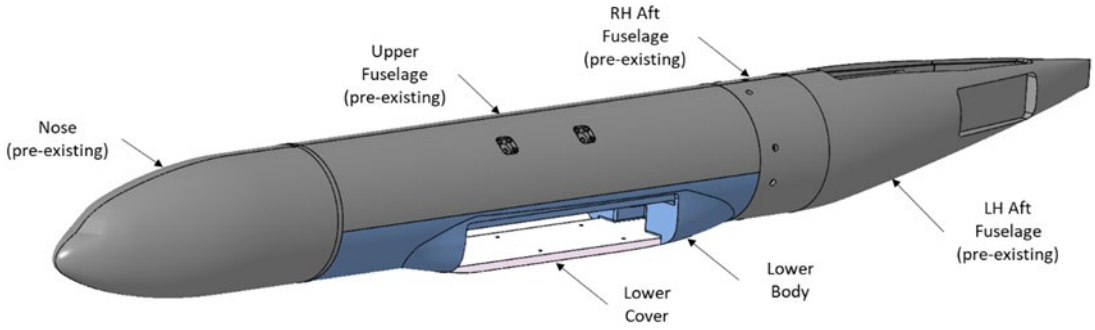


Fig. 16 2.7%-scale Full Span Fuselage components.

The new semispan fuselage, shown in Fig. 17, was designed as one continuous part from nose to tail with access panels for the ESP package, mounting block, and AOA bracket. A lower cover was included in the design of the semispan fuselage to allow access to the inboard row of fasteners. A portion of the fuselage contour was restored by the integral internal flap bracket assembly and is captured with the flap bracket design. The fuselage and fuselage covers were fabricated using 13-8 SS H1150M. The fuselage was assembled using A-286 fasteners.

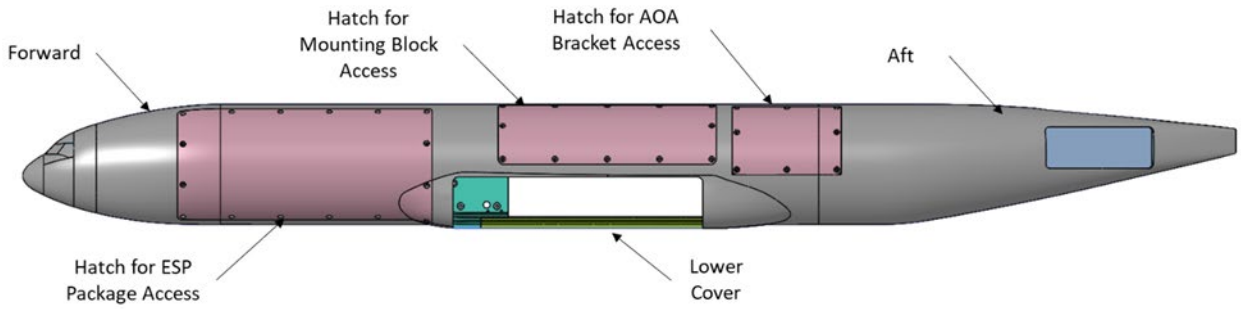


Fig. 17 2.7%-scale CRM-HL Semispan Fuselage components.

The semispan ESP package, shown in Fig. 18, was designed to house three 64-port ESP modules in the forward section of the fuselage, which accommodates the 189 static pressures in the left hand wing. The ESP package consists of two parts foam/fiberglass housing and a nylon additive manufactured frame. The ESPs mount to an aluminum plate, which acts as a thermal mass with two rectangular film heaters on the back of the plate. The plate fastens to the housing with flat head screws from the outside. Each ESP fits into the recesses in the plate and fastens with screws and clamps from the top of the fiber glass tub.

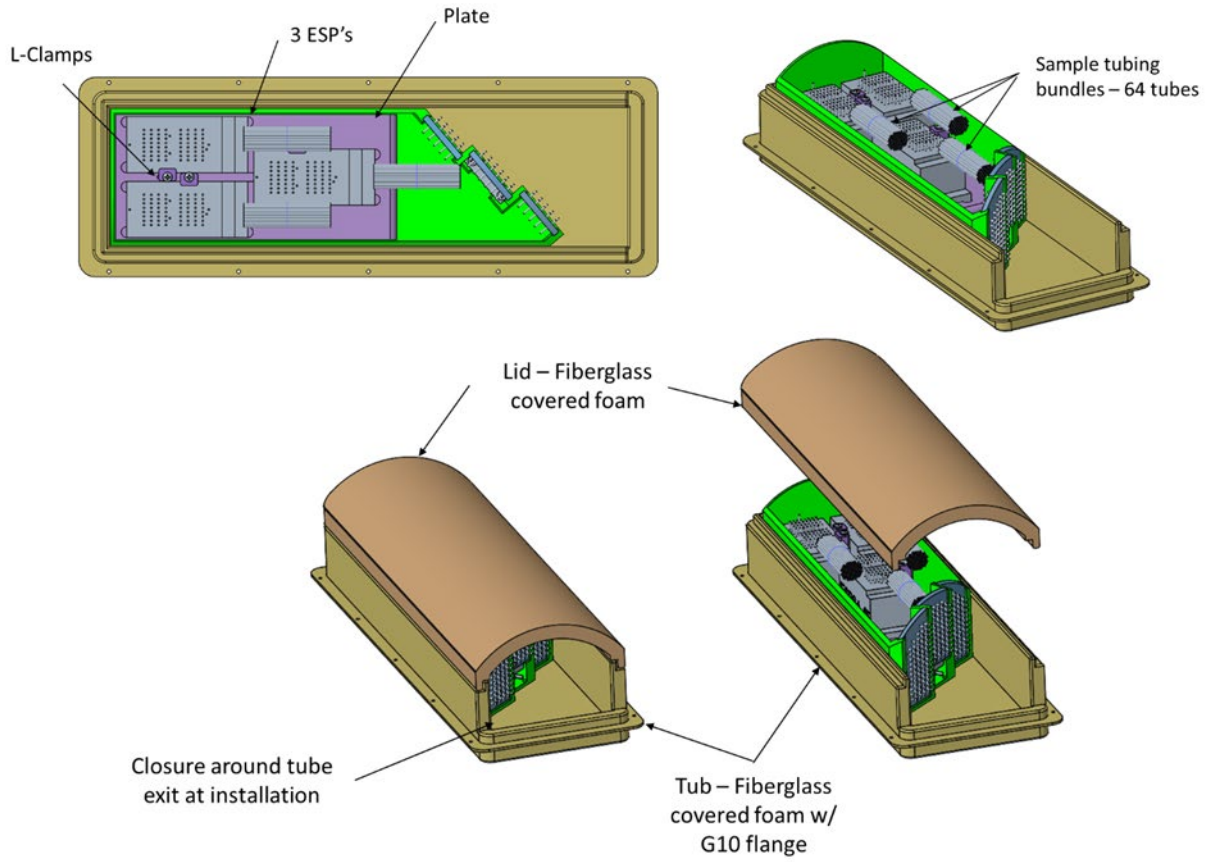


Fig. 18 2.7%-scale Semispan ESP Package.

D. Wing Assembly

The wing spar, shown in Fig. 19, was designed to attach modular high lift components that can be removed with no impact to the rest of the model. The components include the nacelle-pylon and landing gear. The part breaks were largely influenced by the geometry of each modular high lift component. The wing geometry uses the HLPW-4 scaled OML [3]. To allow for reasonable machining the trailing edges were re-lofted by Boeing, resulting in a .200" trailing

edge at full scale and a .010” trailing edge at model scale. The wing was fabricated using Vascomax® C-250 similar to the other CRM wings designed for testing in the NTF.

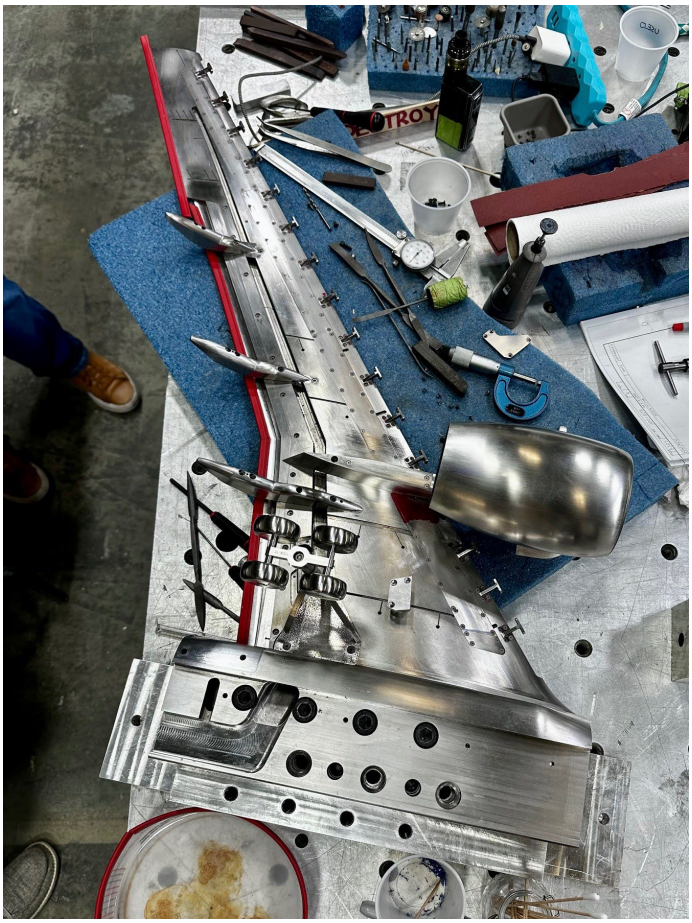


Fig. 19 Right hand wing assembly during fabrication (09/04/2024).

The previous 2.7%-scale CRM test articles were designed as cruise configurations without the ability to be tested in the deployed configuration. The 2.7%-scale CRM-HL was designed to be tested with a deployed leading edge assembly and a deployed trailing edge flap assembly. The strake, aileron, and wing tip are designed as integral components to the main spar. Multiple dynamic pressure transducers were installed in all three components.

The 2.7%-scale CRM-HL main spars were designed for static pressure tubing, dynamic transducer wiring, and miscellaneous instrumentation to be routed through the wing assembly into the fuselage without compromising the OML. While the contour was restored in all areas of the test article, using covers or epoxy, the intent was to maintain a clean upper surface of the wing. As a result, the instrumentation routing was primarily performed on the lower surface of the wing to preserve the upper surface OML.

Similar to the 5.2%-scale CRM-HL, all model instrumentation troughs exposed to the flow were designed to be filled with a mixture of epoxy and carbon microspheres once instrumentation work was complete. As of the fabrication of the 5.2%-scale CRM-HL, the original carbon microspheres are no longer being manufactured [6]. LaRC and ReCoM contractors procured a supply of carbon microspheres from a new vendor to complete instrumentation efforts.

The new carbon microsphere and epoxy mixture is particularly noteworthy in the wing, which is home to the largest instrumentation troughs in the wind tunnel model, shown in Fig. 19. The leading and trailing edge pressures are exposed to the flow independent of the epoxy and carbon microsphere filler. The introduction of a new carbon microsphere mixture, along with machining errors during fabrication, prompted additional materials research. The nondestructive evaluation of two separate test specimens, shown in Fig. 20, were performed using a Keyence after the discovery of a small undercut in the right-hand wing and an undercut in the fuselage fairing (integral to the right hand wing), during fabrication.



Fig. 20 Filler test specimens.

The undercut in the wing measured .050”W X .060”D at its maximum dimensions. It was decided that the undercut was superficial, and a plan was initiated to fill the contour. The first test specimen was prepared with six fillers to be evaluated on a small piece of Vascomax® C-250 before, during, and after liquid nitrogen (LN2) submersion. The test specimen was machined at six locations, using the same dimensions as the undercut, to explore options to restore the contour of the wing. The six materials explored, shown in Fig. 21, from right to left were 1) Silvabrite 100 (Ag 0.5, Sn 95.5, Cu 4.0), 2) Weldment – material not defined as welding test articles is not an acceptable corrective action for cryogenic wind tunnel models, 3) Staybrite 8 (Ag 5.5 – 6.0, Sn remainder), 4) BAM CM-1 mixed with Hysol/Loctite 9309 (new 1:4 by weight ratio), 5) Hysol/Loctite 9394, and 6) Indium Corp 119 (50 Sn, 49.5 Pb, .5 Sb).



Fig. 21 Pre LN2 submersion of filler test specimen.

The test specimens were both vacuum bagged in SS foil and evacuated to 30 microns prior to being submerged into a bath of LN2 (approximately 20-25 Liters) until the LN2 stopped boiling indicating thermal equilibrium within the cryogenic medium. This was timed to be 20 minutes of submersion. They were then removed and allowed to return to room temperature. This process was repeated for 10 cycles prior to being removed from the vacuum bags, evaluated, and submerged in LN2 for further evaluation. When the specimens were removed from the vacuum bags, it was discovered that roughly a 34 mm section of the 9394 filler departed during LN2 submersion[§], as shown in Fig. 22. The filler may not have been fully bonded from the start, which could have been the cause of the failure. A roughly 0.1 mm gap in the cross-section of the Staybrite 8 was measured when the specimen was immersed in LN2. Otherwise, no detectable changes were found in either block.

[§] Alexa, J.A., “NTF LN2 Exposure Draft Final 1”, 2024. (Internal project document)

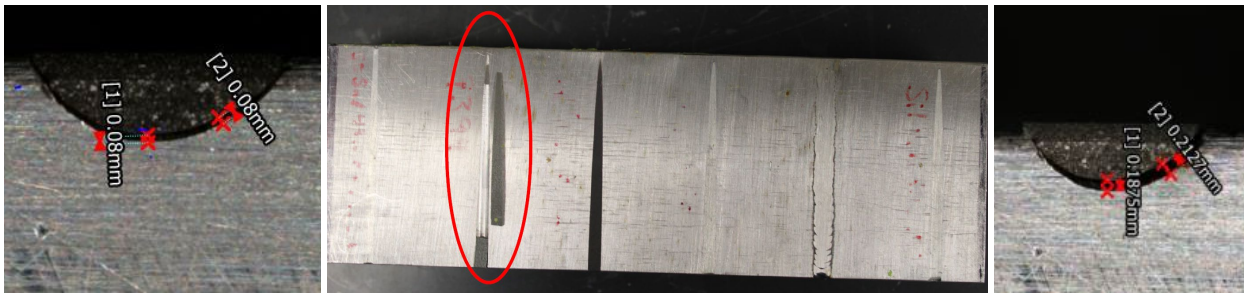


Fig. 22 9394 Pre-LN2 imaging (left) and post LN2 submersion (middle and right).

The solders were carefully considered with the understanding that tin-rich solders exhibit low temperature ductile-to-brittle transitions [11]. As a result, Indium Corp 119 soft solder and Silvabrite #100 hard solder (previously used on the 5.2%-scale CRM-HL) were approved for use in the NTF post material testing, with a recommendation for use of soft solder over hard solder where possible to reduce the amount of heat exposure to the maraging steel. Any areas that might need hand worked after application, to meet surface tolerance requirements, were recommended to be filled with hard solder.

E. Leading Edge Assemblies

One deployed leading edge assembly was designed as part of this effort with provisions for both a takeoff and landing configuration. Two different slat configurations can be tested, a 22° (takeoff) and a 30° (landing) angle. The leading edge features one inboard slat, one continuous outboard slat, and 15 slat brackets; 3 inboard and 12 outboard. The slats and slat brackets were fabricated using Vascomax® C-250 and assembled using A-286 fasteners.

The covers in the leading edge can be removed, after disconnecting instrumentation, with no impact to the rest of the model. The covers feature lap joints to minimize leak paths that have the potential to affect the lift coefficient, C_L. Similar to the 5.2%-scale CRM-HL, the leading edge is designed to keep the slat installed while the brackets are changed out during model changes. While adjustability was considered at this scale, the model is not designed for adjustability in gap and overhang.

The inboard and outboard slats were designed to remain installed while the nacelle-pylon assembly is installed/removed. However, when the nacelle-pylon assembly is removed, a different inboard slat is installed (shown in Fig. 23). This required the fabrication of two separate nacelle-off landing and takeoff inboard slats. This was decided due to the limited cross-sectional area in the slat, allowing very little room for fasteners in this area of the test article. One deployed inboard slat was considered, but the deflection of the slats was not uniform from inboard to outboard. This transition is typically resolved across the slat filler. Additionally, each of these components feature a mortise and tenon joint for durability.

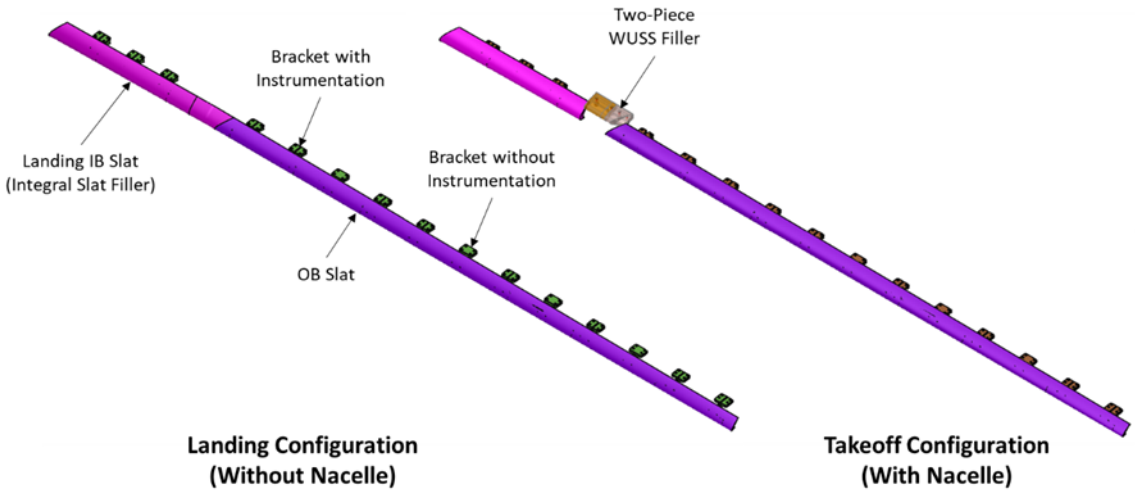


Fig. 23 Slat Filler (nacelle-off) and Slat Filler stowed (nacelle-on) CAD drawings.

Similar to the 5.2%-scale CRM-HL, the slat brackets were designed using a u-shaped bracket (shown in Fig. 24) similar to the description provided in Ref. [2]. The slat brackets were built with the wing OML from the Wing Under Slat Surface (WUSS). The rectangular cross-section of the bracket is scaled from the full-scale CRM with additional height added for strength. The final cross-sectional dimensions were .103" wide and .234" tall. The mounting features were then modified adding additional material on either side of the bracket to accommodate #1 and #2 fasteners. The final width of the mounting feature (slat side) was .610".

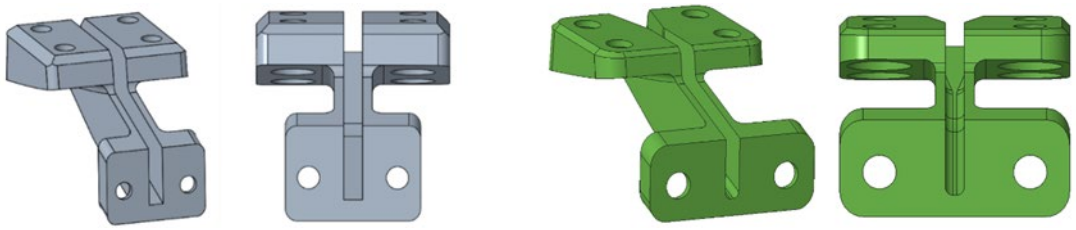


Fig. 24 Landing configuration bracket 5 at 5.2%-scale (left) and 2.7%-scale (right) CAD drawings.

The slat brackets were prototyped by ASEB during the design phase, as shown in Fig. 25, and explored to confirm the slat brackets could realistically accommodate the routing of static pressures. The slat brackets were additively manufactured using nylon, then ABS, and eventually Inconel 718 (stress relieved only) to explore the possibility of 3D printing this component of the test article. The dimensions of the Inconel 718 bracket were within +/-.003" on all dimensions. As a result, the option was given to machine or additively manufacture the brackets. The contractor ultimately opted to machine the slat brackets from Vascomax® C-250 similar to the 5.2%-scale CRM-HL slat brackets. Examples of the final machined brackets are shown on the right hand side of Fig. 25.



Fig. 25 Pictures of slat bracket prototypes.

The decision to machine the slat brackets required they be ganged together as shown in Fig. 26.



Fig. 26 Pictures of slat brackets during fabrication.

F. Deployed Trailing Edge Assembly

One trailing edge assembly was designed as part of this effort with provisions for both a landing and takeoff configuration. While the trailing edge (cove) is technically removable, it is not intended to be removed as the 2.7%-scale CRM-HL was not designed for testing with a cruise trailing edge. For the deployed flap assembly, two different flap configurations can be tested. The inboard flaps can be rigged to 25° and 40°. The outboard flaps can be rigged to 25° and 37°, as shown in Fig. 27.

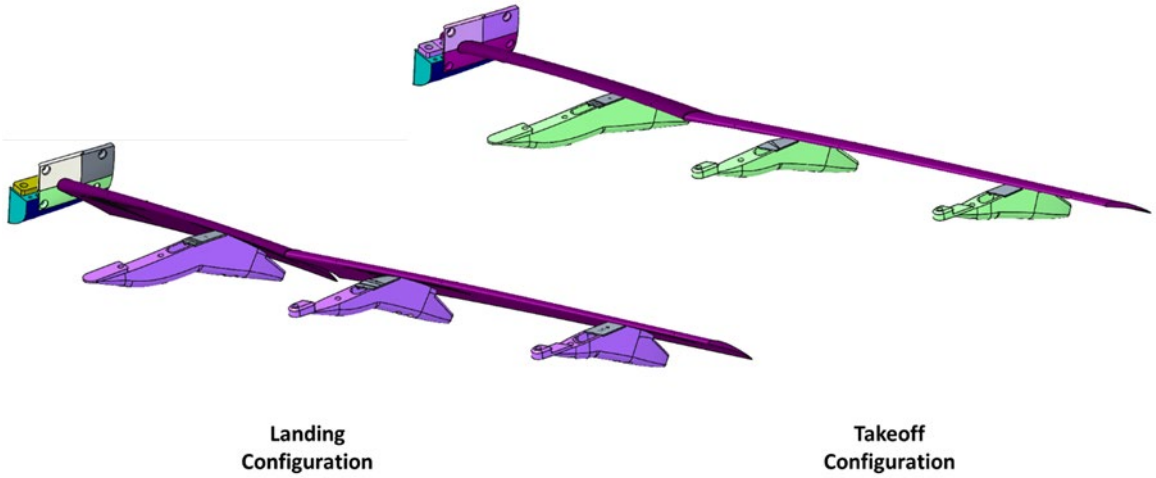


Fig. 27 Flap deployed configurations.

The trailing edge features four flap brackets, two outboard, one inboard, and one in the side of body. The three flap brackets in the flow are designed as integral flap track fairings for added stiffness and to carry the flap load. This allowed the instrumentation to be routed through the flap track fairings with covers used to prevent a pressure build up inside the flap track fairing. The 2.7%-scale CRM-HL flap brackets were fabricated using Vascomax® C-250 and assembled using A286 fasteners.

The flaps were designed to be modular supporting multiple flap configurations with the ability to remove the assembly, after disconnecting instrumentation, with no impact to the rest of the model. Similar to the leading edge, the trailing edge components, shown in Fig. 28 feature lap joints to minimize leak paths that have the potential to affect the C_L. The flap bracket changes are designed to keep the flap installed while the brackets are changed out.

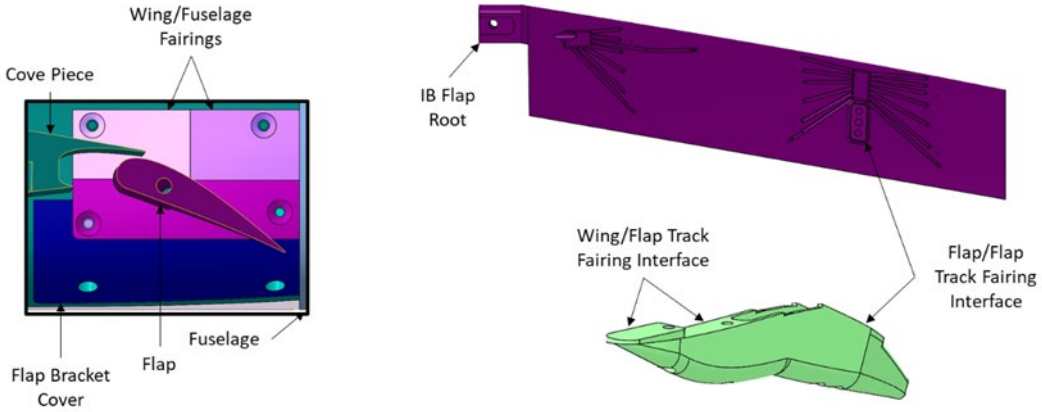


Fig. 28 Trailing edge components (takeoff configuration shown).

The installation sequence of the wing/fuselage fairings is described in Fig. 29. Each section of the fuselage must be removed in this order to access the inboard flap bracket before removing the final fuselage fairing. Each internal flap bracket is unique to its flap deflection. This design allows the possibility of fabricating new fuselage fairings and brackets in the future to test different flap deflections.

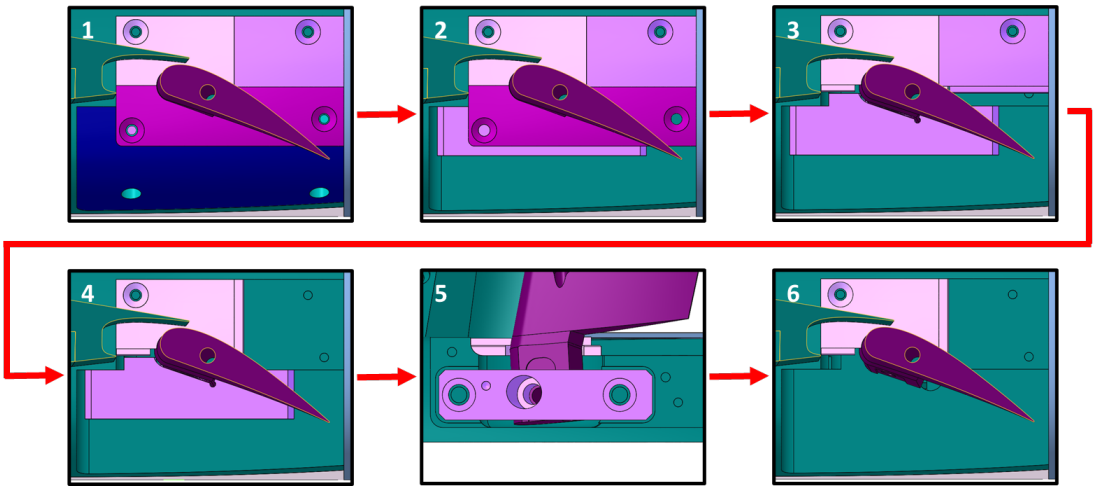


Fig. 29 Inboard Flap Bracket installation sequence.

G. Landing Gear Assembly

The 2.7%-scale CRM-HL landing gear assembly geometry shares an OML with the 5.2%-scale CRM-HL. Similar to the 5.2%-scale CRM-HL efforts, the landing gear truck was the only additively manufactured component in the landing gear assembly, made from DMLS Inconel 718. When the landing gear is not installed, the landing gear door is installed in its place. The final design of the 2.7%-scale CRM-HL landing gear is shown in Fig. 30.

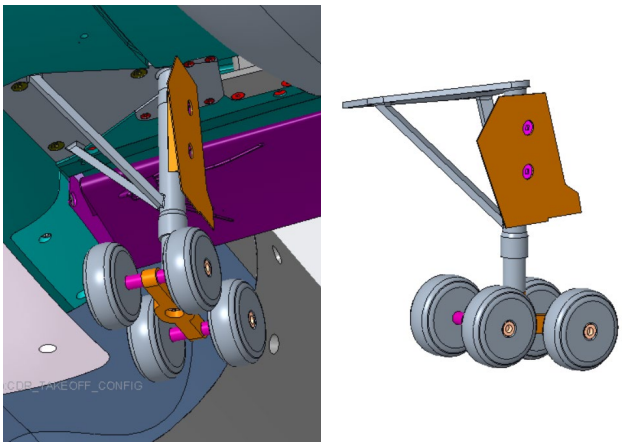


Fig. 30 Left hand landing gear installed (left) and left hand landing gear sub-assembly (right).

The landing gear is equipped with anti-rotation pins to ensure the assembly does not rotate during testing. Additionally, each of the four wheels feature anti-rotation sleeves to ensure they do not rotate during testing. The as-built additively manufactured nacelles and landing gear, post hot isostatic press treatment, are shown in Fig. 31.



Fig. 31 Right hand and left hand additively manufactured nacelles and landing gear trucks.

H. Nacelle-Pylon Assembly

The nacelle-pylon is designed in one integral piece, cowl and pylon, with a breakout panel for a chine as shown in Fig. 32. The nacelle features 8 static pressure ports. There are four breakout panels that can be installed allowing for testing without the chine installed, or with the chine installed in the upper, middle, or lower position, as shown in Fig. 33. This deviates from the 5.2%-scale CRM-HL nacelle chine design, which featured one modular breakout panel [6].

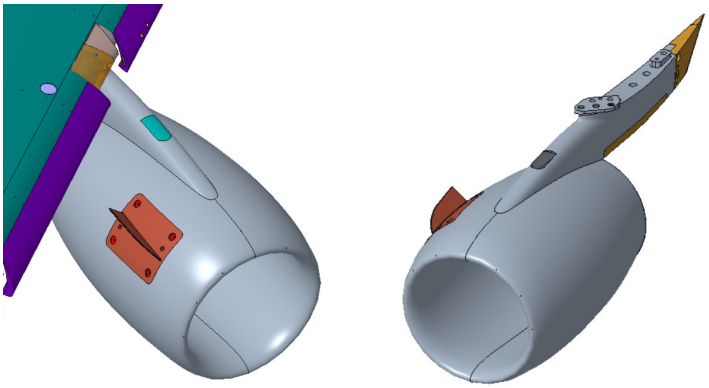


Fig. 32 Nacelle-pylon assembly with pylon filler (left) and nacelle cowl sub-assembly (right).

The 2.7%-scale CRM-HL pylon hatch was designed on the under surface for direct access to the fasteners and instrumentation, and to increase rigidity in the joint. The nacelle-pylon was originally intended to feature a quick disconnect mechanism for the 8 static pressures in the additively manufactured nacelle, however, it was decided during fabrication to eliminate this feature due to fitment issues. Previous versions of the conventional CRM nacelles have been equipped with quick disconnect mechanisms for static pressures.

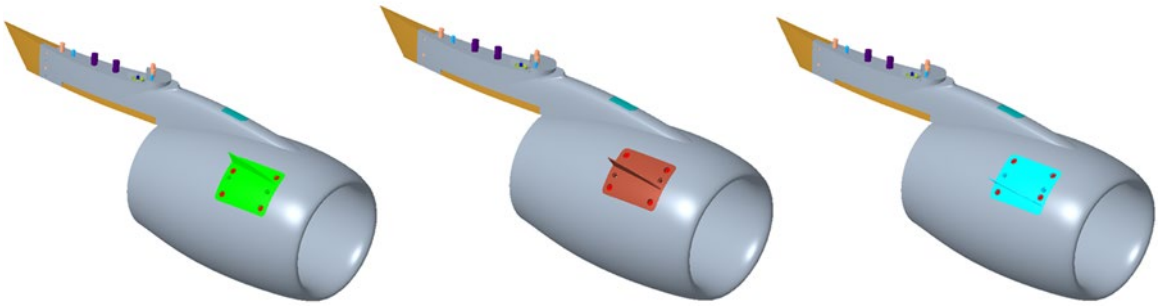


Fig. 33 Upper, middle, and lower chine positions.

Similar to the 5.2%-scale CRM-HL, the 2.7%-scale CRM-HL nacelle was additively manufactured leveraging DMLS Inconel 718 followed by Hot Isostatic Pressing (HIP) treatment [6]. Inconel 718 was selected as a candidate for this additively manufactured test article due to the nickel superalloy's high elastic moduli and high strength [11]. There was no historic precedent for the use of Inconel 718 in the NTF, prior to these test articles, likely because nickel alloys are difficult to machine [11].

The DMLS nacelle serves as one of many manufacturing demonstration articles for future wind tunnel models. Conventional manufacturing techniques require surface routing of instrumentation while additive manufacturing locates instrumentation routing beneath the OML and alleviates the need to violate the surface contour. That is particularly important for smaller scale models, like the 2.7%-scale CRM-HL, where instrumentation routing would violate a larger percentage of the OML. The nacelle was designed with 8 internal passages, referred to as wormholes, that terminate in pressure taps, shown in Fig. 34.



Fig. 34 CAD drawing of DMLS nacelle shaded geometry (left) and wireframe geometry (right).

The nacelle was built oversized by .050 inch, with the extra material to be removed during post machining using a 5-axis Computer Numerical Control (CNC) Machine. No significant shrinkage or difficulties during the additive manufacturing process were reported by the sub-contractor.



Fig. 35 Left hand DMLS parts (left) and right hand DMLS parts (right).

However, after the integral nacelle-pylon was received, the ReCoM contractor realized that the instrumentation cavity in the pylon was filled. The root cause of this anomaly was never identified. The part was salvaged by milling a slot through the pylon conventionally, which yielded slightly less cross-sectional area for instrumentation, leaving behind more material in the pylon. The integral nacelle-pylon is shown during post machining in Fig. 37.

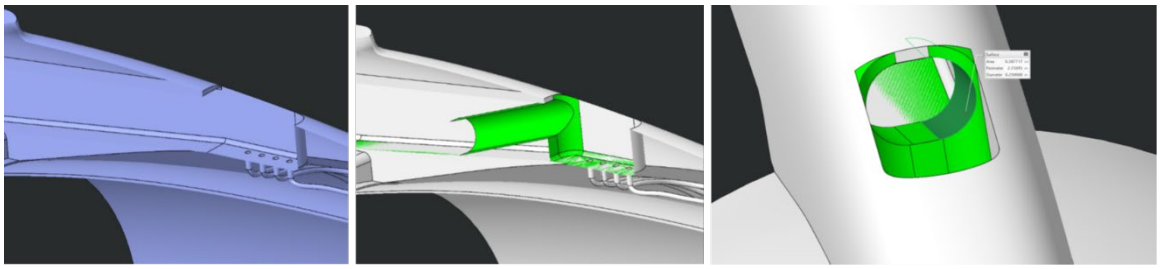


Fig. 36 As-designed DMLS instrumentation cavity (left) and conventional cavity (middle and right).



Fig. 37 Left hand DMLS nacelle-pylon during post machining.

In addition to advancing technologies, there are certain aspects of the manufacturing of the 2.7%-scale CRM-HL that are too difficult to perform on automated machines. The instrumentation routing required the use of hands-on

manufacturing in which current industry personnel are not necessarily experienced. While the fabrication of the 5.2%-scale CRM-HL provided a unique opportunity to reintroduce the workforce to some of these methods [6], the 2.7%-scale still proved a challenge when intersect drilling for instrumentation at shallow angles and tapping maraging steel for small fasteners (e.g. #2-56). Some of the processes required ReCoM contractors to pursue options like electrical discharge machining and thread milling. The majority of the instrumentation in this model was designed to be .040" OD with a .020" ID. However, it was determined mid fabrication, that a .030" OD would be more appropriate for this size model and was used wherever possible.

I. Analysis

FEA (Finite Element Analysis) and conventional textbook methods were used to analyze the model's parts and assemblies in accordance with Wind Tunnel Model Systems Criteria, NASA STD 8719.28 [12]. The FEA analysis was performed using PTC Creo Simulate. The wing spar was analyzed using PTC Creo 5.0 Simulate Finite Element software. The takeoff configuration was used in the analysis since it is more highly loaded than the landing configuration with less available material for resisting loads. The wing spar was used independently to evaluate the assembly's displacement under load. All other components were omitted to decrease the complexity of the model, and since their cross-sectional areas are small when compared to the wing spar, they do not contribute much stiffness to the model. All materials were specified as Vascomax® C-250 with properties taken from MMPDS-24. The loading was applied to the wing spar and distributed, using a ratio of areas, at 14 points along the quarter chord of the wing. The FEA analysis confirmed that the model satisfied the requirements in NASA STD 8719.28 and was therefore safe to run at the prescribed testing conditions requested by the researchers.

III. Conclusion

The NASA 2.7%-scale CRM-HL full span and semispan wind tunnel models were designed, analyzed, and fabricated as part of a multi-year effort with support from multiple organizations. The 2.7%-scale CRM-HL shown in Fig. 38 is third, following the 10%-scale CRM-HL and 5.2%-scale CRM-HL, in a series of NASA CRM-HL wind tunnel models. These test articles are large scale multi-year efforts unique to the ground testing community in their modularity, complexity, and open-source nature.



Fig. 38 2.7% CRM-HL Full Span Buyoff.

Three full span 2.7%-scale CRM-HL wind tunnel testing campaigns have been scheduled in 2025. The first test campaign will be conducted at NASA LaRC NTF Wind Tunnel. The primary focus will be to perform a model checkout, using air runs only, before shipping it overseas. The second test campaign will be conducted at ETW. The third test campaign will be conducted in the NASA LaRC NTF Wind Tunnel. The primary focus will be on Reynolds Number Effects, using cryogenic runs. Additional wind tunnel investigations of the semispan 2.7%-scale CRM-HL will be conducted in the NTF with preliminary results available soon after. The design, analysis, and fabrication of

the 2.7%-scale CRM-HL served as a test bed for integrating additively manufactured test articles in cryogenic facilities.

Acknowledgments

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